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Radio-Frequency Dielectric Heating in Industry

Prepared by
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Palo Alto, California

REPORT SUMMARY

SUBJECTS Industrial electric technologies / Conservation/productivity/load management

TOPICS
End use	Technology assessment
Electrotechnology	Technology utilization
Electric heating	Dielectric materials

AUDIENCE Marketing managers / Customer service engineers

Radio-Frequency Dielectric Heating in Industry

RF heating, with its capacity for uniform heating of nonconducting materials, can solve many industrial heat transfer problems. New cost-effective applications of RF heating could substantially improve productivity and product quality for a wide variety of industrial users.

BACKGROUND Like microwaves, radio-frequency (RF) dielectric technology heats nonconducting materials from the inside outward. Commercial applications of RF dielectric heating date from the late 1930s, and many industries now use the technique for plastics welding, glue setting, and drying. EPRI initiated the present study—in conjunction with examinations of resistance heating, infrared heating, and microwave heating—to explore and extend applications for electricity-based production and fabrication methods.

OBJECTIVES

- To describe the main characteristics of RF dielectric heating and its known and potential industrial uses.
- To develop a set of general guidelines for this technology that will help utilities and their industrial customers identify and assess new cost-effective applications.

APPROACH To compile information on applications of industrial RF heating, the principal investigator interviewed RF heating equipment manufacturers and users in the United States, Europe, Taiwan, and Japan. He supplemented this information with firsthand experience and a review of the technical literature.

RESULTS

- In the United States, there are between 50,000 and 100,000 RF dielectric heating installations. Average power output of these installations is 10 kW.
- Well-established applications include plastics welding, plastics preform heating, glue setting for wood fabrication, textile drying, glue setting on business forms, and veneer drying.
- Advantages of RF heating include good thermal efficiency, reduced material deterioration, rapid heating and drying, uniformity of heating, moisture leveling, and ability to overcome heat transfer problems inherent in processing insulating materials.

• RF dielectric heating is economical in situations where the value of the above advantages offsets the technology's relatively high capital costs. There are many such situations, and paybacks of one year or less are not uncommon.

• The report summarizes industry experience with RF heating and distills this information into general technical and economic guidelines for users. In the appendixes, it presents a concise technical primer on RF dielectric heating.

EPRI PERSPECTIVE

RF dielectric heating has been an industrial technology of proven reliability for nearly five decades, and it promises to form a modest but increasing portion of electrical load for U.S. utilities in coming decades. Microwave technology, which is uniquely suited for applications such as rubber vulcanization, can also be employed in dielectric heating. In many other applications, either RF or microwave heating may be equally effective. Additional information on microwave heating is available in EPRI report EM-3645.

PROJECT

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Radio-Frequency Dielectric Heating in Industry

EM-4949
Research Project 2416-21

Final Report, March 1987

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NOTICE

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ABSTRACT

This report is written to assist utility staff engineers in searching for new applications of RF dielectric heating in industry. RF (radio frequency) dielectric heating is in daily use in industry for plastic welding, drying, and glue setting, but has many more potential applications. In this report successful applications are reviewed, and the reasons for their success are described. Based upon the results of these applications, guidelines for the successful application of RF dielectric heating in industry are formulated.

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RF dielectric heating is widely used in certain industries but little known outside of its field of specialization. Like microwaves, it heats non-conducting materials from the inside outward and hence solves many heat transfer problems. RF is an abbreviation of radio frequency, referring to electromagnetic radiation which is somewhat lower in frequency than microwaves and with a longer wavelength (36 ft. vs. 0.4 ft.). The lower frequencies allow simpler and less costly equipment to be built while the long wavelength favors heating large dimensional pieces with good uniformity. In practice, certain applications are uniquely suited to RF (plastics welding), certain applications are uniquely suited to microwaves (rubber vulcanization) and many others can be accomplished by either RF or microwaves (drying). This report is focused entirely on RF heating; an earlier EPRI Report (EM 3465) was devoted to microwave heating.

RF heating has been well established in industry for many years. There are perhaps 50,000 to 100,000 installations in the U.S.A.; average power is 10 kW. Major areas of applications are plastics welding, plastics preform heating, glue setting for wood fabrication, textile drying, glue setting on business forms, veneer drying and many others. From them, a generalized list of advantages and disadvantages of RF Dielectric Heating is derived; these advantages and disadvantages can then be assessed against new applications to determine whether they are logical candidates for RF heating.

The biggest problem in applying RF heating to new applications is to obtain a good assessment of the economics. RF can do wonderful things but it is expensive to buy and electrical energy is almost always more expensive than gas or oil. However, if the application is a good one, the enhanced productivity more than offsets these expenses and paybacks of 1 year are not uncommon. The best applications of RF heating are probably not in this report because they are the highly profitable trade secrets of their developers.

Using this report, utility engineers can stimulate their clients' interest in using RF to solve heating problems and increase productivity. If the application passes the generalized guidelines contained in this report, and the client is serious, contacting a manufacturer of RF equipment is the next logical step. For convenience, manufacturers are listed for each type of RF equipment.

SECTION 1

INTRODUCTION

Dielectric heating is a means for uniformly heating nonmetallic substances which do not conduct heat or electricity very well. It heats both faster and more economically than conventional methods of heating. It often enhances product characteristics because it is not necessary to expose the products to dangerous temperatures to heat them rapidly and throughout their entire volumes. The total number of dielectric heaters currently installed in the U.S. is not known accurately. Dr. Philip Schmidt, in "Electricity and Industrial Productivity: A Technical and Economic Perspective" EPRI report EM-3640, March 1986, page 15-17, puts the total U.S. installed capacity at between 500 and 1000 MW. Since generators are rated on output power, this could be between 700 and 1400 MW connected load. If the average generator power is 10 KW, this indicates between 50,000 and 100,000 installations.

The present report gives details of the basic applications so that an understanding of them can be obtained. The appendices provide the theoretical background for all applications and a list of many applications. The list is continually increasing.

Dielectric heating is a valuable and reliable tool for many industrial uses. This has been proven over a period approaching 5 decades during which successful applications in many fields have been established. Some of them have even been terminated because the products processed became obsolete (foam rubber mattresses and rayon thread being two examples). Many of the applications have become so commonplace that no one would consider practicing them without dielectric heating. New applications are being developed and these have promise of further expansion.

HISTORICAL

The phenomenon of dielectric heating was known in the late 19th century, but commercial applications date from the late 1930's after techniques of generating high power at high frequencies had been developed. World War II gave a stimulus to its growth by developing new electronic components. This technology, in turn, allowed the development of products and processes which otherwise would not be available. Plastic preheating and wood gluing are two early examples.

Dielectric heating was commercially developed approximately three decades before microwave heating. The latter is better know, however, probably because of its use in the home. Microwave heating is an extension of dielectric heating in many ways, but it has its own unique and valuable characteristics. The frequency used by microwave generators is 100 to 1000 times higher than that for dielectric heating. This gives microwave energy the ability to heat some materials which cannot be heated with dielectric heat. However, because of the higher frequency, difficulties are found in applying it to large and thick objects. These are more easily heated by the lower frequency dielectric heaters. A more detailed explanation of dielectric heating and its comparison to microwave heating is found in Appendix A.

THE ADVANTAGES OF DIELECTRIC HEATING

The primary problem which dielectric heating readily solves is that of heat transfer. Because the heat is generated quite uniformly within the material itself, during dielectric heating there is no need to wait for the heat to flow in from the surface. Other favorable characteristics include:

1. The speed of heating because heat is generated internally.

2. Moisture leveling in drying operations, because dielectric heat preferentially heats the moisture.

3. Rapid on-off control of heating apparatus; i.e. no warm up time.

4. Simple and immediate control of heating rates.

5. No overheating of surfaces to increase speed of heating.

6. Heating takes place while normal room temperatures surround the work piece.

7. Drying can take place in an atmosphere of 100% water vapor.

8. Product deterioration due to high temperatures and long exposure time is reduced or eliminated.

9. High energy efficiency as compared to microwave power.

Reference to the appendices will provide a basic understanding of how these solutions are achieved.

Dielectric heating is practiced on any material that can be called an electrical insulator. Most of these have poor heat conductivity. It takes place in interior molecules at the same time it occurs in surface molecules. This is graphically illustrated in Figure 1-1 which shows a piece of common wood that was heated to the scorching point in the interior whereas the outside surfaces, though also heated, were cooled by the surrounding air. Contrast this with normal heating in which the exterior surfaces can be scorched without the interior molecules receiving much heat. With dielectric heating (also

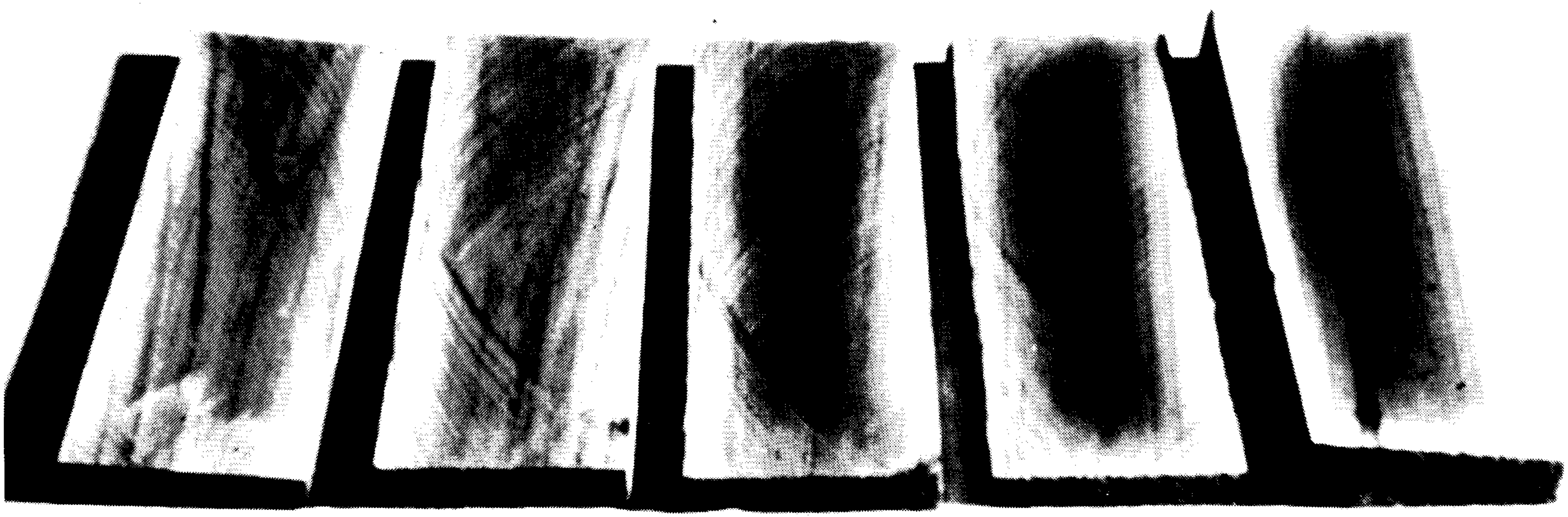


Figure 1-1 This shows the results of deliberately overheating a block of common pine wood between two parallel plates of an RF dielectric heater until it scorched. The outer layers, being cooled by the surrounding air, did not get as hot as the center layers. This graphically illustrates that the heating takes place throughout the material.

sometimes called high frequency or radio frequency heating) rapid yet uniform heating of thick or thin products is readily obtainable without danger of surface damage.

CONDITIONS FOR GOOD DIELECTRIC HEATING

Table 1-1 lists conditions which should generally indicate a good application for dielectric heating. This list is NOT always totally accurate, however, as there are known successful applications which seem to be contrary to some of the points listed. For example sand cores are successfully heated by RF dielectric heating even though they may have widely varying heights; energy costs for drying rayon thread is somewhat more expensive than conventional drying but the labor saving and added value to the product offset this problem.

Table 1-1

CONDITIONS USUALLY PRESENT FOR A SUCCESSFUL DIELECTRIC HEATING APPLICATION.

A. Technical	B. Economic
1- Material is susceptible to dielectric heating.	1- Costs must be supported by
a. Loss Factor above .005*	a. Labor saving
b. Voltage strength good.	b. Energy saving
c. Flat surfaces preferred	c. Space saving
d. Mostly uniform thickness	d. Product enhancement
e. Max. dimensions small compared to a wavelength.	e. Reduced inventory
f. Temp. uniformity through product thickness is needed.	f. Speed of production
g. Sensitivity to too high temps retards heating rate.	g. Value of material is sufficient.
h. Homogeneity	h. Convert batch to continuous process.
2- Can combine conventional heating and dielectric heating.	
3- Effective on very thin or thick materials, (0.001 in. to 100 in.)	

* See Appendix A for definition of Dielectric Loss Factor.

Appendix D lists many of the applications to which dielectric heaters have made definite contributions.

PARTS OF A DIELECTRIC HEATER

A typical dielectric heating machine consists of:

1- A power supply which includes the large controls and supplies the high voltages needed for the oscillator.

2- The oscillator which generates the high frequency energy using power from the power supply.

3- The applicator which contains the electrode system plus any material handling equipment necessary. It may also include such auxillaries as hot air, ventilation, controlled atmosphere etc. It receives the high frequency energy from the oscillator and transfers it to the load material.

4- The control panel which contains the necessary controls(automatic, digital, or manual) to provide the desired regulation of the process.

Sometimes the applicator and controls, and even the oscillator and power supply, are installed as an integral part of another machine so that the dielectric heater becomes merely a component of a larger piece of equipment.

While dielectric heating will take place at any frequency, the use of "high" frequencies permits easy and rapid transfer of large quantities of energy. By "high" we usually mean between 2 and 200 megahertz. In the U.S. normal power lines operate at 60 Hertz so dielectric heating takes place at between 30,000 and 3,000,000 times normal power frequencies. Because these same frequencies are used for radio communications, dielectric heaters must be shielded to avoid emission of radio interference. The shielding is usually supplied as part of a purchased piece of equipment.

Dielectric heaters are surprisingly simple, particularly where the high frequency portions are concerned. Controls may be complex, as needed for special applications, or merely simple on-off push buttons. High power machines are more complex than smaller ones due to the added cooling required for the larger components plus the larger bulk. While dielectric heaters may seem complex at first, they are usually readily understood by normal production personnel after a short familiarization period.

GENERAL

After nearly five decades of experience, U.S. manufacturers of dielectric heaters have specialized in particular applications. Hence, one manufacturer may not really be completely familiar with all aspects of dielectric heating. Because competition between manufacturers is very keen, they are somewhat reluctant to disclose their newest applications. Part of this reluctance is due also to contractual restrictions with their customers who are trying to protect their interests in new developments. For this reason this report contains a list of manufacturers at the end of each section who have been active in the particular type of applications discussed in that section of the report. The lists are not necessarily complete, but should afford a starting point for anyone interested in a particular field.

An often repeated "rule of thumb" in the trade is: "If a heating problem can be solved through use of conventional heating methods use them in preference to dielectric heating." This rule is often true, but not always. Careful consideration should be given to the technical advantages of dielectric heating in many new jobs, and the economics should be thoroughly investigated.

The capital cost of a dielectric heating system will usually be greater than for other nonelectric heating methods, but space, labor, enhancement of the properties of the product, efficiency, pollution, and others factors should also be considered. Additionally, convenience is important. Often the use of dielectric heating will permit other machines in a factory to operate faster and thus the plant may become more productive through use of dielectric heating. In some actual cases these savings have resulted in the higher capital cost being paid off in less than one year of operation.

Dielectric heaters have remarkably long lives. Some machines built during WWII are still operating well although they may have required some modification because the original components were no longer available. This is a credit to those early designers who had to learn how to build machines for the industrial environment based on components and techniques intended for communications services.

The basic circuits are much simpler than those used in communications, particularly in the high frequency portions. Actually some of the circuits now used were originally developed for very early communications purposes when frequency stability was not as essential as it is today. But those transmitters were constructed to operate into a reasonably constant load. In contrast, high frequency heating equipment must be able to deliver power into widely varying loads. These variations result from changes in the electrical properties of the material as it it heated as well as variability in continuously moving products.

Experience gained in the past nearly 50 years of development has resulted in reliability factors exceeding 99% as a norm. This is particularly true if a model of a machine has been manufactured for several years. There is no longer any need to fear unproven equipment. Modern machines are designed with the industrial environment in mind. Maintenance has been simplified and finding trouble is presently quite simple. Additionally, maintenance personnel have become more accustomed to electronic components and have a better knowledge of how to repair them. Of course, where a new application is being developed, there will be unknowns which must be resolved before full and regular production can be achieved. Events indicate that once the process has been developed, the equipment will have great reliability.

SECTION 2

DETERMINATION OF POWER REQUIREMENTS

Determination of the exact amount of dielectric heating power needed to perform a specific heating problem will depend on the type of process in which it will be used. However, the basic principles involved are quite straightforward and follow the applicable physical laws. The purpose of this section is to outline these principles and laws as well as to indicate where they may be applied directly and where it is easier to use empirical data.

In any heating process, whether drying or not, in addition to losses the power is used in 3 ways. One is to bring all the bone dry material up to the desired temperature. Even where drying is not the primary purpose of the heating, heat may cause volatiles to be evaporated. Therefore the second need for heat is to raise the volatiles to the evaporation temperature. The third is to supply the heat of vaporization to the volatiles which are removed. Calculation of these three energy requirements is straightforward.

In other processes there are additional heat inputs, or heat losses, which must be determined. For example, in plastic welding (See section 3) the materials involved are thin and therefore the heat losses to the dies are a large percentage of the total heat needed. Furthermore, heat losses are very difficult to determine accurately. Thus those familiar with the art have developed tables (see table 3-2) which are a guide to power determination. Similarly in manufacturing medium density fiberboard and particle board (See section 5) there is substantial heat input from the press which reduces that needed from the dielectric heater.

For such complex processes other methods of determining the power requirements are needed. Where feasible these are given in other sections of this report. Otherwise, it is best to contact dielectric heater manufacturers to get their advice. If desired, a rough indication can be obtained using the formulas below and adding a substantial allowance for losses.

For economic studies, of course, the total costs are of prime interest and these include the costs of input energy wherever it is used. Thus the cost of energy for blowers, conveyors, hot ambient temperatures inside an oven, etc. must all be included as part of the energy costs

In practical problems the rates of production are the goals to be achieved. These are usually given in terms of daily or monthly production rates. In determining power requirements it is, therefore, necessary to consider down time for change of shifts, changes of tools and dies, maintenance etc. These times are not available for the job of heating and, therefore, the generators must be able to heat more product per hour during the times available to them.

The formulas in this section estimate the high frequency energy required for the dielectric heating. To estimate the input energy to the generator, one can assume that the generator efficiency is between 55% and 65%, depending on the size of the generator. The lower efficiency applies to the smaller generators (under, say, 20 KW) because the costs of operating blowers, controls, etc. is a larger percentage of the total input energy. In dielectric heating there need be no allowance for artificial loads to dissipate unnecessary, but generated, power. In contrast microwave heaters frequently dissipate excess power which cannot be coupled to the work piece.

BASIC PRINCIPLES

As in any heating problem, the input heat must be sufficient to raise the temperature of the product(s) to the level needed for the process. As mentioned above, there are basically four places where the heat can go. These are:

1. The heat required to raise the bone dry material through the temperature range needed. This, of course, is

   $$Q = Wt. \times Sp.\ Ht. \times (T_{final} - T_{initial})$$

   In the fps system of units
   Q = Heat in British Thermal Units
   W = Weight of dry material in pounds
   Sp. Ht. = Specific Heat - a property of the material, BTU/Degree Farenheit/lb.
   T_{final} = The final temperature in degrees Farenheit.
   $T_{initital}$ = The initial temperature in degrees Farenheit.

2. The heat supplied to raise the volatiles' temperature. In the case of water, much of it boils at about 212 degrees F, but some of it is closely bound to the molecules and requires a higher temperature to evaporate. Conservative calculations use the same temperature rise as is used for the dry basic material. This may result in an estimate of total heat which is slightly higher than required. The equation is, of course, the same as in 1 above but using the specific heat of the volatile (1 for water) and the weight of the volatile in place of the weight of the dry material.

3- Heat used to vaporize the volatiles. This depends on the solvent material and on the pressure under which the operation takes place.

   $$Q = Wt. \times (\text{Heat of Vaporization})$$
   Wt = the weight of the evaporated volatile.

At normal atmospheric pressures the heat of vaporization for water is 970 BTU per pound of water evaporated in the fps system of units. For other solvents these figures will depend on the specific heat of the solvent itself.

4- Heat losses (these could be heat gains) to the surrounding air, supporting elements etc. These are usually very small and negligible in some applications. They are the major source or sink for heat in other applications. In a drying operation, where often the surrounding air is heated somewhat to carry away the vapors, the heat losses or gains to the atmosphere and supporting elements are negligible. In a plastic welding operation the losses to the electrodes, which are in contact with the thin materials being welded, are a major heat loss. This report gives some details on these items.

The total heat required is the sum of the above four items.

To convert the calculated heat losses in BTU's or Kilocalories to dielectric generator ratings in kilowatts, the time during which the heating of a known weight of material takes place must be determined. Special note should be taken that kilowatts and kilowatthours are not the same thing. A kilowatt is a unit of power, which is a time rate of the use, or generation, of energy. Kilowatthours are a unit of energy and are equal to the product of the kilowatts and the time given in hours. Table 4-1 lists the factors to be used for several units of time and for both systems of units.

Table 2-1

FACTORS FOR NUMERICALLY CONVERTING HEAT LOSS RATES INTO GENERATOR POWER

Calculated Heat Loss X Conversion Factor = Generator Output.

Calculated Heat Loss	Conversion Factor	Generator Output
BTU / Hr.	1/3413	Kilowatts
BTU / Min.	1/56.88	Kilowatts
BTU / Sec.	1.0547	Kilowatts

When calculating generator power requirements, care must be taken to select accurate data for the material to be processed. For example, when the dielectric heater is installed as part of a complete dryer, the initial temperature, moisture content, product weight, etc. should be that of the material actually entering the electrodes.

Most dielectric heating operations involve the removal of water, either because that is desired, or because the act of heating removes water. The heat required to do this must be provided in order to heat a material above the vaporization temperature. It is not possible to heat a material above this temperature without vaporizing the volatiles and this requires heat.

If the volatiles being driven off by heat are not water, the proper temperatures, specific heat, and heat of vaporization of the particular volatiles must be used.

SELECTION OF GENERATOR POWER

Having determined the power required for a given heating project, the actual selection of the power rating of the equipment can be made. Several factors enter into this choice. If the process is to require the generator to deliver power continuously, or nearly so, (as in a conveyorized process) the generator should have a "continuous duty" rating.

On the other hand, if the operation is such that the equipment need not deliver power continuously, as may occur in some furniture assembly, or plastic welding, an "intermittent duty" rating will be satisfactory. Usually a machine with an intermittent rating will be somewhat less costly and smaller because the components can be smaller.

The "continuous" duty factor machine is rated to operate at least 8 hours per day at full power without stopping. All components will have sufficient cooling to withstand this rigorous operation. Conversely an intermittent duty machine can rest and cool off between "on" times and need only be cooled for the lower total losses of this intermittent operation.

The duty cycle or duty factor is the percent of time the equipment is delivering power compared to the total time operation is required. For example, if a generator is delivering power only 2 seconds for a weld, and it produces welds every 20 seconds, the duty factor is 10%. This means the generator can be so rated. In this case the continuous power of the generator will be approximately 30% of the intermittent rating. (The heating of the components depends on the square of the currents flowing and therefore a machine having twice the currents in its components will require four times as much cooling. Similarly, a machine having a 10% duty factor can handle $(0.1)^{.5}$ = .32 times as much power continuously.)

Generally, because of the availability of standard components on the market (vacuum tubes being an important example) the manufacturers will rate their equipment to have rated power outputs that are convenient to the components available. In selecting equipment, the choice is made of the next higher standard output rating above the calculated power. Using a standard size usually results in a less costly machine than if one is designed especially for a power rating. It also provides some safety factor for unknown losses, and for future larger jobs which might be run on the same equipment.

If the calculation happens to agree exactly with a standard sized generator the selection is more difficult. First, a thorough recheck of the power requirements should be made to be as sure as possible that nothing has been overlooked. Then consultation with the equipment manufacturer should be done. The machine manufacturer will be in the best position to know whether his generator is generously rated so that the safety factors that may be needed by your process are available if required.

In normal production operations there will be variations of weights of individual pieces or in their moisture content. Sometimes a process section ahead of the dielectric heater may have difficulties and the heat or moisture content at the input to the dielectric section will vary. If this is a temporary situation requiring a nominal increase in power from the generator, it may be possible to allow the dielectric heater to be overloaded for a relatively short time followed by a time during which it is under powered to allow the components to cool. Thus the maximum temperatures will not be exceeded for an extended period.

The manufacturer should be consulted in this type of problem. If the electronic components have a margin allowing for higher powered operation, the transformers are the components which will be overheated. The rating of a transformer is based on a preselected life of the insulation. Raising the temperature of a transformer 5 degrees Farenheit is said to reduce the life to 50%, provided the transformer remains at this temperature indefinitely. A short time increase might not seriously damage it. Again, the manufacturer of the equipment will know his design and will be the only one who can give authoritative advise.

SECTION 3

PLASTICS

Plastics applications can be divided broadly into two categories. The older is preheating thermoset resins for molding purposes and the newer is welding thermoplastic sheets together. The latter is by far the largest application of dielectric heating as measured by the number of installations.

PLASTICS PREHEATING

Plastics preheating became popular during WWII to speed the manufacture of products and to substitute for metals needed in national defense. It is an ideal application for RF dielectric heating because thermoset resins need to be heated uniformly to the temperature at which they become soft (and can be molded) but the heating must occur quickly so that the materials do not "set" or solidify. Once this "set" has occurred the material will never again become soft. Phenol formaldehyde and urea formaldehyde are typical of such resins. On the other hand a thermoplastic material, such as nylon, vinyl, polyethylene etc., will become soft every time the temperature is raised high enough. It does not benefit from dielectric heating because rapid heating is not necessary, although most thermoplastics can be heated dielectrically if desired.

General Description

Heating certain plastic material in a press, even in powder form, causes the grains next to the hot die to "set" before the other grains in the volume of the mold become soft. That results in poor filling of the mold which causes defective finished parts. Preheating the powder in an oven or on a hot plate relieves this problem somewhat, but at best the grains become sticky and are difficult to handle quickly without automation. If they are piled up the heating is not uniform.

To help the handling problem, plastic powder is often compressed under high pressure to make preforms. They have regular shapes, often round cylinders, and can be easily moved about by hand. Previously the thickness of the preforms was limited by concerns about curing or setting the compound on the outside without heating the interior. This also causes poor filling of the mold cavities and damages the appearance of the final casting by causing uneven gloss and voids.

Figure 3-1 shows some typical round preforms and the parts they make. Figure 3-2 shows a typical plastic preform preheater with the top open. It is located alongside a 20 Ton transfer press for

Figure 3-1 Typical preforms and the parts made from them.
Photo courtesy of W. T. LaRose & Associates

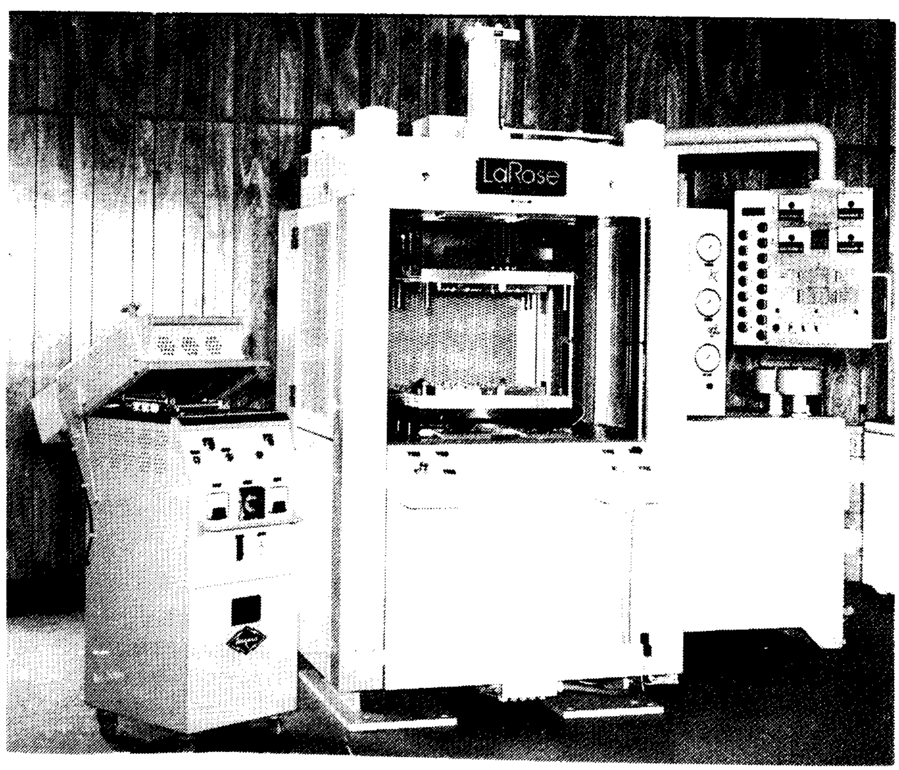


Figure 3-2 Typical plastics fabrication setup with the 5.5 KW preheater to the left and the 20 Ton press in the center.
Photo courtesy of W. T. LaRose & Associates

encapsulating semiconductors. The preforms are placed on the rotator bars in the preheater (to the left), and the top is closed during the heating time which is preselected by the timer in the center of the preheater. They are then manually transferred to the heated press which is subsequently closed for molding the part.

Dielectric heating provided an excellent solution to the problem of rapid uniform heating of the preforms because it heats the entire preform up to the molding temperature quite uniformly in 2 to 60 seconds. Time is subsequently available for manually or automatically transferring the preforms to the mold cavity and closing the press before the full curing takes place. The results are good fill and excellently finished parts.

Within the past decade another method of preheating has come into being which can handle many, but not all, thermoset resins. This method provides the heat by mechanical means. A tapered worm screw mixes and compresses the plastic powder and the friction of these actions causes it to heat. A last increment of heat needed is provided mechanically as the material is forced through a narrow hole, or sprue, at the time of loading the mold cavities so that the plastic material is at molding temperature but not yet "set up". This method eliminates the need for preforming and also produces excellent quality castings.

The characteristics of melamine plastics tend to give the dielectric heating an advantage over the mechanical preheating methods. Most dinnerware, and other melamine products, still use dielectric heating. Certain fillers used in specialized applications usually prefer dielectric heat because their abrasive qualities cause excessive wear of the mechanical preheaters. Of course, there are yet many dielectric heaters in use for preheating phenolics and other easy to handle compounds because the dielectric heaters are already available and eliminate the need for capital expenditures.

Plastic Products List

Among the products that are, or have been made using dielectric heating are pot handles, circuit breaker cases, instrument cases, automotive distributor and other electrical parts, telephones, radio/TV cabinets, washing machine agitators, dinner ware, knobs, telephone parts, telephone central office equipment, blower impellers, lens mounts, encapsulations for micro electronic components, and a myriad of others. These parts are most commonly made of phenolic resins with wood flour as a filler.

More recently some of these, and other, products have been made of thermoplastic resins. Developments which solved the stability problems of these resins through the use of fillers (fiberglass, silica, etc.) have made this possible. Automatic molding machines used for thermoplastics have also added to this change.

Power Requirements And Machine Characteristics

It is difficult to calculate exactly the amount of power needed to heat a given amount of a resin compound. Manufacturers of dielectric heating equipment have developed "rules of thumb" for estimating power requirements. For estimating purposes it is normal to heat between .5 and .75 pounds of preform with 1 kilowatt minute of delivered energy. Much depends on the ability of the preheater to deliver its rated power into the load - particularly to small weight loads requiring very fast heating times.

It is important that the dielectric heater have sufficient voltage at the heating electrodes to be able to deliver the needed power to heat the preforms in the allotted short time. At 27 MHz, it is not unusual for a preheater to be able to develop 20,000 to 25,000 volts (peak) between the electrodes. In this case it will be able to operate with a comfortable air space between the electrode and the top of the preforms. Of course, it is essential that all stacks of preforms be close to the same height.

The requirement that all stacks of preforms have the same heights implies a rectangular shape in the elevation view. Sometimes, as for automated systems, it is desirable to have the elevation view circular in shape-i.e., heat the preforms while lying on their circular sides. In this case the preforms should be rotated around their horizontal center lines. They should make several revolutions in the desired heating time so that the temperature will be quite uniform throughout the volume at the end of the heat cycle. The sketches in Figure 3-3 illustrates stacks of preforms, and the rotational preheating system.

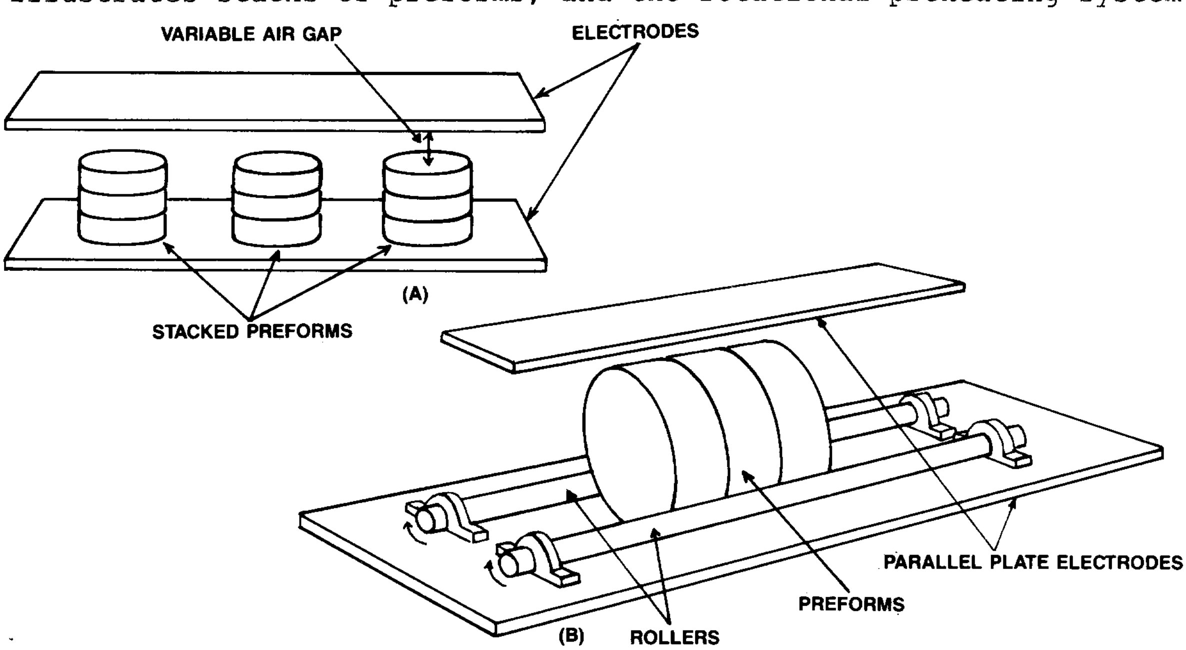


Figure 3-3 (a) Stacks of preforms under an electrode. All stacks should be about the same height.
(b) Round preforms being rotated by the two small driving rollers under them. Rotation provides uniform exposure to the RF field.

Electrodes

Electrodes for plastics preheaters are almost always flat parallel plates (See Appendix C Figure C-1 [b]). Often one electrode is used to support the preforms directly and usually (though not always) this will be the "grounded" electrode. The spacing between the two electrodes normally will be adjustable and the upper electrode may not make contact with the tops of the preforms. This spacing can be used to control the power output of the generator (heating rate). If the spacing is increased, the rate of heating decreases as does the power output. The power input also decreases as the space increases; as always with a dielectric heater, power not required to heat the load is not required from the power line.

If the space becomes too great the heating of the preforms may not be sufficiently uniform. In this case a conducting plate may be placed on top of the preforms, but not otherwise connected.

Occasionally the lower electrode which supports the preforms may be cooler than the preforms. This can cause cool bottoms to the preforms which might be deleterious to the molding. A thin sheet of cardboard, such as comes from a shoe box, or other more sophisticated insulation, will help this problem. The material used will quickly become soiled by the preform powder, but this will not be serious in most cases.

Automation

Systems have been devised to reduce the manual labor and time needed to transfer a hot preform from the preheater to the press cavities. One system uses a group of cups of plastic powder which are filled automatically at a loading station. They are then transferred to the electrode area for heating, and then on into the press for transferring the heated powder to the mold cavities. Other systems are built to handle preforms from hoppers to the electrodes and then into the press. At least one arrangement rolls a round preform onto a rotating mechanism for preheating and then 2 to 5 seconds later transfers the hot piece into the press by a short conveyor.

Figure 3-4 shows another type of automation. The powdered material is loaded from the hopper, on the left, into several insulated cups. The cups are held on a tray which is then indexed into the preheater section. After preheating, the tray of cups is transferred into the press at the right where the mold is closed and the castings are held under pressure for curing. After curing, the castings are removed and the mold cleaned for the next load.

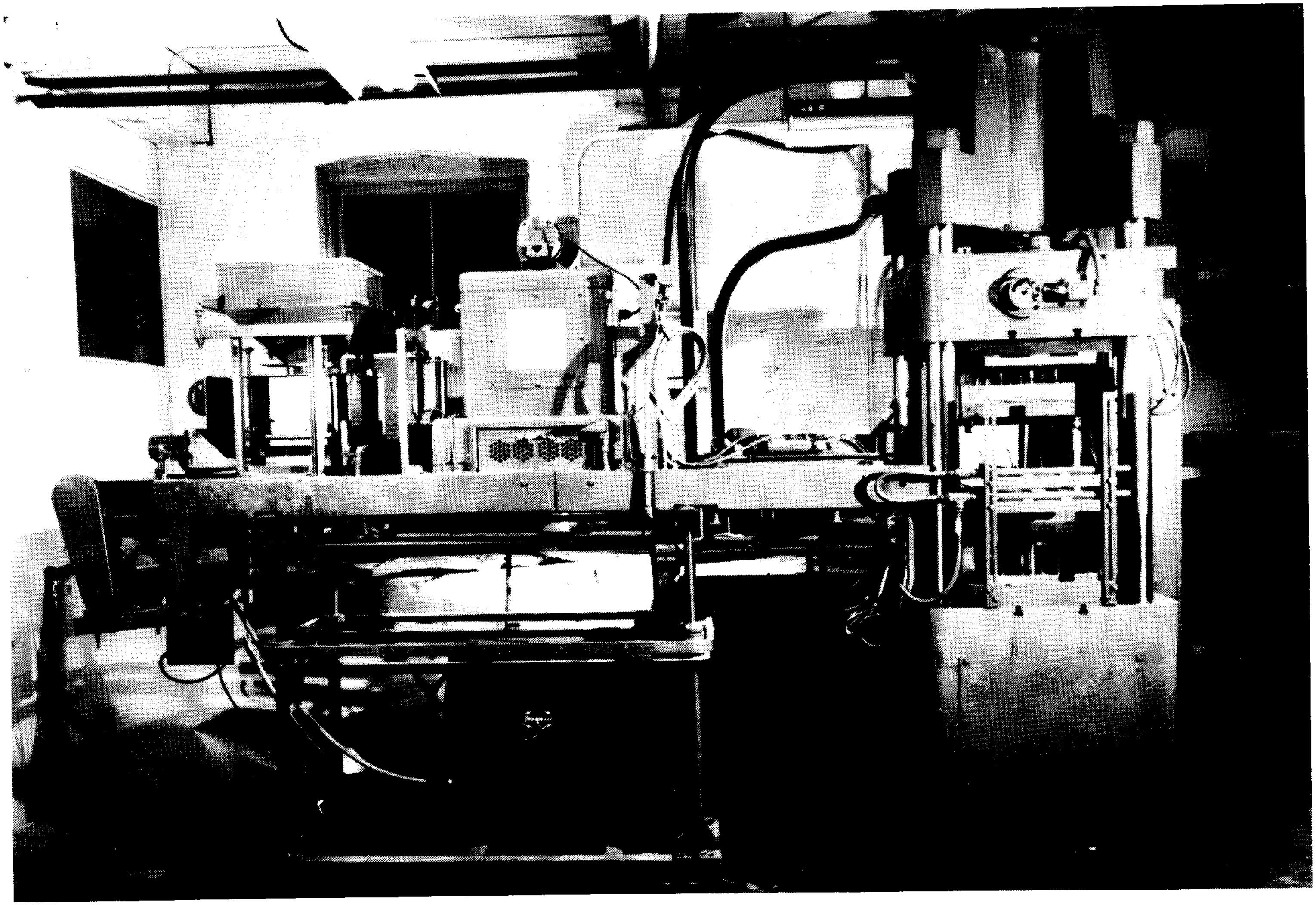


Figure 3-4 An automated powder preheater setup. The powder in the hopper to the left is dropped into insulated cups which move into the 8.5 KW preheater (center with round holes) for heating and then into the press to the right for molding.
Photo courtesy of W. T. LaRose & Associates

Pultrusions

Pultrusion describes a process for making very strong rods. They are usually made of glass roving completely impregnated with polyester or epoxy resins. They are used to couple motor energy from the surface of the ground to a deeply submersed pump near the bottom of an oil well. The strength to weight ratio, plus its elasticity and resistance to corrosion make it preferred over steel for this application.

The impregnated glass roving is pulled through the parallel plates of a dielectric heater. Fast lines operate at 144 in. per min., delivers up to 1.4 KW per pound of material per minute (twice this is needed for epoxy resins) to the material, which is heated to about 185 degrees F (275 to 300 degrees F for epoxy resins). One manufacturer recommends 70 to 90 MHz frequency with electrodes not over 26 inches long. Several electrodes and several lines may be used simultaneously in some instances. The temperature is raised 115 degrees F in less than 11 seconds. After preheating the material is drawn through heated die tubes which allows the accurate final dimensions to be achieved.

Shielding

Because most preheaters are constructed with the generator and the electrodes in the same cabinet, preheaters are the easiest to shield of all dielectric heaters. Maintenance of the shield is important. Particular attention should be paid to contacts which must be opened and closed for each heating operation. These can wear and the high frequency energy can leak out. As discussed in an Appendix B, it requires only a very small amount of energy leakage to cause considerable radio interference. Also it is very important to be sure all the fasteners are in place and tight and that the panels are not warped. Good contact between all cabinet parts is essential.

PLASTIC WELDING

This heading encompassed the most highly developed of all dielectric heating applications. The products produced are varied. A partial list is given in Table 3-1. As can be seen they vary from small plastic containers to automotive trim parts, from small hospital bags to large tarpaulins, and may be produced on simple manually operated machines or on highly automated ones.

Table 3-1

PARTIAL LIST OF DIELECTRIC WELDING APPLICATIONS

Advertising trade mark fittings.
Air Force pressure suits.
Airhouses, fixed or portable
Arrows
Attache cases
Automotive components
- Arm rests
- Car Seats
- Carpet heel pads
- Convertible tops
- Door panels
- Harness cables
- Headrests
- Litter bags
- Rear Windows
- Seat covers
- Seats (embossing - panels)
- Sun visors
- Water Reservoirs

Awnings and canopies

Baby baths
Baby nursing goods
Baby pants
Badges
Bags
Bathroom scales
Beach goods
Belts
Bibs
Blinds
Billfolds
Blood plasma kits
Bulletproof vests
Buttonholes

Canteen liners
Car seats (juvenile)
Carriages
Chaise longue pads and mats
Cigarette cases and lighter covers
Clothing
- Aprons
- Brassieres - brassiere straps

Labels, fabric and transfer
Lawn furniture
Lettering for sport jackets and athletic equipment
Life jackets, vests, and floats
Luggage bindings, linings and pockets

Mats
Medical products
Colostomy bags
Enema bags
Plasma and IV bags
Pulsating mattresses etc.
Metal - vinyl adhesive clad
Mittens
Molded fasteners
Movie screens

Naval dye markers
Notebooks

Outdoor furniture pads and covers
Oxygen breathing tents
Office racks

Packaging
- Ball bearings
- Blister
- Candy
- Drug
- Hardware
- Stamps

Pads
- Beach
- Crib
- Gymnasium
- Heating
- Patio
- Play pen

Table 3-1 (Continued)

Hats and caps
House coats
Jackets
Leggings
Lingerie
Lounge robes
Rain coats
Ties
Special application clothing
Underwear etc.
Collar stays
Containers
Cosmetic cases and kits
Computer cards
Covers
Air conditioner
Aircraft
Boat
Book
Checkbook
Cone
Fluorescent lights
Furniture
Hamper
Industrial equipment
Mattress
Pillow
Pool
Truck and auto
Crib bumpers
Crib mattresses
Curtains

Desk sets
Diaper bags
Diapers
Dog collars
Drapes
Dress forms
Drill holders

Electric blankets
Embossing Designs
Envelopes
Eyeglass temples

Flags
Folding doors
Frozen food cooking and defrost bags
Furniture
Chair backs and seats
Upholsters cushions, seats

Golf carts
Golf club covers
Grommets for garment bags
Guide cards

Pool
Station wagon
Paper cups and containers
Photo albums
Place mats and coasters
Pocket protectors
Pocket secretaries
Pool liners
Powder puffs
Purses

Quilting, vinyl synthetic fabrics
Applique process for fabrics

Record envelopes
Reinforced plastics - pultrusions
Ribbons for tying packages

Safety equipment
Salt water conversion kits
School supplies
Shoe components
Bows
Heel pads
Insoles
Ornaments
Seal and cut
Shoe embossing
Shoe uppers
Sock linings
Shower curtains
Signal flags
Sponges
Sporting goods accessories
Athletic bags
Bowling bags
Golf club covers
Gun cases
Stadium cushions
Sterilizers
Sweaters

Tablecloths
Tabs
Tarpaulins
Teething rings
Tents
Tool kits
Towels
Soap packet
Trim
Toys
Beach balls
Dolls
Game kits
Inflatables
Kites
Stick horses
Stuffed toys

Table 3-1 (Continued)

Hair dryer hoods
Handbags
Handles
Hat, wig, and wiglet boxes
Headrests
Hoods
Honeycomb curing

Industrial gloves
Inflatable products
Inlaying on various articles

Key cases
Kits

Travel cases
Truck covers

Umbrellas and covers

Waders
Wading pools
Wallets
Water filled head and eye pads
Window shades
Zipper bags
Zipper, reinforcements
Zippers

Source: Thermex-Thermatron Inc.

The Process

Plastic welding is a descriptive term. The process literally welds two pieces of similar plastic by melting them under pressure at the interface to form one piece. Sometimes two bare sheets are joined, usually with a patterned weld, or there may be several layers of plastic or other material between the two sheets to form padding, shaping materials, or even a space to hold a part to be packaged in a sealed plastic container.

The process is accomplished by placing two sheets of a weldable material, such as polyvinyl chloride, so that one is in good contact with the other and under pressure. An electrode the shape of the desired weld is placed in contact with one sheet; the other electrode is usually a flat piece of metal. Weld lines are often referred to as "rule" lines; the two terms are synonymous. Figure 3-5 shows the cross section of sheets of plastic being welded. When the high frequency is turned on the material between the die and the bed plate is heated with the highest temperature being at the interface between the two sheets. The material is melted and flows slightly outward under the pressure and the two sheets become one.

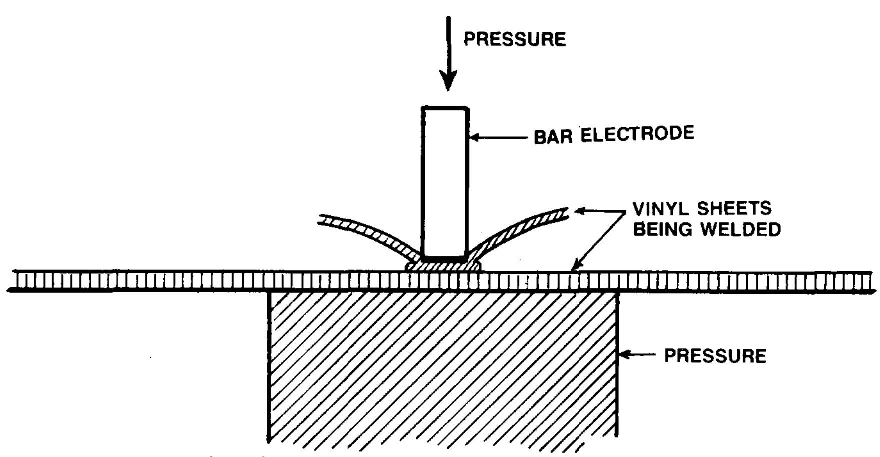


Figure 3-5 This illustrates the cross section of a die being pressed into two plastic sheets to weld them.

Figure 3-6 illustrates a typical bar sealing press. The die in the photo makes two parallel lines when the cylinder presses it onto two sheets of weldable plastic (not shown) and the high frequency is turned on. The essential instruments, timers etc. are mounted on the control box convenient to the operator. The 10 KW generator is in the back of the press structure.

Plastic Welding is Done Faster With Dielectric Heating

While plastic welding can be accomplished without dielectric heating, the process is slow and costly. It is necessary to use a hot die to heat the two sheets sufficiently so they will fuse together. They then must be held under adequate pressure until the die can be chilled to cool them enough for good adhesion. This puts the maximum heat on the faces of the materials which do not want it and requires that the die be heated and then cooled each time a weld is made.

With dielectric heating the weld can be made with cold dies, although with a warm die they will usually bond in a shorter time. The die must never reach a temperature such that it will not cool the weld after bonding. Sometimes dies are water cooled. Due to the electric field, which is placed between the die and the supporting plate, the vinyl between them is heated (see section on theory of dielectric heating in Appendix A). Because of the cool die, the hottest spot appears at the interface between the two sheets, which is exactly where it is needed for welding. Thus the energy costs are low and the process is very fast. Heating times vary from 0.5 second to 10-15 seconds.

If a weld cannot be made in 15 seconds it is almost impossible to make it with the power available because the heat is lost to the cool die as rapidly as it is introduced by the electrodes; the interface between the two sheets must be melted before the die can rob the heat. Sometimes the lack of bond is caused by insufficient pressure, but usually the high frequency energy is inadequate.

To a small degree it is possible to substitute heat for pressure and visa versa, but this can be done only to a limited degree. For strong satisfactory welds, both must be present in adequate amounts. The materials being welded must be weldable of course, or at least must be coated with a plastic that makes proper bonding possible. Table 3-2 provides information on the ease of sealability of various materials by dielectric heating methods.

Area Seals

Area seals heat and seal a substantial and continuous area of materials. An area seal covers an area; it is not a long narrow shape like a line. The die is a conducting plate of the shape desired. The plate may have a pattern in its surface which will be embossed into the plastic.

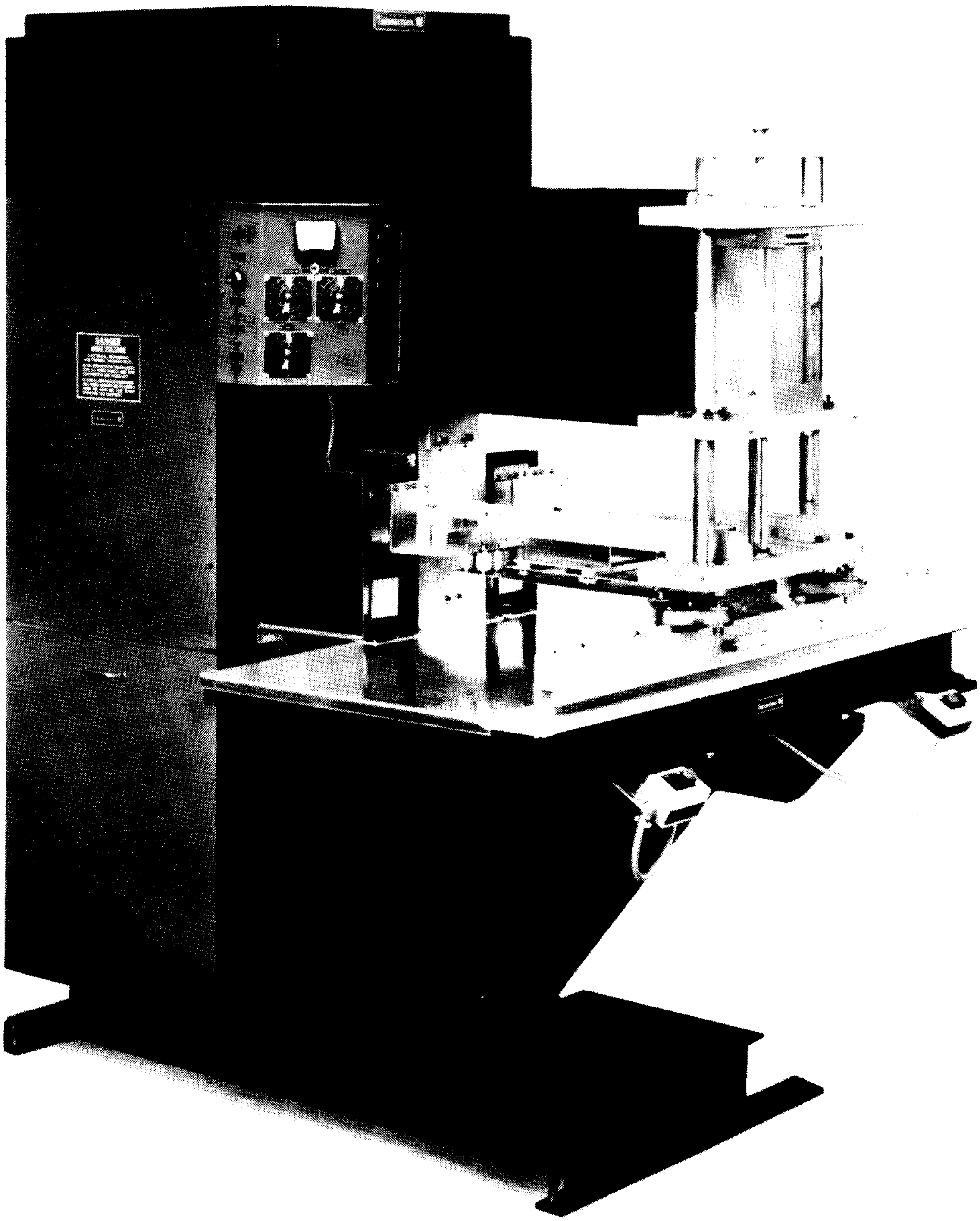


Figure 3-6 This is a typical deep throated 10 KW bar sealer.
Photo courtesy of Thermex Thermatron

Table 3-2

EASE OF SEALABILITY OF VARIOUS MATERIALS BY DIELECTRIC HEATING METHODS

MATERIAL	APPROX. LOSS FACTOR	SEALABILITY RESPONSE GOOD	FAIR	POOR	NONE
ABS polymers	0.025			x	
Acetal copolymer	0.025			x	
Cellulose acetate	0.15		x		
Cellulose acetate butyrate	0.15		x		
Diallyl phthalate polymer glass filled	0.04			x	
Epoxy resins	0.12		x		
Melamine formaldehyde resin cellulose filler	0.2	x			
Nylon, type 6	0.16		x		
Nylon, type 6/6	0.14		x		
KEL-F	0.03			x	
Phenol formaldehyde resin wood flour filler	0.2	x			
Polyamide	0.16		x		
Polycarbonate	0.03			x	
Polychlorotriflouroethylene	0.025			x	
Polyester	0.05			x	
Polyethylene	0.0008				x
Polyimide	0.013			x	
Poly (methyl methacrylate)	0.09		x		
Polypropylene	0.001				x
Polystyrene	0.001				x
Polytetrachluoroethylene	0.0004				x
Polyurethan foam				x	
Polyurethan vinyl film		x			
Polyurethane film (Estane)	0.35	x			
PEP fluorocarbon	0.0006				x
TPE fluorocarbon	0.0004				x
Polyvinylchloride plasticized	0.4	x			
Polyvinylchloride unplasticized	0.06			x	
Polyvinylidenechloride	0.3	x			
Rubber, compounded	0.13		x		
Rubber, hevea	0.015			x	
Silicones	0.009				x
Ureaformaldehyde resin	0.2	x			
Water	0.4	x			

Source Thermex Thermatron Inc.

Bar Seals

A bar seal is a long and narrow seal made by a long bar of metal. The bar may have a pattern in its surface, a popular pattern being one which simulates stitching. Bar seals are made as wide as 1/4 inch. The narrower the bar the more heat per square inch is required. The reason is that the narrower the weld line the greater the percentage of the total heat that will be dissipated laterally into adjacent parts of the plastic. For the same reason, area seals will generally require less power per square inch than bar seals.

Tear Seals

At times it is desirable to cut or controllably tear the welded sheets. This can, of course, be done with cutting dies which have sharp knife edges shaped as desired and forced against the plastic sheets by pressure. Much lower pressure is needed, and therefore a much larger cut can be made, if dielectric heat is used to soften the plastic and make it very thin. In making a tear seal, the plastic is nearly melted along a rather sharp thin line, often adjacent to a bar seal although the tear seal results in some welding. Often the bar welding and the cutting are done at the same time but the final parting is done by tearing along the thin lines. Figure 3-7 shows a "tear seal" tool. Tear seals, with their sharp edges, lose a greater percentage of the heat which dissipates into adjacent materials. Thus a tear seal requires more heat per square inch than does a bar seal.

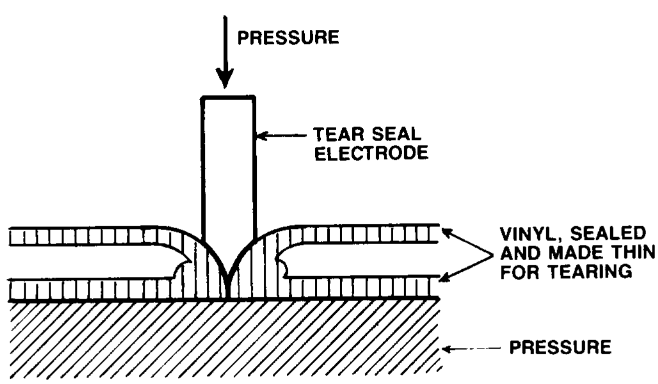


Figure 3-7 Shows the cross section of a tear seal die.

The movement of the upper electrode or die in figure 3-7 is similar to that of the bar electrode in figure 3-5 except that the sharp edge of a cutting die is lower than a bar so that, after heating, the plastic material is thin enough to tear easily along the cutting line.

Plastic Welding Can Be Decorative

Naturally the welding can be made to be decorative as well as functional. Many articles of clothing, such as shoes, or purses, take advantage of this. An extension of the decorative idea, but utilitarian as well, is in automotive trim panels. These door panels, head liners, seats etc. of automobiles will have a pleasing and even multicolored pattern embossed into them, with special decorative strips appearing as metallic lines. Additionally some padding is often embossed into the panels to provide sound proofing as well as a soft "upholstered" look. Sometimes the panel will be supported by a form of fiberboard or hardboard. This is coated with a vinyl so that good bonding to the upholstery can be obtained.

Power Determination

The power required to do a welding job will depend on the area of the weld - naturally a large area weld will require more power than a small one. The area is usually measured in square inches of weld, i.e. the width of the welded area (or the die producing the weld) multiplied by the total length of the weld line. Because of heat losses at the edges of the rule line, an allowance of +1/32 inch should be added to the actual width of the die bar to determine the area of a particular die; for example a bar 1/8 inch wide should be calculated as being 5/32 inches wide. Be sure to include the area of a tear seal if present. Table 3-3 gives data from two manufacturers about the power required for bonding RF sealable grades of flexible vinyl.

At best even table 3-3 can be only a guide. The safest way of selecting the size generator needed for a welding project is to consult with a reputable and experienced manufacturer of generators and presses.

It is virtually impossible to calculate the amount of power required for an embossing or welding operation because so many of the factors involved are difficult to determine. The losses from the edges of the dies, the varying temperature of the die itself, etc. make accuracy impossible. The empirical approach is usually used.

As can be seen by studying Table 3-3, the number of square inches which can be welded varies with the thickness of the materials being welded. The thicker the "sandwich" the more area which can be bonded with a given generator. This is because the heat transfer to the dies on the outer surfaces is less with the thicker materials.

Not shown in Table 3-3, but a factor which may need to be considered into account, is the width of the rule line. Usually, with a given power, a larger area can be welded if the rule line is wide than if it is narrow. This is because in the narrow line the heated area is surrounded by cold vinyl whereas in a wide line the interior parts of the area are surrounded by hot vinyl. Thus width of the rule line is an important factor in selection of generator size.

Table 3-3

POWER REQUIREMENT FOR PLASTIC WELDING

Seal Areas in Square Inches

Power	Total Vinyl Thickness in Inches. .008"	.012"	.016"	.019"	.024"	.030"	.040"	.080"
1KW	2	3	3.5	4	4.2	4.5	5	6
1.5	3	4.5	--	6	--	6.8	7.5	9
2	4	6	--	8	--	9	10	12
3	6	9	--	12	--	13.5	15	18
4	8	12	14	16	17	18	20	24
6	12	18	21	24	25	27	30	36
8	16	24	28	32	34	36	40	48
10	20	30	35	40	42	45	50	60
12	24	36	--	48	--	54	60	72
15	30	45	52.5	60	63	68	75	90
20	40	60	70	80	84	90	100	120
25	50	75	--	100	--	113	125	150
30	60	90	--	120	--	135	150	180
40	80	120	--	160	--	180	200	240
60	120	180	--	240	--	270	300	360

NOTE:
The above chart is based on the use of RF sealing grades of flexible vinyl sheet, proper pressure and timing. It is further assumed the electrodes are well constructed and in good condition. It is primarily for bar sealing. For area seals and tear seals consult with a reputable manufacturer as to modifications to these data.

Table 3-3 Courtesy J. A. Callanan Co. and Thermex Thermatron Inc.

Automation

Automation in plastic welding has been quite highly developed by several manufacturers. Automatic machines involve many operations that have nothing to do with dielectric heating per se. They are concerned with material handling, printing, etc.

For example, a non automated bar sealer is shown in Figure 3-6. It is one in which the pieces to be welded together are placed manually between the die (the long bar which also applies the pressure to the weld joint from the press) and the bed plate. The high frequency energy is then turned on and timers, shown on the left, control both the heating and the cooling cycles.

A commonplace semiautomatic arrangement is illustrated in Figure 3-8 which shows a large turntable to accommodate several operators who are seated around it. The turntable will index as needed to permit the operators to remove and inspect the welded parts, clean and load new parts (this may require two or three stations on complex assemblies) and then return to the weld station. The tooling is arranged with insulation as needed to accomodate the high frequency voltage. It may also contain holding fixtures, cavities, etc. to produce the part(s) desired. The indexing and the dielectric heating are done without any human intervention except to signal the start of an indexing cycle. Often the area where the actual welding takes place will be enclosed with metal to shield the high frequency parts from causing interference.

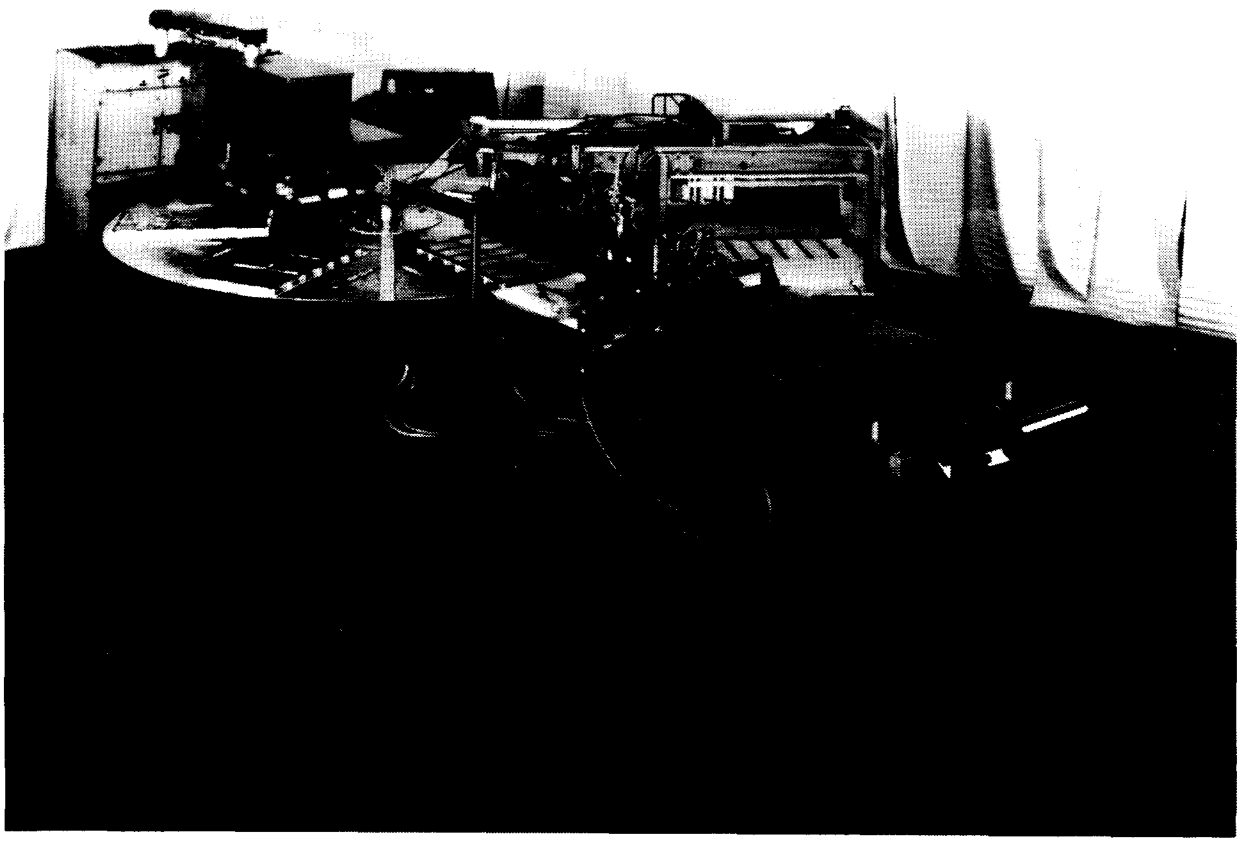


Figure 3-8 A six station rotary turntable for semiautomatic plastic welding operations. Operators can be used at some stations.
Photo courtesy of Colpitt B.V.

Figure 3-9 illustrates another turntable design with two 30 KW generators as part of an 8 station Rotary Table installation in the Datsun factory in Japan. This machine, working 2 shifts, can produce car trim sets for 1 million automobiles per year. The operators seated around the table assemble the various parts of the trim material after which the table indexes for the next operation, including the welding of the materials together.

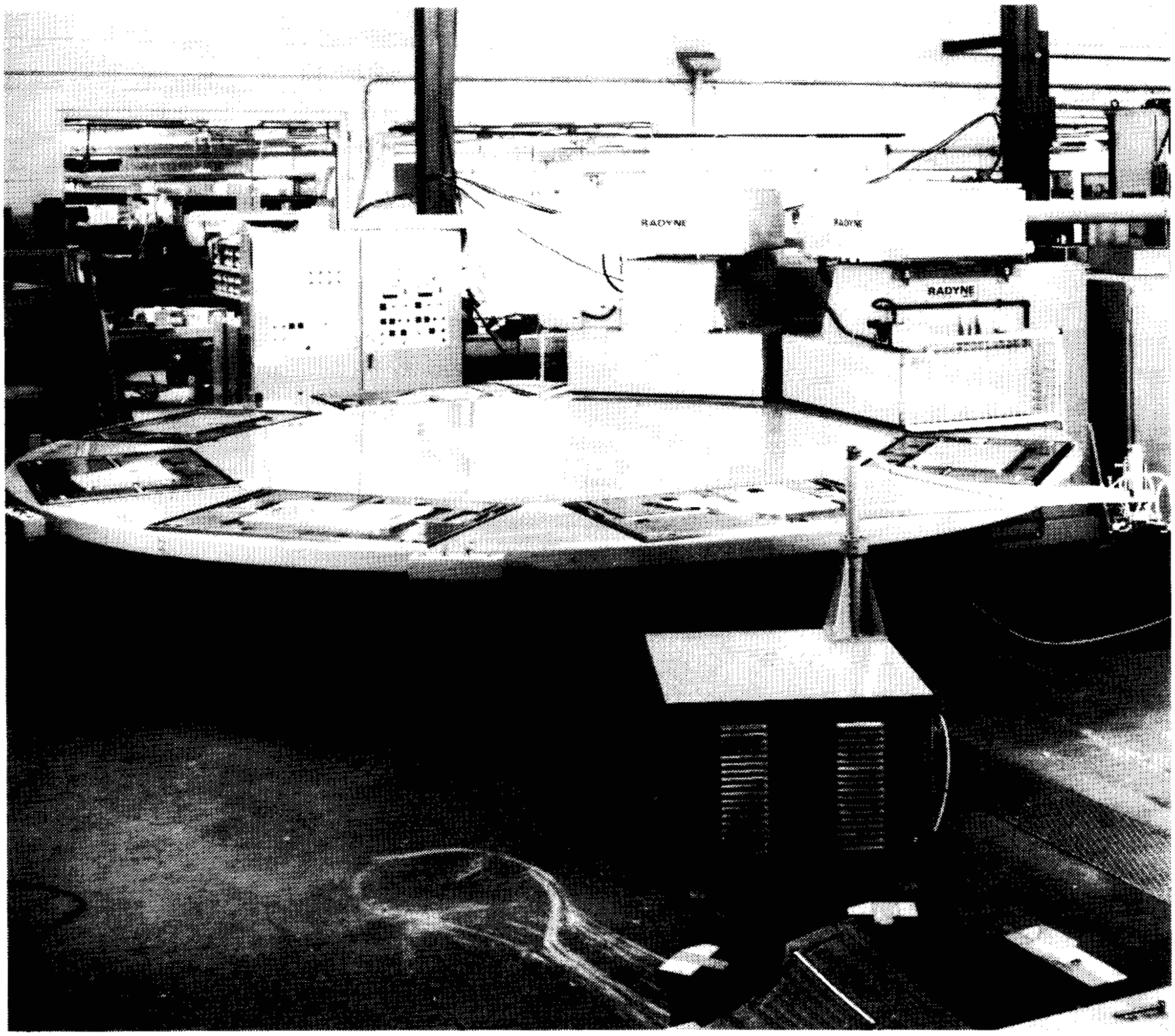


Figure 3-9 A six station turntable, with two 30 KW generators, is in use for making automotive trim parts for 1,000,000 cars per year in Japan.
Photo courtesy of Radyne, Ltd.

The ultimate in automation includes completely automatic handling of all the materials. This means forming them directly from a roll of vinyl, a stock of tubing and auxiliary parts, printing a message on the vinyl, positioning auxiliary parts to be welded into place, and delivering the finished parts to an outfeed conveyor. For example, one machine manufactured in Europe takes rolls of vinyl sheet and tubing as the infeed stock, and delivers filled and sealed bags of blood plasma, properly marked, as the finished product. No operators are required except to load the various hoppers and to be sure the filled bags are carried away without damage. The end user declined permission to publish a photograph of his special machine. A similar fully automated machine, this time for making telephone book jackets, is shown in Figure 3-10.

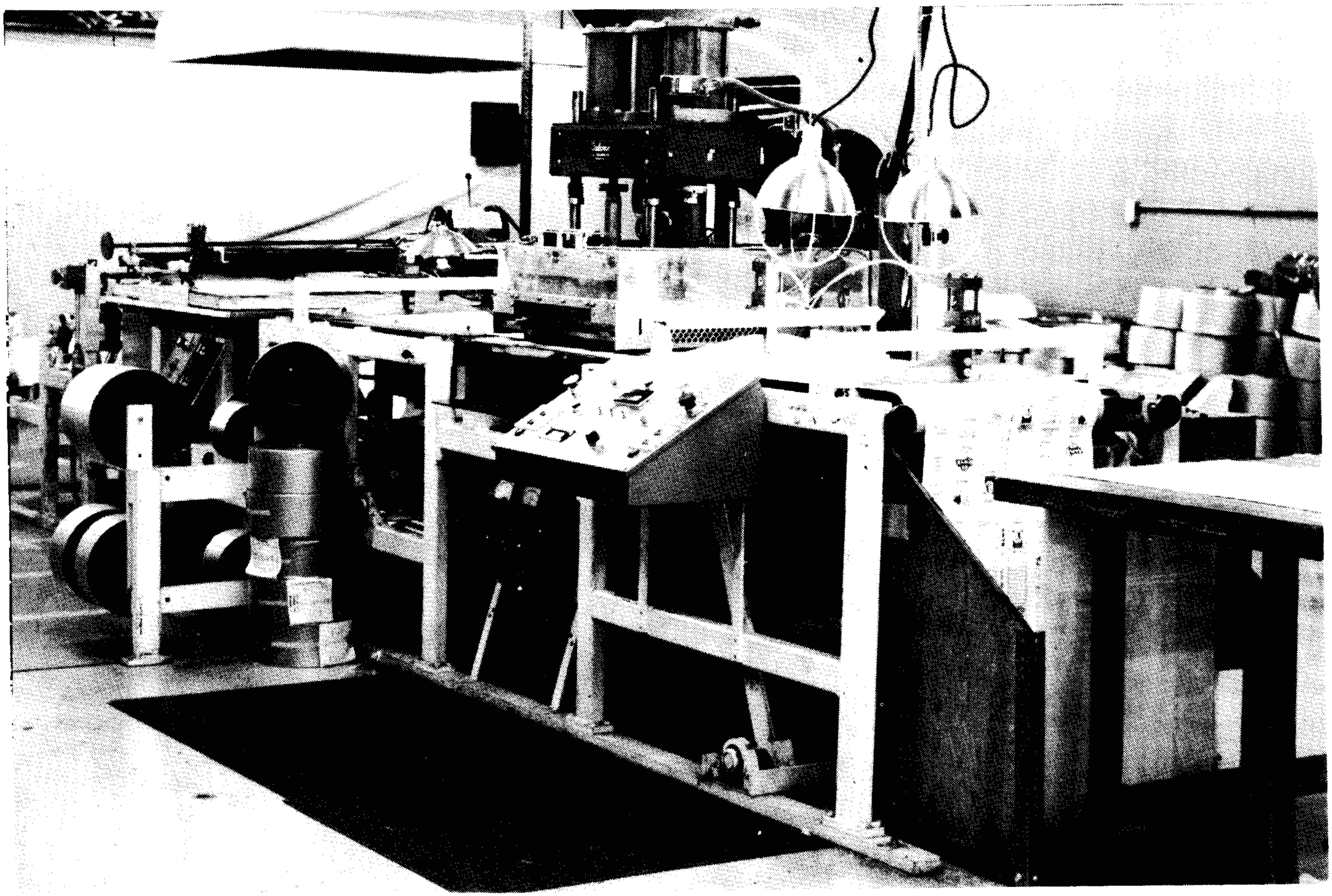


Figure 3-10 Automated machine takes rolls of plastic as input stock and delivers welded and printed telephone book jackets.

Photo courtesy of J. A. Callanan Co.

Figure 3-11 shows a typical setup for bonding heel pads to automotive carpeting. The generator is shown on top of the press; the power supply to the right. The hydraulic press requires only a short stroke, but the closing action also closes the shielding so that radiation is very low. The carpet and the heel pad are loaded onto the tray. A die in the press embosses a pattern in the heel pad material and also welds it to the carpeting. A similar tray extends to the rear of the machine so the generator is kept busy by two operators, front and rear. Presses very similar to this are also used for bonding automotive trim panels for doors, seats, etc. in many automobiles.

On very large pieces, such as water beds, or tarpaulins, the piece is too large to be done at one time. In these cases it is possible to do the job in sections, or "bites", thus simplifying the tooling and requiring a lower powered generator. Such an operation does, of course, require more time per piece. An all in one die would be very large which may have uniformity of heat problems over the large dimensions of the product. Reference to the discussion on selection of frequency found in the Appendix A of this report will aid in understanding this problem.

Figure 3-12 . An automated plastics welding machine accepts rolls of material at one end and delivers sealed products to the conveyor at the right. The generator uses an assigned ISM constant frequency so radio interference radiation is permitted in directions away from the operators who must work in close proximity to the electrodes.

Shielding

Shielding a dielectric welder is a difficult task and for many years it was ignored. It is safe to say that more interference reports come from poorly shielded plastic welders than from other applications of dielectric heating. One reason, of course, is that there are more of them.

As with all dielectric heating, shielding involves protection against radio interference to licensed communications services, such as TV, and personnel protection against the nonionizing radiation coming from a dielectric heating machine. The three basic methods of avoiding radio interference are:

1- Install the entire machine in a metal cabinet;

2- Install the entire machine in a screened room (here there may be several machines within one enclosure);

3- Operate the equipment on a frequency where "free" radiation is allowed by the regulatory authority, (The Federal Communications Commission in the U.S.).

Methods 2 and 3 may not be sufficient for personnel protection, but normally the degree of shielding for this is not as severe as for communications protection.

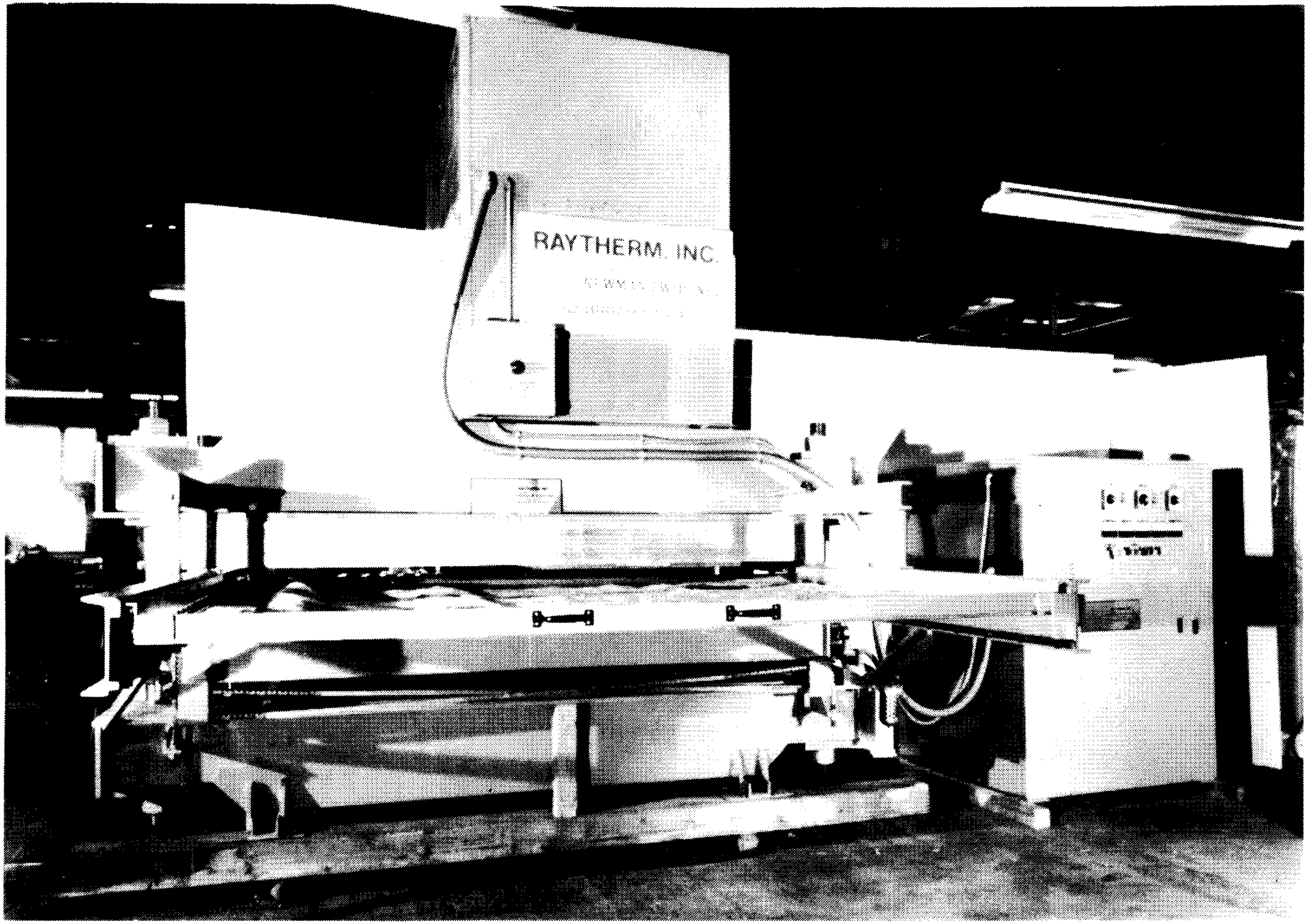


Figure 3-11 Press with 30 KW generator embosses heel pads on automobile carpets.
Photo courtesy of Raytherm, Inc.

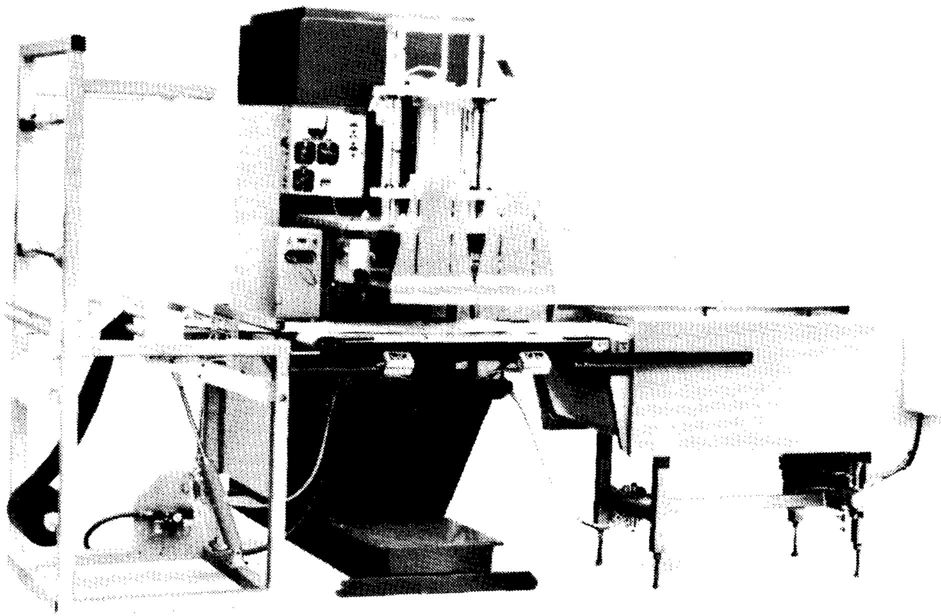


Figure 3-12 The automated plastics welder shown above uses a constant frequency generator, but has platen grounding also, (See text). It accepts rolls of material on the left and delivers sealed products on the conveyor at the right.
Photo courtesy Thermex Termatron Inc.

The major factor in providing good personnel shielding is to make an excellent wide strap connection between the fixed lower plate of the press and the moveable upper one which supports but is insulated from the high frequency electrode shown in Figure 3-10 (the box surrounding the electrode area in the center of the picture). In Figure 3-11 this is accomplished by the lower platen with the tray containing the parts to be welded. When the lower platen raises to close the press the entire high frequency portion of the press is inside a metal box which prevents the escape of high frequency energy.

Figure 3-12 illustrates another approach. The two slotted plates extending vertically at the front of the machine are used to connect the upper part of the press to the grounded bed plate. Note that a well attached piece of wire will not provide the needed connection; a wide strap, also well attached, is required. This is because of the high frequencies involved (about 452,000 times that used for normal power purposes). Not all plastic welders presently have this type of construction, but it is becoming increasingly important. The straps will usually be sufficient for OSHA requirements, but may not satisfy the needs of the FCC. However, in Figure 3-12 the generator frequency has been stabilized to operate within an ISM band where the FCC allows unlimited radiation on that frequency. Harmonics of the operating frequency must be eliminated.

Two problems exist with shielding in addition to its cost, which occasionally can be substantial. One is that poorly designed shielding will probably interfere with the movements of the equipment operator. The other is the need to maintain the integrity of the shield. Shielding requires excellent and complete contact between cabinet parts. Omitting fasteners, which is a common error, will greatly degrade the shielding. Even worse is omission of a panel or door. Well designed shielding will not interfere with the operator, and the maintenance staff should be trained to keep all fasteners in place. The better designed shields will require fewer fasteners and yet will provide the needed contact between cabinet parts. Reference to appendix B will provide better understanding of the basic problems.

Die Protection

Dielectric welders make use of costly dies which can be badly damaged by electric arcs. To avoid die damage, most welding generators are equipped with arc sensing devices which detect an arc between the dies and the platen and stop the high frequency usually in a few thousandths of a second. If the arc is stopped in an exceedingly short time the energy delivered into the arc, and therefore available for melting the dies, is insufficient to cause much damage. With a sensitive arc detecting system very often the arc mark cannot be felt with a finger. This is remarkable because, during the time of the arc, it is as hot as that used in arc welding of metals.

Power Range Common In Plastic Welding

Most welding, or embossing, jobs are done on small parts and need only a few kilowatts of power. However, for applications such as automotive trim panels, vinyl automobile tops, or heel pads on carpets, the power requirements are quite high and 100 KW is sometimes used. In automotive trim applications the surface vinyl, or treated cloth fabric, is bonded to a padding material, also previously treated to make it weldable, and the entire sandwich is bonded to and supported by a low grade of hard board (or even layers of heavy kraft paper) also properly treated for weldability.

LIST OF MANUFACTURERS

The following companies are known to manufacture RF dielectric heaters for the applications in this section.

For addresses at the time of publication please refer to the section on acknowledgments.

IN THE U.S.

J. A. Callanan Co.

Cosmos Electronic Machine Corp.

Kabar Electronics Corp.

W. T. LaRose & Associates

Nemeth Engineering Associates.

Radio Frequency Company, Inc.

Thermex Thermatron

IN EUROPE

Colpitt B.V.

Flender-Himmelwerk GmbH

Paul Kiefel Hochfrequenzanlagen GmbH

Radyne Limited

Strayfield International

Thimonnier S.A.

IN THE FAR EAST

Tai-Yen Industrial Co., Ltd.

Yamamoto Vinyter Co., Ltd.

SECTION 4

DRYING

Drying, or the removal of volatiles from a product, is a dielectric heating application which has been exploited in several industries since the advent of dielectric heating. However, the economic attractiveness of many potential dielectric drying applications largely depends on drying costs compared with the value of the products.

To illustrate, common sand can be dried very readily with dielectric heating but is almost never done because the value of dry sand is not much greater than that of wet sand, and each has a low value compared to the costs of dielectric heating. However, in the case of sand cores for foundries where the labor input has increased the value of the sand, the picture changes and dielectric heating has been used extensively there. It saves labor, reduces tooling costs, makes cores immediately available for use, reduces work in process inventory etc. Advances in other methods of making sand cores has reduced the number of applications of dielectric heating but it is still in use.

As is to be expected based on the theory of dielectric heating (See appendix A) thicker products may find benefit more than thinner ones from the use of high frequency heating. Where uniformity of drying is desirable, dielectric heating has important advantages. For example, when rayon was a popular product, a drying problem (nicely solved) was that of drying rayon cakes. These are thick walled hollow cylinders of thread. In a hot oven the cakes shrink nonuniformly due to nonuniform drying, and this mechanically strains the thread. The strains cause it to accept dye differently than if it were unstrained. Then, when the material is woven, patterns of different shade appear in the woven fabric. Dielectric removal of moisture, with its much more uniform action, eliminated the strains and hence the shade patterns in the woven product.

POWER DETERMINATION

Often the required power for drying can be estimated rather accurately by the methods outlined in section 2 of this report. In some cases, such as drying webs of paper, the determination of the required power should be done using the experience of manufacturers of dielectric heating apparatus. This is because there are heat losses or gains in the process which make calculations, for power determination, inaccurate.

SOME DRYING APPLICATIONS

There are many applications of dielectric drying in use in modern industry. The outstanding ones are: Drying of textile hanks, tow, or cones (see section 6); drying webs of woven or nonwoven fabrics after sizing or dying; hosiery drying; drying moistenable glue on business forms (see section 7); drying ceiling tile; drying sand cores; drying ceramic automobile muffler bodies prior to firing; drying coatings including printing on paper; drying paper during manufacture; drying lumber, and veneers for plywood; drying baked goods; drying fiberglass thread and insulation materials, drying book spines, and others.

Moisture Leveling

Even in drying thin webs of material, where one would think there would be little advantage because webs are not thick, dielectric heating finds advantages. Other helpful characteristics come into play. As mentioned in appendix A on the principles of dielectric heating, when the volatiles are primarily water, the presence of the moisture increases the loss factor of a material and it absorbs the energy from an electric field more readily than where the moisture is not present. In this way the wetter areas absorb more energy and hence dry more rapidly.

In webs, where the moisture is not always uniformly distributed over their area, the dielectric heating puts the heat where the moisture is concentrated and results in a more uniform moisture distribution in the output product. This avoids the necessity of overdrying some areas of the web in order to make sure all of it is below a critical moisture level - usually sufficiently low that mildews will not grow in the rolls of finished product. The overall weight of a roll can be increased because the average moisture content can be higher without exceeding the critical value of product. This increases its worth if it is sold by the pound, as is common. Dielectric heating is normally applied at the "dry" end of the dryer because of the selective drying of wet spots.

Augmenting Oven Dryers

The rate of drying will diminish rapidly in hot air, or infrared dryers when the moisture is no longer easily transmitted to the surfaces by surface tension; with a dielectric dryer the rate of drying can remain high and therefore the length of a dryer may be greatly reduced. This has an important practical implication. If plant is operating "dryer limited", as many of them are, it is possible to markedly increase the plant's drying capability without increasing the length of the drying machine. In other words additional drying capacity can be added without moving any other machinery to provide more room for an additional dryer. In economic terms, this means the addition of a dielectric dryer increases the production capabilities of the plant with minimum cost and delay. Proper economic credit for this should be given to the dielectric dryer when studying the economics of its use. There are plants where installation of a dielectric dryer has resulted in sufficient increase in throughput of the plant that the capital costs of the dielectric dryer, though high, could be amortized in a surprisingly short time, i.e. 1 to 2 years.

Where somewhat thicker products such as ceiling tiles are dried, a hot air drying system may leave a layer of wet material in the center if drying is attempted too rapidly. This is because the insulating qualities of the dry board make the final drying quite difficult. With dielectric heating added near the end of the dryer, the center wet line can be dispersed. It has been found that the conventional sections following a dielectric heater will remove more water than they previously did. This is because the generation of vapor from the center layer transports liquid water to the surface where the hot air can be more effective. Vaporized water occupies nearly 1700 times the volume of liquid water.

ARCING LIMITATIONS

Power determination for drying can usually be done by calculation. However, tests should be made to be sure that undue arcing does not occur at the specified electrical conditions. The required voltage on the electrode system and the configuration of the electrode system (particularly the length) are important to know. After these have been determined and the time required for the drying is known, the power can be calculated as described under section 2 of this report. Once the optimum electrode configuration is found, it may be necessary to increase the length of the electrode to reduce arcing tendencies and yet hold the power capabilities of the machine at the desired level.

GENERAL CONDITIONS

Where it is possible to remove liquids by mechanical means, such as in a centrifuge or a wringer, it is usually more economical to make use of these devices prior to dielectric drying. Also, when a product has a high water content whereby the moisture will augment the heat transfer into a product a hot air system will usually be less expensive than dielectric drying. However, the material being treated must not be overly heat sensitive. One of the most important advantages of dielectric heat is that it can be done in a relatively cool oven or even a saturated moist atmosphere. Also, there are no products of combustion as is the case with fossil fuels.

AVOIDING CONDENSATION IN DIELECTRIC DRYERS.

In a dielectric dryer, it is often desirable to have a warm atmosphere for the oven. At least the electrode and conveyor (or lower electrode) should be heated to avoid moisture condensation on them. A cold upper electrode will soon accumulate moisture which will drip back onto the product and CAN carry an electric arc with it. Often the dripping of the condensed moisture, which may not be pure water, will stain the surface of a product. An electric arc will destroy product.

If the lower electrode, or (where used) the conveyor, is not kept warm or will not readily absorb water (such as might be possible with a fabric conveyor belt) water will condense at the bottom and cause the lower portion of the product to be wet or, at least, to dry last. In this case a product will have the appearance of having sat in a puddle of water during the drying operation and may be stained by the condensate. A warm oven will avoid this problem.

The oven need not be very warm. As long as the oven and the air inside are above the dew point, water will not condense. It is possible, if desired, to do a complete drying operation in an atmosphere of saturated water vapor as long as the vapor does not condense. Rayon drying was usually done this way in which the air in the warm oven is almost completely replaced by water vapor. The water vapor can be collected by a condenser and thus much of the heat of vaporization in the removed water can be recovered and perhaps used for space heating or warm process water.

Some manufacturers prefer to avoid heating the oven; they heat the upper electrode and may use an insulated conveyor belt. In these cases the oven must be constructed to collect and drain away some of the condensed volatiles and to avoid them dripping back to the product. Experience has shown that if the volatile material penetrates joints which must carry high frequency currents, the conductivity of the joint can be reduced due to corrosion and deposits. Interference radiation will develop after some time of operation. Cleaning of such joints is necessary to maintain the shield integrity.

REDUCTION OF HEAT LOSSES

As fuel becomes more expensive, drying efficiency increases in importance. Hot air dryers, particularly where the temperatures are well above the boiling point of the volatiles, tend to lose a large quantity of heat up the exhaust stack. This is the largest heat loss in modern ovens which are usually well insulated. Air recirculation within the oven helps as it reuses the hot air before exhausting it.

In a dielectric moisture removal system, over 95% of the energy leaving the generator appears as heat in the product. With the generator efficiency in the order of 65% (including all circuit losses) the cost efficiency of a dielectric dryer can easily exceed that of a hot air oven, particularly an old one. It can be more economical, and therefore consideration can be given to doing the entire drying operation with dielectric heating. The labor saving features (particularly where automation is provided) plus the higher quality of product, savings in floor space, etc. make such a consideration interesting.

Dielectric dryers have virtually no warm up or cool down time. As soon as the oven has warm air inside it, which normally is within a few minutes after turning on the auxiliary heat, it is ready to use. Dielectric heating requires no operation prior to introducing product. Likewise, since the oven can always be cooler than a hot air type the time for shutting down an operation is very short - a few minutes at most. In an emergency situation where rapid access to the oven interior is required, the dielectric heater permits almost immediate access to a person wearing gloves. Merely by opening all the doors and stopping the blowers, immediate entrance is possible.

PAPER AND PAPER COATINGS DRYING

Paper, being a thin material, would seemingly have little application for dielectric heating. Yet, particularly in the narrower widths, there are an increasing number of plants utilizing it to dry coatings and water based inks on fast moving paper webs. There are several reasons for this, including: a)the ability to dry the paper at high speeds without exposing it to high temperatures, b) moisture leveling, c) the ability to use water based inks which reduces pollution and solvents costs.

Hope was held that the moisture leveling aspect could be applied to primary paper machines. However, these have widths from 8 ft. to over 30 ft. and it was soon discovered that nearly dry paper, which is produced at 1000 to 2000 ft. per minute, requires lengthy electrodes to extract the moisture. Additionally, the stray field electrodes are the most difficult type on which to control the distribution of voltage. These factors have discouraged application of high frequency dielectric heating to primary paper machines. However, for many printed and coated paper products the web widths need not be so great and these applications are beginning to be seen in various places.

Power requirements are not calculable directly. At least one manufacturer of coating drying machines claims to be able to remove 2.2 pounds of water per kilowatt hour of output energy. While it should theoretically be possible to dry more than this, the thermal efficiency is still far superior to other coating drying systems which lose a large amount of heat to the surrounding air. Up to 75% of the cost of thermal energy is saved, according to one manufacturer.

Dielectric heating is often applied to drying the water based varnishes used for book covers, display packages, and glossy publicity materials. One manufacturer claims the ability to remove 5 grams per square meter from varnished papers at the rate of 10,000 sheets per hour with 12KW and 20 KW output generators. (Another user claims to remove 35 grams per square meter at this same rate, undoubtedly with a different coating.) The varnish dryer is often inserted between the offset printer and the product stacker.

It is amazing how many modern products utilize the printing process. A unique one is that of match boxes where the striking surfaces are printed onto a cardboard base, later also printed with multi colored patterns and messages, then creased, folded and filled. In this case an energy saving of 80% over competitive techniques is claimed.

Another manufacturer claims a 50 KW coating dryer will handle a 36 inch wide web at up to 1200 ft. per minute. He says a unique advantage of the dielectric system is to selectively dry the coated wet areas without heating the dry uncoated areas of the paper. Hence browning of the uncoated areas due to exposure to high heat, such as with an infrared drying system, is eliminated. Figure 4-1 shows such a dryer.

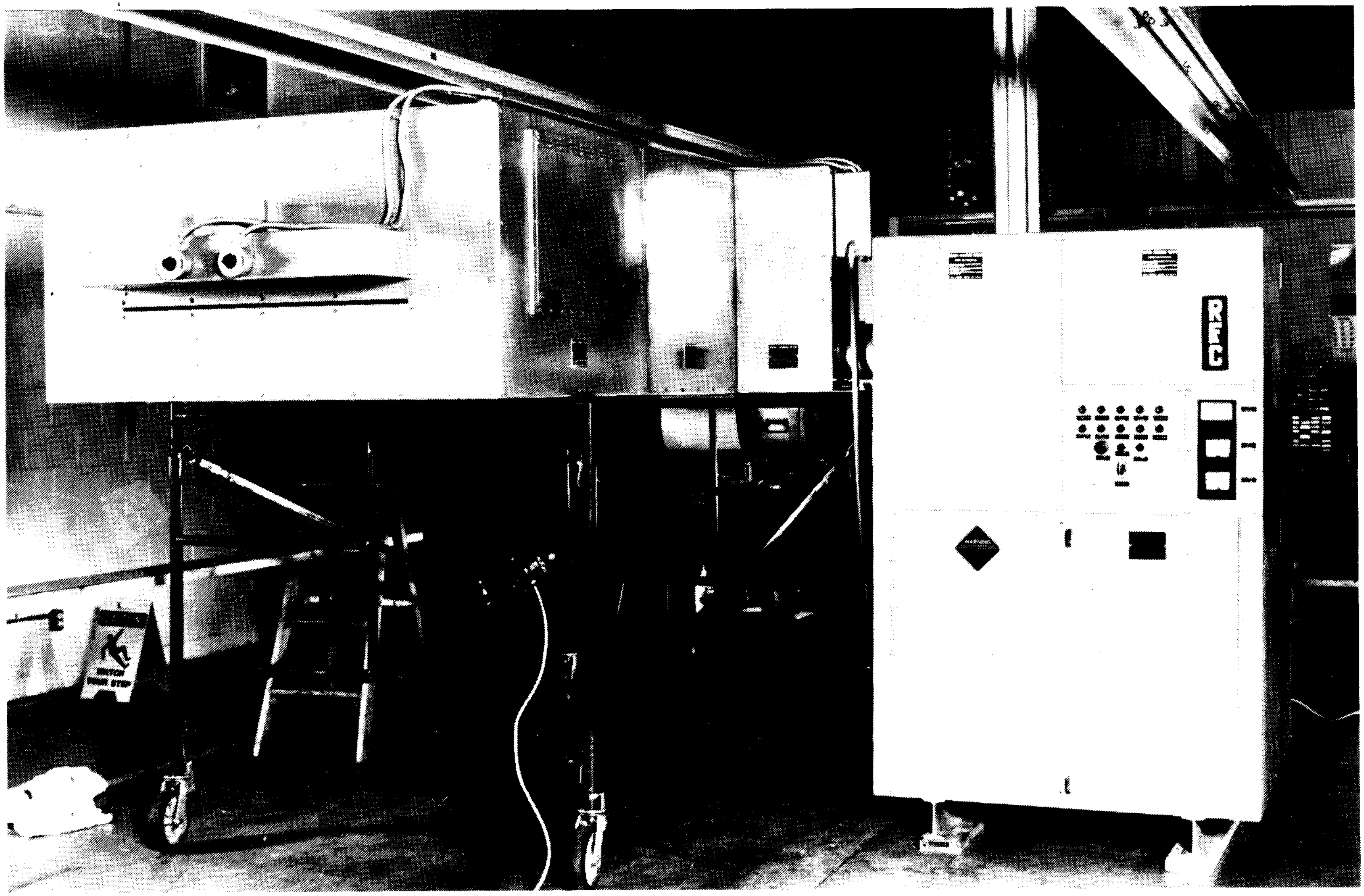


Figure 4-1   A 50 KW Generator with its shielded applicator set up on the user's floor. This machine dries coated patterns of water based coatings on 36 inch webs at speeds up to 1200 ft. per min.
Photo courtesy Radio Frequency Company, Inc.

VENEER DRYING

Veeneer drying is a relatively new application which is finding a valuable place in the manufacture of flat plywood. Althought this plywood was one of the first products to which dielectric heating was applied, the initial application was for the glue in a press. Dielectric heating of plywood was not found to be economical for common flat plywood and therefore was abandoned. It is interesting that a new application veneer drying has now been developed.

A detailed description of this application is found in the Section 5 and therefore will not be discussed further here.

LUMBER DRYING

Lumber drying is a new application which is slowly being adopted. Economic studies by impartial investigators are now becoming available and they tend to show that, compared to investing in a conventional dry kiln, the application of dielectric heating should be less expensive due to lower inventory costs and reduced labor and floor space. A new savings of 16% to 18% per board foot is indicated and this figure does not include the wastage savings. The subject is discussed in more detail in Section 5, Wood Applications.

TEXTILE DRYING

There is a growing number of dielectric heaters being used for drying textiles in various forms such as cones, hanks, webs, etc. The savings include improved product, lowered inventory costs, and uniformity of output water content. More details are found in Section 6, Textiles.

OTHER DRYING APPLICATIONS

One drying application is that of removing water and other solvents from polyurethane foam slabs. These can be made 12 inches or more thick, and it is difficult to get heat to penetrate this thickness of such a good insulating material. In one such installation a 200 kW dielectric heater is used for this purpose. Two generators are located on top of the applicator but the control panels are at floor level for operator convenience as shown in Figure 4-2.

A similar machine, but rated at 150 kW output, is also used for drying fiberglass roving packages weighing 50 pounds each, from 16% moisture to 0% in less than 1 hour.

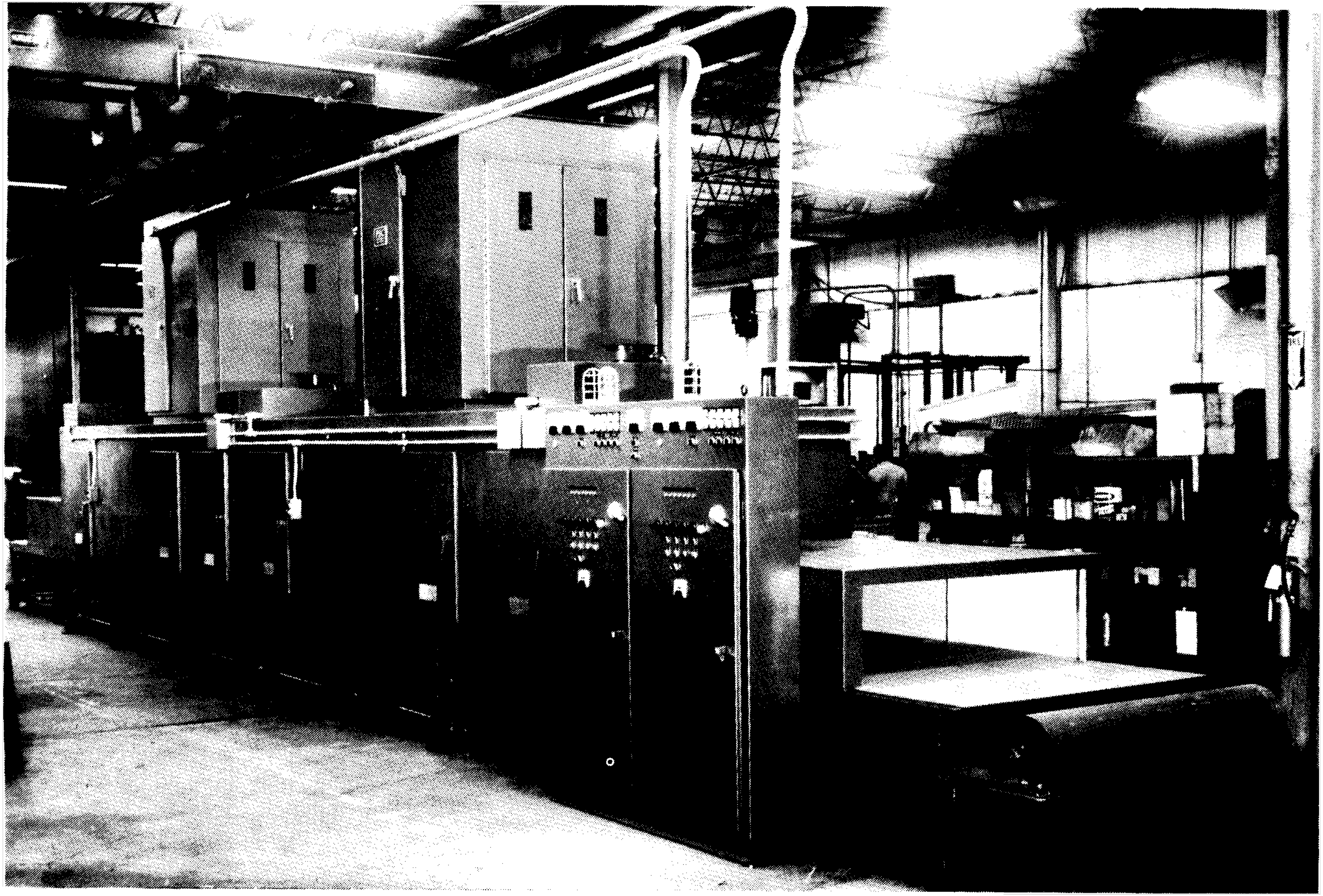


Figure 4-2 This machine, with its two generators mounted on top of the conveyorized applicator, is typical of a 200 KW equipment to dry foamed polyurethane slabs.
Photo courtesy PSC Inc.

LIST OF MANUFACTURERS

The following companies are known to manufacture RF dielectric heaters for the applications in this section.

For addresses at the time of publication please refer to the section on acknowledgments.

IN THE U.S.

- Dimension Drying Inc.
- L L Machinery Co.
- W. T. LaRose & Associates
- PSC inc.
- Radio Frequency Company, Inc.
- Reeve Electronics
- Rosenquist Inc.
- SPECO Inc.
- Thermex Thermatron

IN EUROPE

- Robert Burkle GmbH
- Radyne Limited
- Strayfield International

SECTION 5

WOOD APPLICATIONS

Wood applications are among the earliest of all applications of dielectric heating. Initially flat plywood was fabricated with dielectric heating, but this turned out to be less than economical except in thicknesses 1 inch or greater for which there is little market. However, there followed in rapid succession edge bonding (making wide panels from narrow boards), furniture assembly gluing, curved plywood, fiberboard, and many others. There are still many dielectric heating units being sold for various wood working applications. Table 5-1 shows a list of some of the wood working applications in current use.

With the advent of synthetic resins, the "curing" of which is accelerated by heat, the development of dielectric heating for wood applications also was greatly accelerated. These resins are more waterproof than the formerly used animal glues. Some of them are completely waterproof. Therefore they make joints that are not only immediately stronger but also remain that way for many years. A humid atmosphere will not harm them.

Sometimes, as was true with former glues, the setting, or curing, of a resin is referred to as drying it. Water soluble glues are set by drying, and the water either evaporates from the glue line, or penetrates the adjacent wood. In contrast, synthetic resins "cure" by a chemical reaction and will never revert back to liquid form again. Synthetic resins require mechanically better joints because they will not fill in any voids in a glue line and still form a strong bond as will the animal glues. Better control of wood moisture content is therefore required so the boards are flat and straight when glued. This eliminates voids.

Gluing operations require pressure to hold the joints very close together while the glue is being set. This sometimes requires pressure in two directions as in edgebonding. Often the electrodes that carry the high frequency voltages also apply the pressure, but this is not always true. Figure 5-1 shows several electrode arrangements common to wood applications.

Table 5-1

WOOD WORKING APPLICATIONS

FURNITURE
- Tops
- Drawers
- Case Goods
- Banding Some Tops
- Panel Frames
- Assembly
- Legs

DOORS
- Cores
- Rails

MUSICAL INSTRUMENTS
- Pianos
  - Backs
  - Sounding Boards
  - Cases
- Drums
- Cello Backs
- Double Bass Backs
- Guitars

PLYWOOD
- Instrument Backs
- Cylinders
- Flat Plywood Repairs
- Curved Plywood Chairs
- Curved Plywood Furniture Parts

STRUCTURALS
- Wood Laminated Structural Beams
- End Joints For Making Long Boards

MISCELLANEOUS
- Truck Beds
- Pool Tables
- Drying Veneers for Flat Plywood
- Medium Density Fiberboard
- Particleboard.
- Butcher Tables

Source - Interviews with the dielectric heating industry 1985-1986.

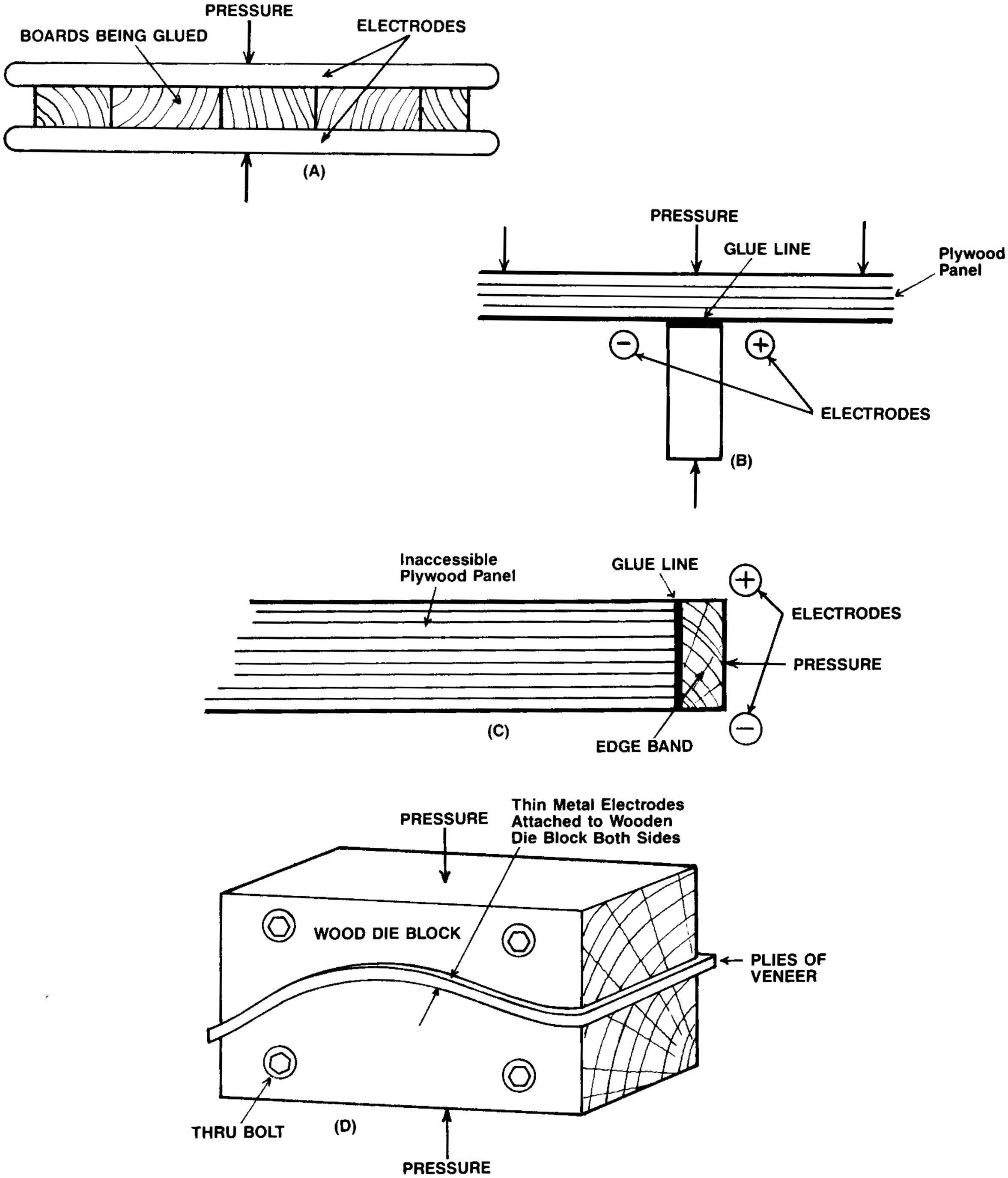


Figure 5-1 Typical Electrodes For Wood Working;
(A) Parallel plate electrodes in contact with the glue. (B) Rod electrodes. The field between the noncontacting electrodes produces the heat in the glue. (C) Electrodes farther from glue line because of inaccessibility.
(D) Typical curved plywood electrodes where all the wood receives heat.

In Figure 5-1 (A), the electrodes are in contact with the glue line and heating is due to both the high frequency current flowing in the wet glue and dielectric heating. The adjacent wood, where it is moistened by the glue also heats somewhat, but most of the wood, being normally dry, heats very little. In Figure 5-1 (B), the electrodes are conducting rods placed near the glue, but not in contact with it. The wood heats where it is in the field of the electrodes, but the glue line, being wet, absorbs heat faster than the nearly dry wood. Figure 5-1 (C) shows a similar gluing operation, but where the electrodes cannot be placed as near the glue line as would be desirable, usually because the glue line is hidden such as in cabinet assembly gluing. Again, the wood heats, but the glue absorbs heat faster than the wood, so it cures. Figure 5-1 (D) shows a typical curved plywood electrode system and die block. The electrodes are sheets of metal fastened to the die faces which are against the veneers. Here all the glue plus all the wood is heated to the glue curing temperature.

POWER DETERMINATION

In most wood working applications it is nearly impossible to calculate the amount of power required for a given application. The difficulty is in determining how much heat is delivered to the glue line, how much to the adjacent wood, and how much to any other wood in the heating field. The temperature rise of the wood will depend on its moisture content which varies at an unknown rate away from the glue line. Therefore, manufacturers of equipment have developed their own empirical methods of determining the needed power. Some of these are given when discussing the specific applications.

In the case of curved plywood, calculation of the required power is easier because the entire load is heated to a uniform temperature and the moisture content and wood weights can be determined rather readily. The methods for this calculation are discussed in Section 2.

EDGE BONDING

Many different products are made by edge bonding. This is the manufacture of wide, long boards from smaller pieces of wood by laying them side by side, and end to end, with all the flat surfaces in the same plane. Glue is applied along the edges of the individual boards, and with pressure from the sides and top, they are glued. Table and cabinet tops may have edge bonded cores with veneers on the top surfaces. In the finest furniture there may be no surface veneer, the whole top being made of solid edge bonded hardwoods. Some doors will also have blocks glued together and a veneer bonded to the surface. There are machines using dielectric heating which do edge bonding operations on a continuous basis; others are batch operations. Both types usually require manual lay up of individual glued boards.

Figure 5-2 shows a small one-man manual edge bonder. The individual boards, with the glue on their edges, are laid on the sloping table to

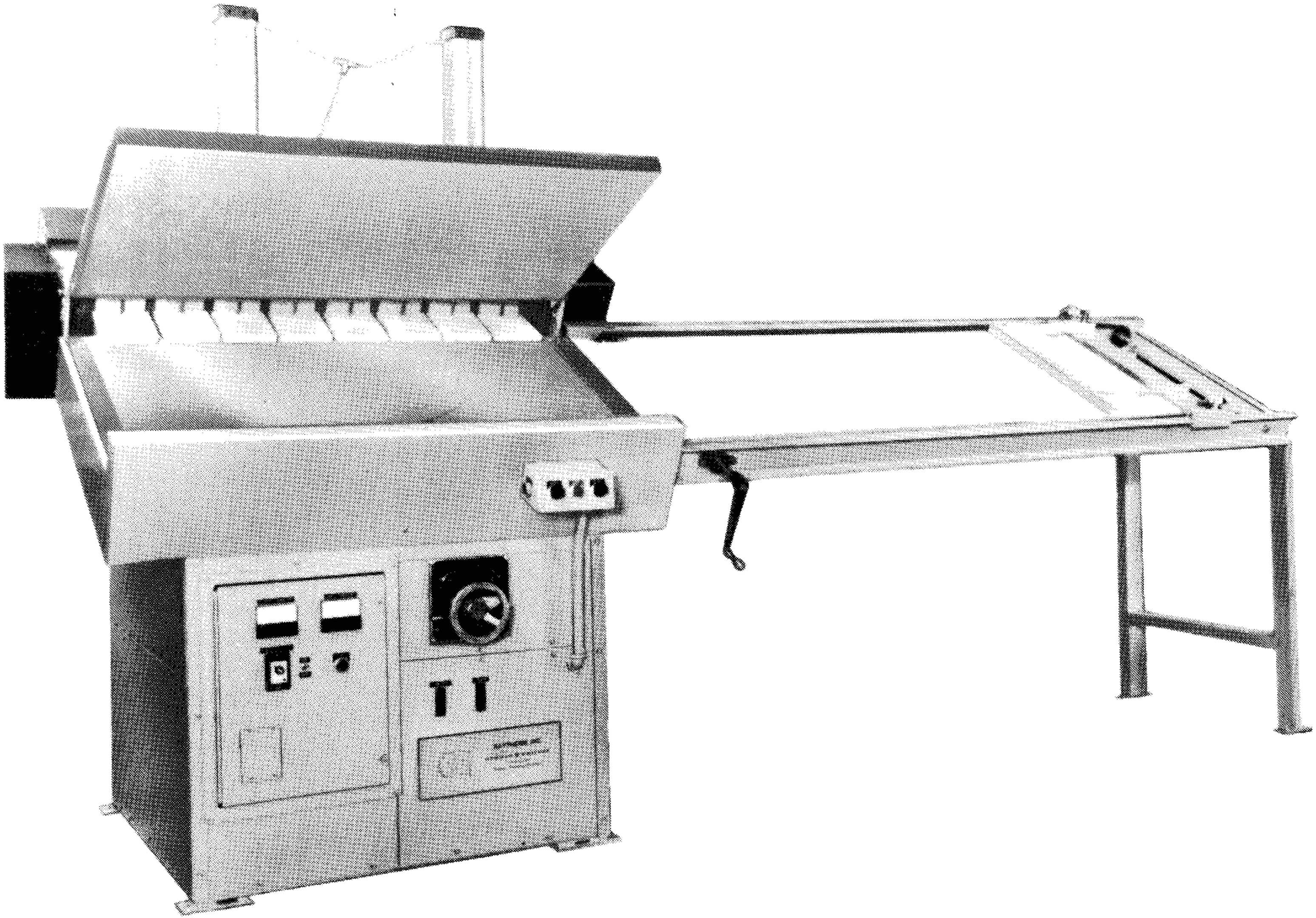


Figure 5-2 A small oneman manually operated edge bonding press. Boards with glue on their edges are laid up on the sloping table to the right and manually loaded into the press. The 2.2 KW generator is beneath the press.
Photo courtesy of Raytherm, Inc.

the right. The whole load is pushed into the press by turning the crank. After press closure and curing, the board is readily removed because the entire top opens and the board is held is tilted toward the operator. Power controls and timer are on the generator under the press.

Figure 5-3 shows an edge bonding equipment with two stations. This unit is set up for one person to load and unload and is arranged so the time of curing one board can be used for loading another one. This gives maximum use of the generator since it does not remain idle during the loading operation. A switch is used to direct the power to the loaded station.

Figure 5-4 shows a larger semiautomatic edge bonding press, with the glue spreader and layup table. The boards are loaded standing on edge. At the center right of the photo they pass over a drum which spreads the glue on the edges, and then they are removed from the upper conveyor and laid on the lower one in proper order. After the press has heated its load, the load on the layup table is moved in and it pushes the heated load out the other end of the press. The shield to the extreme left of the picture encloses the press.

Figure 5-5 shows a similar machine of different manufacture. This one has a 100 KW output generator and is used primarily to produce truck flooring.

Figure 5-6 shows the end view of the interior of an edgebonding press in the closed position. The white pillars with the metallic ends are the insulators for the upper platen and they transmit the vertical pressure from the press. The rather thick blocks to the right transmit the horizontal pressure from the side cylinders. The boards are in the center foreground, and the balance of the press is below them. In this photo the boards are wider than are found in many cases, The upper platen electrode is between the white insulating pillars and the upper frame. The lead from it to the generator is shown rising at about 45 degrees to the right edge of this upper platen. The lower platen is connected to the press and forms the ground electrode.

Figure 5-7 shows the board delivery conveyors, the press, and the generator. Note that the boards are not all the same height, a situation sometimes called profile gluing. This is done especially to reduce machining when manufacturing windows for houses, for example.

Figure 5-8 shows an automated edge bonding machine set up to make two boards simultaneously on a continuous basis. The incoming wood, (right background) is glued (to the right of the operator) and then manually laid on the conveyor. The large "crawler tractor" devices shown just inside the press provide the horizontal and vertical pressure required. At the other end of the machine (and not shown) is a cutoff saw and an unloading conveyor table. The RF generator is shown in the upper background. The machine shown will accommodate boards up to eight ft. long, making a continuous ribbon of glued board 8 ft. wide.

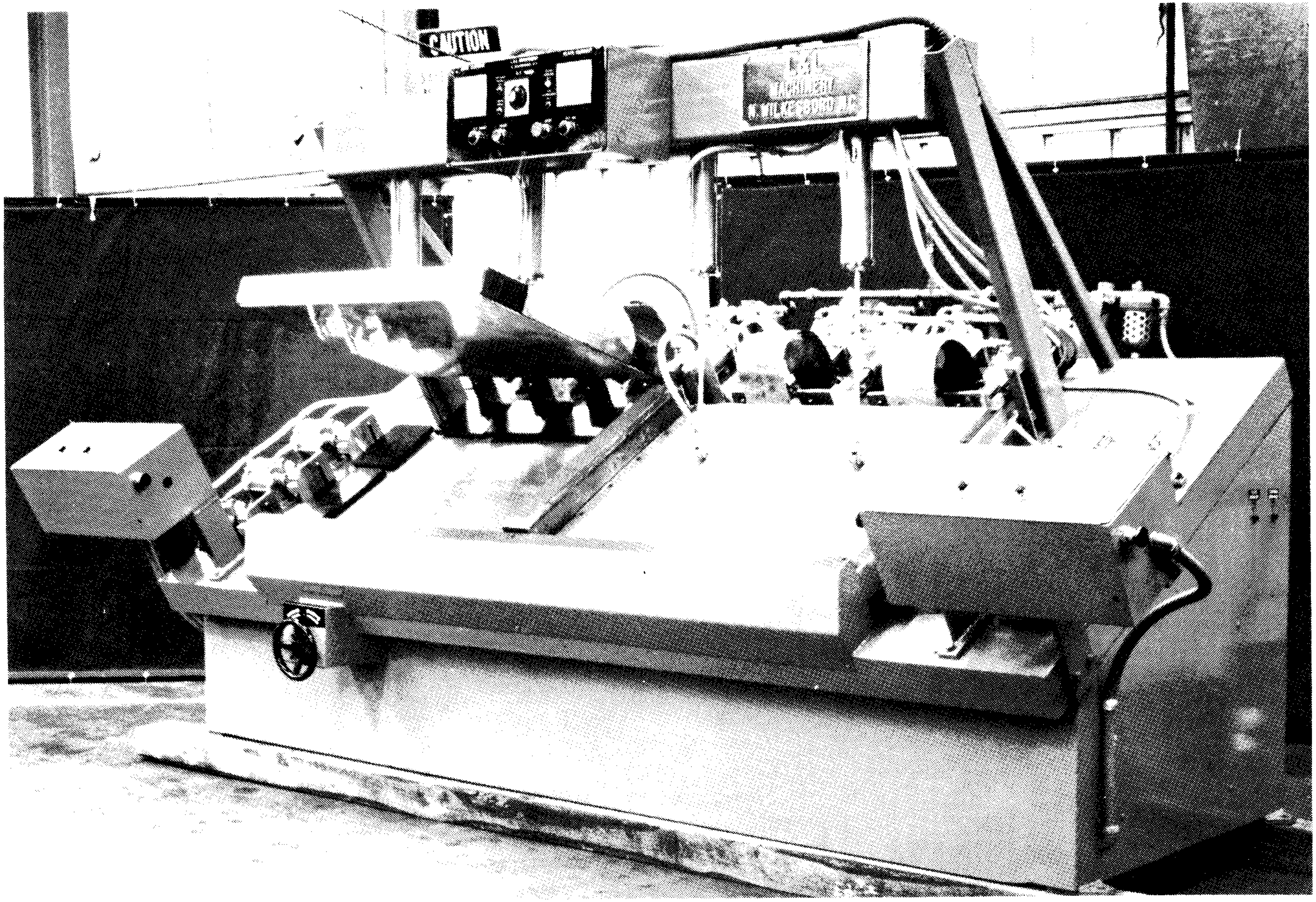


Figure 5-3 A dual edge bonding press set up so one side is loaded while the other is heating. Power from the generator, below the press, is switched between the two sides.
Photo courtesy of L & L Machinery,

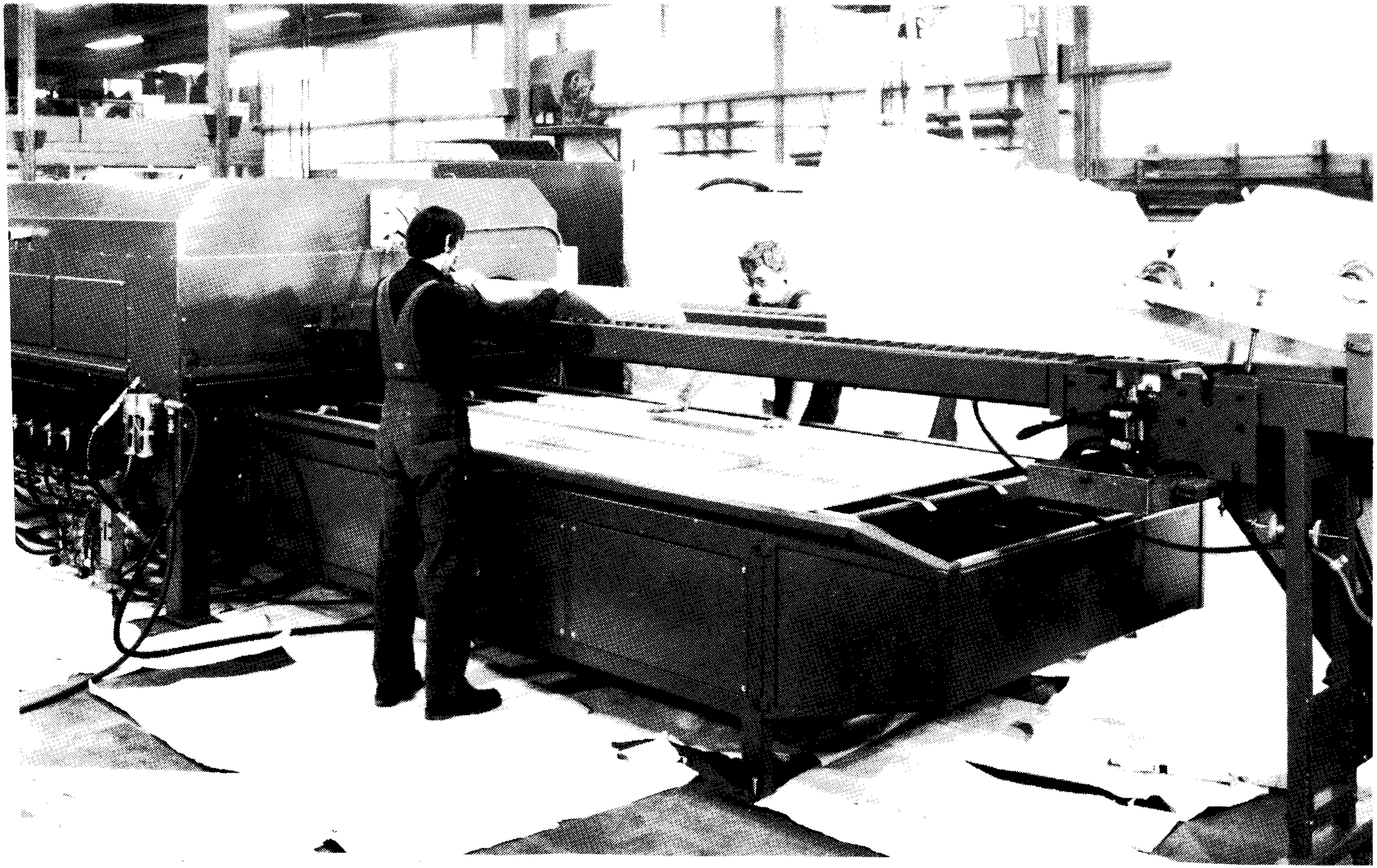


Figure 5-4 A semiautomatic edge bonding machine. The glue spreader is above at the extreme right side. Boards are taken from the upper conveyor and placed on the lower conveyor in the proper order. They are then pushed into the press, which is to the left, by the infeed conveyor.

Photo courtesy of Mann-Russell Electronics, Inc.

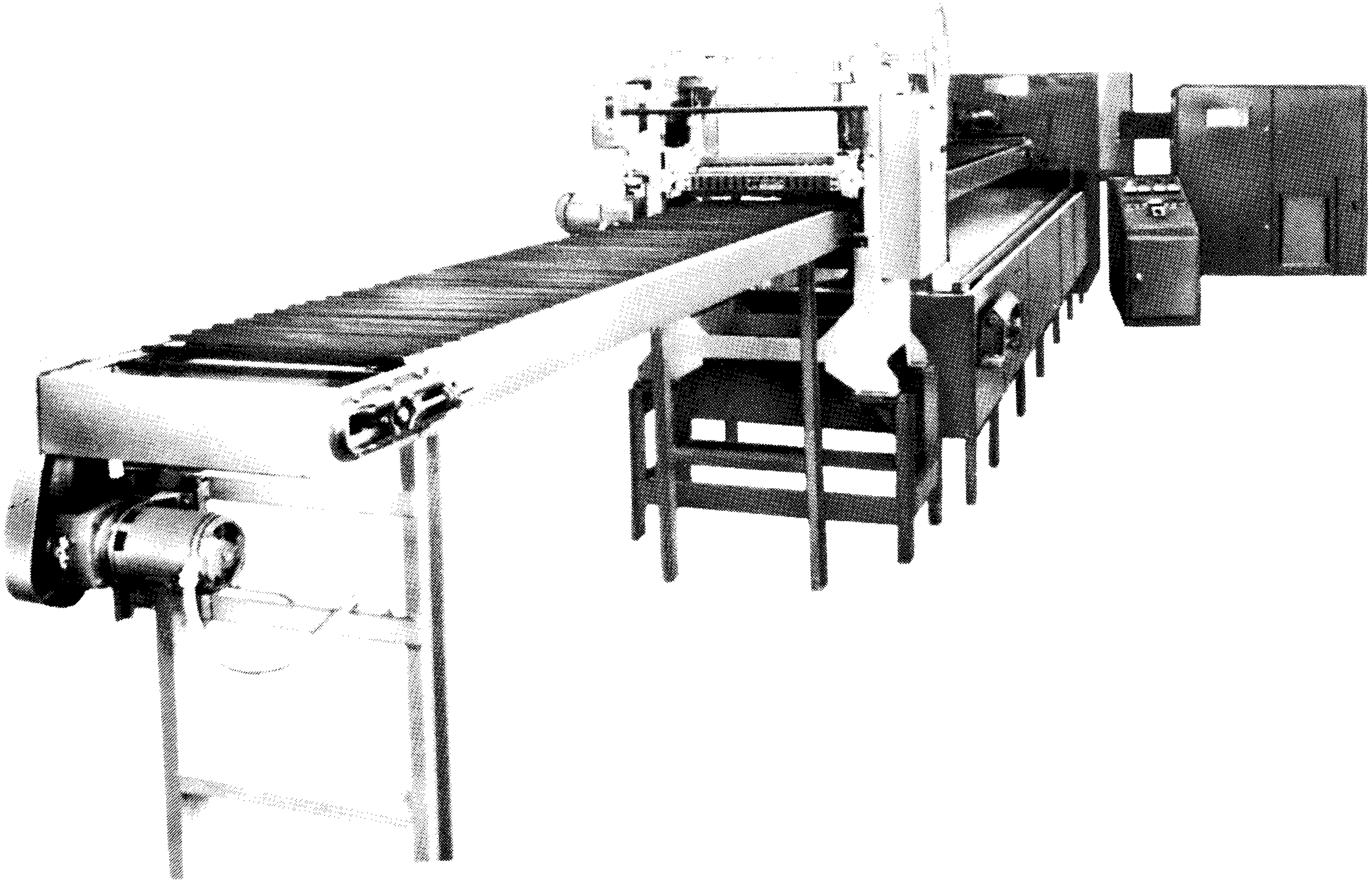


Figure 5-5 This edge bonding machine was designed to make long thick boards, such as for truck flooring.
Photo courtesy of Raytherm, Inc.

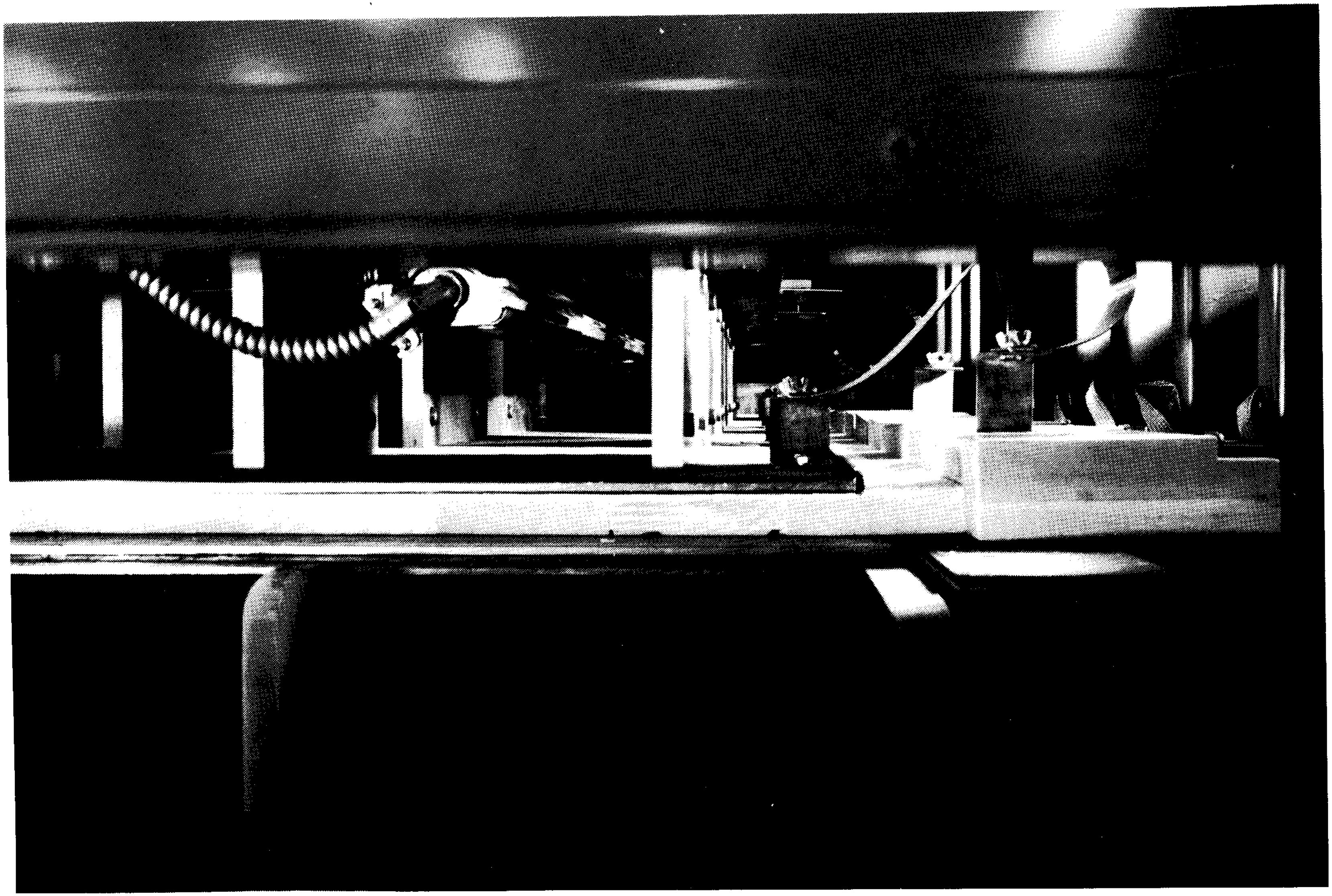


Figure 5-6 End view of the interior of an edge bonding press. This press provides both vertical and horizontal pressure to the boards under the closed platen.
Photo courtesy of Mann-Russell Electronics, Inc.

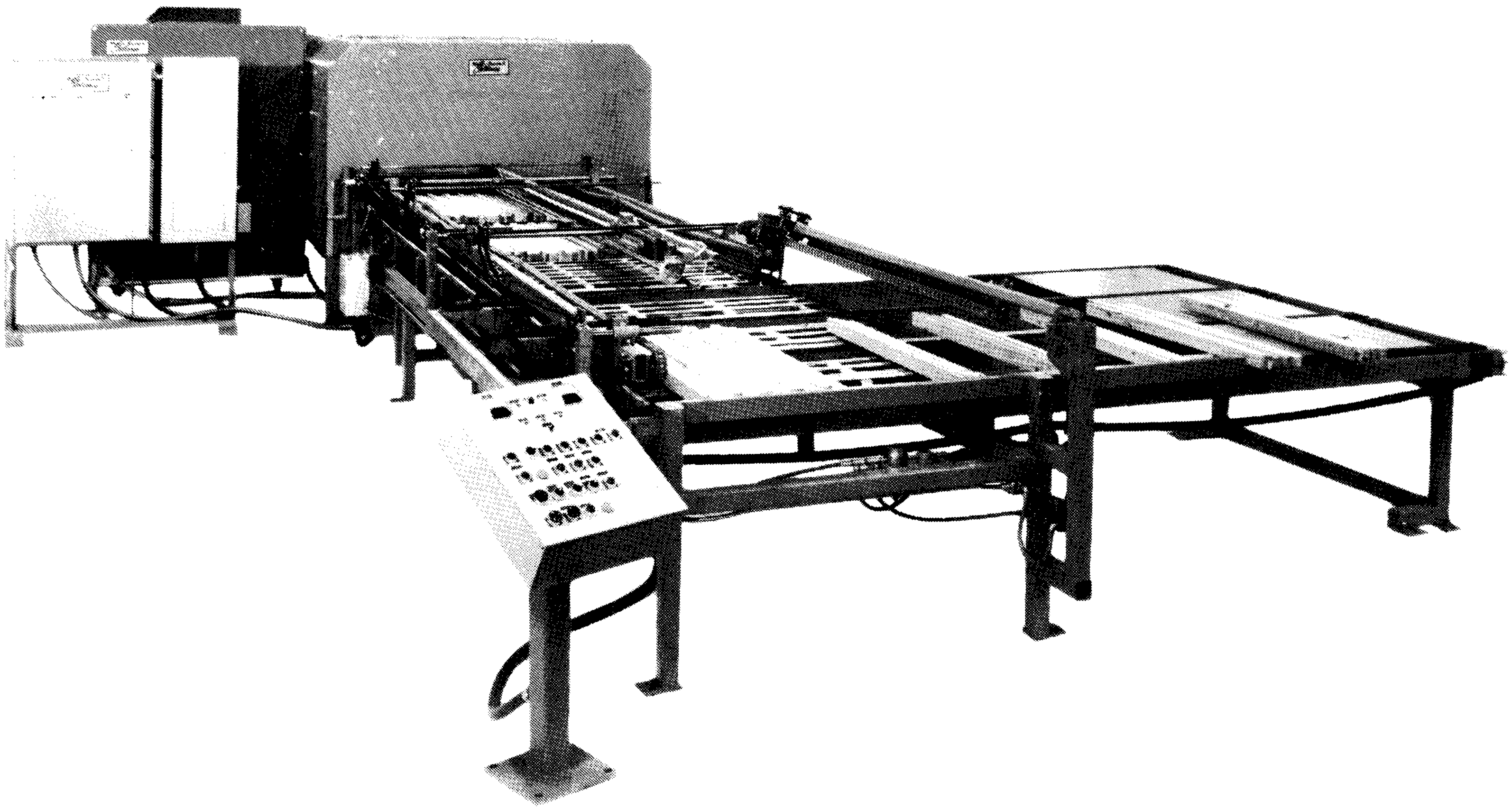


Figure 5-7 A view of the infeed conveyor, the glue spreader, the layup table, the shielded press and generator for an edge bonding machine. The infeed boards are of different heights.
Photo courtesy of Mann-Russel Electronics, Inc.

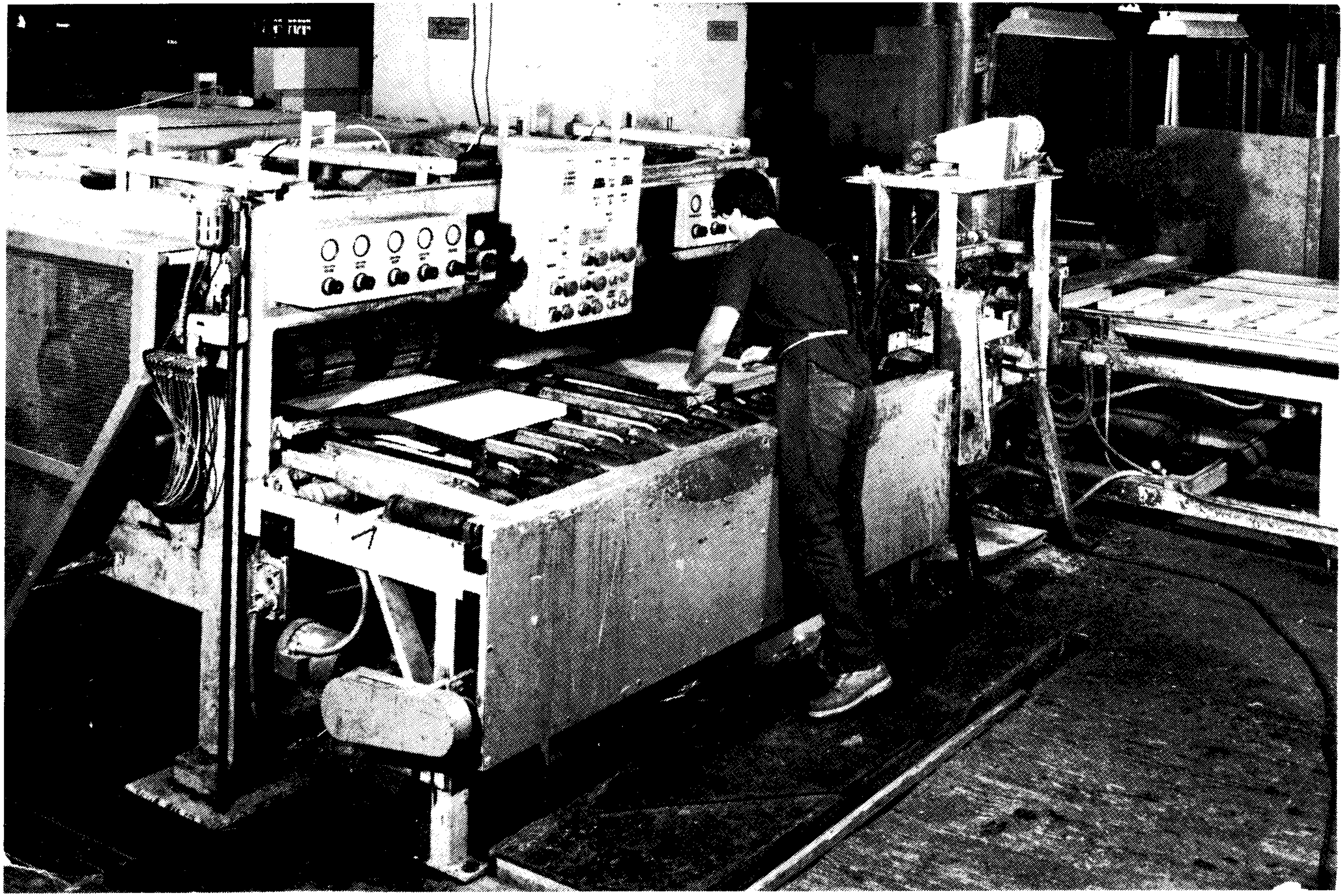


Figure 5-8 This automatic edge bonder can deliver a continuous ribbon of 8 ft. wide board. One operator feeds the stock, another carries away cut and finished boards. The generator is in the background.
Photo courtesy of Mann-Russell Electronics, Inc.

The electrode system used for edgebonding is that shown in Figure 5-1 (A). Pressure is applied through the electrodes to hold all the boards flat and more or less straight. Pressure is also applied to the edges to close the glue lines. The boards should be reasonably straight and well machined so that the edge pressure will be distributed uniformly along the length. Sufficient side (edge) pressure must be applied to close the joints, but if boards are warped too much it is possible to squeeze all the glue out of a joint at some spots and yet not close the joints at other spots so the necessary good contact is not obtained in these places. In either case good bonding will not occur. There must be sufficient glue all along the joint and good contact between all the boards at the time of curing to make a good strong bond.

In determining the required power for edgebonding it is common to allow between 100 and 125 square inches of glue line per kilowatt minute of energy for urea glue, and about 1/3 more than this for polyvinyl acetate glue. PVA glue is more costly but covers a greater area. The area of a glue line is its height (which is the thickness of the boards being bonded) times the total length of all the glue lines, the dimensions being measured in inches. Thicker boards may require more power; thinner ones less.

An advantage of r.f. edge bonded boards is that they can be sent to the next operation (usually planing or sanding) immediately after bonding. With water based glues it may be necessary to wait several days for the glue to dry to its full strength so it will not be torn apart by subsequent machining. The savings in reduced work and in process inventory are obvious.

BEAMS

Modern buildings, particularly large ones, are normally made of steel. However, wood is still a viable alternative. An example is the large sports dome in Tacoma, Washington in which all structural members are made of wood. Figure 5-9 shows part of this building under construction. The beams, which vary in thicknesses up to 40 inches in some structures, were made by a process called laminating which is very similar to edge bonding. The major difference between beam laminating and edge bonding is that the glue lines are much wider for beam laminating (nearly 9 inches in some cases) because the glue is spread on the wide surface of each individual board. The length of the load may be a few tens of feet long. Thicknesses of individual boards are usually between 1/2 and 1-1/2 inches. As in edge bonding, the electrodes are placed in contact with the glue line and the heating is accomplished by conducted currents through the wet glue lines as well as by dielectric heating. Figure 5-10 shows a sketch of a finished laminated wood beam with the electrode position also shown. Usually the laminating presses are made with the electrodes on the sides of the beam (see Figure 5-10) and the height of the beam is in the vertical direction. The upper and lower parts of the press typically are made with moveable pressure means so that a continuous beam may be fabricated from random length, but constant width, boards. The beams are cut to desired length after they exit the press. Each board forming the beam is as wide as the beam, see Figure 5-10, and they are stacked on top of each other after applying the glue. The

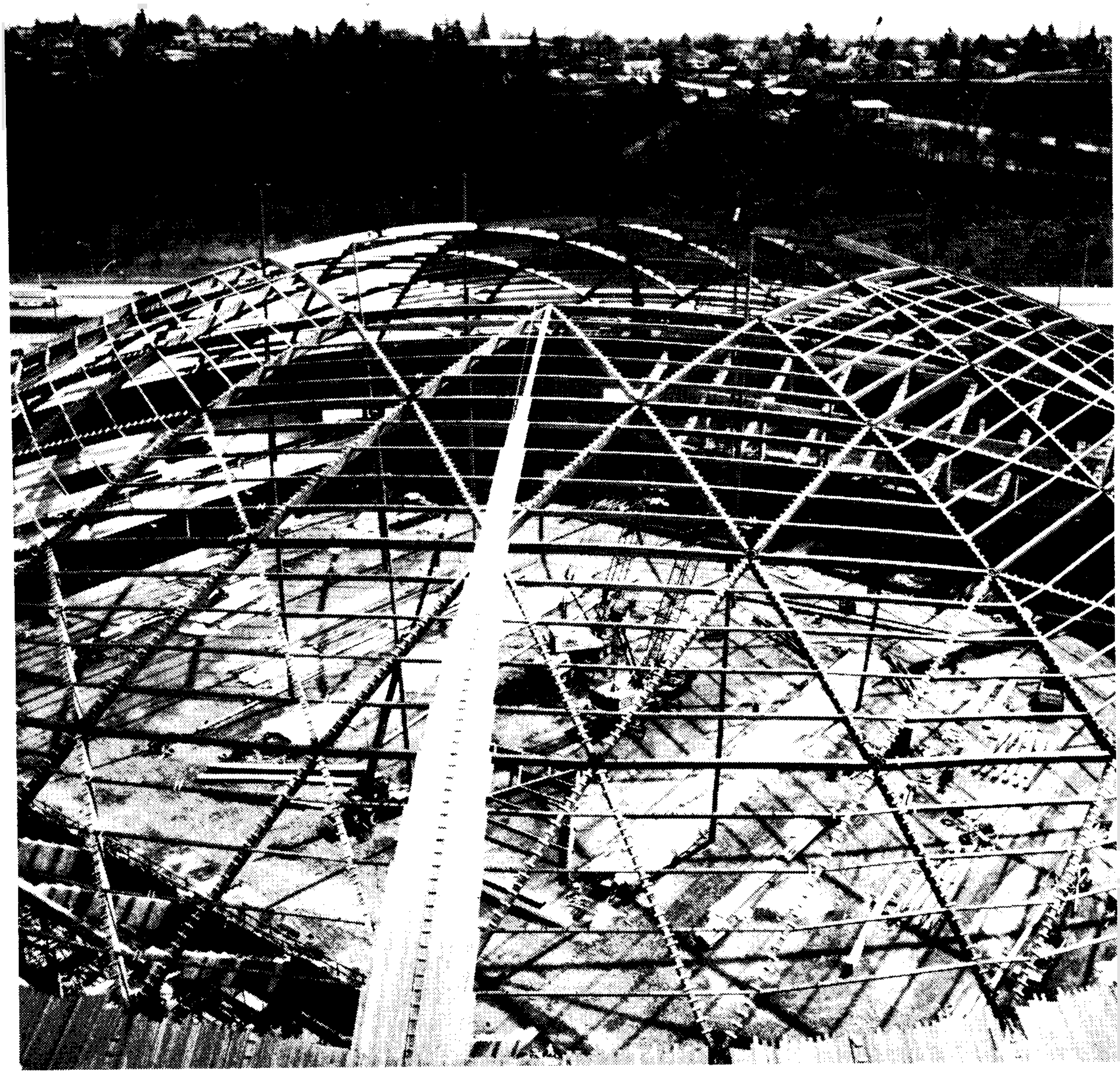


Figure 5-9 An overhead view of the Tacoma sports dome whose structure, including all long ceiling beams, is entirely of wood. The beams are made of dielectrically bonded laminated wood.
Photo courtesy of Mann-Russell Electronics, Inc.

end joints of the boards are randomly located in the beam and arejoined by finger joints (see "Joining Short Boards to Make Long Ones", below). The beams are made with a slight curvature in them so that when they are in the building they will be more nearly straight when the building load is on them.

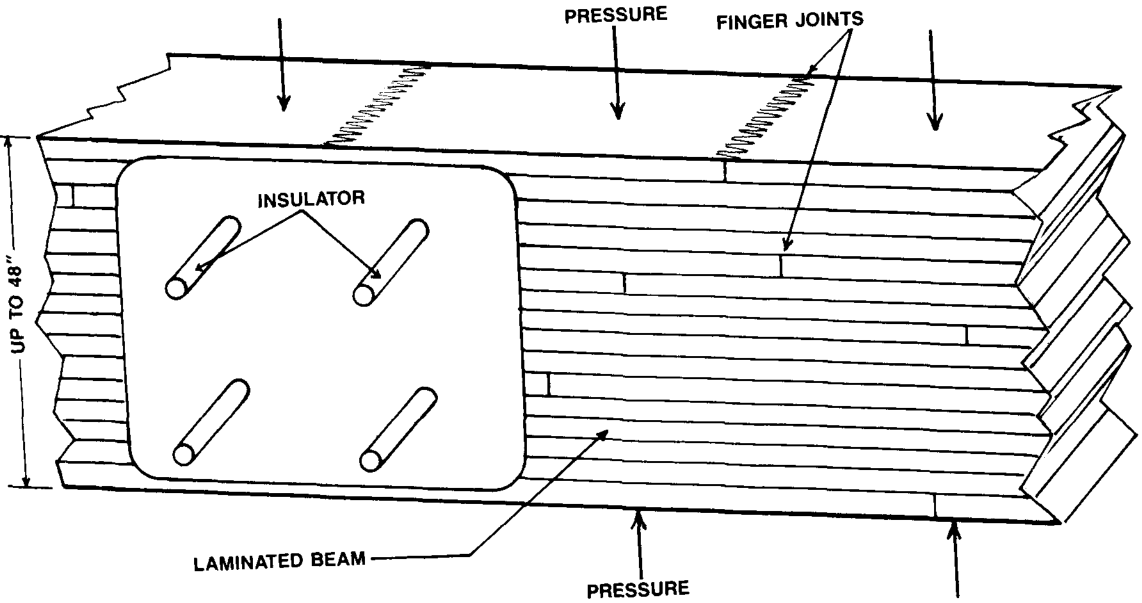


Figure 5-10 Schematic of the Method of Fabricating a Laminated Beam

Figure 5-11 shows an actual laminated beam press which is illustrated schematically in Figure 5-10. The heavy "crawler" conveyors provide vertical pressure while the stack of boards is moving. The electrodes are in the center of the picture. For shielding the entire machine is normally enclosed in a screened room with small ports at either side for entrance and exit of the materials. Otherwise the machine is as open as possible for cleaning and removing defective materials during production.

EDGE BANDING

This application is somewhat similar to edge bonding but also similar to assembly jobs because it uses the electrode configuration of Figure 5-1 (A) or 5-1 (B) or 5-1 (C). The tops of inexpensive furniture are often made using a particleboard core with veneers on all exposed surfaces, including the edges. Much of the modern furniture with its squared off edges is made this way. It is necessary to have a band of wood or printed vinyl around the edges of the particle board core because the particleboard will not receive stain uniformly.

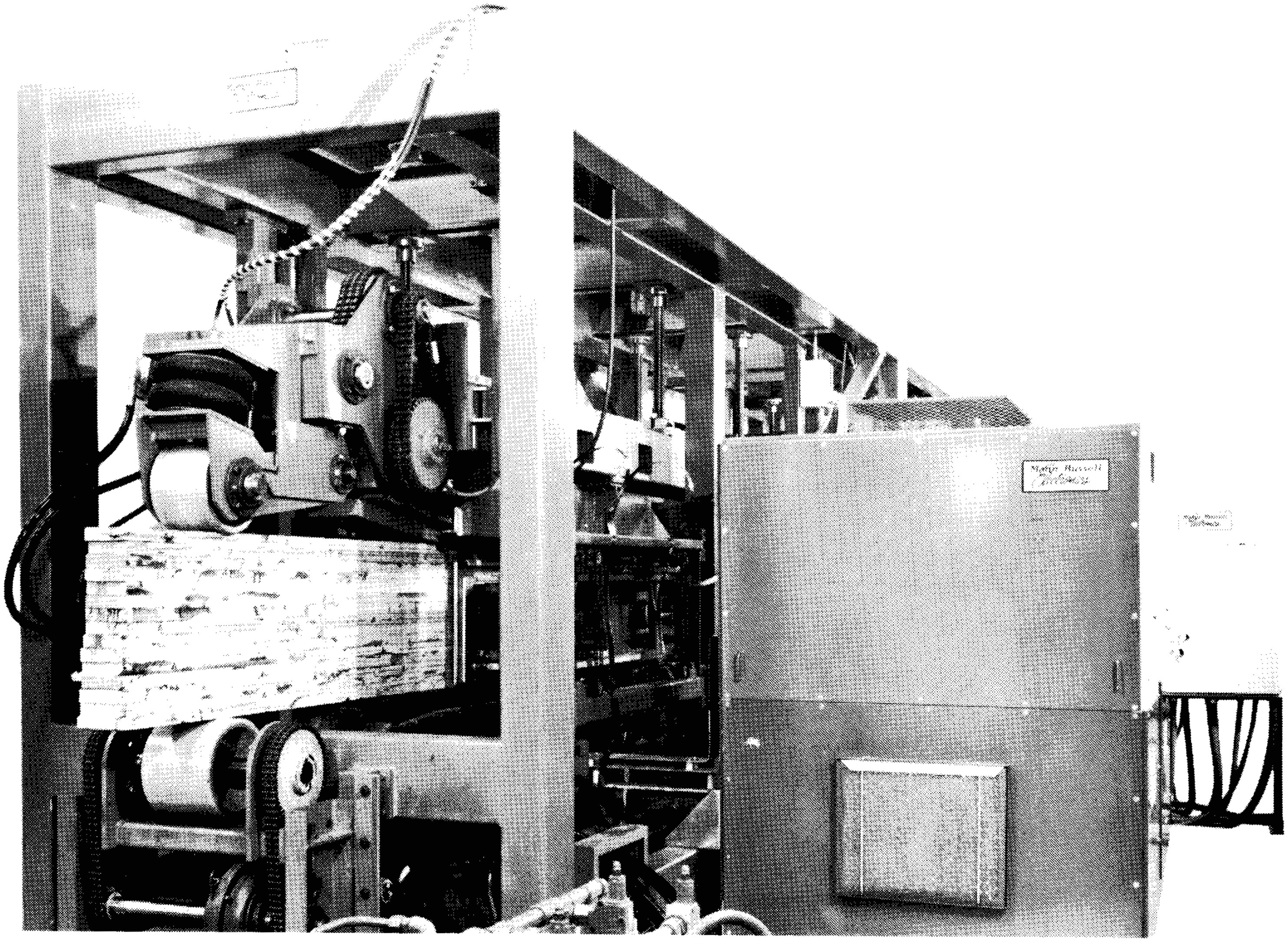


Figure 5-11 A view of a laminated beam fabrication machine. The electrodes are at center. This machine is normally installed in a shielded room. The central large cabinet is the generator
Photo courtesy of Mann-Russell Electronics, Inc.

Edge banding is the application of bands of veneers to exposed edges. It is sometimes done on a continuous basis; other times it is done in a batch press. The electrodes can be placed near the glue lines and the narrow band of veneer is glued along the exposed edges. Alternatively, the electrodes form a "picture frame" around the periphery or, in some cases, may be entirely like an edgebonding press except that horizontal pressure is applied in both directions instead of only one. Power per square inch of glue line required for this application is very similar to that for edgebonding. Therefore the generators for edge banding are usually much smaller than for edgebonding because of the smaller glue line area.

Figure 5-12 shows one type of edge bander. Note the similarity to the edgebonding press of Figure 5-2 except the horizontal, or edge, pressure is applied in both directions.

Figure 5-13 shows two edge banding presses with one 6 KW generator attached. The output of the generator is switched from one press to the other to allow for loading of one press while the other one is heating.

FRAMES FOR PANELS

Where square edges on furniture are not desired, a wide rail is sometimes glued around a central core of particleboard. This wide rail provides sufficient hard wood to machine into shapes used in period furniture, and yet employs the less expensive particleboard for the cores. Veneers are applied to the top surfaces, of course.

Additionally, frames may be fabricated for supporting veneers and thin plywood for cabinet sides. Also, many doors have frames around a hollow core so the locks and hinges can be installed and yet maintain a very light weight door structure. Figures 5-12 and 5-13 show equipment capable of this type of operation.

The frames of the type described above are often glued using dielectric heating. The joints may be mitered or butted. The electrodes are usually small plates placed at the corners of the frame press in a manner similar to that used in edge bonding. If the frame is to be glued to the core material also, as is often the case, the power requirements will be higher, of course, than if an open frame is manufactured. In the latter case the electrodes need only be located over the glue lines.

CURVED PLYWOOD

As its name implies, this material is made of veneers cross banded together as in any plywood, but made in a press having a curved die which is the shape of the final piece being fabricated. Dielectric heating is ideal for this application because it is not necessary to have a heated metal die for each shape; dies are usually made of shaped blocks of well dried maple. Several boards are laminated together using normal synthetic glues, and sometimes are further held

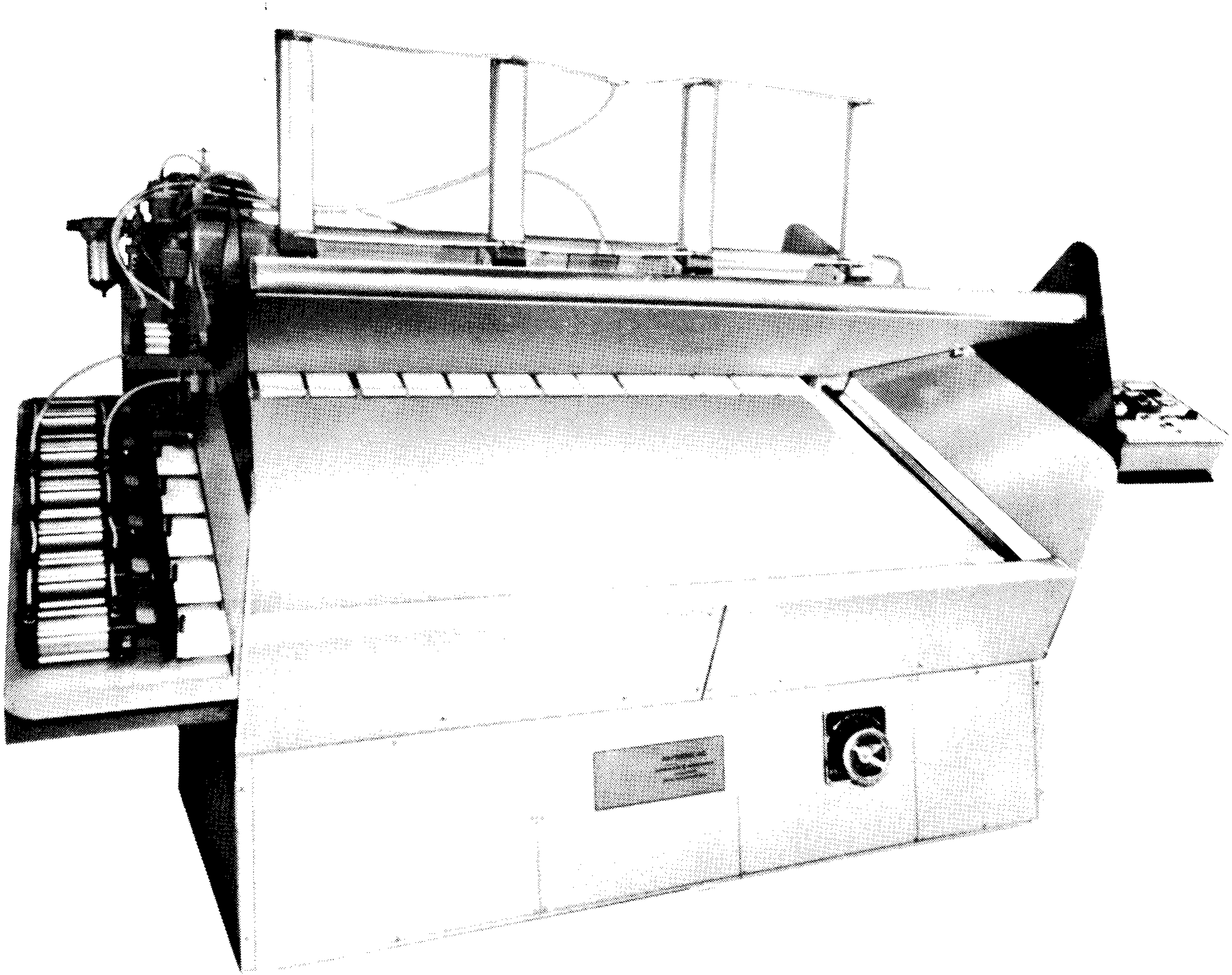


Figure 5-12 A press for applying veneers or rails to the edges of large panels. Pressure is applied from both horizontal directions, and from the top. The generator is under the press.
Photo courtesy of Raytherm, Inc.

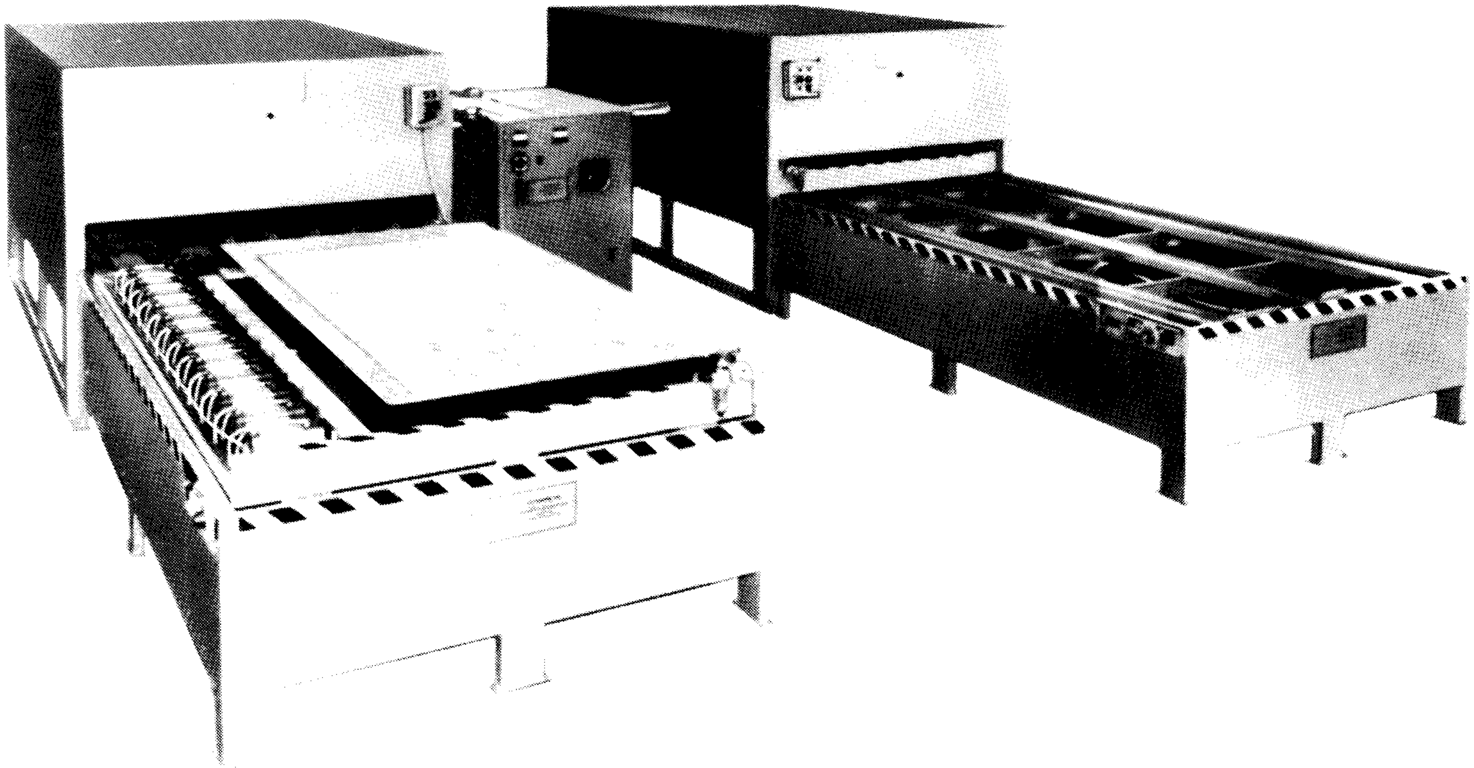


Figure 5-13 A dual machine for applying veneers or rails to the edges of panels. The 6 KW generator in the center can be connected to either press.
Photo courtesy of Raytherm, Inc.

together by long heavy bolts. A male and a female die are made of wood and the curved surfaces are lined with aluminum or copper sheets screwed or tackedinto the die's curved surfaces as illustrated in Figure 5-1 (D). The fasteners should be kept as short as possible, and the sharp points at the ends should be filed off to prevent arcing, though this is not always done.

Pressure is applied to the stack of glued veneers forcing them to conform to the shape of the die. The high frequency heat is then turned on to cure the glue. Low power levels requiring several minutes RF exposure time are usually used in accomplishing this curing so that arcing between electrodes will be minimized by using lower electric fields.

Figure 5-14 shows a typical 48" by 96" curved plywood press and 100 KW generator. Note the shielding on the press. This is arranged to raise out of the way when the press is loaded.

Figure 5-15 shows a 30 KW press for making musical drums. This press is not shielded because the generator operates on a frequency at which free unlimited radiation is allowed by the FCC.

As mentioned above, the power requirements for any curved plywood application can be estimated based on the BTU's required to heat the load and to evaporate any water present. This is discussed in section 2 of this report.

There are many applications for curved plywood. One is the making of long cylinders, later cut to length for musical drums. Another is the formation of the compound curves for the backs of cellos and double basses. Guitars are sometimes made using curved plywood. Most any large curved surface in furniture is also fabricated this way. Some simple chairs are made entirely of curved plywood with the legs being cut from a wide curved sheet, and the seat and back being made of one piece contoured to fit the human body.

THICK BLOCKS

Thick blocks are fabricated with techniques similar to edge bonding except that the boards may be set on edge to achieve a thick block of wood. These blocks are used for wooden truck beds as well as for game tables and butcher blocks. Thicknesses run from about 1 inch to over 3 inches. Power requirements depend on the glue used. For melamine fortified urea resins the normal power requirement is 75 sq. in. per kilowatt minute, but for PVA glues it can be as high as 150 sq. in. per kilowatt minute. The PVA glue is more expensive, but the labor savings more than offsets the higher cost. PVA glues are being formulated with enhanced waterproof properties now. Phenolic glues, which are completely waterproof, are very difficult to bond using dielectric heating and are seldom used. Figure 5-5 shows a 100 KW edge bonding press and glue spreader for producing truck flooring.

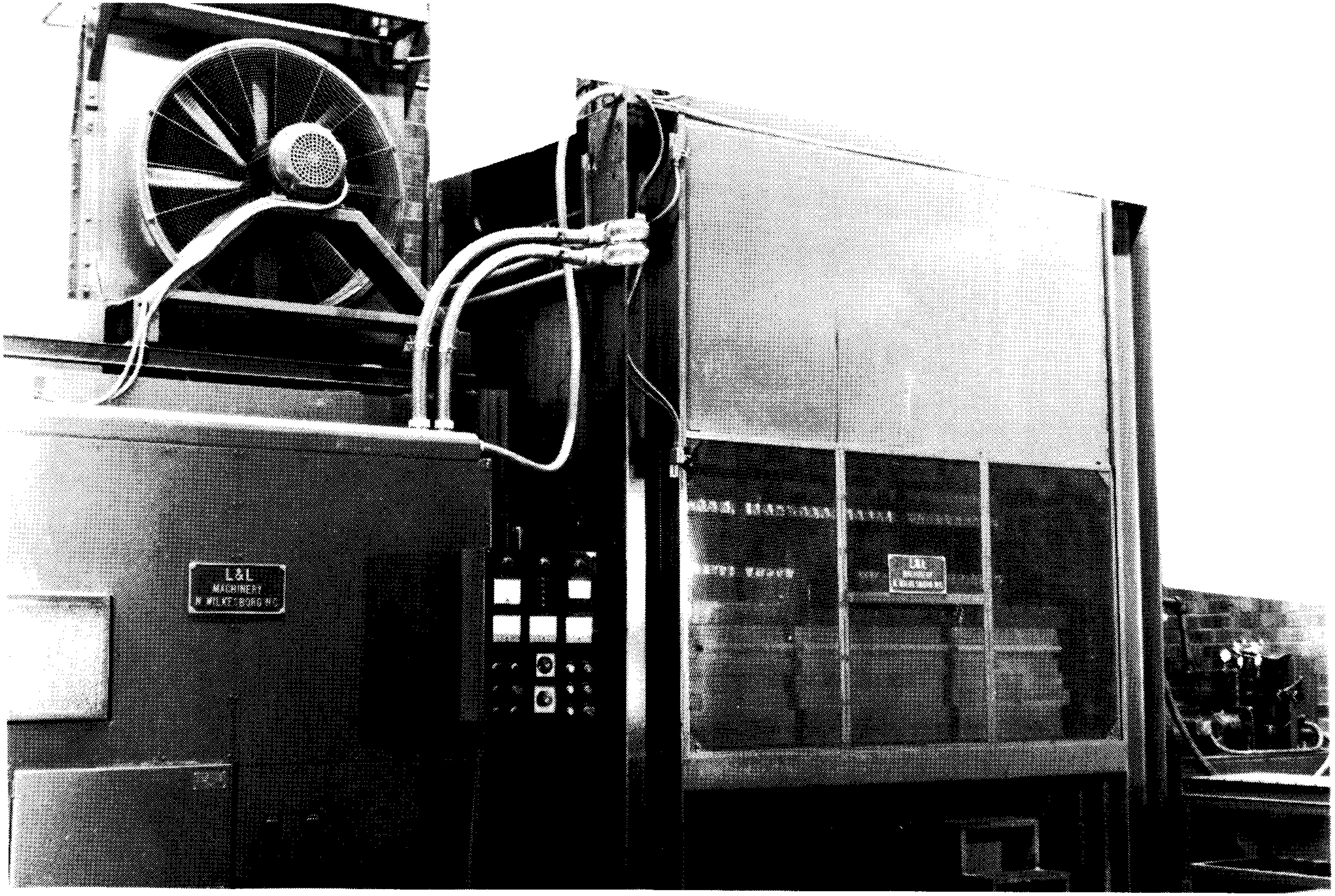


Figure 5-14 A press and generator for curved plywood. The 100 KW generator heats three dies simultaneously, visible through the shield door which can be raised for loading the press.
Photo courtesy of L & L Machinery, Inc.

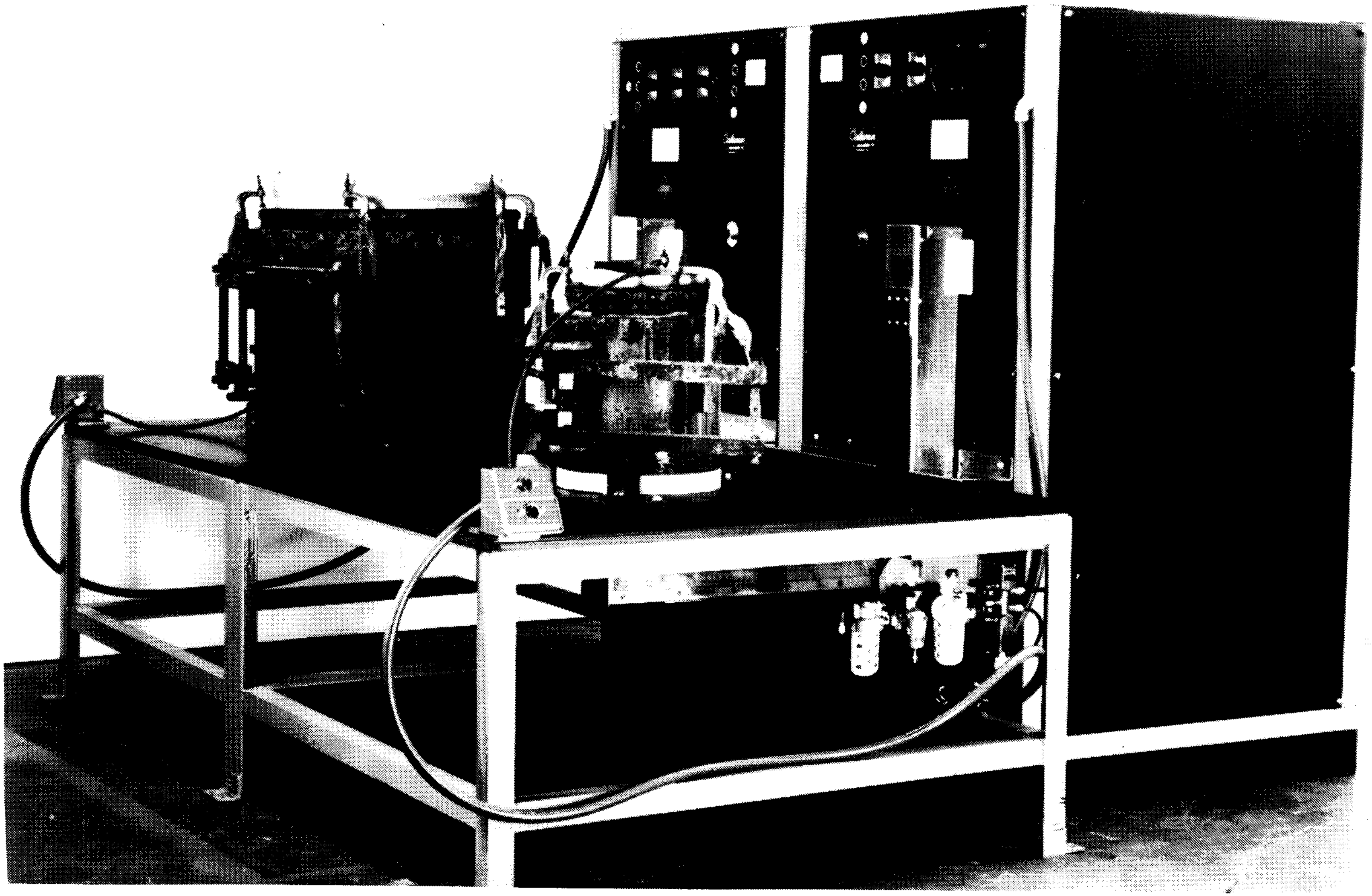


Figure 5-15 This constant frequency generator is shown making cylinders for musical drums. No shielding is needed for radio interference because the operating frequency selected is an ISM frequency. Photo courtesy of J. A. Callanan Co.

FURNITURE ASSEMBLY

After individual parts for furniture have been fabricated, the entire piece may be assembled by gluing sections together. Assembly gluing is an important application of dielectric heating. Through the use of this rapid heating method, and with the synthetic resins, the long waiting time for the older glues to dry is eliminated. This reduces the costs of work in process, and reduces the floor space for storage.

The electrode systems typically used in assembly gluing are shown in Figure 5-1 (B) and (C). Often it is necessary to use the (C) arrangement because it obviates the need for electrodes inside the furniture cabinets. The electrodes would have to be inside the cabinet to use arrangement (B).

VENEER DRYING

In making flat plywood, logs are first placed on a wide veneer lathe to remove, or peel, the veneers from the logs. Next the veneer is cut into sheets and sent through a hot air dryer. Veneer lathe operations are done on green wood because the process benefits from the high moisture content of the wood. Consequently the veneer must be dried after cutting. Unfortunately, the moisture is not uniformly distributed throughout the veneer. Hence to get all the wood sufficiently dry to glue into plywood boards, it is necessary to overdry many sectors.

Economic studies indicate that it is better to cycle the veneer sheets through the dryer quickly and then cull out the sheets that are not completely dry for a separate redrying operation. An optimum between the number of redried sheets and overdried sheets is found empirically.

Normally the redrying is done by sending those veneers that are still wet back to the input end of the dryer and running them through the second time. This overdrys most areas of the sheets. A better way of redrying is to use a dielectric heater. To do this the veneer is stacked about 2 ft. high. It is then put into a hot air oven with dielectric heating. The hot air circulating in the oven primarily removes the moisture evaporated by the RF energy so that it does not condense and drop back on the veneers. The dielectric heater not only removes the moisture, but it preferentially removes moisture from the wetter areas.

There are two additional benefits. The first is the speed of the redrying, which is offset somewhat by the need to cool the stack of hot veneers. The other advantage is the lack of degradation of the veneers because they have not been exposed to the very hot ovens a second time. Instead the quality has improved because of the more uniform moisture which makes them flatter. Experience has proven that when a dielectric dryer is available, it is more economical for the veneer to be cycled through the primary dryer even more quickly than normal, resulting in an increased number of sheets being furnished to the dielectric dryer. This increases plant production of higher quality plywood.

Figure 5-16 shows a veneer dryer installed in a prominent plywood plant in western Washington state. The stack of veneer to the right is ready to be introduced into the all aluminum oven in the background. In the foreground is the control panel for the generator which is immediately to its left.

In another plant where the dielectric dryer is operated 20, 8 hour shifts per week, the weekly production of the plant was increased 10%, from 5,000,000 square feet (equivalent 3/8" veneer) to 5,500,000 sq. ft. The big saving is in the recovery of formerly wasted veneers. Whereas formerly 6% of the throughput was downgraded and over 3% was destroyed, there is none of either with the dielectric redryer. The annual savings in saleable product was well over $300,000.

The power required for veneer drying can be estimated from the weight of the wood and the moisture to be evaporated as suggested in Section 2 on power determination. It has been found that the additional production possible in the primary dryer, and therefore in the plant, will pay for the capital costs of the dielectric heater in less than 2 years time, which makes the application very attractive.

JOINING SHORT BOARDS TO MAKE LONG ONES.

In doors, blocks of short narrow boards are often assembled into a core and the ends are butted together and glued in addition to gluing the sides of the blocks. However, for stronger joints in other types of lumber used in structures, long pieces are made by using scarf joints or finger joints that are glued with dielectric heating. In these joints, the major pressure is perpendicular to the joint to hold the pieces in position. In the scarf joint this also puts pressure on the glue line. In the finger joints the two boards are cut so the fingers apply the glue line pressure to each other when they are driven together. Then a simple through heating electrode, similar to that used in edge bonding, can be applied. Again, the heat required per square inch of glue line should be approximately equal to that of an edgebonding application. Figure 5-17 shows equipment for making finger joints. The generator is housed in the upper metal cabinets, the applicator in the lower enclosures. The boards are fed in through the opening on the left.

Figure 5-18 shows a typical finger jointing equipment. It is built for horizontally cut fingers, with input stock 12 inches long to 8 ft. long. Width and thickness range from 1" X 4" to 2" X 12". The "injector" type infeed section to the left automatically accepts the previously cut and glue-spread finger jointed material. The center of the photograph shows the driveup section which provides the joint-closing force. This pushes against the first retard section which holds the boards against the push of the driveup section. The hydraulic tank on top of the generator is part of the driving mechanism. Following are two 16 ft. electrode sections each with a 20KW or a 30KW generator. The control panel is between the two generators.

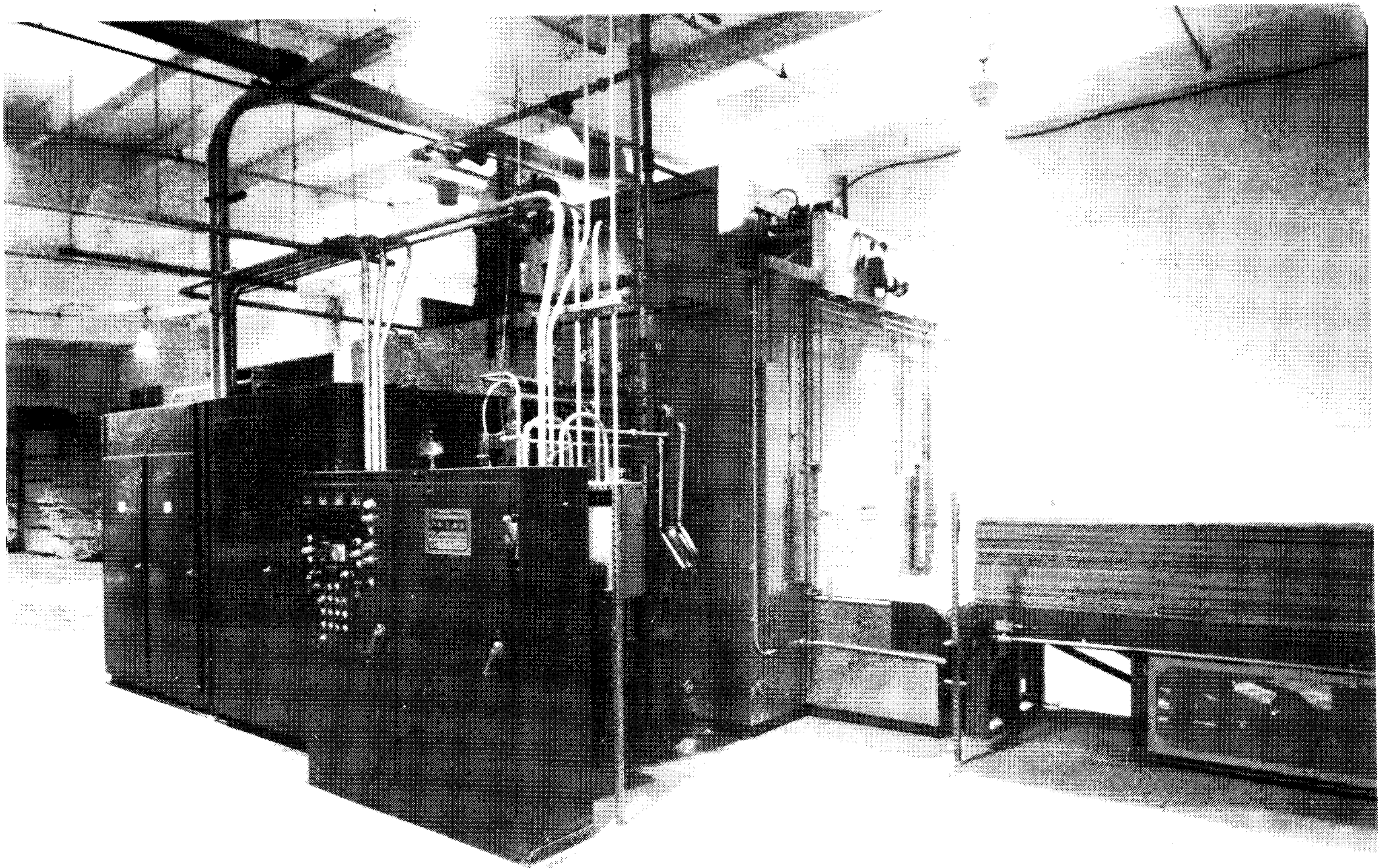


Figure 5-16   The stack of veneer is ready to be redried in the veneer dryer of this photograph. The generator in front is rated at 300 KW output.   Photo courtesy of Speco

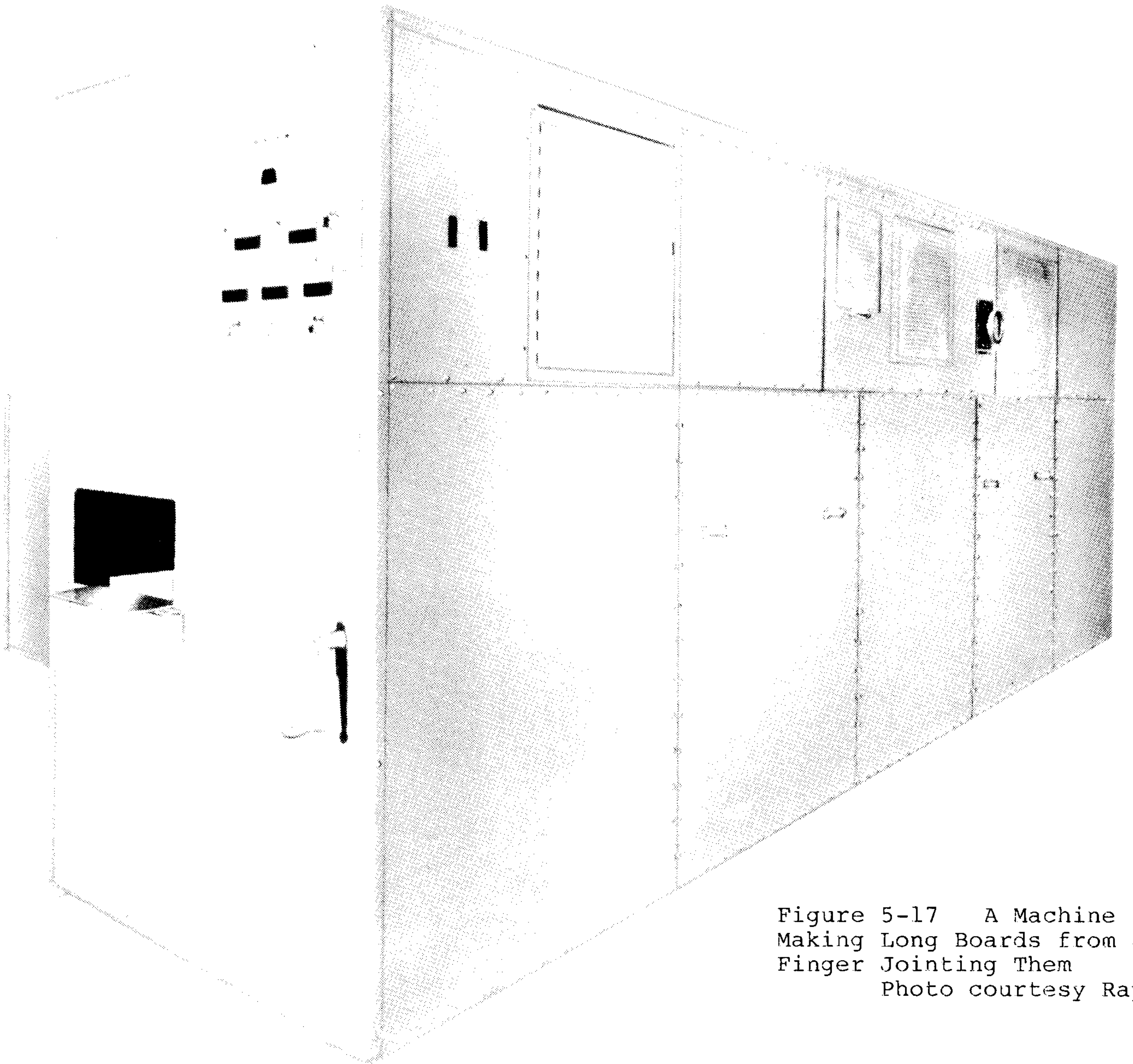


Figure 5-17 A Machine for Dielectrically Making Long Boards from Short Ones by Finger Jointing Them
Photo courtesy Raytherm, Inc.

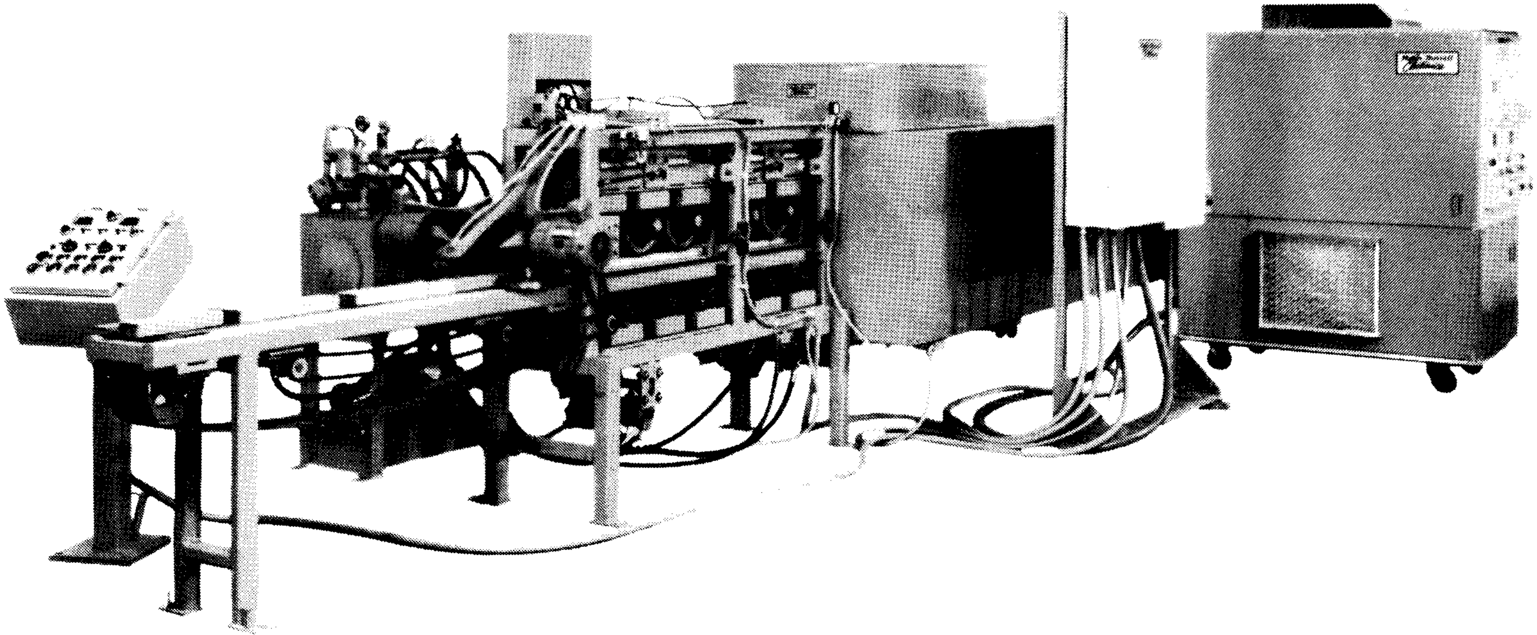


Figure 5-18 Overall View of a Finger Jointer Machine. Cut boards 1ft. to 8ft. long and up to 12 inches wide, with the glue and joints prepared, are loaded to the left. The driveup and retard sections near the center provide the glue line pressure and the 20 or 30 KW generators to the right cure the glue.
Photo courtesy Mann-Russell Electronics

PARTICLEBOARD AND FIBERBOARD

Particleboard and fiberboard are similar, yet quite different in characteristics. Both use wood chips which, in fiberboard, are digested and refined into fine fiber bundles. These are mixed with synthetic resins and waxes and are then formed into continuous mats, trimmed, and prepressed in a cold continuous (usually) press. The prepressed mats are cut into lengths and loaded into a hot press where they are cured. Some plants use dielectric heating to augment the press heat and to produce a higher quality board, as well as a faster cure. There is more advantage to the use of dielectric heating for making fiberboard than with particleboard, although some people believe there are advantages for particleboard also. The primary benefits are in the uniformity of the density of the board from surface to surface, and in the better strength of the internal bond. With dielectric heating it is possible to operate with a cooler press and thus avoid some of the "precure" problems encountered when a mat is placed on a very hot plate. Precure occurs when the resin in the outer fibers cures too rapidly. These fibers cure before pressure is applied, resulting in a soft surface that must be sanded off later.

These applications use the highest powered generators of any wood working application. Generator powers run from 250 KW output to 1500 KW output. Time cycles vary with wood thickness from around 90 seconds per heating cycle to 4 or 5 minutes. If no dielectric heating is in use, the board thicknesses are usually limited to around 3/4", particularly for fiberboard. Even in these boards it is not difficult to see the differences in density through the thickness of the board. With dielectric heating thicknesses up to 2 inches or more have been made with little discernible density striations.

The presses for these products usually have multiple openings. Their designs are somewhat different than standard hot presses in order to accommodate the high frequency voltages and currents. The presses range from single opening to 8 openings. Multiple opening platen dimensions will accommodate boards 5ft. by 12 ft., 5ft. by 18 ft. and 5 ft. by 24 ft. with one single opening press accommodating 8 ft. by 65 ft. boards. These standard sizes are common U.S. standards; boards and presses can be any desired size. These figures are for the finished dimensions of the boards, hence the dimensions in the press must be greater to allow for the necessary trim and sanding of the surfaces.

A photograph of an entire fiberboard pressing machine is difficult to get because it is a very large machine. The presses are over 50 ft. high, and extend on all sides of the boards by 4-5 ft. These dimensions dwarf even a large generator. Figure 5-19 shows the side of a multiple opening press installed in a fiberboard plant. The structure to the left is the cage for the unloader which receives all the boards as they are pushed out of the press by the loader. The end door of the press shield, which is closed, can be seen through the unloader structure. The two large "ears" sticking out to the right are the shields for the simultaneous closing mechanisms which close each opening at a varying rate so all the platens come together at the same time. These provide rapid closing of the press, and yet each opening is closed slowly enough that the loosely packed fiber will not be blown out of the press. The generator is on the opposite side of the press.

The time for curing the board in a press can be reduced if the fiber entering the press is at a higher temperature. The warmer fiber may also aid the closing of the press and improve the density profile in

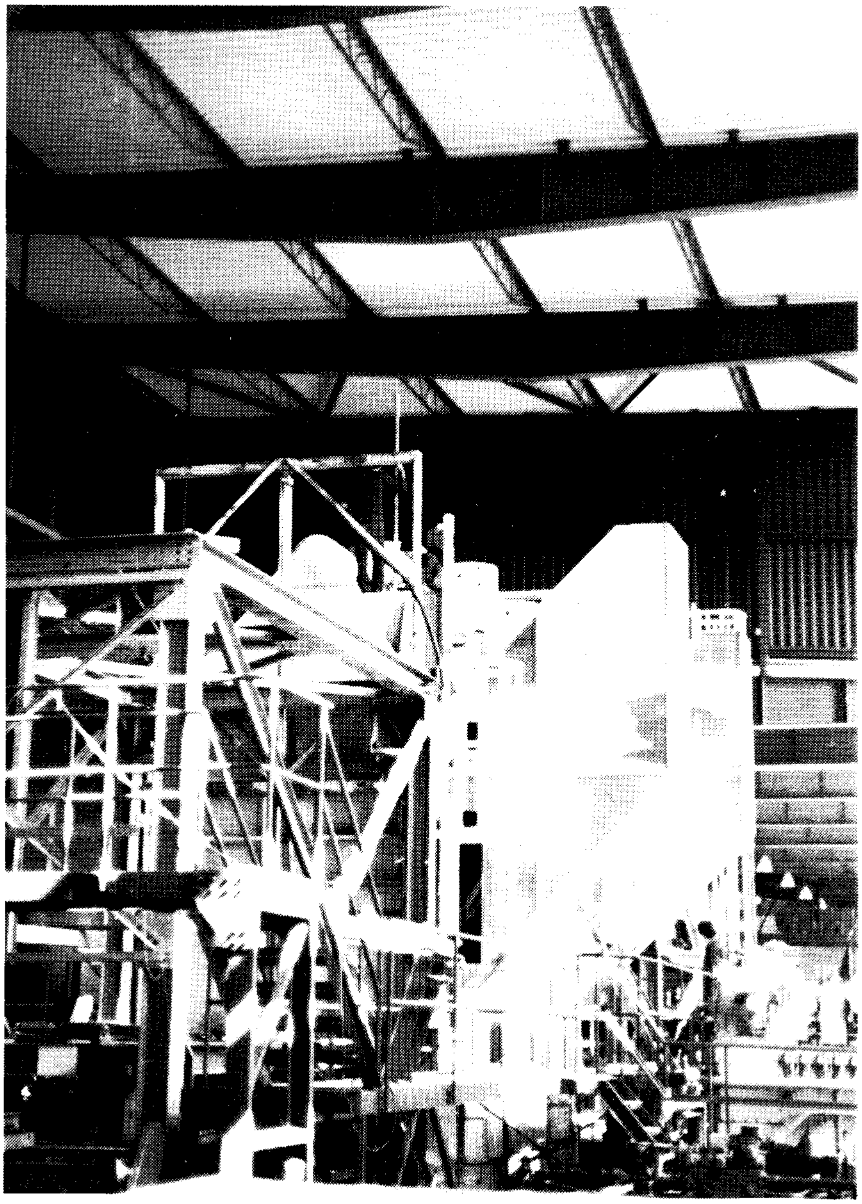


Figure 5-19 Portions of a Fiberboard Press Shield and Unloading Mechanism. The Large Structures are the Shields for the Simultaneous Closer Which is Used to Close all Openings at the Same Time.
Photo Courtesy Thermex Thermatron

the finished board. Dielectric heaters are sometimes used ahead of the main press, and either before or after the prepress, to warm the fibers before loading into the press. This warming must be limited so that the resin binders will not cure too much before the main press can apply pressure. In a normal plant the warming is to 150 to 175 degrees farenheit which allows time for the loading and closing of the press prior to curing the resin. The prewarming will shorten the cure cycle time in the press appreciably. Figure 5-20 Shows prewarming equipment installed in a board plant. The prepress is to the left. The warmer is under the frame structure in the right center of the picture.

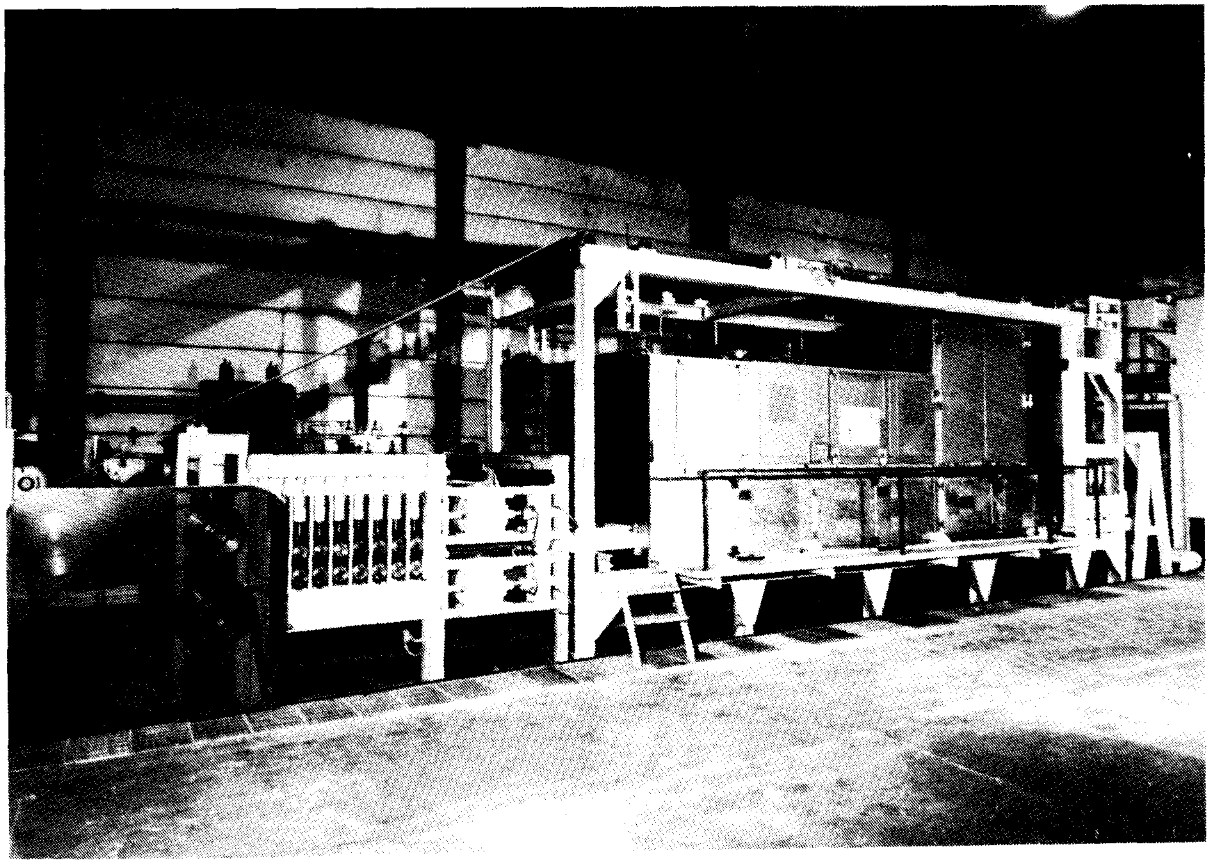


Figure 5-20 The Shielded Machine Under the Structural Frame is for Prewarming the Pressed Mats for Fiberboard or Particleboard Plants
Photo Courtesy of Bison Bahre and Greten.

LUMBER DRYING

This is a developing application of dielectric heating. It requires upwards of 100 KW generator output, although often the generators are rated on input power (over 250 KW is seen). The process normally takes place in a large tank capable of operation at less than atmospheric pressure. Figure 5-21 shows 5 such chambers installed in one plant. The stack of wood in the center background is ready to be inserted in the chambers. Note it is stacked without the use of sticks between layers. The use of the reduced pressure results in evaporation of the water from the wood cells without raising the wood temperature too high. This reduces checking or honeycombing of the wood.

Each chamber has its own generator which is located between the chambers in the photo. The square coaxial line is shown as it enters each chamber at the top. The other end of the coaxial line is connected to generator cabinet.

In dielectric drying, the recommended process is to cut the lumber to the approximate final dimensions, removing all the cull wood in the cutting, and then stacking it without sticks to provide spacing between layers as is often seen in lumber drying kilns. A large load of lumber (6500 bd. ft.) is introduced into the vacuum chamber, and the vacuum is drawn. The high frequency heat is also turned on early in the cycle. The power is controllewd to prevent arcing inside the chamber and is applied for 1 to 3 days depending on which variety of wood is being processed. Soft woods dry more rapidly than hard varieties. This time is contrasted with the conventional kiln, where 90 to 120 days is required for a load of red oak. Also, since it is precut prior to drying, no waste lumber is dried, thus saving energy. Essentially all the wood dried is useable.

The vacuum pump removes the water vapor from inside the chamber. As the drying takes place, the electrode voltage needed for a given power rises. Toward the end of the cycle the pressure in the chamber must be increased, or the power input must be reduced, to avoid arcing inside the chamber.

Dielectric drying costs between $150.00 and $450.00 per thousand board ft. of lumber, depending on type of wood. Because only good wood is introduced into the dielectric kiln, well over 95% of the wood that is dried is usable; it is claimed that much less than half the conventionally dried wood is finally used. No time or money is spent drying material that will be culled later. Additionally, the cost of stacking without the sticks is much less than in a normal kiln. Of course, there is a certain amount of shrinkage of dimensions during the drying operation, and the input lumber must be cut large enough to compensate for this shrinkage.

Economic studies of this application are now being made by impartial organizations. It appears that there are several areas of savings due to the application of dielectric heating. These include energy costs, plant floor space, initial capital costs, labor costs, reduced inventory costs, and reduced wastage, with a net savings of 16% to 18% per board foot not including wastage savings.

Figure 5-21   Five Lumber Drying Chambers are Shown With a Typical Load of Lumber Ready for One Machine. The 200 KW Generators are Hidden Between Adjacent Chambers.
Photo courtesy of Dimension Drying, Inc.

A popular application of wood drying which is decades old is that of drying small blocks of wood species that are readily degraded by conventional methods. Golf club heads are made of persimmon wood. When exposed to air certain parts turn a dark unacceptable color shortly after the log is felled. When dried immediately with a dielectric heater this wood retains its normal white color and has a higher value. Figure 5-22 shows four 12.5 KW generators on one conveyor for drying golf club heads prior to shaping them to the final form.

GENERAL

While these are the major wood working applications, there are others, including the making of embossed patterns in boards, making die cylinders for cutting machines, usually made of curved plywood, etc. The list of vendors is long. Detailed information on specific applications can be found by consulting one of them.

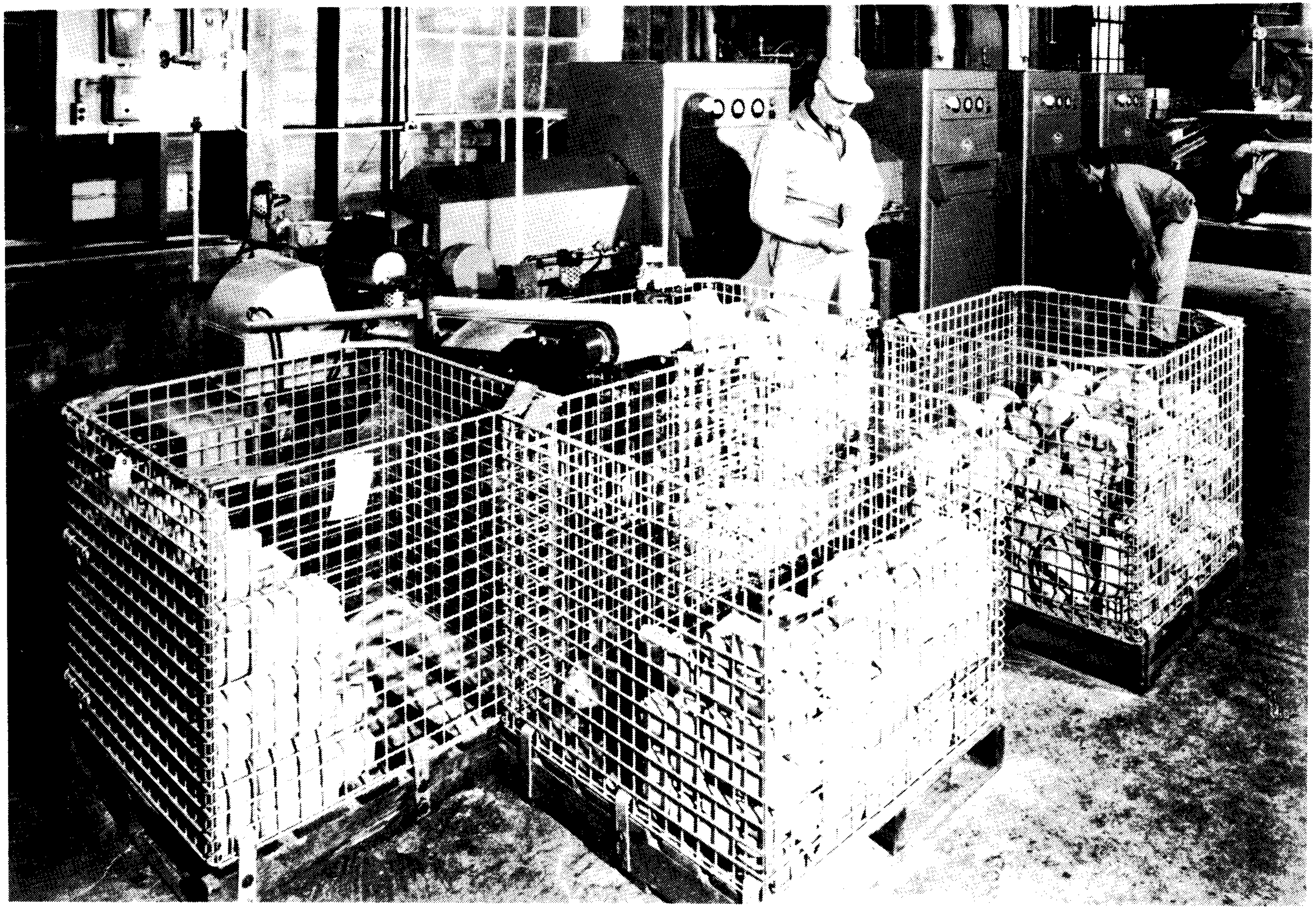


Figure 5-22 Four 12.5 KW generators on 1 conveyor for drying golf club heads prior to machining.
Photo courtesy of W. T. LaRose & Associates

LIST OF MANUFACTURERS

The following companies are known to manufacture RF dielectric heaters for the applications in this section.

For addresses at the time of publication please refer to the section on acknowledgments.

IN THE U.S.

- J. A. Callanan Co.
- Dimension Drying Inc.
- L. L. Machinery Co.
- W. T. LaRose Associates
- Mann-Russell Electronics Inc.
- Nemeth Engineering Associates.
- Raytherm, Inc.
- Rosenquist Inc.
- SPECO Inc.
- Thermex Thermatron

IN EUROPE

- Bison Bahre & Greten
- Robert Burkle GmbH
- Flender-Himmelwerk GmbH
- Herfurth GmbH
- Metau Impianti s.r.l.
- Radne Limited

IN THE FAR EAST

- Tai-Yen Industrial Co., Ltd.
- Yamamoto Vinyter Co., Ltd.

SECTION 6

TEXTILES

The primary use of dielectric heating in textiles has been drying of all kinds. The earliest application was the drying of rayon "cakes" which was done for many years until rayon was replaced by other synthetic fibers. Rayon, a product made from trees (via pulp, viscose, etc.) is spun into rotating buckets to form a cake which, after washing, requires careful drying. The product shrinks considerably and uniformity of drying is essential. Nonuniform drying causes mechanical strains in the yarn to be unevenly distributed along the filaments. These differently strained filaments produce different dye shades and undesirable patterns in woven fabrics. Dielectric drying under proper conditions solved this problem.

The primary advantages in the use of dielectric heating for drying textiles are speed, lower costs, ease of operation, lack of degradation of color, lack of degradation of other yarn characteristics which can be caused by exposure to high temperatures, and close and uniform control of the final moisture content. Labor saving is also important. Only 1 person is needed to remove the yarn (hanks, cones, muffs or tow) from the centrifuges used for extracting most of the moisture and place it on the conveyor belt of the dielectric dryer. Space saving is another important advantage as dielectric drying can take place in minutes instead of hours. Because of the speed, and small size, the energy required to accomplish dielectric drying is also lower than that for other drying. Table 6-1 gives comparative figures for three types of dryers and three types of fibers.

Table 6-1

COMPARISON OF COSTS FOR DYE BOBBIN DRYING OF WOOL, COTTON, AND POLYESTER

	Wool	Cotton	Polyester
Initial Moisture (%)	45	55	10
Final Moisture (%)	18	9	2
Fresh Air Dryer			
Drying time (h)	2.1	3	1.6
Energy consumption (Kwh/lb)	0.345	0.494	0.264
Steam consumption (lb/lb)	2.2	2.8	1.8
Energy costs ($/lb)	0.0421	0.0569	0.0330
Pressure Dryer			
Drying time (h)	0.8	1.0	0.75
Energy consumption (Kwh/lb)	0.131	0.163	0.122
Steam consumption (lb/lb)	1.3	1.6	1.3
Cooling water consumption (gal/lb)	0.839	1.02	0.839
Energy costs ($/lb)	0.0256	0.0318	0.0250
Dielectric Dryer			
Drying time (h) *	0.83	1.33	0.31
Energy consumption (Kwh/lb)	0.213	0.340	0.0771
Energy costs ($/lb)	0.00372	0.0243	0.00569

* With Dielectric drying, the water is extracted mechanically before drying.

Note: Throughput 550 pounds dry fiber per hour
Cost for power $0.065 per KWh
Saturated steam at 90 psi $17.73 per ton
Cooling water $0.0036 per gallon
Bobbin weight 1650 pounds
Plastic bobbin sleeves.

Source: H. Chr. Grassman, Siemens, Erlangen, West Germany "High-Frequency Drying in the Man-made Fibre Industry" Chemiefasern/Textilindustrie 33/85 (Jan, 1983) 48-41, E3-E5.

Note that the pressure dryer is somewhat faster than the dielectric dryer in some cases, but the dielectric dryer costs are much lower in all cases.

ELECTRODES

All types of electrodes are used in textile drying (See appendix C). If a web of woven material is to be dried, the stray field electrode is useful; in the case of strands of tow, the dispersed field electrode is used; in the case of bobbins the parallel plate electrodes are used. Air sufficiently warm to carry away the evaporated moisture is usually recommended and provided. The temperature of the air need not be high; only high enough to be above the dew point within the oven.

This avoids condensation of the removed moisture which, if it drips on the product, will stain it and can cause arcing. Some manufacturers prefer to have the air flow downward through the material because it tends to hold the material to the conveyor belt (which is porous) as well as help remove the moisture.

POWER REQUIREMENTS

The generator power for dielectric drying can be rather easily estimated by the procedure outlined in section 2 of this report. The volume of air exhausted from the oven need not be excessive as long as it carries away the moisture. Therefore the warm air need not be used for drying. An oven temperature of not over 175 to 215 degrees farenheit is normal. The generator power capabilities, of course, will depend on the amount of material to be dried and especially on the amount of water to be evaporated. However, powers range well upwards of 100 KW in many instances. Some installations will have several smaller generators connected to the same conveyor so the material passes from one generator to the other during the drying process. In small installations these smaller generators may be used singly.

The majority of dielectric textile heating equipment manufacturers are European. Several of these are exporting their equipment to the U.S. with considerable success. The largest equipment will process about 1 ton of wool per hour on a conveyor 4.5 ft. wide. It requires 5 to 20 minutes exposure time to the RF to complete the drying. Bobbins made of metal are processed with the axis horizontal. Bobbins with nonmetallic cores can be placed on the belt with their axes vertical (see Figure 6-1). A low loss plastic is preferred, however. Hanks are laid on the conveyors, overlapping each other somewhat. Because hot air circulation is not needed for drying, placement of the material packages on the belt is not critical.

WOOL BALE WARMING

One non-drying application is that of warming raw wool bales. These are wool fleeces directly from the shearing sheds and may contain all sorts of foreign material. The bales, particularly if transported during cold weather, must be warmed in order to separate the fibers. With cold bales the lanolin, which is part of the wool, is solid and holds individual fibers tightly. Bales are large; about 5 ft. by 2.5 ft. by 3 ft. or larger. They weight 350 to 800 pounds each. It requires around 20 minutes to warm a bale with dielectric heating and each bale requires a 30 KW generator. Without dielectric heating the bales are put in a warm room for several days or even weeks, depending on their temperature when received.

BONDING INTERFACING TO FINE FABRICS

Another nondrying application is that of bonding interfacing material to fabric for making men's and women's suits or the like. The interfacing is added so the finer materials will hold their shape during the life of the garments. In Europe the finished material and the interfacing are stacked in alternate layers so several can be cut

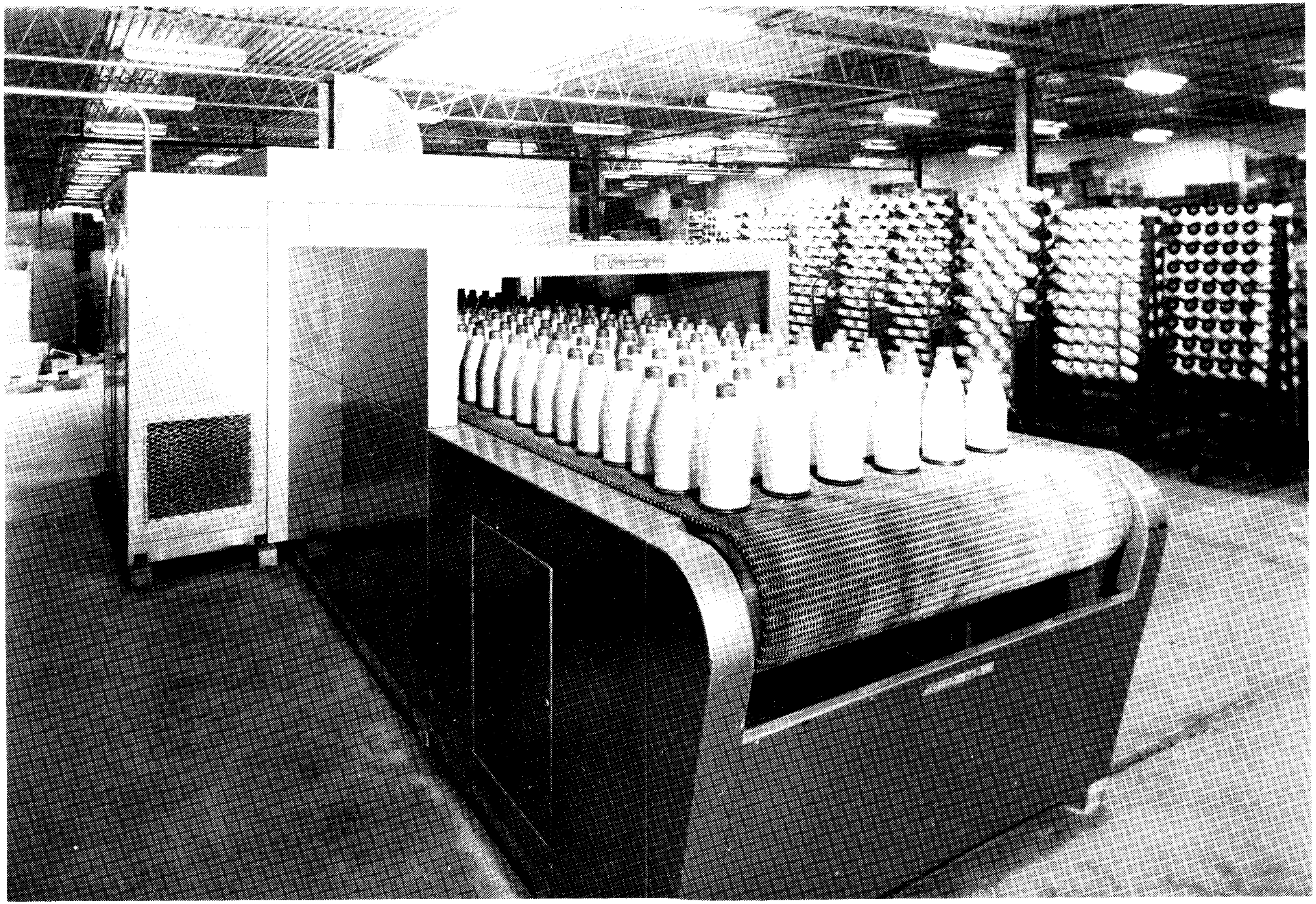


Figure 6-1   A 20 KW Conveyorized Dielectric Heater is used for final drying fiberglass yarn wound on insulating bobbins.

Photo courtesy of PSC Inc.

at one time. The stacked material is then sent through a dielectric heater which heats it and bonds the interfacing to the fine material. Later the pieces are separated and sewn into garments. Figure 6-2 shows a conveyor load of such stacks going into a dielectric heater. About 0.08 Kwh per pound of material is required for this operation.

DRYING PANTYHOSE

Drying pantyhose is the final operation prior to packaging. After spinning the hose, 144 pair are put into a bag for further handling through the dying, washing, and drying operations. Generally the contents of each bag will have the same size and, after dying, the same color. After washing a load of bags is put into a centrifuge to remove the excess moisture. The bags are then put into a dryer. Some dryers merely lay the bags closely packed on a coarse heavy screen, and circulate hot air through them. Other dryers circulate the hot air while the bags are being tumbled such as in a clothes dryers. For dielectric dryers the bags are closely packed on a conveyor which carries them between the parallel plate electrodes of a dielectric oven. Often the warm air exiting from the generator will be led into the oven to help remove the evaporated moisture.

Advantages of the dielectric drying of pantyhose are high thermal efficiency, no color degradation due to exposure to high heat, and no lost desirable yarn characteristics from high heat exposure. Most pantyhose are made of nylon yarn. One characteristic of nylon is that it heats rather readily in a dielectric heater. Therefore, although the moisture tends to increase the heating rate of nylon, it can be overheated in a dielectric dryer. Overheating is first noticed when certain components of the dye coloration start to separate thus changing the color of the finished goods. Other fibers do not exhibit this overheating tendency.

DRYING BULK YARN

The largest use of dielectric heating in textiles is in drying bulk yarn in various type packages. Most popular is drying wound bobbins of yarn, or thread. When the bobbins are made of an insulating material they may be placed with their long dimension perpendicular to the plane of the electrodes. This is illustrated in Figure 6-1. If metal bobbins are used it is preferred to place these on a conveyor with the long dimension of the bobbin parallel to the electrodes. Even though the bobbins form round packages, the resulting drying is quite uniform although certain parts may dry before others. As mentioned, this would not be desirable in yarns such as undyed rayon because the nonuniform drying would leave strains in the yarn, but for other materials, or for predyed yarns, the strains do not cause problems.

Yarns are also packaged in "hanks" which are loosely wound without any supporting bobbins. Hanks are simply layed on the conveyor belt, overlapping if desired, and passed through the RF field. Again parallel plate electrodes are standard.

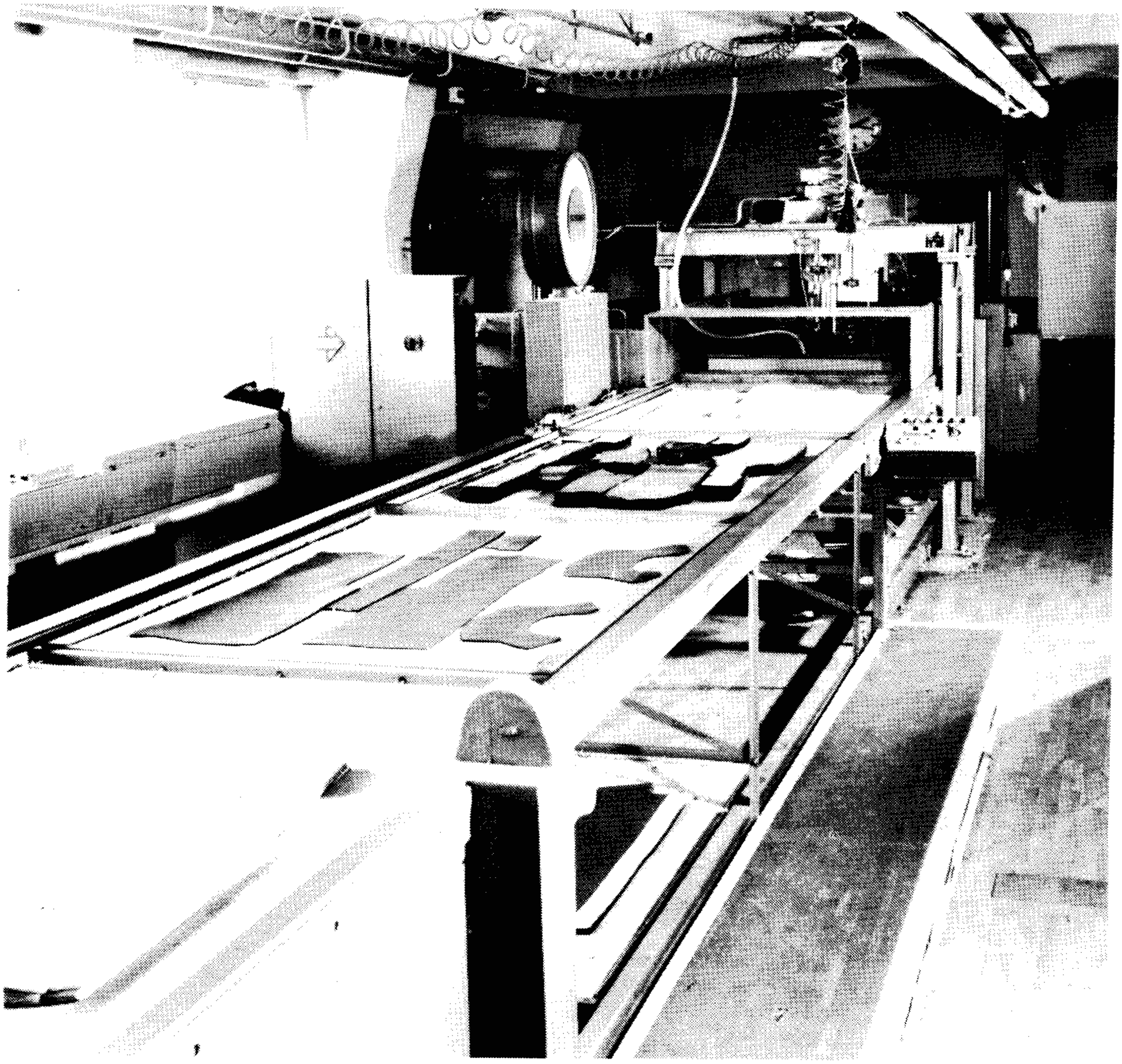


Figure 6-2   A Machine used to bond the interfacing or interlining to fine fabrics to make them stiff enough for outer garments for men and women.

Photo courtesy of Paul Kiefel Hochfrequenz-Anlagen GmbH

DRYING TOW AND WEBS OF WOVEN MATERIAL

"Tow" is used to describe a long (endless) group of strands of yarn or thread. In this case the tow is passed through the field from a "staggered" strayfield electrode. Several tows can be dried at the same time, when placed as parallel strands. A conveyor can be used to support the tow but, if it is kept under sufficient tension to maintain spacing to the electrode rods, the conveyor need not be used. It can also be passed around pulleys and redirected past the same electrode several times.

A "web" is usually woven material, but it can be a number of threads all laid parallel in one plane, or a nonwoven fabric. These require a onesided strayfield electrode as webs usually have little thickness. Such an electrode is illustrated in Figure 6-3. Figure 6-4 shows a machine used for partially drying a web of special fabric prior to compressing it. This indicates the number of threads per inch is increased to a specified density. Again a conveyor may be used, or the material can be dried under sufficient tension to maintain electrode spacings. Often a web can be passed around pulleys and thus can be directed to both sides of a onesided strayfield electrode.

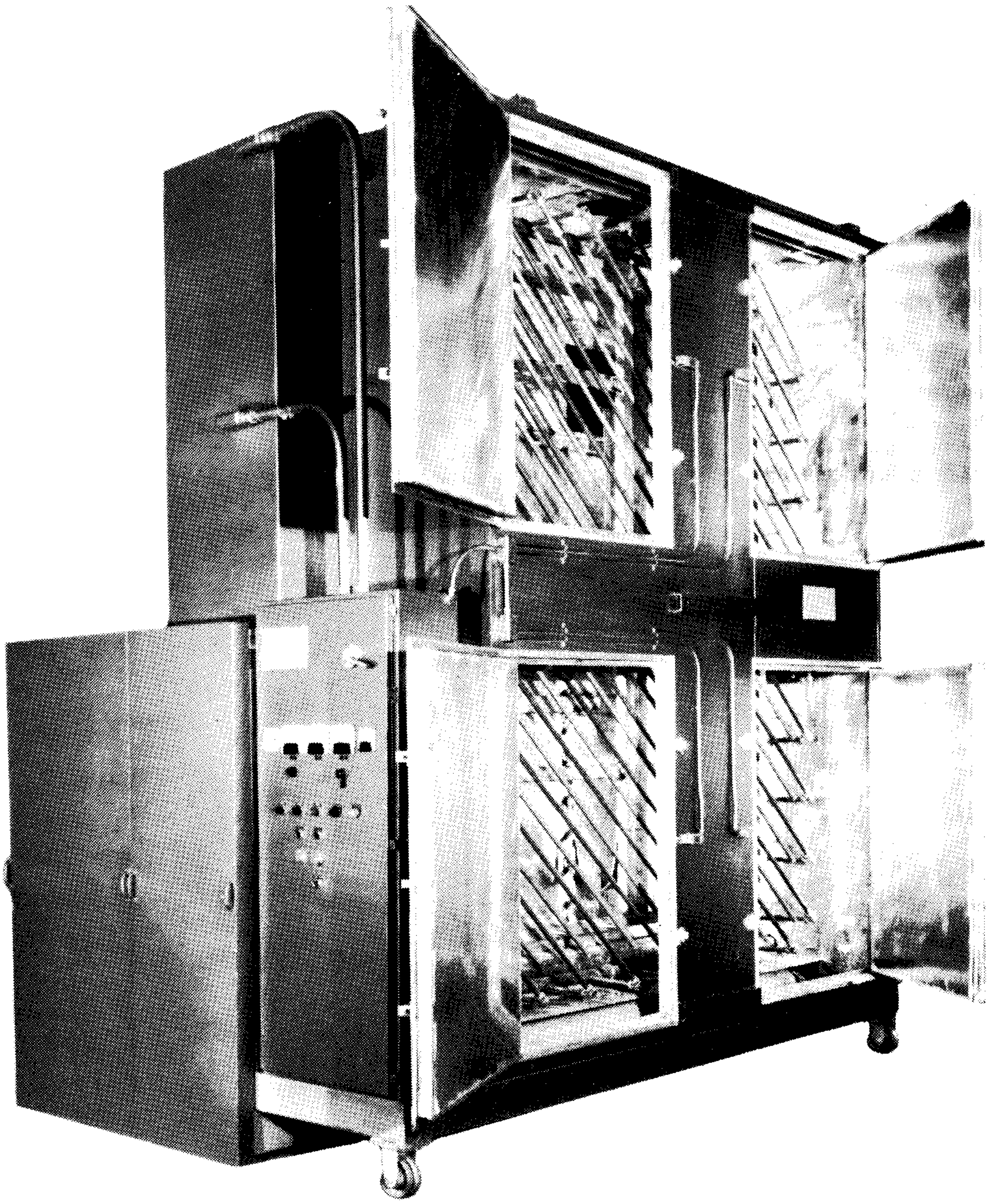


Figure 6-3 This stray field electrode system is placed vertically to save floor space. With proper pulleys it can dry webs of all types.
Photo courtesy of PSC Inc.

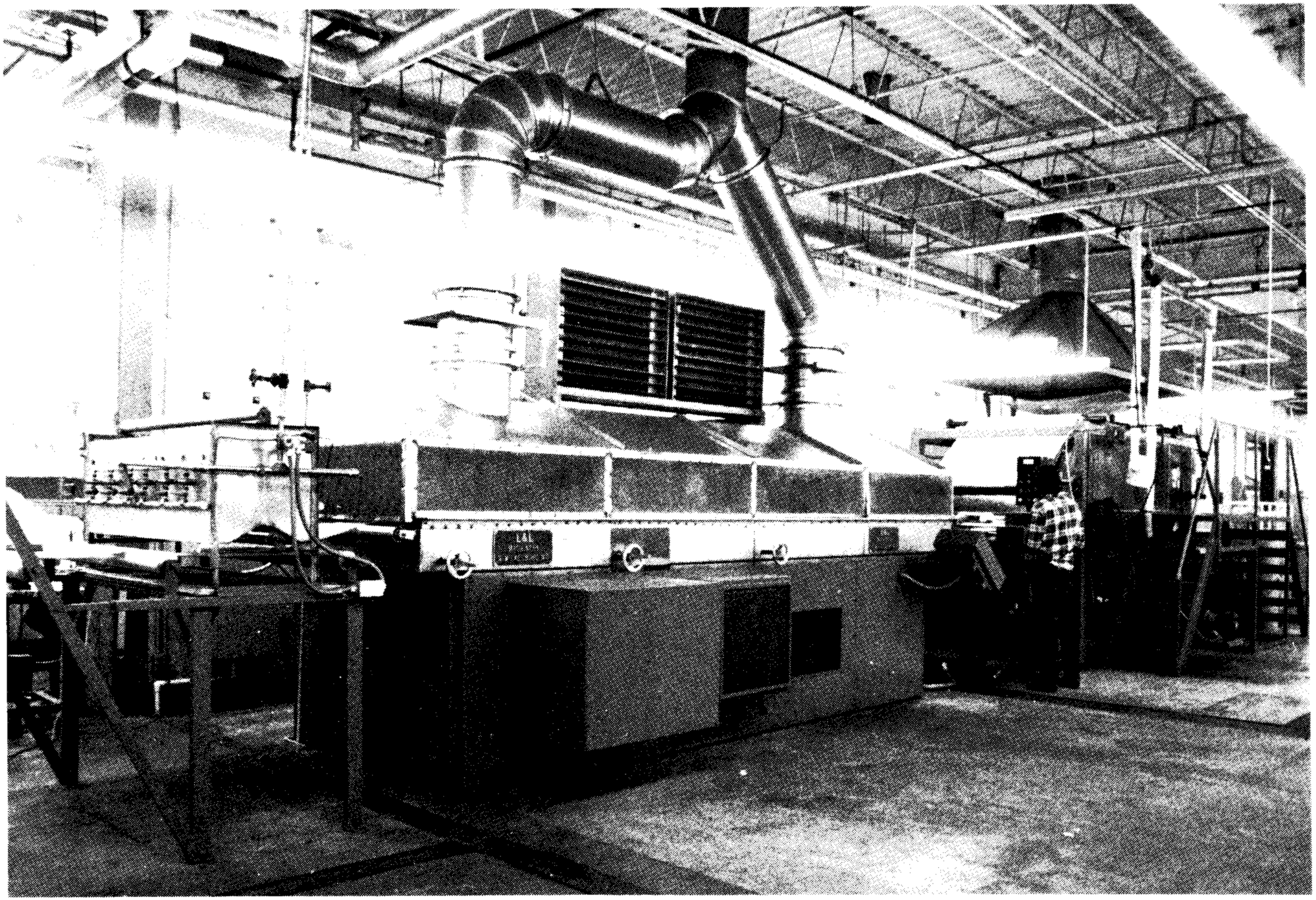


Figure 6-4 A Fabric Dryer is used for partially drying a woven web of fabric prior to compressing, or increasing its density.

Photo courtesy opf L and L Machinery Co.

LIST OF MANUFACTURERS

The following companies are known to manufacture RF dielectric heaters for the applications in this section.

For addresses at the time of publication please refer to the section on acknowledgments.

IN THE U.S.

L L Machinery Co.

W. T. LaRose & Associates

PSC inc.

Radio Frequency Company, Inc.

Reeve Electronics

Thermex Thermatron

IN EUROPE

Robert Burkle GmbH

Herfurth GmbH

Paul Kiefel Hochfrequenzanlagen GmbH

Radyne Limited

Strayfield International

SECTION 7

BUSINESS PRODUCTS

Business products include paper envelopes and forms used in the daily operations of business and government. There are the familiar envelopes of all types which are usually provided with remoistenable glue used for sealing them. Forms are usually multipage documents for standard business transaction that may include pages which can be folded into envelopes. Business forms are either cut into sheets or are fan folded so they can be used in automatic machines.

The dielectric heaters for drying glue on forms are normally used in conjunction with other machines, a collator being one. A collator is the machine that brings the various layers, or rolls, of printed paper and carbons together in the required registration prior to the gluing operation. Because there are several good collators on the market, U. S. dielectric heating manufacturers have adapted their machines to fit them. Unless care is exercised in wording the sales agreement, this can lead to a situation where an unsatisfactory total installation may be blamed on "the other machine" by one of the manufacturers. For new sales one manufacturer will often take full responsibility. In case a dielectric heater is added to a collator special agreements must be made. In Europe, where the dielectric heater manufacturer usually makes his own collator, the responsibility problems are avoided.

There are several advantages to the use of dielectric heating for processing business paper, the major being the increase in speed which is possible. Another is that cold glues can be used. With dielectric heat only normal care is required because the glue lines are totally set, or dried. This ensures that all layers of multipaged forms are firmly held in place. Another advantage is that the papers are not embrittled by the application of high temperatures which are normally required to dry glues that are covered by layers of paper. These problems and their solutions by dielectric heating are discussed below.

As with other applications of dielectric heating, reduced floor space and faster production are normally obtained. This comparison is easily made as it is possible to remove the older drying systems and substitute the dielectric drying directly in its place.

The length of the new dielectric heater will be between 5 and 11 ft. and higher quality also results from the use of dielectric heating.

ELECTRODE SYSTEMS

Because of the thin materials to be heated, either in layers of remoistenable glue for envelopes or in the glue lines for forms, the electrodes for processing business forms are of the stray field type (See Appendix C). The electrode elements may be either round rods or flat strips with rounded edges. The elements may be either perpendicular to the centerline of the flow of the forms or they may be diagonally oriented (see Figures 7-1 [A] and 7-1 [B]). The latter seem to provide better transfer of heat to the narrow glue lines which are perpendicular to the flow of the forms. This is due to the space which must exist between the narrow glue line and the electrode rods. The space reduces the "coupling" of the field to the wet glue line. With diagonal rods the glue lines will have no such space and therefore coupling is enhanced.

Occasionally the electrodes used along the edges of forms will be made of small plates, or the ends of rods, to provide an electric field only at the edges of the paper. Some manufacturers have the small rods, or angles, located at the edges of the forms where the glue lines, or glue spots, are deposited (See Figure 7-1 [C]). In this case the set of rod electrodes for at least one edge of the paper has to be adjustable to accommodate various widths of forms. Figure 7-1 (D) shows another alternative where vertically placed rods are located under the glue lines as they pass over them. The stray fields from these rods heat the glue.

TENTING

If the sheets of a multipaged form are allowed to slip a little when the glue is not fully set, the fold line of one page will not lie on top of other fold lines for other pages. If the glue sets with the pages in this position, "tenting", or small bulges at the fold line, will occur when they are unfolded for use. This makes them difficult to feed through automatic machines. Dielectric heating speedily dries the glue lines before the fan fold is made so the layers cannot slip and cause tenting. Lacking dielectric heat, particularly where the moisture is dispersed into the paper, the glue lines may not be completely dry when folded.

SMUDGING

Business forms usually include carbon paper if multiple copies are desired. Some specially treated papers do not need "carbons", but most do. Smudging of the carbons caused by overheating the waxes in them can be a problem. Dielectric heating can be carefully controlled so that the heat reaching the carbons does not melt the waxes in them. Occasionally the coating of carbon material on the papers may be kept clear of areas where glue is deposited to aid in avoiding smudging.

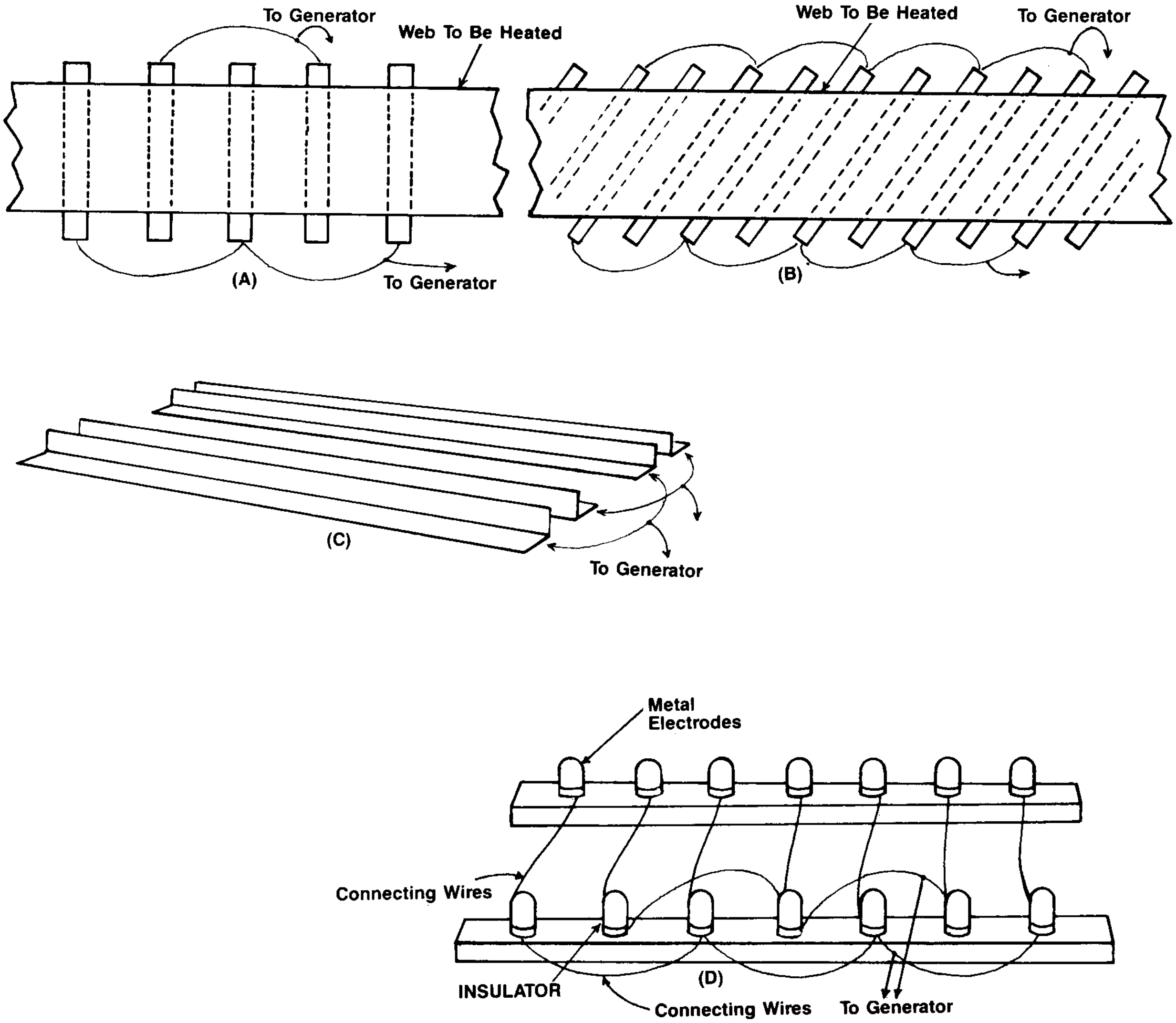


Figure 7-1 Electrode Systems for Heating Business Forms

COMPETITIVE SYSTEMS

The use of dielectric heating competes well with the use of other systems of gluing, some of which feature a glue which melts with heat. With hot melt glues, the clean up time to clear the many nozzles, pumps, and valves, all of which must be kept hot, is considerable. There is also danger of burning the personnel who may try to adjust glue flow, etc. With dielectric heating the water based glues are readily cleaned and never need heat in the deposition system. More flexibility of the forms through use of the cold glues, such as Dextrin, Polyvinylacetate (PVA) or a mixture of the two, is also claimed for dielectric heating. The glues are less brittle than other types, and the papers are not dried out due to excessive exposure to high temperatures.

Cold glues can be dried without dielectric heat by running the equipment slow enough to permit the water in the glue to disperse into the paper. Howerer, this is particularly slow when multipaged forms are being processed or where a coating on the paper retards this dispersion. The process can be speeded by using hot air, or hot plates at the glue lines. However, this tends to embrittle the papers and smudge the carbons whereas with dielectric heating, the wet glue lines are heated faster than the dryer paper and the moisture content of the basic paper is not greatly changed. Overdrying of the glue and paper substrates does not occur with dielectric heating. Also the volatiles, being water, are nonpolluting.

Not all applied glue is for holding the forms together. Remoistenable glues or water based pressure sensitive glues are also applied to business forms and are dried with dielectric heating.

RATES OF PRODUCTION

Rates of production with the modern business forms machine are quite high. As many as 24 or more lines of glue can be dried at rates as high as 1000 ft. per minute. Some manufacturers claim 14 part forms are being dried at the rate of 540 ft. per min. These higher rates increase the productivity of the collator, as its speed is limited by the glue drying equipment. Web coating weights of up to 35 grams per square meter, or 7 pounds per 1000 sq. ft., are normally dried "instantaneously" at a rate of well over 10,000 sheets per hour at 1000 ft. per minute. Some machines have adjustable drying area control so that certain areas can be left unheated if this is desired.

POWER REQUIREMENTS

Business form dryers are normally rated from about 5 KW to 25 KW output power. Because the number of glue lines, etc. varies so drastically, it is best to consult with one of the manufacturers listed at the end of this section of the report about the specifics of a proposed drying operation in order to determine the power output requirement. At least one manufacturer will not state the expected production rate through use of dielectric heating; he will state that its use will raise the speed of a line 2 to 3 times that of running the same product without dielectric heating.

Occasionally hot air is used in conjunction with the dielectric heating in order to carry away the moisture. The hot air does not remove much, if any, moisture from the paper itself, because its temperature is relatively low and the residence time in the oven is very short. Machines vary in length between 6 ft. and 12 ft. At 1000 ft. per minute for a 12 ft. long machine, the residence time is considerably less than 1 second so the drying from the hot air is unimportant.

The RF generators are usually located beneath the electrode system. They are usually air cooled and sometimes the warm exhaust air is emptied into the electrode enclosure to remove the moisture. The entire cabinet is usually made of aluminum to provide good shielding, and consequently radio interference is very low. Figure 7-2 shows a 10 KW generator beneath the applicator. The lid is up to show the electrodes for gluing the edges of business forms at the rate of 750 ft. per minute using a waterbased adhesive.

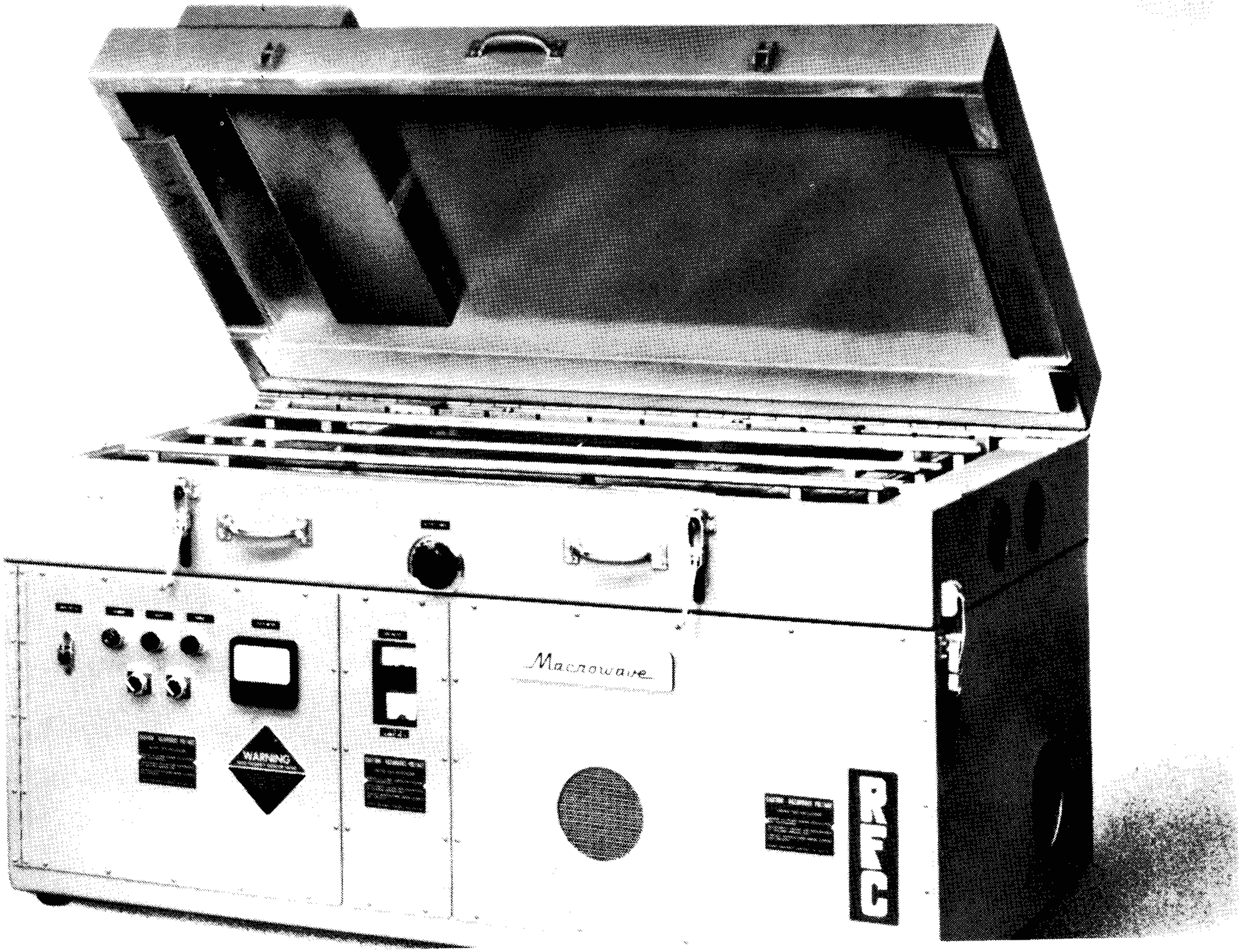


Figure 7-2   A 10 KW gluing machine for paper forms which uses waterbased adhesives and runs at speeds up to 750 ft. per minute.
Photo courtesy of Radio Frequency Company, Inc.

LIST OF MANUFACTURERS

The following companies are known to manufacture RF dielectric heaters for the applications in this section.

For addresses at the time of publication please refer to the section on acknowledgments.

IN THE U.S.

Radio Frequency Company, Inc.

SPECO Inc.

Thermex Thermatron

IN EUROPE

Strayfield International

SECTION 8

MISCELLANEOUS

Space limitations will not permit a separate section for every application of dielectric heating in use today. This section will be used to briefly describe some applications which are in daily use, but with fewer machines installed in these industries.

CERAMICS

Ceramic products are made of special clays which are mixed with water to give them the needed plasticity so they can be formed. A problem which this industry faces is that of making sure the molded parts are well dried before they are introduced into the very hot ovens where the clay is fused into a ceramic. Seemingly this would be an ideal spot for dielectric heating because of its ability to heat the moist areas and thus remove the water.

The difficulty with dielectrically heating many wet ceramic parts is that the clay has very little strength and is nonporous. Water expands some 1700 times when it turns to steam and this great expansion can build up internal pressures in the body of the part and cause it to rupture. The densely packed clay particles do not provide a convenient pathway for the steam to escape. Thus in most cases there is little advantage to the inherently rapid heating possible with dielectric heating.

There are some ceramic parts which employ dielectric heating for drying. Generally they include almost any part which has a very thin cross section. Thus the internal water does not have far to go to get out. Typical of this type of structure are the ceramic bodies which support the platinum salts for catalytic automobile mufflers. The ceramic walls are very thin, but there are many of them. In a dielectric heating field the thin walls of the structure readily give up their moisture, which exits via the passages mormally used by the automobile exhaust gases.

Some small diameter post insulators are dried in a dielectric oven prior to firing in the kiln. Other small ceramic parts are similarly treated.

A product coming into increased use is ceramic insulation board composed of ceramic fibers held in a sodium silicate matrix. In this product, which is replacing asbestos, the fibers do not absorb the water contained in the binders which hold the mat together. The drying is done on a dielectric heater which includes a conveyor so the material can be passed through the heating field in a continuous stream.

FILM DRYING

The production of photographic films and papers is accelerated through the use of dielectric heating to remove the moisture deposited during the various phases of processing. The entire operation must take place in complete darkness and this requires good reliability of the dielectric heater. A stray field type electrode is used for this work. Microwave installations for the same type of work are also used.

GRINDING WHEELS

Particularly large grinding wheels can be made more rapidly by curing them with dielectric heating. The carborundum or alumina grit is bonded by a resin which must be thoroughly cured before the wheel is safe to use. Dielectric heating, where the heat is generated internally as well as externally, aids in this process. There are not many dielectric heaters used for grinding wheels because the market is small.

FOUNDRY CORES

This is a rather old dielectric heating application, but is still in use, particularly in brass foundries. The cores, made of sand and a binder, form the holes in castings. The binder must decompose shortly after the metal is cast against it so that the sand left from the core can be removed easily. Old cores were made using an oxidizable oil and required baking in an oven overnight. Later, after the advent of synthetic resins, the cores were made using a flour-type binder to give the cores strength while the resin was uncured. The core is then passed through a dielectric field where the water in the sand is boiled out and the resin cured. This meant that instead of waiting overnight for the cores to bake in an oven, they could be used within a few minutes of forming them.

Later, other resins were developed which were cured chemically by passing carbon dioxide through the sand. This proved easier than dielectric heating. However, the process does not work well for brass and certain other metal castings and these foundries still use dielectric heating to cure the cores. In the past several years microwave energy has also been used for foundry core curing.

BOOKS

Books, whether sewn or not, require adhesives to hold them together. These adhesives can be hot melt type or water based. The latter require dielectric heating for rapid production and have the advantage of not exposing the paper to high temperatures and thus running the risk of scorching it. This application is largely practiced in Europe to date, but seems to be successful and gaining momentum. Several European dielectric equipment manufacturers have equipment in the field.

In addition to reduced danger of discoloring and weakening the paper, a saving of as much as 70% of the required energy is claimed for the dielectric heater, which requires 1 to 2 seconds exposure time. The process consists of conveying the books to the electrode area with a light pressure against the spines of the books to ensure contact. A stray field electrode with about 5000 volts at 27.12 MHz is needed. With an electrode 3 meters long, 3000 to 5000 books per hour can be bonded. The generator power rating is 10 KW. Having 2 or three such machines in tandem can increase the production rate. The maximum reported to date is 9000 books per hour. Time saving is up to 4 hours because there is no need to stack the books for drying and cooling. Figure 8-1 shows a book binding equipment in the manufacturer's plant. A strayfield electrode system requires 1 - 2 seconds exposure to the RF.

FOOD

In the U.S. applications of dielectric heating to the food industry have lagged. Microwave heating has filled the void possibly because early successes were not found for RF dielectric heating. However, in Europe the picture is different. There are at least three different applications in the food industry which have resulted in multiple sales to the same end users plus new buyers. These are: a) post baking and drying systems (one company claims over 100 such installations); b) meat thawing; c) fish thawing. The data presented here is through the courtesy of several European dielectric manufacturers, but primarily from the U.K. However, there is little doubt some of their data came from their installations in the U.S. Still, the acceptance of the new dielectric heaters by the European baking industry has been more complete than in the U.S.

RF Post Baking And Drying

The contribution of dielectric heating in this bakery application is its ability to remove moisture selectively and arrive at a more uniform distribution in the final product. Speed is also an important factor, as is the lack of overbrowning the baked goods while removing the final water. The improved uniformity of the ultimate moisture also results in a stronger product with no checking. Variations in final moisture improved from a 2% variation to 0.5% variation after the RF post baking. Certain products are carefully dimensioned to be sure of uniform stacking in the packages and the stronger products due to the RF drying facilitate this operation. Lack of internal cracking also aids in applications of fillings in sandwich cookies.

Increases of 30% to 50% in production of baking ovens are claimed as routine, with occasional 100% increases in production. This is achieved with very little, if any, increase in floor space and only minor modifications to present baking ovens. The post baking equipment is usually placed toward the outfeed end of the ovens so the proper color of the baked goods can be achieved and subsequently the balance of the moisture removed. There is no difficulty in making

Figure 8-1 This equipment is used for setting the glue on book spines. The conveyor is not showen. The backs of the books are passed down the slot visible at the top of the long horizontal bar.
Photo courtesy of Herfurth GmbH

dielectric heaters to comply with all health standards of the country. Powers vary from 1.5 KW to multiple 50 KW units on 1 conveyor. Figure 8-2 Shows 4 30KW units on a single conveyor for post baking of cookies. The white panels carry lights to indicate where trouble may be encountered so it can be repaired in a minimum of time.

Electrodes Variations in the height contour of individual cookies can be handled more uniformly with a "staggered" field electrode system (see Appendix C). This requires a nonmetallic conveyor belt and bed plate so that the horizontal components of the field will not be short circuited.

Meat Thawing

One of the big advantages of using RF for meat thawing is the reduction in weight losses which are normal in compared to slow thawing operations. This can amount to as much as 3.5% savings in weight which, at the price of meat, is worth the effort. A 20 KW meat thawing system can handle 940 pounds of meat per hour (saving nearly 33 pounds per hour drip loss). Figure 8-3 shows thawed meat emerging from a line of 4 20 KW generators.

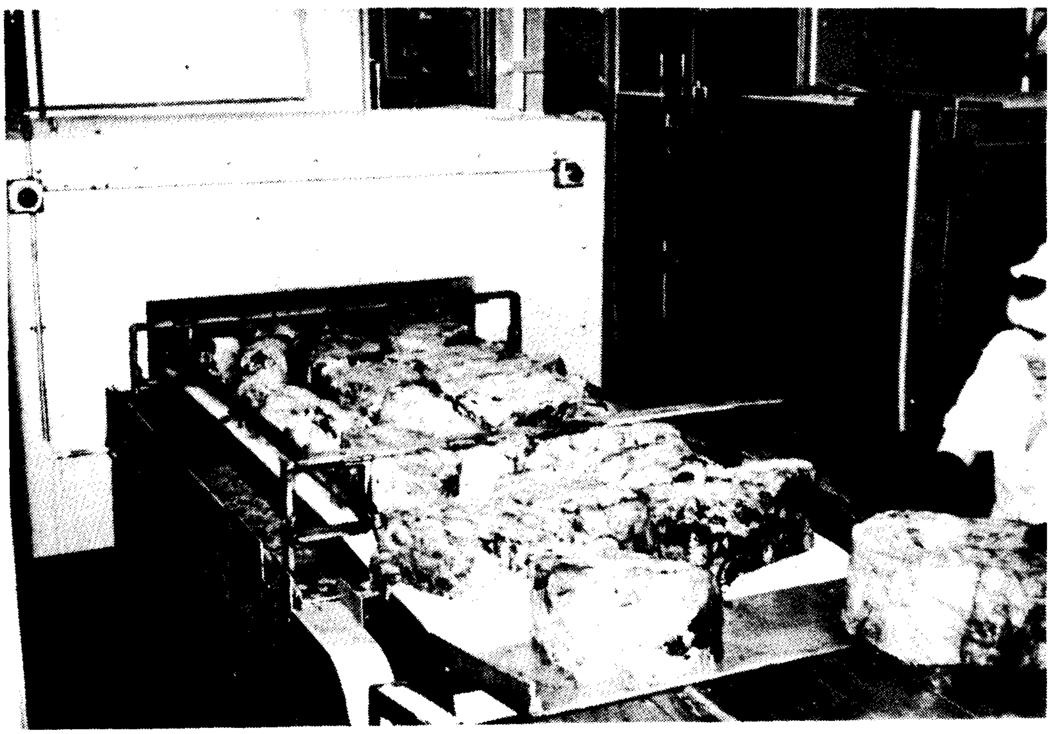


Figure 8-3 Meat is shown exiting from a dielectric thawing unit ready for further processing.
Photo courtesy of Radyne, Ltd.

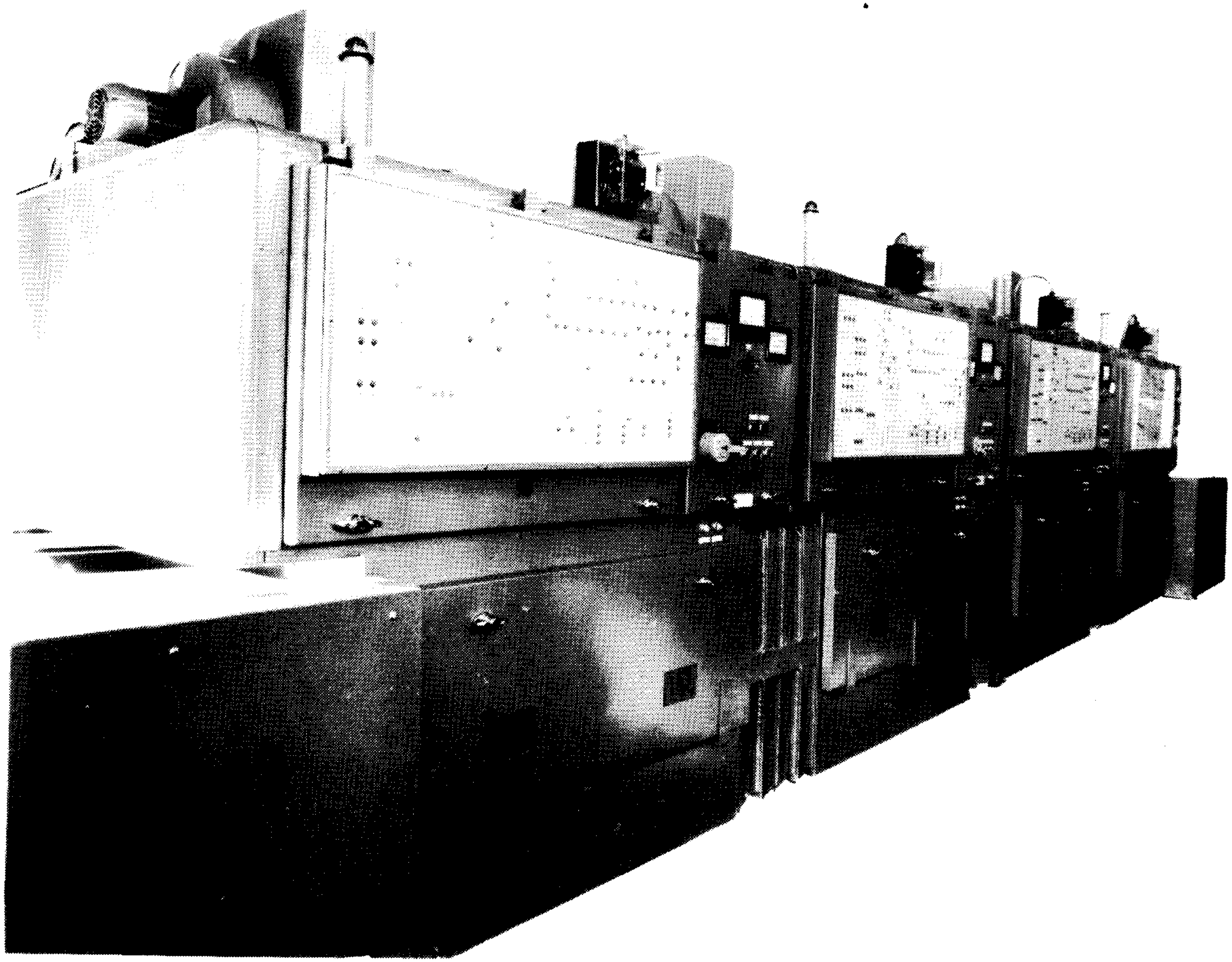


Figure 8-2 The four generators shown are arranged on top of a conveyor which is attached to a baking oven so the goods can be dried to the desired moisture content without danger of over browning them.
Photo courtesy of Radyne Ltd.

Fish Thawing

While most of the fish thawing units are installed on shore, some are installed on board fishing trawlers. This was done so that when fish were more plentiful than the on board cannery could process, they would be frozen. Later when cannery time was available, the fish would be thawed and canned.

The process is to place the fish in water filled plastic trays and pass these through a dielectric heater. The water is needed to fill the gutted fish to get a more uniform mass for heating. The trays are covered during this pass. The fish are then transferred to a water heating conveyor where it is carried back to the input end of the machine. This water comes from the dielectric generators with a little makeup water added.

For fish with a high oil content, the water immersion is not needed. A whole white fish is available for filleting about 100 minutes after the process is started. White fish fillets need about 50 minutes for thawing; high oil content fish may require only 15 minutes. One 20 KW generator will thaw between 400 and 800 pounds of fish per hour, depending on the characteristics of the fish.

ROLL FORMS

Nearly all paper and cloth is handled in roll form. Sometimes it is desirable to heat these materials in the roll form to remove the last vestiges of excess water or to cure a coating material. To ensure uniform heat the rolls are rotated during the heating process.

GENERAL

There are other applications of dielectric heat which have not been discussed because of proprietary considerations. If these are broadly interesting they will be made known before long. Heating cigars for moisturizing, putting the plastic parts on temple pieces of eye glasses, and puffing textiles to give them more bulk, are some that come to mind. Additionally, new applications are being developed for special reasons and these may not be disclosed at the time because of agreements between the ultimate users and the equipment manufacturer. It is safe to state that there are yet many undeveloped applications for dielectric heating which have great potential, but for which no one has desired to invest the venture capital in learning how to exploit them. The art of dielectric heating is not dead. Imagination and willingness to invest the time and talent to develop the new ideas will prove this in the coming years.

LIST OF MANUFACTURERS

The following companies are known to manufacture RF dielectric heaters for the applications in this section.

For addresses at the time of publication please refer to the section on acknowledgments.

IN THE U.S.

J. A. Callanan Co.

Cosmos Electronic Machine Corp.

Dimension Drying Inc.

Kabar Electronics Corp.

L. L. Machinery Co.

W. T. LaRose Associates

Mann-Russell Electronics Inc.

Nemeth Engineering Associates.

PSC inc.

Radio Frequency Company, Inc.

Raytherm, Inc.

Reeve Electronics

Rosenquist Inc.

SPECO Inc.

Thermex Thermatron

IN EUROPE

Bison Bahre & Greten

Robert Burkle GmbH

Colpitt B.V.

Flender-Himmelwerk GmbH

Herfurth GmbH

Paul Kiefel Hochfrequenzanlagen GmbH

Metau Impianti s.r.l.

Radyne Limited

Strayfield International

Thimonnier S.A.

IN THE FAR EAST

Tai-Yen Industrial Co., Ltd.

Yamamoto Vinyter Co., Ltd.

SECTION 9

ECONOMICS

INTRODUCTION

In previous sections the successful application of RF dielectric heating to a number of industrial processes was discussed. For these applications, RF dielectric heating has proven its economic value. Hence it is probably safe to apply it expecting similar benefits. But what if some of the factors differ in other plants? How should one evaluate RF dielectric heating for a new situation or even a new process? This section attempts to provide some guidelines to aid in evaluating RF dielectric heating for the specific situation facing a prospective user.

KNOW YOUR EXISTING COSTS

In studying the economics of changing equipment or processing, it is important that the costs of the present production methods be well known. It is sometimes difficult to find them because of interrelationships between machines within the plant. For example, the steam boiler may be used for several parts of the process and its operation must then be placed on the cost per pound basis, or some similar value. To arrive at these data it is necessary to consider labor, capital costs, maintenance, floor space, etc. or the costs determined will be unrealistically low. In comparing costs of a new process vs an old one, a comparison between the two cannot be made without accurate costs of the present methods.

EACH PLANT IS A UNIQUE SITUATION

The situations in individual plants control the costs and these situations differ from plant to plant. There are many costs which must be minimized including material, labor, overhead, capital, maintenance, utilities, space, pollution etc. Competing methods of manufacture enter into the economics equation and must be analyzed. Old equipment which has been "written off" will sometimes make a facility cheaper to operate. However, labor saving methods, energy efficiency, pollution, etc. inherent in the new methods and equipment often offset capital costs. Improvement in the quality of a product is also very important.

Each situation requires realistic consideration of all factors and careful analysis should be applied before deciding to purchase new equipment. Where information can be obtained, the experiences of competitors and others using similar equipment should be carefully analyzed also and included in all considerations. One purpose of this report is to provide information which will guide these deliberations. The factors mentioned below are the result of experience in evaluating the use of dielectric heating for many applications.

Not all products and processes which can use dielectric heating should use it. Most insulators can be heated or dried using high frequency heat, but for many of them the process has no economic advantages. In some situations the cost of manufacture may be raised rather than lowered. The capital costs, which are usually higher for dielectric heating than with other forms of heat, cost of fuel (electricity) etc. may be prohibitive. Each situation must be analyzed on its own merits before making the decision to buy.

ADVANTAGES OF RF DIELECTRIC HEATING

1- It overcomes heat transfer problems.

2- It provides preferential heating of wet spots and wet areas.

3- The speed of heating is greatly improved -- minutes in place of hours.

4- It reduces labor requirements.

5- It improves the quality of products.

6- It reduces pollution.

7- Presently installed dryers may be operated at higher speeds when dielectric heating is added to the existing dryer.

8- It improves thermal efficiency.

9- Drying uniformity is improved.

10- It reduces heat degradation of products.

11- Some products and processes are not feasible without dielectric heating.

12- It reduces floor space requirements.

13- Dielectric heating does not require the use of a hot oven to accomplish drying although a warm oven to carry away vapors may be useful.

14- Dielectric heating has been in use for nearly 50 years; experienced users can be found in many industries.

15- Either thick or thin materials may be processed in about the same time - more power is required for thicker materials of similar areas, however, due to the increased volume of material in the thicker pieces.

16- It can convert a batch type operation into a continuous process.

17- It can augment conventional heat particularly at the dry end of drying ovens.

18- There is no need to overdry certain areas in the material to make sure the wet areas are below a critical moisture content.

19- It provides reduced inventory of work in process and tooling.

20- In drying, overheating is deterred due to reduction of heat absorbed in dry materials plus reduced oven temperatures.

DISADVANTAGES OF RF DIELECTRIC HEATING

1- It usually has high capital costs.

2- Electrical BTU's are expensive.

3- Expensive components are used and will need occasional replacement.

4- Maintenance personnel may require some training. Generally this is not a major factor.

5- Special test equipment could be needed. This is more probable in large and high power installations.

6- All generators and applicators must be shielded against radio interference and to protect personnel.

7- The expense of RF dielectric heating may be more than the product can support.

8- If a conventional oven is already installed and operating satisfactorily, is the change worth it?

9- Operators and supervisors may require some learning time because of a new process.

10- Highly irregular shapes may heat nonuniformly in certain applications. In drying this is less of a disadvantage because the RF energy seeks the moisture

11- Certain products will not heat in a dielectric heating field. If the electrical conductivity is too high this will be true. Microwave energy might be a solution.

DISCUSSION OF ADVANTAGES OF DIELECTRIC HEATING

Overcome Heat Transfer Problems

Several advantages are derived from the ability of dielectric heating to overcome the heat transfer problems in insulating materials. This is the single most advantageous characteristic of the process. Because the heat is generated in the center of a material at the same time it appears at the surface, any heating process can be done faster than with conventional heat alone. Furthermore, dielectric heating does not require a hot oven to produce the speed; it is as effective on thick materials as on thin ones. Because of this, dielectric heating sometimes makes possible products and processes not otherwise feasible. It improves the characteristics of others. Also the surface characteristics of all products can be improved because very hot oven is not needed for higher speed.

Moisture Leveling

An additional set of advantages come from another characteristic of dielectric heat, namely, that it will deliver more power to wet areas within a material and less to the dry areas. This can result in a saving of floor space in drying operations because the "dry end" operation can be speeded up. If uniformity of moisture is important, as in paper or veneers for example, the fact that the moisture profile of the dried product will be much more uniform than with other dryers may be a significant economic advantage.

Uniformity of Heating

In preheating plastics, large preforms can be heated uniformly throughout, thus making the flow of material in the mold easy and uniform. There will be no precured pieces to block the flow of the plastic as it fills the mold or to mar the surface finish of the final molded product. Rayon thread will accept dyes more uniformly due to high frequency heating. The uniformity of heating causes the natural shrinking of the fibers in a cake to occur without uneven stressing.

In medium density fiberboard, and to a lesser extent in particle board, the density of the board is more uniform from top to bottom. This makes it possible for the board to hold a screw better, and the internal bond is stronger. In plastic welding, the die need not be so hot that the welded material will not cool properly while under pressure. Formerly the dies had to be heated, then cooled, then heated again to weld the next piece. With dielectric heating the dies can be cold and yet accomplish the weld.

In business forms, the uniformity of the resin cure avoids "tenting" of the continuous forms which can be caused by movement of the layers of paper due to incomplete curing of the glue. In plywood, the veneers have a more uniform moisture content and therefore lie flatter and bond more uniformly.

Paper coatings can be dried uniformly, leaving a flat sheet. Also water based inks can be used, thus avoiding pollution problems and costly recovery of spent solvents which, incidentally, can not be reused.

Rapid Heating And Drying

Many products can be heated or dried more rapidly, and with less inventory of work in process or tooling. Also it may be possible to convert a process into continuous or intermittently continuous operation in place of waiting a long time for a product to gain temperature in a hot room or oven. In sand cores for foundries, the cores can be baked in a few minutes and then used immediately. It is no longer necessary to wait overnight for a batch of cores to be baked as with old fashioned methods. This reduces the cost of core plates which are often needed to support the core in the green state. This same savings was found in the case of ceramic catalytic muffler bodies which must be placed on a carrier to support them as they dry prior to firing. Again, the time for drying was cut from hours to minutes thus saving in process inventory and floor space.

Augment Conventional Heating With Dielectric Heating

Whether to augment a conventional oven or to do all the drying with RF dielectric heat depends on several factors which may be unique in a given factory. These include at least the following:-

1- Is a conventional dryer already installed? If so, and if it is in good condition, adding RF dielectric heating is a good way to increase production with little, if any, increase in floor space.

2- Will the cost of electricity, usually higher per BTU than that for other energy forms, be offset by savings in labor, better speed, improved quality, savings in space etc? If so it may be economical to do the entire drying job with dielectric heating. If not, augmentation is probably called for.

3- In cases where the entering moisture content is very high, the moisture itself will aid in conducting the heat inward, thus offsetting one of the advantages of RF dielectric heating in the early parts of the dryer. Later, when the outside has completely dried, dielectric heating will be much faster than conventional ovens. This dictates augmenting the conventional dryer and putting the RF dryer near the outfeed end of the conventional oven where any ability to seek out the water, as well as heat throughout the volume, is best applied.

4- If the total heat requirement is very large, it is possible there will be little space savings over a conventional oven. Also, in some products, the rate of heat input can be so great the material will be ruptured internally. These products should be tested.

5- The capital costs of several very large generators may exceed that of more conventional ovens. Then, in cases where the moisture itself helps conduct the heat inwardly, augmenting the conventional oven is preferred.

Therefore, unless there is some special reason for raising the temperature uniformly and rapidly at the wet end, such as to set a resin, the high frequency dryer is often placed at the dry end of the line where it is more effective than conventional heat. Because the dielectric heating selectively favors the wetter areas of a material, this may reduce the length of a dryer as much as 25% for a given production rate. Conversely, it may be a method of increasing dryer capacity where there is no more space for additional dryers. Also, present dryers may be able to operate faster, if a high frequency drying section is added, because it is no longer necessary to over dry certain areas in order to get all the product below a critical moisture content.

In conventional drying operations, some flat products have a line of moisture throughout the midsections where the heat does not penetrate well because of the very good insulating properties of the dry materials. This is more obvious in drying wide sheets of moderate or high thickness. At the dry end of a conventional dryer the rate of removal of this center moisture is very slow. With dielectric heating the energy is delivered directly to the wet midsection where it moves the moisture toward the surface and out. Surprisingly, it has been observed that where conventional drying sections follow a high frequency dryer, they will dry more rapidly than those immediately ahead of the RF section because the center moisture was carried outwardly by the steam caused by the dielectric heater. These conventional dryers easily remove moisture from near the surface. At atmospheric pressure water expands some 1700 times as it changes from liquid to vapor! This great expansion can push liquid water with it, as there is insufficient heat to convert all the liquid to vapor simultaneously.

Reduce Material Deterioration

In drying textiles the time of residence in the high temperature is reduced from hours to minutes. This not only reduces heat deterioration of the product due to the shorter time exposure, but also reduces work in process inventory. Also, the oven need not be hotter than the dew point to remove only the moisture. Therefore the product is never exposed to high heat.

Reduce Floor Space

It has been found that often a dielectric heater will require less floor space than a conventional dryer. This is because of the greater speed of heating. An example is in warming bales of wool which have been transported across great distances in cold weather which solidifies the natural lanolin in the wool. In place of a warm room which will hold hundreds of large bales of wool (4ft.X4ft.X4ft and larger) and in which the wool must remain for days, a dielectric heater requiring only 1000 sq.ft. will be able to heat three bales in some 20 minutes. Again this represents a savings in floor space, energy, and inventory.

Good Thermal Efficiency

The thermal efficiency of a dielectric heater is quite good. Of the energy drawn from a power line approximately 60% will arrive in the product. In hot air ovens by far the largest amount of heat used is exhausted directly up a chimney.

Reduce Labor Costs

Labor costs are often lower with a dielectric heater than with other forms of heat. Some installations are equipped to operate completely unattended. These may have higher capital costs due to the automation which is included in the controls. Some installations share the operator costs with other machines or other parts of the process. In many applications only one operator is required to load and unload the dielectric heater and its associated press or conveyor.

DETAILS OF DISADVANTAGES OF RF DIELECTRIC HEATING

Admittedly, as with all products and processes, there are disadvantages to the use of dielectric heaters. It is well to know what they are to be prepared for them. In places where electricity is not very expensive, the fuel costs of a dielectric heater will be low and vice versa. If a plant has a well trained electrical maintenance force the new problems of the high frequency generator will not have the impact that it would in a plant with a poorly trained electrician, etc.

High Capital Cost

One deterrent to the installation of a dielectric heater is its initial capital cost. While there are exceptions to it having a high capital cost, such a situation is not usual. This will vary with the power rating of the generator, whether the generator alone is considered or whether the cost includes the applicator also.

Initial cost will vary between manufacturers of the equipment and the sophistication of the controls, the power output etc. An estimate might be between $1000 and $4000 per kilowatt of power output. This wide range will include the applicator for a rather low powered generator in a sophisticated process as the high side, to simple high powered equipment with a simple applicator on the low side. As with all buying, one should receive quotations from several sources. It is usually best to write a somewhat detailed specification which outlines what is expected of the equipment. This way bids can be compared. Alternatively the specifications can be supplied by the vendors, but should be sufficiently detailed that comparisons can be made.

Operating Costs

Another deterrent to dielectric heating can be the cost of electricity. However, be sure a comprehensive comparison of all fuel costs are made before determining that electric costs are too high. The thermal efficiency of a dielectric heater can be considerably higher than for other heating methods. This can offset the higher energy costs. Labor to maintain and operate the equipment should be included. A steam boiler may require an operator which would not be required if electricity is used.

Maintenance Costs

Maintenance could be a deterrent. The cost of vacuum components in the equipment is probably the most expensive single item because these components may wear out or burn out. The larger the generator the more expensive the components, of course. Tube life will vary with the generator and the tube type. Normally a tube will last many times its guaranteed life, which will be 1000 to 3000 hours of filament life. (The filament creates the light seen inside the tube and must always be on during use). The maximum tube life ever observed in the field is not known because after several tens of thousands of hours the records are not kept. Some tubes have lasted for years of operation. Others have had lives only slightly better than the guaranteed life, or even less in unique situations.

Similarly, vacuum capacitors, (usually used only in the high powered generators), have a definite life. Variable capacitors, used for adjusting the equipment to deliver full power under variable load conditions of the heating products, have a shorter life than fixed vacuum capacitors. This depends on the extent of adjustment and how often the adjustments are made.

It is well to have special test equipment available if a high powered generator is used. A high voltage tester is invaluable in determining whether a tube or vacuum capacitor is good. This is a somewhat dangerous instrument because of the voltages it can deliver and should be used by a trained electrician only. They are, however, simple to use. They cost between $1000 and $5000.

Because of the somewhat unfamiliar techniques used in high frequency heaters, maintenance personnel may be uneasy at first. The best thing to do is to have them work with the installer and become familiar with the location of all components. They also should study the instruction book which will often have special information about the high frequency circuitry and its maintenance. Usually there will be a special section on "trouble shooting" which will be helpful to a new electrician.

Shielding

Shielding must be designed with full consideration of the problems of the operators of the equipment. A simple shield can be a metal box totally enclosing the high frequency parts of an equipment. But if frequent access to the interior is required, access doors must be easily operated (sometimes automatically) to minimize the labor to open and close them as part of loading and unloading an applicator. Shielding can be designed and constructed so that all the necessary operations can be carried out without a loss of shielding effectiveness.

Maintenance of the shielding to prevent radio interference must receive constant attention. Sometimes it is completely ignored without peril. There is often a tendency for personnel to forget to restore a part of the shielding. If this occurs a dielectric heater could cause serious radio interference. The Federal Communications Commission, as well as OSHA, etc., have rules about the use of shielding. Generally, if all the originally supplied shields are in place and fastened with ALL the fasteners originally provided, shielding will not be a problem.

High Valued Product

Serious consideration should be given to the value of the product being processed in a dielectric heater. To be ludicrous but to illustrate, wet sand should not be dried with dielectric heating. It cannot be burned, it is very inexpensive, it holds lots of water, it is often very usable in the wet stage. However, more costly materials such as textiles, plastics, dinner ware, ceramics, insulation board, furniture, etc. have sufficient inherent value that dielectric heating makes good sense. The value of the materials is often enhanced with this type of heating, or other advantages mentioned above are present.

SUMMARY

The factors listed above are intended to guide a person considering the purchase or use of a dielectric heating apparatus. They indicate most of the factors which enter into the economical success or failure of an application. Most were taken from experiences gained in over 40 years of work in the field.

Because each plant has its own unique situation, definite cost information cannot be given. These will vary between plants and between their managers. The factors outlined above are all important under many situations that have been encountered. They can be used as a check list to make sure a thorough analyses is completed, particularly where the money involved is important to the economic well being of the company.

SECTION 10

CONCLUSIONS AND RECOMMENDATIONS

Since 1941, when commercial applications of RF dielectric heating started, it has been in daily use in increasing numbers. Some of the originally manufactured machines are being used today. While it preceded commercial industrial use of microwave heating by several decades, many uses receive no publicity because users often consider their application to be confidential. Surprise at its success in some places is sometimes expressed because of the secrecy in many applications.

Surprise may also be expressed at the reliability of dielectric heating machines. The more modern machines experience reliability factors exceeding 99% in modern factories where normal maintenance precautions are taken. Maintenance and production personnel generally find that any special procedures attributable to the high frequency aspects are readily understood. However, they find it necessary to develop some special insights to help them analyze problems quickly. Once these are learned, difficulties are minimal.

Most nonconductors of electricity can be heated by RF dielectric heating. Economic considerations prevent the commercial use of dielectric heating in many cases. However, economic conditions are subject to changes so that what was considered uneconomical a few years ago may now be successful. As is pointed out in several sections of this report, careful analysis of the conditions in a particular factory is needed before launching into a new field. Often they are successful if the situations are understood beforehand.

Many industries are presently users of RF dielectric heating as described in this report. Their successes are based on the technical foundations briefly described in the appendixes herewith. The economics have been acceptable in several environments and under factory production conditions. The illustrations herewith are but a few examples in specific factories. Details vary, even in the same basic application. Success should be expected in similar applications. New uses, adopted after careful economic study based on a proper technical foundation should be equally successful.

Machine operators may find the shielding surrounding an applicator can be annoying. But supervisors of departments, or entire factories, where dielectric heating is in use should be diligent in making sure the operator access problems are solved without removing shielding. This is essential in order to avoid interfering with communications services of all sorts.

When dielectric heating was in its infancy and before its limitations as well as its real strengths were known, there were many who predicted great things for it. Many of these predictions have worked out, but not without the normal learning pains required in any new field. Other great expectations, not based on thorough hard headed analysis, have long since been forgotten. This has been somewhat responsible for the skepticism about "RF" heating. Additionally, since some people feel they can build an oscillator to deliver high frequency energy without serious development work, poorly designed equipment has been sold.

Care should be exercised in selecting a dielectric heating manufacturer to be as certain as possible of his successful experiences in the field of interest. Check into his reputation by contacting some of his customers, if at all possible. Try to become acquainted with him, or his representative, and make a well thought out judgement as to his competence and willingness to stand behind his product.

The nearly five decades of experience with high frequency dielectric heating has proven its value as an industrial tool. That it will continue to be successful in new and better ways in the future is assured by the basic values of this type of heat for industrial purposes.

APPENDIX A

FUNDAMENTALS OF DIELECTRIC HEATING

This section will try to make clear the "how" and "why" of dielectric heating. Understanding them is not difficult but may require some study. The reward will be the ability to understand why things happen as they do and what might happen in new situations. Although some formulas are given, they need not be used unless it is desired to put numbers on the parameters to gain a better appreciation of their scale.

In the last part of the 19th century, investigators learned that dielectrics do not return all the electric energy imparted to them by an electric field. However, no practical use was made of this knowledge until just prior to World War II. By then the necessary components, such as vacuum tubes etc., had been developed which could provide enough power for heating to become noticeable. Early capacitors were found to get hot when high frequency currents were carried. Some of the heat was due to the resistance in the conductors; the balance was generated in the dielectric itself.

Investigators soon learned that the heat seemed to appear throughout the entire volume of a dielectric simultaneously. In the light of present knowledge, this is what would be expected based on the fact that an electric field penetrates throughout a dielectric whereas it stops at the surface of a conductor. Figure A-1 shows an electric field penetrating a dielectric (an insulator) whereas it does not penetrate a conductor.

It is this penetration of the electric field that makes dielectric heating so interesting. That the field penetrates the insulator should not be surprising. Everyone knows from experience that radio waves (which are electromagnetic fields) penetrate buildings although the steel structure, when present, tends to reduce their strength.

HOW DIELECTRIC HEATING WORKS

It is accepted today that all matter is made up of atoms and molecules. These are composed of electrons, protons and even smaller particles. In certain materials the electrons of molecules are strongly held, so that even in an electric field the entire molecule is electrically neutral. In other materials, the electrons are freer to move so that in an electric field one part of any particular molecule will have a slight positive charge on it while the opposite part will have a slight negative charge. The entire molecule is electrically neutral, but in an electric field it has a tendency to orient itself so the positive end tends to move toward the negative part of the field and vice versa.

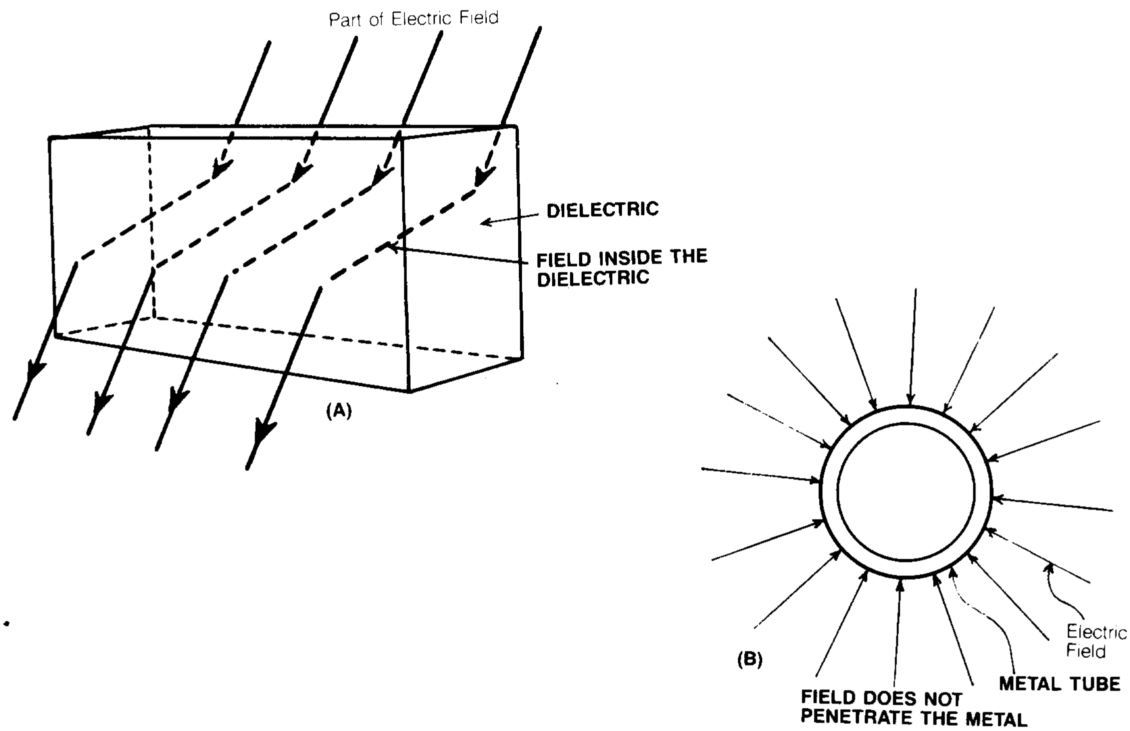


Figure A-1 An insulator and a conductor are shown immersed in an electric field. The field is represented by the fine lines sometimes called "lines of force." The change in direction as the field enters and leaves the insulator is known as refraction and is similar to the bending of light passing through a vessel of water. For a metal tube, all the lines of force terminate on the surface of the metal and do not penetrate it.

Molecules which can have slight positive and negative parts (and these comprise most of the nonconducting materials known) are called "polar" molecules because they exhibit polar characteristics, i.e. they can be "polarized" by an electric field.

Thus if a polar molecule material is placed in an electric field ALL the molecules will tend to be oriented so their positive ends face the negative part of the field, and vice versa. (See Figure A-2). Now, if the field is reversed in polarity, the molecules will tend to follow the reversal so as to turn to line up with the reversed field (Figure A-2 [B]). Again ALL molecules in the field have this tendency.

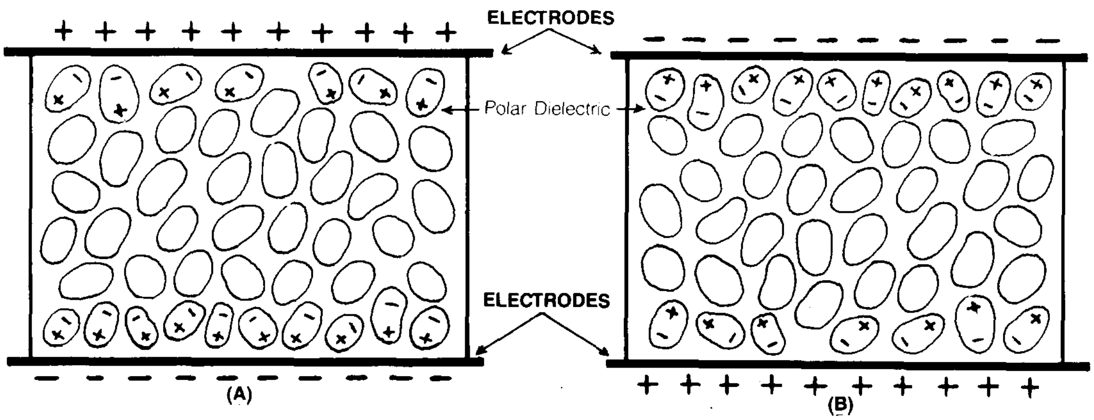


Figure A-2 All polar molecules in an electric field will try to rotate in synchronization with the field.

What will happen if the field is reversed at a rapid rate? The molecules will try to follow the field reversals and will become agitated. This molecular motion is exhibited as heat within the material. If the agitation is high, due to having a strong electric field (high voltage), the heating will be stronger. If the reversal of field takes place millions of times a second the agitation is more frequent and the heat will also increase. The important concept to remember is that ALL the molecules within the material that are exposed to the field will be agitated simultaneously - i.e. all the molecules receive heat from the field at the same time. The heat energy is derived from the rapidly reversing field which receives its energy from the generator of the voltage which sets up the field.

Various materials have varying degrees of polarity. A completely nonpolar molecule, i.e. one that will not be polarized in an electric field, makes the best insulator, particularly for high frequency voltages. It will not heat appreciably in a high frequency electric field. Teflon, polystyrene, certain grades of ceramics, polyethylene, silicone, and polypropylene, and other materials are all good insulators and mostly nonpolar. On the other hand, wood, rubber, vinyl, many other plastics, and textiles are polar to varying degrees. If a material has water in it, such as wet textiles, wet ceramics, etc. it is highly polar and heats very readily.

We have discussed the influence of the electric field (the voltage), the frequency and the polarity of the molecule on its ability to be heated by dielectric power. The ability of each material to absorb energy is defined as its dielectric loss factor. This is a unique property of that material. It usually varies with its temperature as well as with the frequency of the dielectric energy. The higher the dielectric loss factor the greater will be its heating rate in an RF heater of sufficient power. The dielectric loss factor can be expressed as the product of two other properties of a material, thus:

Dielectric Loss Factor = Dielectric Constant X Loss Tangent.

The dielectric constant is a measure of the energy storage capability of the material; the loss tangent is the ratio of the energy dissipation (or loss) capability of the material to its energy storage capability. These properties of materials are listed in the Chemistry and Physics Handbook, the Encyclopedia of Modern Plastics, and other handbooks. Table A-1 lists the dielectric constant, loss tangent, and dielectric loss factor for some common materials.

TABLE A-1

DIELECTRIC PROPERTIES

Material	Dielectric Constant (1 MHz)	Loss Tangent	Dielectric Loss Factor (1 MHz)
Epoxy Cast Resin	3.6	0.019	0.068
Melamine, Cellulose filler	5.8	0.046	0.27
Mica, Glass Bonded	7.6	0.0018	0.013
Nylon	3.5	0.03	0.105
Phenol Formaldehyde Wood Flour Filler	5.5	0.05	0.275
Polyethylene	2.3	0.0005	0.00115
Polystyrene	2.5	0.00025	0.000625
Polytetraflouroethylene	2.0	0.0002	0.0004
Porcelain	7.	0.012	0.081
Rubber	2.6	0.0014	0.0036
Steatite	6.5	0.002	0.014
Vinyl Chloride, unfilled	4.0	0.095	0.38
Water	80	----	----
Wood, Birch	5.2	0.065	0.338
Maple	4.4	0.033	0.0145
Oak	3.3	0.039	0.129

Material Adapted from various sources by the author.
NOTE: Values will vary with sources of information, temperature, frequency, moisture content etc.

THE DIELECTRIC HEATING EQUATION

The frequency, voltage, and material characteristics are all related by The Dielectric Heating Equation. This is written as:

$$P = 2\pi f E^2 C \tan\delta \quad \text{.......................} \quad \text{A-1}$$

Where

P = Power delivered to the dielectric in watts.

f = Frequency of the energy in hertz (cycles per second).

E = Voltage across the dielectric in volts

C = Electrical Capacitance in farads

$\tan\delta$ = The loss tangent of the material, a pure number.

The electrical capacitance, C, contains the physical dimensions of the material being heated and its dielectric constant. The relationship of these factors is:

$$C = \frac{0.224\ A\ K}{t} \quad \text{........................} \quad \text{A-2}$$

Where

C = Capacitance in picofarads (10^{-9} Farads).

A = Area in square inches

K = Dielectric constant

t = Thickness of the material in inches.

The equation indicates that the higher the voltage across the dielectric the greater will be the power delivered to the work. However, it is obvious that the power delivered to the work will be limited by the capability of the generator. Therefore, the voltage cannot be increased without limit unless the generator will supply the needed power. Also, the frequency has limitations, as does the voltage (discussed below), which are important in a practical dielectric heating situation. All the factors are interrelated and the limitations of each must be recognized. Within these bounds, the equation is important to the understanding of "what happens" when conditions have changed.

SELECTION OF VOLTAGE

Assuming the generator is sufficiently powerful to provide the energy needed, the voltage between the two electrodes (one is usually grounded) is limited by the creation of electric arcs between the electrodes, and from the electrode to the work material. These arcs can be damaging to the material being heated and to the equipment itself unless stopped exceedingly quickly. Therefore voltages should be limited to a value well below the arcing voltage of the system.

The design of the electrodes, and their maintenance, can be large factors in determining the arcing voltage. Another factor is the space between the electrodes and the work material; even the shape of the work material can be important in critical situations. Drops of water, which may fall from the electrode, can carry arcs with them if high voltages are present. Some materials have a greater tendency to arc than others. Homogeneity of the material can be a factor also.

Generally, sharp corners, particularly on the metallic surfaces of the electrode, must be avoided because they concentrate the field and cause arcing. A rounded surface having an appreciable radius of curvature is much preferred over a sharp point which has a very small radius of curvature. Thus, if an arc occurs, and it causes the surfaces of the electrode to become pitted and to have sharp points on it, the surface should be smoothed off with a file or sand paper to remove the sharp peaks. Dents are less of a problem. Be sure to wipe the area with a damp cloth to remove metallic dust.

SELECTION OF FREQUENCY AND SIZE OF ELECTRODES

Most dielectric heating is done at frequencies in the range of 2 MHz to 200 MHz. The lower frequencies are easier if used with high loss factor materials, such as wet glue; they are used for large objects such as are common in wood working applications. The higher frequencies are used in heating small loads, such as plastic preforms, where the low loss factors require them. In many countries the special "ISM" (industrial, scientific and medical) frequencies, which allow unlimited radiation within a narrow band, are preferred. The ISM bands in use for most dielectric heating are 13.56 MHz, 27.12 MHz, and 40.68 MHz. These frequencies are usually too high for large wood loads, however. The reasons for this are described below.

Equation A-1 above indicates that for a given power delivered to the load, the higher the frequency the lower the required voltage for equivalent power output. Raising the frequency, therefore, seems advantageous. This is true for loads whose dimensions are not too large. On large dimensioned products the voltage between the electrodes may not be the same at all points on the electrode. It will be higher toward those edges or ends of an electrode away from the point where the generator is connected (feed point). Equation A-1 indicates that the power delivered, and therefore the heating rate, will be proportional to the square of the voltage between the electrodes. Therefore for uniform heating at all points on the surface of the electrode it may be necessary to reduce the frequency so that the voltage is uniform at all parts of the electrode. (Lower frequencies have longer wavelengths which promote more uniform voltages across the electrodes).

To illustrate, if the voltage at the feed point is 95% as high as that at the ends, the heat at the feed point will be only 90% as high as at ends. This can be serious, although, as will be seen below, it may not be as bad as it sounds.

The question is: "How high a frequency can be used without too much difficulty with uneven voltages?" Stated in another way: "How large can an electrode and load be without uneven heating difficulties?" The safest path to take in deciding this is to consult with a manufacturer of dielectric heating equipment (see lists at the ends of sections).

To one seriously contemplating the use of dielectric heating, the "how and why" of frequency selection is of interest. The physical principles involved are scattered among several text books. They have been gathered together and are presented here with a minimum of detail. Sufficient background theory is necessary to understanding but it should not be found beyond normal understanding. Some facts must, of necessity to avoid complicating the discussion, be presented without proof where excessive details are needed for proof.

"Stubs", which are small inductances connected strategically along long electrodes, have more value than is usually acredited to them. They solve several problems including the one of achieving the required uniformity of voltage along long electrodes. Normally they do not require much adjustment throughout a wide range of load configurations although there are exceptions to this statement. The discussion below illustrates one example of their use.

"Wavelength" is a concept of measuring a distance which is inversely synonymous with "frequency". Its relationship is closely tied to the size of the electrodes or loads which can be processed and is therefore pertinent to the following discussions. Basically, the longer the wavelength the lower will be the frequency of operation. Per equation A-1 the lower the frequency the higher the voltage needed for a given power.

The following is offered as an aid to understanding frequency selection. It is also useful in understanding adjustment of stubs. This information is not known to be available as one discussion elsewhere. It should be used with caution, however. Usually the manufacturers will provide answers which are based on the following theory plus their own experience in these matters.

Electrodes which are not too wide will behave much like an electrical power transmission line having losses in it. At any frequency, if electrical transmission lines are long enough and do not have anything connected to them along the way, the voltage between the lines will rise as one progresses from the generator toward the open end. The reasons for this rise in voltage are beyond the scope of this report but they follow known logical physical laws. In a simple line situation the distribution of voltage will approximates a cosine function curve and it will be high in some areas and low in others as shown in Figure A-3.

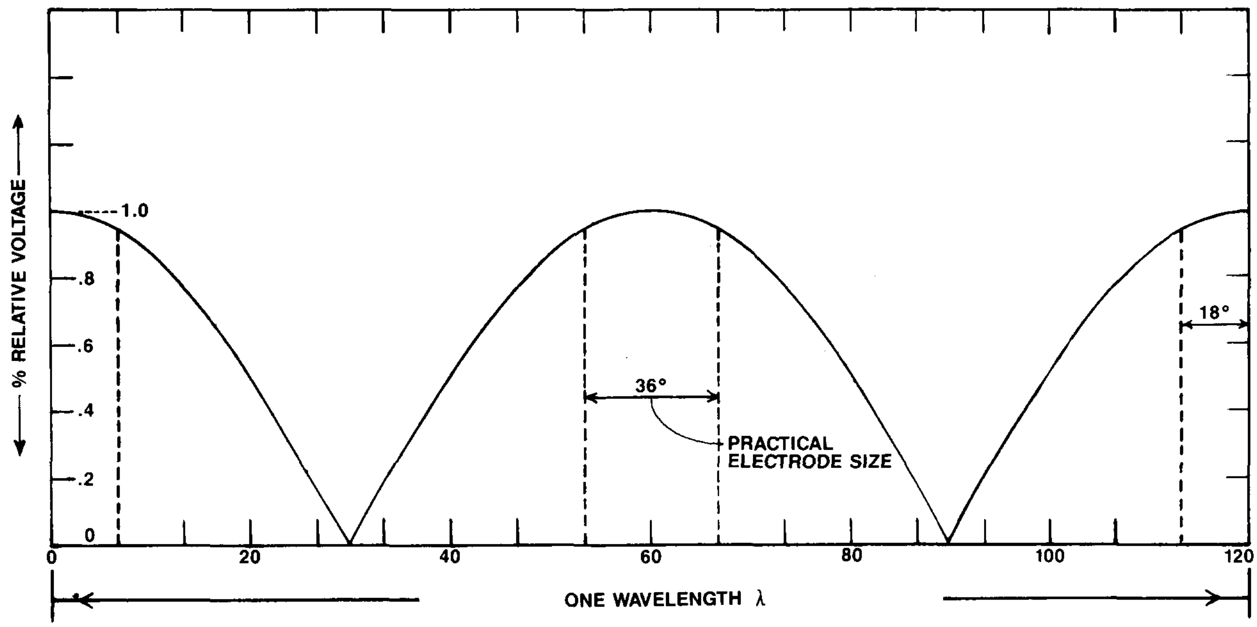


Figure A-3 Illustrates the voltage along a long transmission line (which is similar to an electrode system). The figure illustrates a line (electrode) which is a full wavelength (λ) long.

If the line length is a full wavelength long (the length in feet will depend on the frequency selected, see Table A-2), starting from the open end the voltage between the lines will drop to nearly zero, increase again to full magnitude, and drop to nearly zero again, and then will rise to a high value again. Figure A-3 illustrates this. Such large excursions are totally unacceptable in a dielectric heater where the voltage should be nearly equal at all points on the electrode. A practical electrode system, then, can be only a fraction of a wavelength long. A wavelength is said to be 360 degrees long, so a practical dielectric heating electrode can be only a few degrees long. This is illustrated as the space between the dotted vertical lines, and from a dotted line to the ends in Figure A-3. Table A-2 shows the wavelength, in feet, and the length, measured from the feed point to an end, which will keep the voltage above 95% of maximum at any point between two electrodes for various frequencies.

Table A-2

ELECTRODE LENGTH AND WAVELENGTH vs FREQUENCY

Frequency	Wavelength Ft.	Unstubbed Electrode Length for 95% Minimum Voltage
60 Hertz	16,404,200'	820,200'
1 MegaHertz	984'	49.2'
10 MHz	98.4'	4.92
30 MHz	32.8'	1.64'
100 MHz	9.84'	0.492'
2450 MHz	0.401'	0.020'

The figures in Table A-2 are for an electrode with a dielectric constant nearly equal to 1 and for unstubbed electrodes. For materials having higher dielectric constants the above lengths must be reduced by $(K)^{.5}$ (see equation A-2 for definition of terms). At least to a first approximation, the overall dielectric constant must include the effect of the air gap, if any, between the electrode and the material to be heated as well as the dielectric constant of the material to be heated.

The lengths given in the right hand column of Table A-2 are measured between the feed point, where the generator is connected to the electrode, and the electrode's end. The critical distance is the distance a voltage wave must travel from the feed point to the end of the electrode. Therefore, if the feed point is located in the center of the electrode (the electrode is center fed) where the wave can travel toward both ends simultaneously, the total length can be twice that given in the table because the voltage can rise from the center to each end and yet remain above the targeted 95% figure. Figure A- 4 illustrates this.

There are dielectric heating applications where the voltage need not be so closely controlled at 95% or better. For example, in a drying operation the loss factor of the load decreases markedly when the material becomes dry. In this case, a region of higher voltage may become dry before a region of lower voltage, but the rate of heating at the high voltage region will be reduced because of the lower water content. This gives the lower voltage areas a chance to "catch up". If a wider voltage variation can be tolerated, the length of the electrode can be greater. For example, if the minimum power can be 80% of maximum, the length can be about 50% longer than those given in table A-2.

Where a conveyor is being used, the voltage control along the length of the conveyor is less critical than across the conveyor. As the material on the conveyor passes from a region of high voltage to one of low voltage the heating rate may go down but all locations on the conveyor will receive the same amount of heat as they pass the same locations. Conveyorized equipment will, in this way, mask voltage variation problems. However, the variations from side to side are important as they will not be masked by the motion of the product.

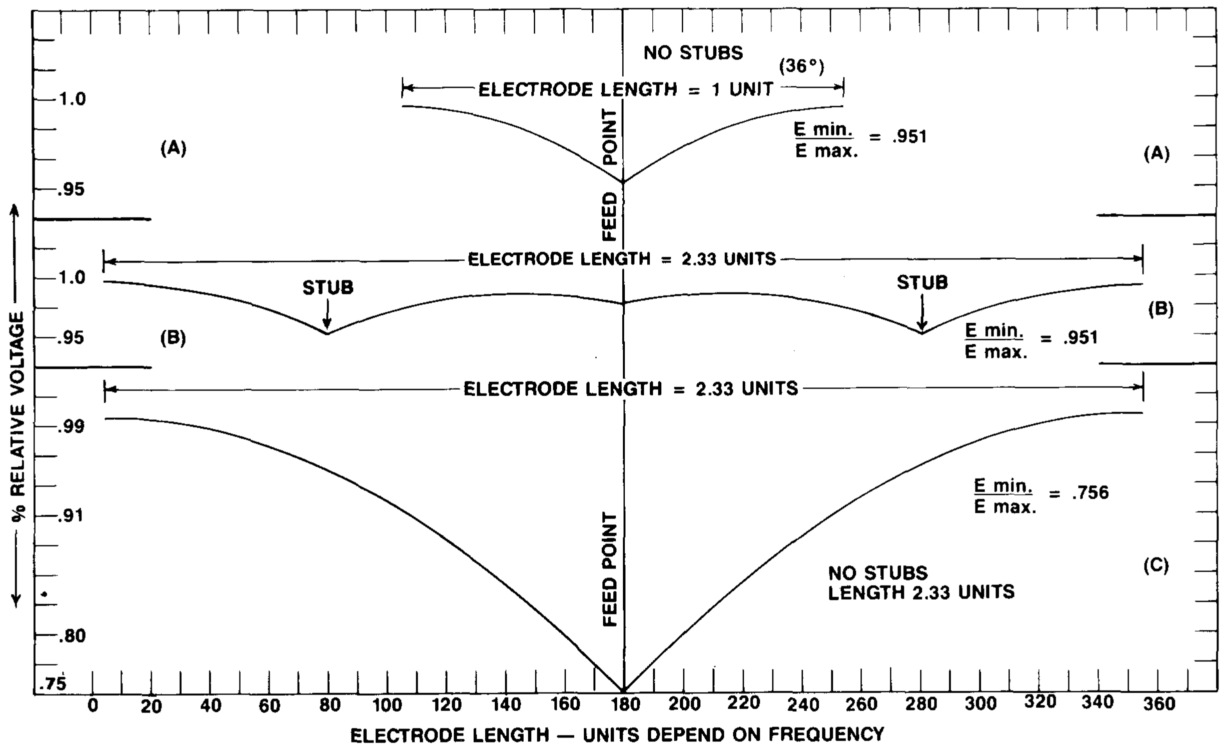
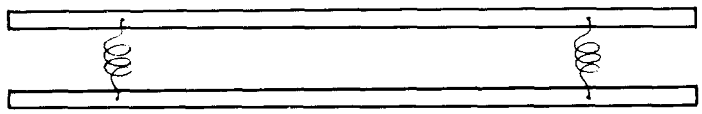


Figure A-4 Illustrates the voltage distribution on a short center fed electrode system. Note the similarity to the center part of Figure A-3 between the dotted lines. The three parts of the Figure A-4 (A), (B), and (C), are all drawn to the same horizontal scale. (A) shows an unstubbed electrode of maximum length to keep the voltage above the 95% level. (C) shows the same figure , but the length is 2.3 times as long. (B) shows an electrode 2.3 times as long as (A) but with stubs to control the voltage distribution (see the discussion of "stubs").

STUBS

In practical industrial situations it is necessary to process large sized loads at fairly high frequencies. This can be done through the use of devices called "stubs". These are merely inductances, of the proper value and number, to reduce the voltage variation along an electrode system (See Figure A-5).



PARALLEL PLATE ELECTRODES WITH 2 STUBS

Figure A-5 Schematically illustrates stub connections to a parallel plate electrode.

The voltage will be lower where the stub is connected; the lower the inductance the lower will be the voltage at that point. Figure A-4 (B) illustrates the electrode voltage on a center fed system with stubs placed near the ends. Notice that the electrode is considerably longer than without the stubs. For comparison purposes Figure A-4 (C) shows an unstubbed electrode the same length as in Figure A-4 (B). Note how the stubs control the voltage distribution.

Very often stubs are merely wide copper or aluminum straps connected between the electrodes. They have the appearance of being short circuits, but because of the high frequency (some 500,000 times that coming from the power lines) the straps are really inductances and are far from being short circuits. Often they are adjusted by the manufacturer and can be left there. Where a very wide range of loads must be accommodated, it may be necessary to adjust the stubs at the extremes of the range and there will be a wide range of loads at which either adjustment will serve. Usually a stub near each corner of the electrode will be sufficient; for very long electrodes intermediate stubs may be necessary. Their actions are similar to that illustrated and discussed above.

Stubs provide a secondary (sometimes the only) function. That is they adjust the electrical characteristics of the load to that which the generator needs for full effectiveness. This is the only function of a stub located at the point of feed of the electrode.

The width of an electrode can also be troublesome for higher frequency operation. The same basic principles apply. However, a little consideration will bring the realization that stubs can be used only at the edges of the electrodes; there is no way to put a stub and any other place across the electrode. This limits the maximum width of a product or the maximum frequency which can be used.

While similar phenomena occur on other types of electrodes (see Appendix C) the magnitude of the effects may not be simple as discussed above. A wide electrode, for example, will not necessarily approximate a cosine distribution of voltage in both width and length directions. In a stray field electrode system none of the dimensions given in Table A-1 apply. They will be considerably too large and must be reduced by and amount that is determined empirically. If the stray field electrode is located on only one side of the web so that stubs can be placed between electrode rods as well as along the electrode, better uniformity may be obtained than if the stray field has an electrode on both sides where the only location for the stubs is at the edges.

In summary there is a limitation to the maximum frequency which can be used - particularly for the larger stray field electrodes.

NONHOMOGENEOUS MATERIALS

Some materials are made of a mixture of several ingredients. Sometimes the ingredients have quite different loss factors; other times one ingredient may absorb more moisture than others and thus have a higher loss factor. These possible nonuniformities, if present, will result in uneven heating throughout a product. While this may not be serious, at times it can be particularly noticeable if a material is overheated for some reason. For example, in wood products, a knot in a piece of pine is likely to have more rosin than other points and may heat more than the rest of the wood. Thus the first thing to burn would be a knot. In products made with clay fillers, the clay may hold more water than other ingredients. This can cause some overheating; it can also cause a concentration of the electric field at those points and may result in arcing.

Total uniformity throughout a material is generally not necessary for successful dielectric heating but stubs can help. However, excessive concentrations of certain materials also can cause heat distribution difficulties and sometimes care must be taken to try to maintain degree of homogeneity.

MOISTURE LEVELING

The moisture leveling characteristic is a beneficial example of nonhomogeneity in materials. For a given moisture content, a material will have a certain dielectric constant and loss factor. The loss factor will be higher where the moisture is higher. A higher loss factor results in a higher heating rate, other factors being held constant. Raising the temperature also increases the loss factor, and the heat input increases. As the moisture is evaporated the loss factor will drop and the rate of heating will drop also.

Given a nonuniform moisture distribution in a product, the rate of heating at any point will depend on the loss factor (controlled by the moisture content) at that point. Thus, a spot of high moisture, and therefore of high loss factor, will receive a higher amount of energy than an area of low moisture. This will cause the high moisture spots to heat faster and the moisture to be evaporated at a higher rate. Hence moisture will be evaporated from that (formerly) high moisture spot faster than at other spots. When the moisture content reaches the same level as at other spots, it MAY continue to heat somewhat faster because it may be somewhat hotter. However, soon it will have a lower moisture content than elsewhere and its heating rate will be reduced. Thus, as the moisture is being removed from the entire material, the originally wetter spots will be the first to be reduced in moisture until they are equal to or somewhat below the originally dryer spots, and the moisture content of the entire volume is made more uniform. This automatic moisture leveling characteristic of dielectric heating is most important in many drying applications.

APPENDIX B

SHIELDING

WHY SHIELDING IS NECESSARY

As appendix A of this report indicates, the frequencies normally used for dielectric heating are in the range of 2 MHz to 200 MHz, with the lower frequencies normally being used for the larger loads. These frequencies are also used for radio communications, which legally have priority over dielectric heating. As all countries, the U.S. has an agency, the Federal Communications Commission (FCC), to regulate the use of all frequencies of the electromagnetic spectrum for civilian use. The National Telecommunications Information Agency (NTIA) of the Department of Commerce has this responsibility in the U.S. for governmental uses.

The rules vary from country to country. In Europe the countries are geographically rather small, but the populations are relatively large, whereas in Australia the opposite extreme is found. These create differing problems and therefore differing regulations of communications and the uses of the electromagnetic spectrum.

Many dielectric heating installations have higher power capabilities than any communications transmitters. The largest U.S. AM broadcast station is only 50 KW, and large TV stations are around 25 KW. For TV stations a high gain antenna is used to direct the signal down toward the receiver; these stations are rated in "effective" radiated power. By contrast, dielectric heaters have power capabilities of from 1 KW to 1500 KW. This concerns communications interests, who feel that such high power may disrupt their communications. In all countries, rules have been made to govern the allowable radiation from dielectric heaters, sometimes called ISM (Industrial, Scientific, and Medical) devices. The power they are legally allowed to radiate is measured in milliwatts, (thousandths of a watt) rather than kilowatts (thousands of watts). The ISM equipment are allowed only one millionth of the radiation from even a small broadcast station. Therefore shielding of a dielectric heater to avoid radiation is essential in all installations.

While it is true that a dielectric heater is intended for heating and that efficient operation requires that all the power be delivered to the load (radiated power is lost heat), most users are happy to find 99% of the generated power showing up in the load as heat. But if the generator is capable of 50 KW, this means that the radiation is 0.5 KW, or 500,000 milliwatts! Therefore, shielding must not only be present, but it should be well designed AND MAINTAINED.

In addition to the FCC, which is primarily concerned with the protection of communications interests, there are at least two other governmental agencies concerned with electromagnetic radiation. These are The Occupational Safety and Health Administration (OSHA) and the Center for Devices of Radiological Health (CDRH), formerly known as the BRH. The former is part of the Department of Labor; the latter is part of the Food and Drug Administration. They were instructed by the U. S. Congress to formulate rules to protect personnel against possible harmful effects of electromagnetic radiation of the nonionizing type. The limits of radiation set by them also require well maintained shielding as an essential part of all dielectric heating installations.

International pressures, as well as internal pressures from our own governmental agencies, have caused the FCC to seriously consider reducing the allowable limits of radiation from dielectric heaters (ISM devices). It seems probable that future shielding requirements, and enforcement, will be more restrictive. This adds emphasis to the importance of shielding dielectric heaters.

DEFINITION OF A SHIELD

A Shield is merely a metallic box surrounding the parts of the equipment having high frequency voltages and currents. The best shield is a watertight welded box with no openings. Obviously such an enclosure is impractical for any use. Actually it need not be completely watertight, but it must have excellent conductivity between all parts of the box so that currents which are present in significant amounts on the inside walls can flow freely. Any gap in the box, such as caused by a loose screw, can permit leakage of a small amount of energy. Many such gaps can add up to excessive radiation. Recall that only one millionth of the power capability of a generator is legally permitted to escape!!

Formidable as this may sound, good shielding is not really difficult to construct. Care must be taken that it does not interfere with the movements of the machine operator. Furthermore, the shielding is best constructed of a low alloy aluminum because of the need for good contact between panels. Sufficient fasteners are essential.

THEORY OF SHIELDING

The most often puzzling, and perhaps ignored, aspect of any cabinet containing electrical parts and wiring is that there are currents flowing on the interior surfaces of the box even if the box is not connected to the circuit! At 60 Hertz these internal wall currents are very small. However, at frequencies that are 33,000 to 3,330,000 times higher than power line frequency of 60 Hertz, the interior surface currents can be measured in tens of amperes. The following explanation will illustrate how this can occur.

Figure B-1 shows the cross section of a metal room (box) with an insulated metal table inside. A battery is shown under the table arranged so it can be connected between the table and the floor.

Before any connection is made, the positive and negative charges on the surfaces of the walls, ceiling, and metal table are equally distributed.

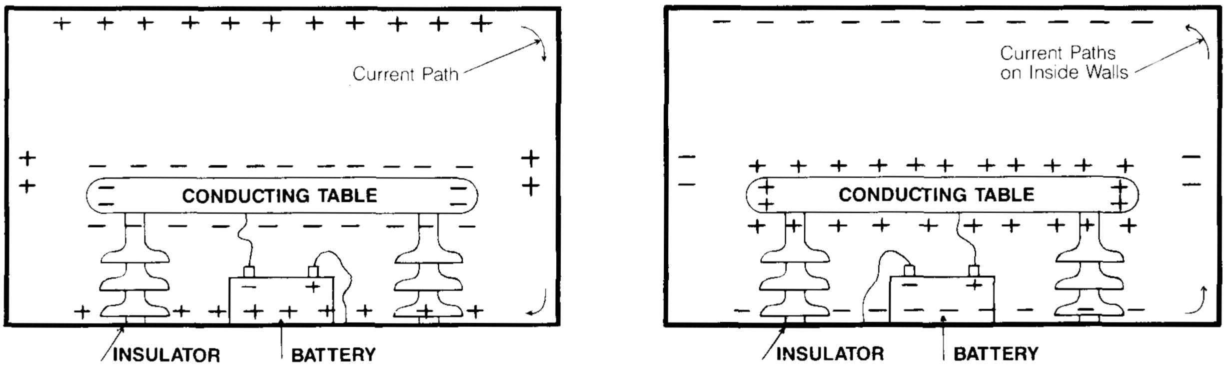


Figure B-1 Cross Section Of A Metal Room With An Electrically Charged Insulated Table

If the positive end of the battery is now connected to the floor, and the negative end to the table, there must be a redistribution of electric charges so there are more negative charges on the table and more positive charges elsewhere - mostly on the ceiling above the table, the floor under it, and in the walls opposite the table. These charges are held in this abnormal distribution by the voltage in the battery. But for the very short interval of time when the redistribution of charges occurred there was a slight current flow in the walls. An interval of 1 cycle of high frequency is measured in fractions of a millionth of a second so a microsecond (1 millionth of a second) is a significantly long time in terms of dielectric heating.

Reversal of the battery terminals will cause another redistribution of charges on the interior surfaces and the table and, therefore, another short interval of small current flow in the walls. These same short-interval currents will occur each time there is a reversal of battery polarity. Therefore, if the battery terminals are reversed many times a second, say 27.12 million times a second, there will essentially ALWAYS be a current flowing in the walls of the metal cabinet.

These currents cannot be avoided. At high frequencies they are greater than at power line frequencies. They must have a path through which to flow. If the path is interrupted the currents may find their way through the slot of the interrupted path to the outside, and then back to the inside. These external currents will cause radiation of energy which, of course, is undesirable as well as illegal.

CONSTRUCTION OF A GOOD SHIELD

It is necessary to have access doors and panels in any practical enclosure. Sometimes it is necessary to have a conveyor to carry products into and out of the shielded area. How is a shield constructed to provide the needed conductivity and yet provide the strength and accessibility needed for any machine? There are certain basic principles which are not difficult to follow and which will lead to an adequate shield design.

It will be seen that a shield is not just any old metal box. Such shields have been constructed, but they usually lead to operator complaints and to removal of the annoying parts by the operators or their maintenance personnel. Removal of any shield part usually results in an illegal installation because of excessive radiation.

The Basic Considerations For A Good Shield

To summarize, the basic considerations for a good shield include:

1- Avoid situations which impede the flow of interior currents. This usually requires a welded cabinet if steel is used (paint used to avoid rusting will not conduct currents where panels overlap). The use of aluminum as the material of construction is preferred if the overlapped joints are not painted. Nonmagnetic stainless steel is also a good shield, though more expensive than aluminum. Painting anywhere in the cabinet except in areas of electrical contact will not harm the shield.

2- Use sufficient fasteners for mounting doors and access panels to ensure good current paths between panels. Fasteners should be spaced not more than 3 to 6 inches apart. Shorter spacings may be necessary for the higher frequency equipment [See Figure B-2 (A)].

3- An alternative to many fasteners is to use flexible conductive materials between panels, or between doors and their frames, so that the gaps that occur between neighboring panels with widely spaced screws are filled with a conducting material through which the currents may readily flow [see Figure B-2 (C) and (d)].

4- Windows should be covered with aluminum or stainless steel having small holes punched in it to permit viewing and also to permit currents to cross the window openings. It is usually wise to paint the outside of the perforated metal a flat black color to avoid reflections from room lights PROVIDED the areas of contact with the cabinet walls are NOT painted [See Figure B-2 (B)].

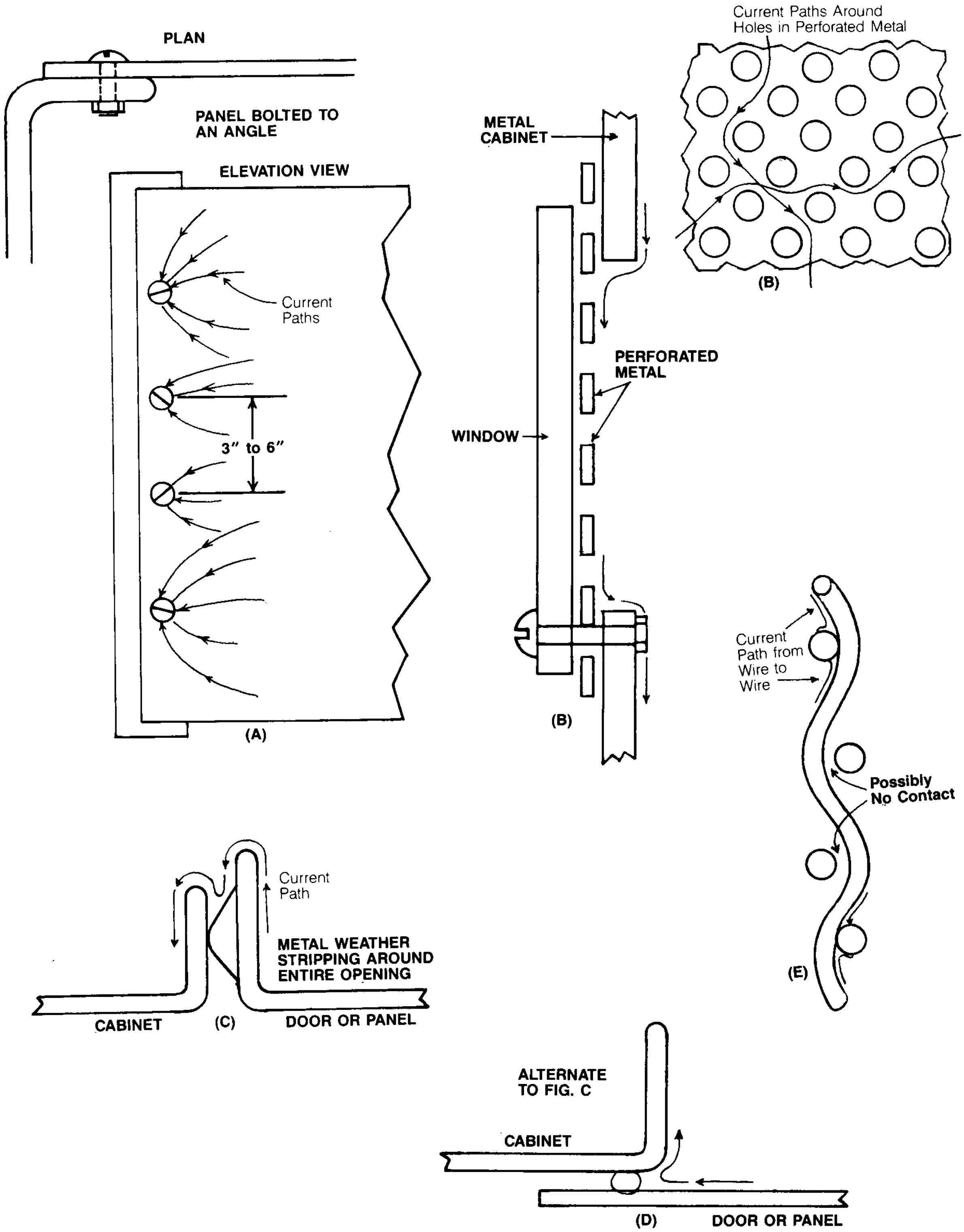


Figure B-2 Examples of Good Shield Contact Construction

5- Ventilation openings should also be covered. If a ventilation duct, for the first length which is at least as long as three times its largest cross sectional dimension, is made of a good conducting material which will not rust, and if this duct makes excellent contact with the cabinet, no screen may be necessary (See Vestibules below).

6- Occasionally, contact surfaces between panels may be treated with a good conducting material, such as copper plating. Paint may then be used over the rest of the metal cabinet provided the copper plated contact surfaces are not painted. The copper plating should be at least 0.001 inches thick.

7- Any pipe or conduit entering the enclosure should be well bonded to it. The best bond is a typical "floor flange" but often a very short ground strap between the metal of the conduit and the inside of the cabinet will suffice. Voltages picked up by the pipe while inside the enclosure must be short circuited to ground before it leaves [See Figure B-3 (A) or (B)].

8- Hoses carrying air or water, if of small diameter, may pass through the cabinet without special treatment if the generator operates at the lower frequencies. Be sure the hoses have no metal in them. Larger hoses may require a short "vestibule". Internally the metal pipes should be well connected to the interior of the cabinet near the exit hoses so that liquids will not conduct the high frequency energy to the outside of the cabinet.

The most important consideration in the design and construction of a shield is the contact between shield parts. Thorough consideration of this factor can not be too highly emphasized. That is why windows must be screened and doors equipped with some sort of contact material to fill the gaps between fasteners. For conveyors, and other large openings, "vestibules" are helpful. (See Vestibules, below). This also emphasizes why good maintenance of shielding is so important. An excellent shield design can be completely ruined by carelessness even though nobody will notice any difference in the operation of the equipment.

Figure B-2 shows several examples of good shield contact construction. The small arrows indicate the approximate current paths. The exact paths are very difficult to determine and they depend on the geometry of the components inside the shield and the voltages on these components.

Figure B-2 (A) shows two panels bolted. Note that the currents must crowd together at the fasteners. If the fasteners become loose and are made of steel, the bolts may become red hot and even melt holes in an aluminum panel they are supposed to fasten. Three inches to six inches spacing between bolts is a good interval, except for frequencies approaching 100 MHZ where spacing should be closer. Maintenance personnel should be instructed in the importance of replacing ALL the panel fasteners; just the number of fasteners required to mechanically hold a panel in place are not enough for good shielding purposes.

Figure B-2 (B) shows the current paths around windows with the perforated metal. Note the shield is in contact with the cabinet; the transparent part of the window is either outside of the cabinet, or (as shown) on the inside of the perforated metal. Use of woven bronze or aluminum screen is better than nothing, but the contacts between wires crossing perpendicular to each other may not be good, causing a diagonally flowing current to find a circuitous path which will probably be one having high resistance [Figure B-2 (E)]. Hence the perforated metal is preferred because there are no contacts between wires to become corroded.

Figure B-2 (C) shows a method of including some "weather stripping" between the door and its frame. Note that the contact pressure is present even when the fasteners are not loose. This type of design permits doors having single opening handles and yet it provides good contact. The doors may be somewhat difficult to open and close due to the friction of the "weather stripping", but the design provides excellent shielding for openings.

Figure B-2 (D) shows another method of handling the contact material for doors. A metallic mesh material is fastened into a groove in the door or the frame to provide the flexible contacts between. This construction does not provide the contact pressure automatically, but depends on the door being sufficiently rigid for good pressure to occur even with a single point door handle. Such construction seems successful, but requires good maintenance to make sure the contact material does not become burned due to high currents.

INTRODUCING PIPES INTO SHIELDING.

Metal pipes, if not well connected to the cabinet, can carry small amounts of energy out of the cabinet. The pipe, which continues throughout the interior of the building, can act as an excellent antenna and therefore radiate any energy it may have picked up inside the cabinet. Energy can also transfer from one pipe to another even though they are not connected together, if they are in close proximity to each other.

The best way to avoid radiation from building pipes is to keep energy from getting out of the shield. This is done by providing a conducting path from the pipe to the cabinet interior. Figure B-3 (A) illustrates a pipe flange used for this purpose. The threads of the pipe make good connection to the flange, and the flange can make good connection to the cabinet if any intervening paint is removed at the point of connection. The flange surrounds the pipe and has several bolts holding it to the cabinet.

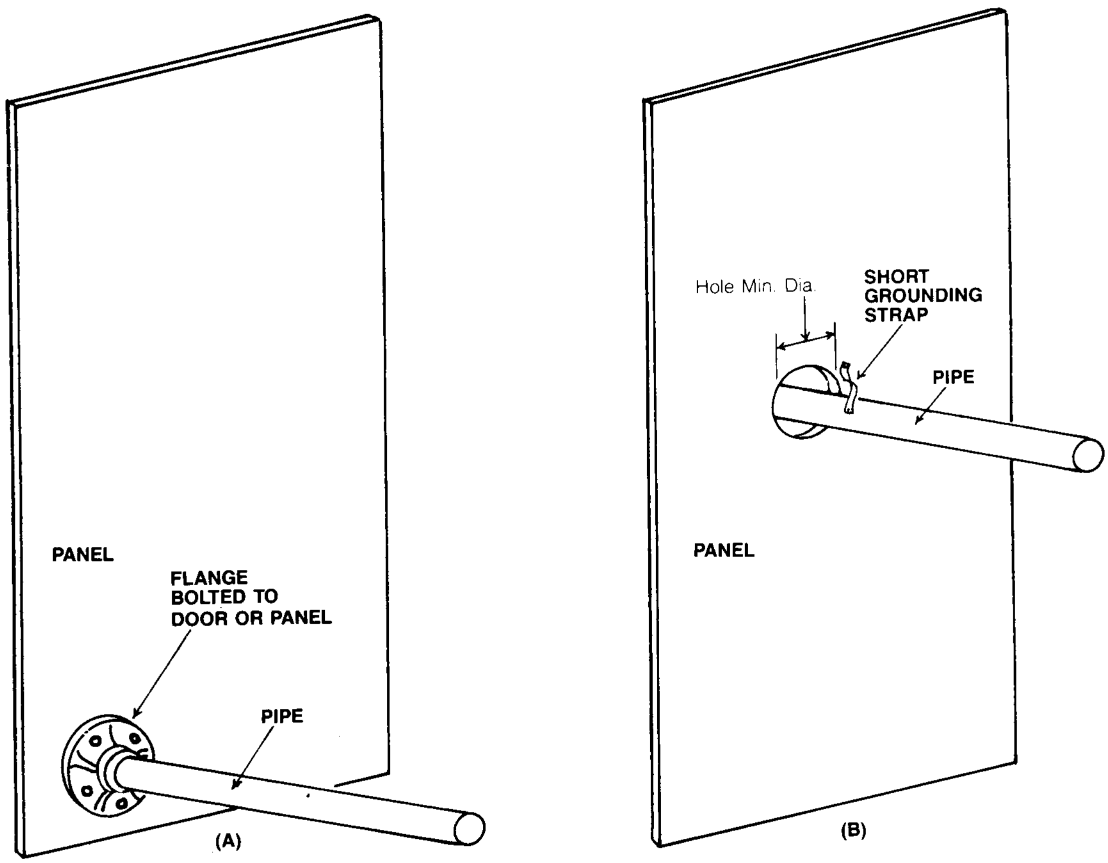


Figure B-3 Methods Of Introducing Pipes Into Shields

An alternative method, not as good but often adequate, is illustrated in Figure B-3 (B). Here a short piece of heavy wire (heavy to withstand the mechanical wear and tear) or a metal strap is well bonded to the pipe as by welding or soldering and subsequently connecting to the cabinet using as short a length as is possible. A piece of wire, at the frequencies 33,000 times those normally used in power lines, is not a short circuit but an inductive lead. The larger and shorter the wire, the closer to a short it becomes; inches of excess length can be important. If a wide strap is used in place of the wire an improvement in bonding will be obtained, and the ultimate is to use a flange as mentioned in the foregoing paragraph.

Water is a conductor, though not a good one. Non conducting hoses, WITHOUT METAL REENFORCEMENT in them, can be used to pass water, and air, through a cabinet. The diameter of the hole should be minimized or a vestibule provided. Because water can conduct electricity, the metal pipes inside the cabinet should have as much energy short circuited to the cabinet as is possible. This should be done near the exit hole to minimize additional pickup of energy on the pipes beyond the grounding connection. Having accomplished the grounding, the normal impedance of the water inside the hoses may be sufficient to avoid appreciable radiation.

The installation site of a dielectric should be selected to be free of nearby pipes and wires as far as is possible. Long metallic objects, even building structures on occasion, can act as good antennas because their lengths happen to resonate at an operating frequency of the high frequency machine. All pipes should be kept well away from the dielectric heater. Preferably incoming water and power should come underground or exit the area quickly. Telephone wires or paging system wires can also be a problem if they are near a radiating dielectric heater. Here is where precautions to avoid cabinet leaks is of maximum importance.

VESTIBULES

As was mentioned above, if the internal currents (shown dashed because they are on the inside of the cabinet) do not find a direct path across an opening, they must detour around it. They will take the easiest path, and in the case of a large opening this may be on the outside of the cabinet as well as on the inside. If the "outside" path is also shielded so that the currents cannot get all the way to true outside surface no radiation can escape. Figure B-4 illusrates such a situation.

Figure B-4 shows the end of a conveyorized dielectric heater. Because the current paths are inside the cabinet they are indicated by dashed lines. Note the large opening in the main cabinet. The direction of flow of the major part of the current would force currents outside the cabinet were it not for the vestibule extensions. These extensions provide a path for the flow of the currents without permitting them to get outside the cabinet. This avoids much of the radiation which would otherwise escape if the vestibules were not present.

If the vestibules are too short the currents will flow outside and radiate. Also, the narrower the vestibule the better it will shield. There are two reasons for this. A narrow opening will radiate less energy than a wide one. But more importantly, if the vestibule is wider than a half wavelength the currents will find easy ways to get out. Any tube of metal will have a "cutoff" frequency below which it will not allow radiation to escape into space. This is a fundamental property of any waveguide and a vestibule is basically a wave guide.

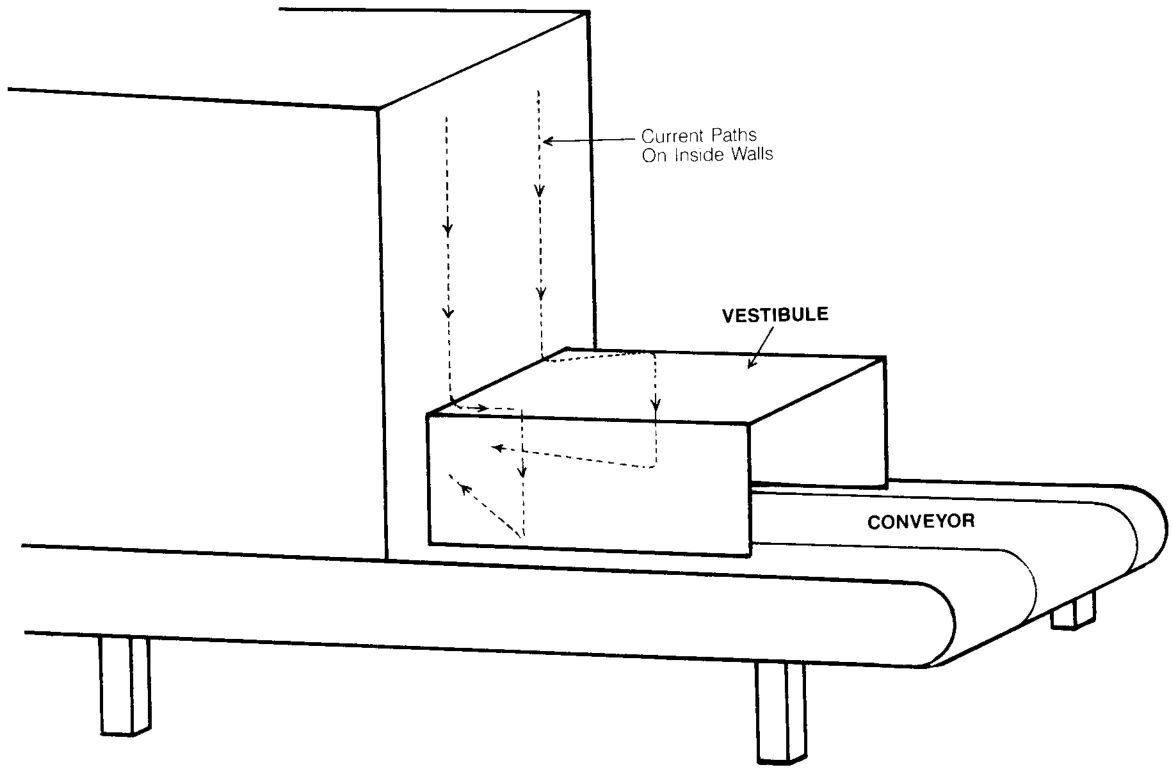


Figure B-4 Currents In A Typical Vestibule

The waveguide effect is not usually a problem at the fundamental, or primary operating frequency of a dielectric heater. However, a harmonic (integer multiple) of the operating frequency can be higher than the cutoff frequency of a vestibule. This is particularly true of a wide vestibule. Therefore it is wise, where the product permits, to have several narrow vestibules in parallel rather than one wide one.

For a vestibule to be effective it must not have any conducting metal within its space. Pipes should be kept outside; but if they must be inside, they should be installed along the walls or ceiling, as close and as well connected as possible. A piece of metal within a vestibule will cancel its effectiveness.

The length of a vestibule recommended by most engineers will vary between 1 and 2 times its width. This gives added advantage to the narrow structures as they need not be as long as the wide ones. Also the width of the vestibule will depend on the type and orientation of the internal electrodes. If the major voltage between electrodes is in the direction from top to bottom of a vestibule the length needs to be longer than if the major voltage direction is along a conveyor such as is true with a stray field electrode.

CONCLUSION

With thought and imagination the construction of a good and reliable shield is not difficult. The best time to do the shielding is in the original design and manufacture of the equipment. It is legally important because of the three government agencies regulating the maximum emissions permitted from dielectric heaters. It is also important because of the possibility of interfering with others' rights and property.

One problem with some of the shields seen in plants is that those building them have overlooked their effects on the operators of the equipment. However,shielding can be constructed so it will serve its purposes without hindering machine operation. As stated previously, attention to shielding details listed in this section, plus consideration of the problems faced by the operators, must be included for a successful design.

APPENDIX C

ELECTRODES

In dielectric heating, the electrodes are the conductors which provide the dielectric heating field for heating the product. The shape of the electrodes, their location with respect to other electrodes, and their location with respect to the surrounding grounded metal parts control the shape of the heating field.

The intensity of heating which takes place at various locations between the electrodes defines the shape of the heating field. The shape is best visualized by drawing lines of force which aid the imagination (See Shapes of Fields, below). In some electrode structures the heating is quite uniform throughout the region between electrodes; in others it is not. In these latter the size of the air gap between the metal electrode and the product being heated will greatly affect the rate of heating.

The type and shape of the electrodes best suited to a particular heating job will depend both on the heating job to be performed and on the shape of the pieces being heated. For example, between parallel plate electrodes, irregular shapes will heat nonuniformly, regular shapes will heat uniformly. With irregular shapes sometimes the electrode is shaped to improve the uniformity of heating; at other times the nonuniformity of heating is masked by the changes in the loss factor of the pieces being heated and a sufficiently uniform final temperature may result. This is particularly true in drying operations where, as the water evaporates, the loss factor decreases markedly so that locally overheated areas may not end up much hotter than other regions.

SHAPES OF FIELDS

In attempting to visualize the possible shape of a field, there are some basic concepts and principles which will help. These are:

"Lines Of Force"

The exact shape of a field depends on the shape of the dielectric being heated, the space between electrodes, the shape of the electrodes, variations in dielectric constant and loss factor throughout a piece to be heated, air space between the electrode and the load piece, etc. An exact mapping of the field is not worth the long tedious effort to accomplish it. The exact shape will change as temperatures change, as moisture content change, as air gaps change etc. A general understanding of the factors involved, however , can be quite helpful in deciding on electrode types, determining reasons for unusual occurrences, etc.

A "line of force" is the path a unit charge of electricity would follow if it could be isolated and set free in a static field. In a high frequency field it would merely vibrate in the field which changes from + to - and back to + during each cycle of the high frequency. A line of force will ALWAYS terminate on a good conductor perpendicular to the surface of that conductor at the point in question. Thus, as shown in Figure C-1 (a), the field between two parallel plate electrodes, (in a space well inside the space between them) will be parallel lines uniformly spaced throughout the region between the electrodes, and perpendicular to their surfaces In this type of field the intensity of heating a homogeneous material will be uniform, or very nearly so, throughout the region of the electrodes. We say this type of field is uniform. In Figure C-1 (b) is shown a parallel plate electrode system with a material with an air gap over it. The presence of the air gap causes an intensification of the heating near the top of the electrode space at the edges of the material; otherwise the field is quite uniform. This intensification is greater for materials having a higher dielectric constant than for those with lower dielectric constants. For most heating applications the nonuniformity is minor. Where it is important, a metal plate resting on the material and extending beyond it by a distance about equal to the material thickness will avoid most of the nonuniformity caused by the air gap, but will maintain the feature of the gap for other control uses.

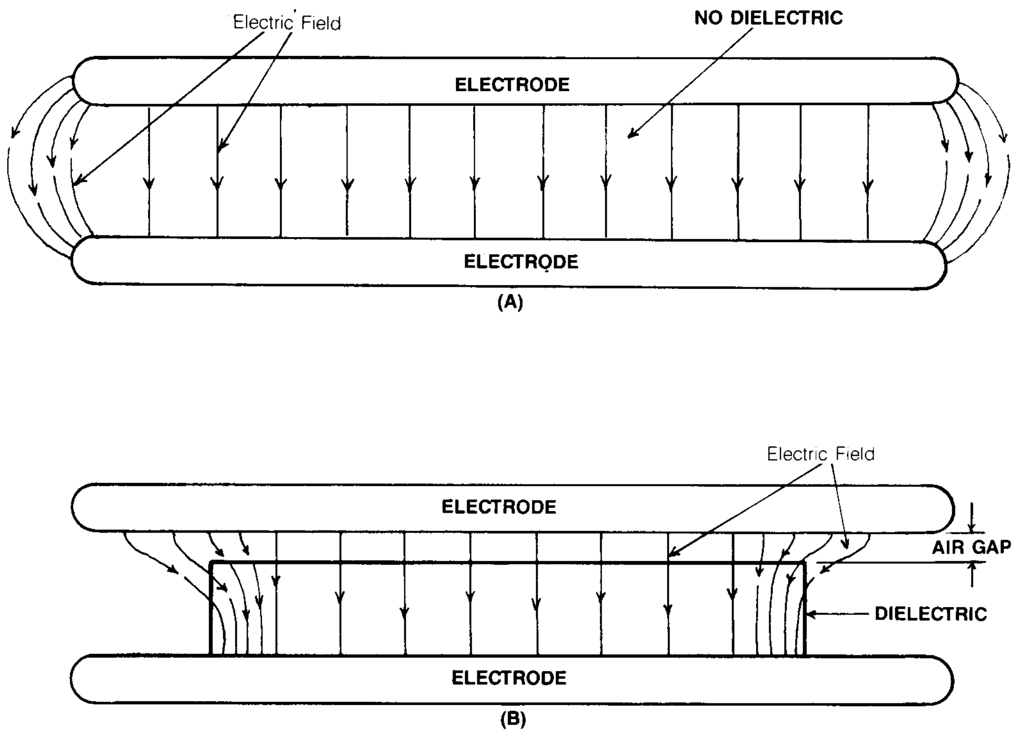


Figure C-1 The Field Between Parallel Plate Electrodes.
(A) Field with no dielectric. (B) Field with dielectric and air space present.

When using round or flat rod electrodes, the lines of force must terminate perpendicular to the surface of the rods as shown in Figure C-2. In the space between the round rods the lines of force go generally in the direction of the other electrode. Some may take what seems like the long way around.

It was stated above that the shape and disposition of the electrodes, the shape of the work piece, and the amount of air space between the electrodes and the dielectric will affect the shape of the field. This is shown in Figures C-1 and C-2. Note that the presence of a dielectric tends to draw the lines of force toward themselves in Figure C-2 (B). Also note that the lines of force do not enter a dielectric perpendicular to its surface as they do in a conductor. The path of the line is bent, or refracted, as it passes through the line between two media of different dielectric constants. Light does a similar thing as is easily seen by looking at the handle of a spoon in a glass of water.

A variation of the electrodes shown in Figure C-2 is called the "staggered stray field" or "dispersed" field electrode. The difference is that the positive and negative electrodes are in different planes, usually one above the other. Where there is a dielectric present it will be between the two planes of the electrodes. This type of electrode configuration is useful in heating thick webs and it delivers heat more uniformly to both the top and the bottom surfaces, and throughout the thickness. If the single plane electrodes illustrated in Figure C-2 were used on thicker materials, more heat would be delivered to the surface closest to the electrodes.

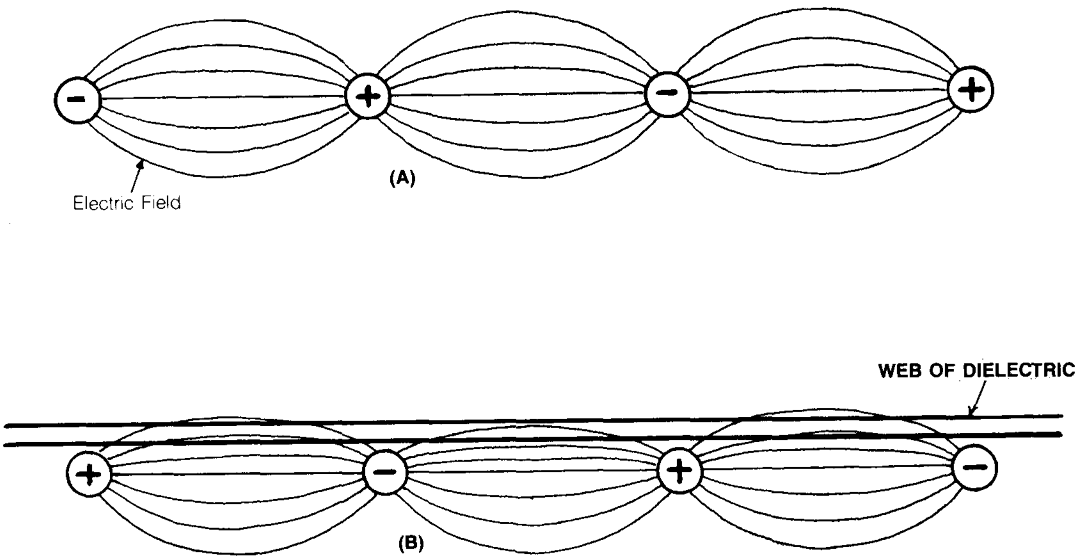


Figure C-2 Round Rod Stray Field Electrodes
(a) No Dielectric Present (b) With Dielectric Above the Rods

Practical Electrode Structures

Normally, for safety and often for convenience in using a conveyor belt, etc. one of the electrodes is "grounded," which means it is attached to the interior of the cabinet or shield which surrounds the electrodes. As is illustrated schematically in Figure C-3, this can affect the shape of an electric field, particularly if the grounded cabinet parts are about the same distance from the ungrounded electrode as is the grounded one. The field from the ungrounded electrode will extend to any grounded metal in its vicinity, and need not go exclusively to the other (grounded) electrode.

With parallel plate electrodes, where the spacing between them is small compared to the width or length, this has little effect on the field. However, there are loads where the gap between electrodes is wider than the other dimensions. One such application is the warming of bales of raw wool. In this case, unless special precautions are taken, the top of the load will heat considerably more than the lower parts as illustrated in Figure C-3 (A). All of the field goes through the upper parts of the bale which are adjacent to the ungrounded electrode, but only a part of it will go all the way through the bale to the grounded electrode [See Figure C-3 (A)].

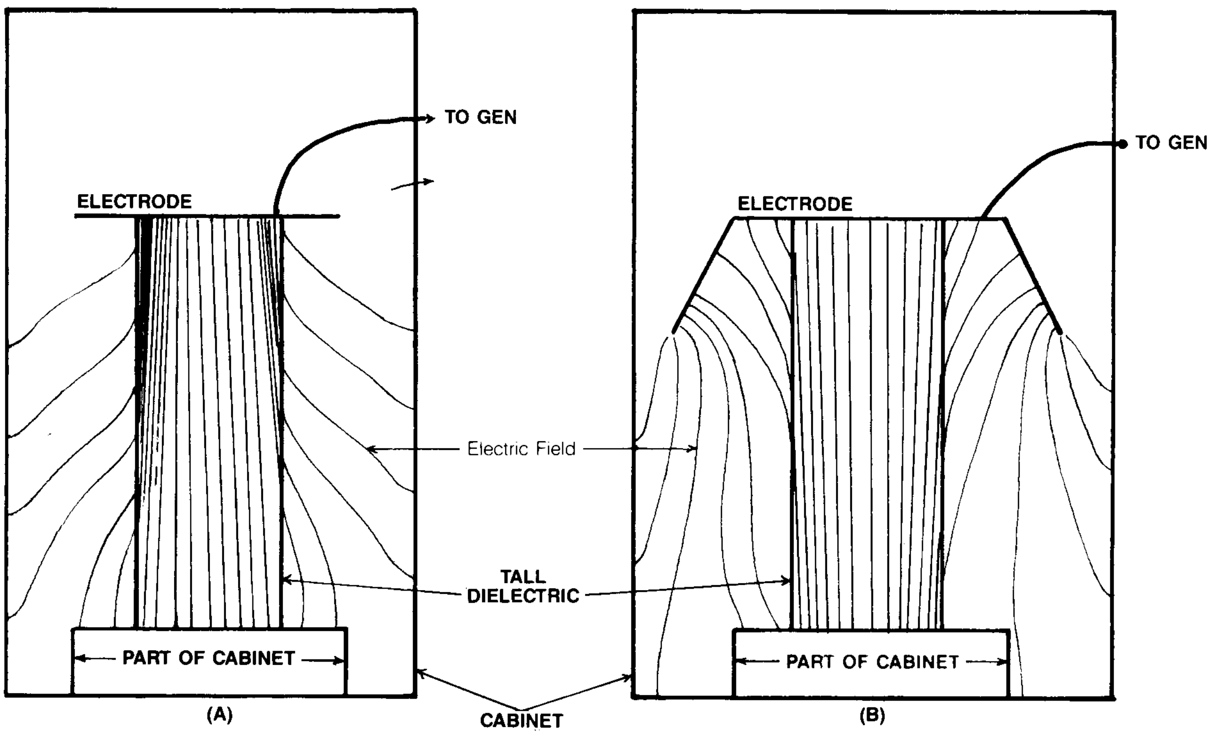


Figure C-3 Practical Electrode Systems
(A) Widely Spaced Parallel Plates (B) Modification of (A)

Figure C-3 (B) shows an electrode structure which can help this problem. As seen from the figure, much of the field going to the grounded cabinet parts does not pass through the top portions of the load and therefore a more uniform heating is obtained. The shape of the ungrounded electrode must be determined experimentally. Complete uniformity of heating is not likely to be obtained by this expedient, but sufficient uniformity can be achieved in most practical applications.

The parallel plate electrodes are usually used for heating thick loads. What is thick is sometimes difficult to assess, but certainly any load upwards of 1 or 2 inches should be handled best by the parallel plate electrode.

The stray field electrode is usually used for very thin materials. The field is then directed along the material being heated, which direction permits a much greater "coupling", or transfer of the energy, to the load than would a parallel plate electrode where the thinness of the material prevents good coupling.

The stray field electrode will have its greatest heating rate next to its surface. The strongest field strength in a stray field electrode is between the rods at their center lines. The load material cannot be placed there, but the closer it is to this line the greater the heating rate. Therefore for thicker materials, the stray field system will heat the lower surface more than regions above this surface. This is avoided by the staggered stray field, or dispersed field electrode. A flat rod electrode shape may provide better coupling to the work material than a round one. However there is no heating effect on top of a flat stray field electrode; heating starts at its edge where the small radius of curvature may provide enhanced heating, but also provides a greater possibility of arcing.

The dispersed field electrode is a combination of both the stray field electrode and the parallel plate electrode. The field is directed diagonally through the thickness of the load material, but it is still more parallel to its surfaces than it is perpendicular to it as would be the case for the parallel plate electrode system. Thus the dispersed field electrode is useful in the transition zone between very thin and normally thick load materials.

There is no sharp line where one type of electrode system should be used in preference to another. The manufacturer of the dielectric heating equipment will have his suggestions to share with a prospective user. The choice of the best electrode system will be determined by the size of the electrode system, the smaller being preferred for more uniform heating. For example, it is easier to add "stubs" or voltage control means (See appendix A) to a stray field system, than it is to the dispersed field system. The stray field system is more likely to require the stubs than is a parallel plate system. The location of the dispersed field system on both sides of the load material leaves only the ends of the rods available for adding stubs.

Again, the dielectric heating equipment manufacturer, or some person experienced in the field, will have exposure to many products and should be consulted if serious consideration is being given to installation of a dielectric heater. The selection of the electrode system best for any new product will depend on the frequency of the generator, the shape and size of the load materials, moisture content etc. Many times it is possible, by arranging the load material differently, to make several types of electrodes function well. Stacking many thin sheets may be preferably to attempting to process many individual sheets because a set of parallel plate electrodes is easier to construct and operate than a stray field set. Alternately, the problems in arranging the sheets so they can be stacked may dictate the use of stray field type electrodes anyway.

APPENDIX D

SURVEY OF APPLICATIONS

SIC*	APPLICATION	NOTE	LITERATURE CITATIONS
001	Increasing the Fertility of Seeds	1,2	Nelson and Stetson. "Use of Microwave and Lower RF Energy for Improving Alfalfa Seed Germination." Microwave Power Symposium, 1974 Milwaukee, WI
001	Drying Agricultural Products	2,3	Toshiba Review International, June 1973
230	Drying of Salt	1, 3	Brown Boveri Review, 1969, p. 58.
241	Drying of Refractory Products	1,2,3	P. Kolbusz. "A Comparison of Microwave and Radio Frequency Drying of Pottery Products," The Electricity Council, 197 ECRC/R506, 1972
242	Accelerated Concrete Curing	1,2	Watson. "Curing of Concrete." Microwave Power Engineering, Vol. 2.
247	Drying of Size on Glass Fiber	1	
248	Curing of Resin Bonded Abrasive Wheels	1,2,3	
257	Drying of Pharmaceutical Powders and Pills	2,3	
258	Drying of Gelatin	1,2	
258	Drying of Water-based Adhesives	1,2,3	See SIC 471
260	Drying of Synthetic Fibers	1, 3	Morrow. "Radio Frequency Measurements and Calculations on the Loose Rayon Fiber Dryer". The Electricity Council, ECRC/M636, 1973 Hodgett and Morrow. "The Drying of Acrylic Tow by Radio Frequency Power". The Electricity Council, ECRC/ R671, 1973.

*Standard Industrial Classification

SIC*	APPLICATION	NOTE	LITERATURE CITATIONS
311	Drying of Sand Cores	1,2,3	Cresswell. "Curing of Molds and Cores by RF Heating." Foundry Trade Journal, April 1970.
329	Melting of Cordite in Bombs	2	Hayes. "Melting Explosives From Obsolete 750 lb Bombs With the Use of Microwave Heating." Microwave Power Symposium, 1974 Milwaukee, WI
344	Drying of Water-based Phenolic Resin PC Boards	1	
344	Laminating Flexible PC Boards	1	
350	Drying of Flocked Boards for Car Trim	1, 3	
350	Welding of PVC Interior Trim for Cars	1, 3	Dielectric Heating. The Electricity Council EC4202(11.81)
370	Welding of Camera Cases	1, 3	
370	Inserting Metal Side-pieces into Spectacle Frames	1, 3	
412	Blanching of Vegatables	2	Decareau. "Cooking and Baking of Food." Microwave Power Engineering, Vol. 2
412	Cooking of Chicken	2,3	May, J. "Applications of Microwave Energy in Preparation of Poultry Convience Foods." Journal of Microwave Power, Vol.4, No.2, 1969
412	Cooking of Meat Slurrey to Form Cubes	2,3	
412	Cooking of Turkey	2	
412	Defrosting of Fish	1,2	Jason and Saunders. "Dielectric Thawing of Fish" Food Technology, Vol.16, 1962 pp. 101-112. Decareau. "Thawing of Frozen Food." Microwave Power Engineering, Vol. 2 Brown Boveri Review, 1969

SIC*	APPLICATION	NOTE	LITERATURE CITATIONS
412	Defrosting of Fruit	1,2	Weil, Moeller, Bedford and Urbain, J. "Micrwave Thawing of Individual Quick-Frozen Red Tart Cherries Prior to Pitting." Journal of Microwave Power, Vol.5, No.3, 1970
412	Defrosting and Tempering of Meat	1,2,3	Saunders. "Dielectric Thawing of Meat and Meat Products." Journal of Food Technology, 1966 "Microwave Defrosting Unit" Brown Boveri Review, 1969, pp. 54-55 "Microwave Meat Tempering Recovers Costs in Six Months." The Electricity Council EC4212, 1981. "Warehouse Meat Tempering Under Cooperative Study," The National Provisioner Inc. 14 October 1978.
412	Drying of Potato Chips	2	Jolly, "A Review of Operational Highpower Microwave Industrial Process Systems in the U.S.A." UIE Congress, Paper N404, 1968. Davis, Smith, and Olander "Microwave Processing of Potato Chips." Potato Chipper, Vol. 25, 1965. O'Mear. "Finish Drying of Potato Chips." Microwave Power Engineering, Vol. 2
412	Heating of Prepared Meals	2,3	Decareau. "Heating of Precooked Foods." Microwave Power Engineering, Vol. 2.
412	Laver Roasting	2	Toshiba Review International June 1973.
412	Pasturization of Hams	1	"RF Pasaturization of Cured Hams." Journal of Food Science, Vol.35, 1970 p. 618.
412	Pasturization of Milk	2	Brown Boveri Review. 1969, p. 56.
412	Softening of Butter	2,3	
416	Deactivating Flour	1,2	Copson, "Conditioning of Flour." Microwave Power Engineering. Vol. 2.

SIC*	APPLICATION	NOTE	LITERATURE CITATIONS
416	Drying of Pasta	2,3	"Microwaves Dry Pasta Food." Food Processing Engineering, Vol. 44, No.4, Jan.1972, p.18
419	Extended Preservation of Cakes	2,3	
419	Extended Preservation of Sliced Bread	2	Brown Boveri Review, 1969, p. 57, Olsen, "Microwaves Inhibit Bread Mold." Food Engineering, July 1965.
419	Extermination of Parasites	1,2	Brown Boveri Review, 1969, p.57, Copson, "Conditioning of Flour" Microwave Power Engineering, Vol 2, Academic Press "Some Effects of Microwave on Certain Insects Which Infest Wheat and Flour," Journal of Econ. Entomology, Vol 49, 1956, pp. 33-37. Nelson and Whitney. "RF Electric Fields for Stored Grain Insect Control." Trans. ASAE, Vol 3, 1960, pp. 133-137
419	Microwave Roasting of Beans	2	Bhartia, Hammid, and Mostowy. "Microwave Bean Roaster." Microwave Power Symposium, 1974, Milwaukee, WI
419	Microwave Bread Baking	2	Decareau, "Cooking and Baking of Food." Microwave Power Engineering, Vol.2, Academic Press. Brown Boveri Review, 1969, p. 55, Chamberlain. "Microwave Energy in Baking of Bread." FMBRA Bulletin, June 1973.
419	Post baking of Biscuits	1,2,3	Holland. "High Frequency Baking." Biscuit and Cracker Institute Conference, 1963. Holland, "Dielectric Post Baking of Biscuit Manufacture." Baking Industries Journal, Feb 1974 Roe. "High Power Conveyorized Dielectric Heating Plant." UIE Congress, Paper 406, 1968 "Up to 30% More Biscuits with RF Post Baking." The Electricity Council. EC4290 1982

SIC*	APPLICATION	NOTE	LITERATURE CITATIONS
419	Post-baking of Breakfast Cereals	1,2,3	See Post-baking of Biscuits
419	Proofing of Dough for Bread	2	Brown Boveri Review, 1969, p. 55
419	Proofing of Doughnuts	2,3	"High-speed Proofing of Doughnuts." Baking Industries Journal, May 1971 Schiffmann, Stein, and Kaufmann. "The Microwave Proofing of Yeast-raised Doughnuts." Bakers Digest, Feb. 1971
421	Accelerated Freeze Drying and Vacuum Drying	2	Hoover, Markantomatos and Parker. "UHF Dielectric Heating in Experimental Acceleration of Freeze Drying of foods." Food Technology, Vol. 20, 1966, pp. 103-110. Hammond. "Economic Evaluation of VHF Dielectric Versus Radiant Heating for Freeze Drying." Food Technology, Vol. 21, 1967, pp. 51-59. Toshiba Review International, June 1967.
421	Drying of "Chalky" Type Sweets	1, 3	
421	Drying Soup Powder	2	
421	Inhibition of Salmonella and Other Bacterial Growth	2	"In the Bag Microwave Processing." Food Trade Review, March 1981
421	Melting of Chocolate	1, 3	
421	Melting of Honey	1,2,3	
421	Melting of Raw Cocoa Butter	1	
423	Drying Instant Coffee	2	
424	Drying of Malt	1,2	
424	Pasteurizing of Beer	1	Brown Boveri Review, 1969
424	Pasteurizing of Soft Drinks	1	Brown Boveri Review, 1969
424	Torrification of Barley	2	
428	Drying of Carpets and Carpet Backing	1	Clements. "Improvements in the Carpet and Paper Industries." UIE Congress Paper 402, 1968.

SIC	APPLICATION	NOTE	LITERATURE CITATIONS
428	Drying of Textiles	1,2,3	Driscoll. "Measurements on the Dielectric Properties of Wool and Other Textile Fibers at Radio Frequencies." The Electricity Council, ECRC/M659 1973 Hulls, P.J.."The Commercial Application of Dielectric Heating." Journal of Society of Dyers and Colorists, Vol. 98, July/Aug 1982' "Rf Cuts Thread Drying Costs." The Electricity Council EC 3755, 1982 "How Pretty Polly Cut Drying Costs by Over 80%" The Electricity Council EC4084, 1981 "More Speed Less Energy at Illingworth, Morris." The Electricity Council, EC4291 1982
428	Heat Setting of Nylon Rope	1, 3	
428	Printing of Carpet Tiles	1, 3	Textile Month, Nov. 1974, P 96
429	Drying of Tobacco	1,2,3	Hirowe, Abe, and Saits. "Some Effects of Microwave Heating on Tobacco". IMPI
431	Heating of Wool Bales	1, 3	Bottomley, "Dielectric Heating of Wool Bales." Wool Record June 1970
437	Dye Fixation	1,2,3	"New Radio Frequency is the Hot Fast Route to Massive Savings." The Engineer 7 April 1977.
437	Dyeing of Wool	1,2,3	"Pad Batch Microwave Dyeing of Wool." Textile Chemist and Colorist, May 1972
437	RF Transfer Printing	1, 3	Textile Month, Nov. 1974, P 96
440	Drying of Leather	1,2,3	"Microwave Conditioning of Leather." The Electricity Council, EC3608 1976
453	Manufacture of Plastic Baby Pants	1, 3	
453	Sealing of Seams on rainwear	1, 3	
453	Textile Bonding	1, 3	

SIC	APPLICATION	NOTE	LITERATURE CITATIONS
453	Transfer Printing of Finished Knitted Garments	1, 3	Textile Month, Nov. 1974 pp 96-97
461	Drying of Timber	1,2,3	Miller. "Radio Frequency Lumber" Drying Methods." Canadian Forest Industries, June 1966 Czopek and Shorckmann. "The High Frequency Drying of Beach Wood in a South German Timber Mill." Electrowarme International, vol.26, No.12 Dec. 1968 Pound. "A Continuous Method of Drying Timber." UIE Congress, Paper N403, 1968 Dean. "System for Drying Timber." Wood, Sept 1970 Morrow. "Moisture Levelling in the RF Drying of Beach." The Electricity Council, ECRC/M675 1973 Driscoll. "The Dielectric Properties of Beach and Cedar Woods." The Electricity Council, ECRC/M683 1974
461	Drying of Veneers	1,2,3	
461	Manufacture of Chipboard	1, 3	Brown Boveri Review, 1965, pp
461	Manufacture of Fiberboard	1, 3	
462	Drying of Wooden Shoe Lasts	1, 3	
462	Drying of Golf Club Head Blanks	1, 3	
462	Making Structural Beams	1, 3	Carruthers, "Electrical Heating and the Manufacture of Laminated Wood Members." UIE Congress, Paper N405,1968 Brown Boveri Review 1965 Pound. "Present Day Applications of Radio Frequency Heating in Woodmaking" Wood, January, February, and March 1957
462	Glue Heating in the Furniture Industry	1, 3	Brown Bovery Review, 1965 "Radio Frequency Curing of Woodworking Adhesives." The Electricity Council, EC3347, 1976
462	Making Reconstituted Cork Board	1	

SIC	APPLICATIONS	NOTE	LITERATURE CITATIONS
471	Drying of Adhesives on Carton Board	1, 3	
471	Drying of Adhesives on Stationery Products	1, 3	"Radio Frequency Drying of of Water-based Adhesives." The Electricity Council, EC3348 1976 "40% Energy Savings With RF Drying of Plastic Films." The Electricity Council, EC4085 1982 Hulls, P.J. "Adhesive Drying and Curing With Radio Frequency." Paper Technology and Industry, Vol.22, No.2 March 1981
471	Drying of Glue for Blister Packs	1, 3	
471	Moisture Profiling of Paper	1,2,3	"Never Mind the Width - Feel the Quality." The Electricity Council, EC4318, 1982 Driscoll. "Measurements of the Dielectric Properties of Paper and Board at Radio Frequencies." The Electricity Council, ECRC/M556 and M692 1973 Jones and Lawton. "A Comparison of the Use of Radio Frequencies and Microwave Energy in the Moisture Profile Correction of Paper and Board." The Electricity Council ECRC/R663 1973 Burkitt. "An Assessment of the Economic Incentives for Improving the Moisture Profile of Paper and Board Products." PIRA, TS62, 1969 Sutherland and Harmer. "Economic Feasibility of Electric Drying." PIRA. TS62 1969 Sutherland and Jones. "Pilot Scale Trials of RF Dielectric Moisture Leveling." PIRA, TS102 1972 "RF Electrical Drying of Paper and Board. Paper, February 1974
472	Drying Matchbox Striking Edges	1, 3	"Strike a Light - an 80% Energy Saving." The Electricity Council, EC4237 1981

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473	Drying of Water-based Printing Inks.	1,2,3	
481	Drying of Contraceptive Sheaths	1	
481	Preheating of Rubber	1,2	"Microwave Rubber Preheating" The Electricity Council EC 3436 1976
483	Curing and Preheating of PVC Sheet	1,2	
483	Fabrication of Life Jackets and Life Rafts	1, 3	"Survival With RF Welding" The Electricity Council, EC 4201 1981
483	Preheating of Thermosets	1, 3	"Radio Frequency Preheating of Thermosetting Plastics." The Electricity Council, EC 3607 1976
483	Preheating of Thermosets	1, 3	See page 3-2 this report.
483	Production of PVC Sheet	1,2	
483	Sealing of Seams on Sunblinds and Awnings	1, 3	"Radio Frequency Welding of PVC Coated Polyester Textiles" The Electricity Council, EC 4022 1979
483	Welding and Embossing of PVC	1, 3	
483	Welding and embossing of PVC and other plastics.	1, 3	See Table 3-1 this report.
490	Drying of Adhesive on Flocked Games Boards	1, 3	
490	Drying of Photographic Prints	1,2,3	
490	Manufacture of Tennis Racquet Handles	1, 3	Brown Boveri Review, 1965
495	Welding of PVC Stationery.	1, 3	"Radio Frequency Welding of Plastics." The Electricity Council, EC3351 1976
500	Cracking of Concrete	2	Watson, "Breaking of Concrete." Microwave Power Engineering, Vol. 2
500	Mending of Asphalt Roads	2	Bosiso, Spooner, and Granger "Asphalt Road Maintenance With Mobile Microwave Power Unit." Microwave Power Symposium, 1974, Milwaukee, WI

SIC	APPLICATION	NOTE	LITERATURE CITATIONS
612	Small Scale Pie and Bread Baking	2	
--	Wood working Gluing	1, 3	See Table 5-1 this report
---	Business Forms	1, 3	See Section 7 this report
---	Gluing of Book Spines	1, 3	See section 8 this report

NOTES

1 Feasible with RF Dielectric Heating

2 Feasible with Microwave Heating

3 Commercial Installations Exist

Table adapted from: British National Committee for Electroheat. "Dielectric heating for industrial processes," Appendix 1, 1983, with additions by the principal investigator.