Can Small Boxes Model the Atmospheric Greenhouse?

In other words:

Do boxes similar to solar collectors warm up by converting the incident sunlight to infrared and concentrating it?

This would mean they are similar to the atmospheric greenhouse and could be used as models to help explain it.

Or

Do they warm up mainly by suppressing convection?

Which would mean that attempts to use them to model the atmospheric greenhouse actually miss the mark.

My purpose here is to look for evidence that could back up decisions by teachers concerning whether to use such boxes.

(References 1, 2 located on Panel 15)

MY ABSTRACT

Atmospheric trapping of infrared leads to a warmer surface, but there has been questioning about whether solar collectors and greenhouses also act in this way. These systems also control convection, which might be responsible for the warmer temperatures. Schools need models of the atmospheric greenhouse but should not use models that actually demonstrate something else. I have used small boxes resembling solar collectors with a black absorbing interior but covered by materials of differing infrared transmission properties. After determining relative infrared transmission ability using two methods, I measured their interior temperatures with varying degrees of insolation and ambient temperature. Whenever infrared transmission differences were clear, the greater transmission (smaller trapping) corresponded to a lower internal temperature. This leads to greater confidence that infrared trapping in these devices does affect their temperatures, thus crudely modeling atmospheric effects, regardless of any convection effects present.

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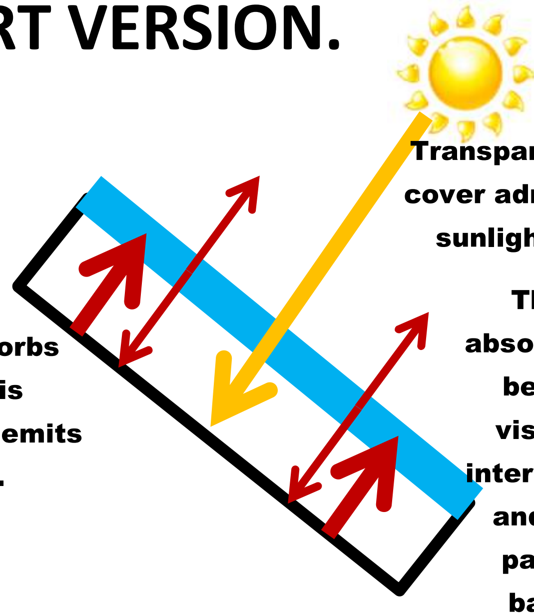
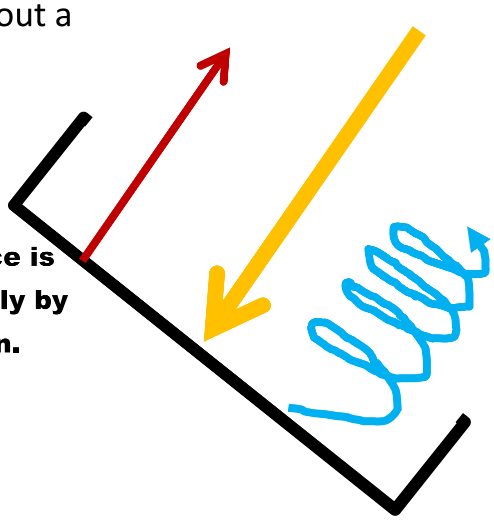
(See a link to a PDF file of this presentation at the gibbworld URL)

HERE IS THE SHORT VERSION.

1. Boxes with a black interior can become very warm. The advertised mechanism is shown in the figure to the right.



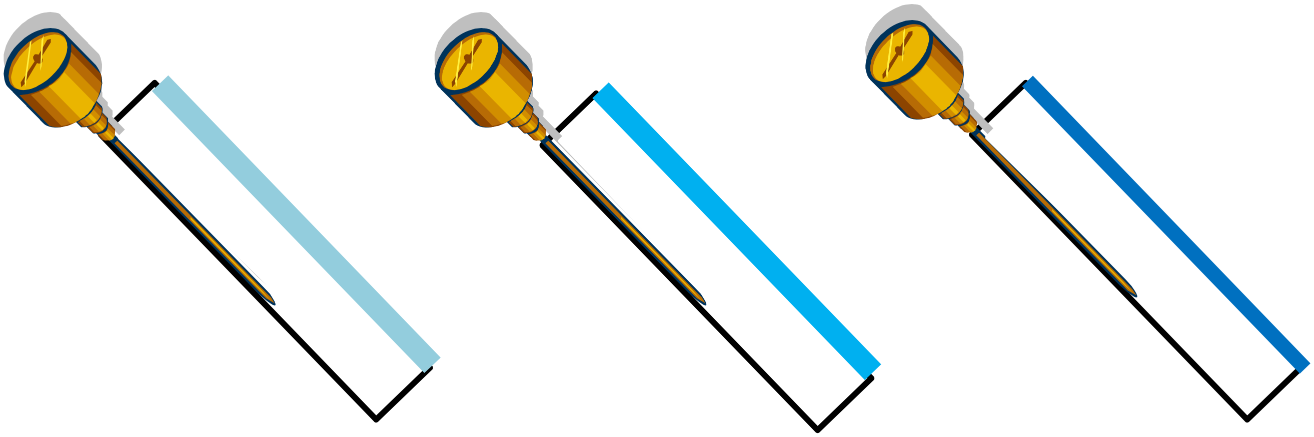
2. However, an alternate explanation has often been put forward. Incoming sunlight can warm the black interior even without a cover. (Ref. 3, 4, 7 ,8, 12)



3. If the box is covered, the convection is suppressed though not eliminated. According to this alternate theory, the suppression of convection allows more energy to be lost by radiation thus increasing the temperature, and furthermore this effect is large enough to account for most of the temperature increase. Thus any role played by infrared trapping would be very small or insignificant.

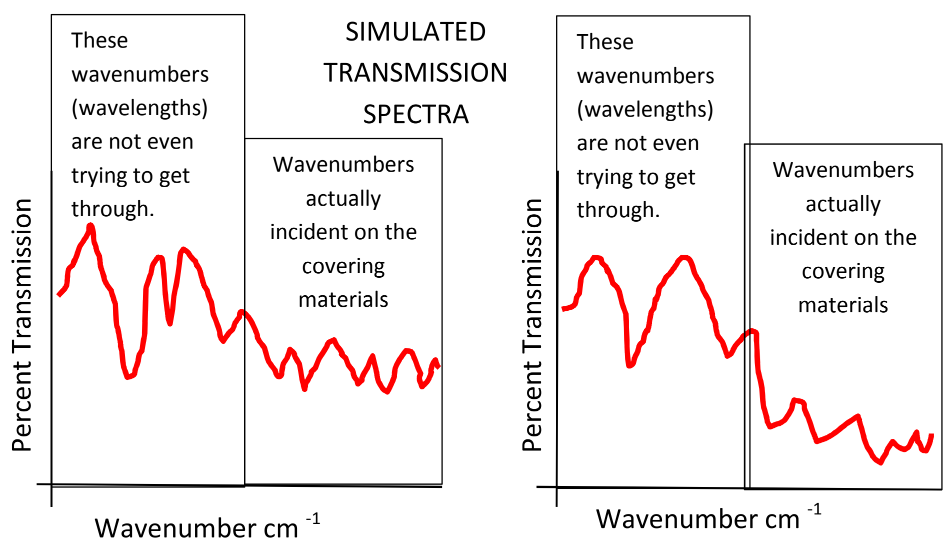
4. If an infrared trapping effect is large enough to be observed, then it is large enough to use as the basis for demonstrating an atmospheric greenhouse effect. That should be true even with convection effects also present (as, in fact, they are on the earth itself). (Ref. 5, 6)

5. Here I used covers of varying ability to absorb infrared. If the trapping of infrared is significant enough to observe, then a covering material with high absorbance (and low transmitting ability) should be associated with a higher internal temperature. (Panel 5)



6 I stuck a cooking thermometer in each box to measure the temperature near the black material lining the bottom (black foam board). The thermometers themselves reside inside of a reflective metal tube (I took one apart and checked). They are not in direct sunlight. The tubes are designed to be stuck into a hunk of meat being cooked, but they served the purpose here. (I'm retired. I use what I find.)

7. I borrowed the use of an infrared spectrometer and obtained transmission spectra for each material that I used. It detected wavenumbers from 400 cm^{-1} to 4000 cm^{-1}. In fact the infrared emissions from the bottom of the boxes were significant only below about 2000 cm^{-1} or 2500 cm^{-1} (depending on the exact temperature). (Panels 6, 8) (Ref. 14)

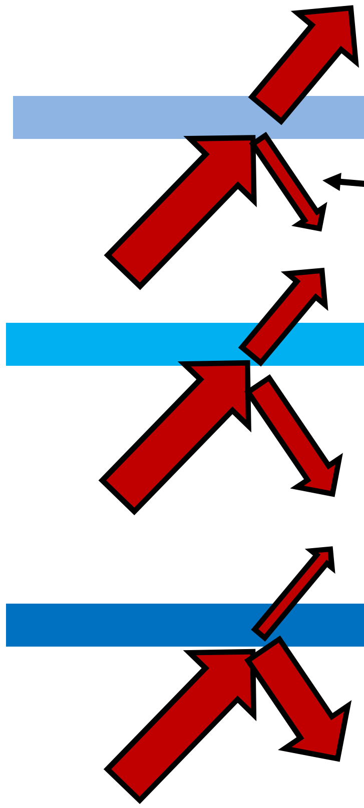


8. It was possible to qualitatively notice which covering material was transmitting more and which less. Here the right-hand material is transmitting less and thus trapping more infrared at least in the wavenumber range actually used. (Panels 6, 8)

9. I also pointed an infrared thermometer through each covering material at a hot surface. This was an attempt to check the transmission properties by a different method. The apparent temperature observed through the transparent material would increase with the percent transmitted since the thermometer would "see" the hot background better. See panels 7 and 9 for details. This method did succeed in finding the same relative transmission from one sample to another as found using the spectra.

10. So I was able to line up the box covering materials in order of IR transmitting ability. The next step is to use this to predict the relative temperatures near the black foam board at the back of boxes covered by these materials. (Panels 5, 7, 9)

11.



MEASURED	EXPECTED
Highest Transmission	Lowest Temperature
Intermediate Transmission	Intermediate Temperature
Lowest Transmission	Highest Temperature

NOTE: With high transmission, there is not very much Infrared energy left over to radiate back into the box to raise the temperature.

EXPECTATIONS SIMULALTED IN A GRAPHIC

12. So finally, here is the result: The temperatures varied as expected. Whenever there was a clear difference in IR transmitting ability, the highest transmitters produced the lowest temperatures, and the temperatures in the boxes varied with transmitting ability as expected. In one set of trials there were several covering materials with IR transmissions too close to one another to distinguish. The temperatures were similarly close. In another set of trials, the IR properties were more spread out as were the temperatures. (Panels 12, 13)

13. In Panel 14, I have made a rough estimate of the ability of convection control to produce the observed temperatures. This estimate suggests that convection falls short. (Ref. 10, 11)

14. **AND A CONCLUSION. So I would conclude that, as mentioned in paragraph 4 above, the IR trapping effect is large enough to observe thus making such boxes useful as a model to help explain the atmospheric greenhouse. (See Details from Panel 5 on)**

15. A word about commercial greenhouses: They can be leaky and often need standard furnaces. They can trap infrared as well, but the prime consideration is to let in enough light for the plant growth. So they have their own set of issues, and this project, which is about models for classrooms, does not necessarily say anything about greenhouses. (Ref. 13)

And Here Are the Details…

I have used two separate groups of box covering materials.

Group 1 consisted of several very high absorbance (very low transmissibility) materials and several of very low absorbance (high transmissibility).

HERE THEY ARE:

SAMPLE MATERIAL (FIRST GROUP) Obtained from various local stores as well as from the pile of junk in my garage.	Rough Percent Transmission of IR wavelengths estimated from transmission spectra.	Expected Direction of Temperature Increase when Used to Cover Boxes & placed in the Sun. (In two distinct temperature groups, H_T & L_T)
Window Glass	LOW (1%)	H_T
Glass from a Picture Frame #1	LOW (1%)	H_T
Glass from a Picture Frame #2	LOW (1%)	H_T
Hard Plastic from a File Folder Box (Acrylic)	LOW (5%)	H_T
Plastic Film Wrapping from a Photo Album (Polyethylene)	HIGH (85%)	L_T
Plastic Film Wrapping from a set of Cake Holders (Polyethylene)	HIGH (85%)	L_T
GLAD Wrapping (Polyethylene)	HIGH (90%)	L_T

With Group 2, I tried to find materials with intermediate transmissibilities in order to see if the temperature would change more or less smoothly with the transmission properties.

HERE THEY ARE:

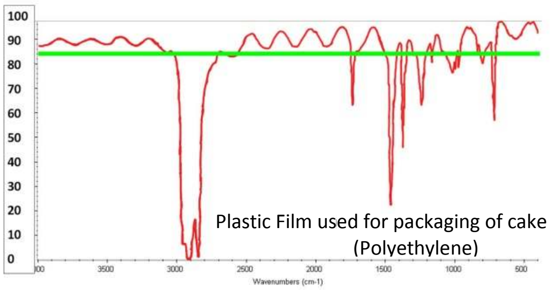
SAMPLE MATERIAL (SECOND GROUP) Plastic sheets such as these are available online from various hobby stores. The GLAD is available pretty much everywhere.	Rough Percent Transmission of IR wavelengths estimated from transmission spectra.	Expected Direction of Temperature Increase when Used to Cover Boxes & placed in the Sun. (But more smoothly varying this time)
Polyester .03 in thickness	3%	
Polyester Unknown Thickness [A]	5%	
Polystyrene .015 in thickness	25%	
Polystyrene .01 in thickness	30%	
Polystyrene .005 in thickness	40%	
GLAD (Polyethylene)	90%	

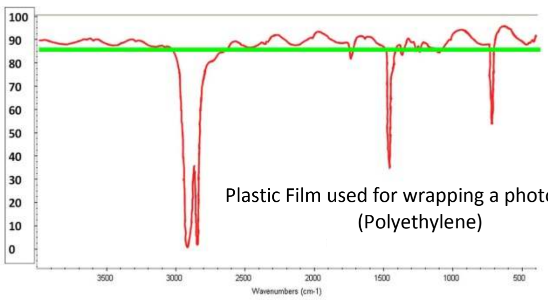
Each group also contained a box with no cover at all. This was useful as a control, to determine how much additional temperature increase might be attributed to the cover. It was used also for some convection estimates.

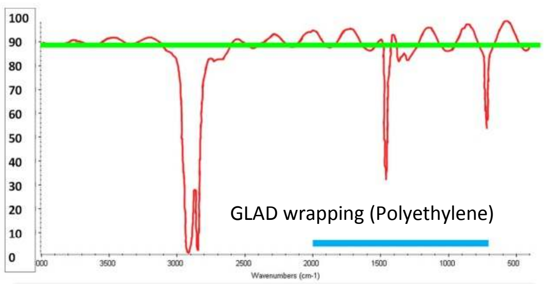
A - This came from some packaging and was somewhere around .015 in thick. It was given to me part way through my second set of trials. By the way, sorry about using inches, but that's how they were labeled.

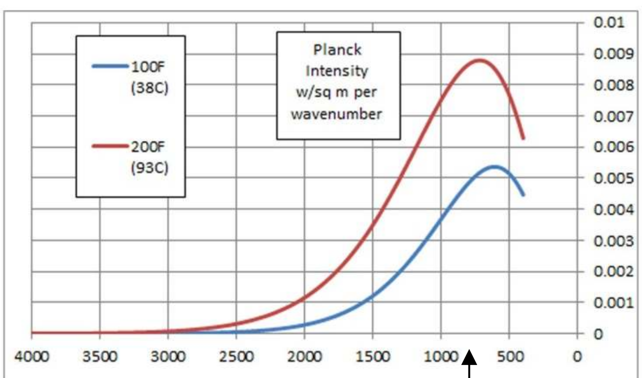
TRANSMISSION SPECTRA First Set of Covering Materials

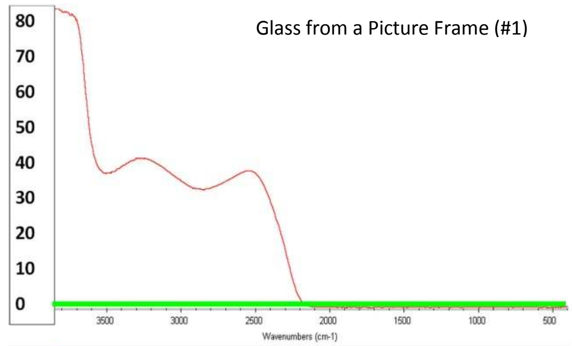
Percent Transmitted vs. Wave Number

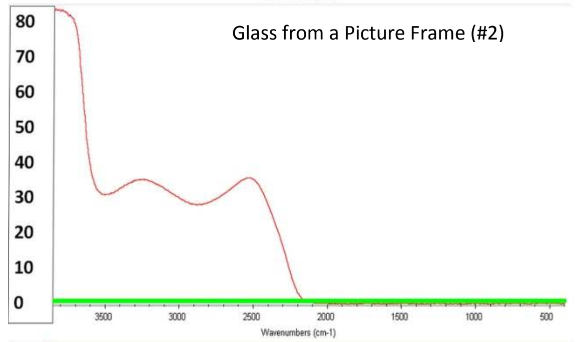


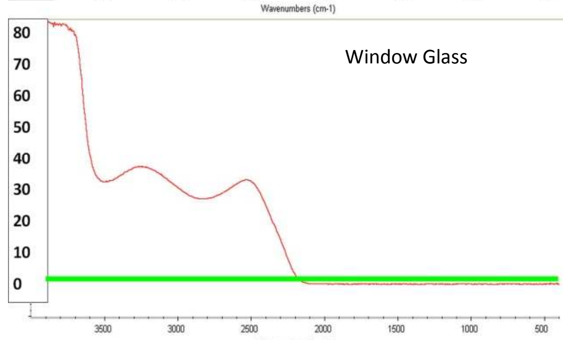


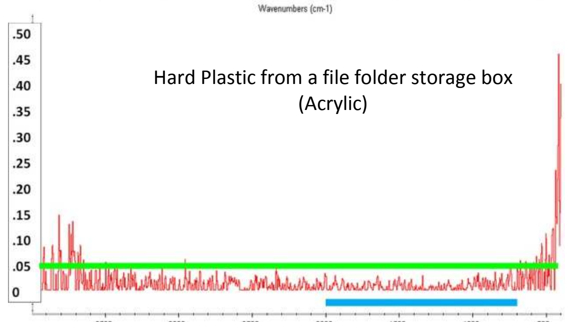


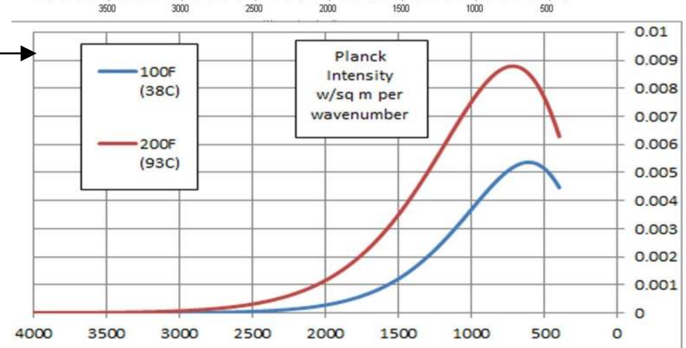










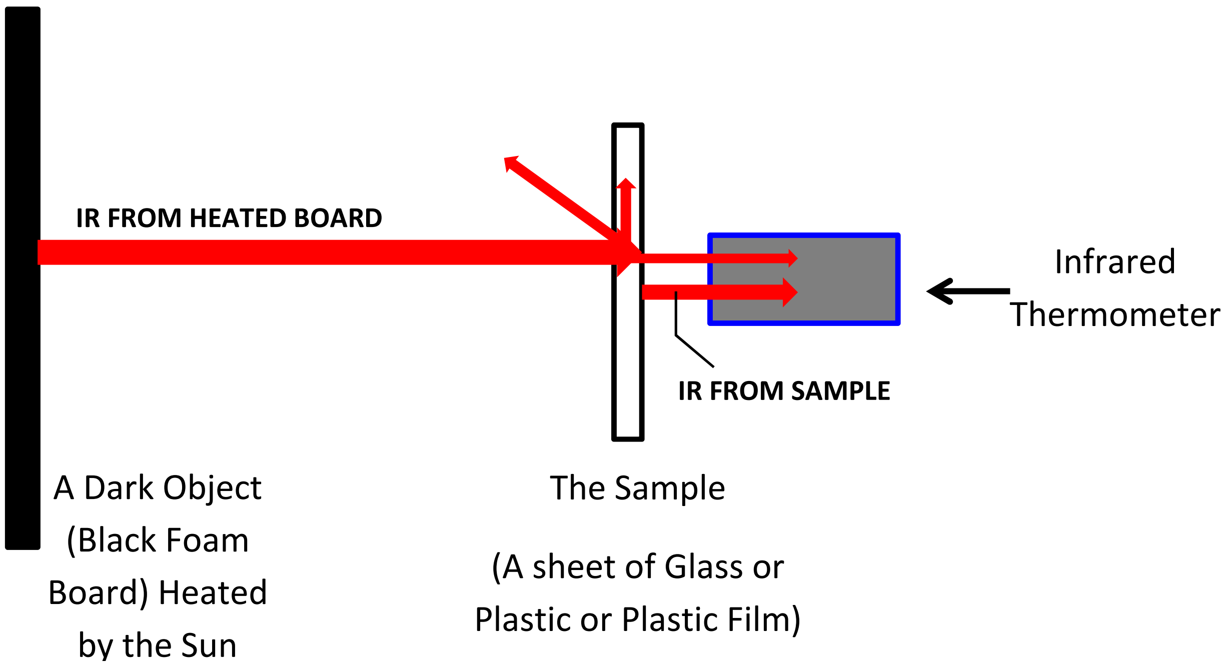


These black body graphs show emissions at typical temperatures of the black foam board at the back of the boxes. Emissions at these wave numbers are incident on the covering materials. The red transmission spectra give the percent of the incident emissions that get through.

GREEN LINES: These are rough estimates, just made with the eyeballs and used in the tables, of the average percent transmission for each material. They *only apply to about the right half* of the graphs. There is little or no ir radiation at other wave numbers incident on the materials.

BLUE LINES: They show the wave number range detected by the infrared thermometer used in the next panel.

LINING UP THE TRANSPARENT COVERS (FIRST GROUP) ROUGHLY IN ORDER OF IR TRANSMISSION USING A THEROMOMETER



See Green Lines, Panel 6

SAMPLE MATERIAL	BLACK OBJECT TEMPERATURE (^{o}C)	AMBIENT (& SAMPLE) TEMPERATURE (^{o}C)	APPARENT TEMPERATURE OF DARK OBJECT THROUGH SAMPLE (^{o}C)	Rough Percent Transmission of IR wavelengths estimated from transmission spectra.
Window Glass	52.9	27.5	27.5	LOW (1%)
Picture Frame Glass #1	52.9	27.5	29.1	LOW (1%)
Picture Frame Glass #2	61.9	39.4	41.8	LOW (1%)
Hard Plastic (Acrylic)	52.9	27.5	30.9	LOW (5%)
Plastic Film #1 (Photo)	52.9	27.5	47.5	HIGH (85%)
Plastic Film #2 (Cake)	52.9	27.5	47.7	HIGH (85%)
GLAD (Polyethylene)	52.9	27.5	47.9	HIGH (90%)

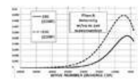
WHAT IS HAPPENING HERE

The infrared thermometer reads temperature by picking up infrared emissions from the target. Here it is looking at the black background through the apparently transparent sample. If this sample does not transmit ir, then the thermometer will just read the sample temperature. With increasing transmission the thermometer will "see" the black background better. So as the transmission increases from low to high, the apparent temperature read by the ir thermometer will also increase from near the sample temperature to near the background temperature.

TRANSMISSION SPECTRA Second Set of Covering Materials

Percent Transmitted vs. Wave Number

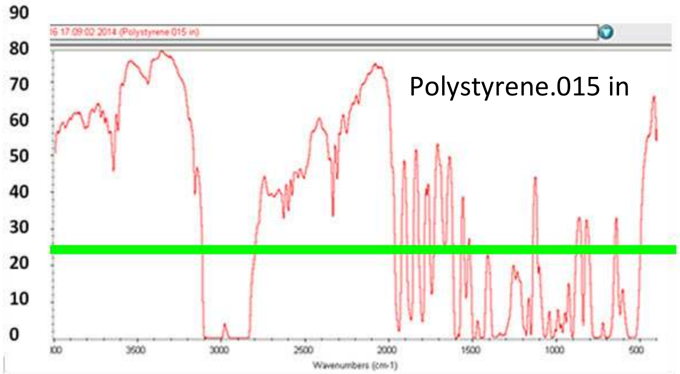
BLACK BODY SPECTRA BOTTOM OF PAGE

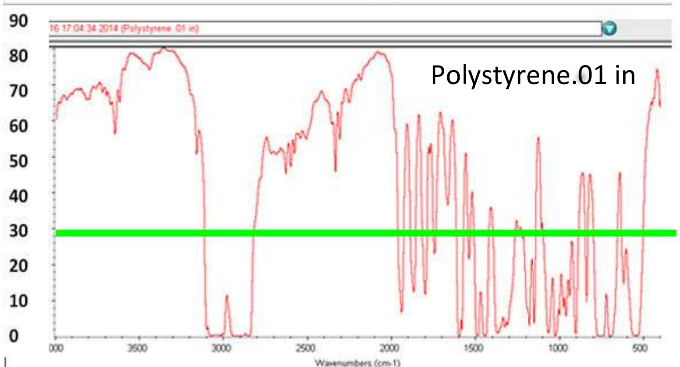


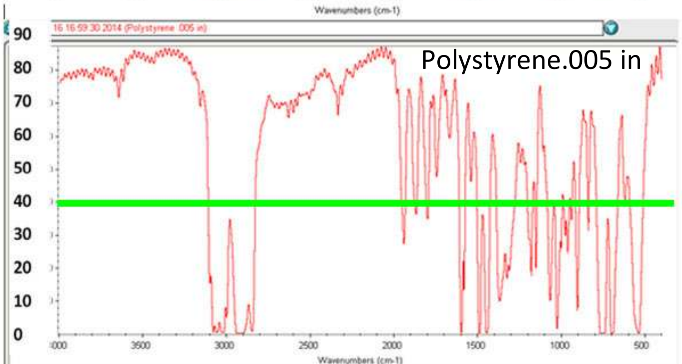
They show emissions at typical temperatures of the black foam board at the back of the boxes. Emissions at these wave numbers are incident on the covering materials. The red transmission spectra give the percent of the incident emissions that get through.

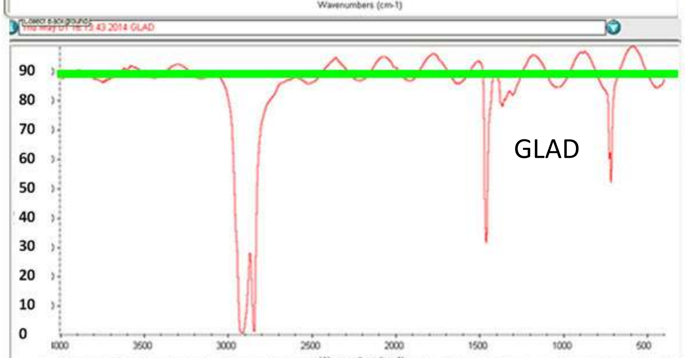
BLUE LINES: They show the wave number range detected by the infrared thermometer used in the next panel.

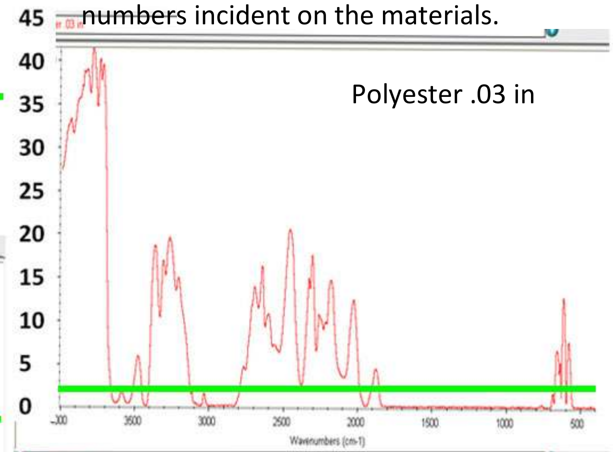
GREEN LINES: These are rough estimates, just made with the eyeballs, of the average percent transmission for each material. They *<u>only apply to about the right half</u>* of the graphs. There is little or no ir radiation at other wave numbers incident on the materials.

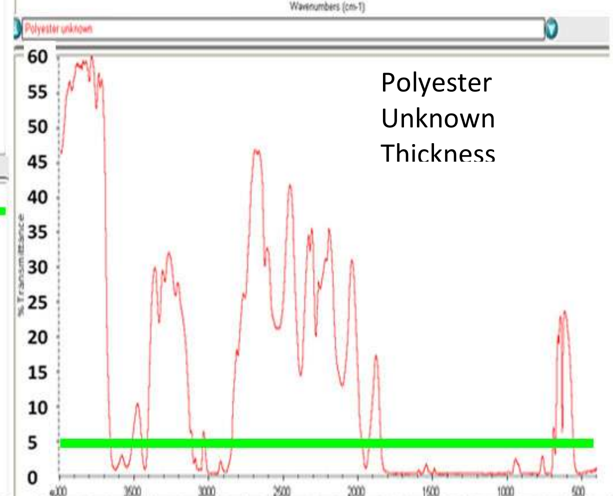


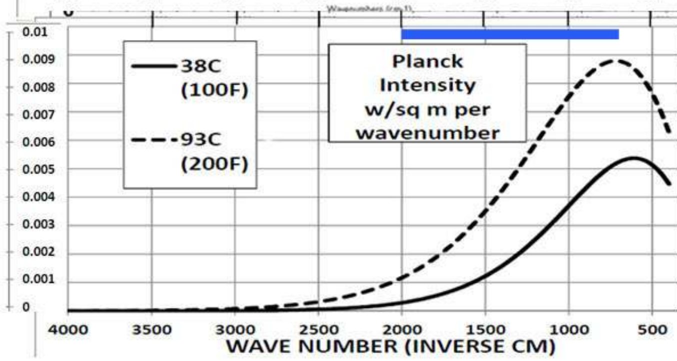


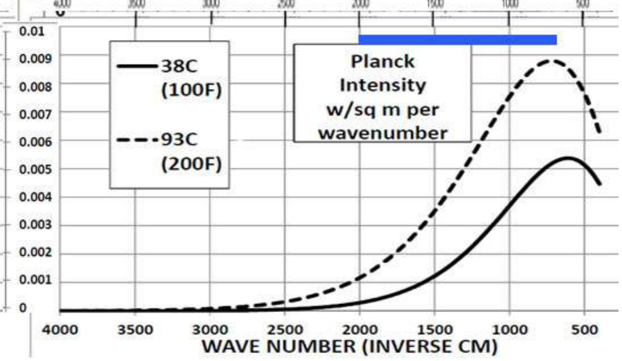




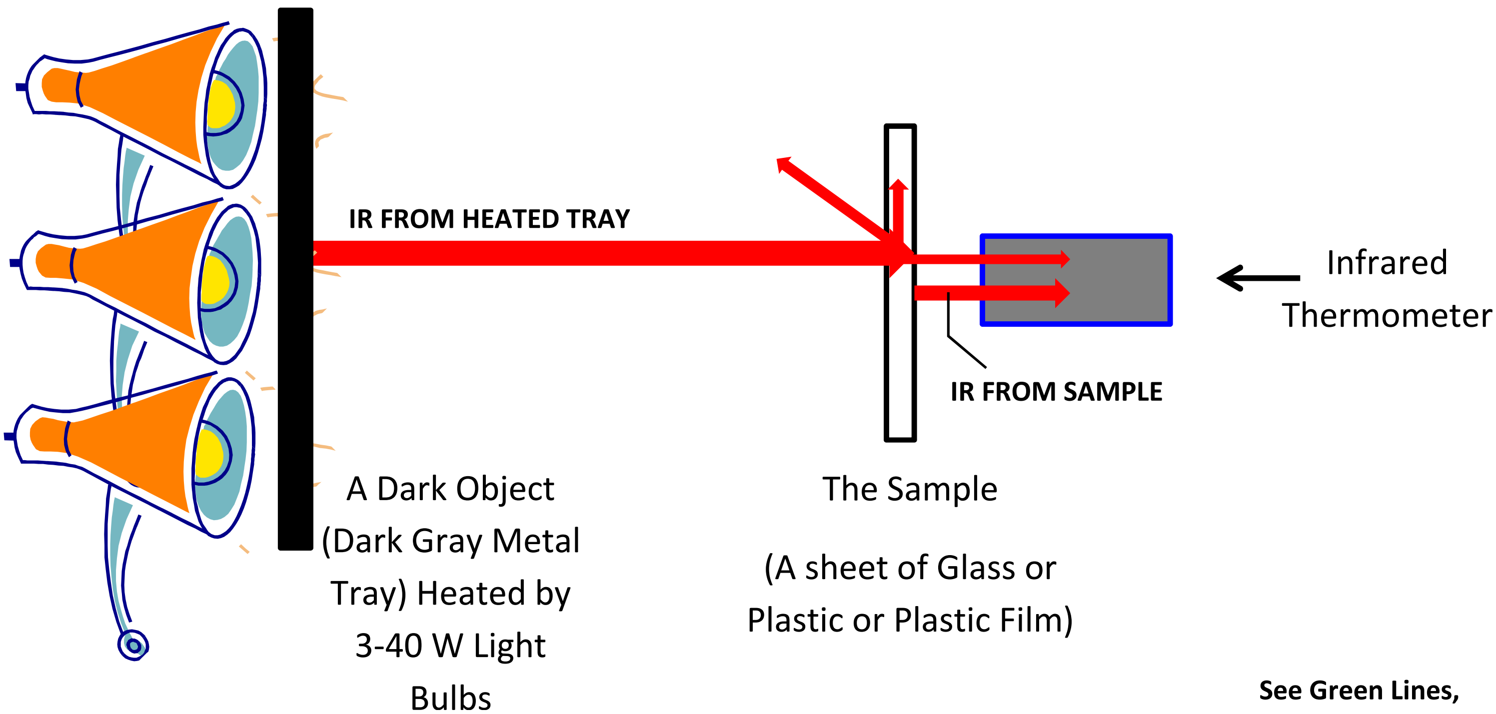








LINING UP THE TRANSPARENT COVERS (SECOND GROUP) ROUGHLY IN ORDER OF IR TRANSMISSION USING A THERMOMETER



SAMPLE MATERIAL	METAL TRAY TEMPERATURE (°C)	SAMPLE TEMPERATURE (°C) (Temperature of Electrical Tape on Sample)	APPARENT TEMPERATURE OF METAL TRAY THROUGH SAMPLE (°C)	See Green Lines, Panel 8 Rough Percent Transmission of IR wavelengths estimated from transmission spectra.
Polyester .03 in	59.9	27.4	28.1	3%
Polyester Unknown Th.	66.1	26.2	26.6	5%
Polystyrene .015 in	60.6	27.7	33.6	25%
Polystyrene .01 in	58.9	28.5	36.8	30%
Polystyrene .005 in	60.4	28.6	43.7	40%
GLAD (Polyethylene)	59.9	28.5	58.1	90%

SIMILAR RESULTS HERE

This is essentially the same procedure as in the previous panel except using light bulbs as a source of heat. As we look from the top (polyester) sample to the bottom (GLAD), the percent transmission of infrared increases steadily, as estimated from the ir spectra. Also, from top to bottom, the apparent temperature read on the ir thermometer looking through the sample steadily moves from near the sample temperature toward the background temperature. This agrees with the transmission as estimated from the spectra. It is hard to tell the difference between the two polyester samples, but an inspection of the transmission spectra suggests the .03 in one would transmit a little less.

TRANSMISSION OF SOLAR WAVELENGTHS

It is important that each material tested pass nearly the same percentage of insolation as the other materials in the same trial. Otherwise we could not be sure that a higher internal box temperature was not produced simply by more sunlight entering the box. One indication of the effect of changing insolation is to note that the thermometers in all boxes were observed to fall quickly if a cloud passed in front of the sun.

I used a light meter that was sensitive to solar wavelengths to test this. I just set the meter up on a tripod, pointed it at the sun, read it, then slipped the material to be tested in front of the meter, and read it again. I picked days with steady insolation for this, but the meter can fluctuate a little (see table below). So I made several trials and averaged them.

This is an example of data, using the GLAD wrapping, which is the only one used in both groups. I took the data in order – one without the sample, one through the sample, the next one without, and so on.

Insolation Without the Sample (W/m^2)	**Insolation Through the Sample (W/m^2)**	**Percent Passing Through (using data in the same row and the row above)**
1174		
	1099	93.61%
1173		93.69%
	1096	93.44%
1171		93.60%
	1110	94.79%
1174		94.55%
	1108	94.38%
1171		94.62%
	1110	94.79%
	AVERAGE	**94.16%**
	AVG ROUNDED	**94%**

Here are the results for each material used.

SAMPLE MATERIAL FIRST GROUP	**Percentage of Solar Wavelengths Passed Through**		**SAMPLE MATERIAL SCOND GROUP**	**Percentage of Solar Wavelengths Passed Through**
Window Glass	89%		Polyester .03 in	91%
Picture Frame Glass #1	89%		Polyester Unknown Th	89%
Picture Frame Glass #2	87%		Polystyrene .015 in	92%
Hard Plastic (Acrylic)	93%		Polystyrene .01 in	91%
Plastic Film #1 (Photo)	93%		Polystyrene .005 in	92%
Plastic Film #2 (Cake)	94%		GLAD (Polyethylene)	94%
GLAD (Polyethylene)	94%			

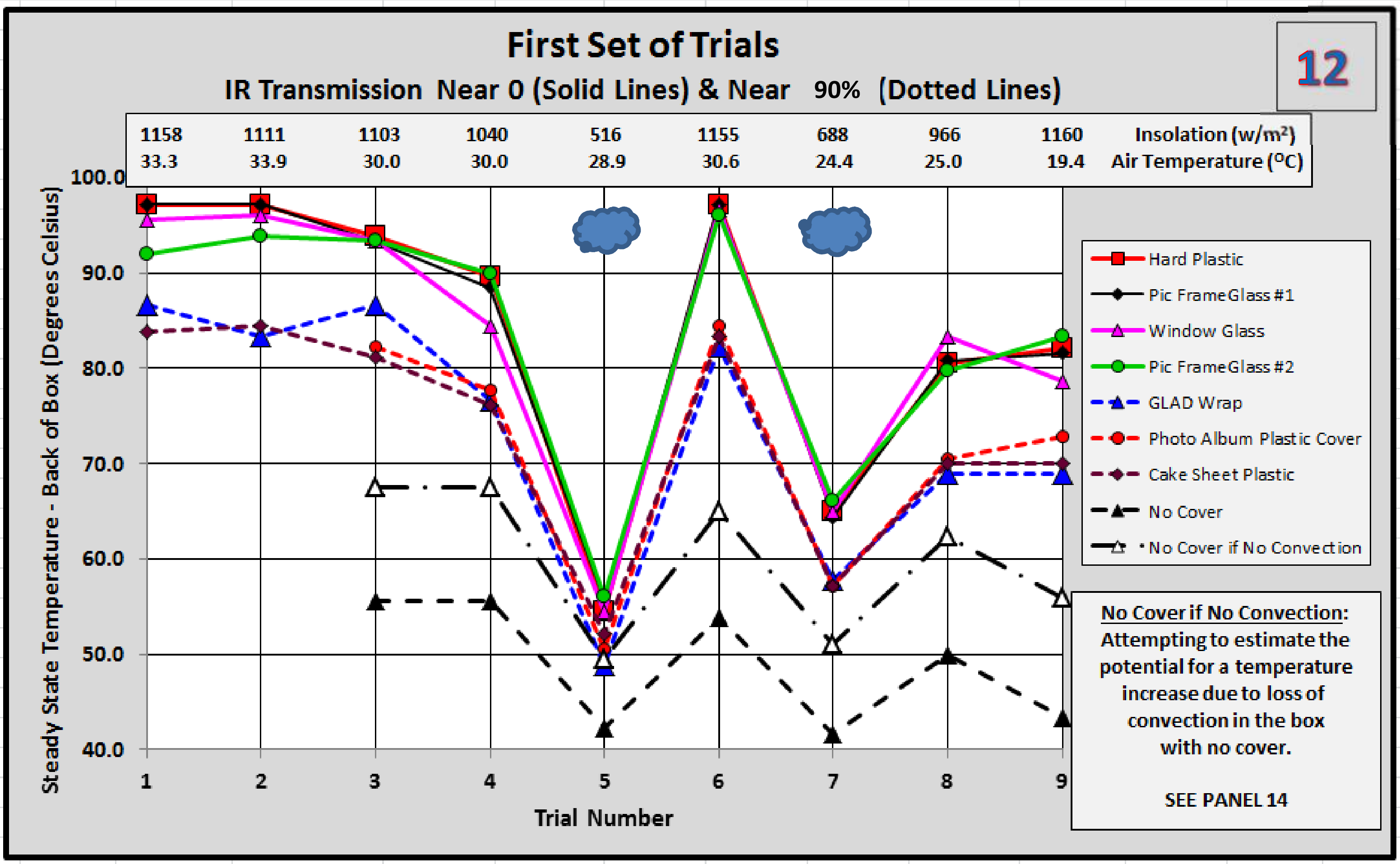
Notice that the highest percentage of sunlight was passed by the GLAD, which produced the lowest temperatures in a box. The lowest percentages were the glass materials and the polyester, which produced some of the highest temperatures. So the temperature differences from box to box during any trial must be associated with something other than the amount of insolation entering the box.

SOME OTHER CONSIDERATIONS WHEN SETTING BOXES IN THE SUN TO CHECK THEIR TEMPERATURES:

1. I checked the thermometers against one another by placing them in a glass of water, all at the same depth, which had been microwaved to a temperature a little below boiling. Some analog thermometers were inconsistent, but the digital thermometers agreed within a degree as the water cooled. I used thermometers that were consistent to a degree sufficient to distinguish the different box temperatures.
2. I placed all the boxes in my backyard directly facing the sun and waited for their temperatures to become steady. This generally took around 40 minutes, unless the insolation was changing due to shifting clouds. That was occasionally a problem (see the next item).
3. Usually, I picked days with steady sunlight. In some cases, I had variable clouds, and on those days (marked on the graphs) I used an average of several measurements. That is true both for box temperatures and for insolation and was necessary because the insolation would change in less time than it took for the temperatures to steady. This allowed me to try a few days of lower insolation.
4. I performed the trials in my back yard, which is pretty well sheltered from the wind by trees, a cliff, the house, and lilac bushes (unless the wind is from the west). Thus I was able to pick calm conditions for these measurements. Even in a few cases when there was some slight wind motion of branches high up, I had calm conditions on the ground. See Panel 14 for the convection estimates where I needed this.
5. I used that light meter to measure the insolation in w/m^2 for each trial.

Boxes used here for the first set of trials and platforms for holding them. Notice the control box with no cover (extreme right). The 30-cm rulers show the scale. Sometimes paper stuffing was necessary to keep the thermometers touching the bottom. They measured 3 cm x 16 cm x 24 cm. Notice the drought conditions, which at least gave me a lot of days of weather that was good for this project.

For the second set of trials, I put new coverings on the same boxes, but I had to stop them all down a bit since some of the coverings were not wide enough otherwise.



RESULTS FOR THE FIRST SET OF TRIALS

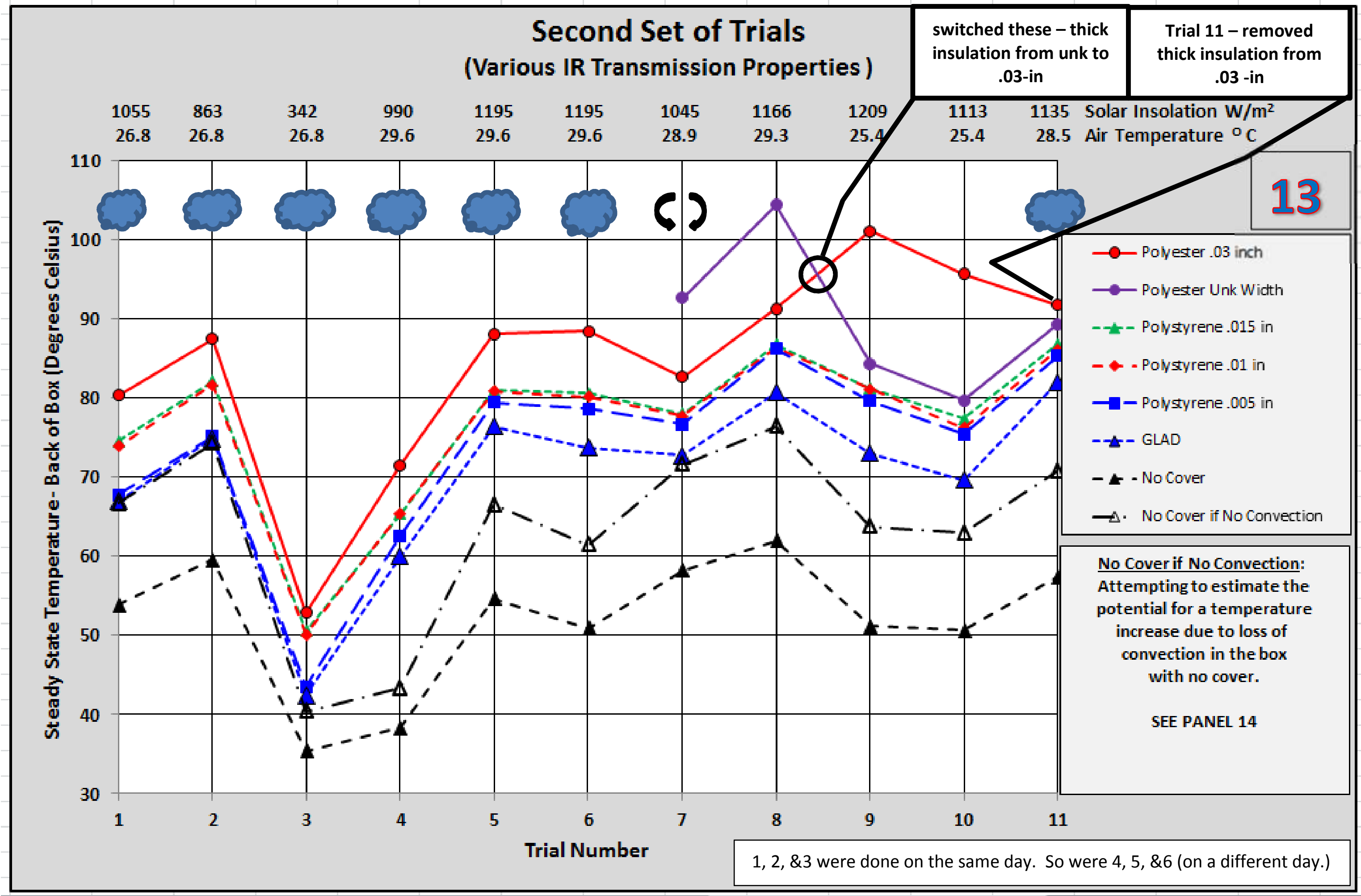
The dashed line (black, solid triangles) gives the temperatures of a box with the same black foam board backing but no cover at all. It always achieved the lowest temperature indicating that adding a cover does increase the temperature in a box.

The next line up (dashes and dots – black, open triangles) is an attempt to estimate the potential for a temperature increase in the no-cover boxes due only to suppressing all convection. It almost always came out below the actual temperatures of the covered boxes, except occasionally for the GLAD-covered box. This suggests that suppressing convection is not enough to produce the observed temperature increases. See panel 14 for details.

The other dashed lines are the temperatures of the plastic films (polyethylene films) that just barely trapped any infrared and transmitted nearly all of it. Their temperatures were always lower that the others.

There are 4 solid lines for the glass and hard plastic (acrylic) covers, although they are so closely packed it is hard to see them all. These materials trapped most of the infrared and only transmitted a little. They always achieved the highest temperatures.

Trials 5 and 7, marked with little cloud images, are the only trials in this group in which shifting clouds made it necessary to use averages of insolation and box temperature (points 2 and 3 in Panel 11).



RESULTS FOR THE SECOND SET OF TRIALS

The two bottom lines (no-cover and estimate of removing convection) are the same as in Panel 12. The weather had changed from the first set and it was raining again, but I had more days of shifting clouds (Cloud Symbols) . Trials 1, 2, and 3 were taken on just one day, as were trials 4, 5, and 6. This represents seven days, 3 of which had shifting clouds.

After trial 6, I rotated the covering materials among the boxes (Symbols) to ensure the boxes were similar.

In the legend, the covering materials are listed in increasing order of expected temperature (Panel 5 and the ones following it). GLAD should produce the lowest and the .03-in polyester should produce the highest temperature. The temperature lines in the graph do indeed increase in the expected way with two apparent exceptions (discussed next).

The unknown-thickness polyester was given to me after trial 6, and after looking at the transmission spectra, I expected it to be a little cooler than the 0.03-in polyester. But in trials 7 and 8, it came out quite a bit warmer, and I thought I had a counterexample. But after Trial 8, I discovered that the black foam board I had used in this case was 6 to 7 mm thick rather than about 5 mm for the other boxes. So this box had extra insulation in back, which could increase its temperature.

To check the insulation theory, I switched the unknown-width and the .03-in polyester covers. Now the .03-in polyester had the extra insulation. Notice that in trials 9 and 10, the unknown-width drops back to a temperature just a little above the other materials while the .03-in polyester increases dramatically. After Trial 10, I removed the thicker insulation and made sure all the foam boards were the same. The .03-in dropped back to where it had been.

So extra insulation must have accounted for the apparent counterexample, and the temperatures came out in the order expected from examining the transmission properties of the covering materials.

"NO COVER IF NO CONVECTION" GRAPHS

Short Explanation

The boxes with no cover are cooled partly by radiation and partly by convection. Assume that the convection is simply not there and that all the cooling is by radiation, producing a higher temperature. Could it be high enough to explain the other box temperatures? This is supposed to be an estimate of the maximum potential temperature produced by suppressing convection. The temperatures so calculated are well below nearly all of the temperatures of the covered boxes suggesting that a loss of convection is not enough.

A Numerical Example of This Temperature Calculation

Regarding Trial 8, First Set: (Incoming Solar Radiation = 966 w/m^2), No-Cover Box Temperature = 50 ^{O}C which, in Absolute temperature, is 273 + 50 = 323 K.

Corresponding radiation is $\sigma T^4 = 5.67 \times 10^{-8} * 323^4 = 617$ w/m^2

σ is the Stefan-Boltzmann Constant = 5.67×10^{-8} w/(m^2 K^4).

The air temperature is 25 ^{O}C, so the convection loss is

$$h(T_{BOX} - T_{AIR}) = 4(50-25) = 100 \text{ w/m}^2$$

This is Newton's Law of Cooling with the heat transfer constant h = 4 W/(m^{2}K) **[for no wind. This is why I needed calm days – Panel 11, Point 4.]** **(Ref. 10, 11)**

Suppose that there is no convection and the 100 w/m^2 is added to the radiation to keep the energy balance intact. The total radiation would be 617 + 100 = 717 W/m^2.

Box temperature = $(717/\sigma)^{0.25}$ = 335 K, which is 335-273 = 62 ^{O}C.
(This is plotted on the "No Cover if No Convection" graphs.)

BIBLI-O-WEB-O-GRAPHY

SOME ADDITIONAL REMARKS AND REFERENCES FOR

CAN SMALL BOXES MODEL THE ATMOSPHERIC GREENHOUSE?

This is a reference to the Physical Science Basis of the 2013 IPCC report. The reason for teaching the atmospheric greenhouse possibly with little boxes as models is to explain the basis for global warming.

1. Cubasch, U., D. Wuebbles, D. Chen, M.C. Facchini, D. Frame, N. Mahowald, and J.-G. Winther, 2013: Introduction. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Chang [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Here is a reference to one attempt to use models similar to these boxes in schools.

2. Full Option Science System (FOSS) Program, Lawrence Hall of Science, Berkeley, CA 94720, Phone: 510-642-8941, Fax: 510-642-7387, Web Site: http://www.fossweb.com

The following old paper seems to have started the controversy about whether boxes such as these really model the trapping of infrared or whether they just show the control of convection. It is a very short note, and it is not easy to figure out just what the author actually did, but it is still quoted anyway.

3. Wood, R. W., “Note on the Theory of the Greenhouse”, Philosophical Magazine (1909 Vol. 17, pp. 319-320).

The following two web links each contain Wood’s entire text (Reference 3 above) as well as detailed criticism of what he said.

4. http://www.wmconnolley.org.uk/sci/wood_rw.1909.html,

   http://www.drroyspencer.com/2013/08/

The following web link contains a report on a 2009-10 experiment similar to what I did that fails to replicate Wood’s experiment from Reference 3. This does not contain as many cases of covering materials and does not make a comparison with a no-cover case. Nevertheless it also suggests that there are problems with the convection-control-only idea.

5. http://boole.stanford.edu/WoodExpt/

This paper in the Physics Teacher examines the effects on the temperature in a box when light is allowed to enter through 1, 2, and 3 panes of glass. More panes increase the box temperature probably because of adding IR trapping ability. (You have to be careful what you use, though. I tried this with GLAD and found that extra sheets of GLAD can cool the interior of the box probably because GLAD is not very good at trapping IR anyway. Adding more probably subtracts more from the visible light entering than it adds in IR trapping.)

6. Victoria Filas and Ludwik Kowalski, “A Greenhouse Box”, Phys. Teach.14,169 - 170 (1976)

On the other hand, the following link, as indicated in the title, claims to have successfully repeated Wood’s work and claims to find that there is no difference in box temperature with covers of glass, acrylic, and polyethylene. In my experiments, the glass and acrylic came out about the same in box temperature as well as in IR trapping ability. But the polyethylene covers I used produced much cooler box interiors and also hardly trap IR at all. I am not sure what the difference in this paper is, but there may be a clue in Reference 5 above. Both used very deep boxes which seem to have allowed a distribution in which the warm air moved to the top. I used very shallow boxes which did not seem to allow for *the same kind of separation. So it is possible that in the link below the thermometers were in the wrong place. In addition, Reference 13 points out that the polyethylene used in greenhouses contains an IR additive that boosts its IR trapping ability. So this author may have gotten ahold of some of that. In any case, the transmission of the precise material used for a box cover should be determined for each experiment. In any case, I need to think about this paper some more.*

7. http://www.biocab.org/Wood_Experiment_Repeated.html

The following is a theoretical paper that claims to show that infrared trapping is not possible in a situation such as the boxes that I used here or in a commercial greenhouse. It is also frequently quoted.

8. R. Lee, "The 'Greenhouse' Effect", Journal of Applied Meteorology, 12, 556 (1972).

The following paper is an analysis of the paper in Reference 8 showing that, in fact, IR trapping is possible and is likely responsible for the temperature increase. In other words, this author says that Lee in reference 8 is mistaken.

9. E. X. Berry, "Comments on 'The Greenhouse Effect' ",Journal of Applied Meteorology, 13, 603 (1973)

The following two papers in The Physics Teacher analyze solar collectors and greenhouses and show that, while convection plays a role, it cannot explain all of the temperature increase in these systems. In other words, they do a better job of analyzing convection, without becoming too complicated, than I did in Panel 14 and represent one source for the value $h = 4\ W/(m^2K)$ *that I used.*

10. Matthew Young, "The Greenhouse Effect", Phys. Teach. 21, 194 – 196 (1983)

11. Matthew Young, "Solar Energy Part II – The Greenhouse Effect" Phys. Teach. 14, 226 - 229 (1976)

The next one is just one example of many on the internet of someone using Wood's paper (Reference 3) to claim that such boxes as these work just by controlling convection.

12. http://buythetruth.wordpress.com/2008/12/08/greenhouse-nonsense/

This problem of convection vs. IR trapping is often framed in terms of commercial greenhouses. However, the paper at the following URL (dealing with instructions on how to build and maintain commercial greenhouses) suggests that they present different issues. It makes clear that they really do exchange air with the outside, lose heat to the soil, among other losses, and that any attempt to argue convection control vs. IR trapping oversimplifies them quite a bit. In winter climates, the main heat source is neither of these but rather an old fashioned furnace (or a modern furnace). They often use polyethylene for the cover, in spite of what I found for the IR transmission of this substance. However, the polyethylene they use is probably thicker than GLAD and it contains an IR additive that boosts its ability to trap IR. The main consideration for them is to admit enough light for plant growth. Here I am interested in models that might be useful in a classroom, and greenhouses ought to be analyzed on their own.

13. http://www.sare.org/content/download/61997/845719/ENC07-098_Reducing_Greenhouse_Energy_Consumption.pdf?inlinedownload=1

And, finally, I would like to thank the supplier of the spectrometer that I used.

14. Thanks to Dr. John Bonte and the Chemistry Department of Clinton Community College, Clinton, IA for the use of the department's infrared spectrometer.

There is a link to a PDF file of this presentation at www.gibbworld.com