

INVESTIGATION OF POLYCARBONATE AS A SUITABLE "GREENHOUSE" MATERIAL FOR THE SOLAR COOKER

John Harrison
Florida Solar Energy Center
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GENERAL

The purpose of this investigation, and hence this report, was to determine if polycarbonate material (also referred to throughout this paper as Lexan, a well know product name) could be used as the material for the solar cooker greenhouse. At this point, two materials are being considered for the greenhouse: borosilicate glass and polycarbonate plastic. (*I have used italics to emphasize certain points through the report.*)

The main concern about each material at this point, and by this author, is as follows:

1. Borosilicate glass

Better know by it's major private brand name, Pyrex. This material seems ideally suited for the greenhouse applications. It can withstand high temperatures, and is in fact, manufactured for conventional oven uses.

Pyrex is a tough glass material that can withstand heat, solar radiation, and reasonable handling. It appears to be the ideal material for this solar cooker greenhouse.

The perceived disadvantage of this material is the final weight of the product could severely impact the shipping costs of the final cooker kits.

If the eventual greenhouse incorporates Dewar type technology, then borosilicate (or some type of glass material) will have to be used due to pressure and structural requirements.

2. Polycarbonate material

Know as Lexan and several other polycarbonate product trade names.

Polycarbonate has been used in solar application as the glazing for flat plate solar collectors. Primarily, the structured polycarbonate glazing material has been used.

Questions remain as to:

1. What types of temperatures can the material withstand without severe and permanent degradation *in the current solar cooker greenhouse application?*
2. What are the affects of long term *and concentrated* UV and solar radiation on the material?
3. What is the impact of long term and *frequent* high temperatures on the material?
4. *How applicable is the Lexan product information fact sheet information in relation to this project. In other words, the greenhouse would present a case much worse than standard Lexan products have been tested (or developed) to in the past.*

Overall, I believe that polycarbonate material *may not* be applicable for a non-Dewar type solar cooker greenhouse. This is stated due to the fact that the solar cooker “greenhouse” application presents probably what is the worst case scenario for the use of Lexan. When GE refers to UV degradation, it is not related to use in such aggressive (environmental wise) products as we are investigating (solar cooker greenhouses). Instead, they are concerned about UV degradation in conventional alone application (signs, street light diffusers, traffic light housing, stadium chairs, outdoor enclosures, etc). Outdoor exposure tests have been conducted but not in a product that will be assailed constantly with solar radiation (UV included), heat, etc., in a concentrated manner. Therefore, it is difficult (or, at least questionable) to transfer manufacturer’s statements regarding polycarbonate characteristics and capabilities to the solar cooker greenhouse.

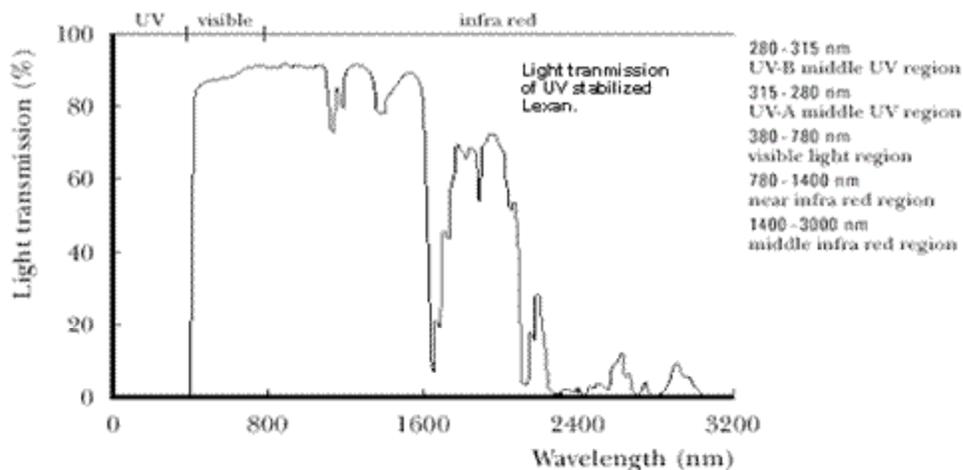
In addition, investigations would have to be conducted to determine the feasibility of producing a final product in the greenhouse bowl shaped configuration. Undoubtedly, questions would then arise as to the application of product characteristics that were perhaps developed for flat sheet applications. How would transmissivity be affected? Would structural stresses due to initial UV degradation of the outer surface affect overall structural capabilities. What are the effects of micro-cracks in this oval configuration?

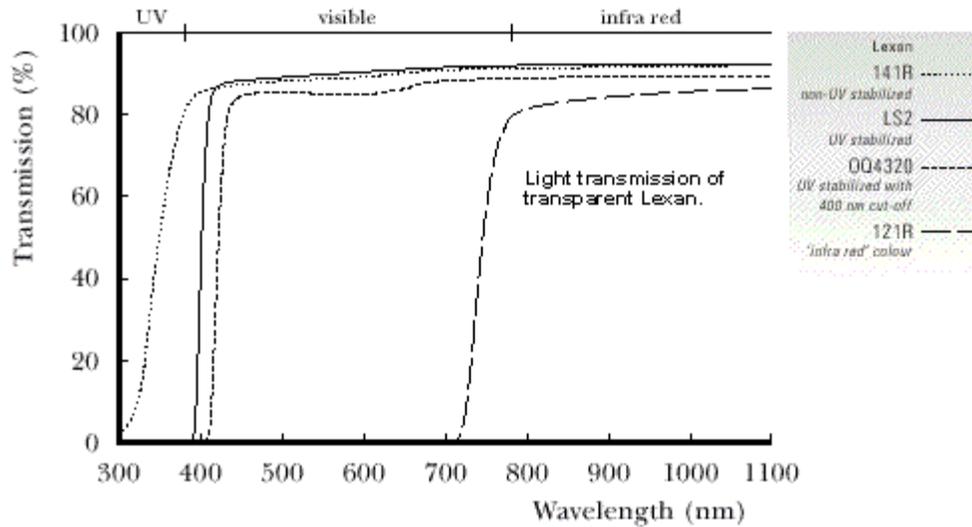
In order to assess Lexan’s viability as a greenhouse material for the solar cooker, the material would have to undergo, in its solar cooker “greenhouse” configuration, long term exposure testing to ascertain its viability for this application. *Therefore, this long term use and exposure testing, there is no guarantee as to what the effects of using Lexan in such a harsh application (solar cooker greenhouse) would be. Without these test, this author does not feel confident providing a certainty regarding Lexan’s applicability in this project. The costs to produce a Lexan greenhouse (bold shaped) prototype would undoubtedly also be very costly.*

POLYCARBONATE CHARACTERISTICS

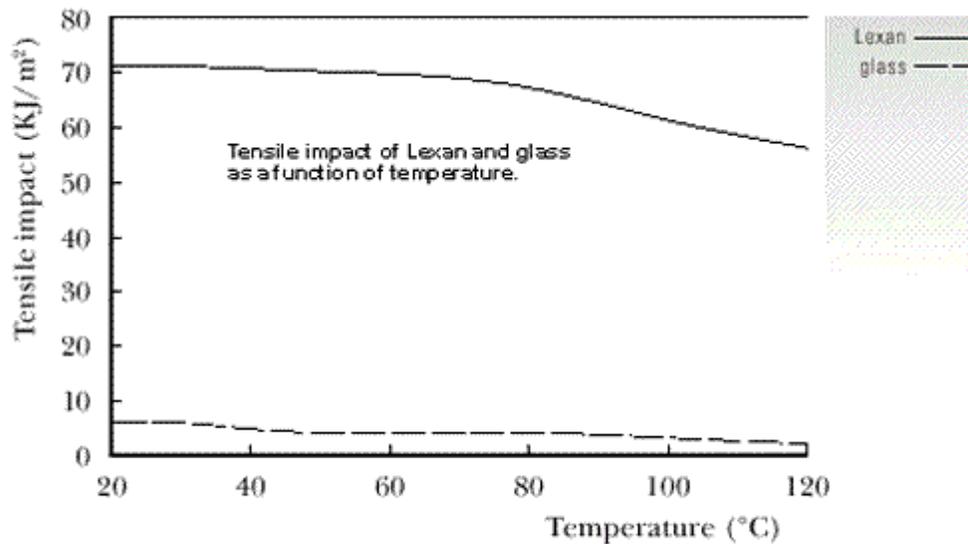
Polycarbonate has numerous manufacturer stated characteristics that appear quite positive. These include:

-High transparency





-Toughness (Polymer Plastic Corp claims that Lexan is 17 times more resistant to breakage than glass.) See GE figure below:

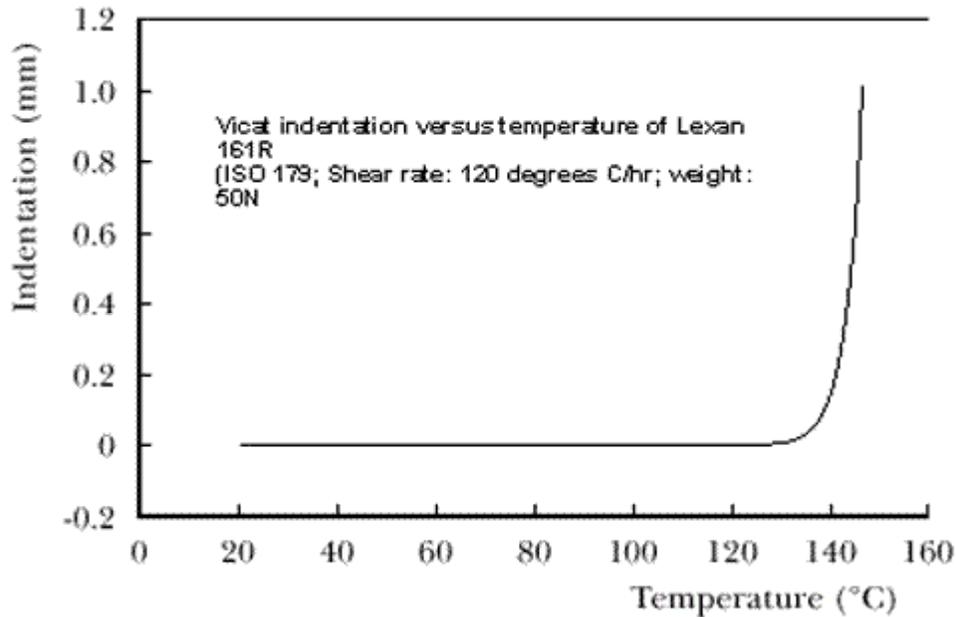


- Heat stability
- Can have UV protective additives added (UV induced damage is limited to the very outermost layer - about 25 microns)
- Lightweight for transportation purposes
- Easily obtained (in sheets as well as possible tube form – investigations would have to be conducted to determine the feasibility and costs of molding into oval greenhouse structures)
- Easily worked (if used in flat sheets, etc.)
- Lightweight

Yet, Lexan also has some negative characteristics that cannot be overlooked. These include:

-The UV degraded outer layer develops very small micro-cracks that can serve as crack initiators and can reduce the overall ductility of the material after very long exposure.

-Although Lexan has good thermal properties, the softening temperature point is much less than borosilicate glass. See figure below.



-Once the outer layer is degraded, the rest is subject to natural aging and discoloration. The usual pattern of discoloration (mainly for colored materials – but also affects transparency to an extent) due to UV exposure is as follows:

- Induction period (little or very slow visible change)
- Fast discoloration, reaching almost the final color
- Very slow discoloration

-Much more expensive than glass (per local glass vendor quote)
-One manufacturer states that there is currently a long lead time for the Lexan resins due to the demand for it. This manufacturer also states that the cost is \$\$\$ out of \$\$\$\$ - based on comparison to other plastics. (The author surveyed several web sites that sell standard Lexan sheets and discovered that the usual cost was approximately \$7.50 to \$8.00 per square foot.)

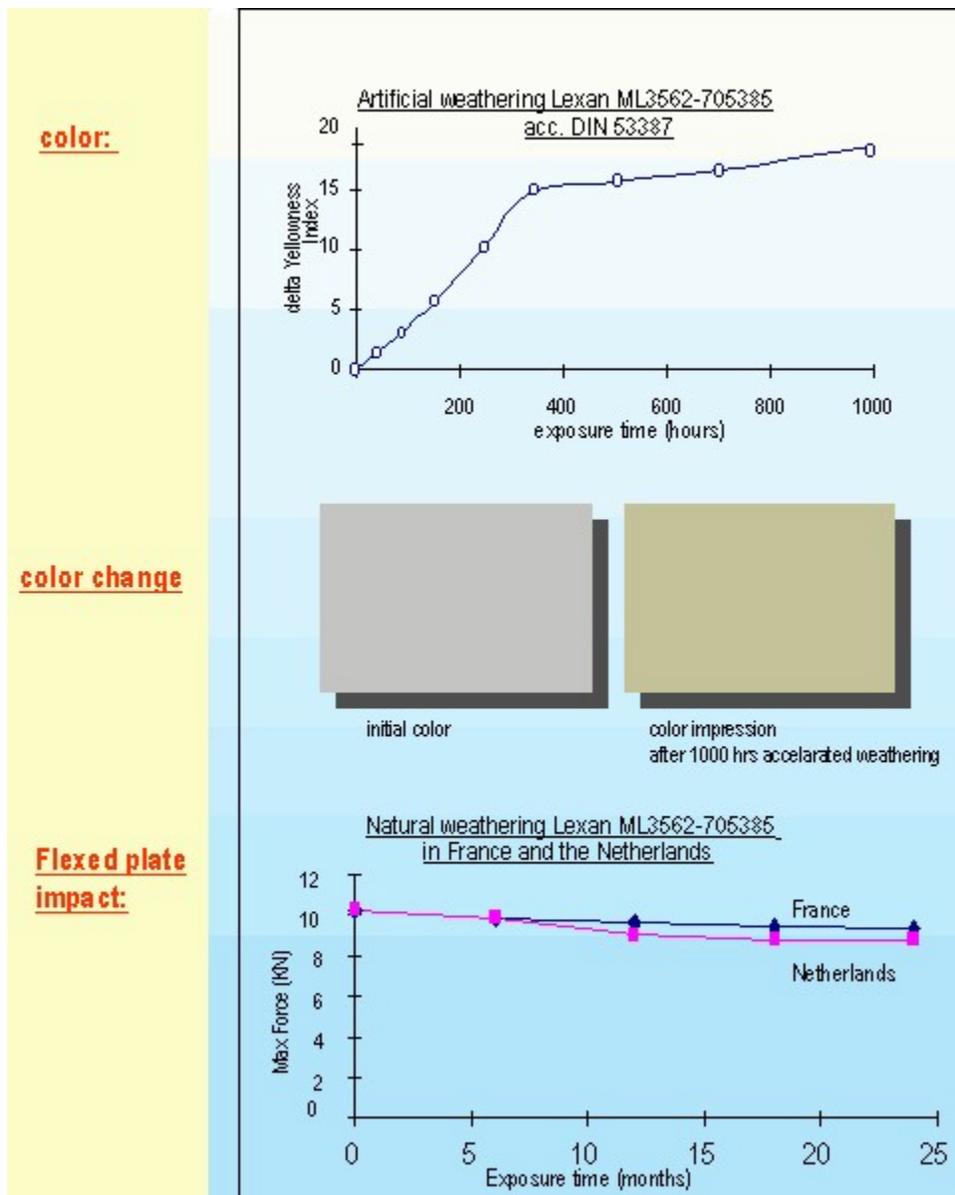
FROM GE PLASTICS WEB SITE DOCUMENTS

(Note: This information was obtained from the GE document "Weathering – A Practical Approach." GE developed the plots and tables listed below during weatherability testing of various Lexan products.)

Color changes

-Change in color is usually the first indicator of weathering, *followed by surface flaws, which eventually become stress centers for crack initiation.* Nevertheless, GE states that a discolored part likely still has excellent mechanical performance.

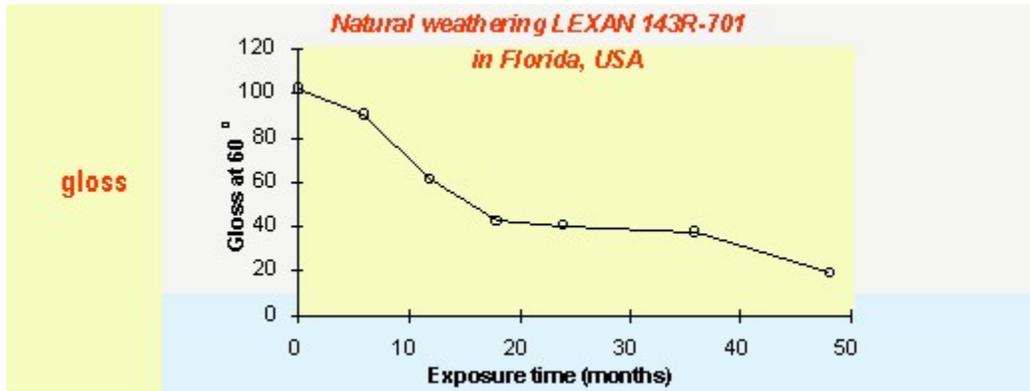
-When exposed, the color will shift to the yellow side, initially rapid, but eventually reaches a maximum yellow tint. This includes transparent material as well. (See change figure below)



Outer gloss

-For transparent materials (which would be the case in this application – solar cookers), *the initial gloss of the material becomes hazy. The haze increases and transmission is reduced over time due to erosion of the top surface.*

Lexan when new has a definite exterior gloss. The gloss level was reduced by 40% of its original value after one year on a sample of Lexan tested in Florida environment. As mentioned previously in this report, this was a result of the erosion of the top surface during exposure. See plot below.



Factors Affecting Weatherization of Lexan (in order of severity)

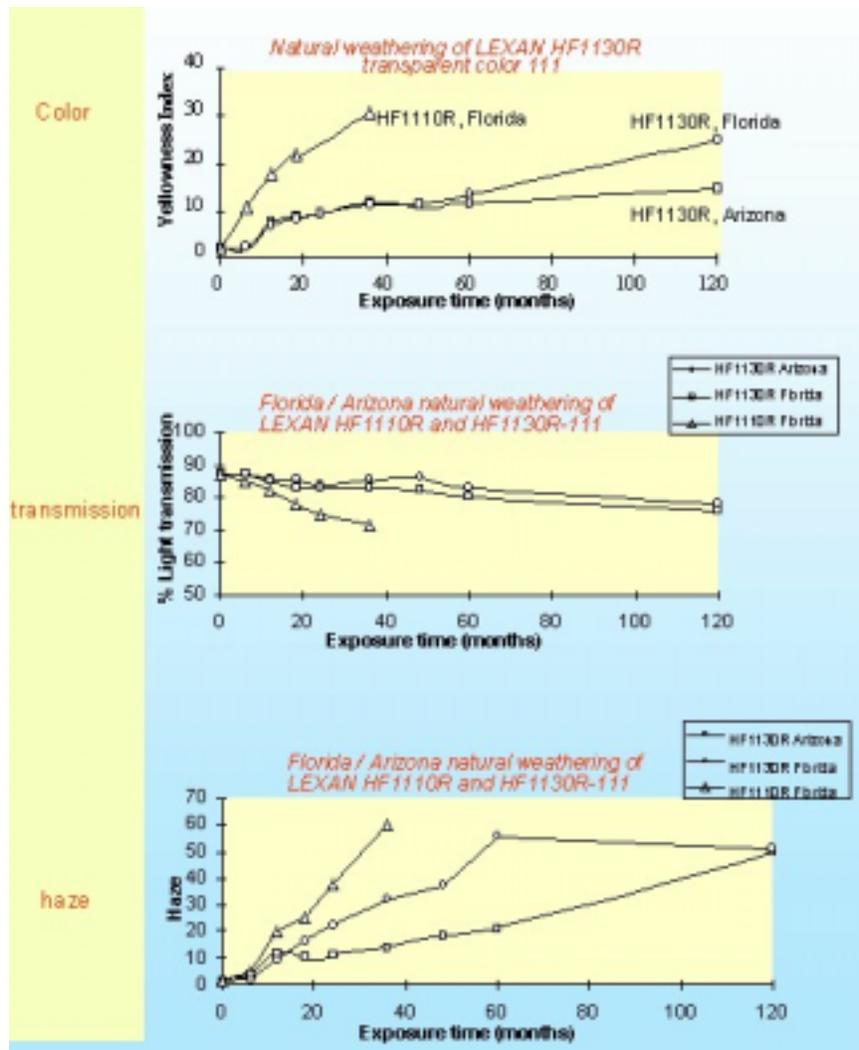
Transmission

-Excellent retention of light transmission of long exposures (See Transmission figure below)

UV radiation

- This is the main cause of discoloration of Lexan
- Direct sunlight is more aggressive than sunlight filtered through glass
- UV rays attack only the very top surface

See plots below.



Temperature

- High temperature is a major contributor for discoloration
- Discoloration due to high temperature is throughout the whole thickness
- Typical usage temperature is 60-80° C (140-176° F)
- One GE fact sheet on Lexan states that the RTI is up to 125° C (257° F) (RTI: Relative Temperature Index is the maximum service temperature at which the critical properties of a material will remain within acceptable limits over a long period of time.)
- As temperature increases Lexan's tensile strength decreases. As the temperature decreases, Lexan resin becomes slightly stiffer and more brittle.
- Temperatures of over 100° C (212° F) will accelerate discoloration
- A major distributor (and molder) claims that the maximum temperature for Lexan is 300° F for short durations and 150° F for long term.

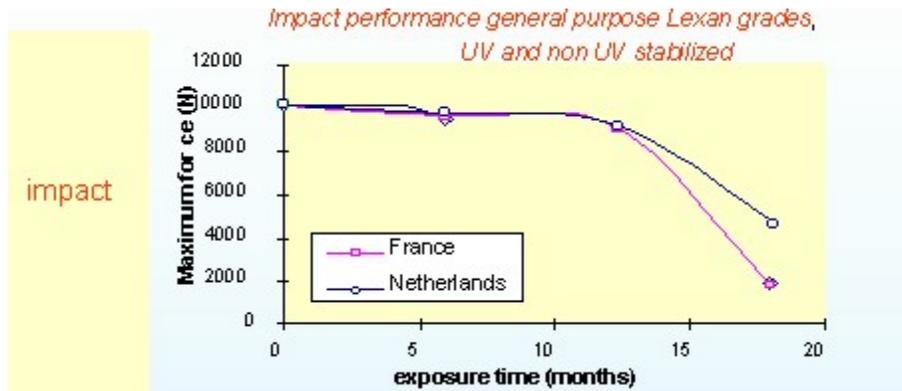
Moisture

- Moist climates accelerate the degradation process
- Moisture primarily affects the gloss and haze of Lexan, and in combination with heat, it can also decrease impact resistance
- (Which could be a factor if moisture is also introduced from within the greenhouse from condensation)

Surrounding environment (air pollution, dust, sand, etc.)

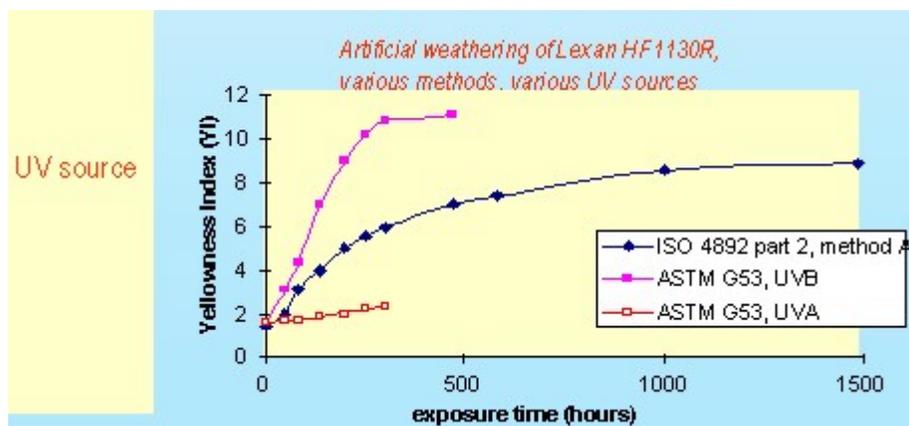
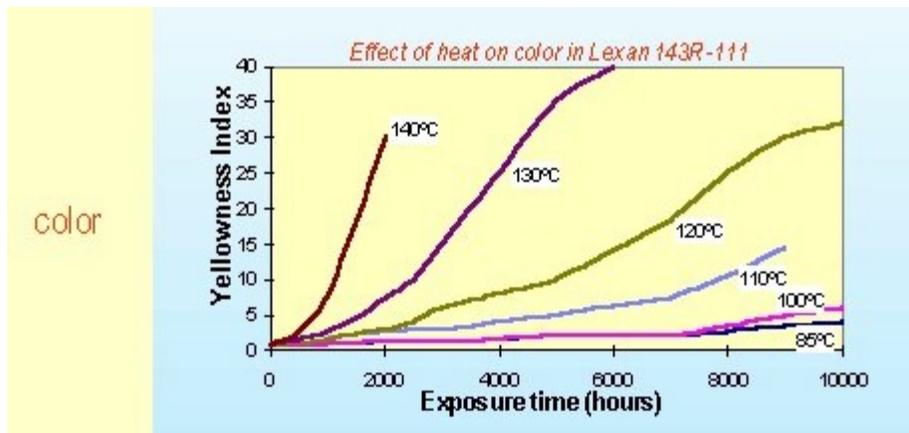
- Acid rain and a variety of gasses (not listed) will also accelerate the degradation of Lexan
- Fine dust and sand can damage the surface and result in a reduction of gloss level
- Factors vary greatly by the geographical location, time of year and industrialized level.
 - In heavily industrialized areas, factors such as air pollution and moisture will have an affect on Lexan
 - In areas such as Arizona, high levels of solar radiation and high temperatures would affect the Lexan
 - In areas such as Florida, the Lexan would be affected by high humidity (moisture)

The chart below provides information on the impact of PC materials. GE states that impact is very high compared to other transparent plastics.



GE also states that *the effect of weatherization is more severe in transparent grades compared with opaque grades*, since many pigments are used in opaque colors that serve to shield the Lexan from UV rays by UV absorption or reflection. Dark colors are more stable than light colors.

See plots below of heat and weathering effect on Lexan



GE listed several examples of applications in which Lexan polycarbonate grades have been proven to be successful, even under critical conditions. These include the following “transparent” grades:

Application	Lexan Family	Lexan grade name	Color
Street light diffuser	Transparent non FR, UV	123R, HF1130R, 143R	Natural
Waterproof luminaire diffuser	Transparent non FR, UV	143R	Natural

Specification sheets were obtained for the following GE Lexan resins that appear to have the best characteristics for use in the solar cooker project. These products incorporate both UV protection and are available as transparent materials. (Note that only some polycarbonate resin final products are available as transparent.) Fact sheets reported the optical and thermal characteristics important to this project.

Resin Material	Thermal Index**	Light transmission, .10"	UV Stabilization	Refractive Index
Lexan 143*	130 ⁰ C (266 ⁰ F)	88%	X	1.586
Lexan 123	100 ⁰ C (212 ⁰ F)	88%	X	1.586
Lexan 1130	100 ⁰ C (212 ⁰ F)	88%	X	1.586

*GE states that the 143 resin is the material of choice for emergency light diffusers...as, in addition to its glass-like transparency for a high light output...it provides impact resistance, heat resistance, and structural weight.

** "The maximum service temperature at which the critical properties of a material will remain within acceptable limits over a long period of time." The "end of service" life is defined as the time at which a material property has degraded to 50% of its original value.

Interestingly, GE provided the following table comparing various plastic materials. They are graded from Excellent to Very Poor and are identified as either transparent or opaque. *Note that Lexan does not fare that well, achieving primarily fair to poor in weatherability and thermal aging.*

Polymer		Opaque		Weatherability ^{b,d}			Thermal Aging ^{b,d}		High Energy Radiation ^{b,e}
		Transparent ^c		Color	Physicals	Gloss	Color	Physicals	
Poly(tetrafluoroethylene)	Teflon	O		e	e	e	e	e	p-f
Poly(vinylidene fluoride)	PVD F	T		e	e	e	e	e	p-f
Poly(methyl methacrylate)	PMM A	T		e	e	g-f	g	g	p
ASA	Geloy	O		g	e	f	g	g	
Polyethylene	PE	O		g	p (a) ^f	wp	g	p	f-p
Polypropylene	PP	O		f	vp (a) ^f	wp	f	vp	p
Polyoxymethylene (polyacetals)	Delrin	O		p	p	wp	f	p	f-p
Poly(vinyl chloride)	PVC	O/T		p	p	wp	p	vp	f
Poly(vinyl chloride) + TiO ₂ ^a	PVC/TiO ₂	O		g	g	p	p	wp	f
Polyamides (aliphatic Nylons)	PA	O		g	f	g-f	f	f	p-f
Polycarbonate	PC	T		f-p (a) ^f	f-p	p	f	f	a-f
Polycarbonate (FR Salt)	FR PC (Salt)	O/T		f-p	f-p	p	f	f	g-f
Polycarbonate (FR ArBr)	FR PC (ArBr)	O		p	p	p	f	f	g-f
Poly(phenylene oxide)	PPO	T		wp	g	wp	vp	vp	g
Poly(phenylene oxide)/Polystyrene	Noryl	O		wp	g	wp	p	p	g
Poly(ethylene terephthalate)	PET	O		g	g	p	g	g	g-f
Poly(butylene terephthalate)	PBT	O		g	g	p	g	g	g-f
Poly(BPA terephthalate)	Ardel	T		wp	e	g	g	g	g
Polysulphone (BP A)		T		wp	p	p	f	g	e-g
Polyurethane (MDI Based)	PU	T/O		p	p	p	p	f	e-g
Polyacrylonitrile	PAN	O		f	g	p	p	p	
Polystyrene	PS	T		f	p	f	f	f	g-e
ABS	ABS	O		p	p	f	f	f	g
FR ABS (ArBr)	FR ABS (ArBr)	O		p	p	p	f	f	
PC/ABS	PC/ABS	O		f	g	p	g	g	g
PC/PBT	PC/PBT	O		p-f	g	p-f	g	g	g-f

Key: e-excellent, g-good, f-fair, p-poor and vp-very poor; O-Opaque, T-Transparent

(a) Note that most commercial polymers contain stabilizers and some can be more effectively stabilized than others.
 (b) Encyclopedia of Polymer Science and Technology, John Wiley & Sons, Vol.17, pp.796 and 797.
 (c) Ibid., Vol.13, pp. 685, 686 and 700.
 (d) Opinion of author--indicated by the use of italics.
 (e) Note that the relative rating for a transparent resin may change when it is pigmented.
 (f) High concs. of TiO₂ (e.g. 5+%) generally improves weatherability.
 (t) Stabilized system.

It must be noted that GE manufactures a variety of plastic materials. Materials such as Geloy (auto exterior trim) have excellent UV protection but unfortunately are not available in transparent versions. Other GE plastic family related products such as Cyclocac, Cycoloy, Enduran, Gesan, Noryl, Prevex, Remex, Siltem, Supec, Ultem, Valox, and Xylex are not suitable for this application for various reasons including some not being transparent, low transparency, low heat resistance, etc.

GE also manufactures a line of Thermoclear multiwall sheets that initially deserved investigation. The Thermoclear line features a GE proprietary "both sides" surface treatment to protect the material from UV degradation. The material can be obtained in the following width increments; 6 (82% solar transmission), 8 (82%), 10 (74 – 81%), 16 (76%), 20 (64%), 25 (44%), 32 (38%)mm. Of course for solar applications, only the 6 though 10 mm versions would be applicable. Since this

material has channels between the outer and inner surfaces, sealing presents specific challenges. Special tapes have been developed for sealing. In most glazing applications, specific neoprene clamps have been developed to secure the material to window frames, etc. In addition, thermal expansion of this material is approximately 3mm per linear meter. Regardless, since this material comes only in sheets, it would not be feasible for the solar cooking project unless the greenhouse was constructed in a square configuration.

Another possible GE standard Lexan product, other than the standard Lexan resins listed above is:

-Lexan MR10 sheet (comes in sheet version only) is listed as being the most UV/abrasion resistant polycarbonate glazing material available. One manufacture has these sheets available in 1/8" and 1/4" thickness. Light transmission (for 1/8") is reported as 88%. Solar transmission values were not reported. MR10 is used primarily as glazing material in commercial facilities. Once again, this material could only be used in a square type greenhouse configuration. (Note that the warranty found (signs only) for this material is inclusive only for the material's use in signage applications.) In addition, the cost of this product appears to be quite high.

The GE developed table below indicates weathering characteristics for Lexan sheet for sign products. Lexan sheets for sign products include the above MR10 material coated with

COMPARATIVE WEATHERING DATA													
OPTICAL PROPERTY	OUV HOURS					MONTHS - SOUTH MIAMI							
	0	500	1000	1500	0	6	12	18	24	36	48	54	60
Coated LEXAN® Sheet*													
% Transmission	87.6	86.5	85.0	84.9	83.4*	83.5	83.3	84.5	82.8		83.5		84.4
Yellowness Index	0.2	2.1	2.3	4.4	0.9	-2.4	-1.8	-1.0	-0.3	0.5	1.4	2.1	3.3
Delta YI		1.9	2.1	4.2		-1.5	-0.9	-0.1	0.6	0.4	0.5	1.1	2.4
% Haze	2.2	2.6	3.3	5.3	0.7	1.4	2.5	3.8	4.2	4.6	5.3	5.2	6.2
Uncoated LEXAN® Sheet													
% Transmission	87.6	85.2	83.8	80.4	87.0	87.0	85.0	83.0	83.0	83.0	82.0		80.0
Yellowness Index	0.2	12.0	12.9	15.9	2.1	1.8	6.7	8.3	9.3	11.2	11.0		13.5
Delta YI		11.8	12.7	15.7		-0.3	4.6	6.2	7.2	9.1	8.9		11.4
% Haze	2.2	3.1	23.6	60.0	1.1	2.0	9.4	16.2	22.4	31.9	37.2		55.7

*Lower light transmission values are attributable to .250" gauge sample used. Other samples were .125" gauge.

From Hubbell, Inc. White Paper

Polycarbonates Versus Acrylics

The following information came verbatim from a white paper (Application and Limits of Polycarbonate and Acrylic Lenses (*In this case, the word lenses is used instead of luminaires.*)) developed Hubbell, Inc. a company that develops electronic and electrical products. They also produce exterior lamps that use Lexan as luminaire lenses. Other than the GE plastics web site, this paper provided probably more relevant (to our situation) information regarding polycarbonates.

When it comes to selecting a container material for strength, consider these factors: *basic strength, ambient temperature and design.* Will the luminaire be located in an area where damage through vandalism is likely or would the only lens contact be

occasional and light? Will it be exposed to temperatures with wide shifts in range? Will maintenance be a problem? Is the environment dusty or dirty? In the following, chart boxes with an "X" indicate an appropriate design choice.

	Polycarbonate	Acrylic
Impact:		
Heavy	X	
Light	X	X
Ambient Temperature:		
Cold	X	
Moderate	X	X
Hot	X	X
Environment:		
Clean	X	X
Dusty	X	

The second major attribute of these plastics is their light transmitting abilities. Both acrylic and polycarbonate are excellent choices for lens material as they have high transmissivity ratings and show very little hazing.

	Polycarbonate	High Impact Acrylic	Standard Acrylic
Transmittance:	86-89%	89%	92%
Haze:	1-3%	4%	2%
Refractive Index:	1.586	1.49	1.49

In lighting applications UV is a well known stressing agent of plastics - all transparent plastics will yellow under UV - but it is in many ways the most controllable. Polycarbonate without a UV inhibiting additive will show strong yellowing upon exposure to natural and artificial sources of ultraviolet (such as sunlight and HID lamps). High impact acrylic also yellows, though not to the same degree, and standard acrylic shows little UV induced yellowing. *The use of a UV inhibitor in polycarbonate formulation reduces yellowing significantly.*

Does yellowing present more than an aesthetically displeasing effect? Strangely, the data are split. Standard falling ball impact tests on polycarbonate indicate that there is no loss of material strength. *Furthermore, an ASTM Yellowness Index Rating of 25 for polycarbonate results in a loss in transmissivity of only 5%.*

On the other hand, yellowing is a sign of degradation of the plastic molecule. Heat and ultraviolet act to break the molecules. This surrenders the intrinsic strength of the material as the molecular structure no longer consists of long intertwined chains

but fractured segments. This may be reflected in reduced strength of parts with formed surfaces as these surfaces tend to localize stresses.

From a specification point of view, one must be concerned with the temperature of the lens. *Polycarbonate has a viable working temperature of around 90°C (approximately 195° F).* Working temperature is that maximum allowable temperature for a material that will not result in a loss of physical characteristics.

Unfortunately, there are other causes of yellowing that are extremely difficult to anticipate. Stresses in the manufacturing process can cause premature yellowing even if the other environmental stresses are within the limitations described. Some of these fabrication stresses include the amount of regrind or reprocessed material in the lens, excessive molded in stresses (a function of the lens design itself), processing temperature and improperly or insufficiently dried resin. These factors are not perceivable in a finished product and the manufacturer must be constantly aware of the possibilities of molding stress and must test samples for quality.

Additional sources:

Engineering Laboratories, Inc:	Max service temp of Lexan = 250 ⁰ F
EFunda (Engineering Fundamentals):	Trade names for polycarbonates: Lexan, Makrolon
Flex-Lex Plastic Mfg:	UL continuous use temperature: 212 ⁰ F
Other trade names:	Makrolon, Hyzod, Tuffak
Polymer Plastics Corporation	General description of polycarbonates and other plastics

Various web resources on plastics and polymers.