Lulzbot TAZ Printer: Heat Bed Upgrade

CHARACTERIZATION AND DESIGN DOCUMENT

PRELIMINARY RESULTS & STATUS
(Version 7/9/13 Release)

For

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Preface

The Lulzbot Taz is an open source 3D printer, created by Aleph Object, Incorporated. Lulzbot uses dielectric heating to heat the plastic filaments for printing 3D objects. The coordinate system of the TK-0 correlates the xy-plane to latitudinal/longitudinal traversal. Traversal along the z-axis correlates to a height change. The print nozzle of the TK-0 is capable of traversing along the x-axis and the z-axis. The print bed of the TK-0 is capable of traversing along the y-axis. The bed has to be hot so the material doesn't stick and the material has to cool slowly enough for the next layer to stick to it. This project focuses on modifications to the print bed; therefore stability during y-axis motion must be maintained.

Intrepid Research and Development designed a "drop in replacement", improving heatbed performance, temperature distribution, and repeatability including providing a removable glass plate and increased print area while maintaining the existing system power supply and cost targets. This document contains results of experimentation with prototype designs and performance characterizations as well as design Objectives and Requirements (see the following sections: Objectives & Requirements, Contacts, and References. Project objectives were achieved with an analog design, namely, a 12"x12" commercial off the shelf (COTS) Kapton heater, powered by 120 VAC, was integrated with our mechanical design enclosure and operated at 180 Watts (existing power limit). Further details on these designs and preliminary results are provided below. Intrepid has already placed an order for two custom Kapton film prototypes specifically designed to further improve performance and control while facilitating production of a drop in replacement heat bed suitable for Taz's existing 12V 15A power supply. Trade space with respect to targeted cost bogey are analyzed. Delivery is expected by the end of July with final integration and characterization occurring shortly thereafter. The final version of this document will contain complete design documentation, including a bill of materials (BOM) and CAD models, as well as characterization results, lessons learned, and recommendations for future improvements.

I. Summary & Conclusions

(Additional Details forthcoming in August)

Intrepid Research and Development (IRD) has improved the heat bed design and performance while maintaining use of the existing 12V (15A 180W) power supply. Performance and usability improvements include:

- Even print bed temperature distribution - less than 10C variation from center (85C) to edges
- Reduced time to temperature / improved heat up time - around 5 minutes
- Ease of use / repeatability including:
    - Providing a removable glass printing plate for ease / quicker repeated use
    - Three point leveling for easy user fine tuning
    - Maximized print area to full 300 mm x 300 mm by eliminating top clamps

These improvements were accomplished through optimization of the heating element (utilizing a custom Kapton film design) and system thermodynamic design (suitable combination of insulative and conductive materials). These improvements are targeted for Taz Batch 3, to be produced in August and released in September.

II. Objectives & Requirements

1) Objectives

The primary goal of this effort was improving the TAZ (originally the TK-0) heatbed printing surface while maintaining a financial cost goal of around $100 for this part of the unit. Intrepid was to provide a working prototype of the parts required for the heatbed, leveling, and clamp/area Improvements along with corresponding proof of concept design documentation. The ideal solution (from Seth 5/22/13): Intrepid provide everything from the aluminum plate to glass plate; a "drop in replacement" with bed mounting scheme, leveling, heater, etc. all in one targeted for Taz Batch 3 Gen2 design spin.

The primary areas addressed for improvement were:

1. **Heating concerns (gradient distribution and time to temperature):** biggest problem is part warping due to uneven heat distribution. This was Intrepid's primary area of focus**.**
2. **Ease of repeated setup and stability of surface / ease of leveling during use:**
   - **2.1. Increased Print Area:** Currently (TK-0) clamps are reducing the xy-plane 300mm x 300mm glass to 275mm x 298mm usable area. The desire is to increase the usable area as close to 300mm x 300mm as possible.
   - **2.2. Stability:** Retain or improve the stability between the leveling screws and the print/heat platform: able to stay in place – assume this means not vibrating or shifting, wiggling etc.. during use / uneven weight loading of a potential 3-D object
   - **2.3. Ease and sustainability of leveling:** Current issues because of level adjustments determined in adjusting silicon pad (which is squishy) and can cause the glass on top to move undesirably. Intrepid looked into leveling based on the final top surface in order that any possible deflection in the silicon pad beneath will not change level.
   - **2.4. Repeatability:**
     - 2.4.1. **Removable Top Print Plate:** Would be nice to have removable glass plate, not glued w/ heater to bed as done currently (Seth mentioned 5/22/13). Reason is for rapid mfg of parts – take off glass plate to let part cool and replace with new one before heater completely cools. Be able to ensure that the leveling screw settings are not affected by removal of the entire print/heat platform. Another issue is needing to readjust level every time the glass is popped in and out = look into ensuring this level stays fixed.
     - 2.4.2. **Active Holding Desired** – provide the ability to flip over the printer and the plate won't fall out.
   - **2.5. Z-Height:** Retain or improve the amount of z-height available

2) Requirements

The following requirements, specifications, and reach goals guided the design efforts.

1. **Weight (from Seth 5/22/13)**
   - Heatbed assembly not to exceed 5lb.
   - Current Taz version is 4lb 2oz.

2. **Power:** Desire to work with a 12V DC 15A supply (180 W)
   - 24V doable (360W, 15A): they think they can run their system off 24V but prefer not to.
   - Willing to go up to 400W for a short time if heat up time can be significantly reduced = AC power to only our modified (induction) heatbed parts is allowable (but not preferred due to UL / OSHA issues with AC on chassis / high currents etc.).

3. **Cost:** Improve the heat bed / table surface for the TK-0 while maintaining a financial cost goal of around $100 for this part of the unit (plate, induction coil, peripherals, clamps, leveling screws, etc.)

4. **Heat Distribution (Primary Focus):** The biggest problem is part warping cause of uneven heat distribution. Improve the uniformity of the heat distribution – currently the temperature profile indicates that edges of the platform remain cooler than the center. This is creating complications with 3-D printing on the edges / corners of the plate.
    - **Current Taz System:** 30deg C gradient from the center to the corners of our heatbed [temp set at 85C]. If you move in about 1-2 inches from the corner it's only a 10deg C gradient. Point measurements with thermistor on plate. (from Seth 5/22/13).
    - **Intrepid Design: requested to be optimized for 85C and not to exceed variability of +/- 10 degrees from center to edges.**
        - 110-120C characterization and utilization a reach goal
    - **Thermistor and Control Scheme:** Prefer to utilize existing Taz thermistor control scheme as possible, i.e., don't implements a 2 zone control scheme requiring firmware changes,
        - Honeywell 100KOHM Thermistor, Digi-Key part number 480-3135-ND, http://www.digikey.com/product-search/en?x=-1031&y=-73&lang=en&site=us&KeyWords=480-3135-ND

5. **Warm-up Time:** Improve the amount of time required to bring the platform to the required temperature
    - Ramp up heat bed to temperature quickly ~ Desire 5-6 min. to warm up heat bed up to 85 deg. C (120C reach goal – not a driver) and any lower temp.
      NOTE: Before Taz system, TKO had to be set for 120C to get 85C, but with Taz, 85C thermistor = 85C plate temp [Seth 6/14/13]

6. **Maximize Print Bed Area and Improve Leveling:** Currently (TK-0) clamps are reducing the xy-plane 300mm x 300mm glass to 275mm x 298mm usable area. The desire is to increase the usable area as close to 300mm x 300mm as possible. A 3-point leveling scheme is also desired allowing for easier user fine tuning and more consistent results by removing the flexibility inherent with the spring clamps.

7. **Heat bed Layers and Dimensions: Goal is to have the summary of layers (total heatbed thickness) as thin as possible (not to exceed current 16 mm height) and no adhesives allowing disassembly and replacement of individual parts.**
    - **Taz's Heat Bed Layers (top to bottom):** 16 mm = glass (3.5mm) + heat pad (1mm) + air gap (8mm) + aluminum plate (3.5mm).
      1) PET Tape: adhesion for polymer
      2) **Borosilicate glass:** 300mm (=11.81") x 300mm x 3.5 mm thick – main table (Conductivity = 1.14 W/m C).
          a. Not to exceed 300 x 300 plate size at this time [Seth 6/14/13 conversation]
      3) RTV glue: sticks glass to heat pad
      4) **Silicon heat pad (12"x12") w/ thermistor (and open loop control)**
          - Think they're using 2.5 or 5 for safety purposes. Lulzbot didn't know, thought was 2 but limited by voltage (12V – 15 A) to around 1.
          - Current pad Thickness = 1 mm
              - Pad comes in different thicknesses (as low as 0.1mm)

5) ABS corner standoffs that are independently adjustable in each corner
6) **Aluminum plate (3.5 mm) with (8 mm)** air gap –helps for heat transfer (Conductivity = 205 W/m C)
   a. Not to exceed 14”x14” heatbed x/y area at this time [Seth 6/14/13 conversation]
   b. Must retain access to the slots in the side of the aluminum plate (wiring access)
   c. Seth recommended we maintain air gap for heat distribution purposes
7) Housings for bushings (igus LM10UUs) – slide on rods (below)
8) Two 10mm smooth rods (table slides on these rods via the bushings)

8. **Robustness:** Request the system be ruggedized to survive for repeated use and capable of surviving shipment without disrepair; survive 4 foot drop test.

9. **RoHs compliant:** Restriction of the Use of Certain Hazardous Substances in Electrical and Electronic Equipment (RoHS).

10. **Miscellaneous:** reduce materials, easier to use, reduce setup time (heat, level, etc.).

III. Final Proof of Concept: Two Zone Kapton Film with Insulated Enclosure

Improved existing system with alternative geometries, better materials, different thicknesses (plate), insulation (enclosure), etc…

1) Kapton Film Insulated Enclosure

Final Results Achieved:
(forthcoming in August)

Custom Kapton Heat Bed Design (Top-Down Description):
(Current design below, subject to change; final version forthcoming in August)

1. **Top Glass Plate:** Standard Taz top glass plate (3.5 mm thick, 30cm X 30 cm)
2. **Aluminum Sheet Insulation:** exact specs TBD
3. **Two-Zone Polyimide Kapton Film Heater:** 12” x 12”, 1 mm, 12 VDC, 171 ±5% watts total (15 Amps max.)
    a. 2 separate circuits
       Inner circuit 12VDC, 61.60 watts, 2.338 ohms ±5%
       Outer circuit 12VDC, 109.40 watts, 1.316 ohms ±5%
       (Outer circuit consists of 2 different zones for the edges and the corners).
    b. 2 Honeywell #135-104LAG-J01 Thermistors (only 1 used in final control scheme): 100K ohms (±10%) thermistor mounted into through hole in heater (one in center and 1 at edge).
    c. See Figure 2. Layout of Custom Kapton Heater Circuits (12”x12”, 171 W +/- 5%, 2 Zones)
4. **Insulation:** Thin layer as needed to minimize heat lost below the Kapton film
5. **Bottom Insulated Plate**: Fiberglass plate to provide vertical support; with insulation as necessary
6. **Mechanical Enclosure:** enclose the sides and optimizing heat to the surface while minimizing heat sinks, keeping heat away from the bottom stage. Supplement with insulation as necessary while allowing for support from the bottom and compression from the sides with flush surface maximizing usable print bed area.
7. **Mounting Spacers:** air gap maintained with three point leveling system allowing for user fine tuning; made of insulative material to keep heat from bottom stage
8. **Existing Taz bottom aluminum plate** (3.5mm thick)

2) Bill of Materials (with Prototype vs. Production Costs)

(Current design below, subject to change; final version forthcoming in August)

IRD HEAT BED BOM (Top-Down)		Prototype Cost / Unit	Productions Qtys. Cost / Unit		Notes	Link
1	**Standard available Taz top glass plate (3.5 mm thick, 300 mm X 300 mm)**	$13.50	$13.50		Existing Taz Part	
2	**Aluminum Sheet Insulation**	$24.00	$10.00	= Estimate		http://www.whimsie.com/aluminumsheetmetal.html
3	**Polyimide Kapton Film** (1 mm thick), 12"x12", 1.25 W/in^2, 120 VAC, 1.5A, 20 Ohms (run at 180W)	$550.00	$55.00	$45-$65	Custom = $1100 for two, with productions quantities at $45-$65. Lead time on production quantities?	http://thermalcircuits.com/
4	**Insulation** (minimize bottom plate heat sink) - household fiberglass or silicon		$10.00	= Estimates		-
5	**Bottom Plate** (structural support): 2.0mm thick, 300mm x 300mm = Fiberglass?	$20.00	$10.00	= Estimates		-
6	**Mechanical enclosure and insulation scheme:** (enclosing the sides and optimizing heat to the surface while minimizing heat sinks, keeping heat away from the bottom stage)	$195.00	$40.00	= Estimates		
7	**Mounting Spacers** (three point leveling system allows for user fine tuning and made of insulative material to keep heat from bottom stage)		$10.00	= Estimates		
8	**Taz Bottom Stage (aluminum plate, 3.5mm thick)**	$16.75	$16.75		Existing Taz Part	
	TOTAL	***$819.25***	***$165.25***			
	$135.00	***= Cost of Intrepid's new / added parts ($165 total cost minus the cost of the standard Taz top glass plate and bottom aluminum plate)***				

Figure 1. Bill of Materials for Intrepid's Heat Bed

3) <u>CAD Models and Drawings</u>

(more details forthcoming in August)

Custom Two-Zone Kapton Heater:

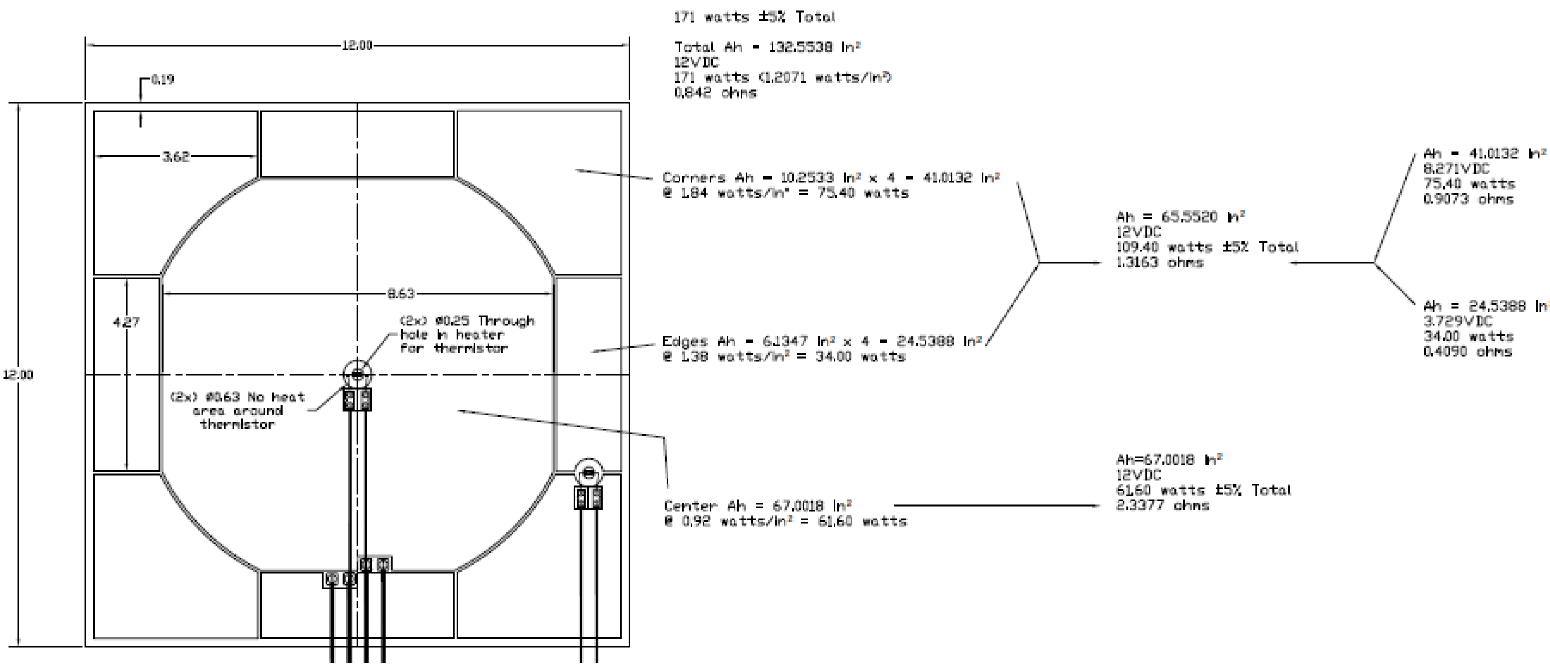

Figure 2. Layout of Custom Kapton Heater Circuits (12"x12", 171 W +/- 5%, 2 Zones)

IV. Other Investigations and Lesson Learned

1) Initial Analysis

Initial design, testing, and characterization utilized silicon head beds, resistor arrays and a myriad of thermal insulation materials to ascertain an appropriate design suitable to achieving all objectives within the given requirements. Ultimately, a heat bed design based on a Kapton film heating element and thermally insulated enclosure was produced. The Table below shows the results of our initial analysis in arriving at a Kapton Film design.

Critical ideas for heating possibilities. (+++ for Pro, --- for Con, ? for unsure, 0 for neutral)								
Critical Thinking Spreadsheet	Time	Degrees (C)	Evenness	Height	Complexity	$	Safe	
Goals	10 mins to 5 mins	85-120 deg	better evenness	Better or same	Simple	100	Keep Safe	**Overall Rating**
Ideas:								
Resistive Heating	(+)	(+)	(-)	(+)	(++)	(-)	(+++)	**A**
Inductive heating	(++)	(++)	(-)	?	(--)	(---)	(+++)	**C**
Silicon Resistive Heater (Kapton Film)	(+)	(+)	(+)	(++)	(++)	(+)	(+++)	**A+**
Fluid (air, brakefluid)	(++)	(+)	(++)	?	?	(-)	(-)	**B**
Di-electric	?	?	?	?	(---)	?	0	**D**
Ferro Fluid	(--)	(++)	(++)	(+)	0	(--)	(-)	**C**

Figure 3. Heat Bed Qualitative Design Trades

2) Preliminary Results: COTS Kapton Film (120VAC) [July 1, 2013]

The following results were achieved with a commercial off the shelf (COTS) Kapton heater (12"x12 Kapton film, powered by 120 VAC, operated at 180 Watts = an analogous design) integrated with a fiberglass enclosure.

Promising Results Achieved:

1. Improved temperature gradient from center to corners: currently 85C at corners (with even distribution) requires 40Vrms
    a. Allowed is 12VDC * 15 Amps = 180 Watts
    b. Very even temperature distribution (well less than 10 deg. C), most within 5 deg. C
    c. 85C is achieved at the very sides and corners well below our allowed power requirements --> Power required is (40V)^2 / 20 ohms = 80 Watts, or well less than half of allowed power.
2. There is great evidence to suggest an even temp. distribution above 110 C is possible within the allowed power requirements
3. Currently the total thickness of the heater (including the glass and alumni plate) is approx. 10 mm and the top glass plate is removable
    a. X/Y dimensions are maintained at 30 cm x 30 cm but lack of clamps provides increased print area
4. Warm up time to 85 deg. C is about 5 minutes.

5. Although the results we are achieving are with a 120 V AC rated Kapton film, we know these results are equivalent with a 12V DC film rated up to 15 amps (only 7 amps for 85 deg. C)

COTS Kapton Heat Bed Design (Top-Down Description):

9. Standard available Taz top glass plate (3.5 mm thick, 30cm X 30 cm)
10. Aluminum Foil Insulation: 5-6 pieces thick on top of Kapton film
11. Polyimide Kapton Film (1 mm thick), 12”x12”, 1.25 W/in^2, 120 VAC, 1.5A, 20 Ohms (run at 180W)
    a. “Kh-1212/(*)-P” (see “KH Series, Rectangular, 115 Volts” very bottom one on list @ http://www.omega.com/ppt/pptsc.asp?ref=KHR_KHLV_KH)

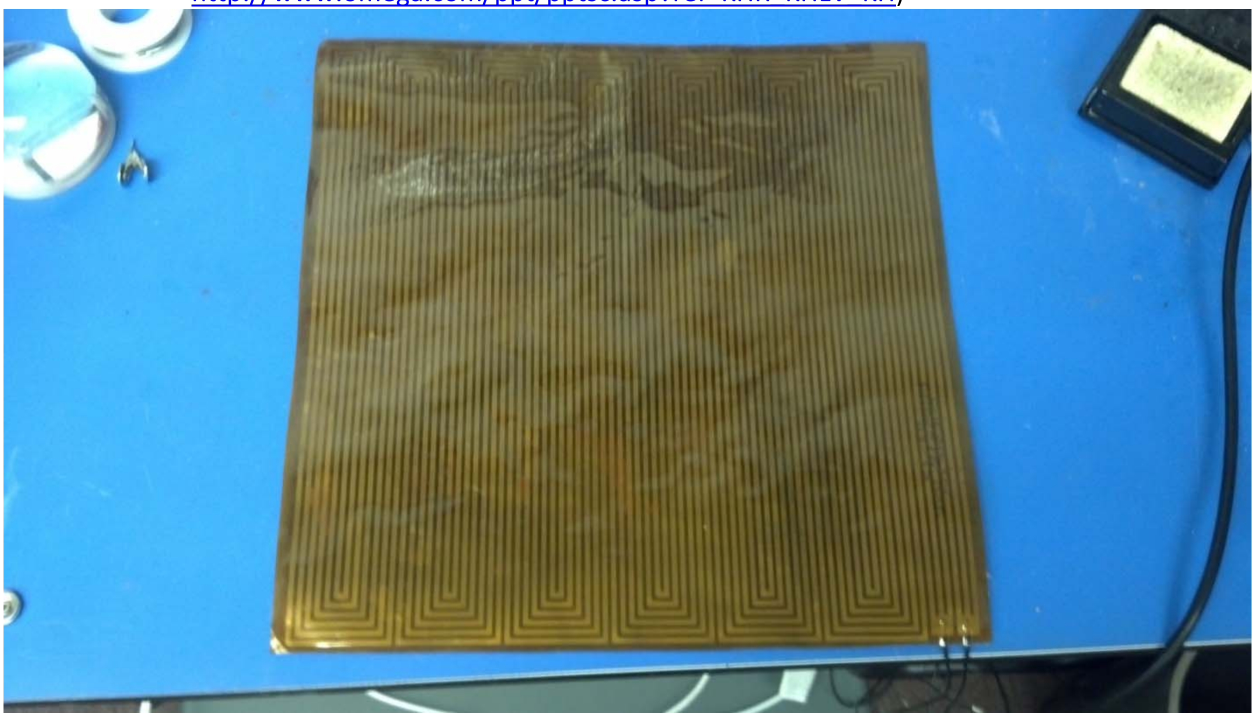

Figure 4. Picture of COTS Kapton Film

12. Insulation (fiberglass, 2mm thick) around outside edge and enclosing the sides and keeps heat off aluminum plate with 8” X 8” whole in middle: maintains air gap for temperature distribution.
13. Existing Taz bottom aluminum plate (3.5mm thick)

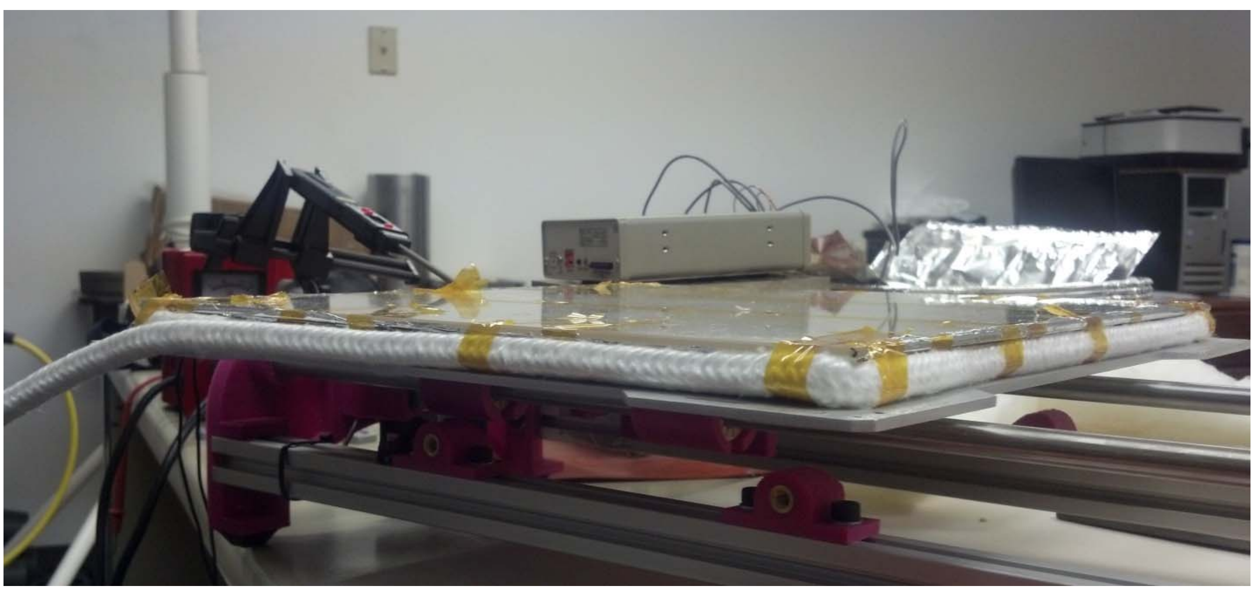

Figure 5. Pictures of Preliminary Prototype with COTS KAPTON and Insulation

This design meets the requirements for temperature gradient and heat up time as well as the fitting within the mechanical and cost constraints; 10 mm thick (vs. 16 mm for Taz) and production version is estimated at $105 +/- $20. See the figure below for price analysis.

IRD HEAT BED PRICING		Prototype Cost	Productions Qtys. Cost		Notes
1	Standard available Taz top glass plate (3.5 mm thick, 30cm X 30 cm)	$ 13.50	$ 13.50		Existing Taz Part
2	Aluminum Foil Insulation: 5-6 pieces thick on top of Kaptan film	$ 11.00	$ 10.00	Cents on the $	$11 for entire roll. Alumnim plate on order of $10-20 for non production quantiteis
3	Polyimide Kaptan Film (1 mm thick), 12"x12", 1.25 W/in^2, 120 VAC, 1.5A, 20 Ohms (run at 180W)	$125	$ 55.00	$45-$65	COTS = $125, custom = $1100 for two, with productions quantities at $45-$65
4	Mechanical enclosure design and insulation scheme: - Prelim Prototype: Insulation (fiberglass, 2mm thick) around outside edge and enclosing the sides and keeps heat off aluminum plate with 8" X 8" whole in middle - Final Prototype: glass therm or high temp plastic filament with bottom glass plate	$ 195.00	$ 40.00	$30-$50	bottom glass plate costs ~ $30
5	Existing Taz bottom aluminum plate (3.5mm thick)	$ 16.75	$ 16.75		Existing Taz Part
	TOTAL	*$ 361.25*	*$ 135.25*		
			$ 105.00	***= Cost of Intrepid's new/added parts***	

Figure 6. Intrepid Heat Bed Pricing Analysis

Ruggedization and optimization of the prototype remains; including integration of the Kapton film suitable to the 12V power supply and refining the assembly/enclosure mechanical design / insulation scheme with active holding.

Next Steps:

1. Intrepid has already placed an order for two custom Kapton film prototypes specifically designed to further improve performance and control while facilitating production of a drop in

replacement heat bed suitable for Taz's existing 12V 15A power supply and within the cost bogey targeted. The design features a 2 zone / 2 thermistor approach with different watt densities at the corners than in the middle allowing independent control of these zones. Delivery is expected by the end of July with final integration and characterization occurring shortly thereafter.

2. Mechanical enclosure design and insulation scheme is being finalized
    a. Enclosure fabrication ongoing with finalization of top plate removal scheme and active holding to be implemented. 1 of 2 scenarios likely:
        i. "glasstherm" (fiberglass composite) parts for enclosing sides and active holding that mimics existing clamp system but can withstand higher corner temps and still allows for removal of top plate with 4 screws
            1. Perhaps use higher temp higher 3d printer plastic material filament and print parts
        ii. Use bottom glass plate (sandwich), perhaps 2 mm thick, for improved structural integrity and to remove need for fiberglass insulation (while maintaining air gap)
            1. Thinner glass plates procured – experimentation with heat times and temp gradient ongoing (impact on gradient and 120C)
    b. Explore replacement of aluminum foil for improved robustness and durability with repeated use; thin aluminum sheets have been shown to warp
3. Integrate custom Kapton and enclosure with optimization for 85C (heat time and gradient) and characterization at 120C.
4. Provide final characterization results and bill of materials with shipment of final heat bed deliverable (in early August).

3) <u>Inductive Heating</u>

IRD characterized a COTS inductive heater for applicability to the Taz system with identification of issues and notional design concept considered. It was determined that induction heating would require more power than currently available within the Taz system and other alternatives showed more promise; see Figure 3. Heat Bed Qualitative Design Trades.

Other notes on Inductive Heating:

1. The volume of the COTS inductive heater did not allow for direct experimentation with Taz's heat stage dimensions.
2. Induction is more variable (heat gradient from initial experiments) and harder to control; would necessitate custom design of coil geometry - deemed too expensive.
3. Warping an issue: material issues (use steel for plat) and finely controlled closed loop (feedback) system needed.
4. AC Power Issues:
    a. Heat calculations show that 150/200W is required to heat the glass plate to 100/150F in five minutes assuming the plate is perfectly insulated and perfectly conductive. This means that 300/400W would be required to heat the glass plate alone. The material required to distribute the heat more evenly will require about 50% more wattage.
    b. Need to go to AC to meet ramp up time with induction heating design. The potential 24V DC power supply is capable of ~360 watts, therefore AC for induction is likely to be the more desirable solution.
    c. Allowed Approach: have one power line that splits 120 AC to induction heat system and DC to rest of original TAZ powered components... As mentioned in our original report, using AC power/induction heating may be necessary for a 5 minute warm up. We

assume that if this design scenario keeps DC power for the rest of the TK-0 printer but has power/ management to run AC - and we meet the price target - this would be an acceptable solution.

   i. PMAD conditioning electronics and cost concerns?

d. FCC testing needed for induction? Not if comparable to COTS stove tops.

4) Material Properties and Insulation Trade Space

(forthcoming in August)

5) Future Considerations

(forthcoming in August)

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References

1. "Lulzbot TK-0 Print Bed, Preliminary Report" March 18, 2013. Proposal to Customer.

2. "TAZ" = Production version of TK-0 Printer:
    a. **Access to the TAZ files at http://download.lulzbot.com/TAZ/**
    b. The TAZ
    c. TAZ BOM: http://download.lulzbot.com/TAZ/hardware/TAZ-BOM.ods
    d. TAZ Marketing: http://www.3ders.org/articles/20130514-aleph-objects-introducing-new-lulzbot-taz-3d-printer.html

    TAZ Specifications
    - Print Area: 298mm x 275mm x 250mm (11.7in x 10.8in x 9.8in)
    - Print Volume: 20,500cm3 (1238 in3) of usable space
    - Top Print Speed: 200mm/sec (7.9in/sec)
    - Print Tolerance: 0.1mm (0.0039in) in X and Y axes. Z axis is dependent on layer thickness
    - Layer Thickness: 0.075mm to 0.35mm (0.003in - 0.0138in)
    - Supported Materials: ABS, PLA, HIPS, PVA, and wood filaments
    - Usable Filament Sizes: standard 3mm (0.1in)
    - Physical Dimensions
        - Overall Dimensions: 680mm x 520mm x 515mm (26.8in x 20.5in x 20.3in)
        - Weight: 11kg (24.25lbs)
    - Electrical
        - Power Requirements: 110 - 220 VAC
        - Temperature: Maximum operating temperature (Extruder), 240C (464F)
        - Temperature: Maximum operating temperature (Heated Bed), 120C (248F)
    - Priced at $2,195.

    TAZ BOM/Parts: http://download.lulzbot.com/TAZ/hardware/

3. TAZ public message board concerning current heat beds:
   http://forum.lulzbot.com/viewtopic.php?f=36&t=80

4. Access to the TK-0 files at http://devel.lulzbot.com/TK-0/
    a. AO-101-User_Manual
    b. "BOM2_finalVergent"