THERMOFORMING THREE DIMENSIONAL SET AND COSTUME ORNAMENT FROM THERMOPLASTIC SHEET

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ABSTRACT

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By Robert G. Dunton, Jr.

This study of the technique of thermoforming theatrical ornament was prompted by the appearance of vacuum formed ornament on the theatrical market. Because the thermoforming process and the ornament produced by this method seemed to have inherent advantages for stage use, this study was undertaken to determine if thermoformed ornaments could be easily and economically produced in educational and community theatre scene shops.

In the thermoforming process a suitable plastic is heated until it becomes soft and pliable. It is then formed by mechanical means or by differential air pressure into the desired shape, normally through the use of a mold. The simplest type of thermoforming, and the one most applicable to theatrical work, is that of vacuum forming.

Vacuum forming is of two types, straight vacuum forming and drape vacuum forming. In straight vacuum forming the thermoplastic sheet which has been heated to its forming temperature is placed over a female mold in

which small holes have been drilled in order to permit the evacuation of air from the mold. These holes are placed in sufficient number to allow the plastic sheet material to be forced into the details of the mold by atmospheric pressure. When the air is evacuated from the mold through the use of a vacuum pump, the plastic is immediately formed in the desired shape.

In drape vacuum forming a male mold is used and the heated sheet is first draped over the mold before the vacuum is applied to form the sheet.

After contacting various thermoplastic sheet suppliers, it was determined that a low cost thermoplastic termed Styrene was a suitable plastic for thermoformed objects to be used on the stage. This material in thicknesses from .0010" to .0020" was found to be from three to four times cheaper than the thermosetting plastic material known as Celastic used in many theatre shops. It was determined that the economical use of the material would then be directly related to the cost of suitable equipment for use in forming the plastic sheet.

After reviewing the literature on the process of thermoforming, many commercial plastics companies were contacted and their literature reviewed. It was determined that the most economical commercially produced equipment for thermoforming was beyond the reach of most educational and community theatre budgets. Thus the essential problem involved in the study was to devise plans for a machine that could be inexpensively built in the theatre shop.

Utilizing the information gained in the review of the available literature, a machine capable of performing the techniques of vacuum forming and pressure forming was designed and constructed. The cost for the materials needed in the construction of the machine was approximately $71.00, from five to thirty-four times cheaper than commercially produced machines.

Operation of the constructed machine revealed that it was capable of forming many types of theatrical ornament with sufficient detail for use on the stage. Several discoveries were made relative to the improvement of the constructed equipment and its cost, but as their incorporation into the completed machine would have involved rebuilding the machine, they were not incorporated into the completed machine.

The study concludes that thermoforming is a technique which presents many advantages to the theatrical technician, the chief of these being almost infinite and rapid reproduction from one mold. In addition, the construction of a suitable machine for thermoforming is possible within the budget of most educational or community theatres, and the plastic sheet material required is relatively inexpensive.

Approved ______________________

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CHAPTER I

INTRODUCTION

Although we today tend to believe that the use of plastics is a comparatively recent technological development, plastics have been formed since the time of the Egyptian Empire. It is true that the big plastics boom which we are now experiencing dates primarily to the time of the second world war when plastics were developed to replace materials which were in short supply, but plastics have been in evidence throughout history. Thermoforming or heat forming of plastics is one of the oldest processes for shaping plastics. The process consists of heating thermoplastic sheets to their softening temperatures and forcing the hot and flexible sheet material against the surface of a prepared mold by either mechanical, air, or vacuum pressure. When the heated plastic is held to the shape of the mold and allowed to cool, the plastic retains the shape and the detail of the mold.

In ancient Egypt thermoforming was used to produce decorative food and beverage containers from tortise shell, about the oldest known thermoplastic.

The Egyptians found that this translucent, mottled, and warm yellow material would soften when placed in hot water and that in its softened state it could be formed into a variety of useful and decorative shapes which they prized very highly.

Since the time of the Egyptians the process of thermoforming has not changed greatly and today the basic principles used by the Egyptians are employed, although the plastics themselves have changed greatly. Through modern technology thousands of new plastics have been invented to fulfill many types of specialized purposes. More plastics are being developed daily, and it is said that we have not yet seen the beginning of the development of the true potential of plastics or of the plastics industry.

> Right now plastics are progressing through what might be called the Replacement Stage. They have proved better in thousands of applications than the materials of the past . . . plastics have been chosen because of superior performance in filling existing needs.
>
> But it is possible to see a new dimension - call it the Innovation Stage - when plastics will make possible things that have never been done before. New shapes, new designs, new applications stemming from plastic's astonishing and limitless versatility will permit a fluidity, a grace, a technological beauty of line and purpose that is sure to become the hallmark of a new way of life and a new American culture.[1]

When we consider the tremendous growth of the

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[1]Dudley-Anderson-Yutzey, "The Society of the Plastics Industry," <u>The New York Times</u> (May 26, 1968), p. 3.

plastics industry since World War II, the effect of plastics on our culture and our daily lives, and the role of plastics in replacing and improving so many of the common and specialized products in our society, it is difficult to understand why plastics have not made a greater in-road on the technical and design aspects of the theatre. It has only been in the last five years that plastics have been produced for use on the stage. Probably this lack of the use of plastics is the result of three main factors. The first of these is the lack of any significant research centers or money for the development of these centers or research projects in the field of technical theatre. The second has probably been the thought that plastics are expensive and of a more permanent nature than is desired for use on a stage that we think of as less permanent than plastics, while the third is probably related to the comparatively small purchasing power of the theatre as opposed to the rather considerable market provided by the television and display industries. Therefore, those developments that have been made in this field have been directed primarily to these latter markets. Little thought has been given by theatre workers to the economical advantages of plastic in the reproduction of various set and costume ornaments, or even to the cost of their initial production. Plastics have many advantages over other stage materials that make them an excellent material for use on stage. Low cost plastics such as Styrene[2] cost approximately .50¢-.70¢ per square yard, while light weight Celastic[3] costs approximately $2.13 per square yard. This represents a saving of approximately $1.43 to $1.63 per square yard, or enough to buy three to four times the amount of plastic for the same price as an equivalent cost amount of Celastic. Nor does this take into account the cost of solvent for the Celastic. There is also the advantage of weight. While Celastic is not a heavy material, plastic is somewhat lighter, while it is much lighter than many of the other materials used to produce properties and set ornament on the stage, i.e., wood, plaster, asbestos, plastic wood, etc. Plastics are also more durable than many of

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[2]Styrene: Polystyrene: A water-white thermoplastic produced from coal tar and petroleum gas. Styrene is considered to be an ideal material for vacuum forming. Many types of modified styrenes are also produced and are used for forming the interiors of most refrigerators.

[3]Celastic: A waterproof thermosetting plastic impregnated on fabric which, when immersed in a solvent such as acetone, methylethyl keton or methyl acetate for a few seconds immediately becomes self adhesive and at this stage is soft and moldable as a wet fabric. Within a half hour most of the solvent evaporates from the Celastic and it then takes on a stone-like hardness and permanently holds its new shape. Celastic is available in three standard weights: thin, medium, and heavy. Celastic Manufacturing Company, 609 Schuyler Avenue, Kearny, New Jersey 07032.

these substances. A larger advantage of plastic, however, lies in the ease of production of plastic pieces. Making the original mold for a thermoformed product may take as long as making the finished object by one of the conventional means of production if an actual object that can be used for a mold is not available, but reproductions from the mold can be produced in less than a minute. Wood properties require a great deal of preparation and plaster requires time in molding, mixing the plaster, and setting. Celastic requires the molder to work the material into all the recesses of the mold and the solvents are sometimes unpleasant to work with. Plastic molding is rapid, is not unpleasant, requires little or no finishing except paint, and is usually of a generally higher quality than any of the above methods of reproduction.

CHAPTER II

EXPLANATION OF THE PROBLEM

The Purpose of the Study

Assuming that the foregoing principles are true, the purpose of this study was to determine whether the thermoforming of plastics could prove to be an inexpensive means of swiftly and dependably producing stage properties and set and costume ornament in the non-professional theatre operating on a low budget. It was hypothesized that this method could be proved to be a faster and easier means of production than the methods currently being used in the non-professional theatre. Considering the cost factors already presented, it should be fairly obvious that the cost of the materials would certainly be cheaper than the materials currently being used. The deciding factor then becomes the cost of the machinery to be used in forming the plastic into the desired shape.

Limitations of the Study

Because the chief factor in determining whether thermoforming could be proved to be an inexpensive and fast means of producing and reproducing stage properties and set and costume ornament lies in the cost of construction of a machine for thermoforming, the study is chiefly concerned with the development of an effective machine for this purpose. The study is limited to the development of thermoforming equipment that could be "home made" by the theatre technician. Because there are numerous types of plastics and many methods of finishing them, with many different processes and types of paint, detailed consideration of these methods was not within the scope of this study.

Definition of terms

Thermoforming. Thermoforming is a relatively simple process of heating a plastic sheet, then forming it to conform to the shape of the product by either a differential air pressure or via mechanical means. To properly understand thermoforming, one must be familiar with the large variety of operating techniques used in the process. These techniques include vacuum forming (Figure 1), drape forming (Figure 2), match mold forming (Figure 3), slip ring forming (Figure 4), plug assist vacuum forming (Figure 5), plug assist pressure forming (Figure 6), vacuum snap-back forming (Figure 7), pressure bubble immersion forming (also known as billow forming) (Figure 8), trapped sheet, contact heat, pressure forming

(Figure 9), and pre-heat plug assist pressure forming (Figure 10). The use of the term forming in plastics technology does not include such operations as molding, casting, or extrusion in which shapes or articles are made from molding materials or liquids or materials which cannot be easily reheated and reformed.

Stage properties. Stage properties are considered to be any decorative or practical element used on the stage as a part of the stage picture which is a part of the design but which is not permanently attached to the setting, i.e., bottles, lamps, ashtrays, books, pictures.

Set ornament. Set ornaments are considered to be any decorative pieces which can be affixed to the stage setting itself. These might include moldings, picture frames, stair spindles, fireplace moldings or any other permanently or semi-permanently attached decoration.

Costume ornaments. Costume ornaments are decorative elements such as jewelry, armour or armour decoration, shoe buckles, masks or any other rigid costume element which is used to enhance or complete the costume design.

Non-professional theatre. The non-professional theatre is to be considered as any theatre group in which the actors do not consider acting as their sole means of livelihood. This generally is to be taken to mean the educational and community theatre organizations.

Inexpensive. Inexpensive is to be defined as less expensive than commercially produced products or the cost of an article which can be produced from materials which are initially less expensive than those presently being used in the non-professional theatre.

Thermoplastic. A thermoplastic is a plastic or moldable material which is capable of being repeatedly softened by heat and hardened by cooling. Thermoplastics are to be distinguished from THERMOSETTING plastics which are plastics which undergo a chemical reaction by the action of heating, catalysts, or ultraviolet light which lead to a relatively infusible state. Thermosetting plastics cannot be reheated and reformed as thermoplastics can. Throughout this paper, the word PLASTICS is used to indicate thermoplastic materials as distinguished from thermosetting plastic materials.

Three dimensional. The term three dimensional is a rather misleading term when it is applied to the processes of thermoforming. The term generally means an object which has the dimensions of height, width, and depth or the impression of various distances. This is true of the thermoformed product also, but the thermoformed product does not have the quality of solidity which we normally associate with the three dimensional object. When the thermoformed object is viewed from the back, it appears simply as a negative mold of the front view of the object. This is an extremely important factor when considering the use of the thermoformed object on stage, for a stair spindle, for instance, will look like a solid stair spindle only for 180 degrees or possibly less. If we look at it from the rear it will look like a negative image of a stair spindle. This is generally true for most molded articles unless the molding is completely encapsulated by the mold. In order to make an article appear completely solid it would be necessary to join two halves of the thermoformed object, but this is a somewhat difficult task when we attempt to join surfaces of .00010" - .025" together. If the object has square corners, two molds of the object may be used by placing them next to each other when forming. The two can then be easily folded together, but this is impossible if the two objects have irregular edges. Flaps may also be built into the product if possible. These then provide more surface area for joining if these flaps are not objectionable in the final product. Perhaps the best way to think of the three dimensional possibilities of the thermoformed object is in terms of bas relief. This should be an important consideration when the designer or theatre technician contemplates thermoforming an object for use on the stage.

CHAPTER III

DESIGNING THE THERMOFORMING MACHINE

When designing the thermoforming machine the designer's first consideration must be the use of the finished product. For work on the stage there are several important considerations that differ from those that we would consider in designing a machine to produce a commercial product. The first of these is the fact that the object will be viewed by the audience from a reasonable distance and does not have to stand close inspection. Therefore, minor imperfections can be tolerated by the theatre technician. Secondly, the most important consideration is that the object is seldom required to duplicate the original but needs only to look like the original object from the point of view of the audience. Therefore, in most situations we do not have to be concerned with the problem of solidity as previously mentioned. This is not to say that some objects may not have to appear solid, however, for in the arena situation the audience may be seated on all sides of the object. Generally these considerations tend to eliminate the necessity for the use of the more complicated forming techniques such as plug forming. The normal thermoforming methods that would be

applicable to stage work would then be those of vacuum forming, blow or pressure forming, and drape vacuum forming. Probably the most useful of these is that of drape vacuum forming as it enables the theatre technician to create a positive or male mold rather than a negative or female mold. It is usually easier to create a male mold than a female mold as the molder can determine exactly what the final product should look like rather than having to work in reverse. These considerations lead us then to a determination that the best type of machine to design would be one which could utilize the three techniques mentioned above: drape vacuum forming, pressure of blow forming, or vacuum forming.

The next consideration in the design of a thermoforming machine must be the type and size of plastic to be used in the machine, this being a determination of the size of objects that the theatre worker wishes to form and the amount of money available for the construction of the machine. It would be best if the theatre worker could construct a machine that would be capable of forming any size of plastic but this is both difficult and expensive to accomplish, although it is possible.

A discussion of the many types of plastics available for thermoforming is beyond the limitations of this paper but the chart below will provide a basic idea of the various types.

CHART I

GUIDES TO SELECTING THE PROPER PLASTICS[4]

Type of Plastic	Characteristics	Forming Applications
ACRYLIC	Wide range of colors from transparent to opaque. Unaffected by most chemicals and solvents except strong oxidizing acids, acetone, and lacquer thinner. Odorless, tasteless, non-toxic. Excellent shatter resistance, excellent resistance to outdoor weathering and indoor aging, 1/2 to 1/3 the weight of glass, rigid, good impact strength, exceptional optical properties, good light transmission, good heat resistance for a thermoplastic, burns about like wood. Should be sawed rather than sheared, machines like wood or soft metals. Very even thinning during forming, not as flexible when heated as some plastics, preheating time for forming not too crucial, will not take very intricate shapes except in mechanical forming, good plastic memory.	Cast acrylic is preferable for free blowing. Satisfactory for mechanical stretch forming of shallow draws. Satisfactory for vacuum and blow forming with molds on shallow draws with less complex shape and detail.
RIGID VINYL	Wide range of colors from transparent to opaque. Unaffected by many chemicals, poor resistance to organic acids. Odorless, tasteless, non-toxic. Good impact strength, fair resistance to outdoor weathering, excellent resistance to indoor aging,	Very good for vacuum and blow forming. Especially good for deep drawing by any means.

CHART I (Continued)

Type of Plastic	Characteristics	Forming Applications
	rigid, good optical qualities, flammability self-extinguishing. Can be sheared, machines well. Exceptionally even thinning during forming, heating time not too crucial, exceptional deep drawing qualities, exceptional plastic memory.	
CELLULOSICS (CELLULOSE ACETATE) (CELLULOSE ACETATE BUTYRATE)	Wide range of colors from transparent to opaque. Decomposed by strong acids and alkalies, only slightly affected by weak acids and alkalies, little affected by hydrocarbon. Odorless, tasteless, non-toxic, except fresh butyrate sheet which has an odor. Excellent resistance to indoor aging, fair resistance to outdoor weathering, good impact strength, good optical qualities, slow burning, some types self extinguishing. Can be sheared or sawed, machines well. Some tendency to "web" at corners in forming, heat and heating time critical, tends to bubble and lose clarity when overheated, only fair deep drawing properties, butyrate superior to acetate in most forming qualities, careful design and control will eliminate most of the above shortcomings.	Satisfactory for vacuum and blow forming with molds. Satisfactory for medium draws by mechanical means. Commonly used in transparent sheets for food packages.

CHART I (Continued)

Type of Plastic	Characteristics	Forming Applications
STYRENES	Wide range of colors from transparent to opaque, except a high impact type which is not available in transparent. Unaffected by many chemicals except oxidizing acids and aromatic and chlorinated hydrocarbons. Odorless at room temperature or below, tasteless, non-toxic, strong odor if overheated. High impact type exceptionally good resistance to sharp blows, tough, durable, slow burning, very stable at low temperatures, only fair resistance to outdoor weathering, tends to yellow with indoor aging. Can be sheared, tends to "gum" in sanding. Exceptionally flexible when heated for forming, some tendency to unevenness in mechanical forming, exceptionally fine detail possible, rather poor plastic memory, lowest cost of the thermoplastics.	Very good for vacuum and blow forming with molds. Not particularly suited to free blowing. Fair for deep drawing by mechanical means.

[4]Di-Acro, How to Form Plastic Sheet Materials with the Di-Acro Plastic Press (Lake, City, Minnesota, 1967), p. 9.

Determining the size of the machine is dependent on the size of plastics available. It is best to determine which plastics are readily available to you by contacting your local sheet supplier in advance of designing the machine. Generally plastic may be purchased either as sheet stock or as roll stock. Roll stock is usually available in widths based on even footage although odd widths are available if you order a sufficient quantity. With roll stock, of course, the length can be whatever you wish. The same is not necessarily true of sheet stock, however, but many various widths are available. Vinyl, for example, is often produced in both 20" x 50" and 21" x 51" sizes. Styrene is often produced in 20" x 40", 24" x 24", and 40" x 72" sheets. It is therefore very important to first decide the size and type of sheet that you plan to use before attempting to construct a machine unless you find it possible to construct a machine that will adapt to varying sizes of plastic sheet. The use of styrenes, however, is recommended as they are the cheapest plastics available which are well suited for vacuum forming.

Type of machine

There are many types of vacuum forming machines and they all have their own distinct advantages. It should be noted here that this paper has concerned itself with the construction of a "machine" as distinguished from an apparatus. The machine concept is one in which all the elements necessary to the vacuum forming process are included in one device. This is not absolutely necessary for successful vacuum forming to be accomplished. It is possible to use elements that are separate from each other. That is, the heater and the forming table do not have to be a part of the same device. For instance, it would be possible to heat the thermoplastic sheet in an ordinary oven and then transfer it by hand to the forming table where it would then be clamped and formed. This, in fact, is the general procedure used in the construction of outdoor sign faces. This method makes it easier to adjust the size of the formed part[5] as only the top half of the clamping frame is needed, for the platen or vacuum chamber collar can serve as the bottom half of the clamping frame. The exposed portion of the platen can be blocked off with polyethylene sheet to prevent loss of pressure. However, this type of production does not lend itself to the most rapid reproduction of the formed part and was therefore eliminated from consideration by the writer. Other

[5]This adjustment of course can only be a reduction in size from the maximum size of the platen.

types of machine design might be those of: (1) the upmoving platen or the down moving clamping frame wherein the two elements meet by a straight upward or downward motion. This is probably the best type of design, as it enables the sheet to stretch evenly over the entire mold while the swing clamping frame stretches unevenly over the mold as it hits one side of the mold first. (2) The swinging clamping frame may be one in which the clamping frame is hinged to the table and is swung from the heater to the platen or it might be one in which arms are used as the hinging device to enable the clamping frame to descend on the mold with a movement closer to one of ninty degrees. The use of the upward or downward motion of the clamping frame or platen was eliminated from this design due to the fact that they require more mechanical elements in order to accomplish this motion and thus they are more complicated and more expensive designs for the theatre worker to construct. The design on which this researcher decided was one with the hinged arms which is relatively easy to construct and which allows the plastic to drape over the mold from an angle of approximately sixty degrees, dependent on the height of the mold.

The heater also can be brought into position in many different ways. It can be swung over the sheet, or it can travel over the sheet, or the sheet may be moved under or over the heater. The use of the hinged clamping frame, however, pretty well dictates the use of a permanent heating element over which the clamping frame can be moved and this is the method used in the design explained in this paper.

General Considerations in the Design

Because the thermoforming operation is dependent on heat and the heating of the thermoplastic sheet, all of the fixtures for the production of the formed part should be designed with consideration to the conservation of wanted heat and the elimination of cooling influences. Heat should not be conducted away from places which need to be warm or hot. This means that all surfaces which conduct heat should be insulated. For this purpose asbestos sheet, rubber gasket material, phenol formaldehyde, or asbestos cement is used. The heater should be insulated and the clamping frame should be insulated from the thermoplastic sheet. An attempt should be made to keep the mold and the platen warm and all air drafts should be kept from the machine.

Heating. Probably the most difficult consideration in the development of a thermoforming machine is determining the method of heating. Most plastics become plastic at a temperature around 375 degrees F. If a heating temperature of approximately 400 to 500 degrees F. can be maintained, there is little difficulty in rapidly heating the sheet for forming. The difficult problem, however, is in determining the method of heating. When working with electricity, the technician will find that there is no clear relationship between the wattage of a particular heating element and the amount of its heat output. Many types of heating elements are available and some are more efficient than others, but very few are rated in terms of their heat output. Therefore, any estimate of the wattage output necessary to heat a sheet of plastic to its forming temperature can only be taken as a general indication and cannot be relied upon as an absolute. The best that the technician can do is to proceed on the recommendations of various manufacturers and be prepared to add heating elements if necessary. Estimates of the amount of wattage necessary to heat a sheet of thermoplastic to its forming temperature range from five to twenty-five watts per square inch. It was found that a watt density of approximately nine watts of infra red radiation per square inch from 375 watt R/40 bulbs was sufficient for this experiment. That is not to say, however, that a high watt density might not be more desirable. These lamps were operated at maximum temperatures. It would be preferable to use more lamps and operate them at lower temperatures, to obtain maximum efficiency.

Spotty heating is sometimes a problem when heating the plastic sheet and this can be overcome by shielding the plastic from direct radiation by placing an absorbing plate between the lamps and the plastic. This sheet will then absorb the heat and re-radiate it at a lower temperature. This technique was not found to be necessary in connection with the design of the machine explained here, nor with the forming of any objects yet formed on the machine.

In order to preferentially heat the sheet in areas that you may or may not want to stretch and become thinner, it is possible to place a large chicken wire screen under or over the heater on which pieces of ordinary screen wire can be placed for preferential heat treating of the sheet. These pieces will absorb some of the heat and prevent the plastic from heating evenly.

Another method of insuring uniform heating over the entire surface of the platen sheet is to use stainless steel reflectors to radiate the heat uniformly.

The size of the heater should be slightly larger than the maximum forming size of the clamp. This is necessary to assure even radiation of heat and to allow the clamping frame itself to be heated so that it does not conduct heat away from the plastic sheet. This undesirable heat conduction can also be prevented by insulating the clamping frame itself from the plastic sheet by the use of a gasket.

In order to control the radiation of heat from the heater it is also desirable to make the distance of the heater from the plastic adjustable if possible so that the heat can be controlled.

The best heaters also produce a higher watt density pattern around the edges of the sheet and have a cooler center in order to help overcome cooling side drafts and heat escape from the clamping frame.

The Clamping Frame. The clamping frame is used to hold the plastic sheet in position for heating and for forming. It is most important that the clamping frame be tight on most types of plastic sheet. If the frame is not tight on the plastic sheet, it is likely that the sheet will pull loose from the clamping frame. If this happens, the sheet will not form a tight seal with the platen and the vacuum chamber so that the vacuum or air pressure will escape and the sheet will not form well. Plastic sheet often shrinks upon heating because most sheet is pressed into shape in the manufacturing process. If the sheet can be held tightly in the frame, it will not shrink from the edges of the clamping frame. If the sheet is held in the clamping frame and upon contact with the mold does not form well, the sheet can be reheated and reformed. Upon heating it will return to its original shape due to a particular characteristic of plastic called "plastic memory." If the grip of the clamping frame on the sheet is broken, however, the edges will not be held and the sheet will not return to its former shape because of the original pressing process used in its manufacture.

In the construction of the clamping frame, extruded aluminum is recommended because of its weight and because it will not tend to conduct the heat away from the sheet as much as a steel clamping frame. However, fabricating aluminum, and particularly welding aluminum, would be very difficult in most theatre shops. A steel clamping frame, if it is adequately insulated, will be found sufficient for most purposes.

Another desirable feature of the clamping frame is that it be adjustable in length and width in order to accomodate different lengths and widths of plastic sheet stock and make possible different clamping and mold areas. This, however, is difficult to accomplish practically in the design of a thermoforming machine as it also demands that some adjustment be made with the platen in order for it to form a tight seal with the clamping frame.

The clamping frame must be adjustable in depth in order to clamp plastic sheet of different thicknesses. The maximum thickness of sheet effectively formed by the thermoforming process is considered to be 1/4 inch, so the thickness should be variable from 0 to 1/4 inch.

The clamping frame may be lined with a gasket of sponge rubber, cork, or asbestos to insulate the plastic sheet from the frame and to better hold the sheet in the clamping frame itself. If none of these substances are used, the clamping frame itself may be roughened or a bead may be welded along the edge of the frame to better hold the sheet tightly in the clamping frame.

The Platen. The platen is the surface upon which the mold is placed or of which it is a part and upon which the plastic rests when the sheet is being formed. Plywood, masonite, and hardboard are often used for the platen and the vacuum chamber. If the platen is large, it should be constructed of a material of a thickness sufficient to practically eliminate deflection of the platen. The platen may be reinforced with 2" x 4"'s, if necessary, to eliminate deflection. When using plywood, masonite, or regular lumber stock, all the joints should be caulked before assembly. The edges should not be glued, however, as the glue will often deflect and crack, thus allowing the vacuum or air pressure to escape. The outside of the seams can also be scotch taped to further protect the platen from leaks. A ridge of some kind should be built into the platen in order to provide a more efficient seal between the sheet and the platen. Air holes in the platen should not be more than 0.04 inches.

The Surge Tank and the Pump. Most commercial machines incorporate a surge tank located in the air-line between the pump and the platen. The surge tank is used to contain either the reserve vacuum or the air pressure necessary to form the plastic sheet after it has been heated and to provide this pressure rapidly. Thus, pressure in the surge tank is built up to a point greater than actually needed for forming in order to permit rapid forming when the operator opens the line. Ordinarily, 28 pounds of vacuum pressure per square inch are provided with only 14 pounds per square inch normally required actually to form the sheet.[1] The surge tank is usually one and one-half to two times the capacity of the vacuum chamber. A galvanized hot water tank or cold water pressure tank can be used and some commercial machines even use small oil drums. If a surge tank is used, it should allow for a water drain and a vacuum or pressure guage, while air, water, and oil filters are desirable accessories. The surge tank should have one-and-a-half or two-inch pipe connections to connect to the vacuum chamber.

The pump may be a rotary pump or a piston pump. Milking machines may be used for pumps and can often be bought second hand at farm sales. A two stage compressor used in reverse with the connection made at the intake is also a possibility for use. This would be particularly handy if the theatre had paint spraying equipment. It was found, however, in this study that an ordinary vacuum cleaner supplied more than enough vacuum or air pressure necessary to form heated sheet 24" x 27" in size and from .010 to .020 in thickness. The vacuum cleaner can be permanently connected to the vacuum chamber or a one-inch pipe nipple can be installed below the valve at the vacuum chamber. Over this nipple the hose from the vacuum cleaner can then be easily connected.

Valves. Valves should be provided within arm's reach of the operator to control the vacuum or air pressure as it enters the vacuum chamber so that the operator can easily control the forming of the heated sheet. In a sophisticated machine two valves would be supplied so that both air pressure and vacuum could be controlled by the operator. In this case the operator might use the vacuum valve to control the forming of the heated sheet and the air pressure valve to help release the formed sheet from the mold.

Tooling for vacuum forming. The type of tooling used for the thermoforming depends upon (1) the material, (2) the article to be produced, (3) the number of units required, and (4) the desired properties of the finished product in terms of thickness, strength, and strain areas.

Positive molds are preferred as they give sharper detail, are easier to produce, and produce more normal stability of the formed part. Rapid changes in sections of the mold must be avoided because of a characteristic of plastic called "notch sensitivity" which simply means that ninty degree angles and sharp corners crack easily. Steps and right angles are particularly dangerous in this connection.

Any plastic sheet material is stretched when it is formed. Naturally it becomes thinner, and in vacuum forming this thinning will be greatest at the area of the deepest draw. To minimize this reduction in thickness for a given depth of draw, adequate draft[6] should be built into the mold to provide a thicker, stronger, and stiffer formed piece. This will also facilitate the removal of the formed piece from the mold. Generally this draft should be from fifteen to thirty degrees, depending on the depth of draw from one and one-half to five inches.

Often existing objects can be used for molds. When this is done it is usually preferable to examine

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[6]Draft: The angle or taper from the perpendicular of the sides of the mold. Adequate draft insures smoother forming and easier removal of the formed part from the mold.

the object closely to see where the sheet may be pulled into or around the mold, making it difficult to remove it from the sheet. This can be corrected by placing the object in a bed of clay and placing clay in any recesses which may be classified as undercuts. It is possible to predict to some degree the action of the heated sheet on the mold by placing a piece of polyethylene film such as a plastic cleaners bag over the mold, turning on the vacuum, and observing the action of the film.

Materials for Molds. As mentioned above, it is possible that existing objects may be used as molds when they are properly used. In addition many other materials may be used to construct molds.

When using wood for molds, close grained woods should be used if a large number of reproductions are to be made. The wood should be both dry and hard. Mahogany, maple, birch, and plywood are often used. The wood should be sealed with synthetic resins, high temperature varnish, or casein. Regular varnish or shellac should not be used as it will melt on contact with the hot sheet material. The side grain of the wood should be used when possible. Masonite and compressed woods may also be used.

Ordinary modeling clay may be used for a mold, but it is suitable for only one forming cycle (Figure 25).

Ceramics are another type of mold material used in the thermoforming process. These include regular ceramic materials and special plasters. Ordinary plaster of Paris is sufficient for several moldings but will not stand up under numerous reproductions. When these molds are complex, it is possible to reinforce them with florists screen, nails, or crumpled masses of chicken wire placed in the set plaster in order to give strength to the mass after the plaster has set.

Plastic materials may also be used, but their use is much more specialized. Briefly, those plastics generally used are cast phenolic resins, epoxy resins, and filled polyesters.

Vacuum Holes. Vacuum holes in the mold are necessary to permit the sheet to be drawn into the crevices of the mold. The number and size of these holes to be drilled into the mold will depend upon the contours of the mold, the type and thickness of the sheet material, and the desired depth and rate of draw. The diameter of vacuum holes should range from .0060 to .0010 inch, depending on the thickness of the sheet material used, and whether or not the finished product will show the image of the vacuum hole. Each vacuum hole should be back drilled to within one-eighth inch of the surface with a large diameter drill. The holes should usually be spaced two to three inches apart in large flat areas while holes should be placed possibly as close as one-quarter inch apart where fine detail is needed. If desired, slits may be substituted for vacuum holes. If insufficient detail is obtained in parts of the product, and there seem to be enough vacuum holes, the vacuum holes should be checked to be sure that they are all open before the decision is made to add more heat to the sheet. If all the holes are open, then the sheet is probably not hot enough.

CHAPTER IV

CONSTRUCTION OF THE THERMOFORMING EQUIPMENT

When this researcher contemplated the construction of thermoforming equipment, first consideration was given to thermoforming techniques that would be most applicable to stage work. It was decided that an attempt would be made to design a machine that would accomplish as many of the simpler thermoforming techniques as possible. This meant that an attempt would be made to construct a machine capable of vacuum forming, drape vacuum forming, and pressure or blow forming. This was accomplished by designing a removable platen that could be removed for vacuum forming or pressure forming and could be used for drape vacuum forming when it was in place. Pressure forming can also be accomplished with the platen in place. In order to keep the length of the hinged arms from being too long and unwieldy, and to keep the machine as compact as possible, it was decided to make the vacuum chamber capable of forming to a depth of 5 1/2 inches, or the depth of a standard piece of 1" x 6". This depth could be increased, however, by constructing the vacuum chamber beneath the surface of the table.

The next consideration was the size of the clamping frame. This researcher decided on a size of twenty-four inches by twenty-seven inches because this is the approximate size of half a sheet of Cinabex, and a decision had been made to attempt the forming of this material. It was later decided that this size was a poor selection as it was difficult to procure styrene or rigid vinyl sheet stock that could be cut to this size. This researcher would recommend that anyone attempting to build thermoforming equipment capable of thermoforming Cinabex build a machine capable of forming a standard size of plastic such as styrene in twenty-four by twenty-four inch size and then cut the Cinabex if he desires to experiment with forming this material. Of course, Cinabex is no longer being produced, and the technician might consider that the size of the replacement material, said to be called Majoroid, may not be produced in the same dimensions as Cinabex. This may also influence the selection of a size for the clamping frame and the machine.

The hinged type clamping frame with arms eighteen inches in length was used because it was considered to be the easiest type of machine to construct. The arms were made eighteen inches long because this gave a movement as close as possible to ninty degrees and still made it possible for the platen and the heater to be placed close together. Determining this length for any machine is mostly a trial and error process, although the designer must realize that in order to get a smooth and effective movement of the clamping frame, the base plate for the arms or the center of their radius should be approximately one-third of their length below the platen. Thus, for arms of twenty-four inches, the platen should be approximately eight inches high, or eight inches above the base plate of the arms.

The Machine Table. The machine table was constructed of 3/4-inch plywood four feet wide by six feet long (Figure 11). Plywood was selected because it is a standard material in the theatre shop and because it is easily worked. The table would not have to have been four feet wide or six feet long, but it was felt that this would allow space around the machine on which the theatre worker might wish to place equipment with which he was working, and because the surface area would make it possible to alter the relationship of the various elements if this was found necessary in the construction of the machine. If the theatre worker wished to duplicate the principles used in this design, it would be possible to construct a machine with table dimensions of two feet eight inches by five feet. This would permit the arms of the clamping frame to be mounted on the sides of the table and would eliminate the base plates.

This would also permit the heating unit to be mounted at the surface of the table and the vacuum chamber to be built under the surface of the table. Thus, the machine would be a little more streamlined in its design as the surface areas would be even with the surface of the machine. It would also eliminate the lumber needed to frame the heater above the table and would reduce the amount of asbestos needed to insulate the wood from the heater.

The Heating Unit. The heater was constructed in the shape of a rectangle with interior dimensions of twenty-three inches by twenty-six inches. This allowed the heater to be slightly larger than the exposed sheet in the clamping frame to make it possible to let the clamping frame sit on the surface of the heater but still leave a portion of the clamping frame exposed to the heater so that it could be partially heated to help eliminate the problem of its cooling the sheet by conducting the heat away from the plastic sheet. The heating box was constructed of number thirty gauge galvanized sheet metal (Figure 15) and although this material is relatively light, it was found sufficiently strong to support the infra red lamps and their sockets. The heater was constructed to a depth of thirteen inches to allow a distance of approximately five inches between the surface of the bulbs and the exposed thermoplastic sheet. Porcelain receptacles were used and were mounted on the surface of the sheet metal and wired with number fourteen asbestos insulated wire. Note should be taken here that IT IS ESSENTIAL TO SUPPLY A GROUND WIRE FOR THE HEATING UNIT TO ELIMINATE THE DANGER OF ELECTRIC SHOCK. The 375 watt R/40 infra red lamps were mounted two and one-quarter inches from the edge of the heating box and at evenly spaced intervals in order to provide for a high watt density pattern around the edges of the thermoplastic sheet. Those in the center of the heater were spaced approximately seven inches on center (Figure 12). This heating unit was found to be adequate for the purpose for which it was designed, but the theatre technician with more money at his disposal might want to use more than sixteen lamps on closer centers to assure more rapid heating of the sheet. Placing these bulbs in series with a dimming system would make it possible for the operator to control the amount of heat output for the heating of thermoplastic sheet of any thickness.

It should be stated here that other types of heating elements are undoubtedly more effective than the infra red bulbs used in this design. The bulbs, however, have the advantage of being easy with which to work. If the theatre technician wishes to use a different type of heating element, he will find it difficult to determine the amount of wattage needed in the heating element to produce the amount of heat required to heat the plastic sheet to its forming temperature. Additional experimentation in this field would prove valuable for anyone wishing to construct a thermoforming machine, however. One source of heat that might prove effective for this purpose might be old broiler units from an electric oven. Experiments with heating plastic sheet under the broiler of an ordinary oven have shown that the broiler unit provides a rapid means of heating the plastic sheet. Broiler units from an old oven would eliminate the cost of the infra red bulbs and considerably reduce the cost of the entire machine. However, the size of the broiler units would then determine the size of the heater and, to a large extent, the size of the thermoplastic sheet used in the machine.

Power required to operate the heater was two circuits of 110 volts rated at twenty-five amperes each. In a permanent setup, it would be best to operate the machine on 220 volts. The lamps were wired in four parallel circuits and then combined into two twenty-five amp circuits of 110 volts each.

The Clamping Frame. The clamping frame was made in two pieces which were then hinged together (Figure 13). The bottom half of the clamping frame was constructed of one-eighth inch by one inch angle iron. The material was measured to produce an inside diameter of twenty-four inches by twenty-seven inches. The technician should be careful when constructing this half of the clamping frame to allow some extra space for the thickness of the angle iron and the fact that the angle iron is slightly round in the inside corner. Thus, the exterior dimensions of the bottom clamping frame should be close to one-quarter inch larger all the way around the frame to allow for this variation. After the sides of the clamping frame had been laid out on the stock, forty-five degree pieces were cut out of the stock where the corners were formed. The stock was then heated and carefully bent with the aid of a square to assure that all the corners were square. Then the corners were welded together and ground flat. These welds are best made if the edges of the two surfaces to be welded are first ground to an angle of forty-five degrees and the weld is made on the bottom of the frame.

The top part of the frame was constructed of 3/16" by 3/4" angle iron. The technician should be careful when forming this part of the clamping frame to fit the top frame into the bottom clamping frame and make sure that there is a clearance of approximately one-eighth inch around the edge between the two frames. When this piece is laid out the technician should carefully measure the position of the corners and then simply make a cut into the bottom foot of the angle iron so that the angle iron can next be heated and easily bent. The nature of these corners will require that the technician cut four approximately three-quarter inch squares and weld them into the corners of the frame. All welds on this part of the clamping frame should be made on the top portion of this frame to keep the bottom surface of the frame flat.

In order to construct the adjustable hinge, a piece of the one-inch angle iron stock was cut approximately one and three-quarter inches long. A slot approximately one-half inch long was cut in this piece starting approximately one-quarter inch from the bottom of the piece. A position approximately one-third of the way across the back of the bottom of the clamping frame was then determined (Figure 13) and a one-quarter inch threaded hole was made here. A one-quarter inch stove bolt with a lock washer was then used to bolt the angle to the back of the bottom clamping frame (Figure 13). By loosening this bolt the distance between the two halves of the clamping frame can then be adjusted to accommodate sheet stock of different thicknesses.

Next a piece of one-inch angle iron approximately two inches long was welded at one end to the top part of the clamping frame. This should be done while the top clamping frame is resting in the bottom frame, as there . be a ap of approximately one-quarter inch which have t e f l when this weld is made in order ake th ngle level.

ow a p of o inch bar stock was wel the ted pi sure that it would re traigh and d hen it was adjusted. The op of this pi was bev ed to an angle of forty-five degrees so tha would the upper part of the clamping frame be raise far as possible when the frame was open n order ake it easy to insert the thermoplastic t (Figur).

Next a e slightly larger than one-quarter inch, preferabl ive-sixteenths inch was drilled through both of these o inch angles at the center of the area where they join o that a one-quarter inch bolt could be inserted here which the two sections of the clamping frame could hinge (Figure 13).

Next, two pieces of one-inch angle iron were welded opposite the hinges on the bottom part of the clamping frame, making sure that they did not extend below the bottom surface of the frame. These were also mounted slightly below the surface of the frame to make it possible to exert more clamping pressure than if the angle was flush to the surface. Next, two pieces of one-inch angle iron were welded parallel to the bottom of the top part of the frame so that they would line up with the pieces welded on the bottom part of the grame (Figure 13). Again these should be welded while the top part of the clamping frame is resting in the bottom part of the frame as a section between the angle and the frame will again have to be filled when it is welded in order to allow the piece to be parallel to the bottom part of the clamping frame when it is completed. Now it is possible to clamp the two halves of the clamping frame together in the front opposite the two hinges by utilizing two spring clamps. For this purpose two battery clips were used. These proved to work very well and were inexpensive to purchase (Figure 16).

Finally, four three-eighth inch nuts were welded to the sides of the bottom frame to permit the swinging arms to be connected to the bottom clamping frame with three-eighths inch bolts (Figure 19).

After this welding has been completed, it will be found that the heat of welding has shrunk and twisted the metal slightly. In order to make the surfaces flat again, so that they will meet squarely, it will be necessary to bend the metal frames so that they correspond to each other. This is a trial and error process and can best be accomplished by setting the frames on blocks of 2" x 4" and jumping on the frame until by trial and error, and by fitting the two pieces together to check them, the two pieces are made to fit as flush as possible. Minor variations will be compensated for by the asbestos strips which should next be cut and glued to the two joining surfaces of the clamping frame (Figure 13). These can be adhered to the surfaces of the clamping frame with Permatex cement. The asbestos will not only compensate for the minor variations in the frame but will also help to hold the thermoplastic sheet to the frame by providing a rough surface which will resist the shrinking pressures of the thermoplastic sheet and at the same time insulate the thermoplastic sheet from the cold clamping frame.

Because of the variations in the surface of the clamping frame caused by the welding of the various pieces to the frame, it is recommended that the clamping frame be constructed with three hinges rather than two, and that the hinges be placed one on each corner and one in the middle of the rear of the clamping frame, and that the angle used for clamping be placed opposite those on the front of the clamping frame. This would better help to overcome the variation in the surfaces of the frame, as it appears that this variation occurs mostly in the corners of the clamping frame.

Swinging Arms. After the clamping frame has been completed, the arms can be constructed. These were constructed of 1/2" x 3/16" flat stock, eighteen inches long. A hole drilled at either end of these 7/16 inch in diameter will permit the arms to pivot on three-eighths inch bolts placed through them into the nuts on the frame (Figure 13) and through the base plates constructed of two-inch by one-quarter inch angle iron (Figure 16). The bolts should be inserted into the nuts on the clamping frame with washers in between to allow the arms to swing more freely. The base plates were simply drilled to accomodate the bolts for the swing arms and were then drilled on the opposite face so that screws could be inserted to attach the plates to the top of the machine table. Again, if the machine were constructed with a width of two feet eight inches, these plates would be unnecessary and the arms could be bolted directly to the sides of the machine table. This might also prove to be a little more smooth in the operation of the frame as the sides of the table would also serve to guide the arms and prevent some of the side sway inherent in this design. It was found that mounting the base plates of the two rear arms approximately 1/16" behind the position where they would normally be placed, determined by placing the frame on the vacuum chamber collar and extending the arms rearward after bolting them to the clamping frame, a tight seal between the rear portion of the frame and the chamber could be assured when the operator placed downward pressure on the handle of the frame and created an adequate seal on the front portion.

Although not really necessary, it was found easier to operate the machine if the clamping frame was counterweighted. This was accomplished by tapping a one-quarter inch hole just below the three-eighths inch bolt at the top of the swing arms. Into this was threaded a one-quarter inch eye bolt. The nut on the bolt was used to lock the eye into place against the arm (Figure 13). To the two eye bolts on either side of the frame were attached a short length of rope. A running pulley was placed on this rope and the pulley was connected to another length of rope which ran to an overhead pulley and a series of pulleys which led to the rear of the machine where a bucket of sand was used to counterweight the weight of the clamping frame.

The Platen and Vacuum Chamber. The vacuum chamber was constructed of one-inch by six-inch white pine (Figure 11) and was constructed to fit inside the clamping frame with approximately one-eighth inch clearance all the way around (Figure 16). The sides were caulked with ordinary caulking compound and then put together with one and one-half inch screws. The chamber was then screwed to the table of the machine after this joint was also caulked. A hole was then cut in the middle of the chamber area to accomodate a one and one-half inch pipe floor flange. The floor flange was screwed to the bottom of the table after caulking compound was placed between it and the table surface to insure a tight seal. A one and one-half inch floor flange was used because it was the only size available when the machine was built, and adapters then had to be used to use one and one-quarter inch pipe connections to the vacuum cleaner.

The platen itself was constructed of one-quarter inch hardboard because some of this material was on hand. 1/56 inch diameter holes were drilled in this material at one inch intervals (Figure 12). This was an attempt to construct a universal platen so that any object used for a mold could simply be placed on top of the platen and so there would be a sufficient number of vacuum holes close enough to the edges of any object so a separate platen would not have to be constructed for every mold used in the vacuum forming process. It would probably be possible and more desirable to place these holes at one-half inch intervals to enable a larger number of holes to be lined up along the edges of any mold used. These holes were back drilled with a one-quarter inch drill to assure smooth passage of air to or from the surface of the platen. It was found necessary to reinforce the platen with two pieces of 2" x 2" placed one-third of the distance across the length of the platen. In order to provide air and vacuum channels to the surface of the platen, one-quarter inch holes were drilled through the 2" x 2"'s wherever the holes on the platen came above them. These channels then permitted the differential air pressure to flow through these holes to the surface of the platen.

Finally, the platen was screwed to the surface of the vacuum chamber after first caulking the surface of the vacuum chamber. The 2" x 2"'s were screwed to the sides of the vacuum chamber with one and one-half inch screws. The use of screws makes it possible to remove the platen so that the vacuum chamber can be used for straight vacuum forming. If the air supply is reversed, it can be seen that the machine can also be used for blow or pressure forming. Thus, the machine has the potential for accomplishing all of the forming techniques for which it was designed.

Next a collar of 1" x 3" white pine was placed around the vacuum chamber (Figure 13) to provide a ridge on which the clamping frame could rest (Figure 16). This was placed three-eighths inch below the surface of the platen so that when the clamping frame rested on the surface of this collar, it would be approximately one-quarter of an inch below the surface of the chamber and an effective seal would be created between the sheet and the vacuum chamber. It was necessary to drill one-half inch holes into this collar over the screws which attached the platen to the sides of the vacuum chamber in order to permit the removal of the platen.

<u>The Vacuum Source</u>. Probably the most expensive part of any thermoforming machine would be the vacuum or air source. Because of this, one objective of this study was to determine whether a device as simple and inexpensive as a vacuum cleaner could be used. It was found that a household vacuum cleaner was more than adequate for the requirements of this machine, and, in fact, it was found desirable to reduce the amount of vacuum provided by the machine in some instances. In order to construct a more permanent machine, a one and one-quarter inch nipple was brazed to the intake and the output of the vacuum cleaner so that it could be attached to a coupling used to connect it to the vacuum chamber (Figure 17). It is necessary in this design to manually disconnect the vacuum cleaner and turn it around and reconnect it to switch from vacuum to air pressure or vice versa. It would be possible to connect the vacuum cleaner with a series of pipe and valves so that two valves could be manipulated to control the air or vacuum pressure, but this might prove to be a much more expensive way of handling the problem. Of course, the idea of the use of the vacuum cleaner was to determine whether a household vacuum cleaner could be used to provide the

vacuum and air pressure necessary for the operation of a thermoforming machine of this size. A regular vacuum cleaner would not have to be converted in the manner described above in order to operate the thermoforming machine. The vacuum cleaner hose could be slipped over a one-inch nipple to use the vacuum cleaner to provide vacuum or air pressure to the thermoforming machine. The vacuum cleaner could then also be normally used in its regular capacity. If the theatre technician desired to permanently attach a vacuum cleaner to the machine, a used vacuum cleaner could probably be purchased for a relatively low price at a vacuum cleaner sales center.

CHAPTER V

THE COST OF THE THERMOFORMING MACHINE

The total cost of the thermoforming machine as designed was approximately $71.00. This figure does not include incidental materials like screws and nails that the theatre technician could be expected to have on hand, nor does it include the vacuum cleaner, as it is assumed that he will have access to a vacuum cleaner. This figure is well below the cost of a commercial machine to accomplish the same thermoforming techniques. The most inexpensive thermoforming machine discovered by this researcher that can be compared to this design has a forming area of twelve inches by eighteen inches and is sold for $295.00.[7] Machines forming twenty-four inch by twenty-four inch areas run up to and above $2350.00.[8] These machines are certainly more sophisticated and desirable than the machine described in this study, but their sophistication is not necessary for most theatrical requirements. It is possible that by

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[7]Plastic Products Company of Utah, Catalog Number 4000 (2340 South West Temple, Salt Lake City, Utah, 1967).

[8]AAA Plastic Equipment Incorporated, Controlled-Step Vacuum Forming Machines (2215 W. Berry, Fort Worth, Texas).

using different materials, such as oven broiler units and other scrap materials that would normally be found in the theatre shop, a thermoforming machine based on the principles set forth in this paper could be built at a cost to the theatre well below $50.00. The following analysis shows that an inexpensive machine can be constructed in accordance with the definition listed in the limitations of this paper.

Cost Accounting of the Thermoforming Machine

CLAMPING FRAME:			
22# angle iron and bar stock	@	$ .30 per pound	$ 6.60
3 feet 36" asbestos sheet			.23
1 tube Permatex cement			.85
LUMBER:			
1 sheet 4' x 8' x 3/4" plywood			7.00
36' 1" x 6" #2 white pine	@	.10 per foot	3.60
12' 2" x 4" fir	@	.14 per foot	1.68
HEATER:			
16 375 watt R/40 infra red bulbs	@	$1.50 each wholesale	24.00
30' 14/1 asbestos insulated wire	@	.08 per foot	2.40
16 Porcelain sockets	@	.37 each	5.92
4 Romex connectors	@	.15 each	.60
10' ground wire	@	.09 per foot	.90
1 ground clamp	@	.50	.50

Cost Accounting of the Thermoforming Machine (Continued)

20' 12/2 rubber covered wire	@	.20 per foot	4.00
2 male plugs	@	.39 each	.78
10 1/2# 30 gauge galvanized sheet metal	@	.30 per pound	3.15
PIPE:			
1 - 1½" x 1¼" coupling			.85
2 - 1¼" x 2½" nipples	@	.30 each	.60
1 - 1¼" union			1.35
2 - 1½" x 3¼" nipples	@	.37 each	.74
1 - 1¼" valve			4.95
1 - 1½" floor flange			.45
		TOTAL	$ 71.15

CHAPTER VI

THE THERMOFORMED PRODUCT

There are many ways to finish the thermoformed product, both before and after it has been molded, and before and after it has been trimmed from the plastic sheet. There are also many ways to utilize the thermoformed product in the completed stage design. This area, however, is not within the limitations of this paper. It should be sufficient to say that most plastics can be finished with the casein paints used for general stage work, although many other types of paint can be used. In this connection, the designer might find that some plastics have two distinct surfaces, i.e., a matte surface and a glossy surface, and he will probably find it desirable to form his product with the matte side on the outside, as this will give him a better surface for the adhesion of paint. Thermoformed materials can be easily attached to set pieces through the use or ordinary masking tape. Many other types of paints and dyes can be used and different techniques are used with all of these materials. Other means may be used in finishing the thermoformed sheet also, methods such as reverse engraving, back painting, etching and silk screening are used.

These methods and the various materials used in the finishing of thermoformed products are largely dependent upon the types of plastic used in the forming process. Therefore, this area of the thermoforming process would benefit most from a complete and detailed study of the qualities of various plastic materials that could be used, and the methods of finishing them, thus providing the theatre worker with ideas for the creative use of plastics as a part of the total stage design.

The example of the thermoformed product in this study is a design created by Alan M. Armstrong, II, for the God mask required in "J. B.," written by Archibald MacLeish. An existing mask of gauze impregnated with glue was used as the basic mold. Clay and heavy twine were then added to this to complete the design (Figure 18). It was found that it was necessary to reinforce the back of the original mask with clay, styrofoam, and blocks of wood as the mask collapsed when subjected to the vacuum pressure. After this was done, the mask was easily formed in .0020 Styrene (Figure 19). The finished mask, painted with casein paint and shellaced, was used in the 1968 Michigan State University Summer Theatre Festival production of "J. B."

This mask could have been produced in many different ways. It could have been molded in clay and then formed in Celastic, paper mache, fiberglass, gauze and glue, or glue and felt. All of these methods, however, would have required that the theatrical worker mechanically form the materials over the mold. This would have required much more time and also more materials than were required by the thermoforming process. After the basic mold was created, only one minute was required for the actual forming of the mask, and this was accomplished without the use of irritating solvents or messy glues. Because this mask was molded partly in modeling clay, it was possible to form only one object from the mold, but if the mold had been created in a more substantial material, many copies of the original could have been produced at the rate of one a minute. It would also have been possible to create a more substantial mold by using the initial product as a negative mold to produce a final positive plaster mold which could have been used to mold further reproductions.

The cost of the material used to produce this mask was approximately thirty cents. Mass produced ornament, commercially produced, costs approximately ten times this amount, although it does have the advantage of not requiring the designer to produce his own mold or have his own thermoforming machine. To have taken this design to a commercial plastics forming company and request that they form the mask would have been even more expensive, probably prohibitively so. It would also have been less convenient and may have required more time of the designer than that required by the use of his own machine.

The distinct advantages of using this process, then, were a saving of time in production, not of the mold necessarily, but of the completed product, a cost less than the use of Celastic and of most other conventional materials, and ease of production. The mask produced was also of high quality and conformed to the exact wishes of the designer who made the mold himself rather than turn to the available products of a commercial producer.

Thermoforming plastic is not the answer to all of the designer's ornamentation problems. It cannot, for instance, compete in cost with the production of paper mache ornament unless the designer's time is taken into account as a cost factor. It is also subject to the three dimensional limitations explained in the definition of that term in the second chapter (pages 9-10). It does, however, provide a rapid and relatively inexpensive method of producing high quality ornament for use on the stage.

CHAPTER VII

EVALUATION AND CONCLUSIONS

It has been shown that an inexpensive machine for the thermoforming of plastic stage properties can be constructed in the theatre shop. It has also been shown that the thermoforming process is not only capable of almost indefinite reproduction or a formed part, but that that part which has been reproduced is produced more cheaply and with less effort than through most of the methods presently available to theatre workers. In the last few years several companies have begun production of plastic scenic and costume ornaments. It is the opinion of this researcher that these products may be too expensive for the community or university theatre to purchase. It should not be difficult for the theatre technician to see the advantages that his own thermoforming machine would give him. He could produce reproductions of his own design at reasonable cost with a minimum amount of effort. In this regard it is significant to note that the thermoforming process has advance possibilities far beyond its purely ornamental ones. C.B.S. Television in New York is currently producing vacuum formed scenic panels of approximately four feet

by twelve feet in size. These panels are formed in the shape of various textured wall surfaces, such as brick, stone, shingle, and clapboard. The thermoformed sheets are then stapled to a rigid frame such as is normally used in regular flat construction. The machine used by C.B.S. to accomplish this cost them approximately $45,000.[9] It is entirely possible that the theatre technician could build a machine capable of producing panels of this size much more inexpensively. It might even be possible that a machine of this size could be built in the threatre shop for under $500.00. This is not to say that it would be as refined as the machine used by the Columbia Broadcasting System, nor would it be capable of the variety of operations which that machine is, but it could certainly closely approach the capability of it in regard to most of its completed products.

This paper has concentrated also on the replacement value of the plastics and the thermoformed product as a substitute for the present methods of ornament construction and has not attempted to delve into the creative use of plastics on the stage. This is a sadly neglected area in the field of technical theatre. Some work has been done in the television, and movie, and display industries, but little has been done in the legitimate

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[9]Alfred E. Landolph, Purchasing Agent, Columbia Broadcasting System, Personal Letter (February 6, 1968).

theatre. Consider for a moment the various qualities of the following ideas: acrylic plastics have the ability to "pipe light." In the sign industry sheets of acrylic plastics have been etched with letters and the rest of the surface of the signs have then been opaqued. By placing a light at the edge of the sheet, and by introducing color medium between the light and the sheet, the color of the letters is made to change as the color medium is changed. What are the possibilities here of building flats of acrylic sheet and then changing their color by this process? Or how about flats made of acrylic plastic having wallpaper patterns engraved into them so that the color of the wall paper pattern could be made to change from moment to moment, or act to act?

Recently a refrigerator with a plastic door was introduced. The door appears to be a coppertone door until the housewife touches the handle of the refrigerator. At this point the light in the refrigerator goes on and the housewife can see through the door into the refrigerator to see what kinds of foods are there before opening the door. What might the possibilities be here for the use of plastic on the stage as a type of scrim? There are many other design possibilities in the field of plastics. Recently plastics coated with sponge rubber flocking and foil finishes have been introduced which hold promise for use on the stage. Plastics are available in many colors in addition to transparent and translucent materials. These hold much promise for use on the stage. Certainly the effect of light on transparent plastics could be extremely interesting and might prove to produce new effects which are not obtainable on the stage by any other means. Again, of course, the question arises as to who will do this research. This type of research is expensive. When the researcher does not know exactly what he will encounter, he must often work by the trial and error method. The cost to one person involved in this type of research is almost prohibitive. This study was found to be quite expensive because of several false starts. If this study has accomplished anything, the hope is that it will whet the curiosity of the theatre technician and show him that there are opportunities in the field of plastics. At the same time this researcher hopes that it will show that there is a potential here to be developed and encourage organizations to spend the money to promote this type of research in the theatre. This researcher believes that the academic theatre is often too concerned with historical research in order to determine past theatrical practices. Consequently, the future possibilities of the theatre are often neglected. It is true that we built on the past, but that does not mean that we have to live in it or conform to it. The theatre of tomorrow which we hear discussed today will not be built yesterday, but today and tomorrow. It is hoped that this paper can serve to point out where modern technology can be applied to theatrical practices in order to help stimulate the creative development of the theatre.

APPENDIX

FIGURE 1. STRAIGHT VACUUM FORMING.
The plastic sheet is clamped and heated. A vacuum beneath the sheet (A) then causes atmospheric pressure to push the sheet down into the mold. As the plastic contacts the mold (B), it cools. Areas of the sheet reaching the mold last are thinnest (C).

FIGURE 2. DRAPE FORMING.
The plastic sheet is clamped and heated (A), then drawn over the mold or by forcing the mold into the sheet. When the mold has been forced into the sheet and a seal created (B), vacuum applied beneath the mold forces the sheet over the male mold. By draping the sheet over the mold you first drop the sheet touching the mold on the mold surface and it remains close to the original thickness of the sheet. Side walls are formed from the material draped between the top edges of the mold and the bottom seal area at the base. Final wall thickness distribution is shown in the drawing (c).

FIGURE 3. MATCHED MOLD FORMING.
Matched molds of wood, metal, plasters, epoxy, etc., can be used to press the sheet to shape. The heated sheet may be clamped over the female die (A) or can be draped over the mold force. As the mold closes, it forms the sheet (B). Mold vents allow trapped air to escape. Clearance between the mold force and cavity of the mold depends upon tolerances required in the part. Excellent reproduction of mold detail and dimensional accuracy can be obtained from matched mold forming, including lettering and grained surfaces. Material distribution of the formed part (C) will depend upon the shape of the two forms.

FIGURE 4. SLIP RING FORMING.
Heated plastic sheet is placed across the female die. As the press closes (A) pressure pads clamp the sheet lightly to allow it to slip under controlled tension as the mold force is pushed into the sheet. Air beneath the sheet is vented (B) to avoid creating a backpressure. As the mold finally closes, the pressure pads exert maximum holding pressure against the sheet retaining enough of the sheet to avoid losing the final formed shape. Vacuum or air pressure then can be applied (C) beneath the sheet to form it over the mold force or pull it into the cavity. However, neither air nor vacuum is needed as long as the mating mold sections fit properly. Uniform wall thickneww as illustrated in drawing (D) depends upon proper control of sheet slippage as well as upon the specific geometry of the part involved.

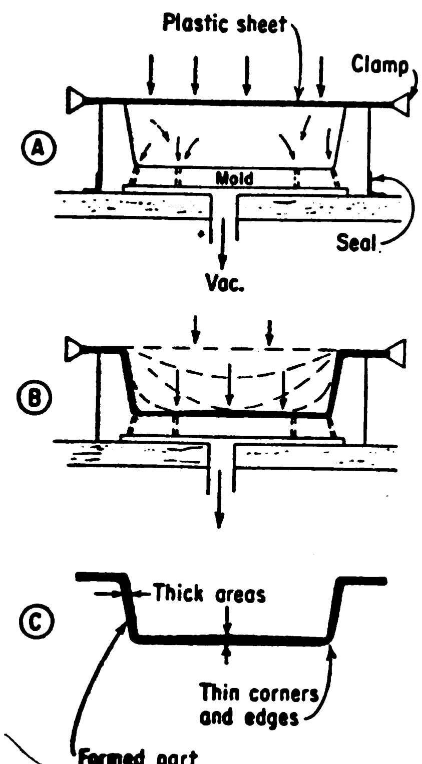


FIG. 1: STRAIGHT VACUUM FORMING.

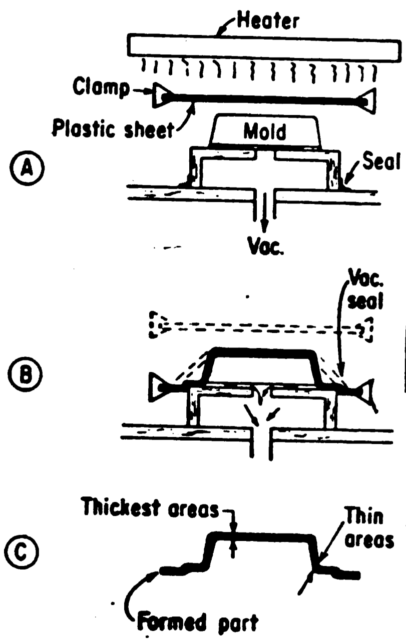


FIG. 2: DRAPE FORMING.

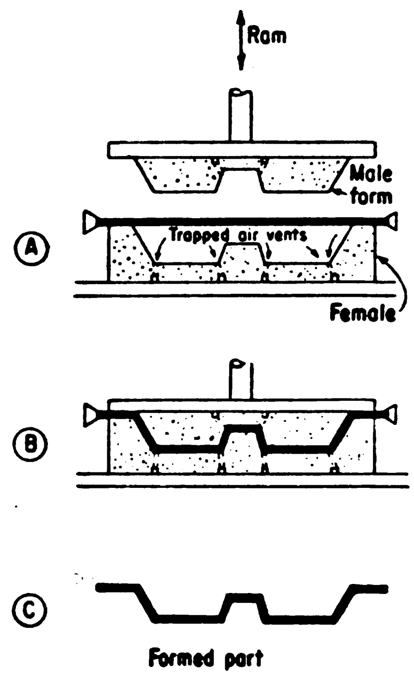


FIG. 3: MATCHED MOLD FORMING.

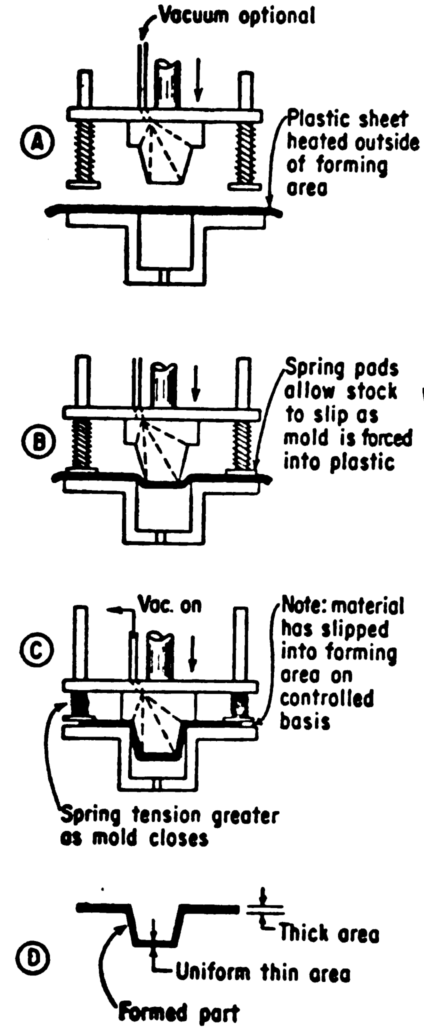


FIG. 4: SLIP RING FORMING.

FIGURE 5. PLUG ASSIST VACUUM FORMING.

After the plastic sheet is heated and sealed across the mold cavity (A) a plug, shaped roughly as the mold cavity but smaller, is plunged into the plastic sheet and pre-stretches the material. When the plug platen has reached its closed position (B) a vacuum is drawn on the mold cavity to complete formation of the sheet. Wall thickness can be varied by changing the shape of the plub (C). Areas of the plug touching the sheet first create thicker areas due to the chilling effect. Consequently, plug design is a most important factor in determining just what the geometry of the formed part being produced by this technique will look like.

FIGURE 6. PLUG ASSIST PRESSURE FORMING.

Plug assist pressure forming is similar to plug assist vacuum forming (A and B), except that as the plug enters the sheet air under the sheet is vented to the atmosphere. When the plug completesits stroke and seals the mold, air pressure is applied from the plug side. The air pressure can enter through the plug or from behind the plug (C). Those areas of the sheet first making contact with the air are chilled sooner. In some cases, heated air is required. Plug temperatures are also important. Plug assist pressure forming can be controlled to produce uniform material distribution over the entire formed part as shown in (D).

FIGURE 7. VACUUM SNAP BACK FORMING.

After the plastic sheet is heated and sealed over the top of the female vacuum box (A) a vacuum applied at the bottom of the vacuum box pulls the plastic material into a concave shape. The latter can be controlled by turning vacuum on and off to maintain a constant shape in the sheet. When the plastic has been pre-stretched, the male plug enters the sheet (B) and a vacuum is drawn through the male plug. Vacuum beneath the sheet is vented to the atmosphere or light air pressure is applied in place of the vacuum. External deep draws (D) can be obtained from the vacuum snap back pressure for forming items like luggage, auto parts.

FIGURE 8. PRESSURE BUBBLE IMMERSION FORMING.

Once the heated plastic sheet is clamped and sealed across the pressure box (A) controlled air pressure applied under the sheet causes a large bubble to form. The sheet pre-stretches about 35 to 40 percent. When it is preformed to the desired height (B) a plug is forced into it (C) while air pressure beneath remains constant. When the male plug closes on the pressure box, higher air pressure beneath the sheet and vacuum beneath the mold creates a uniform draw.

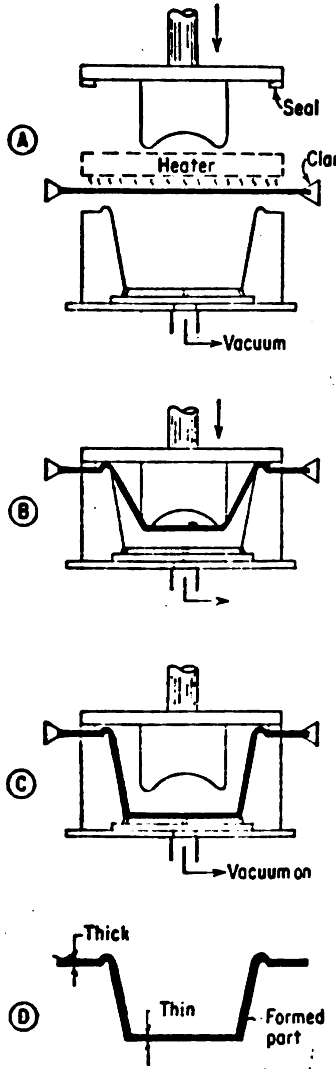


FIG. 5: PLUG ASSIST VACUUM FORMING.

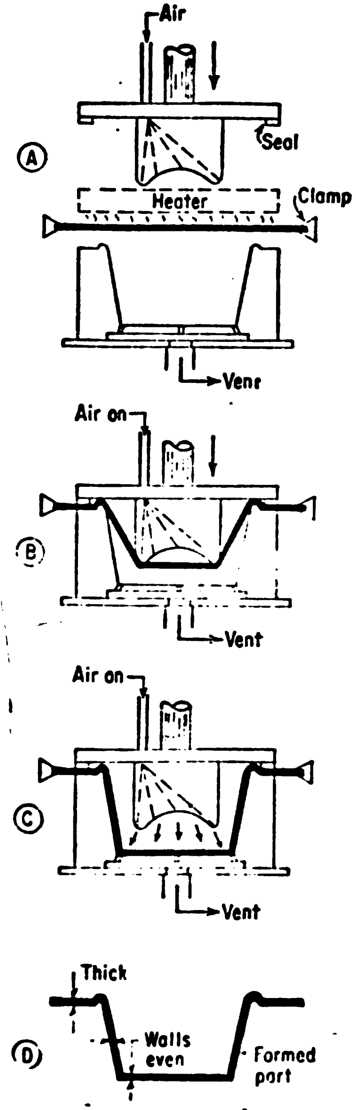


FIG. 6: PLUG ASSIST PRESSURE FORMING.

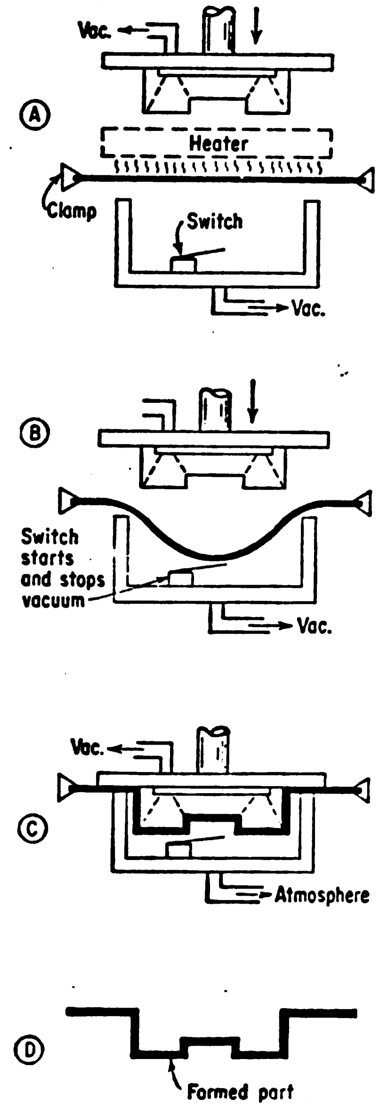


FIG. 7: VACUUM SNAP BACK.

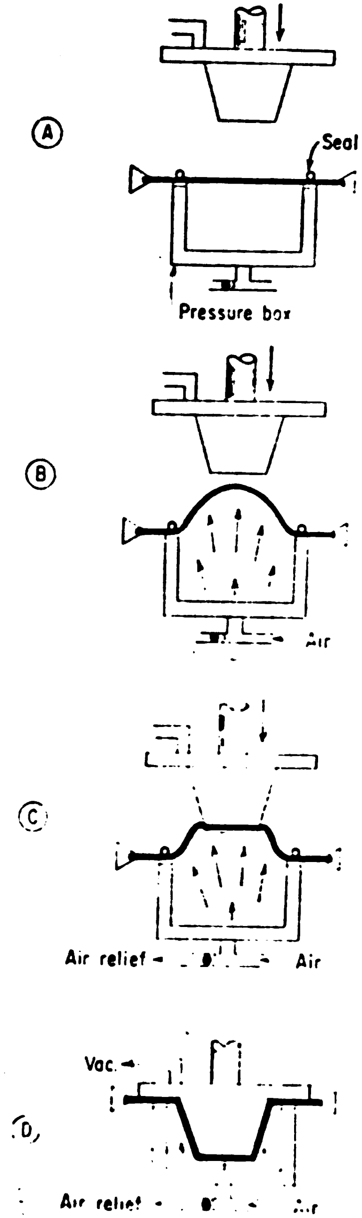


FIG. 8: PRESSURE BUBBLE IMMERSION FORMING.

FIGURE 9. TRAPPED SHEET, CONTACT HEAT, PRESSURE FORMING. Plastic sheet is inserted between the mold cavity and a hot blow plate. The plate (A), flat and porous, allows air to be blown thro[illegible]h its face. The mold cavity seals sheet against the hot plate. Air pressure applied from the female mold beneath the sheet blows the sheet totally against the contact hot plate. A vacuum (B) also can [illegible] on [illegible] hot plate. After predetermined heating, [illegible] is ready for forming. Applied air pressure [illegible] the hot plate forms the sheet into the female mold. Venting (C) can be used on the opposite side. Steel knives can be inserted in the molds for sealing. After forming (D) additional closing pressure can be exerted.

FIGURE 10. PRE-HEAT PLUG ASSIST PRESSURE FORMING. Roll plastic sheet is fed through top and bottom preheaters. (A) The hot sheet then is indexed between the top and bottom rams of a forming press where the parts are plug-assisted into female molds and formed by air pressure and vacuum. Next the rams open (B). During the forming process additional plastic sheet has been heating in the pre-heating section (C). Now new, pre-heated material is indexed into the forming ram area (D) and the entire thermoforming cycle as described above is repeated.

(Figures 1-10 from the article "Thermoforming" by David R. Zelnick, Modern Plastics Encyclopedia (New York: McGraw Hill, 1966), the 1967 issue.

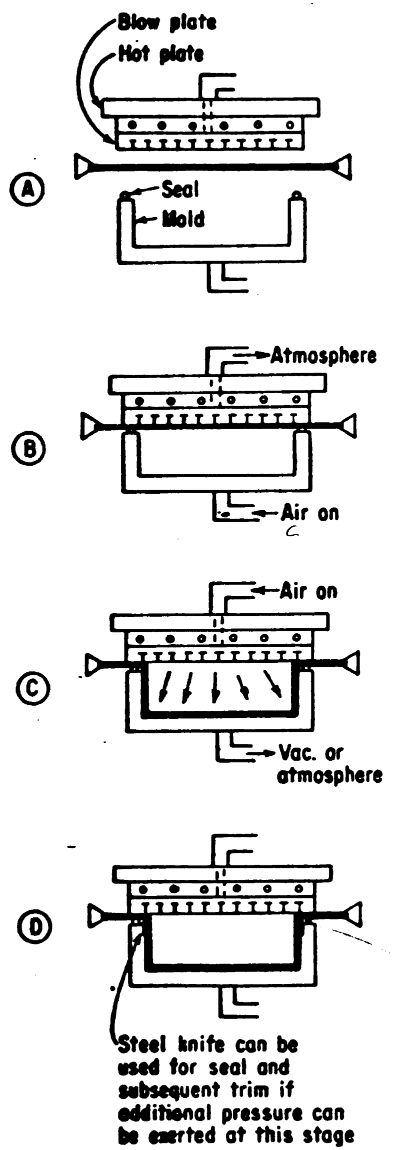


FIG. 9: TRAPPED SHEET, CONTACT HEAT, PRESSURE FORMING.

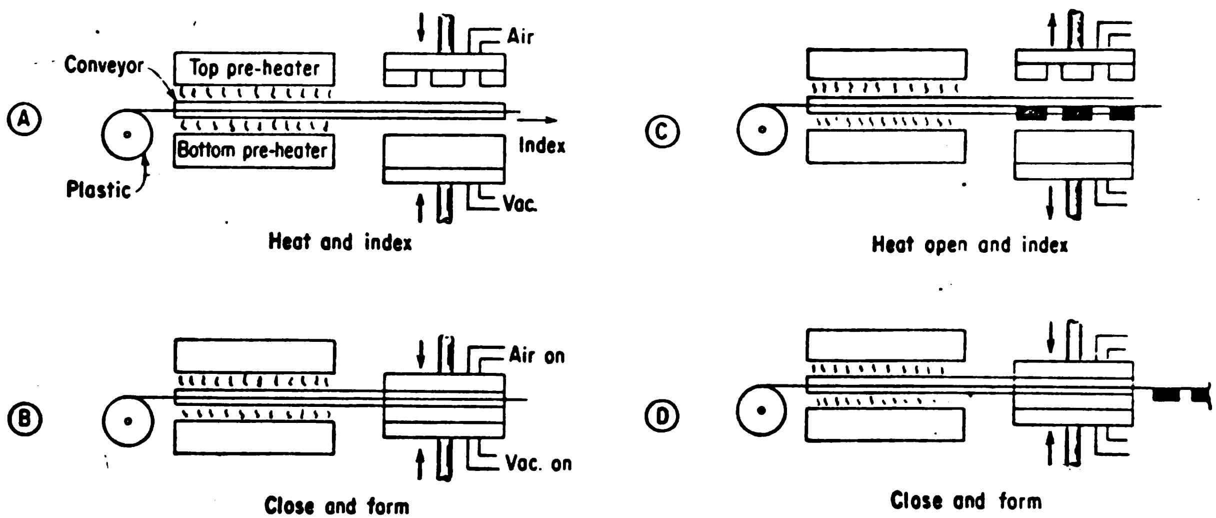
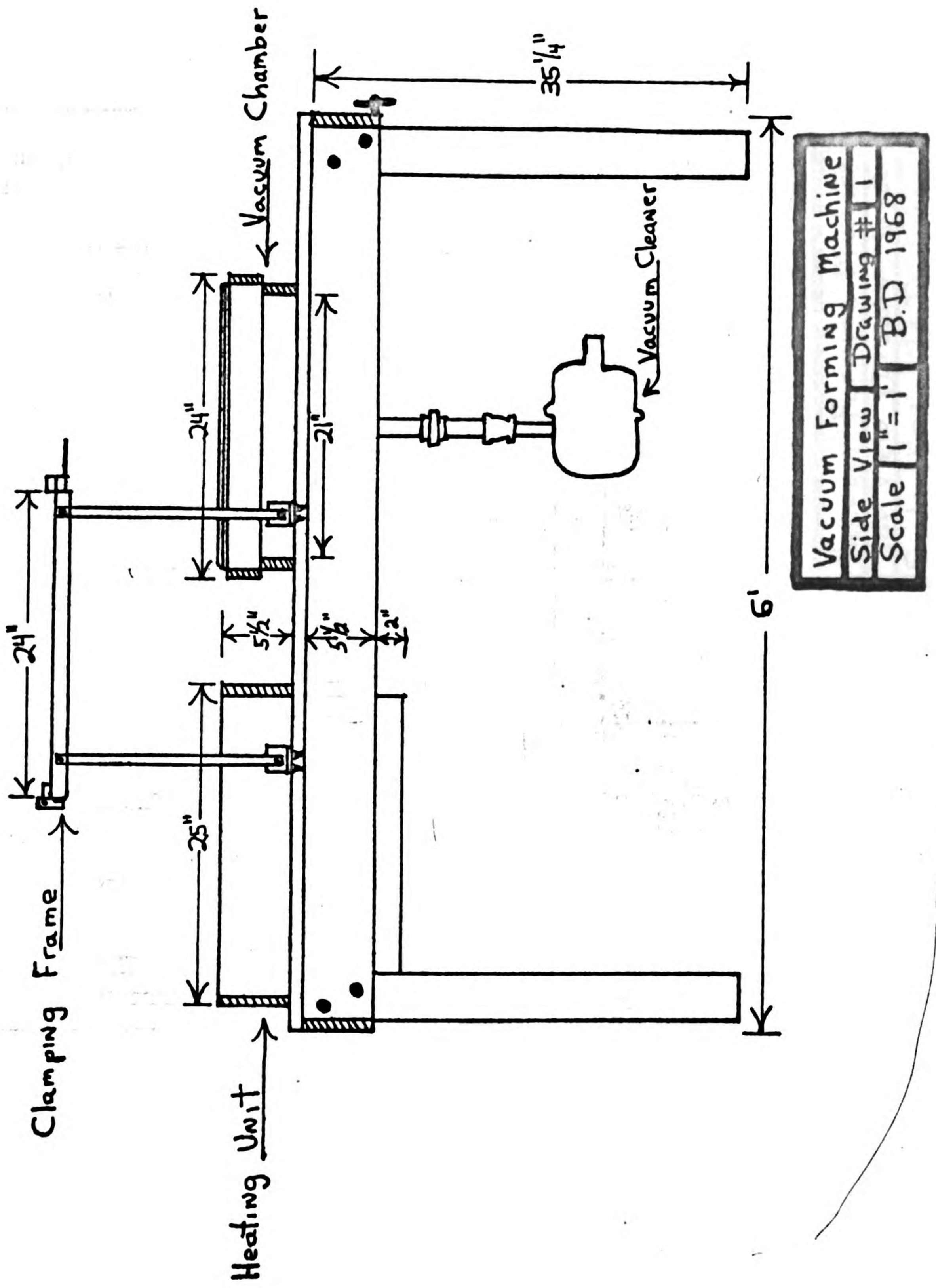
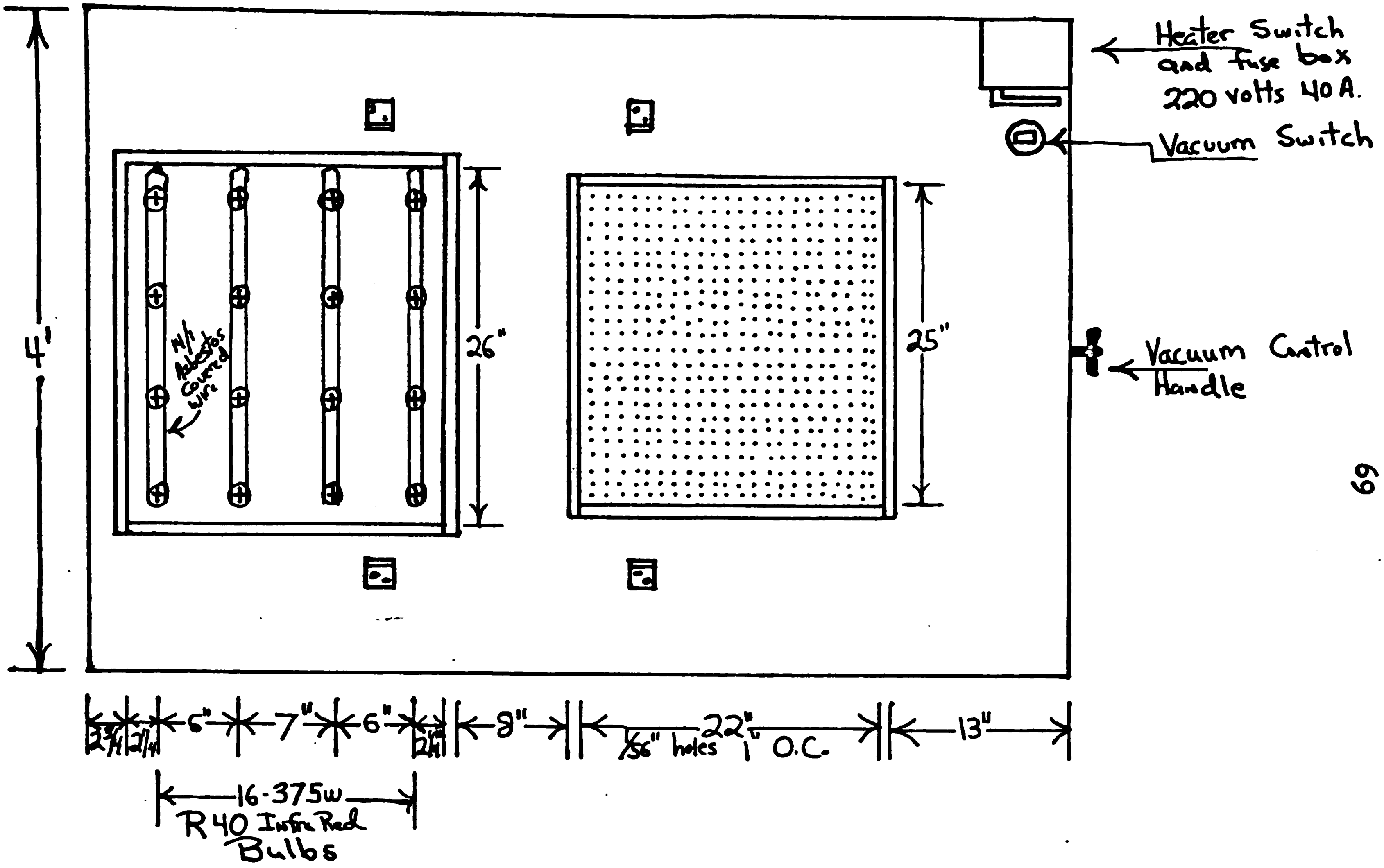
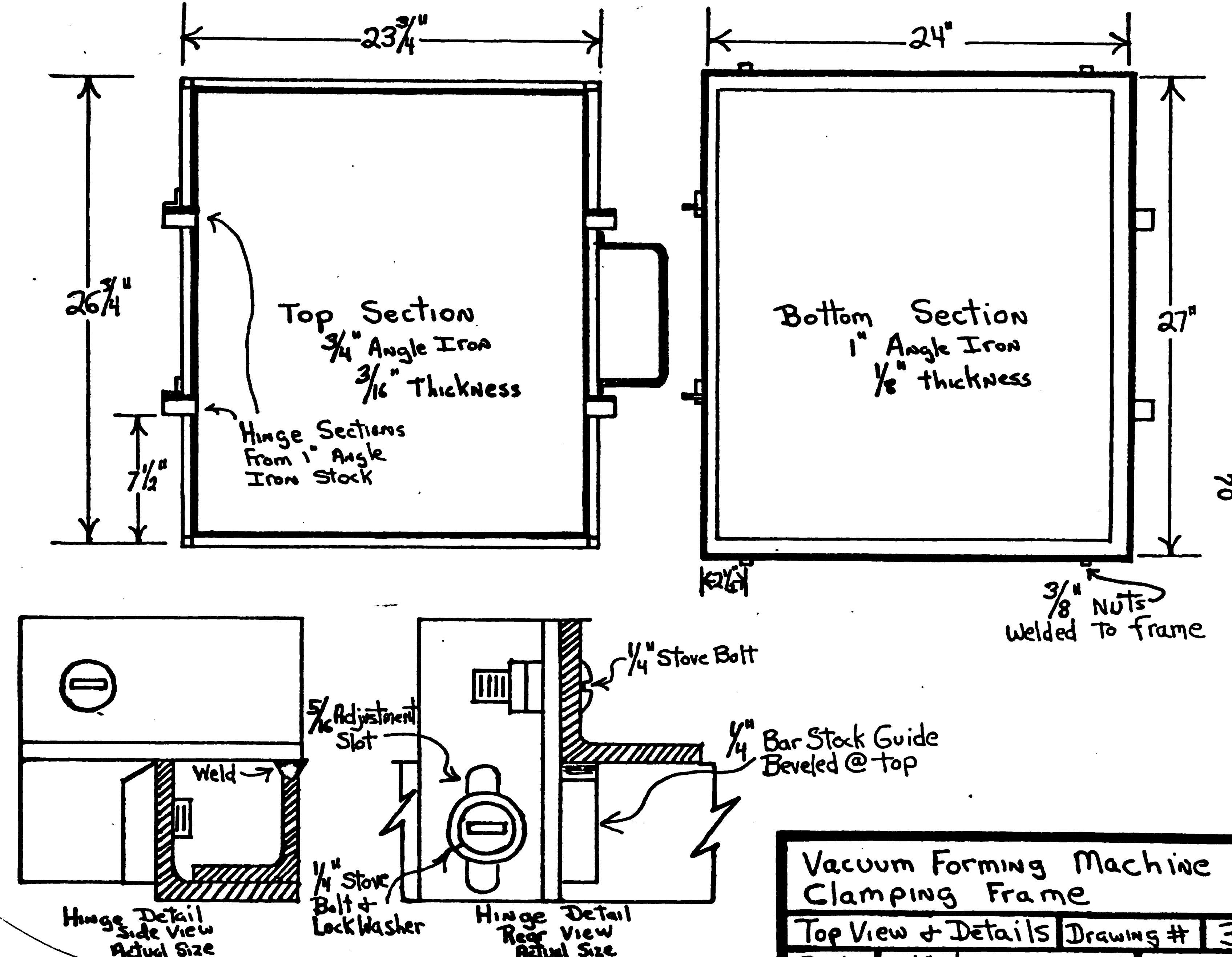


FIG. 10: PRE-HEAT PLUG ASSIST PRESSURE FORMING.


Vacuum Chamber
35 1/4"
Vacuum Cleaner
24"
21"
24"
5 1/2"
5 1/2"
2"
25"
6'
Clamping Frame
Heating Unit
Vacuum Forming Machine
Side View
Drawing # 1
Scale 1" = 1'
B.D 1968



Vacuum Forming Machine		
Top View	Drawing #	2
Scale	1" = 1'	B.D. 1968



Vacuum Forming Machine Clamping Frame			
Top View & Details		Drawing #	3
Scale	1 1/2" = 1' or as marked		B.D. 1968

FIGURE 14. View of Thermoforming Machine from Front.

FIGURE 15. Heating Unit as Seen from Above.

FIGURE 16. Clamping Frame in Position on Platen.

FIGURE 17. Household Vacuum Machine.

FIGURE 18. Clay and Glued gauze God Mask Mold.

FIGURE 19. Formed God Mask Before Trimming and Painting.

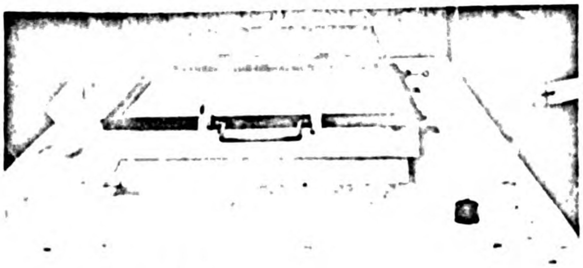


Figure 14

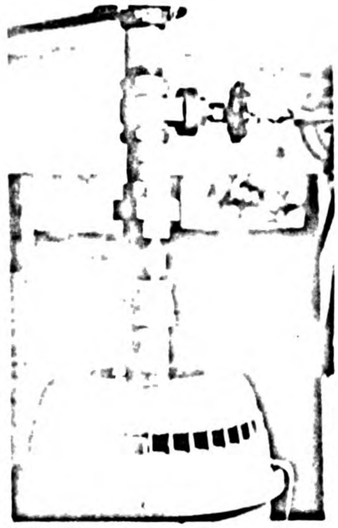


Figure 17

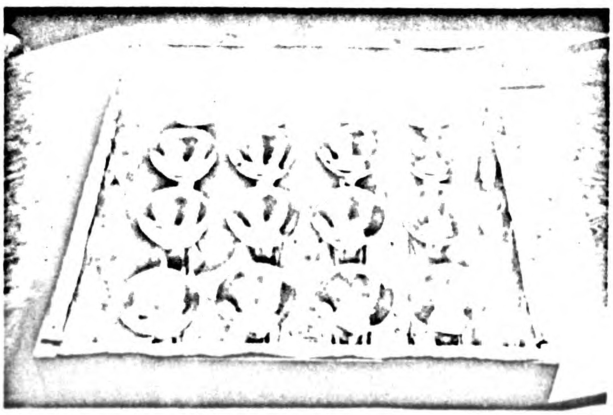


Figure 15

Figure 18

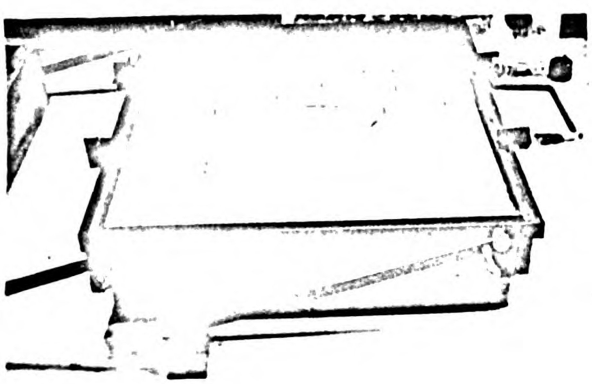


Figure 16

Figure 19

CHART II

TROUBLE SHOOTING FORMING

TROUBLE	REASON	SUGGESTED CURE
BLUSHING	Molded too cold Exceeding yield point	Increase heating time Increase molding speed
WEBBING	Molding too hot Vacuum too slow Layout too close	Shorten heating cycle Increase area and number of holes Use drape grid assist
SHEET SCORCH BUT NOT PLASTIC	Heat Input/Min. Too Rapid	Use lower heat Longer Cycle Heat both sides
MOLD RELEASE DIFFICULT OR IMPOSSIBLE	Draft insufficient Undercuts Mold "Roush" shrunk on mold	Increase and/or polish mold Eliminate or, if minor use air assist Polish and lubricate mold Change to female mold if possible Cut down dwell time in mold
PLASTIC BUBBLES	Overheating Moisture Entrapped Air	Extend Cycle and lower heat Preheat sheet slowly Check for moisture in air if blow molding Correct venting or add vacuum holes
CRACKING	Stress concentrated Poor design	Increase radius of all angles Re-work design - add reinforcements Increase heat

CHART II (Continued)

TROUBLE	REASON	SUGGESTED CURE
WARPING	Stress Improper cooling Poor design	Try slower mold entry and more heat Allow to cool on mold longer Eliminate long flat surfaces
EXCESSIVE SHRINKAGE OF SHEET	Stress in sheet	Shorten time under heat and elevate temperature Change sheet layout

General Tire, _A Manual of Low Pressure Forming of Thermoplastic Sheet_ (Lawrence, Massachusetts, 1967), p. 24.

SOURCES OF MATERIALS FOR THERMOFORMING

ADHESIVES:

Bostik
B. B. Chemical Division
United Shoe Machinery
Cambridge, Massachusetts 02139

Cadillac Plastic and Chemical Company
1511 Second Avenue
Detroit, Michigan 48203

CLAMPS:

Adjustable Clamp Company
417 North Ashland Avenue
Chicago, Illinois 60622

De-Sta-Co Corporation
350 Midland Avenue
Detroit, Michigan 48203

Knape and Vogt Manufacturing Company
658 Richmond Avenue
Grand Rapids, Michigan 49504

Knu-Vise Products Division
Lapeer Manufacturing Company
3056 Davison Road
Lapeer, Michigan 48446

HEATING EQUIPMENT:

A.A.A. Plastic Equipment Company
Post Office Box 11510
2509 West Berry
Fort Worth, Texas 76110

Edwin L. Wiegand Company
7613 Thomas Boulevard
Pittsburgh, Pennsylvania 15208

Faratron
Subsidiary of Thermatron-Wilcox-Gibbs
214 West 39th Street
New York, New York 10018

General Electric Company
Large Lamp Department
Nela Park
Cleveland 12, Ohio

Honeywell Incorporated
Aparatus Controls Division
2747 Fourth Avenue South
Minneapolis, Minnesota 55408

Hotwatt Incorporated
128 Maple Street
Danvers, Massachusetts 01923

COMMERCIAL THERMOFORMING MACHINES:

A.A.A. Plastic Equipment Company, Incorporated
Post Office Box 11512
2215 West Berry
Fort Worth, Texas 76110

Abbott Machinery Division
Dynamics Corporation of America
Post Office Box 1083
Scranton, Pennsylvania 18501

American Remolit Corporation
79 Madison Avenue
New York, New York 10016

Atlas-Vac-Machine Division
Koehler-Dayton Incorporated
401 Leo Street
Dayton, Ohio 45404

Auto-Vac Company Incorporated
Post Office Box 557
Tabor City, North Carolina 28463

Brown Machine Company
Beaverton, Michigan

Comet Industries Incorporated
1320 North York Road
Bensenville, Illinois 60106

Di-Acro Division
Houdaille Industries Incorporated
300 Eighth Avenue
Lake City, Minnesota 55041

Plasti-Vac Incorporated
1091 North Davidson Street
Post Office Box 4453
Charlotte, North Carolina 28205

FINISHING OF PLASTICS:

PAINTS:
The Glidden Company
Graphic Arts and Sign Finishes Division
11001 Madison Avenue
Cleveland, Ohio 44102

Keystone Refining Company, Incorporated
4821-31 Garden Street
Philadelphia, Pennsylvania 19137

Lilly Varnish Company
666 South California Street
Indianapolis, Indiana 46225

United States Paint, Lacquer and Chemical Company
Singleton at 21st Street
St. Louis, Missouri 63103

TEXTURING:
Roll, Die and Mold Decorators Incorporated
801 North Meridian Road
Youngstown, Ohio 44509

WELDING OF PLASTIC:
Kamweld Products Company, Incorporated
742 Providence Highway
Norwood, Massachusetts 02062

PLASTICS SUPPLIERS:

American Hoescht-Corporation
Hostachem Division
270 Sheffield Street
Mountainside, New Jersey 07091

American Renolit Corporation
79 Madison Avenue
New York, New York 10016

Cadillac Plastic and Chemical Company
15111 Second Avenue
Detroit, Michigan 48203

Capitol Plastics Company
814 Fisher Building
Detroit, Michigan 48203

Cast Optics Corporation
214 South Newman Street
Hackensack, New Jersey 07602

Commercial Plastics and Supply Corporation
630 Broadway
New York, New York 10012

Diamond Alkali Company
300 Union Commerce Building
Cleveland, Ohio 44115

E. I. DuPont DeNemours and Company
Plastics Department
Wilmington, Delaware

The Dow Chemical Company
Plastics Department
Molding and Extrustion Sales
Midland, Michigan 48640

Eastman Chemical Products, Incorporated
Kingsport, Tennessee 37662

Foster Grant Company, Incorporated
Leominster, Massachusetts

General Electric Company
Chemical Materials Department
Pittsfield, Massachusetts

The General Tire and Rubber Company
Chemical Plastics Division
1708 Englewood Avenue
Akron, Ohio 44309

Gilman Brothers Company
Gilman, Connecticut
(Suppliers of foamed, flocked, glittered and foil covered sheet)

Monsanto Company
800 North Lindbergh Boulevard
St. Louis, Missouri 63166

Purex Corporation
Post Office Box 958
Woodside Drive
Richmond, Indiana

Rohm and Haas Company
Independence Mall West
Philadelphia, Pennsylvania 19105

Seilon Incorporated
Plastics Division
Newcomerstown, Ohio 43832

Shell Chemical Company
Synthetic Rubber Division
113 West 52nd Street
New York, New York 10009

Sweedlow Incorporated
Department E 1
12605 Beach Boulevard
Garden Grove, California 92642

PLASTIC THEATRE SUPPLIES:

Alcone Company Incorporated
32 West 20th Street
New York, New York
(Negocoll and Celastic)

Celastic Manufacturing Company
609 Schuyler Avenue
Kearny, New Jersey 07032

Columbia Broadcasting System, Incorporated
Alfred E. Landolph, Purchasing Agent
52 West 52nd Street
New York, New York 10019
(Plastic Scenery)

Costume Armour Incorporated
429 West 53rd Street
New York, New York 10019

Tobins Lake Studios
2650 Seven Mile Road
South Lyon, Michigan 48178
(Easy-Ornament)

Plabras Armour
Giesen Company
38 9th Street
St. Peter/St. Paul, Minnesota 55102

Polymer Corporation Limited
Sarnia, Ontario, Canada
(Plastic Rubber sheet stock)
(Available from
Northwestern Costume House Incorporated
3203 North Highway 100
Minneapolis, Minnesota 55422

MATERIALS FOR MOLDS:

Cerro Sales Corporation
300 Park Avenue
New York, New York 10022
(Low Melting Point Alloys)

The Decorators Supply Corporation
3610-3612 South Morgan Street
Chicago, Illinois 60609
(Plaster ornaments that could be used for molds)

Kish Industries, Incorporated
1301 Turner Street
Landins, Michigan 48909
(Epoxy resins)

Tech Consolidated Incorporated
20 Dickey Street
Derry, New Hampshire 03038
(Electroformed molds and dies)

Union Carbide Corporation
Plastics Division
270 Park Avenue
New York, New York 10017
(Epoxy resins)

United States Gypsum Company
101 South Wacker Drive
Chicago, Illinois 60606
(Gypsum plasters and cements)

TOOLS FOR WORKING WITH PLASTICS:

The Cutawl Corporation
Bethel, Connecticut 06801

Lemmon and Snoap
2618 Thronwood S.W.
Grand Rapids, Michigan 49509

VACUUM PUMPS:

Central Scientific Company
2600 South Kostner
Chicago, Illinois 60623

The Stansi Scientific Division
Fisher Scientific Company
1231 North Honors Street
Chicago, Illinois 60622

Worthington Corporation
426 Worthington Avenue
Harrison, New Jersey

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