



How to take a working curve measurement and create exposure settings from it

by **bad-zima** on September 15, 2016

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Intro: How to take a working curve measurement and create exposure settings from it

What is a working curve

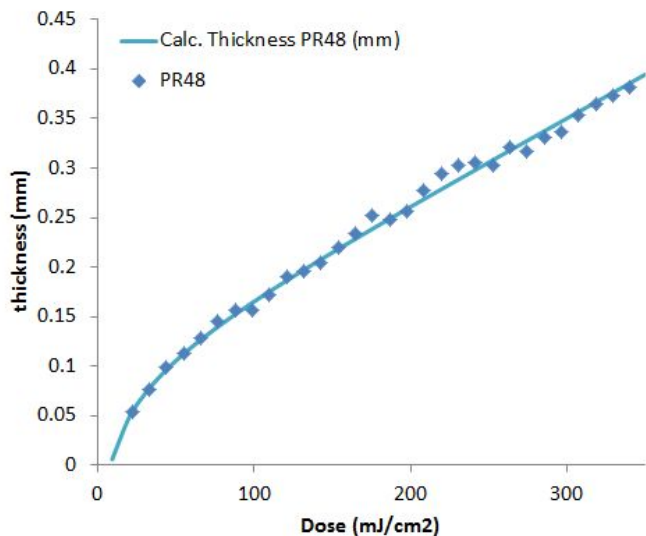
A "working curve" describes the thickness to which a resin cures as a function of the light "dose" for a given light source. While this may sound pretty lame, understanding this concept is key to understanding SLA and DLP 3D printing. With the working curve one can quickly generate printing settings without a lot of testing. It also allows one to quantitatively compare the curing properties of one resin versus another.

The other reason the working curve is a powerful tool, is that the measurement is very easy and can be done in less than 10 minutes (with practice!). The only required tools are a micrometer and 3D printer. The measurement is pretty straight-forward for pure radical systems as the layer thickness depends on the dose. Light intensity, oxygen inhibition, and the polymerization exotherm certainly can play a small role, but the technique is surprisingly robust. The only situation where I would expect significant deviations is in cationic and other living polymerizations.

That being said the measurement is not necessarily easy, as the resulting films are delicate. It takes practice to produce consistent measurements of 50 to 200 micron thick films, but the results are definitely worth it.

Can I just watch a video rather than read thru this lame Instructable?

Yes. Look no further.



Step 1: What can one do with a working curve

1) QC

The working curve is probably the easiest and simplest test to determine if a batch of resin will cure the same as a previous batch.

2) Resin design

The working curve can be modeled by several different equations. The parameters provide insight into the chemistry and allow comparisons between different components.

3) Closed Printers

Matching the working curve is the main part in making a resin work in a printer where the printer parameters cannot be directly controlled by the user.

4) Printer settings Development

The working curve can be used to estimate the required dose to cure a layer of a given thickness.

5) Modeling of the polymerization The working curve is the easiest measurement that can be compared to theoretical models.

6) Intensity variation mapping

Variations in intensity across the printer bed can be mapped using the working curve.

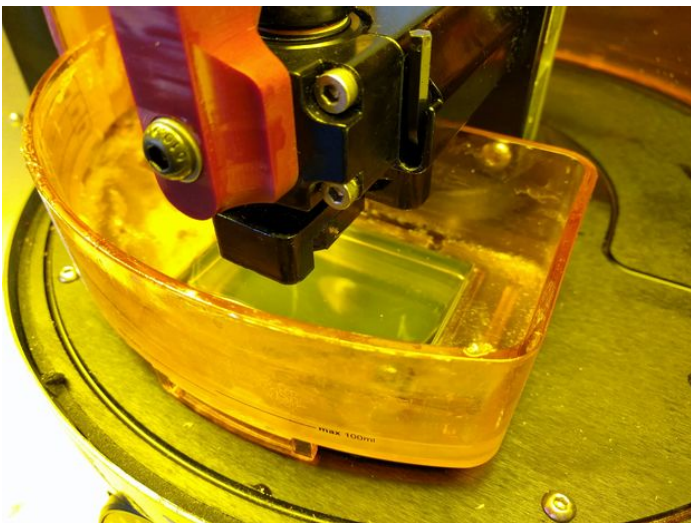
Step 2: Limitations

The biggest limitation of the working curve is that it is very difficult to measure films as thin as the layers used in a DLP/SLA printer. Thus models need to be used to extrapolate the results into the region of interest. If the model is poor then the results of the extrapolation will be poor. The thinner the layers one can measure then better the results will be. The second limitation is that on the ember printer the growing layer grows both towards the window (PDMS) as the inhibition layer is depleted, and away from it as the dose of energy accumulates. As the former is much smaller this effect is minimal. This effect can be eliminated by placing a glass slide on the PDMS window (which also allows much thinner and less mechanically strong layers to be measured), but the comparisons to printing becomes weaker. The third limitation is that reciprocity is not strict in a DLP/SLA printer due to oxygen diffusion and the resulting thickness can depend on both the dose and the light intensity

Step 3: Printing the test

Printing the test is straight forward.

- 1) Clean the entire external optical path of the printer: the PDMS window, the glass bottom of the window, and the printer window. Acetone can be used on all of the surfaces; however, only optical paper should be used on the fragile PDMS.
- 2) Measure and adjust the light intensity (Ember and Form1+).
- 3) Remove the build head from the printer.
- 4) Load the attached print
- 5) Start the print
- 6) After the tray has stopped rotating during the homing procedure open the door to stop the printer and cover the entire window with a layer of resin. This should be several millimeters thick to best minimize oxygen diffusion from the atmosphere. Close the door and allow the print file to run.



File Downloads



DOC15.zip (39 KB)

[NOTE: When saving, if you see .tmp as the file ext, rename it to 'DOC15.zip']

Step 4: Cleaning the print

The printed test is very fragile as it is less than 50 microns thick in places. To clean it 1st mount the tray vertically and spray it with isopropanol (IPA). The film should slowly slide off. If it does not the resin may not be appropriate for Ember*. Next carefully peel it off the window or tray bottom. The layer will be covered in resin. Do not soak it in IPA or other solvents as it may swell. Instead blot it dry with a paper towel until it is entirely free of resin.

* If the layer is adhered to the window no oxygen inhibition layer exists!



Step 5: Measure and record the panel thicknesses

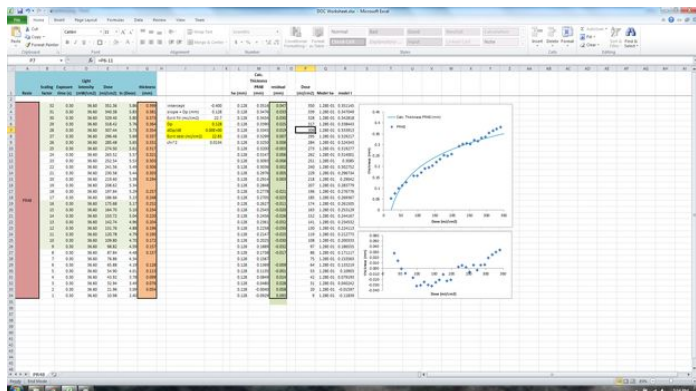
Once the film is clean orient so side of the print that was in contact with the window is facing down. This side should be completely flat as it was in conformal contact with the window. The other side should vary in height across each panel.

Next rotate the film about the axis normal to its plane (do not flip the film over, think mentally testing for chirality!) so that the top left corner has a missing panel. This panel only received 0.6 mJ/cm² so it should not have cured. Measure the panels left to right and top to bottom. The top left panel corresponds to "1" and the bottom left to "32".



Step 6: Plot the data

- 1) Download the attached spreadsheet.
- 2) Enter the name of the resin in the red cell
- 3) Enter the thickness of each panel in the orange cells (numbered 1 to 32). If a panel was missing leave it blank and delete the cell in the corresponding row from the green column.
- 4) If the fit looks good (all of the residuals are random) then you have the working curve and the model parameters E_{crit} and D_p0 . If one or two points are way off you can delete them and the corresponding green cell. If the whole plot looks like a constellation, you probably have the order of panels wrong (wrong orientation when measuring?). If the residuals appear to have a systematic deviation (like the above plot) continue to the next step.



File Downloads



DOC Worksheet.xlsx (24 KB)

[NOTE: When saving, if you see .tmp as the file ext, rename it to 'DOC Worksheet.xlsx']

Step 7: Apply a simple model

PR48 and many other resins need to be modeled by using a simple model that accounts for "bleaching" of the light absorbing molecules. These resins contain components (like OB+) that become transparent to the light from the projector the more they are exposed to it. The model on the previous page is simply,

$$\text{thickness} = D_p * \ln (\text{Dose} / E_{crit})$$

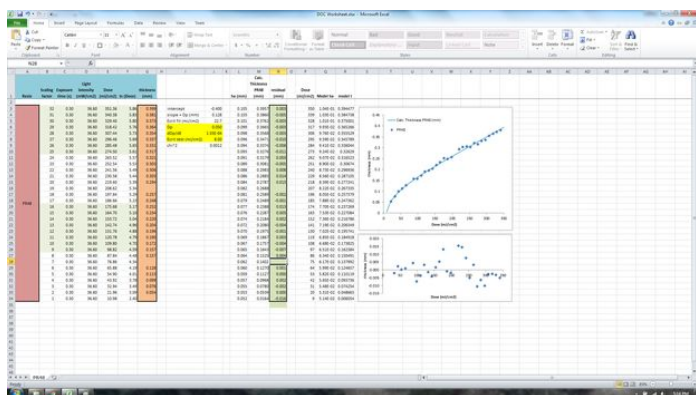
where D_p is a constant referred to as the penetration depth (or sometimes, h_a) and E_{crit} the critical dose or amount of energy necessary to convert the resin from a solid to liquid. This model is explained in Jacobs Rapid Prototyping and Engineering, and is more or less derived from the Beer-Lambert law in a hand waving fashion.

A handy model to account for bleaching is assuming that the penetration depth is a linear function of the dose,

$$D_p = D_{p0} - dD_p/De * \text{Dose}.$$

The downside of this model is that it is non-linear and the coefficients can only be arrived at iteratively. You will have to change the values in the yellow cells until you are happy with the model.

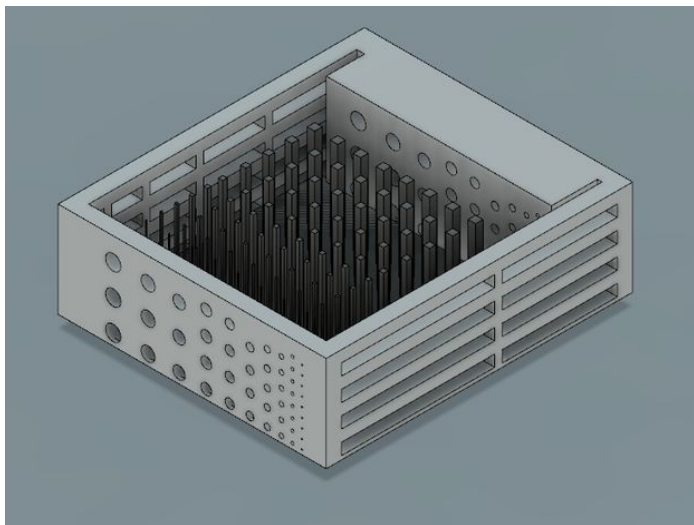
If it still does not fit (resins with large D_p 's typically) you need a different model. The spreadsheet password is "ember", fix it to fit your needs.



Step 8: Do a test print

The working curve provides a good estimate of the dose you will need to cure to a given layer thickness, but it is only a start. Typically, the mechanical properties of the resins are not fully developed at the dose where the top edge of a panel formed. This dose is probably much closer to the gel point where the material is only a lightly crosslinked goo rather than a rigid solid. For a given layer thickness the dose you might want to use for printing is probably 120% to 200% of that estimated from the working curve.

To figure what does you actually want to use you need to do some prints. The BJA-28 test print is useful for this. Print it, record the corresponding feature sizes, and then increase the dose until the 200 micron thick posts form. This is near the upper limit of resolution for an Ember in video mode and for high aspect ratio features (nearly 50!). The test also provides information on the smallest holes that can be printed (a function of D_p and the resin mechanical properties and viscosity). The test artifact also has unsupported spans, most resins can easily print the 10 mm upper limit of this test artifact. If the result is anything less either the dose needs to be increased (unless the goal is a very soft resin).



File Downloads

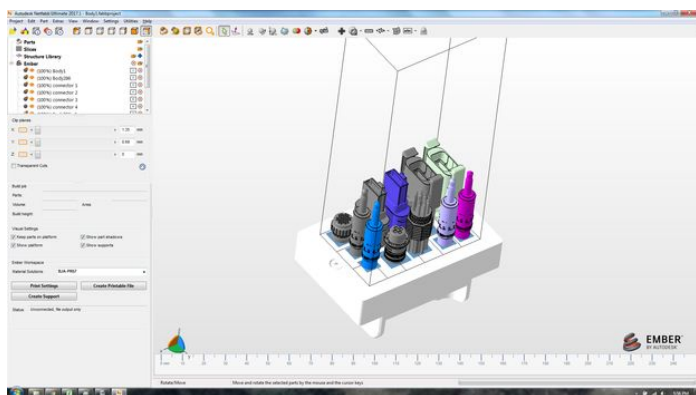


BJA-28.stl (1 MB)

[NOTE: When saving, if you see .tmp as the file ext, rename it to 'BJA-28.stl']

Step 9: Try some other models

The attached .stl is a plate of other easy to print models.



File Downloads



Plate.stl (10 MB)

[NOTE: When saving, if you see .tmp as the file ext, rename it to 'Plate.stl']

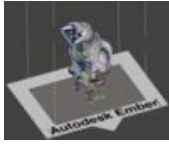
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Re-Pairing Your Ember by Porda



Calibrating Ember's Rotation Homing and Jamming Sensors by cappiep



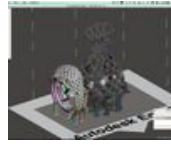
Meshmixer: Installation by ppalin



Pixar Decals by Porda



Adjusting Ember's Homing and Jamming Sensors by cappiep



Meshmixer: Export for Ember by ppalin

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