



THERMOFORMING MANUAL ENGINEERED MATERIALS GLOSSARY AND TROUBLESHOOTING GUIDE

PREFACE

Just what you always wanted! Another boring manual on the thermoforming process. So why did we do it? Mostly duress! There were some people that felt it would be useful to document some of the information I have accumulated over these many years and share it with you. Does this mean that this manual is a totally comprehensive document on everything there is to know about thermoforming? NO! However, it is a fairly good depiction of what this business is all about.

To the best of my knowledge, I have refrained from uttering any falsehood regarding the various aspects of this industry. Hopefully the information contained within this manual will be helpful in getting a grasp on the thermoforming process and provide you with information that is useful in addressing some of the problems and situations that you may confront. Should this manual be used as the only authoritative document regarding thermoforming? NO! There are many excellent things written on the thermoforming process and many new developments and methods are being put forth all the time in this industry. However, I think you will find the information contained within this manual is based on tried and true empirically tested data.

Should you be so inclined to seek a more explicit explanation on any of the information contained within this manual, we invite you to do so by calling Spartech at 800-677-4338.

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Leroy M. Boser

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DESCRIPTION OF VACUUM FORMING

Simply stated, vacuum forming is the process of taking a flat sheet of plastic and changing it into a contoured shape. This is accomplished by putting a piece of plastic into some type of clamping mechanism, heating the sheet up to a forming temperature, stretching the heated sheet of plastic over a mold, sealing the heated plastic sheet on the edge of the mold base, and removing the air from within the mold cavity, thereby through atmospheric pressure, forcing the material up against the mold surface. Is that a mouthful or what? Well, all of this is necessary to get the job done. Following this process will allow the plastic to assume the shape of the mold surface.

As one might imagine, this is a versatile process and you can make a wide variety of parts this way, but there are also some limitations as to what you can do. Pulling this heated plastic over a mold is going to stretch the hot plastic unevenly causing thinning

and weak spots in various areas, depending on the shape of the mold and the forming technique you use. In light of these facts and because injection molding does not have many of these restrictions, why would anyone persist in doing vacuum forming?

The simple fact is that vacuum forming has some very big advantages over injection molding and also over other plastic forming processes. First, mold costs are dramatically reduced, in some cases by 90%. Second, we can prototype small runs economically compared to other processes. Third, we can make large parts more economically than most other methods. And fourth, we can get into the vacuum forming business quite easily without extensive capital costs. These and other issues will be dealt with in more detail later but for now, I would like to address the various methods and techniques employed in the vacuum forming process.

VACUUM FORMING TECHNIQUES

There are many different thermoforming techniques that one can employ in the thermoforming process. The type of technique you choose will be determined by the geometry and shape of the part you are trying to make, along with the degree of difficulty of the part, and what your equipment is capable of doing. I would like to address each one individually by describing it and explaining why you would use each of these techniques.

1. DRAPE FORMING—BOTTOM (Figure 1)

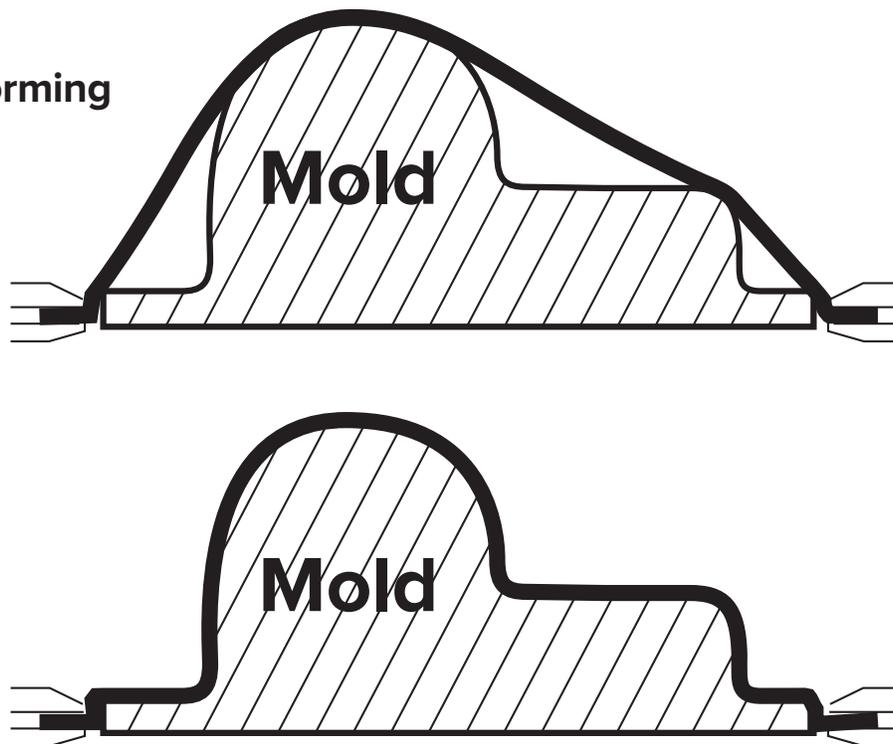
Essentially DRAPE FORMING—BOTTOM is clamping a piece of sheet plastic in some type of clamping mechanism, putting this material into a heating oven, heating the plastic sheet up to a desired temperature, retracting it from the oven, draping it over a mold, trapping the sheet just inside the clamping mechanism over the edge of the mold flange, and applying a vacuum to the mold chamber. This is quite simple and anyone can do it with very little capital investment. All one needs to do is acquire a basic heating oven, a rudimentary vacuum system and construct a mold out of any one of a number of inexpensive materials such as wood and you are in business.

Basically what happens when you heat the sheet up in the oven, the sheet reaches a forming

temperature but it ends up with a slightly uneven heat. This happens because the clamping mechanism acts somewhat as a heat sink and drafts in the oven or defective heating elements cause further heating disparities. This will be addressed later in the troubleshooting section. As the sheet reaches approximate forming temperatures, it will sag somewhat in the clamp frame due to the thermal expansion properties of plastic, the actual softening of the plastic, and sheer gravity overcoming the hot strength of the plastic. Also the actual surface of the plastic will be slightly hotter than the interior of the sheet. When you remove the plastic from the oven, the surface of the sheet will cool off very quickly so you do not have much time to actually form the material, usually only seconds. Next you actually drape the hot plastic sheet over the mold. This causes the plastic that touches the mold to cool very abruptly and freeze onto the mold surface wherever it actually touches the mold. This chilling may be 50° to 100° F on the areas that touch the mold on the mold surface side in just a matter of seconds. This makes the plastic considerably harder in these areas, and when you apply the vacuum to stretch the material over the rest of the mold, the plastic will stretch more easily from the hotter areas, thereby thinning those areas more readily. As you stretch the hot plastic over the mold and

Drape Forming

Fig. 1



trap the edges next to the clamp frame to the mold flange, you further thin out the plastic. However, you have no choice in doing this, as you need to get a seal around the mold flange to be able to apply the vacuum. Finally the vacuum is applied to force the rest of the plastic up against the mold to chill it. After a few minutes, the plastic contacting the mold will chill enough to be below its heat distortion point. This phenomenon will also occur on the surface side that is exposed to the air but at a much slower rate. At that point it can be removed from the mold and the excess trim removed to take on the dimensions of the designed part.

Generally speaking there are some drawbacks to this technique in molding. First, you are going to have a lot of competitors and price pressures will be severe. As I indicated earlier, almost anyone can get into this business using this technique. Second, this technique is not capable of producing parts that are very complicated. Wherever the plastic touches the mold is essentially where it ends up. Consequently, any part that is a little more complicated could end up with some thinning in some areas that are not acceptable. You just do not have any control to move the plastic around to other areas of the part. This will also cause the thinning to be uneven and the texture may appear different on various areas of the part. Third, you are very likely to have chill

marks on various areas on the part. This may be cosmetically unacceptable and other techniques may have to be employed to overcome this.

However, the other side of the equation shows that there are some quite beneficial aspects to this technique. First, you can produce parts via this method quite economically. It is probably the most economical thermoforming method we can use. Secondly, the parts produced via this method are normally totally acceptable for the application they are being used even though they may have some cosmetic deficiencies. If you have a part that is not very difficult and has a relatively easy draw ratio (term to be defined later), not only is it likely to be the most economical technique, but it is also likely to require less engineering work to get the whole thing designed and produced. Third, it does not require highly trained personnel to produce parts by this technique. And fourth, as with most vacuum forming techniques, you can make multiple parts on one mold. In many cases these parts will be quite different from one another. This would vary depending on the complexity of the parts and the general size that the vacuum forming machine is capable of handling. All in all, if you have a choice, this is probably the best method you could select provided the part geometry allows you to use this technique.

2. DRAPE FORMING—TOP

If you look at Figure 1, DRAPE FORMING—TOP is just like DRAPE FORMING—BOTTOM except it is upside down. The technique is exactly the same but the results are slightly different. The first thing you will realize is that you are going to have to have some kind of a superstructure support system to suspend your mold from. This is called a platen and is capable of moving up and down via some type of pneumatic or mechanical system mounted to some type of solid framework. In this instance, the clamping mechanism that clamps in the plastic sheet is usually supported on a trolley system that can be moved into or retracted from the oven.

As before, the plastic sheet is heated in the oven and when it reaches forming temperature, it is removed from the oven on the trolley and positioned underneath the suspended mold. At this point, you will note a very subtle difference. When you remove the heated sheet from the oven, it sags just as before but the direction of the sag is away from the mold. If you are using a male mold, the mold shape relative to the mold flange does not touch the heated plastic quite as soon as it does in using drape forming—bottom. You are dropping the mold into the sag of the material. This allows you to apply the vacuum slightly sooner during the forming process and does not normally produce as many chill marks as the drape forming—bottom technique. Because you can heat the sheet a little hotter and get a little more sag, you may also have a little less stretching and thinning than the previous technique. A lot of this depends on the mold design.

3. PLUG ASSIST—BOTTOM (Figure 2)

PLUG ASSIST—BOTTOM forming is very similar to DRAPE FORMING—BOTTOM except for one important difference. Everything happens in the exact sequence as in DRAPE FORMING—BOTTOM up until just before applying the vacuum. As before, you heat the sheet, remove it from the oven and drape it over the mold. However, just before applying the vacuum, you push the hot plastic into various pockets, ribbed cavities, and steep walled sections via a plug assist to move the extra plastic down into these areas. The purpose of this technique is to allow extra plastic to be moved toward the bottom of these areas before it is thinned out. Here is basically how it works.

A plug is constructed out of some insulate material, such as wood, and covered with a soft cloth material, such as felt. This prevents the material from

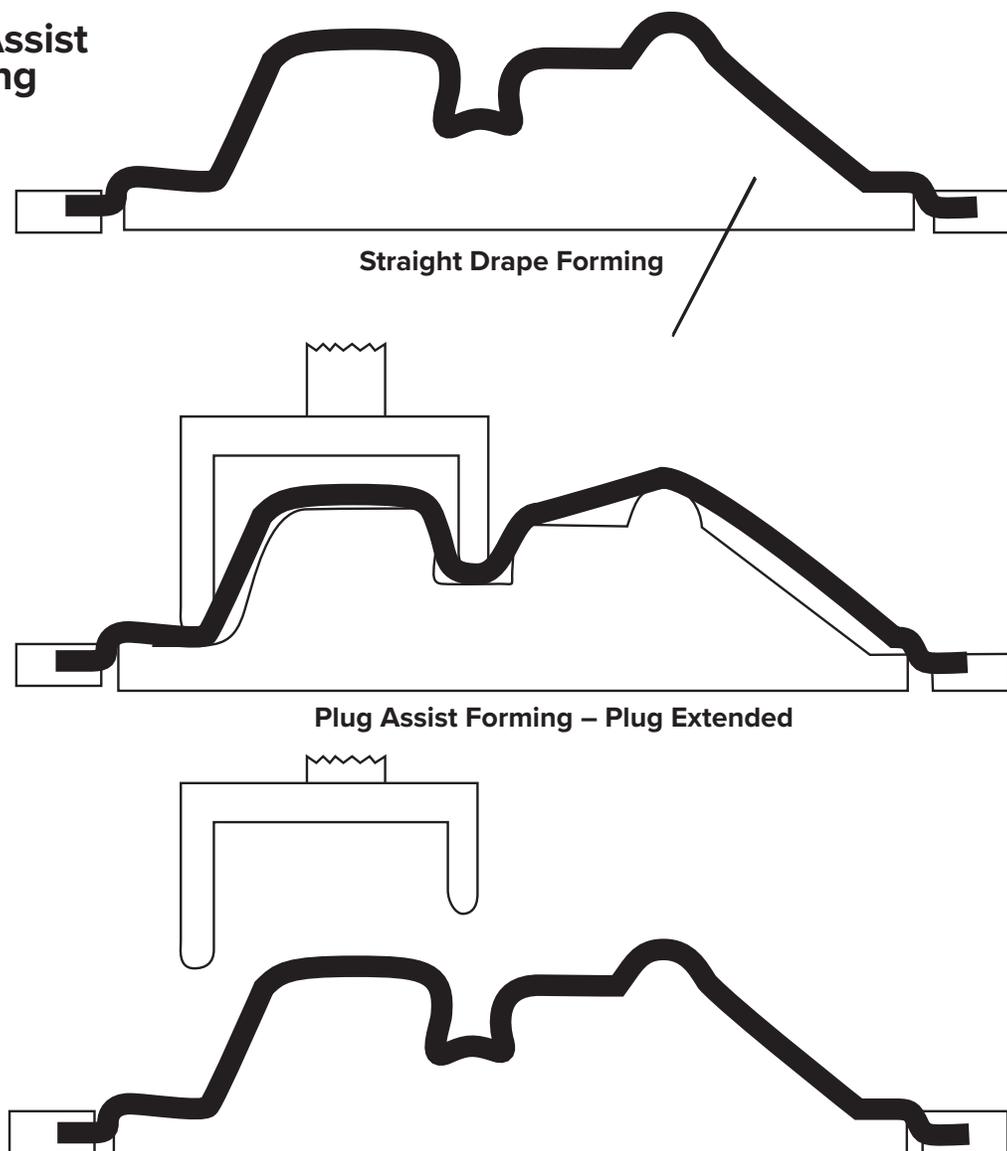
picking up plug marks when the plastic is in the hot state. The plug is constructed in such a way that the surface area of the plug will move the maximum amount of hot plastic down into a cavity. Thus the amount of clearance the plug has in relationship to the vertical mold wall is important. This will be dictated by the geometry of the mold. The depth the plug goes into the cavity is also important. The reason this is so is because you only have so much plastic to work with over any given area of the mold as you are stretching the hot plastic over the mold surface. What you are essentially doing is taking a little of the plastic that would have been formed unto the upper vertical walled area, and moving it down to the bottom of the cavity and the bottom vertical walled area before the vacuum can be applied. You are just redistributing the available plastic a little more uniformly. As you might imagine, the way the plug is constructed and the depth that it is inserted into the cavity are important.

Another consideration is the way the technique is employed. It should be obvious that this technique would be difficult to employ manually. Thus you will need some kind of a machine with both a top and bottom platen to mount the mold and the opposing plug unto. The mold will be mounted onto the bottom platen and the plug will be mounted onto the top platen. As a slight variation to the previous technique, it will be necessary for both the bottom and top platen to move up and down. You must also be able to control how far up and down both of these platens go to prevent them from smashing into each other. Typically the plastic sheet is mounted into a clamping mechanism and placed on a trolley that can be moved into and out of the heating oven. The accuracy point that the clamping mechanism stops when you retract it from the oven is important because you will need to get a good seal around the clamping mechanism relative to the mold flange. This will require the trolley to stop in the same position each time. This stopping point is also important in getting the plug to contact the plastic relative to the mold position each time in order to insure consistent material distribution on the part.

Finally it should be noted that it is possible to move one or both of the platens that support the mold and plug assist together to control which of these touches the hot plastic first. This can affect how the material is distributed and where chill marks may appear depending on the shape of the mold. The advantages to this technique over the previous

Plug Assist Forming

Fig. 2



ones should be obvious. First, you will get better distribution of material and therefore less thinning. Second, the amount and severity of the chill marks you experience will be lessened and thirdly, the complexity of the part you can make will be increased.

4. PLUG ASSIST—TOP

As was the case in DRAPE FORMING, PLUG ASSIST

- TOP is just like PLUG ASSIST
- BOTTOM except that it is upside down and just as in DRAPE FORMING, reversing these positions changes the outcome of the forming results and changes what you can accomplish. See Figure 2. Again you will note a subtle difference. Since the mold is mounted unto the top platen, the sag of

the hot plastic as it is removed from the oven is away from the mold and towards the plug assist. This again allows you to push the mold

into the natural sag of the material and get a little better material distribution. It also allows you to do one extra thing that can be significant. If you bring the bottom platen up first, you push the plug through the hot plastic causing a tenting effect that will keep the material from touching the mold quite as soon and allow you to distribute the plastic better in the cavity areas. This happens because the plastic does not freeze unto the mold quite as quickly. This technique is probably the most ignored technique in vacuum forming. There are many instances when employing this technique would be

the difference of getting a good part as opposed to an acceptable one.

5. SNAP BACK—TOP (Figure 3)

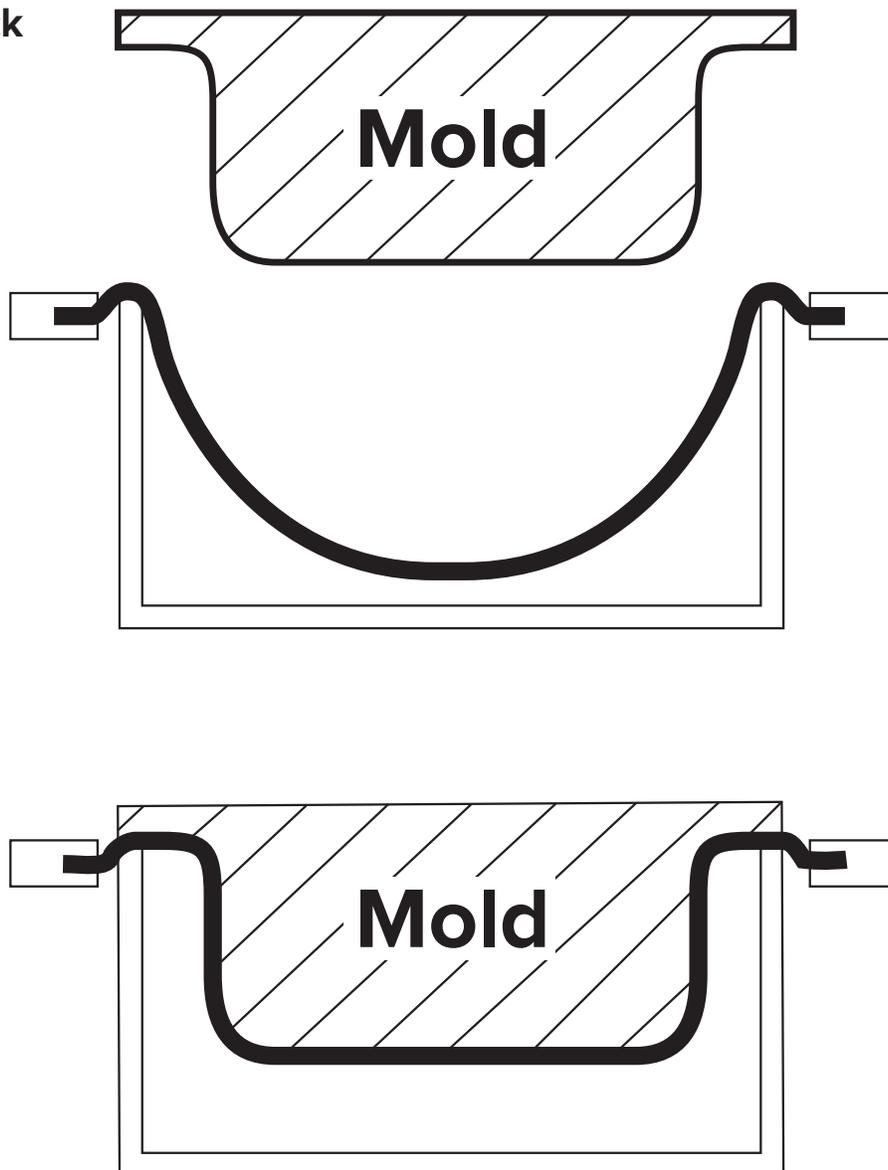
This technique is considerably different than the four previous techniques. In this technique, the material is clamped into a clamping mechanism and supported on a trolley system similar to the PLUG ASSIST—TOP method. Attached to the bottom platen is a vacuum box that is nothing more than a box that has outside dimensions the same as the outside dimensions of the mold flange. The box has a depth of a few inches deeper than the height of the mold itself. It also may or may not be contoured to roughly match the shape of the mold. Attached to the top platen is the mold in an upside

down position. As you might imagine, both of these platens must be able to move up and down freely and must have a mechanism that is able to control how far they go up or down to prevent them from crashing into each other.

How does the technique work? After the plastic sheet has been properly heated in the oven, it is retracted and brought into the forming station. Next the bottom platen that has the vacuum box on it is raised up through the clamp frame and the vacuum box creates a seal against the sheet. Then a vacuum is slowly applied to the vacuum box and the sheet is pulled down into it causing a hemisphere shape to form. This creates a draw ratio on the sheet material of approximately 2 to 1. In other words, the sheet

Snap Back

Fig. 3



thins down to about half of its original thickness. Then the mold on the top platen is lowered into the hemispheric shape of the sheet in the vacuum box until the flange of the mold compresses the trapped sheet between the vacuum box and the mold flange. At this point the vacuum is turned off in the vacuum box and a vacuum is applied to the mold chamber. This causes the sheet to snap up against the mold surface, hence the term “snapback”. Then the vacuum box is dropped away from the mold to allow the plastic to cool on the mold. The depth that the bubble draws down into the vacuum box is either controlled by an electric eye in the vacuum box or by timing how quickly we remove the air from the vacuum box. This is in conjunction with how quickly we insert the mold into the bubble created in the vacuum box. The machine is cycled in such a manner as to automatically discontinue the vacuum in the vacuum box when the mold is extended into the bubble.

Why would anyone want to go through all of this to make a part? Well, there are some definite benefits. If you again imagine the above procedure, you will probably come to the conclusion that the material distribution of the part on the mold will be better. This indeed happens. As you predraw the material into the vacuum box, you are uniformly stretching this material that more closely approximates the shape of the mold than by normal drape or plug assist forming. Then when you snap the material back unto the mold, it does not have to stretch as far in the remaining portions of the mold that have not touched the sheet yet. As you may realize, once hot plastic sheet touches the mold, it freezes on that spot and no longer thins on the frozen area. However, it does continue to thin in the remaining areas until all of the mold surface area is covered. Since the hemispheric shape more closely approximates the shape of the mold, less thinning needs to occur and the part thickness is more uniform.

A second reason for using this technique is the amount of material you may need to make the part. It can be shown through a draw ratio mathematical formulation that the thickness of the starting sheet can sometimes be reduced or the length and width dimension of the starting sheet can be reduced by using this technique. This can also, on occasion, improve the cycle time required to make the part. This is especially true on the cooling cycle time.

One can also make multiple cavity molds for the snapback process but it is necessary to think this out carefully. If the part is quite difficult, it will be hard

to control the predraw depth in the vacuum box and get them all to be uniform. Any small change in heating stability of the elements in the oven or any drafts through the oven may cause the sheet to be hotter in one area as opposed to another thereby resulting in non-uniform bubbles in the vacuum box. As you might imagine, this becomes more difficult as the complexity of the part increases.

So why don't we use snapback for all parts? Well, the simple fact is that this technique is a bit more complicated and does require more time for a set-up. It also requires a better set-up man and a better machine operator to run these parts. If one of the other simpler methods does the job, it makes good sense to go for simplicity. This leads us to addressing technique number six.

6. SNAP BACK—BOTTOM (Figure 3)

As you might imagine, this technique is exactly like “Snap back—top” except the mold and vacuum box are reversed and mounted to opposite platens. So if it is the same, why do it? Well, there really isn't a good reason except some people find it easier to work with the mold on the bottom platen and find it beneficial to have the bubble settle unto the mold. They also find it easier to observe the bubble being pulled up into the vacuum box. This is especially true when you run a rotary machine that has a high frame set-up.

However, setting it up this way does require you to take greater care in lining up the clamp frames with more uniform spacing between the clamp frame itself and the outside edge of the vacuum box. It is also sometimes necessary to drive the vacuum box through the heated plastic sheet a little further to insure a good seal and get the bubble to pull up into the vacuum box consistently in regards to time.

There is one definite benefit in employing this method if the part is a little smaller. The bubble will be draped away from the vacuum box and take slightly longer to vacuum up into it. This will allow you to delay the platen that the mold is attached to and slightly increase your processing window with the actual snapping of the material onto the mold.

7. BILLOW FORMING—FEMALE (Bottom, Figure 4)

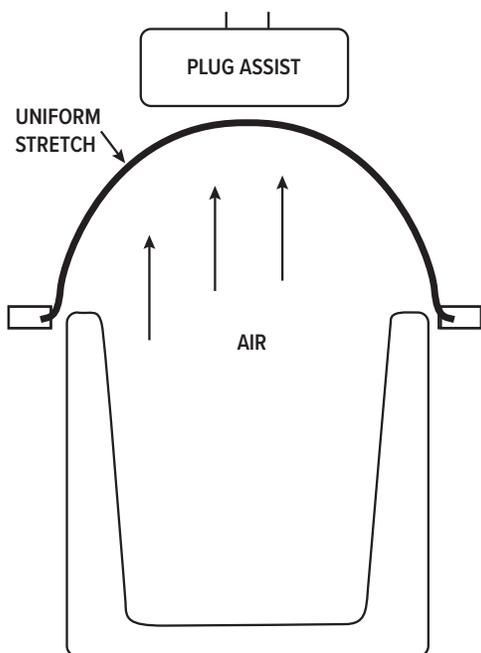
Now we are getting into some complex thermoforming procedures. These techniques can only be done on a limited number of thermoforming machines and will require some well-trained people to implement these processes.

Let me describe the first of these, namely **BILLOW FORMING—FEMALE (BOTTOM)**. Basically what happens is we place a female mold in the bottom platen of the vacuum-forming machine. Then we put a plug assist in the top platen that roughly conforms to the contour of the female cavity of the mold in the bottom platen. To hold the sheet, we use the same type of clamp frame and trolley system we used for snap-back bottom or top. Next we send the sheet into the oven to heat it up and retract it when it is properly heated. When the sheet is properly located in the forming station, we send the female mold in the bottom platen up through the sheet to make a good seal all around the clamp frame. Then we blow air through the vacuum holes in the female mold to form a bubble over the cavity of the female mold. This bubble is extended until it trips the light beam of an electric eye set at a specific desired height. When the bubble reaches this maximum desired height, we start extending the plug assist from the top platen. As the plug assist starts penetrating the hot plastic bubble formed over the female mold cavity, we start exhausting the air out of the mold cavity. This can either be done automatically with the thermoforming machine or by manually bleeding a valve through the external wall of the mold. As you can imagine, as you extend this plug further and further into the mold cavity, the hot plastic will billow around the plug in a fashion that is highly dependent upon how fast you bleed the air out of the mold cavity or how fast you extend the plug. This will also affect the hot plastic material distribution around the plug and how it is distributed against the

female cavity of the mold when you finally employ the vacuum.

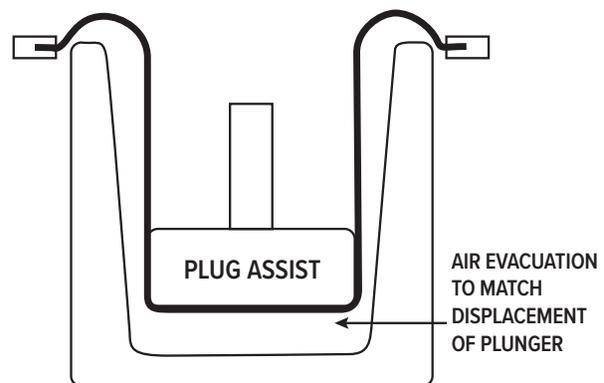
It should be obvious by now that this is a complicated thermoforming process and requires a pretty accurate set-up and a high degree of timing during the extension of the plug assist and the evacuation of the air from the mold cavity. Typically it is much better to bleed off the air manually as opposed to automatically by machine as a machine cannot exhibit any judgment if processing conditions change slightly. However, it is also obvious that if you bleed off the air manually, the operator will have to exhibit a good deal of judgment and will have to be a pretty good operator.

So what are the benefits of going through all this misery? Well, for one thing these techniques afford the best material distribution you could expect to get with the vacuum forming process. Secondly, these techniques allow you to get the most uniform material distribution over the large area of a complex part you could expect. Thirdly, these techniques allow you to put the most severe draw ratio on the hot plastic material you can hope to get without actually pulling a hole in the material. It is very common to get draw ratios of five to one. Fourth, this particular technique allows you to pull a pretty uniform grain throughout the entire part. And fifth, this technique allows you to form the most difficult female parts that can be done with the vacuum forming process. There are parts that can only be formed properly by using this technique.



Billow Forming

Fig. 4



8. BILLOW FORMING—FEMALE (Top)

Again, “billow forming—female top” is just like “billow forming—female bottom” except the mold and the plug are reversed on the platens. However, the results are equivalent. The plus for doing it this way as opposed to “billow forming—female bottom” is just personal preference. Secondly, it is easier to adjust the plug, which is critical in this process. Third, it is easier to blow the bubble in this position as you are already using the natural sag of the material, and fourth the material doesn’t chill as quickly on the mold flange. The big minus is it is harder to see what is going on when you are evacuating the air out of the bubble so it becomes necessary for the operator to have a better “touch”. Both techniques will work equally as well on any given part that requires this process.

9. BILLOW FORMING—MALE (Bottom)

This technique is just a role reversal of “billow forming—female bottom”. Essentially what we are doing is putting a billow blowing contoured box on the top platen and the male mold on the bottom platen. Again, to hold the sheet, we use the same type clamp frame as in the techniques above and send the material into the oven to be heated to the proper temperature. As before, the trolley moves the heated sheet out into the forming area. When the sheet is properly located in the forming station, we send the billow box down to make a seal all around the clamping area. Then we blow a bubble that extends downward until it goes down the proper distance where it will trip the electric eye and hold the bubble in that position. When the bubble is extended to the proper place, we send the male mold up into the bubble where it will start to billow out the bubble because of the trapped air. When the bubble billows out the proper amount, we start bleeding off the air in the bubble to prevent it from bursting and to distribute the plastic around the male tool as it is extending into the bubble. Again, it is proper to do this manually or automatically with the machine but the manual method as in “billow forming—female” affords a little more control, as an experienced operator would exercise good judgment as the mold is extended. This would be similar to poking your finger into a blown up balloon and letting the balloon wall envelop your finger. As one might imagine, this will require the billow box to be somewhat contoured to fit the mold or you are likely to get webbing in the corner areas. It is generally necessary to miter the corners of the billow box just as you might in running the “snap back” technique when the part has a square or

rectangular geometry. When the mold is all the way extended, the vacuum comes on and pushes the material tightly against the mold where it is cooled to hold the shape of the mold. When demolding, these parts usually require a delicate coaxing with the air eject to get them off the mold.

As we noted in “billow forming—female bottom,” this is a complicated thermoforming process. It requires just as accurate of a set-up and just as accurate timing when the mold is being injected into the billow bubble and you are bleeding the air out of the bubble as we did in the “billow forming—female bottom” technique. Obviously it is necessary to have an experienced operator to run this technique and a good set-up man to properly align the mold and billow box before starting your run.

So why not just use snap back and avoid all this extra trouble. Well, primarily when we design the billow box, we usually make it with a fair amount of flange space on the periphery of the billow box so we have extra material to work with. This allows us to feed this material around the mold and the horizontal flange of the part so we can get more material in these areas. This especially allows us to get better flanges than we could obtain with snap back. We are also better able to control the gauge of the material on the top of the mold. In some cases where the part is taller than it is wide, this may be the only way to manufacture it and to prevent the serious chill marks that result in making just such a part. So there are some definite benefits in going through this extra trouble.

10. BILLOW FORMING—MALE (Top)

As you might have guessed by now, “billow forming—male top” is just the same as “Billow forming—male bottom” except the billow box is on the bottom platen and the male mold is on the top platen. Just the reverse of “billow forming—male bottom.”

And for the life of me, I just don’t see any advantage of doing it this way except personal preference. The results are the same. I guess that some people may feel that you are better able to observe what is going on with the billow. Maybe so, I’m just the writer describing of the technique.

11. ZERO GRAVITY

Now there’s a real trick without being in outer space. This somewhat improperly described technique requires a whole new type of thermoforming machine and is very popular in Europe. Essentially

what you need is a machine that has a bottom platen that is contained within an enclosed box that you can inject a mild amount of air pressure. On this platen you mount a standard male vacuum-forming mold that is capable of protruding out of a hole in the top of the box. On a frame that merely goes up and down via some mechanism on the side of the machine (essentially a top platen), you mount a clamp frame similar to the ones in the above techniques. This clamp frame has a sealing mechanism on the bottom of it that seals over the hole in the top of the box that the mold is contained within. The hole can be sealed over by lowering the clamp frame and pressing it against a seal ring on the top of the box.

Here is basically what happens in the process. A movable top and bottom oven is rolled out over and under the clamp frame with the plastic sheet in it. The plastic is heated to the proper temperature and then the ovens are rolled away from the heated sheet. Next the clamp frame is lowered over the seal on the enclosed box with the mold in it. At this point the proper amount of air pressure is injected into the enclosed box and the plastic sheet rises up in a standard billow bubble. This can be either controlled manually, by time, or by an electric eye at the side of the machine. When the bubble is just the right height, the mold from inside the pressure box is extended up into the bubble. When the mold is fully extended, a seal is made around the edge of the mold base, the bubble is allowed to settle over the mold, the air is turned off and the vacuum is applied to the mold, usually very slowly. When the part is cool enough, the air eject is turned on and the part is demolded. Because the mold is trapped inside the box, the air eject is very efficient and difficult parts can be demolded quite easily as the seal is actually under the clamp frame. Hence we get the name zero gravity as the blown bubble merely floats above the mold until the air is released and the vacuum is applied.

So what are the good, the bad, and the ugly in this process? Well, the first thing that should be apparent is chill marks are virtually eliminated as the material has no way of freezing on the mold and chilling off. Actually nothing but the flange of the mold has touched the plastic until the vacuum was activated. Secondly, by vacuuming the part very slowly, you are less likely to need some kind of plug assist to prevent the part from webbing. However, if the part does have a propensity for webbing, it is more difficult to apply a plug assist to prevent it. You will

have to use a pneumatically activated plug that is external to the normal machine operation. Third, on materials that have very sharp melt points, you can hold the top oven over the sheet through the actual forming of the part if the part isn't too tall and doesn't hit the oven elements. This is especially useful in forming some homopolymer polypropylene parts where the melt index is very sharp. A sharp melt index will cause a plastic to be too stiff to form at a certain temperature and too soft to form at a slightly higher temperature. I have seen some very difficult parts with sharp melt indexes made this way with excellent results.

Well, what are the bads? The most glaring is the amount of set up time it takes to get going. You have to go through the entire process of enclosing and sealing the mold in the pressure box and then making sure the seals on the pressure box and the clamp frames don't leak. You also have to have a method of adjusting the size of hole that the mold protrudes through on the top of the pressure box. And then there is the problem of heating elements breaking more frequently on a moving oven. This can get expensive.

All in all, this technique has some extremely good features but it has not caught on in the United States where speed seems to rule.

12. PREBLOW PLUG ASSIST FORMING

Here is a system that is used rarely and usually only in conjunction with pressure forming. If you are trying to make a part in a female textured mold that has a very large draw ratio and you are having difficulty keeping the material from chilling before it contacts the mold surface, this may be the solution. Normally a part of this nature should be formed using the "billow forming—female bottom" technique but the dwell time on the plug is just too long to keep it from chilling the plastic and getting any grain detail on the part.

Here is how it works. You have a deep draw female textured mold in the bottom platen and an insulated plug inside a pressure box on the top platen. As in the above techniques, the sheet is clamped into a clamp frame and run into the oven to be properly heated, usually to the hot side. Then it is brought out and the bottom platen is elevated until it seals off around the clamp frame and the mold. Next a bubble is blown that is usually quite extensive and exaggerated that practically conforms to the female cavity of the mold below. At this point the mold is lowered slightly to allow the seal to break and the

bubble to drop down into the female cavity below. Then the mold is quickly brought up again while the plug is simultaneously plunged into the mold cavity. This allows for an intense prestretch of hot plastic sheet without cooling it off significantly. As you might imagine, this whole process occurs in just three or four seconds so the sheet does not have enough time to cool off. Then the vacuum is turned on and the air in the pressure box is activated to force the material up against the mold walls.

So what's the point? Well one would be surprised at the uniformity of the mold wall and the uniformity and extra grain detail you are able to get because the material does not cool off as much before it hits the mold surface. Also, some materials have

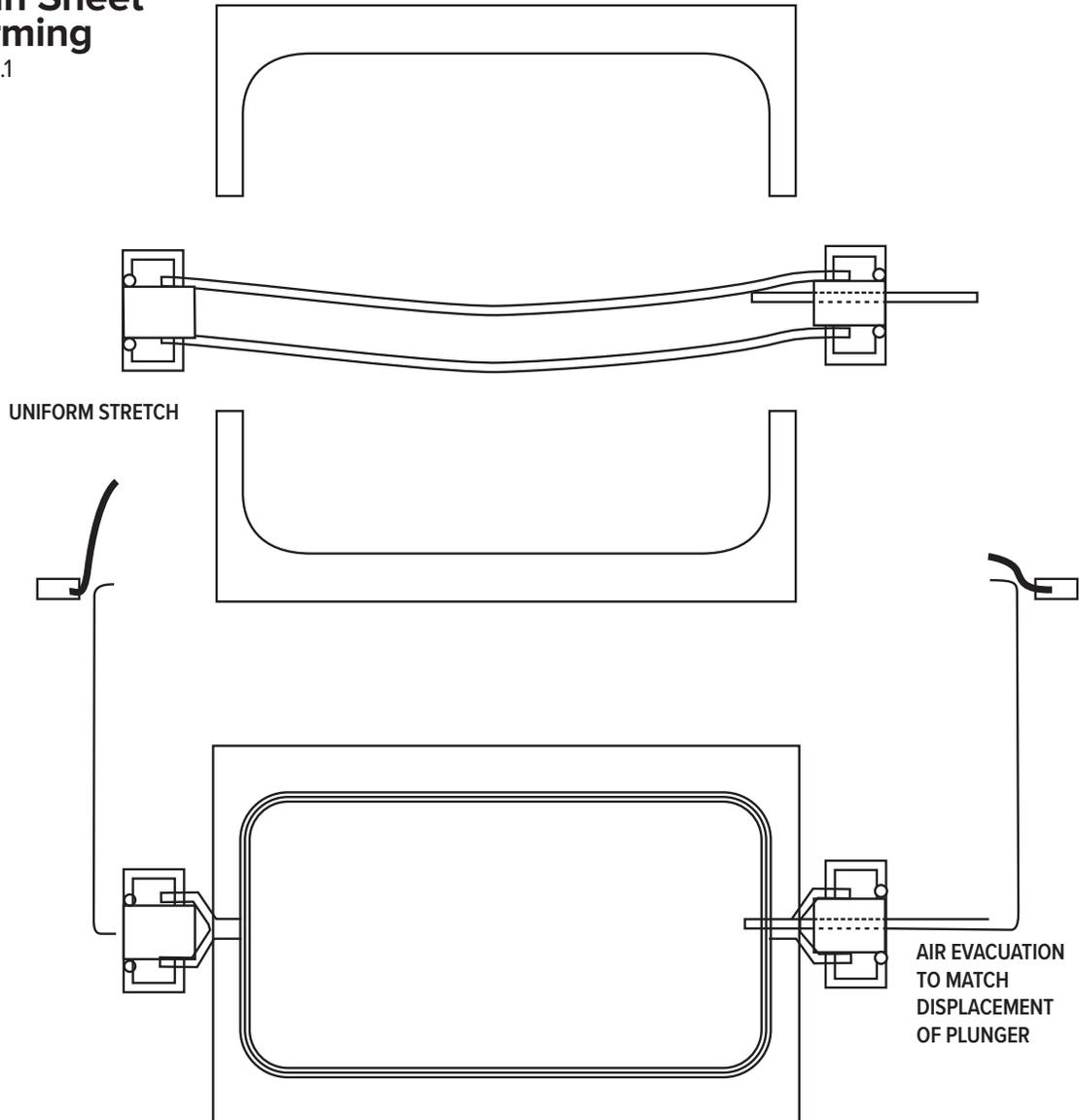
very good hot strength and do not sag much no matter how hot you get them until you actually scorch them. This would require you to push them down into the cavity and chill them off and get a wall thickness that is less uniform. As I said, this is a little used technique and people usually try hard to avoid it as most thermoforming machines are not wired to use it.

13. TWIN SHEET FORMING (Figure 4.1)

There are really two types of twin sheet forming processes. One type uses a single-station vacuum-forming machine with a double clamp frame set up. This is what is shown in Figure 4.1. The other is using a four station rotary thermoformer with a double oven. Let us describe both processes.

Twin Sheet Forming

Fig. 4.1



In the case of the single station set-up, two pieces of plastic are put into two clamp frames that are separated by some type of spacer block. Within this spacer block is an air ejector pin that allows you to inject a small amount of air between the two sheets of plastic to keep the sheets separate during the heating cycle, if necessary. The sheets are then placed into the oven to be heated to an acceptable forming temperature. A couple of things should occur to you immediately. First of all, you can only heat one side of each of the sheets. This is going to extend the heating cycle and is going to give you less control of actually heating the sheet. Also, you will not be able to heat two different sheets that have too much disparity in sheet thickness because you would have to have one of the oven sides considerably hotter than the other does. Obviously this eliminates single sided heating. After the sheet is heated up, it is retracted from the oven and brought into the forming area. The two platens are closed and the heated sheets are drawn into their respective cavities. At this point it is worth noting that these molds are almost always female, although it is possible that one would be female and one would be male if the male mold wasn't too prominent. As the vacuum is being applied, a blast of air is blown through the air injector pin to prevent a vacuum chamber being established in the cavity between the mold. After the parts are cooled, the platens are separated and the air injector pin is retracted from the part and the part is removed from both clamp frames.

This type of twin sheet forming is usually done with amorphous plastic materials that will not stick together unless the plastic is quite hot. This technique has been gaining in popularity lately. The reasons are simple. First of all you can make an enclosed chamber similar to roto-molding. Secondly, you can make parts that are stronger structurally. It is even possible to make kiss-offs in the part that really adds to durability and structural integrity. Air conditioner supports come to mind.

The second method of twin sheet forming is the four station rotary operation. This type of thermoformer is equipped with two heating ovens but does not require a double clamp frame. Here is what happens. The sheet is loaded into the first station and it is run into the first oven to start the heating process. Then the next sheet is loaded into the second station while the first sheet is being partially heated. Then the first sheet is cycled into the second oven and the second sheet is cycled

into the first oven. When the first sheet is heated to the proper forming temperature, it is cycled into the forming station. The second sheet now is in the second heating oven. When the first sheet gets to the forming station, the mold on the bottom platen comes up and the sheet is formed onto this mold. Then the clamp frame is opened up and the mold is retracted. When the second sheet reaches forming temperature, it is cycled around to the forming station and the top mold on the top platen comes down to form the second sheet. In the interim, the bottom platen with the bottom mold and formed part is extended to smash together with the top platen that contains the mold with the formed part. Don't worry, we're not going to break your machine. The clamping pressure is finite and we can control how closely we bring the platens together. Anyway, when the two hot plastic sheets meet, they are fused together and you have a twin sheet part.

As you might imagine, timing is everything. It is crucial to get the first sheet out of the oven when it has reached its forming temperature and also get the second sheet out when it has reached the proper forming temperature. Oven settings are critical and staggering the cycles with the proper timing is a must. The whole process is tricky, but there are a

lot of fantastic parts being made this way. This process has revolutionized the production of plastic pallets.

Again we can see some impediments and limitations. It is going to be difficult to run sheets that are not the same thickness or you will throw your whole cycle out of whack. Secondly, you don't get this equipment at the "five and dime." It is expensive and it takes good people to set it up and run it. However, the success of this process is really obvious when you witness the amount of new parts being made this way.

14. MATCHED-MOLD THERMOFORMING (Figure 4.2)

Matched-mold Thermoforming is a little different than other methods of thermoforming. It is not mandatory to have a vacuum system to employ this method of thermoforming, although occasionally some formers do. Essentially what happens is we get two identically matched molds, one male and one female, and trap a heated plastic sheet between them. First we heat up a plastic sheet somewhere above the glass transition temperature point. Then we retract the plastic from the oven and place it

between the two matched molds. Next we close the platens with some force and allow the plastic to take the shape of the cavity between the two molds. It is not necessary to heat this sheet up to the temperature required for a single sided mold, but if you want to pick up good detail for lettering or texturing you may want to do so. It is necessary to have some venting holes to let the trapped air escape.

Obviously it will be important to have the two molds match well. Typically one of the molds may have a rubber coating to prevent breaking one of the molds if they were not properly aligned. Set-up can be a real challenge in this process. Common sense will tell you that if the molds are not aligned almost perfectly, your finished parts will be too thick or too thin in some areas and probably unusable. To

alleviate this problem, these molds will usually have locator pins that are in place during the set-up.

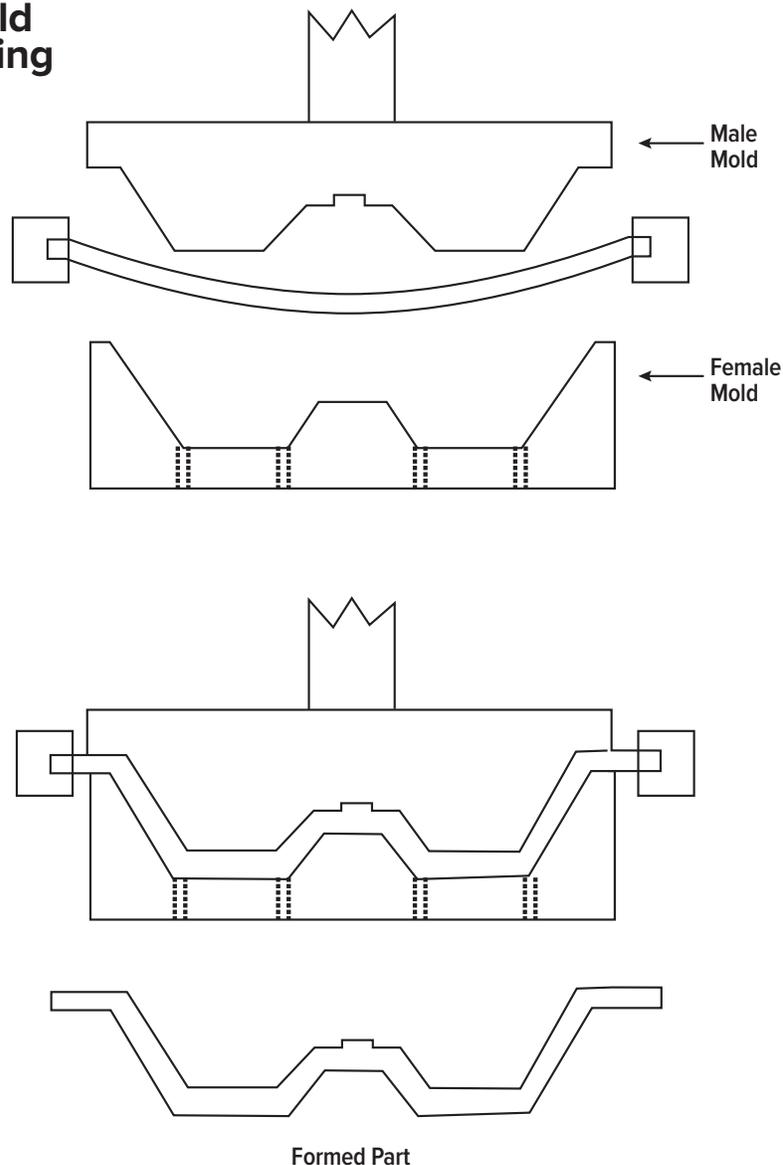
This process is quite popular in the automotive industry where carpet material is laminated to a plastic substrate. The trunk liners in your car are typically done this way.

15. FREE FORMING OR BUBBLE FORMING

This is a process that is used for a lot of clear plastics. Whenever a clear plastic touches a mold, the plastic automatically loses some of its transparency. To prevent this, a former may elect to blow a billow or draw a bubble into a vacuum box and let the material cool into the resultant shape. To do this, the plastic is placed into a clamp frame

Matched-Mold Thermoforming

Fig. 4.2



and heated up inside an oven. Then the sheet is removed from the oven and sealed over a vacuum or billow box. Next vacuum is applied to draw the bubble into the box or air is blown into the billow box to produce a bubble over the box. When the bubble or billow has reached the desired depth or height, the vacuum or air is shut off to the solenoid valve by tripping the light beam from the photocell by virtue of the bubble or billow breaking this beam.

Finally, the bubble or billow is allowed to cool in the air. In most cases, this process is helped along a bit by having cooling fans blowing air unto the cooling part.

This process is used extensively to make skylights and clear signs. Anytime it is necessary to get high grade optical clarity in a part, it is likely that you will need to employ this technique to make the part.

16. HAND FORMING

Here is an often neglected thermoforming technique. In some cases it is the only thing that makes sense. Let me describe the technique to you. This technique does not require a forming machine in the same sense as the above techniques. All that is needed is an oven and a mold attached to a vacuum system.

A piece of plastic is either hung on a clamping mechanism from one of its four sides or placed on a flat tray or conveyor system and placed into the oven. When the plastic has been heated to its proper temperature, it is retracted from the oven or conveyor belt and released from the clamping mechanism or picked off the conveyor belt by hand. Hopefully you are using insulated heat gloves. Then the pliable hot plastic sheet is draped or wrapped around the mold and the vacuum is turned on to force the hot plastic against the mold. The mold is

designed in such a way that the edges have a raised piece that extends above the plain of the mold and provides a seal for the hot plastic sheet.

So why would you want to go through all this trouble if you could just let the machine do all the work? Well, as we said earlier, in some cases this is the only thing that makes sense. Let me give you some examples. Plastic shells for body casts are almost always made this way. It would be extremely difficult to form a full body cast without getting some serious thinning in various parts of the cast. Even if you designed a very complicated articulated clamp frame, you would not be able to get the same dexterity you could accomplish by using a manual method. The largest forming job I have ever been around was done by wrapping a vinyl foam, substrate laminate sheet around a console mold. This technique allowed you get a very uniform material thickness on the finished part. This was done with a substrate thickness that was considerably less than it would have been if it were done with a forming machine. The process was efficient and produced a high quality part.

Some parts have an extremely low volume and a hand-forming situation may be the best alternative. It is much easier to drag out a mold that is attached to a forming stand and connect it to a vacuum line than it is to set the same mold in a forming machine and adjust all the clamp frames. It may be just a matter of minutes as opposed to an hour and you don't have your machine tied up for just a few parts. So give it some thought. This may be your best alternative. We all have forming jobs that we wish we didn't have but we need to do them because we have to humor a customer that provides us with a lot of good parts to do.

DRAW RATIOS

Draw ratios are what I consider to be the most important concept to master in thermoforming. This term could be more aptly expressed as a stretch ratio. Simply stated, the draw ratio of any given part is the amount of surface area you have to cover on the mold and the mold flange divided by the amount of material you have inside of the seal edge of the mold flange. In other words, the amount of area you have to cover divided by the amount of material you have available to use.

To further elaborate on this concept let us go to an example. Let's take a female cavity mold ten inches by ten inches by ten inches or generally speaking a cube. This means that the bottom of the cube area is ten inches times ten inches or one hundred surface square inches. This is also true of all four sides of the cube. If we add all of these surface areas together, we have five hundred surface square inches to cover. However, the hole in the top of the cube is ten inches times ten inches and therefore we only have

one hundred available inches of plastic to stretch over the five hundred surface square inches of the interior of the mold. Hence we have a draw ratio of five to one and if we wanted to end up with a .100 inch wall thickness, we would have to start with a sheet with a beginning gauge of .500 inches. See Figure 5. If you were familiar with the thermoforming process, you would suddenly realize that this is impractical. However, before we get into probable options, let me get the draw ratio scenario into a mathematical formulation that covers the draw ratio of a rectangle or a square.

To start, let us define some terms to make the formula more understandable.

- D** = Draw Ratio
- H** = Height of the Part
- L₁** = Length of Part
- W₁** = Width of Part
- L₂** = Length of Available Material
- W₂** = Width of Available Material

Here is the formula.

$$D = \frac{2H(L_1 + W_1)}{L_2 \times W_2} + 1$$

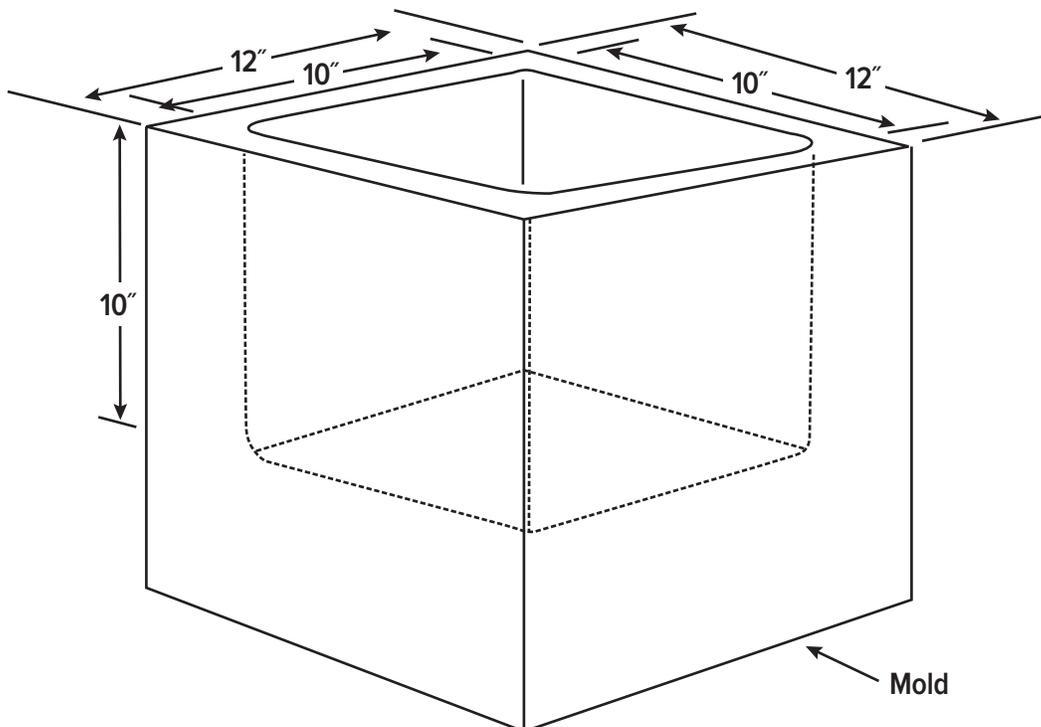
So what does this mean? In the above example, the mold is a female tool so the length and width of the part is the same as the length and width of the available material. Since in the above example

the height, width, and length of the part are all ten inches, by following through the formula we get $2 \times 10 (10 + 10) / (10 \times 10) + 1$ or $4 + 1 = 5$. This is the same value we got empirically by reasoning through the process above, namely a 5 to 1 draw ratio. Again as stated above, this is not practical so we have to look for other options.

Usually a good option to female drape forming when the draw ratio is too great is to redesign the part around the snapback process. Before we actually do this, let us set up a rule that is quite useful to follow in the snapback process. For every four inches of height on the mold, we should have a minimum of one inch of clearance between the vacuum box wall and the vertical wall of the mold. Thus if you convert the 10" x 10" x 10" female cube mold into a male mold for the snapback process, you need to build a vacuum box that has a minimum clearance of two and one-half inches from the vertical mold wall and the inside of the vacuum box. This is because the mold is 10 inches high. By incorporating these new values into the above formula, we find that the height, width, and length of the mold are still the same. However, the amount of available material went from 10 inches times 10 inches, or 100 square inches, to 15 inches by 15 inches or 225 square inches. See Figure 6. This is a significant amount of more material to work with. However, since we now have to cover the flange of the mold inside

Drape Forming

Fig. 5



the vacuum box, we also have more surface area to cover. Since the top of the mold and the flange area of the mold are identical in area to the inside dimension on the vacuum box, we just add the four sides of the mold to the inside dimension of the vacuum box. Then we divide it by this inside dimension, (that is, available material). This is indeed what we are doing with the above formula. Two times $10(10 + 10)/15 \times 15$ (available material) + 1 gives you a draw ratio of 2.78 to 1, which is much more feasible in getting a formed part that is acceptable to a customer. See Figure 6. It should be noted that one of the objectives of thermoforming design is to keep the draw ratio of a part under 3 to 1 if it is possible. This will help immensely in controlling the amount of scrap you get in a job and the overall uniform distribution of material on the part.

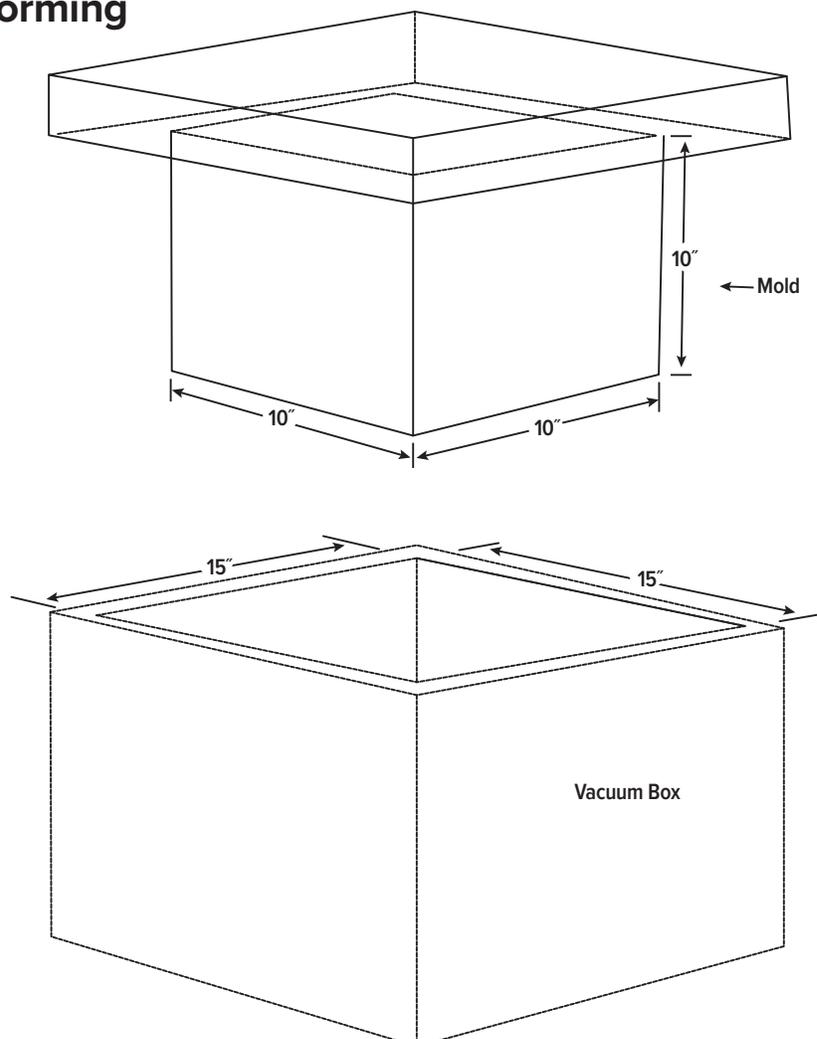
As a sidelight, it should be noted that this would most likely save a small amount of material that will be needed to make the part. In the above example

on the female mold, you would need a sheet that has a dimension of 14" x 14" x .500 thickness. This sheet would weigh 3.71 pounds in ABS. The sheet dimensions needed to get a comparable part with the snapback process would be 18.5" x 18.5" x .278 thick and would weigh 3.61 pounds. This is not a substantial amount but it is something. The real savings would come in the quality of the end part and the fact that the part made by the snapback process would require less than half the time to make and therefore would save a considerable amount of money in machine time. It is important to understand this concept to properly select the thermoforming process that will enable you to get the best part you can get.

As I indicated, the formula stated above would cover all draw ratios that are concerned with squares or rectangles including secondary draw ratios. But what are secondary draw ratios? It is rare that a functional part is a perfect square or rectangle. In

Snapback Forming

Fig. 6



most cases, the part has a protrusion or pocket or depressions in it that will create a secondary draw ratio that will cause the part to be thinner in this area. If this pocket is a square or rectangle, you can use the exact above formula to calculate the draw ratio of this secondary square or rectangle. Again, it is important to observe these areas on a print to properly select the forming technique you should use and thickness of the sheet you need. Obviously this would be very important when quoting the part.

However, all shapes do not fall into the category of a square or a rectangle. To accommodate a spherical shape, we need to employ the following formulas. The first one holds when you are forming a spherical shape into a female mold and the second one comes into play when you are forming a spherical shape over a male mold. Here they are:

$$D = 2\pi r^2 \text{ FEMALE MOLD}$$

$$D = \frac{2\pi r^2 + ((L_2 \times W_2) - \pi r^2)}{L_2 \times W_2} \text{ MALE MOLD}$$

$$D = \pi r^2 + \pi dh \text{ FEMALE MOLD}$$

$$D = \frac{\pi r^2 + \pi dh + ((L_2 \times W_2) - \pi r^2)}{L_2 \times W_2} \text{ MALE MOLD}$$

As I indicated in the beginning of the discussion of draw ratios, this is an important concept to understand and it is invaluable in determining what process technique to use and what the cost of the part will be.

IMPORTANT CONCERNS IN VACUUM FORMING

To make successful parts in vacuum forming, there are four important areas that you need to pay absolute close attention to. The four areas are PART DESIGN, TOOLING DESIGN, MATERIAL SELECTION,

and PROCESSING TECHNIQUES. Ignoring any one of these areas could cause your part to be unsuccessful or fail in its application. Let us address these functions as they apply to this process.

PART DESIGN

This is probably the most important consideration in getting a good part that will perform the function you want it to. Here are a number of things that go into deciding whether it makes sense to proceed. First, does the part lend itself to vacuum forming? What do we mean by this? Well, is it possible to employ one of the aforementioned processing techniques and make an acceptable part? It is possible that the tight detail or the mounting requirements that the part has to meet is just too difficult for the

process. Careful review of the print and a candid discussion with the design engineer could save a lot of embarrassment later. As a matter of fact, it is very important to establish a rapport with the engineer in this situation so you can tell him that something is not practical without having the fear that you might lose the job. So let us review what some of these part design considerations might be.

SIZE

Size is definitely a consideration. If a part is too large for your equipment, that is a problem. Usually though, sheer largeness is not an impediment to vacuum forming. If the machine has a large enough platen and a long enough platen stroke, you can form practically anything. I have seen a waste disposal tank that was 25 feet long, 10 feet wide and 4 feet deep that was vacuum formed. However, it is possible that a part is too small to be practical to vacuum form it. A case in point would be a thimble.

It is certainly possible to vacuum form it but there is no way you can compete with injection molding. To tie up a vacuum-forming machine when a small injection-molding machine could do it automatically would make no sense. Also, you may not be able to get the detail you need on such a small part or for that matter the wall thickness you might need.

SHAPE

Shape is a consideration too. There are certain shapes that do not lend themselves to vacuum forming because the draw ratio in certain spots and sometimes the entire part become too great. A long thin tube that you would want to form in one piece

without a seam would be an example. Enclosures that have to remain seamless are also impossible to do. Varying the wall thickness as in injection molding is impractical too. Generally speaking though, there are not many shapes that can't be vacuum formed.

DRAFT

Draft is a primary consideration on part design and it depends upon whether the mold is a male or female mold. If you have a part that is not very tall and you are using a male mold, say one to two inches high, it is possible to have as little as two degrees draft if you are willing to employ an extended demolding cycle. However, if your part is considerably taller than that, say eight to ten inches, you will probably need a minimum of five degrees draft and you

should probably have more. This is not necessarily true for a female tool. Since the plastic is likely to shrink away from the mold as it is cooling, you don't need any draft at all. As a matter of fact, it is possible to make parts that have a slight negative draft as long as the shrinkage is enough to clear the inside mold wall. The difficulty comes in making the tool, a concern not normally entertained by the part designer.

UNDERCUTS

Another part design consideration is the use of undercuts. There are many instances where the use of undercuts will make the assembly of the part easier or dramatically enhance the cosmetics of the total part assembly. However, there are some limitations on what can be done with this design feature. For instance, if you are using a male mold and you are going to make an undercut, it is axiomatic that you will have to make a movable piece in the mold in order to get the part off. Also, making an undercut all around the mold will require an extremely complicated tool. If you are doing this with a female tool, you will have to incorporate

flippers in your tool in order to remove the part. Both of these conditions will limit the amount of undercut you can make. But don't despair. Most processing techniques can't make undercuts at all.

As a rule, undercuts on a female mold will depend on the length, width, and depth of the mold, but generally it is not advisable to have undercuts of more than one-half inch. In fact, it is best to taper off the depth of the undercuts in the corners of the mold to less than one-fourth of an inch. It is rare that you would need fasteners in the direct corners of a part, as you would have assembly problems anyway.

RADII

Radii are important in good part design. Can you make parts with right-angled corners? Sure! Is it good part design? No, not usually. Plastic is just like any other material. A right-angled corner is an accident waiting to happen. Where will the first fracture point be on a part? You got it, right on the right-angled corner. This is the area that can take the least stress. Do people still do it? Sure, the stylists still have a lot of clout.

Generally speaking, the amount of radius you put on a part is related to the size of the part. This is

true because if you are using a female mold, a deep draw part will get pretty thin on the bottom of the mold and thus the part will usually be quite flimsy on the corners. Usually if a part has a more than a two to one draw ratio I would like to see a minimum of a one-half inch radius or a forty-five degree mitered corner. At a three to one draw ratio I like to see a full inch radius. When you deal with a male mold the problem is different. The corners are quite strong but just down from the corners you are likely to see some very unsightly chill marks and there will also be a greater propensity for webbing on the bottom

of the part on the corners. About the same rules apply to a male mold. If the draw ratio is two to one or more, the minimum radius should be one-half inch. If the draw ratio is three to one, the radius should be at least one inch. As a matter of practical

thermoforming sense, the ball radii in each of the corners of the part should be doubled for each respective draw ratio unit. Structurally, this will yield a more durable part.

TEXTURE

Texture is another design parameter to consider. Why is this something to be concerned about? You should be able to have anything you want. This is true, but depending on the draw ratio of the part, some textures may become severely distorted. If the draw ratio of a part is three to one, it is common sense to expect the grain texture to spread out by three times. This has got to change how it looks and the part may not be as attractive with the stretched out texture. If you have a texture with a pattern, the pattern could become elongated or flattened and look significantly different on different parts of the part. Even more problematic is the fact that when parts are formed, there are various draw ratios within the same part. This can make grain distortions even more apparent.

The depth of the grain in relationship to the starting thickness of the sheet also has some bearing on what grains you can select. Suppose you have a sheet that is .100" gauge and you select a deep levant grain. This texture has a grain depth of about .012". This means that the bottom of the extruded sheet is only .088" thick. If you apply a draw ratio

of two to one to this material the peak thickness of the part will theoretically be .050" and the low parts will be .044" and the grain depth will go from .012" to .006". Common sense, huh! Sometimes common sense doesn't prevail. In actuality, what really does happen is that during the heating process of thermoforming, the valleys of the texture get slightly hotter than the peaks. The thinner parts of the heated sheet have inherently less hot strength than the peaks. When you stretch the material over the mold, the valleys will spread apart more readily than the peaks and the thinning in the valleys will be exaggerated, probably by at least a factor of two. Thus structurally the part may be weakened in the valley areas or even excessively thin. As is the case, generally most plastics are notch sensitive and in high stress areas (right-angled corners) failures can occur. So, depth and width of grain need to be considered when designing a plastic part. Hey, this isn't a doom and gloom scenario. By properly considering the shape of the part, the draw ratio of the part and the sheet thickness that you start with, you can select most grains that would enhance the styling of the formed part.

COLOR, GLOSS and APPEARANCE

This has more to do with the cosmetics of an assembly or part than its function. However, if you check with the sales and marketing people, this may be one of the most important factors in selling the assembly. Generally speaking it is almost always easier to sell an assembly that is more attractive than one that is not, assuming that the function of the two assemblies are equivalent. An instrument panel in a vehicle is a case in point. Most of these parts have a soft texture, have a dull gloss look to them, and a color that is easy on the eyes. The reason is obvious. An instrument panel with these features would be less taxing on the eyes and less stressful when you have to stare past it for an extended period of time.

Another group of parts would be computer or medical instrument fascia. In most cases they are pressure formed within the thermoforming process.

These parts usually require crisp design lines, colors that are soft, with a dull gloss look. This has more to do with sales appeal than function. Pressure forming can give you that look and still give you a part that is structurally sound. Some of this has to do with material selection but we will address that later.

Then again, color, gloss and appearance may have nothing to do with the part. A twin sheet formed pallet would be an example. Color, gloss and appearance are essentially irrelevant but function is everything. It doesn't do much good if a pallet is attractive if it falls apart under load. Generally speaking, you can have any level of cosmetics you are willing to pay for that is commensurate with sales and marketing requirements. A little thought up front when in the design mode should guide one to make rational decisions here.

PART INTEGRITY and FUNCTION

What does the part or assembly have to accomplish? In what environment will the part be used? Some of this is material related which we will address later but there are some general things to be considered. One of them is load bearing. SURPRISE! Plastics are normally not considered to be load-bearing materials, but if you are careful in your design parameters, it is surprising what you can do. Let us go through a few design characteristics. How about ribs? No, not the kind you get in restaurants. From an engineering standpoint, it is clear that a flat sheet of metal stood on end is not as strong as a ribbed piece such as a channel iron. Otherwise bridges would be made out of flat steel as opposed to tube stock or I-beams. Well, the same is true with plastics. A ribbed part has more load-bearing ability than a flat walled part. This is especially true with a waffling effect on the plastic part supporting the underside of a bathtub. A .125" starting gauge piece of ABS formed into a waffle and glued unto the underside of the tub bottom will easily support 300 pounds over a one foot square area. You have to know, there are a few 300 pound dudes that take showers.

Arches and domes are also designs that can enhance appearance and add to structural integrity. An example is the slight arched effect on pick-up bed covers. A flat sheet of plastic suspended over the bed will surely sag in the middle and collect water in a rainstorm. However, a one and one-half to two inch dome formed into this type of cover will not only provide for rain run off but will even support a significant amount of snow load. Note the design of

plastic covers for outboard motors. Another dome. These parts are usually only about .150" thick but yet will support a 250 pound person standing on it. Another prime example that typifies the arch principle is a canoe. On the flattened bottom, the canoe must be thicker or it will flex in that area in what the industry notes as oil canning. However, on the sides or the ends where there is a considerable amount of curvature, the wall is stiffer even though it is thinner.

Thickness of the plastic can also be a factor in part integrity. Some parts are simply just too thin to have any structural integrity. This is usually a function of the starting thickness of the sheet and/or the draw ratio during the forming process. Physics is physics. If you have a draw ratio of two to one and you want to end up with a finished gauge of .100", there is no way that a sheet with a starting thickness of .150" will get you there. One has to realize that this distribution will not be totally even so some areas will be more and some less than the sought after finished gauge.

Although UV resistance is not considered part of part integrity, if you have a part that is going to be continuously outside, you had better take it into account. If you don't, it is only a matter of time before the part will become brittle and if prone to stress, fail.

More about this later.

TOLERANCES

Tolerances are our next issue. It never ceases to amaze me when I see tolerances specified to the third decimal place on a print. That's plus or minus a few thousandths of an inch. Does anyone think we can get there? The coefficient of thermal expansion of most plastics is around 5 times 10 to the minus fifth inches per inch per degree Fahrenheit (.00005 inches/inch). If a part starts out to be 20 inches long at 70°F, at 20°F this same part will be 19.95 inches long (.00005 x 20 inches x 50°F temperature change). This is a reduction in size of .05" (fifty thousandths of an inch). Obviously measuring the part in different temperature conditions within the plant could make up for more than the plus or minus a few thousandths that you were allowed on the print.

This brings us to what is practical. The first thing that needs to be done is to get the mold or tooling to be correct. This depends on what type of tooling you select but let us say we start with an aluminum temperature controlled tool. When you want to get to a certain sized part, say 20 inches in length, you have to take into account the amount of shrinkage you expect in producing the tool and the amount of shrinkage you expect in the plastic during processing. Aha you say. Different plastics have different amounts of shrinkage and cooling conditions in making the mold castings can vary the size of molds. All this is true. So how do we get to the point of making a 20 inch long part? Well, the first thing

=we have to do is get the mold as accurate as possible. The general guideline for making a mold is to allow one sixteenth of an inch per foot for the aluminum shrinkage when making an aluminum casting. Will this always be right? No but this will get us as close as we can expect. One end of the mold may be .005" to .010" longer or shorter than the other. If accuracy is required beyond this point, you may need to select alternate types of tooling. If you are exceedingly lucky, both ends of the mold will be within a few thousandths of an inch and you will be able to compensate by altering the processing conditions of the plastic.

This brings us to variations in material size. If you look at published data on mold shrinkage of plastics, you will note that you are usually given a range. This is because even if you compare like materials, say a given formula of ABS, there may be very slight variations between runs. However, a significantly greater variation in shrinkage will occur during the forming process. Thus the range published for shrinkage data on ABS is usually .005—.007 inches per inch. So how can we vary the part size through the thermoforming process? If you heat the plastic sheet to the high end of the forming range and you cool the part for an extended time on the mold, you will get a part that is larger than one that you heat to the minimum temperature range. This will happen in spite of taking it off the mold as hot as is allowable without warping. You can actually vary the mold shrinkage by about .002 of an inch per inch. Thus you can vary the size of a 20 inch part by about .040 of an inch. Can you now see why a temperature-controlled tool will give you parts that are more consistent in size? If the tool was accurate in size to begin with and you can home in just the right processing conditions, you will get a part that is consistent in size and also quite close to the actual size you were looking for within the tolerance you were seeking. Now you know why thermoforming is a "black art". You still have to make the part form on the mold with proper material distribution and that in itself may dictate to you where the processing conditions will be. Who has more fun than thermoformers?

Now you know why tolerances on a print can be nebulous. To be sure, once you have a given mold, you should be able to get a consistent sized part. That brings us to tolerances on secondary operations, namely trimming, fabrication, and hole drilling. First of all, it stands to reason that how accurately you can trim something will ultimately

depend on the accuracy and consistency of the formed part, but assuming that all is well in plasticland what can we expect? Generally speaking, trimming accuracy depends on the accuracy of the trimming fixture you produce or the accuracy of the automatic mechanical trimming device you use. What do I mean in each case? If you use a manual trimming device, it will have to be operated by a human being and as a consequence each part will be trimmed a little different albeit only slightly. The reason for this is that the operator is human and he cannot possibly hold the router, saw or any other device he is using in exactly the same way each time. The only way to compensate for this is to build very expensive fixtures that do not allow for any skill or judgment to be used by the operator. Sounds like a fun job! Even with all this, it is probably not possible to achieve trimming tolerances of less than plus or minus a thirty-second of an inch. Anything less will drive the trimming scrap rates sky high and makes the job unfeasible.

The second method of trimming that is getting very popular is robotic trimming with a five-axis router. Depending on the rigidity of the superstructure of these machines, it is possible to achieve accuracies of .010" to .015" if the part is reasonably small and the holding fixture the part is placed on is constructed very soundly and accurately. These machines also allow one to trim parts much more quickly and with a high degree of repeatability with very low scrap rates. The key here is the holding fixture. You have to make it very rigid and the process of locating the part on it foolproof in regard to consistent placement. As just stated above, a good degree of the tolerance is dependent on the size of the part, the area of the part you are trimming and the type of trim you are doing, that is, an exterior flange, a drill hole or an interior cut out on the part.

A third type of trimming is die cutting or punch press stamping. Here you have a fixed sized die cutting through the surface of a formed part. Usually you are limited to one or two trim planes on the part because if you try to trim more planes or irregular surfaces, the cost of the die becomes prohibitive and you can't afford to make the part. However, if you only have simple planes to trim or holes to punch out, this is the most accurate way to do it. Obviously once you get the die right, it is the same size on every punch and the only variance is how cleanly you make the cut through the plastic. This is subject to the type of plastic you are cutting and

how sharp you keep the die. An example of plastics that is hard to cut cleanly is the olefins. Generally though, you can cut holes, slots, or distances between slots to .005". Figure 7 and table 1 gives you an idea of expected tolerances you get with the different types of trimming. There may be some

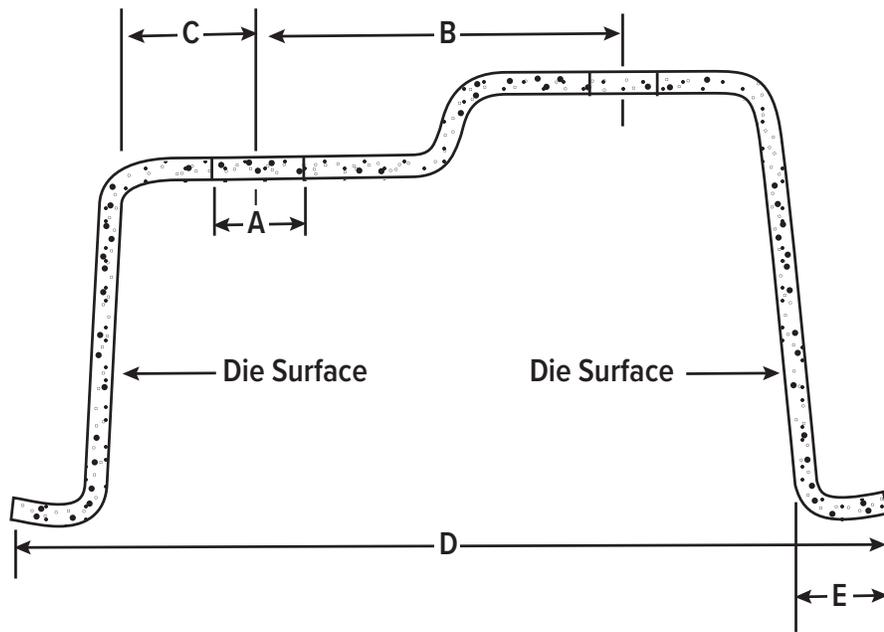
disagreement between different processors and their claims of accuracy, but these are approximate guidelines. As I indicated earlier, the more elaborate the trimming fixtures or trimming machines you use the better your tolerances, up to a point.

SHRINKAGE

Shrinkage has already been discussed somewhat under tolerances but they must also be addressed in terms of what they do to your part design with regard to assembly. Of the two types of shrinkage, namely mold shrinkage and coefficient of thermal expansion, the later one can be more of a problem. Mold shrinkage can be somewhat controlled by material selection and the forming processing

conditions but the coefficient of thermal expansion cannot be controlled. What you see is what you get! It is a near linear value related to type of material, temperature, and the size of the part. Since all these are usually given, we have to design around certain things. The first is mounting plastic parts to dissimilar materials and locking these materials down with fasteners or adhesives.

Fig. 7



DIM.		MANUAL	ROBOTIC TRIMMING	DIE STAMPING
A	first inch	+/- .005	+/- .010	+/- .005
	each additional inch	+/- .005	+/- .000	+/- .000
B	first inch	+/- .020	+/- .015	+/- .005
	each additional inch	+/- .001	+/- .000	+/- .000
C	first inch	+/- .020	+/- .020	+/- .015
	each additional inch	+/- .001	+/- .000	+/- .000
D	first inch	+/- .030	+/- .025	+/- .015
	each additional inch	+/- .001	+/- .000	+/- .000
E	first inch	+/- .020	+/- .020	+/- .015
	each additional inch	+/- .001	+/- .000	+/- .000

Here is an example. Suppose you have a metal frame about 54 inches long that you drill 5 holes 10 inches apart. This would mean that there is a screw hole two inches from each end of the frame. Now let us also say that the end of the metal frame has a right-angled bend on it and your intent is to bend a piece of plastic around this right-angled bend. Then you drill 5 holes in the plastic part to match the 5 holes in the metal frame with very little assembly play. You intend to use this assembly in the inside of a building where the temperature is relatively constant at about 70° F. If you manufactured this part in a temperate climate and shipped it into a temperate area you probably would never have any problems. However, let's change a few things. Let's still assemble this part in a temperate climate, say 70° F, but ship it to an area with a winter climate of say 10° F. If the original distance of the two outside holes were 50 inches, the plastic will want to shrink down to 49.85 inches between the holes (.00005 x 60° F x 50 inches). Obviously the plastic will have to elongate to accommodate this shrinkage. Since the plastic will all tend to shrink towards the center hole, it won't be affected. But the two outside holes will have to elongate by about .075 inches each. If the plastic is a high impact plastic it will probably elongate OK, but if it is a hard plastic, it is likely to crack at the holes. This condition will even be worse where the plastic wraps around the right angles at the ends, especially if the radius is very tight on the end of the plastic and the frame. This is generally unacceptable so it will probably be necessary to slot the two outside holes to accommodate these phenomena and leave a gap between the plastic and the end of the frame.

Now let us take the direct opposite situation. Assume the part is the same as the example above. Let's take the assembly temperature of 70° F and put the part in a hot shipping trailer where the temperature goes up to 150° F. Now we have a temperature change of 80° F and the part between the two outside holes wants to expand to 50.2 inches. But the holes have the part locked down. Something has to give. When plastic is heated up,

it is not brittle so it is very unlikely to crack at the holes. So what will happen. Well, it will warp or bulge up between the holes, but probably not much near the center hole. If the temperature gets high enough, it will approach the heat distortion point of the plastic and it will warp permanently and the only time the bulge will come out is when the plastic cools down below the manufacturing temperature. However, the plastic will have a memory and when the temperature goes up a little, the bulge will come back. So now you see that it is necessary to have the hole slotted in the outside direction too. The total slot requirement is .2 inches + .15 inches or .35 inches total.

The same phenomena occur when you glue a piece of plastic to something with a different coefficient of thermal expansion such as plywood. If you do not use a soft rubbery adhesive the plastic will crack when it gets cold and warp when it gets hot. One must be aware that this condition will be serious or not worrisome depending on the size of the part. When parts are small say, 15 inches or less, it would take a drastic change in temperature to have enough effect on the plastic to create a problem. As you can see from the above figures and using the same environmental parameters, the expansion would be about .067 inches and the contraction would be about .005 inches. The

elongation characteristics of the plastic would probably be enough to compensate for this expansion and contraction and nothing serious would likely occur.

As an alternative to slots, it is sometimes much easier to design expansion and contraction ribs into the part. This is especially effective if you can use these ribs to enhance the appearance of the part. There have been a number of cases where just putting in the company name or logo in a strategic place will accomplish the same objective. Other solutions to this condition are the use of H-strips or overlapping joints when the parts are extremely long, say eight feet or so.

ASSEMBLY and FABRICATION

You have all seen the phrase on a plastics data sheet that you can form, saw, glue, rivet, fasten or do anything with plastics that you would expect to do with wood. This is essentially true but there are some restrictions that do apply just as there are

with wood. One of them is the obvious condition we have described above regarding the coefficient of thermal expansion. Another is the process of gluing plastic to itself or to some other dissimilar material. If we glue plastic to itself, we can usually use a

solvent-based adhesive on most types of plastics. However, if you use a solvent-based adhesive, you must be careful not to use too much. If you do, the solvent will soften the plastic too much and it is likely to “prune” up on you, that is, to get what appears to be a rough surface. If you don’t put enough on, the parts may not stay together. Don’t despair, there is a reasonable window to work with. You can enhance this bond by simply cleaning the surface to be glued with isopropyl alcohol and scuffing up the surface with sandpaper. This is especially effective when gluing plastic blocks or spacers to a plastic part. Often these blocks contain sonically welded in screw inserts.

Some plastics are not easily glued by using solvent-based adhesives. In these cases, you can use an epoxy or urethane based adhesive. When you do this it is usually a good idea to scuff up the surface to be glued with sand paper as these types of glues are mechanical and the bond will be much better if you do this. Another precaution when using an epoxy or urethane adhesive is to make sure that the durometer of these glues are roughly the same as the plastic you are gluing. This allows the glue to flex at about the same rate as the plastic and keep it from cracking when it is under stress.

And then there are OLEFINS. You cannot bond them to unlike materials. However, you can bond them to themselves by using spin welding, plastics rod welding, or just plain using heat to fuse the two pieces together. This is bound to put you in jeopardy of warping one or both of the surfaces you are trying to put together. So care is necessary because I have never seen anyone “unwarp” a part. There are systems that can give you a reasonable albeit not perfect bond. If you are trying to put stickers or decals on an olefin part, you can flame treat or corona treat the surface of the part and this will enhance adhesion well enough to get an acceptable bond. Observe all the plastic road markers along the highway. They are made from polyethylene and

have reflective tape bonded to them.

Riveting or screw type fasteners are perfectly acceptable in attaching two plastic pieces together. The two caveats that are absolutely essential when using this system for joining two pieces together is to predrill the holes and use flat washers on each side of the attached part. A lot of people use self-taping screws to cut through the plastic or worse yet just use metal screws. **THIS IS WRONG!** Most plastics are notch sensitive. This means that when a crack is started, if there is any stress put on it at all, the crack will propagate and likely result in a part failure. Most times this is caused by tightening down the self-taping screws too tightly or using bevel headed screws. However, this can even happen if you predrill the holes and really tighten down the screws too tightly. Even though panhead screws are not very attractive, they are the best types of screws to use in conjunction with washers. This is not as sensitive as it seems. If common sense is used and the screws are moderately tightened this assembly practice will work out just fine. After all, there are literally billions of parts assembled using this technique.

The type of washer you use is optional. Flat metal washers work fine. In the last number of years however, there has been a multitude of plastic washers that are more attractive and have a similar durometer as the plastic material you are trying to fasten together. These washers have less of a tendency to cause cracking if they are a little overtightened. There are even plastic washers that have beveled recessed holes to accommodate bevel headed screws. And speaking of screws, sometimes screws and other types of fasteners come from the supplier with a coating on them or are run through a solvent to degrease them. If any of these substances are harmful to the plastics, these fasteners should be thoroughly cleaned off to avoid any type of chemical attack on the plastic. This is a significant source of part failure.

DESIGN PARAMETERS TO AVOID

Given all of the above design guidelines, are there any specific things we should avoid in planning a plastic part? The answer of course is yes. One of the first things to avoid is a doubled right-angled corner. This is true whether it is made on a male or female mold. If it is made on a male mold and the part has any height to it, you will surely get a very unsightly

severe chill mark. If it is made on a female mold with any depth at all, the corners will be very thin and structurally unacceptable. Generally speaking a ball radius of one-fifth of the height of the part, whether square or rectangular, will keep you from getting into any structural or cosmetic problems in the corners. This is true whether you use a male or female mold,

as you will be able to select a forming technique that will prevent these problems from occurring. Let us present you with an example. Suppose you have a male mold with a width and length of 10 inches and a height of 10 inches. This part is best processed using the snapback technique. So with a height of 10 inches, we would have a ball radius of 2 inches on each corner. If you perform the snapback technique properly, you should get a part that is both structurally and cosmetically acceptable.

Here is where we should inject a key point in part design. Establish a good rapport with your thermoformer and get him involved early. Why rapport? So he can give you a confident NO in regard to a bad design and not fear for losing the job. Since he will have to do the processing, it is important that he be brought into the picture early. Who understands more about the problems he may encounter in forming a part than the thermoformer?

A second no-no in part design if a part is put under stress is sharp right-angled edges whether on the interior or the exterior of the part. This is an accident waiting to happen. If you have any continuous or serious stress on the part, this is where it will fail. This is true of any type of material. If you make a right-angled break on a piece of metal and put some heavy stress on it, if it fails, it will fail on the sharp right-angled break. Does this mean stylists are going to stop designing these types of plastic parts? No, when you're in love, you're in love! They are

not likely to give up what is truly attractive and you have to admit, crisp design lines are really attractive. Will they get away with it? In most cases, yes. Most cosmetic parts are not put under any stress other than the burden of their own weight and this is very unlikely to ever result in a failure. However, it is imperative that the part designer be aware of the potential problems that can result from this practice.

Another no-no albeit not quite as serious, is insufficient draft on a part run on a male tool. When plastic is formed on a tool, the natural physics of materials dictate that the plastic will shrink onto the tool. When this happens, two bad things will result. First, there will be an excessive amount of stress on the plastic as it cools and second, it will be very hard to get the part off the mold. This will result in more stress and a higher reject rate. Again, check with your thermoformer. He will tell you what he is comfortable with. However, the guidelines we use is two degrees for the first inch of height of the part and one additional degree of draft for each additional inch of height. This should allow you to get the part off without using 100% air eject. These are not all the design pitfalls that exist but do address some major ones. So there you have it. Now go out and do the right thing!

Now I would like to address a topic that we probably should have put with thermoforming techniques but it usually is associated more closely with design considerations by design engineers.

PRESSURE FORMING

I have written a whole manual on pressure forming with emphasis on how to make it happen, but we are more interested in design parameters and what can be accomplished by this technique. Simply stated, pressure forming can be limited to two techniques on either a male or female mold but in probably about 95% of the cases it is done in a female mold. Basically it is done either with the plug assist top or plug assist bottom technique described earlier. The only difference is the plug is incorporated within a pressure box. See Figure 8.

So why do we employ this technique if it is essentially the same as plug assist top or plug assist bottom? The simple answer is cosmetics. It is the only way to use the thermoforming process and equal the cosmetic appearance of an injection-molded part. Essentially the structural integrity of the formed part is no better or worse than a part

that can be made with simply plug assist forming. However, it is far superior in appearance. Here are some of the things that can be accomplished.

The first obvious improvement is texture detail and uniformity. During the vacuum forming process, the plastic sheet is stretched out in a non-uniform manner and therefore the texture of the formed part does not match the extruded sheet exactly and it is "washed out" in areas that the plastic is stretched the most. This does not happen in pressure forming. The texture you put into the tool is the same as the texture you get on the part. As a matter of fact the crispness of the texture is superior to the texture you can achieve on the extruded sheet as you are forcing this texture into the mold at a significantly higher temperature than you are embossing the

Fig. 8

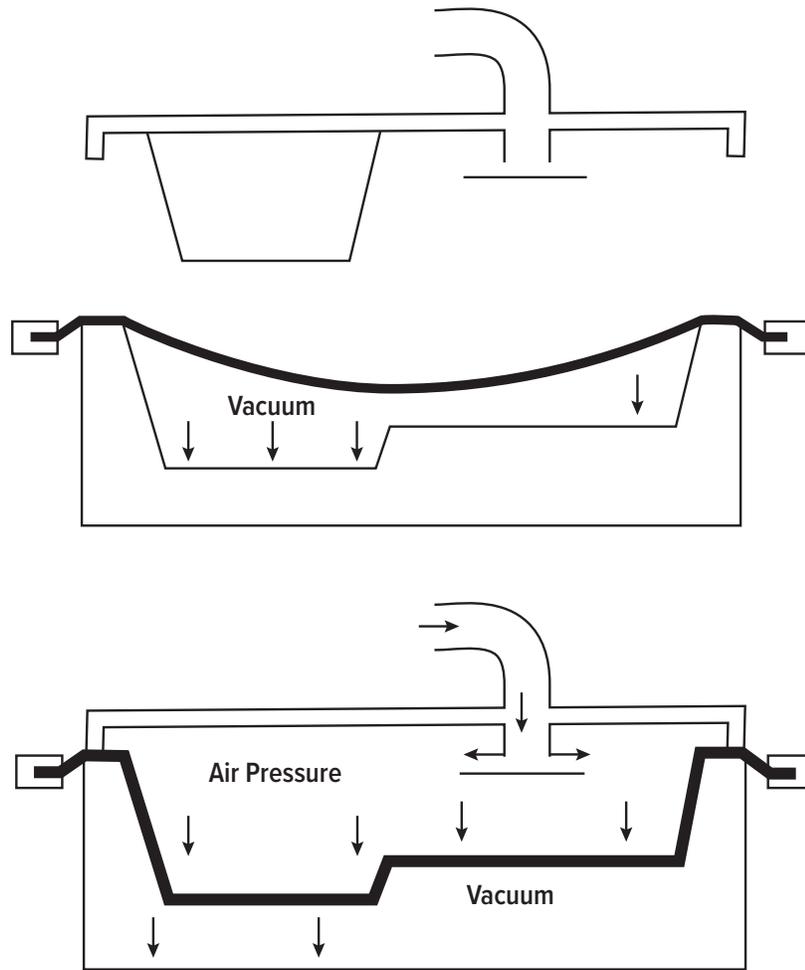


Figure 8 shows how pressure forming provides for the normal vacuum pressure against the mold plus the additional air pressure that is generated from your compressor. This can be as high as 100 additional PSI depending on the size of the mold and the design of the system that holds the pressure chamber against the sealing surface of the mold. Thus the practical 9.8 PSI you get from normal vacuum can be enhanced by a factor of ten thereby giving you much better detail. As a practical matter, we typically add an additional 30 to 50 PSI to the pressure chamber. This is usually sufficient to produce a cosmetically acceptable part.

texture on the extruder itself. Plastics flows more freely as you increase the heat. However, there are limitations. At some point you will heat the sheet hot enough to where it will actually discolor and then you have a reject. It should be noted that there are limitations on the extruder too, as running the embossing roll too hot will cause the plastic to wrap up around the embossing roll.

In addition to crisper textures, we are also capable of putting multiple textures on the part. This can really enhance its appearance and cannot be achieved with any other thermoforming process. We can also make areas where there is no texture at all so that later on we can silk screen these areas or put decals in them. If there is proper draft on the tool, it is even possible to put quite deep textures into the part without jeopardizing its integrity. And it is feasible to further enhance the part appearance by forming the

company logo or other graphics into the surface. We are limited mostly by our imagination.

Another useful design feature of pressure forming is the ability to form attractive louvers into the part that can also function as an air circulation or cooling vent. This is done repeatedly on electronic housings and medical equipment. These vents are opened by trimming the backside of the formed part. It is necessary to think these designs through thoroughly because a poor design will lock the part on the tool or fail to provide enough room to make moveable parts on the mold. Again, talk to your thermoformer. He can guide you.

Design lines and recessed fastener holes are also feasible. Because you are dealing with a molded part that will be pretty consistent once you get the tool right, you can design panels that are next to

each other that have matching features. In addition, recessing fastener holes and insert pockets can really hide unsightly assembly problems. Undercuts are also very useful for this. The whole purpose for pressure forming is cosmetically dress up your product and make assembly easier. Sometimes metal

inserts are even molded into the part for this purpose. So, there are many reasons to use this process to make your parts but the primary reason is to make your product more salable. Good luck, and good designing.

TOOL DESIGN

Tool design is the next major area of concern that must be addressed to assure that you make parts that are acceptable and successful. In my estimation, this is the second most important consideration in producing a good part. If you don't get the tool right, no matter how good you make the material or how clever you are at processing it, the part will not come out right. So what do we need to do and what are the major things to take into account? First of all, can the tool be made? Is it possible to form the part and can it be readily demolded? Remember when we suggested that the part designer and the

thermoformer get together? Well, this is a good time to get both of these people involved with the mold builder.

The first thing we have to determine is what type of material are we going to use and what tolerances are expected. The next thing we need to know is what the part looks like and what are its dimensions. This will be discussed more thoroughly later but we do need to know this up front in order to initially determine what type of tool we have to make. So, what is available?

TYPES OF MOLDS

There are two basic types of vacuum-formed tooling. MALE and FEMALE. Well, what's the fuss? Select one and let's get on with it. Unfortunately it is not that simple. Here are the primary things you need to consider to make a proper selection. First, where are the important dimensions on the part? Are they on the inside or outside? If they are on the inside, then we will have to go with a male mold. Vacuum forming only allows us to control one surface of the part. Either the inside or the outside, so you have to pick the one that is the most important. Let us give an example. Suppose you are building a case for a musical instrument. Obviously the insert that goes inside the case to nest the horn will be a specific size and fit snugly into the case. So the dimension you want to control will be the inside dimension. If the opening is too small, the insert will not fit and if it is too large, the insert will bounce around inside the case and possibly keep the insert from protecting the horn. You've all seen how careful kids are in caring for their horns.

A second concern is the shape of the part. If you are trying to make a shape similar to a gallon pail, a female mold is not going to work very well. A gallon pail is approximately 6 inches in diameter and about 8 inches high. Using the formula for draw ratio of a cylinder presented way back when, we note that the draw ratio is about 6 to 1. This is just not practical,

as it is normally good design practice to keep the draw ratio to 3 to 1 or less. This can be done quite well using a male mold and using the snap back thermoforming

technique. If you need to control the outside dimension of this gallon pail type part, good luck. It is very unlikely you will get a structurally acceptable part. So you see, it is mandatory that you understand draw ratio and have some knowledge of the various available thermoforming techniques. That is why we presented them first.

Another consideration on shape is the part symmetry. If the part is very asymmetrical, it may only be practical to do it as a two up mold. Maybe this is the way it becomes most economical to produce. Take a square box type part that is about 10 inches high and 10 inches wide with one end cut out of it. This is a natural for a two up mold, both from an economy standpoint and practical thermoforming standpoint in reducing the draw ratio.

Appearance is a concern. Which side is the cosmetic side? Take a bathtub for instance. The inside appearance is critical and therefore you could not use a male mold, as the mold surface would cause tooling marks on the inside of the tub. Gloss and smoothness sells in the bathroom industry.

Hey, don't fight it. The same case can be made for texture. If you have a male mold and pull the texture against the mold surface, you are going to wipe out some or all of the textured surface. So if you have a female part that requires texture in the inside, you are going to have to use a female mold. If you have a part that really requires a highly cosmetic finished surface, you may have to use a pressure formed tool. So what you have to accomplish appearance wise may dictate what type of mold you will have to use.

A fourth consideration for the selection of a male or female mold has to do with how the part has to be assembled and if it has a matching part. Undercuts are very popular on matching up an assembly. However, if you need undercuts on more

than two sides of a part, you will most likely need a female mold, as a male mold would be extremely complicated and prohibitively expensive. Sometimes it is necessary to have two parts mate together. In many instances this can best be accomplished by making one mold a female and one mold a male. This will provide you with a nesting effect where the inside surface of one part will be controlled and the outside surface of the other part will be controlled as well. One can readily see that if you need to match a male and female part, it will be necessary to have molds that are fairly accurate with regard to this matching requirement, and it will be mandatory to select a mold making material that will provide you with this accuracy. What are some of these materials?

MATERIALS AVAILABLE FOR MAKING MOLDS

There are a number of materials available for making molds. The one you select will depend on the tolerances that are necessary on the finished part, the cosmetics required, how many parts you need to make, and to an extent, just how much you

can afford to spend on a given project. Let us look at some of these materials, evaluate some of the pluses and minuses, and determine where and why you would use them.

WOOD

Wood is the simplest type of material used in vacuum forming. The number one benefit is the cost. It is cheap! It can also be milled or fabricated into a shape pretty easily and it is very readily available. Most patterns to make a thermoforming tool are made from wood. Generally, a part starts off as a drawing or a print and from this we make a prototype tool or pattern. If a part is to be made from this pattern, it will be necessary to compensate for the shrinkage that will occur during the forming process and thus the pattern will be slightly larger than the expected part. This will depend on the type of plastic you plan to form on it. If you are only going to use this pattern to build a mold, then you will have to build some additional shrinkage into it to allow for the shrinkage you encounter from the mold making material. Thus if you plan to form parts off the pattern and later use it for making the mold, you will have to expand it just before making the tool to adjust for this additional shrinkage. Generally, most amorphous plastic materials have a material shrinkage from .005 to .008 inches per inch and an additional shrinkage of .001 to .010 inches per inch for the mold material depending on what type of material you select to build the mold. Prototypes are usually pulled with a

wooden tool but not always. However, if the wooden tool is used for production, you should be aware of some limitations. First, wood is an insulator and cooling the part on a wooden tool will dramatically lengthen the cooling cycle, sometimes by 5 or 6 times in the case of the olefins. Second, the cooling will be uneven depending on the finished thickness throughout the part. This can cause stress in the part and in some serious cases, warping. Third, sometimes the grain in the wooden tool will transfer onto the plastic and if the material is thin and the grain in the tool is heavy, it will even transfer through to the cosmetic surface. Fourth, wood has moisture in it. If you run these molds in production, they will need a good deal of maintenance because they will dry out and crack. Cracking will transfer through the formed plastic. Finally, there are a limited number of parts you can pull on a wooden tool. This will depend a great deal on what type of wood you use to build the mold, but eventually it will fall apart. So, it is necessary to weigh the costs of this type of tooling versus the results you need to get.

POLYESTER or FIBERGLASS

This is another popular material for making tools. This type of tooling is considered permanent tooling for lower volume projects. Whenever, you have a job that requires less than 2000 parts per year, you should consider it as a viable alternative. It too has limitations but it also has advantages. Again, the first advantage is price. With the exception of wood tooling, it is the most economical way to go. What we do to make this tooling depends on whether we need a male or female tool. Let's suppose we need a male tool. We take the male wooden pattern, wax it up, and make a female fiberglass skin off of it. Then we take this female skin and make a much thicker, more durable permanent male mold from it. This is placed on a mold base just as a wooden mold would, and the same general preparation is done. It should be noted that it is important to use high temperature polyester or when you thermoform parts, the mold will heat up after the first few shots and start to warp. If you have to make a female mold, things are actually easier. You just take the male wood pattern, wax it up, and make a

permanent durable fiberglass shell around it. Then you put it on a mold base and prepare it just like you would a male mold. All this can be done in a relatively short period of time, maybe just days after the pattern is made.

Well, what are the limitations? Most of them are just the same as a wooden tool only not as pronounced. For instance, the cooling cycle is still two or three times as long as a temperature controlled tool but it is only half as long as a wooden tool. The tool will eventually show fine cracks, but it will take a long time so the maintenance is drastically reduced. It will also be difficult to match the accuracy you would expect in a temperature controlled tool but it is better than a wooden one. Parts made off of a cold tool will always be a different size than parts made off of a hot one. However, for parts that are used in the recreational vehicle industry and the like, it is quite adequate and likely the most economical way to go.

EPOXY TOOLING

This is also a very popular way to make tooling and it also has some advantages and limitations. It too is considered permanent tooling but the volume of parts you could expect to form off of this type of tooling is quite high, that is, in the thousands. Here price isn't as big of an advantage as temperature controlled tooling but it is still significant, probably half, but it is definitely more expensive than fiberglass tooling. It is also more efficient than fiberglass tooling. Generally speaking, you can run about 60 to 70% of the parts you can normally run on a temperature-controlled tool. The cooling cycle is definitely better than a fiberglass tool and the tool will last significantly longer too. But the big advantage is the speed with which one can go from a print to a finished tool. In many cases this is done in house by the former. Since he can control the whole process, after he gets the pattern made, he is just days away from getting into production.

There are not many disadvantages in regard to epoxy tooling but one big one is weight. Because you are in many cases pouring a solid cavity or at best a very thick walled structure, this type of tooling may weigh three or four times as much as fiberglass or temperature controlled aluminum tooling. Thus,

it will be more difficult to put this tooling in the thermoforming machine and move it around to get it set up accurately as easily. It will also be harder for the platens to move the mold up and down if the mold is large and you have air operated platens. As in the case of wooden or fiberglass tooling, you do not have any temperature control and so there will still be some variation in part size but it will not be as much as with wood or fiberglass tools. Another difficulty is dealing with the vacuum holes on epoxy tools. Typically you have a much greater mass of material to drill through and this is usually more difficult. And since the hole paths are normally longer, it is easier to get them plugged up with debris during the forming operation. However, this will only be a slight inconvenience. Generally the advantages outweigh the disadvantages by a significant amount because there are a lot of formers out there using this type of tooling as an alternative to aluminum.

ALUMINUM TEMPERATURE CONTROLLED TOOLING

This is the type of tooling that would normally be suggested if it is at all affordable. There are two variations of this type of tooling, namely, cast aluminum or fabricated aluminum. Cast aluminum is just what it sounds like. From a pattern just like the one we made for a fiberglass or an epoxy tool, we make a plaster cast that allows us to make an aluminum shell about three-eighths of an inch thick with water lines cast right into it. This is then put on a mold base just as we would for any other tool except it is normally made out of aluminum. In the case of a fabricated aluminum tool, either a single piece of aluminum block is honed out to make the mold and then gun drilled or a series of aluminum blocks are cut and assembled to produce the tool. This type of tooling is the most accurate in terms of dimensions but it also costs about twice as much as a cast tool. If maximum accuracy is necessary, this may be the only alternative.

Both of these have a lot of advantages and very few disadvantages. Let us go through some of the pluses. First of all, this type of tooling produces the best and most consistent part you will get in the thermoforming process. Because the temperature is totally controllable, you can take the part off of the tool each time at the same temperature and expect the shrinkage to be very similar from part to part. A second plus is the cycle time. This is the fastest way you can make a part in thermoforming. As a matter of fact, if you are using a rotary thermoformer, it doesn't make any sense to run a part without a temperature controlled tool as the mold will overheat so badly that you will have to slow the cycle down to less than the speed of a single station machine anyway. A third plus is durability. It is conceivable that you will be able to pull a half a million parts with very little maintenance off this type of tooling before the tool is unusable. If you were to put a nick or gouge into the tool, it is repairable at a nominal cost. This is very important if you have a job with a high volume of parts. Finally, some

materials are exceedingly difficult to pull without using temperature-controlled tooling. The olefins are perfect examples. Without temperature controlled tooling, you can expect to encounter numerous warping problems. Olefins require very accurate cooling temperatures and these are very difficult to obtain without this type of tooling. Another example is polycarbonate. This material is extremely sensitive to chill marks and if you don't have temperature controlled tools, you will not be able to eliminate them. So, the type of materials you run may dictate this type of tooling.

What are the disadvantages? As we indicated, they are very few. The only ones I could think of are cost and lead times in getting the tool. This is likely the most expensive type of mold in thermoforming but to put it into perspective, in most cases, it is only about 10% of the cost of an injection-molded tool. When you take into account the reduction in cycle times, in most cases if the job has decent volume, you will get your money back on the first run you make. In regards to the lead time it takes to make the tool, most tools can be put into production within four to six weeks of giving a tool manufacturer the order. Admittedly a wooden tool may only take two weeks and a fiberglass or epoxy one may only take three weeks, but the cost required to produce the part on a temperature controlled aluminum tool will probably make up for this. Depending on what you have to do, you will need to select a tool that will meet your needs at the minimum cost. We will talk more about this shortly.

There are other types of tooling that are available. Some of these are iron, ceramic, urethane, plaster and paperboard. None of these are very popular as they all have some severe shortcomings. Typically the heat transfer rating on these materials are very poor. However, they all work to some extent and I have seen every one of them used.

COMMENTS ON TOOLING

Now let us make a few observations and have a general discussion regarding some of the characteristics of the various types of tooling. First, we note that the type of tooling we select will be

dependent on the geometry of the part that we need to produce, the type of process we need to make the part, and the volume of parts that need to be produced. If the volume is low, the tendency will

be to use something inexpensive such as wood or fiberglass unless the part cannot be produced if an aluminum temperature controlled tool is not used. Remember the cost of the part has to be amortized with the part cost and tooling cost included so volume plays an important part in the total cost. The geometry of the part also has a good deal to determine what type of tooling we select. If crisp lines are needed and pressure forming is required, the only practical type of tooling is temperature controlled aluminum tooling. When parts are very large, it is also generally practical to use temperature controlled aluminum tooling. It is hard to keep these large parts from having chill marks if we don't select this type of tooling. And then we have to take into account the process technique we select to make the part. If you are going to use the billow form male or billow form female technique, it just makes good sense to use temperature-controlled tooling. The results with non-temperature controlled tooling will just not be as good. Again, the part will show chill marks and the cosmetics will not be as good.

The type of material you use for the part will also have a bearing on what type of tooling you select. An example alluded to earlier was the use of the olefins. These materials have high mold shrinkage and tend to warp rather easily. To compensate for this, it is very desirable to build tooling with a moat and sandblast the finish. This helps to keep the material in better contact with the mold throughout the cooling cycle. Sandblasting or moating other types of tooling is very difficult and putting in cooling lines to prevent warping if virtually impossible. The real key is the variable shrinkage that we usually get with non-temperature controlled tooling. Sometimes it is totally impossible to use a particular material on a given mold. A case in point is the use of TPO (thermoplastic olefin). No matter what you do, when this material is brought to its forming temperature range, it will sag a lot. If you are trying to form a part that is long and wide but somewhat shallow, there will be no place for the material to go. It will subsequently web and no matter what you mechanically do, you may not be able to get a good part. Thus, material considerations come into play when you select a mold and when you determine what type of forming technique you will use. We will elaborate on this a little more when we discuss materials.

Some parts are very complex, that is louvers, undercuts, dramatic asymmetry or just plain busy. Hopefully you will have addressed this in part design and made good judgments in conjunction with

the thermoformer. Even so, if parts are unusually difficult, it just makes no sense to try to produce them on inferior molds. Again a case in point is an electronic housing. These parts almost always have cosmetic requirements that are demanding. To try to make them on a wooden tool, with the exception of prototypes, is impractical and the results will usually be disappointing. Let us talk about asymmetry a bit. Plastic processing in general does not like asymmetry. This is especially true in thermoforming. Say you have a part that is about 36" x 36" in length and width and about 6" high on one end of the part and 18" high on the other end. Let's say you select snap back as the thermoforming process to make the part. When you pull your bubble into the vacuum box, which end do you accommodate? If you only pull a 6" bubble, the other end will surely pierce through the bubble and stretch the material a quite a bit. This will result in both thinning and chill marks on the 18" end. If you pull the bubble into the vacuum box about 16 or 17 inches deep you will pretty much eliminate the thinning and chill mark problem on the deep end but the shallow end will most likely web. Kind of a catch 22. Can we fix this problem? Sure! However, it will cost some more money to build the tool and require a good deal of design creativity when you actually make the tool. Will the part ever be as good as a symmetrical one? No, but it will probably be quite adequate to do the job. You will more than likely have to over engineer the shallow end to make the deep end adequate. Many times the part geometry will dictate the integrity of the part.

We also mentioned louvers and undercuts. These design features are usually associated with pressure forming and they do affect the tooling you select. Typically the tool will be a temperature controlled aluminum tool and it will be a female. Undercuts are extremely hard to achieve with a male tool. Even with a female, there are certain design parameters you should not violate. Assuming the tool is not inordinately small, that is, something like 6" x 6" in length and width and three inches deep where you don't really have enough room to put an undercut, you should limit the width of the undercut to about a half inch. Any more than this will exaggerate the degree of difficulty that the part will take on during the thermoforming process. In the corners of the part, this width should be reduced to as little as possible, say three sixteenths of an inch to make it easier to form. If you get much more than this in the corners, you will be stealing too much material from the corners, and the bottom of the part will get extremely thin and you may not be able to

do anything about it. Louvers have some design considerations you have to take into account too. Generally speaking, the width of the louver must be at least as wide as the starting gauge of the material. If you try to make them less, depending on materials, no amount a pressure you put on the pressure box for your pressure formed tool may be enough. Remember that you only have air pressure to work with here and shop pressures are normally limited to about 120 PSI. Then too, if you push this window too far, you may not be able to achieve the detail you want on these louvers and sacrifice some aesthetic appeal on the part. These parameters are well known by pressure forming manufacturers, and proper consultation with these people could avert some embarrassing moments later.

Another issue with tooling is surface finish and vacuum holes. When you are looking at surface finish, a good deal depends on the material you use, the actual starting and finishing thickness of the material, and the texture of the material. For instance, if you are using an olefin, almost anything will transfer through the material from the mold, especially if the material is a low gauge material to begin with. Scratches may even show. This would make it mandatory for the mold to be totally cleaned up and sand blasted to put a good surface on it to get good contact. You can see that a wooden tool would transfer about everything. If the material is a little thicker and has a good texture on it, you may be able to get away with a little more in terms of tooling roughness. Some materials are more forgiving. ABS or ABS alloys do not flow as much during the thermoforming process and will hide some of these tooling defects. This is what is known as hot strength and will be discussed in more detail later. These amorphous materials also retain their textures better and tend to conceal some of these tooling marks. The problem obviously becomes more acute when we are dealing with a smooth texture. Everything on a smooth texture shows unless you get the smooth surface from the pressure forming process. This is especially true when the starting material thickness is low and the texture is smooth.

Next we want to address vacuum holes. Whether they show or not depends on three things, their size, the material you use, and the amount of vacuum you have. Of these three things the most important is size. If they were small enough, no amount of vacuum or pressure in the case of a pressure formed tool would allow them to transfer

through the part. However, if they are too large, there will most certainly be a pimple on the mold side of the part and a dimple on the side of the part away from the mold. How big will the dimple be? Again it depends on the material, the material thickness, and the size of the hole. In the case of olefins, the pimples on the backside of the part will show up rather quickly, even with heavier gauged materials. Try to keep them below .030" even with heavy gauge. In the case of light gauge, .030" will very likely not be small enough. When using ABS type materials, it is rare for dimples to show up if the hole is .030" or less. Only if the material is being pulled very thin in pocket areas, say down to .030" thick or less will they begin to show. Well, you say, this will limit the amount of vacuum we can pull through the vacuum holes. Yes, but this is rarely a problem. You can always drill more holes. More importantly, there are usually areas of the formed part that are cut out or off the trimmed edge of the part where you can drill larger holes if you need more vacuum volume. The amount of vacuum holes is important too. Generally on flat areas of a part, a vacuum hole every four or five inches is adequate. However, in pocket areas where the material will still be relatively thick even after forming, it may be necessary to drill a hole every one-half inch.

Another area that must be taken in account when designing a tool is draw ratio or stretch ratio. A good general rule is to keep the draw ratio to 3 to 1 or below whenever possible. Usually this can be accomplished by designing a tool that will accommodate the most optimum thermoforming technique. Note my example on draw ratio pages ago. It was not practical to form the 10" x 10" x 10" part with a female tool but it was practical with

a male tool using the snapback technique. Plastics do not normally like to be stretched below a third of their original thickness. This makes the part more susceptible to stress not to mention the reduction in part integrity. However, the biggest issue here is the reject factor during the thermoforming process. Any time you go past this 3 to 1 draw ratio, you are just asking for the processing reject ratio to increase dramatically. As a matter of fact, failure to consider what the draw ratio or secondary draw ratio of a part will be is probably the number one reason for not being able to process a part successfully.

Next we would like to discuss cooling lines in temperature controlled tooling. First, we should state that cooling lines are not mandatory but they are highly desirable. On some materials it makes no

sense to run the job without temperature controlled tooling. Normally water lines are embedded into the aluminum casting but on some aluminum fabricated tools holes are gun drilled into the base of the structure. Both are very effective in controlling the temperature but gun drilling is a little more difficult to do. There are also attempts to run cooling lines into epoxy tooling. If you fill the epoxy matrix with a lot of aluminum, say 50 or 60%, it is somewhat effective but I personally am not a big fan. The heat transfer is very poor and in no way can the processing cycle compare with temperature controlled aluminum tooling. We also have to consider the distance these cooling lines are apart from each other. With most materials, a four-inch distance from center to center on the cooling lines will be adequate. However, for the olefins, this distance should be reduced to three inches. The amount of tooling surface you have exposed is important too. On olefins, if you exceed 18 square feet of surface it is generally desirable to have an additional thermolator system hooked up to the mold. Olefins are very susceptible to warping. A more than five degree temperature range on the tool will increase the stress put into the formed part and increase the chances for a warped part. A second thermolator system will make it easier to have a uniform temperature on both the inlet and outlet of both systems on the mold. Amorphous materials are not as sensitive. A ten degree temperature variation may slow the cooling cycle slightly but will not have much effect on the part warping. With proper manifolding of the cooling lines, you can effectively control about 30 square feet of mold surface.

A second major reason for having temperature-controlling lines in the tool is to be able to control chill marks. On certain very difficult parts, it is close to impossible to get rid of all the chilling marks but they can usually be made reasonably acceptable. If this cannot be accomplished, it may be necessary

to increase the radii on the part or redesign it. The third major reason for having temperature-controlled tooling is purely economical. This is the only way you can obtain optimum cycle times. Say you are running .187" gauge ABS material on a single station machine. With a temperature controlled tool you are likely to get about 12 shots per hour. With a non-temperature controlled tool you are likely to get only 8 parts per hour. If you use a rotary machine and a temperature controlled tool, you will likely get 20 parts per hour but a rotary machine with a non-temperature controlled tool will still only get you 8 shots per hour. The benefits are obvious.

In many cases it is possible to design the tooling to make secondary operations easier to do or even to eliminate the need for secondary trim fixtures altogether. This is done repeatedly in the RV industry. By building little ledges outside the useable part area, you can run a router with a guide on it along this shelf and trim the part out so it is only necessary to touch it up with a sander. This is not acceptable if tight tolerances are required. However, there are many cases in pressure forming when holes and cutouts are precisely located by designing them into the tool. It is useful to have a good understanding of the thermoforming process to take advantage of what the process has to offer.

A lot can be accomplished with tooling. By thoroughly thinking out what we have to do and understanding what can be done with proper tooling, we can make the thermoforming process and secondary operations easier. This makes everyone more efficient and is likely to be reflected in the quality and the cost of the part. There are many little "tricks" and subtle ideas that can be used in designing tooling and nobody knows them all. Better ways are always evolving. Get in there with the mold builder and former and see how creative you can get.

PROCESSING

Processing is the third major area that needs to be addressed to assure that acceptable and successful parts are made. If the first two major areas of consideration are properly handled, namely GOOD PART DESIGN and PROPER TOOLING, this very important consideration of PROCESSING will be much easier to accomplish. Well, what is involved here? First of all, there are many levels of complexity when considering the vast array of processors. As

we indicated in the very beginning, vacuum forming can be quite simplistic. Anyone with as little as a pizza oven and a vacuum cleaner can actually make parts, and I have seen it done literally. Are the parts sophisticated? No, of course not, but they could be acceptable as prototypes if they are small enough or even production pieces if the parts were thin enough for a minimum amount of vacuum to pull them.

Fortunately for the processors, most parts are not this simple and the volume of parts needed does not allow for such simple methods to be used. So what does a processor need to handle the business that is likely to come his way? Generally, this depends on what type of markets you are interested in. If you are interested in the electronics or medical market, you will need a very sophisticated machine that is likely

to cost a lot of money. If you are only interested in making simple signs from thin gauge materials, you will likely be able to use a machine with single sided heaters that you may be able to make yourself. Let's explore what's required to make various types of parts and examine the equipment available to do this.

EQUIPMENT FUNCTION

Way back when, we described thermoforming as taking a flat sheet of plastic, heating it up, and forming it into a shape. This is accomplished by employing any one of the various techniques of thermoforming. Depending on which one we select will dictate how sophisticated the equipment will be. Here is what we basically need to do this. First, we need something to hold the plastic sheet. It can be something as simple as metal piano frame or what is most frequently used namely a pneumatic clamping frame. This is attached to some type of a trolley

system that we can move in and out of a heating oven and position over a mold. We also need an oven to heat the sheet. This can be done by hot air, radiant type heaters or by gas flame heating. We will elaborate on this shortly. Next, we need some type of mechanism to hold the mold and make it possible to seal the hot plastic around the mold edges. We call this a platen. Finally we need a vacuum system to force the hot plastic onto the mold. Let's talk about the platens first.

PLATENS

Platens are nothing more than a well-stabilized and securely built framework to move a mold up or down. On very simple machines we only have one of these frameworks on the bottom just off the shop floor. In its normal position, it is retracted so we will have enough clearance to be able to pull the clamping frame across the mold without dragging the hot plastic against the mold surface. Well, what moves these platens? The least sophisticated way would be to devise a mechanical means that you could operate manually, and I have seen this done. However, the three most common methods used when employing a machine are pneumatic, hydraulic or rack and pinion drive. Frequently, the rack and pinion drive is described as an electrically driven chain drive.

A pneumatically driven platen is just what it sounds like. It has an air cylinder attached to a framework of the platen and can be moved up or down by actuating an air valve at either end of the cylinder. This is a very popular method of moving a mold into the forming position on a vacuum forming machine. The primary reasons are because it is simple to install, simple to operate, and therefore the least expensive to construct. In most cases, it is adequate to do the job. However, there are some drawbacks.

Whenever you operate something pneumatically that requires a certain amount of force, the response is not immediate. There is a very slight delay before full force is applied so you may get a somewhat "jerky" motion as you push the mold through the plastic or take the part off

of the mold. You may also have trouble getting the mold to seat in the same position relative to the clamp frame each time. On large parts this will sometimes cause you to lose your vacuum seal on the mold. In addition, if the mold is quite heavy, you will need a large air cylinder, something in the order of 10 inches in diameter to raise the mold properly.

Next we would like to discuss chain drive platens, better known as electrically driven platens. In actuality they are rack and pinion drives. They have been around for many years but they are just now becoming the dominant mode for moving a mold into forming position. They have some very distinct advantages. The first advantage is power. Typically you will have a platen closing pressure of five tons or more. This allows you to use the machine as a pressure former if the part is relatively small without investing in a specific pressure forming system. This makes your machine more versatile without

the added cost of the pressure forming mechanism. Even though this system is more expensive than a pneumatically driven platen system, it is still not as expensive as the pressure forming package and it is mechanically much more simple than the pressure forming system. A second advantage is accuracy. Since this system is a direct drive that is tied into a micro-switch, it will stop at exactly the same place each time within a thirty-second of an inch. This makes it the system of choice in pressure forming situations as the pressure box would stop at the identical spot each time and not cut too deeply into the hot plastic. As we have discussed, pressure forming requires tight tolerances in tooling and processing. Another advantage is the uniform speed that the platen moves up or down. If you are using the snapback technique and you are depending on timing to predraw the bubble, this system will give you the most consistent results. The more variables you can eliminate from a process,

the more consistent your processing results will be. This system also allows you to use a plug more effectively. As a matter of fact, this system is so consistent that you can tie in the vacuum flow with the plug extension and often times eliminate webbing on difficult parts. As far as disadvantages are concerned, I can't think of any except cost. In my opinion, it is really worth the extra money.

A third system for moving the platens is a hydraulic system. This too is a quite accurate system and gives you an enormous amount of power if you are going to pressure form. It basically has all the advantages of an electrically driven platen system. In my opinion, the only criticism I can levy on this system is the simple fact that it is hydraulic. It is only a matter of time before you are going to leak oil from somewhere and probably even drip oil on your production parts. If you are willing to keep up with the necessary maintenance, this is an excellent system.

CLAMP FRAMES

As we indicated earlier, you have to have some method of holding the plastic sheet while you have it in the oven heating up. This is done with a clamping frame. Now on very simple forming systems, this can be done with something as simple as two metal frames on a hinge that trap the sheet between them when the mechanism is closed. Typically these frames have little nipples welded on the inside surfaces of the frame that are in contact with the plastic sheet that prevent the plastic from pulling out of the frame during the heating cycle. Most plastics have a built in shrinkage within the sheet that takes effect when the sheet is heated up. Consequently, it is necessary to have good contact with the sheet to the plastic. After the sheet is heated to the proper temperature, the piano frame mechanism is removed from the oven and the hot plastic is dropped over the mold in such a manner as to pinch the plastic on the inside edge of the frame against the edge of the mold base. This provides a seal that allows the vacuum to evacuate the air in the mold and mold support chamber. As simple as this all seems, and it is, it is not very efficient.

Most vacuum forming machines have a clamping system that is attached to a shuttle cart that is operated pneumatically. It is usually comprised of two separate entities. The first is the actual shuttle cart. It is simply a large framework similar to a picture frame that covers most of the heating elements

in the oven. It is usually supported by some metal wheels that fit into a track and are enclosed from both the top and the bottom to prevent the clamping frame from moving up or down. The cart or carriage is moved into or out of the oven area to the forming area by long slender pneumatic cylinders. On large machines this is normally done with a chain drive. Attached to the inside of the cart on both sides is a unistrut that allows you to adjust the actual clamp frames to the size of the mold base.

This brings us to the clamp frames themselves. Normally they are comprised of a flat stationary base plate with a vertical support bar underneath it. Attached to the base plate are small pneumatically operated cylinders that have a gripping bar attached to the cylinders. When the cylinder pistons are extended, the gripping bar sandwiches the plastic sheet between the base plate and the gripping bar. This provides you with good gripping pressure and is very quick and efficient to operate and is far superior to a piano frame. The only negative is the fact that constant heating and cooling will eventually warp the clamp frames and the seals on the cylinders will ultimately wear out from heat and have to be replaced. However, the same warping happens with piano frames and they usually have to be replaced if heavily used too. The pneumatically operated clamp frames can be adjusted back and forth on the unistrut and have adjustable blocks for

the cross members. Consequently it is not necessary to have a separate frame for each mold base as it is with piano frames. The pneumatically operated frames can be used for any number of similar sized

molds. So now we have a method of holding the plastic sheet and a way of getting it in and out of the oven.

FORMING OVENS

A forming oven is nothing more than a chamber with a heating source. We will discuss heating sources shortly. These ovens can be either open or closed. Most ovens these days are what we would describe as semi-closed or almost totally closed. They are usually insulated internally to prevent the heating elements from heating up the outside surface of the oven and making it dangerous. What do we mean by open, closed or semi-closed? A perfect example of a closed oven would be an air convection oven. This is an oven that has no air gaps anywhere and has hot air circulating throughout the oven that

essentially heats the plastic. There are other ovens that are pretty much closed from all five sides and have a door in front of it that goes up and down as required by the loading process. These types of ovens have small gaps in the back of the oven where the clamp frame track extends and gaps in the front of the oven where the door opens and closes. These ovens are what we would call almost totally enclosed. They are pretty efficient but do allow some convective air to leak out and heat up the environment outside of the oven.

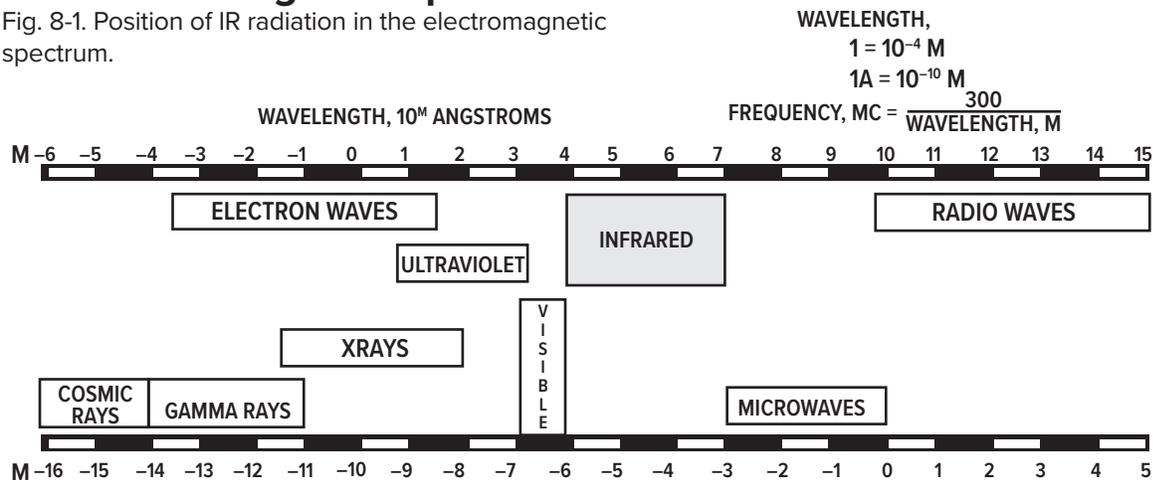
Electromagnetic Spectrum

Locate the infrared spectrum within the electromagnetic spectrum in Fig. 8-1. It is bordered

by visible on one end and microwaves on the other. The infrared region is from .72 microns and 1,000 microns.

The Electromagnetic Spectrum

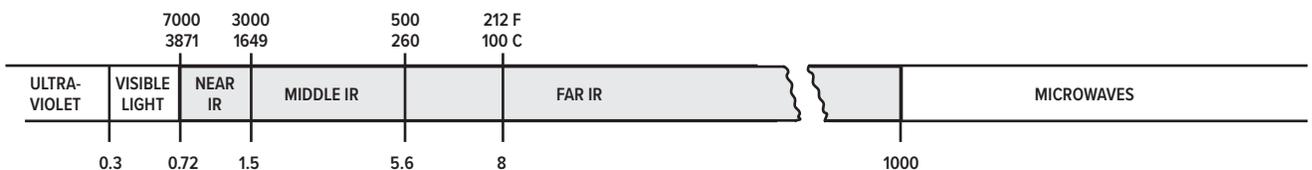
Fig. 8-1. Position of IR radiation in the electromagnetic spectrum.



The Infrared Spectrum

Fig. 8-2.

TEMPERATURE OF PEAK RADIATED ENERGY



Finally we have ovens that are considered open. Typically they have heating elements on the top and bottom that are encased in some kind of a shell. The oven can be open from one, two or all four sides. Obviously this will result in a lot of hot air escaping

into the immediate surrounding area which makes these types of ovens sensitive to drafts and air currents that exist within the plant. However, I can assure you that there are a lot of machines built this way and if used properly, they work fine.

HEAT TYPES

Before we get into heating elements and how the ovens work, we would like to talk about the types of heat available. There are only three types of heat, CONDUCTIVE, CONVECTIVE, and RADIANT. Plastic can be heated by any one, or all of these heating types, but some are more efficient than others are. It is probably easier to explain these heats using an example. If we take a red hot metal rod and touch it against your skin it will cause you some immediate consternation. If we touch it against a piece of plastic, it will most likely scorch the plastic. This is conductive heat and to be effective, this heat source must be only slightly hotter than what you want the item to be heated. Now if we take the same red hot metal rod and hold it a few inches from your skin, you will feel the heat. Part of this heat is coming from the fact that the rod is heating up the air around it and the hot air is heating up your skin. This is convective heat and is usually associated with an air-circulating oven. However, some of this heat is caused from infrared heat waves and is known as radiant heat. Various wavelengths of energy exist everywhere but only a few of the wave lengths

cause things to heat up and only within certain ranges. Infrared waves have a range of .72 microns to 1000 microns on the electromagnetic spectrum. See figures 8.1 and 8.2. A wavelength is measured in microns. One micron is equal to 1/1,000,000 of a meter or about 0.00004 inches (a human hair is about 50 microns in diameter).

From a plastics standpoint, we are only interested in the portion of the spectrum from about 0.1 to 100 microns as this is the region that most of the energy is radiated from a heater we would use to heat up the plastic. The amount of energy radiated by a heater and the wavelength of this energy is determined by a heater's temperature and the surface area exposed. Thus we need to be concerned about the type of heaters we would likely use, as various type of heaters put out different wavelength's of energy. We will address this

concept in a little more depth shortly but first we need to talk about heating elements available for thermoforming ovens.

HEATING ELEMENTS

CALROD

There are numerous types of elements used in thermoforming ovens, and we will try to discuss the ones that are most common. The most ubiquitous of all elements is the CALROD, sometimes referred to as KELROD. This is the type of heater you find in your electric oven in your kitchen. It is nothing more than a resistance wire packed in magnesium inside a stainless steel tube. It is very popular in thermoforming because it is quite durable, reasonably efficient and reasonably inexpensive. Typically these elements are placed in an oven about four inches apart and may run completely from the front to the back of the oven, unless the oven is very large, more than five feet from the front to the back. They are usually grouped together in a 'bank' and the temperature of a number of these elements is controlled together.

In very crude ovens the power is turned on just like a light bulb and you have 100% power input or no power input. Depending on how hot the elements burn, this can be a problem. If the voltage input is high and the capacity to accept voltage is high, the element could burn as hot as 1300° F. This will create a lot of convective heat and will likely scorch the surface of the plastic you are trying to heat. This is not going to be acceptable. We must do something to adjust this condition. Typically what is done in thermoforming is to put in a percentage timer that turns the power on or off through a certain time sequence. Normally this is a 15 second timer. Thus if you want to run the calrod at 50% heat, the timer would allow total power to be supplied to the calrod for seven and one-half seconds and no power supplied to the calrod for the other seven and one-half seconds. The shear

mass of the calrod would retain enough heat while the power was off to keep the calrod temperature reasonably consistent. Well, you ask, why don't you get a shorter timer? Indeed that is what is done when you go to computer controlled relay switches in the more sophisticated ovens. Generally in the less sophisticated machines you only have standard electrical contactors and cutting down the total timer sequence to two seconds would cut the life of the contactor to one seventh. It has been determined over time that a 15-second timer is adequate to keep the calrod heat relatively uniform. If the calrod is reasonably new, the power input is about 480 volts, and the timer is set at about 50%, you can expect the actual calrod temperature to be about 775° F to 850° F. This is important because at this temperature the wavelength of the radiant energy given off of the calrod is about optimum for the absorption of heat into the plastic. This will be discussed more thoroughly later.

The calrod elements in a thermoforming oven could all be operated independently on individual timers but this is rarely the case. The reason they are not is simply the amount

of timers that would be required. Each of these timers is expensive but even more disconcerting would be the number of contactors required. Timers usually are quite simple and have a long life but contactors that are opened and closed every five to ten seconds with 480 volts of electricity going through them get a lot more abuse. So, the fewer contactors you have, the fewer replacement parts you will need as they have a limited life. Thus in an oven with a five foot by eight foot clamp frame for plastic sheet and calrods on four inch centers on both the top and bottom, we would have 28 separate elements on the top and 28 on the bottom. This is a total of 56 timers and contactors. NOT PRACTICAL! Consequently, we typically have four or six groups of elements 'banked' together on the top and bottom called zones. This cuts the number of timers and contactors down to a total of eight or twelve.

There are a number of ways to group these zones. It all depends on how many zones you have and what the size of the oven is. For the five foot by eight

foot oven above, a four zone configuration would have an outside zone of about 18 inches all around the periphery of the oven and three zones that are roughly two feet by three feet in size in the interior of the oven. See Figure 9. If we have six zones in the above oven, we are likely to configure it like figure 10 but this is not the only way it could be done. Much of this is at the discretion of the person purchasing the thermoforming machine or even at the discretion of the machine manufacturer if economics are involved. You should note that both Figure 9 and Figure 10 show a six-foot by nine-foot dimension for the heating zone but we are only talking about a five-foot by eight-foot oven. It is important that the heating elements extend about six inches beyond the maximum sized sheet you can process. This is necessary to heat up the clamp frames. If you don't, the clamp frames will act as a heat sink and keep the edge of the sheet too cold to form with any amount of detail and may even prevent you from sealing the plastic along the mold edge. Hence you may lose some vacuum.

Earlier we mentioned that these calrods should be located on four-inch centers. This is another concept that is quite important and needs to be explained. Since these calrods are round and normally about three-eighths to one-half inch in diameter, the convective heat is given off in all directions but has a tendency to rise. However, the radiant energy waves are given off in all directions too and radiate in overlapping patterns in concentric circles away from the element. If the calrods are close together, these concentric circles will overlap enough to put out a very uniform heat pattern. If the calrods are far apart, say eight inches, these concentric circles will not overlap as well and there will be a space between these elements that will not put out as much radiant energy. Since the radiant energy given off is most effective and absorbed most efficiently when the elements are seven to eight inches from the plastic sheet, there will be an area between these elements that are not being heated as efficiently as the distance is greater than eight inches. Well you ask why don't you just turn up the heat? The answer is this changes the wavelength of the radiant energy and thus the efficiency of absorption into the plastic.

Fig. 9

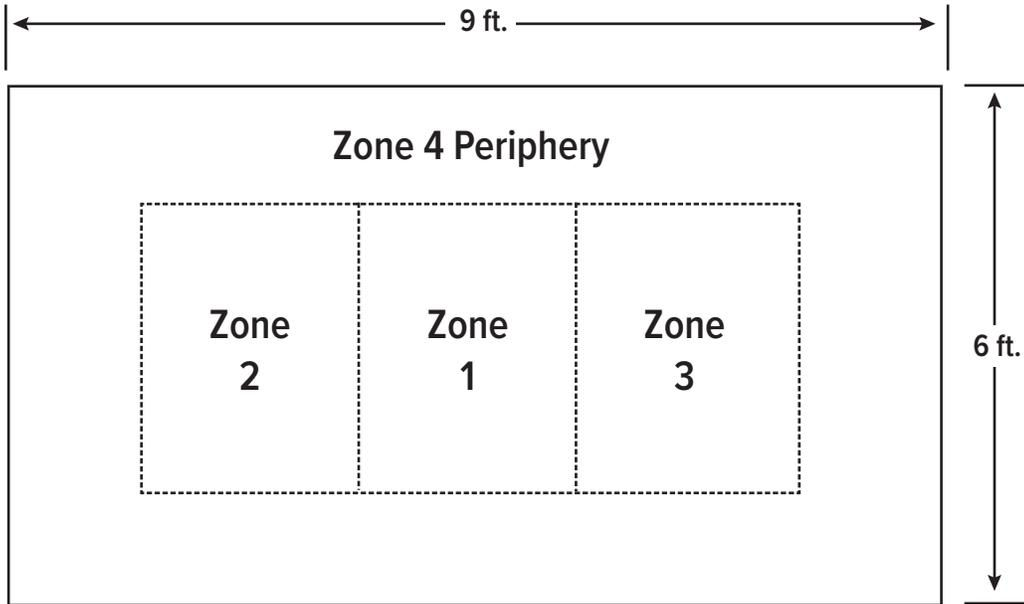


Fig. 10

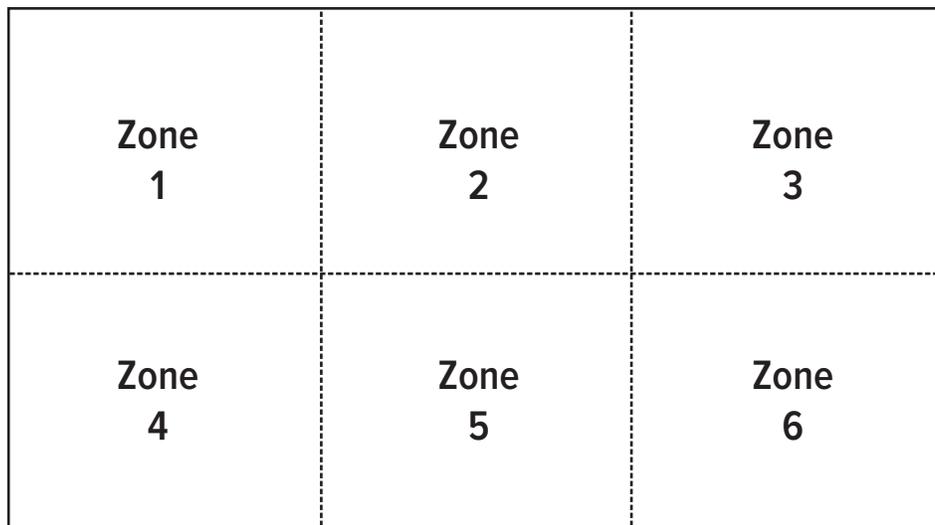
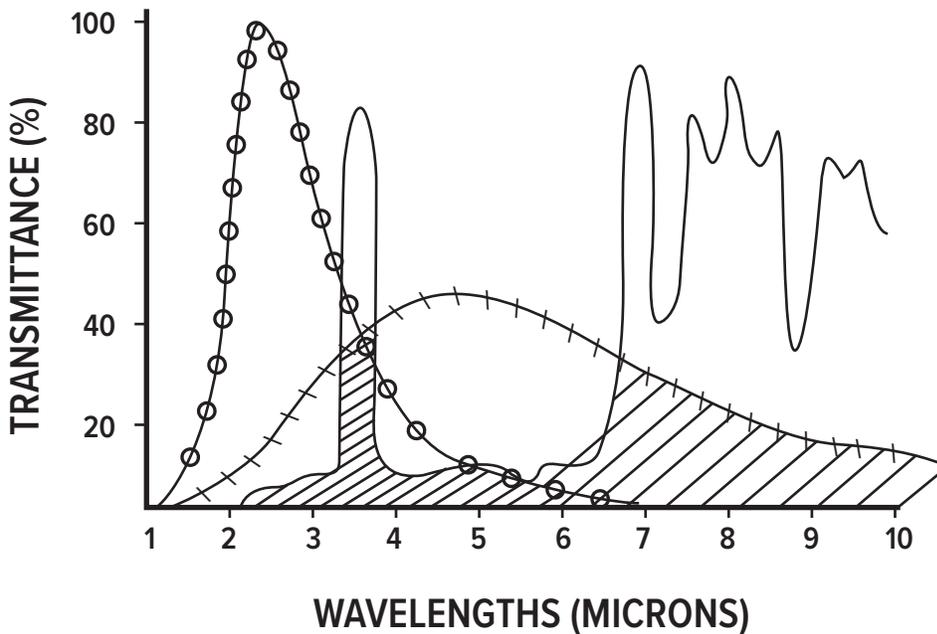


Fig. 11



- Spectral absorption of a typical plastic
- Spectral emission of 1800° F electrical heat source
- ++++— Spectral emission of 750° F catalytic heater

Note: The 750° F catalytic heater has more absorption area than the 1800° F heat sources

Figure 11 shows the energy absorbed by a typical amorphous plastic at various wavelengths. See Figure 11. This is a commercial for catalytic gas heaters but it depicts what we are trying to explain. The solid line is the percent of radiant energy absorbed by a typical plastic at various wavelengths. At this point we should state that energy is either absorbed in the plastic, transmitted through the plastic, or reflected off of the plastic. As you can see in Figure 11, at various wavelengths, plastic is either efficient or inefficient at absorbing this energy. And as we indicated earlier, wavelengths are measured in microns of which the greatest absorption is between six and ten microns with a very sharp and narrow absorption point at about 3.7 microns. Since only energy that is absorbed will be useful in heating up the plastic, the more area we can get under the plastic absorption curve the more efficient a heater will heat up a piece of plastic. Emissivity is also important. A black body will absorb 100% of the radiant energy exposed to it

and the emissivity would be 1.0. 0 emissivity would be 100% reflectance and no radiant energy would be absorbed. A prime example would be a chrome bumper. It has close to 100% reflectivity. Plastic has a normal emissivity of about .95 depending on color. Whites are slightly less and blacks are slightly more. So if we could find an energy wavelength point where the absorption would be 100% we could get a heating efficiency of approximately 95%. I hate to bust your bubble but no such heating energy source exists. Nothing even comes close. Certainly not a calrod.

Somewhere between 750°F and 850°F we get the best wavelength from a calrod. At higher temperatures the wavelength shortens up and the amount of radiant energy absorbed in the plastic decreases but the amount of convection heat available increases. You win some and you lose some! If the calrods were very close together, say one-half inch apart, you ran them at the 800°F

temperature, and they were about seven inches from the plastic, your oven would be as efficient as you could expect it to be. Who could afford and oven like this and the operating cost involved? So, what indeed happens in the real world is a compromise between radiant heat absorption and convection heat output balancing out as best as possible. If the calrod is run at maximum output, it will glow very red with the energy curve moving way to the left, say at about 1.2 microns and almost no radiant energy will be absorbed. But OH WHAT convection heat. Here is where

we get to scorch the surface of the plastic and decrease the physical properties. Who has more fun than thermoformers? There are elements that are more efficient but at a price. We will address them in turn. If a calrod element is operated at about 800°F, the wavelengths given off will vary more and cover more of the absorption range of the plastic. However, if it is operated at about 1300°F, the percentage of absorption will be high through a very narrow range and will likely not cover as much of the absorption range of the plastic. The circled line in Figure 11 shows this more clearly.

CERAMIC ELEMENTS

A second type of heater that is quite popular is the CERAMIC heating element. This is my favorite type of heater. These types of heaters are about two and three quarters of an inch wide and about eleven inches long. They can be grouped in a number of patterns but are normally grouped in sets of two or three elements with about an inch of space

between them. As the name indicates, they are made with a resistance wire trapped within a ceramic shell. When a current is sent through the wire, the wire heats up and subsequently heats up the ceramic body, and as in the case with the calrod gives off both convection and radiant heat. The difference is the space between the heaters. They are quite close together and much more radiant energy is given off per square foot of oven space. It should also be noted that they operate most efficiently at about 50% and about seven to eight inches away from the plastic sheet, just as the calrod. This is where they give off the wavelength of radiant energy that gets the maximum amount of energy absorbed into the plastic. Obviously this requires more elements in the oven and the cost of the oven will be greater. However, since the efficiency will be dramatically improved, the actual cost of operating the oven in terms of power usage and expense will be normally reduced by about 25% over a calrod oven. So there is an eventual payback.

Because there are more elements in the oven, we are going to need more heating element switches. This is usually accomplished by using a computer controller with solid state relays that operate on a percentage of power output basis. This too adds to the expense of the oven but at some huge gains. This allows you to bank the elements into small groups of two or three elements controlled by a computer. Since these types

of relays have a far superior life expectancy, we can afford to use a lot more of them. Obviously our total control of the element heat is much better and the size of the individual heating zone is much smaller enabling us to control heat inputs into given areas much better. Screening is rarely required and if you need to keep some small given area cooler or hotter to get a better part you can do so. Since we are controlling the heating elements with a computer, we can put the entire oven heating profile on a screen and make subtle changes and view exactly what areas we are affecting. This is a tremendous benefit in time and process efficiency. However, just as with the calrod oven, we have to extend the heating elements about six inches beyond the maximum sized sheet you can process. This is true for all type of heating elements.

As we indicated above, the most efficient distance the elements can be placed from the sheet is about seven to eight inches. This is fine for the top oven elements but what do we do about the bottom. On some of the newer machines, a feature is being built into the oven whereby you can raise or lower the element distance from the sheet in just seconds. Thus if you have a material that sags a quite a bit during the heating cycle, you can adjust the oven down. If the material does not sag much or the sheet surface area is small and not much sagging occurs, you can adjust the oven to be closer to the sheet and heat it more efficiently. To accommodate these materials, this feature is usually added when ceramic ovens are used on the bottom. The whole thing boils down to control. Ceramic heaters produce the most efficient type of heat known to heat plastic sheet but also allows you to make the most finite temperature adjustments in the smallest areas. Complicated parts can be produced more easily.

BLACK PANEL HEATERS

A third type of heater that is frequently used in thermoforming is the BLACK PANEL HEATER. Basically they consist of a resistance wire imbedded in a routed out ceramic fiber refractory board and covered with a black panel quartz or glass plate to give off radiant and convective heat. This is my second preference in heat. Quite honestly, they are just as efficient as ceramic heaters. The only drawback is they are much larger and it is not possible to control as small of an area with respect to zones. The smallest heater available is one foot square and each heater does require a separate temperature controller. With the advent of solid state relays and computer controllers, this is not much of a problem. However, grouping elements together does not make much sense. They are already quite large and cover a significant area in the oven. As with the case of ceramic heaters, it is very easy to get an oven

heat profile when a computer controller is used.

These heaters operate very similar to ceramic heaters. The optimum temperature is somewhere close to 800°F where the maximum amount of radiant energy is absorbed. It is also apropos to have the heaters about seven to eight inches from the sheet you are going to heat. Each panel is butted together in such a way that there is very little area in the oven that is not covered. Hence they are quite efficient just like ceramic heaters. The really nice thing about these heaters is they are not likely to be destroyed if you were to accidentally drop a sheet on them. However, they will start a fire just like any other element when they are hot. If you do burn up a sheet, they are easier to clean. If you are just looking for productivity and don't need real tight zone control, this may be your heater of choice.

CATALYTIC GAS

In the last few years this has become a reasonably popular choice of heating element for heating plastic sheet. This is not an open flame as you might imagine. Natural gas or propane enters a gas tight heater pan and is dispersed through a preheated catalyst pad. At the same time, oxygen passes into the pad from the other end. When the oxygen and gas meet, oxidation occurs below the temperature of the flame ignition temperature of the gas. Thus radiant energy is given off along with convection heat. The initial ignition is done with an electric pilot. To make this work, it is necessary to have a gas regulator and feed for each panel that you have in the oven. This will be an automatic incentive to reduce the amount of panels and increase their size. The smallest panels are usually one foot square but normally they are one foot by three, four, or five feet.

When you run the temperatures of these panels to the low side, there will be a tendency to not completely fill the panel with gas and oxygen and you may get cold or dead areas. Typically when you run these heaters on the low end, they operate at about 600°F to 650°F. On the high end they operate from about 850°F to 900°F. When you are on the low end and the panels do not fill, these dead areas will be about 350° to 400°F. The top heaters are normally placed from seven to ten inches from the actual sheet. This is ideal because the radiant energy given off at a temperature of about 750° F is

optimal as far as absorption is concerned. However, when these dead areas are large enough and these

elements are that close to the sheet, you will have trouble heating sensitive materials as there will be some cold spots that steel material from hot spots when you are trying to thermoform the sheet. Fortunately the bottom heaters are further away from the sheet and this affect will be less severe with them even if you have dead spots. Well you say, why don't you just turn up the heat all the way so the panels totally fill? This is great for olefin materials but on many amorphous materials this does not work. They cannot take full heat and will scorch and/or loose properties. You may also go through the forming range too quickly and not be able to form a good part. Some materials are not possible to process at all with these heaters, as you cannot turn them down to a low enough heat. This is particularly true when you run laminates that require different forming temperatures on each side of the sheet. So, for sensitive materials it is mandatory that maintenance be kept up on these heaters to assure that you will not have any dead spots at the lower temperature ranges. When gas heaters are maintained properly they are very efficient for the same reasons given with ceramic and solar panel heaters. Heating cycles are as short as one could expect and the fact that there is very little gap between the heaters equates them to ceramic and

solar panels. The huge plus for these heaters is the energy cost of operation. It is not uncommon to be about a third of the cost of operating a calrod heating system and about two-thirds the cost of ceramic

system. The big concern is the initial cost of installing this system and the maintenance necessary to make sure they are functioning properly. You just have to weigh the pluses and minuses.

QUARTZ HEATERS

This is another fairly popular heating element for thermoforming ovens. There are two types. One is a 'white light quartz' heater, which is merely a transparent quartz tube with a heating element running through it that is under vacuum. These heaters glow with an extremely hot almost white light. They are either totally on or totally off and give off a temperature of 1200° to 1400°F. This is an extremely short wavelength and is not good for radiant energy absorption for plastics. Most of the heat is convection and very harsh. We do not recommend this element for thermoforming. They were used pretty extensively fifteen to twenty years ago but have fallen out of favor. They are also pretty fragile. This may have been an additional reason for their demise.

The other type of quartz heater is a quite a bit more popular although not as much as some of the above heaters. They consist of about a one-half to a three-quarter inch diameter tube with a resistance wire inside of it backed up by an internal reflector. These heaters do not glow white as the above heaters but have more of an amber glow to them. Thus the wavelength of the radiant energy is more medium range and is more effective than the above quartz element. It is also possible to control them with timers or solid state relays so that the temperature can

be adjusted up or down. This allows you to get the radiant energy wavelength to the most efficient it can be for this type of element.

These types of elements are also fairly easy to zone. Quite often you see three or four elements about a foot long banked as a group about four inches apart. The result is an area of about twelve inches by sixteen inches that is controlled by one heater bank. Thus,

your oven control can be similar to ceramic or solar panel heaters. The slight decrease in efficiency comes from the fact that the elements are about four inches apart and there isn't as much radiant energy given off. In other instances, these types of elements are installed as four to six foot long tubes, similar to calrod elements, with three to four elements on a single controller. Obviously this does not afford as much oven control as the smaller banks. It does require fewer relay switches and therefore cuts the cost of oven construction. However, you are right back where you started in the sense that you have less oven control in heating the sheet. There are constant trade-offs that need to be made in terms of cost or efficiency.

NICHROME WIRE

Nichrome wire is another type of heater that is used in the industry. It is especially popular with people that are involved in thermoforming signs. If the part is reasonably simple, these people often opt for single sided heaters that are made of nichrome wire. Why, because it is inexpensive to make an oven with nichrome wire. It is essentially toaster wire that is spaced about four inches apart with 220 or 440 volts of electricity sent through it. It is basically a resistance wire and is coiled up like a thin spring.

These wires are usually attached to an on and off timer just as a calrod element would be and the electricity is on for a period of time and off for a period of time. The difference between a calrod and nichrome wire is the length of glow. When a calrod

is on this kind of a timer, the mass of the element will cause it to hold a reasonably consistent temperature. When the same kind of a timer is used for nichrome wire, the nichrome wire responds almost instantly and goes to a red glow. When the timer is off, the wire cools off very quickly and loses its red glow. The wire does not have enough mass to hold the heat.

This causes two issues. First, when the timer is on, the element glows red and the wavelength is not at the optimum temperature for heating the plastic. Most of the heat used is convection heat. Second, there are short periods when the elements are cooling off dramatically compared to other heaters and almost no heat is given off. This makes them less efficient than some of the other heaters. Typically

they burn out more easily and will require more frequent replacement. Why? Because the element is completely exposed to the air and therefore

deterioration will occur more quickly. All this said, there are still a lot of machines out there with nichrome wire heaters.

OPEN FLAME GAS

This is still used as a heat source in forming plastic sheet and can be a reasonable method for this purpose. If the open flame is very controllable in terms of BTU output and the heaters are positioned well so there are no heating gaps, they can work OK. I have seen them employed at good forming houses. Their primary benefit is economy. They are just as economical to operate as catalytic gas and are less costly to install.

The problem is much of the time they are not installed correctly and they are not maintained properly. You can look at the elements and see hot spots and misalignment. This can be more counterproductive than useful. There is also a

problem with control. In many cases, it is just not finite enough. This type of heating source has largely come out of favor, especially with the advent of catalytic gas heaters. I personally am not a big fan of these heaters but I know some good forming houses that are quite successful with them. There are some plastic materials that just do not respond well to this type of heat. Some materials need to be heated very slowly and it is not possible to turn these types of heaters lower than a certain level. Also, if you need to employ significantly less heat to one side of the sheet as opposed to the other, you have the same problem. Versatility is not the by-word here. Careful thought needs to be given to measure economy versus utility and versatility.

AIR CONVECTION OVENS

This is an often-neglected type of heat source for thermoforming plastic sheet. The normal mind-set is that you need some kind of a machine with a heating source to form plastic sheet. This is not necessarily so. All you really need is a box with a uniform heat source and a method of hanging the sheet in the box. Next you set the 'oven' at the normal forming temperature of the sheet, put it into the 'oven' for ten to fifteen minutes, depending on the thickness, pull it out of the 'oven' and form it over a mold connected to a vacuum line. There are certain parts that can be hand formed better than any machine could ever do. The largest thermoforming job I have ever witnessed

was done by hand forming with multiple molds.

The benefit here is a uniform gentle heat. Because the heat is all convection heat, it is very easy to keep gloss levels low and consistent. It is also a great method of prototyping. It certainly is not preferred over most machine operations but it is an option. Some things such as foam core materials are best formed via this type of heat. If you have wet stock, it will have the best chance of running this way. How often do you here of moisture blistering out of an air convection oven? It can happen but it is rare.

PRE-DRYING MATERIAL

This gives us a good segue into another phenomenon that is very important in processing plastics, pre-drying plastic sheet. Most amorphous plastics are hygroscopic and will absorb atmospheric moisture over time even if they are packaged well. This will cause them to process poorly in the thermoforming process and will result in a substantial loss in physical properties. It could also result in poor material distribution on the finished part or uneven flow during the actual forming technique being employed. If the material is used fairly quickly after extrusion, most likely it will process OK, with

the exception of polycarbonate which will absorb moisture almost immediately even if protected. So if the material is used on a timely fashion, everything will go well and life will be good.

However, in the real world, all does not flow smoothly. Very likely these materials will set around in relatively humid conditions and absorb moisture that will prevent you from processing them properly. This moisture must be driven off. Various materials will absorb moisture at various rates and various amounts, but if left in severe enough conditions,

most of them, with the exception of the olefinics, will need to be dried. This will have to be done at various times and temperatures depending on the heat distortion points of the specific plastics involved. As an example, ABS can absorb up to .2% of moisture and in order to thermoform it properly, you must get that moisture content down to less than .1% but preferably down to .07%.

We have included a chart for the required drying times for polycarbonate and ABS at specific thicknesses. See table 2. Generally speaking, polycarbonate resin suppliers will suggest oven-drying temperatures of 250°F. For ABS the suggested temperatures are between 180°F to 200°F. I am a little bit wary of the 250° F for the polycarbonate because if the sheet is extremely saturated with moisture, running it through the vaporization point of water too quickly could cause some microscopic fracturing of the surface finish. I am more prone to use 220°F to

230°F even though it may extend the drying a little beyond the suggested time on the drying table.

Space does not allow us to list all materials and their drying times and temperatures but you can contact your material supplier for this information. We only listed polycarbonate and ABS because they are so prevalent and are likely to need drying.

It should be noted that more efficient drying would occur in an oven that allows some of the moisture that is evaporated off the sheet to escape from the oven. There are a lot of oven manufacturers out there that have designed their ovens to make this happen. It is not that complicated. You are just trying to bring in air that has a propensity to hold more moisture at higher temperatures and get rid of air that has already increased in relative humidity. You can even build your own oven if you are mechanically resourceful.

POLYCARBONATE		ABS	
Sheet Thickness in Inches	Drying Time	Sheet Thickness in Inches	Drying Time
.020	20 Minutes	.040	4 Hours
.030	45 Minutes	.060	5 Hours
.040	1 Hour	.090	6 Hours
.060	2 Hours	.125	8 Hours
.090	4 Hours	.187	12 Hours
.125	8 Hours	.250	16 Hours
.187	14 Hours	.375	24 Hours
.250	24 Hours		

SCREENING

Screening is a viable and often necessary process in thermoforming. However, it is getting to be a lost art. Why? Well, vacuum forming machines are getting more and more sophisticated, and because of excellent zoning and efficient heating elements, it is not required as often as it was in the past.

Screening is nothing more than taking a piece of window screen and placing it over some heating elements in a certain area to screen out some heat. This will cause the plastic to be slightly cooler in the screened area and therefore when the material is stretched over the tool, the area that is slightly hotter will allow the material to thin out a little more than the area that is a little cooler. Any number of screens can be placed in a given area to screen out more or less heat.

Why is this necessary? If you have a machine with a minimum of heating zones, each zone will cover a quite large area. Since all the heat in this area will be approximately the same, we need a method of limiting the heat to a certain small area. Sometimes it is necessary to keep the center of the blank cooler, as the natural sag of the material will cause the center of the blank to get closer to the elements and become excessively hot. Since the clamp frame around the periphery of the sheet will act as a heat sink, it may be necessary to keep the center of the sheet cooler to keep the whole thing uniform. At any rate, screening allows us to do all of these things when the thermoforming machine is not capable of this type of heat differentiation.

CYCLES

The speed at which we can process various materials is always important to the thermoformer. This speed is largely dependent on the type of material you are processing, the thickness of the material you are using, the type of heating elements you are using in your thermoforming machine, and the integrity and efficiency of the machine itself. Table 3 shows some machine cycles of three common materials using a single station machine and a rotary thermoformer. These cycles assume you will be using temperature-controlled tooling.

If temperature controlled tooling is not used, the machine cycles shown on table 2 don't mean anything. On a single station machine, an epoxy mold will yield approximately 30% fewer parts. However, if an epoxy mold is used on a rotary machine, you

will not get 30% less parts than you get with a temperature controlled mold on this machine, but you will get the same 30% less parts you get on the single station machine. The reason for this is the mold will simply not handle any more parts than is capable of being made on a single station machine. It is all a matter of cooling. An epoxy mold simply cannot take away any more heat than a certain amount. If you have a large amount of parts to make, it just makes sense to get temperature controlled tooling even if it is three to four times as expensive. Usually I like to make the cut off at 3000 parts per year. At a 30% difference in productivity, temperature controlled tooling will get you 3000 parts while you run 2000 parts with an epoxy tool. The result is you have 30% more time that is freed up to run other production.

MACHINE CYCLES			
ROTARY	CYCLES PER HOUR		
Gauge	ABS	Polyethylene	Styrene
.062	50	38	60
.093	40	30	48
.125	30	23	36
.156	25	19	30
.187	20	15	24
.219	19	14	22
.250	18	13	21
.312	15	10	17
.375	12	9	14

SINGLE STATION	CYCLES PER HOUR		
Gauge	ABS	Polyethylene	Styrene
.062	30	23	35
.093	24	18	28
.125	18	14	21
.156	15	11	17
.187	12	9	14
.219	11	8	13
.250	10	7	12
.312	9	6	10
.375	7	5	8

Notes:

1. The above rates reflect times for the average forming job, using machines with ovens of average efficiency. Highly efficient ovens will improve on the above slightly. The above rates also reflect temperature controlled aluminum tooling.
2. Epoxy molds—Use above rates less 30%.
3. Wood molds—Use above rates less 60%.
4. Other materials may require more or less time than the materials above.

MATERIALS

This is the fourth major component of what we consider is important in making a successful part. It is important from a number of perspectives. First, does the material meet the physical characteristics of what we might call “field function?” Secondly, does the material possess processing characteristics that allow you to make the part? Third, can the material be made physically by the extruder in terms of gauge, size, flow characteristics, etc so that the vacuum former can actually get the material?

Fourth, what are the long-term effects of the environment on the material? And finally, does the material allow you to meet the tolerances and consistency required to process it effectively? Let us address these issues and determine where different materials might be appropriate.

All materials possess characteristics that we describe as physical properties. In the plastics industry we have devised a way of testing these materials to provide a clue as to what might happen when they are used in a particular application. The ASTM (American Standard Test Methods) is a governing body that oversees testing methods that measure these properties to give you an idea if a material is feasible for an application. Here are some general characteristics we are likely to be concerned about when selecting a specific plastic for a specific application. Specific gravity (how much something weights compared to the weight of water and to each other). Impact strength (how much abuse can the material take before it breaks). Stiffness (measuring one material as compared to another in terms of relative stiffness). Hardness (what is the materials resistance to abrasion, chipping or cracking). Heat Deflection (at what temperature can the material be exposed to before it distorts). Thermal Conductivity (how much heat can be conducted through the material). Coefficient

of Thermal Expansion (how much something expands or contracts in a given temperature). Chemical Resistance (what chemicals affect it and how much). Flammability (does the substance burn or not). Mold Shrinkage (how much a plastic shrinks after it is demolded). Forming Range (what temperature a plastic can be processed) etc. These are all characteristics that affect how a product will perform in a given application.

Well you say, just give me maximum properties in each category and I'll be covered. Not so fast my good kitchen chemist friend! It is not that simple. Almost all of these physical properties are in direct conflict with at least one other property. Let's take impact strength as an example. Suppose we want to obtain the maximum possible impact on ABS material. This would give you a notched izod of about 12 foot pounds. To do this we will have to load up the formula with a high amount of rubber. This will give you the impact strength you want but it will automatically make the material less stiff and softer. It will not chip and crack as easy but it will scratch and abrade much easier. It is also likely that the heat distortion temperature will be slightly reduced and you will have to make the part thicker to maintain the same stiffness. Thus you see there are always trade-offs.

It is also notable that different materials give you vastly different physical properties when compared to each other. Consequently, we have a variety of materials that are available for thermoforming and it is proper that care be exercised in selecting a material that will be the most appropriate one in terms of function and cost for a specific application. We will review a number of these materials and give you some of the pluses and minuses for each specific material in regard to function and application.

POLYSTYRENE

This is one of the most ubiquitous plastics you will ever run into. Polystyrene is the result of polymerizing the styrene monomer into a long polystyrene chain. This gives us a clear plastic that is very moldable by a number of molding methods (that is, injection molding, blow molding, and thermoforming). The big pluses are that it is relatively cheap and quite easy to process. Witness

all the plastic throw-a-way cups that you see. This material is ideal for this application. The material is clear so you can see what you have in the cup and the heat distortion of the material is about 200° Fahrenheit so you will be able to hold any liquid that you could possible drink. However, observe how easy it is to crush a polystyrene cup. It cracks very easily without much effort at all. So it is not

feasible to use this material to make a shell for a musical instrument case where it would likely take substantial abuse. Polystyrene is a throwaway type material or a material to be used in more decorative

applications as opposed to functional applications. It is also reprocessible and if kept clean, can be used in any number of other things such as toys.

HIPS

HIPS is better known as High Impact Polystyrene and is a hybrid of polystyrene. By adding a little rubber to polystyrene we get a material that is a little more resistant to cracking and breaking but only marginally so. This does allow you to use it in numerous additional applications such as food containers, window shutters, picture frames, shower walls, refrigerator shelves, etc. The addition of the rubber to the formula does increase the impact properties of the HIPS but at a cost. The material is no longer clear. So to make the material more functional you have given up something, namely clarity. As a rule this is of no consequence. We just

pointed it out to confirm a previous statement that changing the physical properties of a material does require you to make choices or trade-offs with other physical characteristics. Although quite useful for numerous applications, HIPS does not provide properties that are useful in physically abusive applications. It is, however, a very user-friendly material. It is quite often said that if you can't form the material out of HIPS, it either can't be formed at all or you thoroughly don't know what you are doing in regards to thermoforming. This brings us to the next material on the food chain.

POLYETHYLENE

Polyethylene is a completely different chemistry in regards to plastic. It is a crystalline material made by polymerizing the ethylene monomer into long chains. There are numerous varieties of polyethylene from Low Density Polyethylene to Linear Low Density Polyethylene to High Density Polyethylene to High Molecular Weight High Density Polyethylene. They all have somewhat different properties but do have a few characteristics in common. They are all quite chemically resistant and are highly resistant to impact and are fairly economical. The downside is the cosmetic deficiencies of these products along with their dimensional stability. If you need a part that requires reasonably tight tolerances in regard to size or shape this is not your material. The typical applications would be tote bins, truck bed liners, pallets, feed bins, tanks, etc. As you can see, all of these applications require the material to take a good deal of abuse but do not require high dimensional tolerances or cosmetic perfection. There are literally hundreds of applications that these materials are suited for. It should be noted that these materials are not necessarily UV stable for outdoor applications. However, all of them can be made that way by providing them with a chemical additive that will protect them from the environment for some period of time.

Thermoforming polyethylene is a different matter. If you normally only form HIPS or ABS parts, you are in for a real shock when proceed to form polyethylene parts. It requires a good deal of thought when designing the mold and selecting the thermoforming technique to make the part. Polyethylene is very sensitive to cooling stresses and in almost all cases you should have a temperature-controlled mold to make the part. Is this more expensive? Yes, of course, but there are a lot of people out there who regretted their decision to cut this corner. When you are considering producing a polyethylene part, you should strongly consider these three factors. Invest in a temperature-controlled tool, get the finished tool sandblasted, and have a moat put around the edge of the tool flange.

The reason is simple. As I indicated, polyethylene is very sensitive to cooling stresses. Secondly, polyethylene has high mold shrinkage. (That is the amount of shrinkage the part goes through after it is removed from the tool). Typically it is about .022 to .030 inches per inch. Thus while it is cooling, there will be a strong tendency for the plastic to shrink and break the vacuum seal on the mold. The addition of the moat will give you multiple sealing edges and help resist this tendency. The sandblasted surface will help the plastic to maintain a better contact to the mold surface to help you get more consistent

cooling. Even though polyethylene can give you some interesting processing experiences, it should not be shied away from. It has some marvelous

physical properties that are extremely useful in some products.

POYLPROPYLENE

This is a material that is similar to polyethylene in its properties. It too is crystalline in nature but is made by polymerizing the propylene monomer. The real difference here is the stiffness of the material, the living hinge characteristic of the material and the slightly

lighter weight. It is even harder to process using the thermoforming processing system, but as with polyethylene it has some physical characteristics that are only attainable with this material. So don't give up on it. For this reason, it is often sold as a copolymer in conjunction with polyethylene. This makes processing it slightly easier. It is much more widely used in injection molding than in thermoforming. Some typical applications for vacuum forming are tool cases with living hinges built into them, acid tanks, food containers, etc.

It has the same dimensional stability problem polyethylene has but it does have a high heat distortion point and is stiffer, so there are some situations where it is preferred.

The above materials are all thought of as more or less commodity type materials. That is, you can get them from one manufacturer as well as another and they will essentially be the same. This is not totally true but is reasonably accurate. Thus they are pretty price sensitive and unless you are looking for specific physical properties one high density polyethylene can be substituted for another just as one styrene material can be substituted for another. So let us get into an area where physical properties have a much higher priority. This is the class of plastics generally known as engineered plastics. The most common of these is ABS.

ABS

ABS is another ubiquitous term to plastics. It stands for Acrylonitrile Butadiene Styrene which are the three components that make up ABS. As an engineered plastic, the physical properties of this material are generally superior across the board. So what do we mean by an engineered plastic? (In some circles ABS is not considered an engineered plastic) Generally speaking an engineered plastic is not a simple polymerized polymer. It is a combination of a number of polymers that are mixed together to get specific types of physical properties or to optimize certain properties. This can be done right at the chemical reactor in the manufacturing of the resin or it can be physically mixed this way in a banbury mixing operation where the various ingredients are forced mixed together.

Why would we do all this? Well, we can custom make a resin to have the optimum physical characteristics we are looking for. This includes price! Suppose HIPS does not meet the physical requirements necessary for a specific product but high impact ABS is an over specification. After all, high impact ABS is more expensive than medium or low impact ABS. We can compound a material that

meets the requirements necessary and keeps the price as economical as possible. A perfect example is refrigerator door panel material. This is usually a low impact ABS material that is at least twice as impact resistant as HIPS and perfectly adequate for this application. Another example might be musical instrument cases. These cases really get a lot of abuse and it makes good sense to make them out of some high impact ABS material. There are literally dozens of grades of ABS's with different combinations of physical properties that meet all kinds of physical requirements. New kinds of combinations are being engineered all the time.

ABS's are used in a myriad of products. Some examples are bath tubs, cases of all types, RV fenders, instrument panels on buses, and literally thousands of other parts. However, it is mandatory that before you select a specific ABS, you should know the environment in which it is going to be used. For instance, if this is an outdoor application, you must protect the surface of the plastic from the UV rays of the sun by putting a protective coating on the plastic. If ABS is exposed to direct harsh sunlight such as in Florida without UV protection, it is not

likely to last six months before losing most of its impact properties. Typically this is accomplished by putting a protective cap layer over the ABS. If you are going to expose the material to an environment where temperatures reach 200° Fahrenheit, it is

wise to select an ABS that will tolerate this type of heat. So match the type of ABS to product requirements. ABS is a fine product and there are a lot of fine ABS materials out there.

PVC

PVC is an acronym for Polyvinyl Chloride. It is not really an engineered plastic but in the realm of thermoforming it is kind of considered an engineered plastic. This is primarily because it is a little more difficult to process PVC using the thermoforming process than it is to process some of the other materials such as ABS or Styrene. When you heat PVC up to a thermoforming temperature, this material softens up dramatically and some of its hot strength is lost, especially when it is slightly overheated. So what does that mean? Well, essentially when you heat plastic sheets within the parameters of a clamp frame, they will sag. Even in its hot state, when you prestretch a material with a vacuum, it will have some memory to shrink or stretch back when you release the vacuum. Thus the sag will lessen somewhat. If the material has poor hot strength, not only will it sag considerably more, but it will have much less tendency to stretch back when the vacuum is released in its hot state before it is actually formed into a mold. Well, PVC does not possess nearly the hot strength as ABS. Consequently, if you have parts with fairly large areas with shallow draws, you may have difficulty getting rid of the excess material to prevent webbing. Hot strength is a much-ignored phenomenon in the extrusion and thermoforming industry.

With all these potential issues, why would someone persist in using PVC as a forming material? Well, as it turns out, PVC has a number of physical properties that make it attractive as a material of choice for some products. First of all, it is one of the most chemical resistant of all amorphous materials. Although not as chemically resistant as the olefins, it is much more chemically resistant than materials such as polycarbonates or ABS's. They are also more resistant to staining. Secondly, PVC is stiffer than ABS and it is much less notch sensitive than ABS or polycarbonate. It also has very high room temperature impacts. So there are applications where PVC would be a much-preferred material over the other two. Although it would not be recommended as an outdoor product without the UV additive, it is somewhat UV resistant in its natural state. The same can be said for flame resistance. You could not recommend it for this application without adding a flame inhibitor, but it is somewhat naturally flame resistant. It can also be a very cosmetic product.

Some applications are bathtubs, shower surrounds, moldings, kick panels, display cases and numerous other applications where cosmetics and durability are required. This material has its place in the plastics industry but it is more often used in combinations with other materials to make up plastic alloys.

PVC/ABS

This is the first of the plastic alloys we want to discuss. It is just what the acronym describes, a combination of PVC and ABS in various proportions, usually with a flame retardant added to it. Depending on what physical properties you are trying to achieve will dictate just what these proportions are. So what are the advantages of a material like this? First of all, if it is compounded right, it is an extremely user friendly material. The hot strength and formability of this material are excellent. If a part is formable with a flame-retardant material, this is the material that will get the job

done. Secondly, this material is very cosmetic and because of its flow characteristics, it really lends itself well to the pressure forming process. Many of the most esthetically pleasing parts produced through pressure forming are made of this material. It takes an impression off of a textured tool better than most any material you can get. A third plus is the dimensional stability of the material after it is formed. Provided you form it and demold it at the same temperature consistently, it will hold the tightest tolerances on a part for part basis. And it is flame-resistant meeting most UL requirements.

Sounds like this material is the best thing since 'sliced bread'. Well, it is a premium material with excellent all around physical properties but no material is a panacea. Because it is an alloy, it is not as stiff as straight PVC. It also does not have a heat distortion point as high as ABS, but it is higher than PVC. Remember what we said about trade-offs. When you get something, you give something. Generally speaking though, this material has more all around pluses on physical characteristics than most.

This alloy is used in more various applications that are highly cosmetic than most materials I can

think of. Some classical examples are electronic housings, medical equipment covers, aircraft, mass transportation, decorative fascia, and a whole host of other products. It can be made suitable for outdoor applications by adding the UV protective cap and as with most amorphous plastics, it can be silk-screened, painted or partially painted, and solvent or mechanically bonded. It is especially amenable to EMI shielding without giving up much of its impact strength. Both the end product user and the processor should be very comfortable with this product.

PVC/ACRYLIC

This is another very good alloy product and as the wording suggests, it is a combination of various proportions of PVC and Acrylic usually with a flame inhibitor added. Again, depending what physical properties you wish to attain will dictate what additives you will

use and what proportions of PVC to Acrylic will be appropriate. Depending on how it is compounded, it too is usually a very user-friendly material. However, here is where customizing the physical properties of a material to a specific niche market or product comes heavily into play. This general alloy is altered in more ways to meet a specific requirement than any material I can think of. For instance, with the flame resistant inhibitor in it, it is more flame resistant at lower gauges than most any other flame resistant plastics available. There are formulas of this alloy available that meet specific UMPTA guidelines for mass transportation. For instance, when general grades of ABS plastics burn, they give off a black smoke. This is unacceptable to a person trying to get out of a subway car when you have a fire as it gets kind of tough to see through black smoke. Well since we can't get rid of smoke when something burns, specific grades of this alloy are compounded in such a fashion as to give off a light smoke that you can partially see through enough to get to an exit. Is this clever or what? The aircraft industry has a different idea as to what a flame resistant material should be. They prefer to have a smoke suppressant in the formula to limit the amount of smoke that is given off when the material burns.

This brings up another point. Everything burns, even steel if you get it hot enough. The point is a flame resistant material will stop burning when the material supporting combustion is removed. A flame resistant

plastic in and of itself will not support combustion. However, the base resins used in these formulas will usually burn quite readily. The chemical mechanisms that are employed in these formulas are what suppress this burning. There are a number of these mechanisms available, but this is not really the place to discuss them. Suffice it to say, they work.

Some other favorable physical characteristics that are indigenous to this alloy are high impact resistance and good chemical resistance. The notched izod room temperature impacts are around 15 foot pounds. This is really high. However, the cold temperature impacts (-20° Fahrenheit) are only so-so, around one foot-pound. In regards to chemical and stain resistance, this is probably the best material available outside of the olefins. It is also a very stiff material for a plastic and sometimes you can down gauge your part and still get adequate structural feel. Does it have any drawbacks? Yes, of course. The heat distortion on this material is none too good, somewhere between 155° and 170° Fahrenheit depending on how the material is compounded. This can sometimes be a problem when it is used in helicopter interiors.

There are a lot of good uses for this product though. This is especially true since you can tweak the formula in so many ways to meet certain specifications. Some product areas that come to mind again are, electronic housings, medical equipment covers, bathware, aircraft interiors, mass transportation parts, etc. As with the PVC/ABS alloy, this material can be capped with the UV protective coating to make it acceptable for outdoor use. This is a fine material and can be silk-screened, painted or glued just like the PVC/ABS alloy. There are a lot of pluses here so don't be afraid to use this product.

POLYCARBONATE

Although this is not an alloy material, it is considered to be an engineered plastic because of some of its unique physical characteristics. The most immediate characteristic that comes to mind is its clarity. It can be purchased as a perfectly clear material that you can see through just as well as standard window glass material. It is much less prone to fracturing or breaking. As a matter of fact, it is the material that is used in the bullet proof encasements that you see at gas stations that provide safety for an employee in the late hours of the evening. Among some of the other physical characteristics that make this material very useful is its toughness. It is commonly found in applications that receive a lot of physical abuse. Industrial guards and amusement game housings come to mind. It is also used extensively as lenses for eyeglasses.

This material can be made UV resistant and frequently it is used in these types of applications. Most of the skylights in houses and motels etc. are made from UV resistant polycarbonate. Because it is very stiff, you can even stand on these skylights although it is not suggested that you do so. Even though the material is quite hard, it may scratch and scuff more than glass and take away from its optical properties. This material also has a high heat distortion point, about 270° Fahrenheit. Obviously this is above the boiling point of water and so you can use it in areas where other plastics just don't make it. It is not limited to clear applications either. This material can be pigmented slightly to give a smoky effect to screen out bright sunlight or provide for privacy. We have all seen windows that you can effect see out of but not into. If you want to have an opaque material, you can do that too. There are lots of parts made from solidly pigmented polycarbonate.

POLYCARBONATE/ABS

Here is another good product, the poor man's polycarbonate. Just as the name suggests, it is a combination of polycarbonate resin mixed with ABS resin in various proportions to get physical properties that best match what are required in the end product. So what are these delightful compromises? The most obvious one and the one that grabs the most attention is cost. Although it is only slightly cheaper, it is cheaper. Another plus

Well, it sounds like this material is a panacea for plastics. Not exactly! It is very good but there are some properties and characteristics about polycarbonate that are not fantastic. The first such property is its chemical resistance. It is very sensitive to such things as oil and gasoline and a number of other harsh chemicals. That is not to say that plastics such as ABS are not sensitive too, but they are not quite as sensitive. However, there are thousands of applications where chemical sensitivity does not come into play. A second problem is the processability of polycarbonate. Because of its high heat distortion point and the sharp glass transition point, this material will normally require temperature controlled tooling to avoid chill marks. The one exception is the polycarbonate part that will be used for skylights. Since these parts are formed with entirely different forming techniques, this added expense can be avoided. Polycarbonate also requires drying before you use it in the thermoforming process. Since it is quite hydroscopic, it is necessary to get rid of this moisture or it will cause tiny blisters throughout the surface of the finished part and weaken its structural integrity. This brings us to the cost of the material. Sometimes this is an impediment in itself. Although not as expensive as some of the highly engineered plastics, it is definitely more expensive than ABS or ABS/PVC materials. Then again it does some things that these materials can't. So nothing is a panacea.

Polycarbonate is an extremely heavily used material in the injection-molding process for a myriad of products. It is not used as extensively in vacuum forming. Some of the more popular uses, as suggested, are for skylights. Additional uses are light covers, shrouds used on assemblies that are next to high heat sources, and parts requiring stiff walls. This material has some excellent qualities and should be utilized more.

is the heat distortion numbers. Although they are somewhat down from straight polycarbonate (270° Fahrenheit), they do have values of somewhere between 240° and 250° Fahrenheit as opposed to straight ABS with values of about 200° Fahrenheit, depending on how you compound the polycarbonate/ABS formula. Some other pluses are derived from the fact that this combination of resin holds much of its original stiffness and toughness.

The biggest plus, however, is the gain in processability. If indeed you thermoform this material reasonably soon after it has been extruded, you may not have to dry it to make it work at all. This is almost never true with straight polycarbonate. Since you have reduced the sharpness of the glass transition point and you do not have to heat the material quite as hot to make it form, you are less likely to get chill marks. This makes the material easier to form and you may not have to use a temperature-controlled mold depending on how difficult the geometry of the part is. The chemical resistance of the polycarbonate/ABS material is slightly improved and it can be formulated in such a way as to make it flame resistant too.

So what do we have here, another panacea? Nope! Just another good product to meet a number of

important physical properties. Although the chemical resistance is slightly improved over polycarbonate, it is nowhere near as good as the PVC/Acrylic material and you may still have to dry the material to form it if you let it lie around. Another thing you give up is clarity. Because of the ABS component, this product can no longer be made clear or even translucent.

Obviously this product has some limitations. That said, it is very useful in a lot of applications. Some of them are electronic housings where heat build up is an issue, flame resistant applications where free chlorine gas given off from PVC is a problem, situations where you need flame retardancy and high heat distortion, heat shields in electronic assemblies, etc. All in all, this too is a good product and should be considered in the product applications.

TPO

An acronym standing for thermoplastic olefin. Essentially what it is comprised of is a polypropylene resin in combination with an EPDM rubber. This EPDM rubber is an ethylene, propylene, diene monomer. The polypropylene is basically mixed with the EPDM rubber to get the TPO engineered plastic. This can either be done in a reactor or by physically mixing these components together. There you have it, everything you ever wanted to know about a TPO and were afraid to ask.

So why would we ever want to go through all this trouble? Well it turns out that TPO has some very interesting physical characteristics and these characteristics can be altered slightly or dramatically by changing the type of polypropylene and by putting various additives into the formula. Generally speaking though, the more highly sought after properties are the high impact strength, especially at cold temperatures, and the stiffness and heat distortion compared to other olefins. TPO's are virtually indistructive. Some of these formulas can be compounded in such a fashion that you get a no-break on a drop weight test at -50° Fahrenheit. Most plastics are past their embrittlement point at this temperature; that is, they will completely shatter if impacted or dropped. The stiffness of these compounds is increased by about 50% over other olefins and again through careful reformulation, you can get heat distortion points of 220° F. This is much higher than is normal for an olefin. Another interesting sidelight is the mold shrinkage values

you get. Normally on an olefin it is common to get values of about .022 to .030 inches per inch. On this material the mold shrinkage normally varies between .011 and .013 inches per inch. As a result, this material is more dimensionally stable on the mold and will warp less after it is demolded than other olefins.

As an added bonus it is paintable. This is the material that is becoming massively popular on car bumpers. To get paint to stick, you have to put certain additives into the formula and you have to first cover the part with a primer coat that is an adhesion promoter that is compatible with the additive. Then you can paint the part with any normal paint such as one that is urethane based. This material can also be made UV resistant, but it is better to go through the paint scenario above. And did we mention chemical resistance? Because this material is olefin based, it is an ideal material to be used where harsh chemicals, gas, oil, and other types of solvents come in contact with it.

However, just like other materials, it has its drawbacks. It is not what I would call a user-friendly material. It is easier to work with than regular copolymer polypropylene but not much. As is the case with copolymer polypropylene, to get it to its proper forming temperature will automatically cause it to sag a lot in the clamp frame and there is nothing you can do about it. Thus you can see if you have a part that is somewhere around three feet by three feet in dimension, the material in the clamp frame

will probably sag at least a foot. So if you have a relatively flat part with these dimensions you will very likely get webbing as there will be nowhere for the material to go. The material will not respond to snapback either. Once you draw it down into the vacuum box, it will just

stay there. It will not spring back when you release the vacuum and if you draw the material too deep into the vacuum box, you will again get webbing.

TPO has a lot of uses. As we just suggested, it is really gaining great favor in the use of car bumpers,

but it is not practical to thermoform this many parts. That requirement is best left to injection molders. However, bus bumpers make sense for thermoformers.

Some other uses are wheel wells on trucks, rock shields under vehicles, harsh chemical shields, gear covers, kick panels, etc. Let your imagination run away with you but don't forget about the processing restrictions you may have regarding part geometry. It's a great material, just use it where it fits.

CONDUCTIVES

Conductives are plastics that will actually conduct electricity. Don't get excited! You won't get electrocuted. They do not conduct electricity in the same fashion as copper wire. Normally plastics are non-conductive or what we might refer to as insulative. However, we can vary the range of conductivity in plastics from an insulative material to something that is considered totally conductive with a resistivity of ten to the minus fourth ohms per square. Wow, what does this all mean? Essentially it means that as long as the piece of plastic is grounded, it will not build up a static charge. Let me give you an example. In winter when the relative humidity is low, it is not uncommon for a person walking on a rug to build up a charge within their body. When you touch a doorknob, you experience a discharge of electricity from your body to the doorknob. If the shock you get is unpleasant, it is likely that the voltage of this discharge was somewhere around 4000 volts. This sounds like a lot, but the amperage was very low and because the air was very dry, the resistance or ohms was very low. Why doesn't this happen in the summer? Well in summer the air is more humid and the moisture surrounding your body does not allow enough voltage to build up within your body to force a discharge.

This is essentially what happens with a static dissipative plastic. The surfactant in the plastic attracts enough moisture so that an electric charge cannot build up on itself so that a discharge can occur. This is not the case with a conductive plastic. Conductive plastics actually conduct a small current that does not allow electricity to build up within itself. Because of the high resistivity, ten to the fourth or ten to the fifth ohm per square, the discharge is very mild and very slow. Typically the discharge time is about two hundreds of a second. This is light

years in electrical time. Thus if any charge comes in contact with the plastic, it is immediately discharged. If you are storing electrically sensitive materials in a conductive plastic box, the charge will never get to the parts in the box.

The common plastic materials that are made conductive are HIPS, ABS, ABS/PVC, HMWHDPE, ABS/HDPE, and straight PVC. We do this by putting a specific type of carbon fiber in a plastic matrix. As you might imagine, some of these materials run better than others, especially when they are loaded with these fibers. Generally speaking, it is necessary to run these materials at a hotter temperature during the vacuum forming process to maintain their conductivity. If the temperatures are too low, there will be stresses built up within the formed part and the carbon fiber contact will have gaps that cannot conduct electricity. Some materials like PVC do not like high temperatures during the forming process so a balance must be struck between maintaining conductivity and getting a good part. As a general rule, conductive materials do not form as well as non-conductive materials of the same kind so care should be taken not to attempt to form parts that are exceedingly difficult for these materials. We typically like to hold the draw ratios to below three to one.

Because of the high loading of carbon fibers to the plastic matrix, these materials do not have impact properties that are comparative to their normal bases. For instance, a typical ABS/PVC material may have room temperature izod impacts of about 7.5 foot pounds where a conductive ABS/PVC material may only have room temperature izod impacts of about 3 foot pounds. This is after adding impact modifiers. Other properties such as stiffness may change somewhat too.

The electronic age of computers with their use of sensitive microchips have made these materials necessary. If you store your expensive motherboards for your computer in non-conductive containers, simple handling on a conveyor belt will cause some of them to fry. This could get kind of

expensive not to mention frustrating for computer customers. The bottom line is, as computer chips have gotten smaller and more powerful, they have also gotten more sensitive to static charges. Conductive packaging along with handling containers is a requirement in this industry.

WEATHERABLE MATERIALS

As plastics have become more ubiquitous, they are being used more and more in outside applications. That means they will be exposed to the ultra-violet rays of the sun and break down. All things in nature are subject to entropy. Plastics are no exception. The ultra violet rays of the sun attack the carbon bonds in plastic polymers and break them up into shorter chains. This affects the physical properties of these plastics. A prime example of this phenomenon is seen with the olefins. Without some sort of protector, these materials will break down very quickly in the sunlight. Somehow we have to screen out the UV rays from the sun. In the case of the olefins, the best way to do this is to put a minimum of two percent of carbon black in the formula. This keeps the UV rays from getting to the carbon bonds but all plastic parts would be relegated to being black. This would make Henry Ford happy but the rest of us may get bored. So other screening agents need to be employed to allow for multiple colors to be available. Well as it turns out, there are a number of chemical compounds available that will do this, although not as well as carbon black. Typically these additives will preserve these olefins for about seven years in outside applications and this is normally sufficient. If not, you may need to consider other materials or go with Henry Ford black.

Then there are amorphous materials such as ABS or HIPS. They break down too from UV exposure. Again putting a heavy level of carbon black in the compound will abate this breakdown. However, because of the nature of these materials, the part is likely to fade into a charcoal gray color over time instead of black despite using black to color the parts. This gives us a unique problem. Additives to the plastic base do not seem to be effective in screening out these UV rays. In these materials The UV rays not only attack the carbon bonds but also break down any butadiene rubber we may add as impact modifiers to plastics such as ABS. If we do not protect ABS from the sunlight, in environments such as Florida the impact properties of ABS will be reduced by as much as 75% within six months.

This could be pretty serious if your part is subject to abuse.

Cheer up my good friends. Plastic chemists have come up with a solution. They have concocted materials such as AES and ASA that can be laminated unto the surfaces of ABS or other materials to substantially slow down this degradation process. AES is a saturated olefinic rubber modified styrene-acrylonitrile terpolymer that has been successfully used in outdoor applications in excess of fifteen years. Tests have shown that degradation levels are kept above 50% of their original property values. In plastics this is pretty impressive. ASA is an acrylic rubber modified styrene-acrylonitrile terpolymer that is used in much the same way.

UV exposure to sunlight is another problem in regard to fading. Again, almost all materials fade in sunlight. It is just a matter of degree. Certain colors fade more than others do. When you expose grays and earth tones to the environment, they do not change color as drastically as bright yellows, reds, or blues. Some of this can be overcome by selecting the best pigment package possible for the UV protective materials but it is not foolproof. Other than certain paints, the best thing I know to protect your color on a plastic part is a material that goes by the trade name Korad. It is nothing more than Acrylic. However, in conjunction with the proper pigment package, it will hold color quite well in the outdoors. It is not as effective in protecting your part from impact degradation as an AES or an ASA would. Nothing is a panacea.

The bottom line comes down to this. If you are going to use your part outdoors and it is made of plastic, you are going to have to protect it from the sunlight. What you select as the protecting agent depends on what you need to accomplish. If color fastness is an issue, Korad is a probable answer. If maintaining your physical properties is the issue, than an AES or an ASA clad material should be your choice.

PETG

This is an Acronym for polyethyleneterephthalate. It is a clear material that has come into favor more recently. Although barely discernable, it is not quite as clear as polycarbonate and it is not UV stable. It

does have some excellent physical properties and it is very user friendly. If you need an indoor part that is clear, this is a hard material to beat.

OTHER MATERIALS

There are a lot of other materials available that can be thermoformed. Listing them all would be cumbersome and besides, I don't know them all. Here are a few more of them. We won't go into detail on the physical properties and uses but you should realize they are not as common as some of the above materials for a reason. Typically they are highly engineered materials that fit specific areas of use and have properties that are specifically tailored to meet some very tightly sought after properties. Some of these materials will be given in their trade name and some will be given in their chemical name.

NORYL Polyphenylene Oxide/Styrene is a flame resistant plastic coming in various formulas that vary the heat distortion properties to meet different specifications. It is similar to PVC/ABS materials.

FOAM LAMINATES Plasticized PVC foam over ABS or PVC/ABS substrate. Used in automotive interiors and boat applications.

DR ACRYLIC Extruded acrylic sheet for outdoor applications.

CAST ACRYLIC Highly cosmetic sheet used as the surface layer of glass fiber reinforced bathtubs.

VALOX—PC/PBT Extremely high impact material used in the automobile industry. **POLYSULFONE** This is a very high heat resistant material, in excess of 350° Fahrenheit. **ULTEMP** This is another very high heat resistant material used in the aircraft industry.

So there you have it. A lot of good plastic materials but by no means all of them. The terrific thing about

plastics is the flexibility you have in designing or compounding a formula that will meet the requirements of your specific application. This is done all the time. If it is economically feasible to come up with a plastic alloy that will meet one of these requirements, you can bet there will be a compounder or an extruder that will be happy to take on the R & D project and then your order.

Let me summarize again what is necessary to get a good plastic part. First, you have to have good part design that is relevant to the vacuum forming process. Second, you have to get tooling that will allow you to work with the material you have selected and be compatible with the geometry of the part you are trying to produce. Third, you must have the proper processing equipment and processing knowledge to accomplish the task at hand. Finally, you need to select the material that will meet the needs of the environment you are going to expose the finished part into. You skip any of these important components and your chances of success are significantly reduced. Do yourself a favor, pay attention to all four of these important points.

This concludes the presentation of the process of vacuum forming. Hopefully we have covered most of the technical areas that would give you insight into what is actually required to successfully implement the thermoforming method of producing plastic parts. If additional information is needed on any specific plastic or what other types of plastics are available for use in thermoforming, you should be able to get it from a resin supplier or an extrusion company. Happy thermoforming!

TROUBLESHOOTING

Now that you have a reasonably good idea on what is involved in thermoforming, you should have no problems with making good plastic parts all the time. If you believe that, I got a bridge in Arizona I would like to sell you. As with anything else, a lot of things could go wrong. So we have to develop a method or system whereby we can diagnose and fix a problem that keeps us from making an acceptable quality part.

The first thing we have to do is define the problem. What is going wrong? What is the anomaly that prevents the part from being acceptable? To highlight this we will set up a system whereby in the left hand column we will describe a situation that is not acceptable and in the right hand column we will offer some potential suggestions that will likely remedy the problem.

Before we do that however, you will have to know something about the machine and the process or forming technique the person with the problem is using. We call these necessary inputs to come to proper conclusions. Let us go over most of these major important factors that can affect the outcome of the finished formed part.

I have done a lot of troubleshooting over the phone in my time. I have a few questions that I feel you need to know the answers to before you can expect to diagnose what may be going wrong or what is objectionable with the part the processor is trying to make. The first obvious question is, "in your own words, what is happening or what is objectionable about the part that you are trying to make?" Is the part tearing? Is the part thinning? Are there flow marks? Are there webs or wrinkles? Sometimes these questions in themselves will be a clue about the processing conditions that are being employed. Before you can solve a problem, you have to know what is objectionable. Maybe the objectionable condition is perfectly normal and the person really doesn't have a problem he can do anything about.

Once we get by the description of the problem, we have to find out about the equipment and the processing conditions. The second thing to ask is, "what kind of machine do you have?" If you are familiar with the various types of forming machines available and you know what the processor is objecting to, you may be able to determine if the processor will be able to do anything about the

problem. For instance, if the processor has a single-side heating oven and he is trying to form a .325 inch thick sheet, there is no solution to

his problem except getting a better machine. So knowing the type and capabilities of the equipment available is pretty useful in understanding what can and can't be done with the part the processor is trying to deal with.

The next question is, "describe the part in terms of its shape, size, desired wall thickness, draft, dept of draw, or anything else that is unique to its geometry." Knowing these facts will likely help you determine what can be done to rectify what is going wrong in the forming of the part. An example would be, suppose you have a part that is 6" x 6" square and 15" high. Can it be done? Sure, but it will require a high sheet cost and have to be made on a good machine with some excellent tooling. So it is imperative to know what the part looks like to determine whether we have a design problem, a processing problem or a technique selection problem. Usually if you question the person long enough, you can get a picture of what the part looks like. However, in some instances, the part is complicated enough that actually seeing the part or going to the processor will be necessary to clarify what is going on. Some parts are difficult to describe.

After these initial important questions are asked, I usually go to the source where about 50% of the problems occur. What kind of oven does the processor have? There are a lot of important questions to answer here. Here are most of them. Does the processor have single-sided or double-sided heating elements in his oven? Some materials such as laminates cannot be formed with single-sided heating elements. Then too, if the sheet you are trying to form is above .187" thick, it becomes somewhere between difficult and impossible to form with single-sided heating ovens. So this is important to know. Then we should ask, "what type of heating element is he using in the oven?" Way back when, I gave you my preference in heating elements. If you are forming some sensitive materials such as foam laminates, the heat may be too harsh, such as heat coming off of white light quartz, or you may not be able to turn it down low enough, such as heat coming from catalytic gas. You need to know what different types of heaters are available, how they

are adjustable, and what type of heat is given off of these different types of heaters. This was addressed back in the equipment portion of this paper. You also need to know what distance the heaters are apart from each other and what distance they are from the sheet that needs to be heated. All this reflects on how uniform the temperature of the sheet is when it is actually formed. Is the oven screened, or can it be screened? Sometimes it is desirable to have varying temperatures on the sheet that is to be formed and the temperature of the heating elements you are using can only be adjusted by screening. Are the heaters on percentage timers and what is the time span of the percentage timers? The typical time span for a percentage timer is 15 seconds. At 50% heat, the timer would be on 7.5 seconds and off 7.5 seconds. This is to preserve the electrical contactors. For calrod heaters this is fine but when you use nichrome wire heaters this length of timer will have the nichrome wire glow red through part of the cycle and part of the time be dark. This can affect how plastic sheet heats up. Then again if the timer is on most of the time, how hot are the elements. If a calrod is glowing red, it is probably over 1000° Fahrenheit. This is fine for the olefins but it may be disastrous for PVC or PVC alloys. Are all the elements working? This is a very common problem. Most of the time when an element is not working, the processor is not even aware of it. When the element is set at say 50% and it is glowing red, there may be an energy override problem. Then again a fuse may be burnt out and no power is coming to the heater. How is the oven zoned? Perhaps we can position the frame in the oven in such a way as to control the temperature on a given

area of the sheet just the way we want to. Then again you may have ceramic heaters where you can actually control the temperature on areas as small as eight inches by twelve inches and screening is rarely necessary. There are a lot of clever tricks one can do. Finally, is the oven fairly well closed in or is it open and subject to a lot of normal plant air drafts. This can affect the consistency of the performance on a part to part basis. This seems like a lot of things that can go wrong in an oven and you are correct for making that assumption. As we stated earlier, probably 50% of our problems originate in the oven. We will refer to oven and heater problems later in analyzing specific problems. Suffice it to say there is a lot here.

Another aspect of troubleshooting that does not get the attention it deserves is tooling. Probably the reason for this is the expense it would cause to change it after it has been made. It's always easier to blame something else other than tool design to try to rectify a bad situation. If a tool is designed improperly, you may get an acceptable part occasionally but generally you are going to have a tough time of it. In the long run, changing the tool may be cheaper than paying for all the plastic scrap you are going to make. There are other minor inputs that go into troubleshooting but they can be addressed within the actual troubleshooting presentation. So without further ado, let us get into the numerous problems that can prevent us from making a good quality thermoformed part by reviewing the Troubleshooting guide starting on page 58.

TROUBLESHOOTING GUIDE

Description of Problem	Possible Causes	Possible Corrective Action
BLISTERS	<ul style="list-style-type: none"> Excessive moisture 	<ul style="list-style-type: none"> Pre-dry sheet at the temperature required for the material you are forming Heat sheet very slowly to forming temperature Protect sheet from moisture before using
	<ul style="list-style-type: none"> Heating sheet too hot 	<ul style="list-style-type: none"> Cut down sheet forming temperature. You may be boiling the stabilizers out of the material
	<ul style="list-style-type: none"> Heating sheet too fast 	<ul style="list-style-type: none"> Lower element temperatures. Generally speaking, element temperatures should not exceed 950° F Increase the distance between the heating elements and the sheet
	<ul style="list-style-type: none"> Uneven heating of the sheet 	<ul style="list-style-type: none"> Check forming oven for elements that are overheating Screen out hot spots
	<ul style="list-style-type: none"> Heat sensitive material 	<ul style="list-style-type: none"> Check with plastic supplier on temperature parameters for the material involved
THINNING	<ul style="list-style-type: none"> Design of the part 	<ul style="list-style-type: none"> The overall draw ratio of the part is too great for the starting thickness of the sheet The part has specific areas on it that exceed the draw ratios of the rest of the part
	<ul style="list-style-type: none"> Sheet too thin 	<ul style="list-style-type: none"> Increase the gauge thickness of the plastic sheet
	<ul style="list-style-type: none"> Uneven sheet temperature 	<ul style="list-style-type: none"> Check for air drafts in the forming oven Check for hot spots in the forming oven. May have defective heating elements Check the sheet for a variation in thickness
	<ul style="list-style-type: none"> Forming technique 	<ul style="list-style-type: none"> Consider where the part is thinning and what forming technique would best address this problem
	<ul style="list-style-type: none"> Bad plastic sheet. Melt index of sheet may be low 	<ul style="list-style-type: none"> Have physical properties of the sheet analyzed
DISCOLORATION	<ul style="list-style-type: none"> Forming temperature too hot 	<ul style="list-style-type: none"> Cut down on the forming temperature of the sheet
	<ul style="list-style-type: none"> Pigment loading too low 	<ul style="list-style-type: none"> Increase pigment loading
	<ul style="list-style-type: none"> Hot spots in forming oven 	<ul style="list-style-type: none"> Check out heating elements
WEBBING OR BRIDGING	<ul style="list-style-type: none"> Poor mold design or layout 	<ul style="list-style-type: none"> Redesign mold Use plug assist or mechanical ring to eliminate webbing Add spacing blocks to take up excess material Increase draft or radii to webbed area Slow down the vacuum speed Redesign ring or plug assist If it is a multiple mold, increase the spacing between parts
	<ul style="list-style-type: none"> Wrong forming technique or bad design on present technique 	<ul style="list-style-type: none"> Select a better forming technique Make mold adjustments to the current technique. Gussets, etc.

TROUBLESHOOTING GUIDE

Description of Problem	Possible Causes	Possible Corrective Action
	<ul style="list-style-type: none"> • Incorrect sheet temperature 	<ul style="list-style-type: none"> • In billow forming, the corners of the sheet may be too hot • In snapback forming, the corners of the sheet may be too cold • Screen out appropriate areas of the sheet
	<ul style="list-style-type: none"> • High sheet sag 	<ul style="list-style-type: none"> • Cut down the heat of the sheet to be formed • Select a resin with a lower melt index
	<ul style="list-style-type: none"> • Vacuum rate too fast 	<ul style="list-style-type: none"> • Slow down the vacuum rate • Use smaller vacuum holes • Restrict the vacuum flow with ball or gate valves in the main vacuum line
	<ul style="list-style-type: none"> • Insufficient vacuum 	<ul style="list-style-type: none"> • Check the vacuum system for leaks • Increase the number of vacuum holes • Check to see if the vacuum holes are plugged up • Check to see if the vacuum holes are in the proper area • Selectively increase the size of the vacuum holes
	<ul style="list-style-type: none"> • Timing the billow in the snapback box 	<ul style="list-style-type: none"> • Get a more sensitive flow valve • Put an electric eye in the snapback box
SHEET PULLS OUT OF CLAMP FRAME	<ul style="list-style-type: none"> • Clamp frames warped 	<ul style="list-style-type: none"> • Put a piece of paper in the clamp frame and see if you can pull it out without tearing it
	<ul style="list-style-type: none"> • Clamping pressure too low 	<ul style="list-style-type: none"> • Seals leaking on clamp frames • Air pressure to clamp frames adjusted to low
	<ul style="list-style-type: none"> • High shrinkage in plastic sheet 	<ul style="list-style-type: none"> • Put double-sided adhesive foam tape with 40-grit emery paper on the clamp frames • If possible, control the orientation in the plastic sheet
LUMPS AND BUMPS	<ul style="list-style-type: none"> • Contamination in the sheet 	<ul style="list-style-type: none"> • Cut a cross section of the lump and examine it to see if looks different than the plastic matrix. If so, it is an extruder issue
	<ul style="list-style-type: none"> • Incompatible plastic mixed within the sheet 	<ul style="list-style-type: none"> • Check incompatible lump with an IR test • Compare color of lump with the rest of the matrix
	<ul style="list-style-type: none"> • Water droplets on hot plastic sheet 	<ul style="list-style-type: none"> • Cut a cross section of the lump and check for compatibility
	<ul style="list-style-type: none"> • Bump on the mold 	<ul style="list-style-type: none"> • Look for a depression on the side of the sheet touching the mold
	<ul style="list-style-type: none"> • Loose debris on the mold 	<ul style="list-style-type: none"> • Look at the back of the formed part for loose debris imbedded within the part
TEXTURE WASHOUT	<ul style="list-style-type: none"> • Draw ratio of the part too great 	<ul style="list-style-type: none"> • Consider a deeper texture

TROUBLESHOOTING GUIDE

Description of Problem	Possible Causes	Possible Corrective Action
	<ul style="list-style-type: none"> Plastic sheet heated too hot, especially on the texture side 	<ul style="list-style-type: none"> Turn down the texture side heaters in the oven Cut down the heater cycle time Cut down the overall heat on the sheet Shade out certain areas of the sheet to keep it cooler and less susceptible to thinning
TEXTURE SEPARATION	<ul style="list-style-type: none"> Texture too deep for starting thickness of the sheet 	<ul style="list-style-type: none"> Select a different texture
	<ul style="list-style-type: none"> Texture has deep furrow lines in a pattern 	<ul style="list-style-type: none"> Select a different texture The material you are using may have poor hot strength and you may need to select a different one Excessive shrinkage in the extruded sheet
	<ul style="list-style-type: none"> Draw ratio pretty large, in excess of 3 to 1 	<ul style="list-style-type: none"> Select a tighter texture Change the processing technique for forming the part
SHEET WON'T FIT INTO CLAMP FRAME	<ul style="list-style-type: none"> Sheet not flat 	<ul style="list-style-type: none"> Place a weight on the bowed up area along the clamp frame Preheat sheet to remove stress
FLOW LINES ON PART	<ul style="list-style-type: none"> Nerve in the plastic sheet 	<ul style="list-style-type: none"> Rerun the sheet
	<ul style="list-style-type: none"> Chatter due to sloppy chain drive on the extruder 	<ul style="list-style-type: none"> Run material on a good direct drive extruder Select a deeper texture
	<ul style="list-style-type: none"> Melt index of resin erratic 	<ul style="list-style-type: none"> Blend resin more thoroughly
	<ul style="list-style-type: none"> Die lines on the back of the sheet 	<ul style="list-style-type: none"> Rerun sheet Run sheet from the oven at a lower temperature Select a deeper texture
BLOTCHY LOOK ON THE TEXTURE SIDE OF AMORPHOUS MATERIALS	<ul style="list-style-type: none"> Excessive heat, especially on PVC containing materials 	<ul style="list-style-type: none"> Cut down the forming temperature heat Select a better texture. Some hair cell textures will do this in PVC containing materials
	<ul style="list-style-type: none"> High oven shrinkage 	<ul style="list-style-type: none"> Check shrinkage and keep within acceptable limits
BLOTCHY LOOK ON THE TEXTURE SIDE OF OLEFIN MATERIALS	<ul style="list-style-type: none"> Poor mold contact 	<ul style="list-style-type: none"> Sandblast mold surface
	<ul style="list-style-type: none"> Uneven cooling on the mold 	<ul style="list-style-type: none"> Get a temperature-controlled mold Check cooling lines for blockages
INCONSISTENT PART	<ul style="list-style-type: none"> Uneven heat on plastic sheet 	<ul style="list-style-type: none"> Check for air drafts in the heating oven Check the sheet for a variation in gauge Check for power output variations
	<ul style="list-style-type: none"> Bad regrind in plastic sheet 	<ul style="list-style-type: none"> Do an IR or a Brabender test to confirm compound consistency
	<ul style="list-style-type: none"> Part too difficult for the forming technique being used 	<ul style="list-style-type: none"> Change to a technique that is suitable

TROUBLESHOOTING GUIDE

Description of Problem	Possible Causes	Possible Corrective Action
WARPED PARTS	<ul style="list-style-type: none"> Parts are cooling unevenly 	<ul style="list-style-type: none"> Use temperature controlled tooling Check temperature controlled tooling for water flow blockages Check the material distribution on the mold. Is the proper forming technique being used? Check if the plastic sheet is being pulled tightly against the mold. Very important in forming the olefins Check cooling fans for proper placement Check for plugged vacuum holes
	<ul style="list-style-type: none"> Mold too cold 	<ul style="list-style-type: none"> Preheat the mold
	<ul style="list-style-type: none"> Clamp frames too cold 	<ul style="list-style-type: none"> Preheat the clamp frames. This is especially important when forming the olefins
	<ul style="list-style-type: none"> Excessive gauge variation on the finished part 	<ul style="list-style-type: none"> Change forming technique to get better material distribution Insert screens in the oven to shade out thinning areas Gauge on flat sheet may be all over the lot. Check various areas of the sheet for gauge differences Check for hot spots in the oven. Do the thin spots occur on the same spot consistently?
	<ul style="list-style-type: none"> Demolding temperature too hot 	<ul style="list-style-type: none"> Increase cooling cycle Decrease mold temperature Get more cooling fans cooling the part
	<ul style="list-style-type: none"> Overheated sheet. Material sagging too much 	<ul style="list-style-type: none"> Cut back on oven cycle time or heat
	<ul style="list-style-type: none"> Poor mold design 	<ul style="list-style-type: none"> Add a moat if you are dealing with the olefins Check for plugged vacuum holes Add more vacuum holes Use an alternate forming technique Sandblast the mold in the case of olefins Check mold for flexing during the vacuum cycle
	<ul style="list-style-type: none"> Poor part design 	<ul style="list-style-type: none"> Avoid large flat areas. Crown the part if possible Put in ribs or cosmetic designs in the flat areas Avoid severe draw ratios
POOR DETAIL ON PART	<ul style="list-style-type: none"> Sheet too cold 	<ul style="list-style-type: none"> Increase heating time in oven Increase heating element temperature Check oven for consistency Check oven for drafts

TROUBLESHOOTING GUIDE

Description of Problem	Possible Causes	Possible Corrective Action
	<ul style="list-style-type: none"> Insufficient vacuum 	<ul style="list-style-type: none"> Check for leaks in the vacuum system Check to see if the system delivers enough vacuum Check to see if the mold is leaking vacuum and/or sealing properly Check to see if some vacuum holes are clogged Check to see if you have enough vacuum holes Check for the proper location of the vacuum holes and are they the proper size
	<ul style="list-style-type: none"> Cold clamping frame 	<ul style="list-style-type: none"> Preheat the clamping frame to get a better seal
	<ul style="list-style-type: none"> Incorrect forming technique 	<ul style="list-style-type: none"> Change forming technique to best suit the geometry of the part Employ a plug assist to get better material distribution and vacuum seal
	<ul style="list-style-type: none"> Hot strength of material too great 	<ul style="list-style-type: none"> Select a material with less hot strength Use pressure-forming technique to make the part
	<ul style="list-style-type: none"> Plastic too thick in area with poor detail 	<ul style="list-style-type: none"> Use a different forming technique to distribute the material better Heat the area with the thick plastic hotter
POOR SURFACE FINISH ON PART	<ul style="list-style-type: none"> Mold surface too rough 	<ul style="list-style-type: none"> Polish mold surface to a smoother finish Sandblast the mold surface
	<ul style="list-style-type: none"> Chill marks 	<ul style="list-style-type: none"> Get temperature controlled tool Run current mold hotter Change forming technique to eliminate chill marks. Adjust predraw depth
	<ul style="list-style-type: none"> Draft angle too severe 	<ul style="list-style-type: none"> Add more draft to the part
	<ul style="list-style-type: none"> Mold surface creates too much drag 	<ul style="list-style-type: none"> Polish mold in selected areas Apply mold release sparingly in selective areas
	<ul style="list-style-type: none"> Air entrapment between the mold and formed part 	<ul style="list-style-type: none"> Add more vacuum holes to the affected area Sandblast mold surface
	<ul style="list-style-type: none"> Dirty sheet 	<ul style="list-style-type: none"> Clean sheet with isopropyl alcohol or deionizing airgun
	<ul style="list-style-type: none"> Dirty mold 	<ul style="list-style-type: none"> Clean mold off with airgun or mechanical means
	<ul style="list-style-type: none"> Dirt and debris in the atmosphere 	<ul style="list-style-type: none"> Put in filtering system Clean up the thermoforming area thoroughly Isolate the thermoforming area
	<ul style="list-style-type: none"> Contaminated sheet 	<ul style="list-style-type: none"> Wipe sheet off before putting it in the thermoformer Separate sheet out that has contaminates imbedded into it
	<ul style="list-style-type: none"> Voids 	<ul style="list-style-type: none"> Cull out affected sheets where possible

TROUBLESHOOTING GUIDE		
Description of Problem	Possible Causes	Possible Corrective Action
	<ul style="list-style-type: none"> • Scratched surface on sheet 	<ul style="list-style-type: none"> • Interleaf sheet. Handle sheet carefully • Avoid dragging the corner of the sheet across the surface of the textured side
	<ul style="list-style-type: none"> • Streaks 	<ul style="list-style-type: none"> • Examine what you are cleaning the sheet with before putting it into the thermoformer • Undispersed pigment in the sheet • Poor mixing during extrusion. Rerun the material • Dirty embossing roll during the extrusion process. Clean the texture roll
	<ul style="list-style-type: none"> • Dust and dirt in the atmosphere 	<ul style="list-style-type: none"> • Keep the thermoforming area clean. Put in a filter system if necessary
CHILL MARKS	<ul style="list-style-type: none"> • Mold temperature too low. Material freezes onto the mold when it touches it 	<ul style="list-style-type: none"> • Increase the mold temperature
	<ul style="list-style-type: none"> • The radius on the part is too small 	<ul style="list-style-type: none"> • Redesign the part to accommodate a larger radius
	<ul style="list-style-type: none"> • Wrong forming technique is being used 	<ul style="list-style-type: none"> • Change the forming technique to an appropriate one
	<ul style="list-style-type: none"> • Insufficient draft angle on the part 	<ul style="list-style-type: none"> • Increase the draft angle
	<ul style="list-style-type: none"> • Plug temperature too low 	<ul style="list-style-type: none"> • Increase the plug temperature • Cover the plug with an insulative material • Use an insulating material to make the plug
	<ul style="list-style-type: none"> • Sheet too hot 	<ul style="list-style-type: none"> • Cut down the oven temperature • Reduce the heating cycle
DIMPLES ON MOLD SIDE OF PARTS	<ul style="list-style-type: none"> • Vacuum holes too large 	<ul style="list-style-type: none"> • Decrease vacuum-hole size
	<ul style="list-style-type: none"> • Sheet too hot 	<ul style="list-style-type: none"> • Reduce the heating cycle or cut down the oven temperature
	<ul style="list-style-type: none"> • Dirt or debris on the mold surfaces 	<ul style="list-style-type: none"> • Clean the mold frequently during the forming operation
	<ul style="list-style-type: none"> • Vacuum rate is too high 	<ul style="list-style-type: none"> • Cut down the vacuum volume
COLOR LOSS OR STRESS WHITENING OR BLUSHING	<ul style="list-style-type: none"> • Sheet too cold 	<ul style="list-style-type: none"> • Heat sheet to a higher temperature before forming
	<ul style="list-style-type: none"> • Sheet too hot 	<ul style="list-style-type: none"> • Cut back on heating cycle to prevent discoloration • Reduce the temperature of the heaters to prevent surface scorching • Reduce the distance the heaters are in relation to the sheet being heated
	<ul style="list-style-type: none"> • Part too thin 	<ul style="list-style-type: none"> • Increase the thickness of the sheet • Change the forming technique to improve the part thickness • Shade the oven or turn down the element temperatures in the area the part is thinning
	<ul style="list-style-type: none"> • Mold too cold 	<ul style="list-style-type: none"> • Increase mold temperature

TROUBLESHOOTING GUIDE		
Description of Problem	Possible Causes	Possible Corrective Action
	<ul style="list-style-type: none"> Poor mold design 	<ul style="list-style-type: none"> Change draft angles Increase radii Change mold geometry to reduce the draw ratio
POOR MATERIAL DISTRIBUTION AND/OR EXCESSIVE THINNING IN SPECIFIC AREAS	<ul style="list-style-type: none"> Uneven heating of the sheet 	<ul style="list-style-type: none"> Check the heaters to see if they are set properly Check for faulty heaters Check for drafts or air currents in the oven Shade oven if element zoning is not possible Check to see if the elements are too close to the plastic
	<ul style="list-style-type: none"> Excessive gauge variation in the sheet 	<ul style="list-style-type: none"> Check the gauge of the sheet
	<ul style="list-style-type: none"> Cold mold 	<ul style="list-style-type: none"> Increase the mold temperature
SHINY STREAKS ON PART	<ul style="list-style-type: none"> Sheet too hot in certain spots 	<ul style="list-style-type: none"> Control the heat in the hot zone of the sheet by cutting down the element temperature in the specific area Increase the distance between the heater and the sheet Screen the entire oven to dissipate the heat more evenly Check the unformed plastic sheet for shiny spots
THIN CORNERS ON THE FORMED PART	<ul style="list-style-type: none"> Sheet too thin 	<ul style="list-style-type: none"> Use heavier gauged sheet
	<ul style="list-style-type: none"> Poor material distribution 	<ul style="list-style-type: none"> Reduce sheet forming temperature Change forming technique to get better sheet distribution Change from female to male mold
	<ul style="list-style-type: none"> Sheet temperature too high at the corners 	<ul style="list-style-type: none"> Use screening or control the temperature of the heating zones
EXCESSIVE SHRINKAGE AFTER PART IS REMOVED FROM THE MOLD	<ul style="list-style-type: none"> Inadequate cooling 	<ul style="list-style-type: none"> Increase cooling cycle time Reduce the mold temperature Employ better cooling fans Place cooling fans in more logistic places Use cooling fixtures
SHRINK MARKS ON FORMED PART	<ul style="list-style-type: none"> Poor seal edge on the mold 	<ul style="list-style-type: none"> Repair or improve the seal edge Put in a moat on the mold
	<ul style="list-style-type: none"> Mold surface too smooth 	<ul style="list-style-type: none"> Put as sandblast finish on the mold
	<ul style="list-style-type: none"> Inadequate vacuum 	<ul style="list-style-type: none"> Check mold and vacuum system for leaks Increase vacuum capacity Check for plugged vacuum holes Add vacuum holes or increase the size as appropriate
DIFFICULT TO REMOVE PART OFF THE MOLD	<ul style="list-style-type: none"> Insufficient draft on a male mold 	<ul style="list-style-type: none"> Increase draft Remove the part from the mold as hot as possible without warping it
	<ul style="list-style-type: none"> Male mold temperature too cold 	<ul style="list-style-type: none"> Increase the mold temperature to keep the part from cooling too much

TROUBLESHOOTING GUIDE		
Description of Problem	Possible Causes	Possible Corrective Action
	<ul style="list-style-type: none"> Mold surface too rough for the draft angle 	<ul style="list-style-type: none"> Smooth out the mold in the areas that are locking on Use mold release in areas that are locking on
	<ul style="list-style-type: none"> Air ejection pressure too low or not long enough 	<ul style="list-style-type: none"> Increase or extend air ejection pressure Add more vacuum holes in strategic places
	<ul style="list-style-type: none"> Wrong mold material used for the required draft angle 	<ul style="list-style-type: none"> Change to the proper mold material Use an appropriate mold release
	<ul style="list-style-type: none"> Undercuts on mold too severe 	<ul style="list-style-type: none"> Reduce the size of the undercuts Increase the air eject pressure Remove the part from the mold earlier in the cooling cycle Put the mold on a hinged frame Put removable parts on the mold that come off when the part is being removed from the mold Use mold release where appropriate
LOSS OF VACUUM SEAL	<ul style="list-style-type: none"> Seal edge on the mold is bad 	<ul style="list-style-type: none"> Repair seal edge on the mold
	<ul style="list-style-type: none"> Material not holding in the clamp frames 	<ul style="list-style-type: none"> Repair clamp frames or put pins in them to grip better
	<ul style="list-style-type: none"> Clamp frames too cold 	<ul style="list-style-type: none"> Heat clamp frames up before running parts
	<ul style="list-style-type: none"> Clamp frames not adjusted properly or not coming up through the seal edge of the mold enough 	<ul style="list-style-type: none"> Adjust the clamp frame properly
SHEET TEARS DURING FORMING	<ul style="list-style-type: none"> Poor mold design 	<ul style="list-style-type: none"> Consider changing the mold geometry Change the forming technique Increase the radii on the part
	<ul style="list-style-type: none"> Plastic sheet too hot before forming 	<ul style="list-style-type: none"> Cut down heating cycle Cut down heater temperatures, especially in specific areas Check for hot spots on sheet
	<ul style="list-style-type: none"> Thinner gauges, sheet too cold 	<ul style="list-style-type: none"> Increase heating time Check sheet for uniform temperature
	<ul style="list-style-type: none"> Poor material distribution 	<ul style="list-style-type: none"> Check the sheet for uneven thickness Check for uneven heating
PLASTIC SHEET STICKS TO THE PLUG	<ul style="list-style-type: none"> Plug temperature is too hot 	<ul style="list-style-type: none"> Decrease the plug temperature Cover the plug with an insulative material Use mold release on the plug
	<ul style="list-style-type: none"> Wrong material is being used for the plug 	<ul style="list-style-type: none"> Change the material to an acceptable material Cover the plug with an insulative material
EXCESSIVE SHEET SAG	<ul style="list-style-type: none"> Sheet heated too hot 	<ul style="list-style-type: none"> Decrease cycle time Decrease heater temperature
	<ul style="list-style-type: none"> Poor hot strength on the plastic material 	<ul style="list-style-type: none"> Select a different material

TROUBLESHOOTING GUIDE		
Description of Problem	Possible Causes	Possible Corrective Action
	<ul style="list-style-type: none"> Sheet area too large in relationship to the depth of draw 	<ul style="list-style-type: none"> Use screening or shading to reduce the heat in the center of the sheet Change forming techniques
SAG LEVELS VARY FROM SHEET TO SHEET	<ul style="list-style-type: none"> Sheet temperature varying 	<ul style="list-style-type: none"> Check for drafts in the oven Check for power variations Melt index of the plastic is erratic
	<ul style="list-style-type: none"> Improper use of regrind 	<ul style="list-style-type: none"> Avoid mixing regrind with various melt indexes Avoid using regrind that has little rheological life left Control the quality of the regrind
BILLOW HEIGHT OR DEPTH IS VARYING	<ul style="list-style-type: none"> Sheet temperature is uneven 	<ul style="list-style-type: none"> Check oven for drafts Check heating elements for power variations Check heating elements for proper operation Screen the oven to control temperatures in given areas of the sheet
	<ul style="list-style-type: none"> Vacuum or air leaks in the billow box or seal edge 	<ul style="list-style-type: none"> Check the seal in the billow box
	<ul style="list-style-type: none"> Air pressure or vacuum volume too great for the size of billow box 	<ul style="list-style-type: none"> Reduce the vacuum volume or air pressure to cut down the sensitivity of the billow. (Widen the processing window) Put in a sag eye in the billow box
SHEET WHITENING	<ul style="list-style-type: none"> Sheet too cold 	<ul style="list-style-type: none"> Increase heating time Increase heating element temperature
	<ul style="list-style-type: none"> Sheet stretched beyond the yield point of the plastic 	<ul style="list-style-type: none"> Change the forming technique Redesign the part
PART CRACKS DURING SERVICE LIFE	<ul style="list-style-type: none"> Part too thin in specific areas 	<ul style="list-style-type: none"> Increase sheet thickness Use plug assists to distribute material more efficiently Fill in the thin areas in the back of the part with epoxy resins Consider changing forming technique
	<ul style="list-style-type: none"> Poor part design 	<ul style="list-style-type: none"> Consider changing part design Increase the radii on the sharp areas of the part
	<ul style="list-style-type: none"> Part formed too cold and is not stress relieved 	<ul style="list-style-type: none"> Increase forming temperature of the part
	<ul style="list-style-type: none"> Part not assembled properly or fastened to other structures improperly 	<ul style="list-style-type: none"> Check assembly technique to see if it commensurate with good assembly practices
	<ul style="list-style-type: none"> Poor selection of materials 	<ul style="list-style-type: none"> Check to see if the physical properties of the material selected
		are adequate for the part produced
PARTS ARE BRITTLE	<ul style="list-style-type: none"> Improper cooling temperature on the mold 	<ul style="list-style-type: none"> Check to see if the mold is too cold Increase mold temperature Check to see if the cooling on the mold is too abrupt, that is, excessive spray misting

TROUBLESHOOTING GUIDE

Description of Problem	Possible Causes	Possible Corrective Action
	<ul style="list-style-type: none"> Plastic heated too hot too quickly 	<ul style="list-style-type: none"> Check for charring of the surface of the plastic and turn down the heating element temperature
	<ul style="list-style-type: none"> Mold lubricant incompatible with the plastic being used 	<ul style="list-style-type: none"> Change mold lubricant
	<ul style="list-style-type: none"> Part cleaned with a harmful chemical during packaging 	<ul style="list-style-type: none"> Check cleaning agents you are using
FLAT SURFACE OF A PART NOT FLAT	<ul style="list-style-type: none"> Flat surface of the mold not properly reinforced. Oil canning during the vacuum cycle 	<ul style="list-style-type: none"> Check the mold for rigidity and durability
FURROWS OR LINES IN THE PART	<ul style="list-style-type: none"> Die lines in the plastic 	<ul style="list-style-type: none"> Rerun the plastic sheet Form the plastic at a cooler temperature
PLASTIC TEARS DURING HEATING OR FORMING	<ul style="list-style-type: none"> Poor hot strength in the plastic 	<ul style="list-style-type: none"> Select a more appropriate plastic
	<ul style="list-style-type: none"> Plastic is partially burnt during the extrusion operation 	<ul style="list-style-type: none"> Test the material to see if the viscosity is OK. Rerun with good material if necessary
	<ul style="list-style-type: none"> High orientation in the sheet 	<ul style="list-style-type: none"> Rerun with the proper orientation
	<ul style="list-style-type: none"> Mixed regrind in the sheet 	<ul style="list-style-type: none"> Use only regrind that is compatible with the virgin part of the sheet Use good quality regrind
	<ul style="list-style-type: none"> Grain texture too deep for the thickness of the sheet being used 	<ul style="list-style-type: none"> Select a texture that will not separate during the heating cycle

Summary

So there you have it. Everything you ever wanted to know about thermoforming and were afraid to ask. However, just to be on the safe side, let us reiterate some of the important aspects of this process.

First of all, as we stated in the beginning of this presentation, thermoforming is the process of taking a flat sheet of plastic and changing it into a contoured shape. To accomplish this, we put forth a number of thermoforming techniques that would allow us to form the flat sheet of plastic into various geometric shapes with progressive degrees of difficulty. These techniques were listed from simple drape forming to plug assist billow forming depending on how complex the part was. If all you were interested in were forming an RV fender for a travel trailer, the simple drape forming technique would do. However, if you were making the cover and fascia of an MRI machine, you would most likely need to use complicated plug assists and employ the pressure forming process. Each of these techniques has been developed to enhance the forming of some particular type of geometry.

So how do we recognize which one of these techniques to use? I wish I could give you some magic formula that would designate which one to use in a given situation but no such magic formula exists. The first thing you have to do is get a thorough understanding of what exact sequence of events occurs within each technique. Then you have to imagine what shapes would lend themselves best to the technique you are observing. In other words, what could be accomplished by employing a specific technique? How would the technique move the plastic into the desired areas and provide you with a structurally sound part with the most uniform wall thickness? There is no substitute for experience here. The best thing to do is start with simple parts using simple techniques and progress to more complicated parts using more complex techniques. As you continue to observe what happens, you will get a feel for how heated plastic behaves. You will especially get a quick education on the various types of plastics as they all behave differently. Don't be afraid to get help. It is better to have a bruised ego than a bruised pocketbook.

An important concept that will help you a great deal in selecting an appropriate thermoforming technique is DRAW RATIO. Master the principles behind this concept and you will go a long way to becoming

proficient at selecting a good thermoforming technique for the particular part you are trying to make. Being able to do the math is important, but understanding the empirical reasoning on this concept is imperative. Hopefully I have made the illustrations and the explanation on this concept clear enough to provide you with some incite into understanding the thermoforming process. It is important to know what can be done with this method of processing plastic and where the limitations are. There are lots of "boat anchors" out there because of the simple statement, "no problem, we can do that"! Employing the principles behind the draw ratio concept should enable you to make sound judgements with regards to thermoforming.

Besides, look how impressed your friends, and maybe even your customers, will be with your analytical knowledge.

In the section following DRAW RATIO, we made a statement that there were four important concerns to produce a successful thermoformed part. They were PART DESIGN, TOOL DESIGN, PROCESSING and MATERIAL SELECTION. Ignore any one of these issues and you could come up with some serious problems but of all these issues, part design and tool design is the most important. Designing the part to accommodate the process and not the other way around is imperative. If you exceed the limitations of what thermoforming can do, there will be much screaming and gnashing of teeth. No matter how much effort you put into the other three essential factors that affect the thermoforming process, you are likely to meet with failure.

So what should you do? Get with the expert! Who better to solicit advice from than the person that will have to live with the consequences of a difficult design than the thermoformer himself? He will most likely have been confronted with numerous issues regarding draft, radii, undercuts, tolerances and the like to give you the proper guidance to assure an aesthetic and functional part. Certainly the guidelines set forth in this presentation should be useful. It is also very beneficial to develop a rapport with your thermoformer. He has to feel comfortable with being able to tell you the truth without you running to another supplier. The reverse is true also. You have to feel comfortable that what he is telling you is reliable.

Once we are assured that the part design is right,

we have to get the tooling people involved in the project. This has to be done in conjunction with the thermoformer. A number of important decisions have to be made. Should the tool be male or female? What material should the mold be made from? Does the tool have to be temperature controlled? What are the tolerances required on the finished part? What thermoforming technique should be used? Putting a good deal of thought and planning into the tooling requirements of the thermoforming process will very likely save you a lot of money and grief down the road. By taking advantage of the general geometry of the part, it is quite likely that you will be able to simplify the trimming phase of producing a finished part. Selecting the right forming technique can also take advantage of the shape of the part and lower processing scrap rates. Sometimes it is possible to utilize the part shape and make multiple up molds that will reduce the amount of plastic required per part. These are all considerations that could give you a competitive edge with regard to the final finished part cost. Again experience is an indispensable ingredient in the total picture.

Next we have the actual thermoforming processing parameters to consider. How complex is this part and what type of processing equipment is needed to do the job? A while back I made a statement that “you can get into the thermoforming business with as little as a pizza oven and a vacuum cleaner.” That is true, but you probably won’t stay in business long. Your competitors will blow you away. What type of equipment you need will somewhat depend on what markets you are trying to address. If you are producing “heat, suck, and ship” parts, you will not need very sophisticated equipment. Your dilemma will be fighting price and profit margins because you are not bringing anything unique to the party. Your only advantage may be location and service. I hope you live across the street from this guy. However, if you are making pressure formed covers and fascia for a \$1,000,000 MRI machine, the parts will probably require tight tolerances and need to be cosmetically appealing. This will require state of the art equipment that is capable of producing highly accurate parts consistently. You are not going to get this equipment from the local hardware store.

I have addressed many of the features that are important and available on thermoforming equipment in the processing section of this manual but it may prudent to reiterate some of the important components again. Heater types come to mind. I cannot stress strongly enough that price and

operating costs are not the only consideration. If you intend to do complex parts, heater performance may be your only practical concern. Some heaters are more efficient than others and can be more readily controlled. Get with someone who has been on a “snipe hunt” at least once and solicit some opinions.

This brings us to oven control. Nothing worse than getting some good heaters and not being able to control them temperature wise. There are a number of controllers available from computer controllers to manual percentage timers. To some degree, what you select will depend on the type of heaters you have but DO NOT under select. You can never have too much control. I can promise you no matter how sophisticated your control system is, somewhere down the line you will wish that your system could do just one more thing. Humans are like that! That goes for oven zoning too. Think long and hard on what you may want to do in the future before you settle on a zoning pattern for your machine. You cannot believe how creative you can get after the fact. This is another time to consult someone who has been around the block at least once. Limitations on oven control are among the most important causes for excessive scrap and the inability to make consistent and successful parts. Poor part design and tool design are the other big impediments.

Another consideration in the thermoforming process is cycle time. Sooner or later your totally understanding customer will insist on more parts than you can provide. So, now you will wish you had a temperature controlled mold or a rotary thermoformer. However, it does you no good to have a rotary machine if you do not have a temperature-controlled mold. I have addressed this concept fairly thoroughly with the cycle time chart in the general manual. Cycle times have everything to do with what type of equipment you have, what kind of mold you are using, the type of plastic you are forming and the thickness of material you are heating and cooling. Most all of your limitations in process time are derived from these conditions. The trick here is to get your customer to give you an accurate projection on the potential volume for this part. Polish up his crystal ball! Knowing what the future volume for this part will be will go a long way to deciding what kind of tooling to build. It could save you both some money too.

A final comment on processing. Plastics generally love water. However, the thermoforming process does not. Consequently, it is imperative that you keep the unformed sheet as moisture free as possible. Generally the sheet manufacturer will

package the material in a polyethylene film to keep the moisture level to a minimum but if the sheet is setting around too long it will very likely need drying in a drying oven. Typically you need to consult the sheet manufacturer or the resin manufacturer to get some guidelines on drying temperatures and times. I gave you a chart for the most prominent ones, ABS and polycarbonate. Most plastics are notch sensitive and forming the sheet when it is wet could diminish the impact properties significantly. Common sense is the byword here.

The fourth major component in producing a successful part is the selection of the material for the application. The problem is there are a lot of plastics that would successfully do the job for a given application. The challenge is to find the plastic that is cost effective and is not over engineering or under engineering the part function. To properly determine what that plastic might be, we have access to the physical property values of the various plastics and we are able to compare them to one another. Once you have a general idea of what these values mean, you should be able to select a material that meets the requirements necessary for the part to function in the environment it will be used. You should be able to compare plastics and other materials with one another to get a good part design and build a safety factor into the part to assure an expected useful life.

There is a myriad of plastics to choose from. Each of them has some unique characteristics that would enhance the function of the part you are designing. However, they are not all “user friendly” to the thermoforming process for the particular part you are trying to produce. Let me give a for instance. If you have a shallow draw part with a three foot by three foot dimension, you will not be able to make this part from polypropylene. There is just too much sag in this material during the thermoforming process and you will not be able to make a web free part. Even though the physical properties of polypropylene may be just perfect for the function of the part, you will most likely need to select another material. This in no way suggests the polypropylene is a bad material. It just has some characteristics that make it inappropriate for that particular job that has to do with processing.

So how do you know these things? You need to consult with someone who is familiar with the various materials you are considering for your project and learn about the idiosyncrasies they may have. Typically a resin manufacturer or a technical person with the sheet manufacturer will be able to help you. Plastics are extremely versatile. The array of

properties available in this class of material is so vast, you should be able to find a number of them that fit your application. For instance, if you want to make a plastic that is weather resistant to sunlight, it can be formulated that way. If you want to make a plastic that is conductive, it can be formulated that way. Some other properties that can be formulated into a plastic compound or are inherent within the compound itself are: flame resistancy, chemical resistance, high heat distortion, color consistency without painting, controlled gloss – either high or low, and making parts that we can see through. There are numerous other properties that make plastics very useful and one should not be shy about inquiring about a plastic that will meet the exact need you want.

Finally, we addressed troubleshooting. As with any process, there will always be anomalies that will prevent things from going smoothly. So what we have done is give you a number of conditions that occur frequently that keep you from making an acceptable part. This is not everything bad that could happen to you and it is not every conceivable solution to the problem but it is a pretty comprehensive list. We tried to address the problem in simple terms and make the potential solutions as brief as possible. Hopefully this will give you some quick clues that will result in the much sought after “aha experience.”

As we indicated, successful troubleshooting requires some knowledge of the equipment you are processing the parts on and a general knowledge of the techniques available to thermoforming. A general idea of what types of molds are available and how each of them responds to the thermoforming process with different materials is pretty useful too. Also, a fair understanding of what heating systems are available and how they function is invaluable. All this contributes to high level of success in fixing the problem.

Well, I hope that some of this information will be useful to you and keep you from situations that are embarrassing and maybe even downright costly. Hopefully everything I have told you is accurate and of some use. My intentions were honorable. I am sure that before the ink is dry on this manual, someone with a stellar invention or idea will make something in this manual obsolete or maybe even ridiculous. I can only hope that when that happens I will be fishing on some inaccessible lake in Wisconsin. So best of luck to everyone, and HAPPY THERMOFORMING.

GLOSSARY OF TERMS

ABS: Acrylonitrile-butadiene-styrene terpolymer

ABSORPTION: Is the process of radiant energy being absorbed in the plastic as it is being heated up.

AIR CONVECTION: Heat energy transferred to a plastic via the movement of hot air about its surface area.

AIR CONVECTION OVEN: The chamber or structure used to deliver hot air to the surface of a plastic.

AES: A saturated olefinic rubber modified styrene-acrylonitrile terpolymer generally used in outdoor exposure applications.

ALLOY: A combination of blended polymers or copolymers that result in unique physical properties not available in the single polymer. An example is Polyvinyl Chloride combined with Acrylonitrile-butadiene-styrene.

AMORPHOUS POLYMERS: Polymers devoid of orderly molecular structures. They exhibit a broad melting range as opposed to crystalline structures.

ASA: An acrylic rubber modified styrene-acrylonitrile terpolymer generally used in outdoor exposure applications.

ATMOSPHERIC PRESSURE: The pressure that is applied to the earth's surface due to the weight of the air surrounding the surface of the earth. At sea level it is 14.7 pounds per square inch.

BANBURY MIXING: A system of mixing materials together using a pair of contra-rotating rotors that force the materials together into a homogeneous blend through friction and pressure. This is an excellent mixing system and probably the best one available for compounding plastic alloys.

BANK: A group of heating elements that are connected together with a common electric circuit.

BILLOW: Pre-stretching a heated plastic sheet by injecting air into a chamber that has the plastic sheet sealed over the edges of the chamber.

BLACK BODY: A body that emits the maximum amount of radiant energy at a given wavelength.

BLACK PANEL HEATERS (solar panels): Heaters with resistance wires imbedded in a routed out ceramic fiber refractory board and covered with a black panel quartz or glass plate.

These heaters are very efficient at giving off radiant and convective heat.

BLEED OFF: The act of letting air out of a mold chamber to allow a billow to stretch uniformly over

a mold so the bubble does not burst during the forming operation.

BLISTERS: A depression on the surface of a heated plastic sheet or part caused by the rupturing of the surface of the plastic as the trapped gases are expanding very rapidly and escaping as the plastic is softening and allowing the rupture.

BRIDGING: This is a condition whereby the plastic stretching across a mold cavity during the forming operation does not pull down tightly against the mold surface.

BUBBLE: A pre-stretched piece of plastic that is obtained by sealing the plastic over a vacuum or pressure box and applying a vacuum or air pressure to this box causing it to develop a concave or convex hemisphere.

CALROD: A resistance wire packed in magnesium inside a stainless steel tube. When sending electricity through this wire, the tube will heat up and give off radiant and convective energy.

CATALYTIC GAS HEATER: An enclosed panel in which natural or propane gas enters into it and is dispersed throughout the panel and ignited. This causes the panel to give off heat through radiant and convective energy.

CAVITY MOLD: A female mold in which a part is drawn into it via vacuum or pressure.

CERAMIC HEATER: A resistance wire trapped within a ceramic shell that will heat up when an electric current is passed through the wire. It is very efficient at given off radiant and convective energy.

CHAIN DRIVE: A system of raising or lowering the platens on a thermoforming machine. Chain drives can also be used to shuttle the plastic into and out of the oven.

CHEMICAL REACTOR: The vessel that is used to polymerize a monomer through the use of heat and pressure in the presence of a catalyst.

CHEMICAL RESISTANCE: The ability of a material to resist having its properties changed when being exposed to a substance that could potentially chemically attack it.

CHILL MARKS: A wavy surface imperfection that is caused by contact of the hot plastic to the mold surface before other parts of the hot plastic contact it.

CLAMPING FRAME (Mechanism): A mechanical means of holding the edges of a plastic sheet while it is being heated in an oven. After the sheet is heated it provides a method of sealing the plastic to the mold edge to make it possible to draw a vacuum.

COEFFICIENT OF THERMAL EXPANSION: The fractional change in length of a material in response to a change in temperature. For plastics this value is somewhere in the range of ten to the minus fifth, times the temperature change, times the length or thickness of the part in inches.

COMMODITY MATERIALS: Materials that generally are similar and can be bought and sold based on current market conditions. For instance, benzene is a commodity. What difference does it make where or who you buy it from?

CONDUCTION: A method of transferring energy to a material or body through direct contact.

CONDUCTIVE PLASTICS: Plastics that can actually conduct an electric current, albeit very weakly and slowly, that will dissipate an electric charge.

CONTOURED BOX – SNAPBACK: This is a box that has roughly the same shape as the mold you are trying to form the plastic over. It has calculated amounts of clearances that prevent the plastic from being pulled into the vacuum box too deeply so webbing and thinning do not occur.

CONVECTION: A method of transferring energy to a material or body via the use of fluids or air flowing about that body.

COOLING: The process of removing heat from a formed plastic part as it is drawn onto the mold.

COOLING LINES: Tubes running through a mold that carry the fluid that either heats up or cools off the temperature of a mold to keep it consistent.

COOLING FIXTURE: A device that is used to hold the shape of a part after it is removed from the mold and is cooling off. Typically it is used to maintain dimensional stability.

CRYSTALLINE POLYMERS: Polymers that have sharp melting points.

CRYSTALLINITY: A state whereby the molecular structure of a resin arranges itself in a symmetrical, geometrical, three-dimensional pattern forming a polymer.

CYCLES – CYCLE TIME: A complete sequence of events that occur in making a plastic part from the loading of the sheet to the loading of the next sheet to make a second part. A time lapse between identical spots within a repeatable sequence of events.

DEPTH OF DRAW: The distance that the mold protrudes out of the mold base or the depth the cavity extends within the mold from the mold base surface.

DIE CUTTING: A system of trimming plastic parts that takes a steel rule die and applies enough pressure to cut through the desired areas of the plastic an stopping against a support plate. A second system is taking two sharpened edges and sliding them past each other through the plane of a plastic part.

DIE LINES: Linear grooves or depressions in the back of an extruded sheet that parallel the machine direction of the plastic sheet. They are usually caused by hang-ups in the die or nicks on the die lips.

DIMPLE: A depression in the surface of the plastic sheet or formed part. The dimple can be caused by a void within the plastic sheet or moisture within the surface of the sheet that ruptures when the sheet is heated.

DISCOLORATION: The process of a plastic changing color through exposure of sunlight or applying a substance to the plastic that chemically attacks it.

DRAFT: The slope of the vertical edges of a mold that is used to facilitate the removal of the part from the mold.

DRAPE: The process of pulling a hot piece of plastic over a mold creating a seal along the mold edges.

DRAW RATIO (STRETCH RATIO): The ratio of the starting thickness of the plastic sheet to the final thickness of the plastic on the formed part. Calculating this ratio depends on the geometry of the part.

ELONGATION: The amount in length a material can increase without breaking when put under stressed tension.

EMISSIVITY: The ratio of radiation intensity from a surface to the radiation intensity at the same wavelength from a blackbody at the same temperature.

ENTROPY: The tendency of an energy system or organized entity to break down.

EPDM: Ethylene Propylene Diene Monomer that is used as a rubber impact modifier in weatherable plastics.

EPOXY RESIN: A thermosetting plastic used for making molds or tooling fixtures.

EXCESSIVE MOISTURE: The amount of water that is absorbed in the surface of a plastic sheet or resin that will keep you from processing it.

FEMALE MOLD: A cavity used to stretch a piece of plastic over.

FIBERGLASS: Fine strands of glass usually encapsulated within a resin matrix. It can be used to make molds or structural parts.

FLAMMABILITY: A measure of the extent to which a material will support combustion.

FLOW CHARACTERISTICS: The ability of a heated plastic to pass through a die, through an orifice, or over a mold in a smooth and uniform way to allow you to make a sheet or formed part.

FOAM CORE MATERIALS: Materials that have gas expanded or air occupied structures between their solid exterior surfaces. Expanded vinyl or polyethylene are good examples.

FORMING TEMPERATURE: The temperature at which a plastic will shape into the geometry you are attempting to attain.

FORMING TEMPERATURE RANGE: The high and low points at which a plastic will be successfully shaped with the detail and dimensional tolerances required for an acceptable part.

FORMING TECHNIQUE: A regimented process of steps that allow you to form a flat sheet into a desired shape. There are numerous processes that will accomplish this depending on how complex a shape you are trying to make.

GAS FLAME HEATING: A heating system that employs an open gas flame to heat up a plastic sheet. This system gives off both, convective and radiant heat energy.

GAS REGULATOR: A device that controls the amount of gas that enters a gas heating system thereby controlling the heat output.

GELS: Hard particles of resin that are similar to the plastic matrix they are in but because of their molecular or cross-linked nature, will not blend in with the other plastic and will leave a tiny blip on the surface of the plastic sheet or part. If they are large enough they will show in the surface of the plastic part as the sheet is thinned out to form the part.

GLASS TRANSITION TEMPERATURE: The temperature at which a rigid plastic softens enough to become somewhat rubbery.

HARDNESS: The property of a material that determines how rigid or resistant to denting a substance is. In rigid plastics this is measured by a Rockwell hardness test.

HEAT DISTORTION TEMPERATURE: This is the temperature at which a plastic will begin to distort as measured with test bars using a standard ASTM test method.

HEATING OVEN: The device used to heat up a plastic sheet to forming temperature. Usually this type of oven is tightly zone-controlled to distribute heat to the desired areas.

HEATING PROFILE: The pattern of heat being applied to a plastic sheet while it is enclosed within an oven so that the heat will be localized within the sheet and allow certain areas to stretch more than others during the forming process.

HEATER TYPES: These are the various types of elements that are used to heat up plastic sheet. General types listed in this manual are: ceramic, solar panel, calrod, quartz, catalytic gas, open flame gas, nichrome wire, and air convection.

HIGH IMPACT POLYSTYRENE: This is a resin composed of numerous styrene monomer molecules polymerized into long polymer chains and dispersed with soft rubber particles throughout the rigid polystyrene matrix.

HOT STRENGTH: The resistance of a heated plastic sheet to being stretched into the shape of a mold.

HYDRAULIC: A system of putting fluids under compression to move the platens on a thermoforming machine up and down. Usually used in conjunction with pressure-forming to allow maximum clamping pressure.

HYGROSCOPIC: The characteristic within a plastic that gives it an affinity to pick up and retain moisture.

IMPACT STRENGTH: The ability of a material to undergo a sudden shock without breaking. This can be tested in plastics via a notched izod or falling dart impact test through standard ASTM test methods.

KORAD: An acrylic film used to hold color stability and UV degradation when laminated to plastic sheet.

LOUVERS: Air or lighting vents designed into a plastic part.

MALE MOLD: A protrusion extending out of a flat plane that is used to form hot plastic over.

MATERIALS: Plastic compounds used to construct useful shapes.

MATERIAL DISTRIBUTION: The process of stretching hot plastic over a mold and maintaining desired thicknesses in specific areas of the part.

MELT TEMPERATURE (POINT): The temperature at which a polymer changes from a solid to a viscous liquid.

MICRO-SWITCH: A device used to electrically stop a moving part on a machine in the same place consistently.

MOAT: A groove in a mold used to provide a good sealing point to prevent a plastic from breaking its vacuum bond with the mold as the plastic is shrinking during the cooling cycle.

MOLD: (v) To shape a heated plastic sheet via heat and vacuum (pressure) into a desired geometry. (n) The cavity or protrusion used to shape a heated plastic sheet into a desired shape.

MOLD BASE: The plane that a mold cavity or mold protrusion is mounted to that is used to seal off the hot plastic sheet during the vacuum part of the forming cycle.

MOLD SHRINKAGE: The amount that the plastic part shrinks in relation to the actual mold size after the part is removed from the mold and has reached ambient air temperature. This value is usually expressed in inches per inch. The typical shrinkage for ABS is .006" ±.001".

NICHROME-WIRE HEATERS: A type of heater unit that resembles a wire in a toaster. It typically heats up to its maximum or cools off fairly quickly.

NOTCH SENSITIVE: Most plastics exhibit a tendency to crack or break along a notch or scratch in the surface if an excessive bending stress is applied to that surface.

OHMS PER SQUARE: The resistance to an electrical charge flowing across the same surface of a piece of plastic.

OLEFINS: A group of unsaturated hydrocarbons of the general formula C_nH_{2n} . Examples are polyethylene or polypropylene.

ORIENTATION: The alignment of polymer chains to create stress in a given direction. With thermoplastic materials this condition causes the molecular structure of the plastic to be stressed more in one direction than the other.

PERCENTAGE TIMER: A timing device that has a total amount of set time, say 15 seconds as 100%. This timer can then be set at a certain percent, such as 50%, in which case it would be allowing a current to flow through a heating element for 7.5 seconds and not allowing it to flow for 7.5 seconds.

PETG: A clear, amorphous, glycol-modified polyester which is polymerized from dimethyl ester or terephthalic acid and ethylene glycol. This gives it a better forming window than PET.

PHYSICAL PROPERTIES: Those characteristics that define the physical parameters of a material, such as stiffness, hardness, impact resistance, chemical resistance, etc. These properties can be tested and compared to other materials.

PHYSICAL TESTING: The process of measuring the characteristics of a material based on standard test methods.

PIMPLE: A raised area on a sheet of plastic or plastic part caused by a hardened particle or contaminant within the matrix of the plastic substrate.

PLASTIC SHEET: A flat piece of plastic having a specific length, width, thickness and texture.

PLASTICIZER: A material that can be added to plastics that allow them to be processed more easily and can change certain of their physical characteristics such as toughness or flexibility.

PLATEN: A movable support mechanism that a plug or mold is attached to that assists in forming a plastic part.

PLUG ASSIST: A mechanical device used in thermoforming to help distribute the heated plastic sheet more uniformly before it actually seats on the mold.

PNEUMATIC: A system where a device is operated via the use of compressed air.

POLYCARBONATE: A polyester of carbonic acid produced by using an interfacial reaction between dihydric or polyhydric phenols and a suitable carbonate precursor such as dichlorocarbonate. It is a clear, amorphous material with good impact strength and a high heat distortion.

POLYCARBONATE/ABS: An alloy of the two different resins that will provide some unique physical properties depending on the mix of the two materials.

POLYESTER: A resin made via the reaction of a dibasic acid and a dihydroxy alcohol. It is used as a resin base to make structural parts.

POLYETHYLENE: A thermoplastic material made by polymerization of ethylene molecules. A large range of polyethylenes can be made by varying the chain length and additives to the polymer.

POLYMER: A organic substance obtained by joining the same type of monomers into long chains. For example ethylene is polymerized into polyethylene through heat, pressure and catalyzation.

POLYMERIZE: The process of joining numerous like monomers into a long chain.

POLYPROPYLENE: A thermoplastic material made by polymerization of propylene molecules.

POLYSTYRENE: A clear, amorphous, thermoplastic material made by the polymerization of the styrene monomer.

PRESSURE BOX: The reinforced box that is draped over the mold in the pressure forming system to provide the added force required to get good detail from the mold surface.

PRESSURE FORMING: A thermoforming technique whereby vacuum and pressure is used to force the hot plastic sheet against a mold surface to get a very crisp impression of that surface.

PROCESSING: The act of converting a plastic resin or sheet into a useful form or shape.

PROCESSOR: The entity that converts a plastic resin or sheet into a useful form or shape.

PROTOTYPE MOLD: The mold that is used to make a part that will be evaluated for fit and function.

PUNCH PRESS STAMPING: The process of trimming a formed part by using a metal die clamped to a movable platen in a mechanical press. Forcing the platen against a fixed base pinches the desired surface of the plastic part and removes the unwanted excess.

PVC: An amorphous thermoplastic material made up of vinyl chloride polymers. It is widely used in wire covering and where a chemically resistant plastic is needed.

PVC/ABS: An alloy of polyvinyl chloride and acrylonitrile butadiene styrene combined to maximize certain physical properties.

PVC/ACRYLIC: An alloy of polyvinyl chloride and acrylic combined to maximize specific physical properties.

QUARTZ HEATERS: A type of heater with about a one-half to three-quarter inch diameter tube with a resistance wire inside of it that is backed up by an internal reflector.

RADIANT HEAT: An electromagnetic transfer of energy from a heating emitter to a material or body one would wish to raise the temperature of.

RADII: The rounded edges or curvature of the shape being dealt with. Typically these radii are designed into the part.

REFLECTED OFF ENERGY: The small amount of radiant energy directed at a plastic sheet that is left over from the energy that penetrates through the sheet and is absorbed by the sheet.

REGRIND: The plastic materials that are reprocessed into plastic sheet or finished parts more than once.

RIBS: A raised or depressed area of a formed part that is designed into it to increase its structural integrity.

ROBOTIC TRIMMING: A mechanized method of performing a secondary operation on a formed part to enable it to comply with dimensional specifications.

ROUTER: A high speed air or electrically operated cutting tool used to trim materials to dimensional specifications.

SAG: The amount of spherical deflection a flat plastic sheet experiences as it is heated to its forming temperature.

SAG BANDS: The supporting system that is attached to the clamping frame to obtain multiple minor sags when using a multiple cavity mold.

SANDBLAST: The process of forcefully blowing sand against an object to clean it or put a fine suede-looking surface on it.

SCREENING: The process of blocking out some radiant energy from reaching the plastic sheet suspended in an oven by putting in metal window screening between the plastic sheet and the heating elements used to heat the plastic.

SEAL: The edge of a mold base that a hot piece of plastic is forced against to keep the vacuum enclosed within the mold chamber while a part is being formed.

SECONDARY DRAW RATIO: After the initial thickness of plastic is determined on a formed part, the thickness of any secondary pockets or protrusions will be determined by the difference in thickness of the material now available divided by the area left over on the secondary area of the part.

SECONDARY OPERATIONS: Those processes that are performed after the initial forming operation is completed, such as trimming and assembly.

SHRINKAGE: The phenomenon whereby a plastic decreases in size linearly and volumetrically as it is cooled. This term also refers to the inherent stress put into the extruded sheet during the manufacturing process.

SNAPBACK: A thermoforming technique that first pre-forms a bubble into a pre-draw box, then plunges a male mold into the inside of the bubble, and as a final step, vacuums the bubble onto the mold.

STIFFNESS: A measure of the flexibility or rigidity of a material. This value is usually expressed in terms of flexural strength or flexural modulus.

STRESS: Pressure applied to a given body to deform or fracture it.

SYMMETRICAL: An object having a mirror image of itself with respect to its centerline. One side of the part is identical to the other side.

SYNTACTIC FOAM: A combination of inorganic foam spheres in a plastic foam matrix. This material is used for making insulative plugs to prevent chill marks.

TEMPERATURE CONTROLLED ALUMINUM

TOOLING: Molds made with enclosed tubes buried within their surfaces that allow cooled or heated water or some other fluid to flow through them to control the temperature of the mold to within a few degrees Fahrenheit.

TENSILE STRENGTH: The pulling force required to stretch or break a given material. This value is usually expressed in pounds per square inch.

TEXTURE (GRAIN): The pattern embedded into the surface area of a sheet or part.

TRANSMITTED THROUGH: The condition where radiant energy given off an emitter goes through the object it is hitting rather than being absorbed or reflected off of that object.

THERMAL CONDUCTIVITY: The amount of heat in BTUs which can be conducted through one square foot of any material one inch in thickness, in one hour, with one degree Fahrenheit temperature differential across the thickness (Btu/hr/ft²/F/in.).

THERMAL EXPANSION (Coefficient of): The fractional change in length (or volume) a one inch object will expand or contract with a one degree Fahrenheit change in temperature. In ABS this value is approximately 5×10^{-5} per inch per one degree Fahrenheit change in temperature.

THERMOFORMING: A system of changing a flat sheet of plastic into a desired shape.

THERMOLATOR SYSTEM: A mechanical device that is used to regulate that temperature of a fluid that is subsequently pumped through heating or cooling lines embedded in a mold to control the mold temperature.

THINNING: The process of taking a finite area of a hot sheet of plastic and stretching it over a protrusion or cavity of a larger area and distributing the plastic over this larger area as best as possible.

TOLERANCES: The maximum and minimum dimensions that are required to allow a formed part to be functional.

TPO: Thermoplastic olefin. Essentially it is a polypropylene blended with and EPDM rubber.

TRIM: The excess material around a formed part that is not part of the finished product. This material is used for clamping or sealing purposes during the forming process.

UNDERCUTS: Those indentations or extensions from a formed part that prevent the part from being removed from the mold without providing some type of movable mechanism on the mold itself.

UNISTRUT: A U-shaped channel with a clamping bar inside of it that can be adjusted very quickly by sliding the clamping bar in either direction of the channel.

U V RESISTANT: The condition whereby a material, in this case plastic, will resist losing its physical properties when exposed to the ultra-violet rays of the sun.

VACUUM: The absence of atmospheric gas within some given system.

VACUUM BOX: A five-sided structure on which a heated plastic sheet can be draped over the sixth side and a partial vacuum drawn within the box to form an inverted bubble.

VACUUM FORMING: A method of using vacuum to force heated plastic against a mold surface.

VACUUM FORMING TECHNIQUES: The various sequence of procedures one can use to shape a heated sheet of plastic to the configuration of a mold.

VACUUM HOLES: The holes in a mold which air can pass through to allow the atmospheric pressure to force the hot plastic sheet against the mold.

VACUUM SEAL: The edge around a mold base that the heated plastic sheet is pressed against to allow a vacuum to be drawn and force the heated sheet against the mold.

VACUUM SYSTEM: The mechanism whereby air is removed from an enclosed chamber to create a vacuum.

VACUUM VOLUME: The size of the enclosed system in which the vacuum is employed. It also refers to the level of vacuum that is maintained within the system. Generally a large vacuum holding tank is employed to keep the inches of vacuum from being drawn down to low.

VOIDS: Small areas within a plastic matrix that have gas pockets instead of the solid plastic material that should be there.

VOLUME RESISTIVITY: The resistance of an electrical charge flowing through the solid structure of the material, in this case plastic.

WARPING: The condition whereby a part is dimensionally distorted from its originally formed shape.

WAVELENGTH: The distance measured from a point on an electromagnetic wave to the same point on the wave as it repeats its phase.

WAVELENGTH OF ENERGY: A measure of the type of energy given from various wavelengths of the electromagnetic spectrum. In plastics we are concerned with the infrared wavelength band of about .7 microns to about 100 microns.

WEATHERABLE PLASTICS: Those plastics that are resistant to physical degrading when exposed to the ultra-violet rays of the sun.

WEATHERABILITY: The ability of a material to resist losing its physical properties when exposed to sunlight.

WEBBS: Excess plastic material that is doubled up on itself and does not flow uniformly against a mold. It usually occurs on the corners of parts with small radii.

WOOD TOOLING: Molds made of wood that are usually used to make prototype parts.

YIELD POINT: That point of stress or strain which if reached will not allow the material to recover to its original shape. Its elasticity has been exceeded.

ZONES: Those areas in a heating oven that the temperature is controlled independently from other areas.

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