A CONTINUOUS-PROCESS RADIO-FREQUENCY FOOD-BLANCHING PILOT PLANT

by

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Present methods for preparing foods, mainly vegetables, for freezing require the application of heat (blanching) in order to retard enzyme activity in the food material and thus prevent spoilage in frozen storage. If vegetables are not blanched, the enzyme activity, although retarded due to low storage temperatures, is not sufficiently retarded to prevent the formation of off-flavor, odor, and color.

Today it is customary to blanch by using steam or hot water to raise the temperature of the vegetable to at least 175°F, and more commonly to 200°F. A principal disadvantage of the usual method is that the heat reaches the center mass of the vegetable by comparatively slow conduction from an over-heated surface layer. Consequently either the temperature or the time required for the food to be exposed to that temperature increases as the mass per unit vegetable increases. For example, cut corn requires only two minutes to blanch by the usual commercial methods, while corn-on-the-cob is not completely blanched at the center after ten to fifteen minutes of live steam.

Another disadvantage of the usual blanching methods is that a considerable portion of the water-soluble vitamins
(e.g., riboflavin, carotene, ascorbic acid) present in the vegetables is leached out (1, p.60). Thirty to forty percent of ascorbic acid (vitamin C) alone is ordinarily lost by oxidation and solution in water during blanching (3, p.43). Ascorbic acid retention is often taken as a criterion of the quality of frozen vegetables and fruits, since its presence in normal percentages indicates care in the selection, handling, preparation, storing, transportation and marketing of these products.

As a result of these shortcomings, utilization of dielectric heating (that produced by high-frequency electrical energy) to achieve the proper blanching temperatures has been considered for several years (2, pp.347-8). Past experimentation by several research groups throughout the country indicated that the heating time could be reduced and the quality of the product improved by this means. Since the dielectric heat is created rapidly and comparatively uniformly throughout the mass of food product, the overheating of the outer surface can be eliminated and the vitamin loss reduced.

However, all of the previous experimentation has been done with batch methods, preventing any true comparison of their results with the continuous-process commercial methods of steam or hot water blanching. Consequently, the Food Technology department of Oregon State College initiated action to obtain the first continuous-process type of
dielectric-heating food Blanching machine, to be built on a pilot plant scale. With it they intended to obtain a valid quality and cost comparison.

In the interests of encouraging potential power applications, the Bonneville Power Administration furnished a substantial portion of the funds necessary to design and construct such a pilot plant. The writer undertook the task of design and construction, due to his interest in machine design and in fulfillment of the requirements for an advanced degree.

II.
SPECIFICATIONS

In order to determine the commercial adaptability of dielectric heating for vegetables, it is necessary to construct and operate a continuous pilot plant which will enable us to compare this method with standard commercial methods as to:

(1) Quality of the finished product, both before and after storage.
(2) Output capacity per unit energy input, for both conventional and new type machines. Dependent on efficiency of energy utilization.
(3) Operating costs per unit vegetable processed.
(4) Fixed investment cost per unit rate of output.
(5) Ease of handling and maintaining the equipment. Is the new equipment of simple enough design to operate reasonably trouble free?

If the above results are to be obtained, the following basic requirements would have to be fulfilled by the pilot plant:

(1) It should be readily adaptable to blanch any vegetable. To partially justify the higher initial investment cost of high frequency power equipment, the machine should be designed to replace the conventional blanching equipment, not just supplement it.

(2) If the optimum design features of a commercial size installation are to be determined, the maximum flexibility of design features must be incorporated in the pilot plant.

(3) The machine should utilize where possible the existing type of facilities in the present food-processing plants (e.g. steam).

(4) The pilot plant machine should be easily disassembled and moved, so that different high-frequency generators may be utilized.

III.

FUNDAMENTALS

A basic understanding of dielectric or high-frequency heating is necessary before that form of energy can be intelligently applied. The term dielectric is usually
applied to materials having poor electrical conductivity (i.e., most non-metals). The phenomenon of heat gain by (or power loss in) a dielectric material may be explained as follows.

When a d-c voltage is applied between two electrodes, a static electric field is set up. If the dielectric material between the electrodes is not a perfect insulator, a small conduction current will flow through the dielectric, causing heat to be produced in the material equal to the product of the voltage drop times the current. This power loss (or heat gain) in the dielectric is termed "conduction loss".

If a high-frequency alternating voltage is applied between the electrodes, the conduction loss still occurs, though it may be somewhat different in magnitude from that for an applied d-c voltage. However, in addition to the conduction loss there is another loss produced with a-c voltage that was not produced when a d-c voltage was applied. This additional loss is usually termed "dielectric loss".

When a-c voltage is applied to the electrodes, the resultant rapid alternation of the electric field produces changing stress conditions in the dielectric material, thus creating molecular friction and heat throughout the material. Dielectric materials that possess good insulation qualities may have a very small conduction loss but a rather large dielectric loss.
The equivalent circuit of a dielectric material absorbing energy in a high-frequency field is shown in figure 1 (5, p.7).

\[ E = \text{effective (not peak) voltage} \]
\[ g = \text{power loss in the dielectric} \]
\[ b = \text{capacitance between opposite faces of the dielectric} \]

Figure 1

An analysis of the equivalent circuit in figure 1 yields the following relationship among the variables that influence dielectric heating.

heat created/unit volume = \( k(pf)(e)(f)(E')^2 \)

- \( k \) = a constant
- \( e \) = dielectric constant of the dielectric material
- \( f \) = frequency in cycles/second
- \( E' \) = voltage gradient = voltage drop per unit of distance between electrodes

It will be noted from the above equation that the heating effect increases directly with the frequency for a fixed value of voltage gradient. However, the power factor and dielectric constant of most materials varies with frequency (4, p.84). Hence, these quantities must be determined at the frequency to be used. Generally it will be found that the product of power factor and dielectric constant does not vary widely with frequency over a small range.
of frequencies.

The frequencies used for food blanching by past investigators have been from ten megacycles (one megacycle equals 1,000,000 cycles per second) to 1000 megacycles, with most of the work being done between 27 and 200 megacycles. There is no universal agreement as to which range of frequencies is ideal, since the choice of any appears to be a compromise. As arcing from high voltages often limits the rate of heating at a given frequency, increasing the frequency appears the logical solution. However, the power factor and dielectric constant both vary with frequency and thus often largely nullify the apparent advantage of the higher frequencies. In addition, localized heating within the dielectric field increases, equipment cost increases, and the efficiency of the electrical machine used to create the high-frequency power decreases as the frequency utilized is increased.

The high-frequency electrical machines used to produce power for dielectric heating are usually identified by one of two names, high-frequency oscillator or high-frequency generator. The term radio-frequency instead of high-frequency is often encountered, since many dielectric applications utilize frequencies that are also used in radio. Fundamentally, the machines are quite simple in design, taking electrical energy at ordinary frequency (60 cycles per second) and voltages, transforming it to high voltages, rectifying it to d-c, and then oscillating it to the desired frequency.
Another basic factor to be considered before starting design is that of economics. A generator's initial cost is a function of power output, frequency, accessories, quality and service after installation. A generator suitable for experimentation work between six and forty megacycles costs about $700 per kilowatt output. Based upon an average tube life of 2000 hours operation, power tube replacement costs will average 1½ to 2¢ per kilowatt output per hour of operation. For applications in the Pacific Northwest, power cost should be substantially less than 1¢ per kilowatt input, due to the favorable periods during which a food-processing plant would require the power (steady demand around the clock during the packing season, which does not include the power-critical winter season). It should be pointed out, incidentally, that a generator efficiency (output/input) of 45 per cent is considered satisfactory.

Amortization costs will depend on the number of hours the generator is used per year and its estimated life before obsolescence. In any case, the amortization cost per hour of operation will probably exceed either the tube replacement or direct power costs. The cost of providing power transmission facilities to the generators must also be considered. Most commercially available generators require 220 or 440 volt input and, of course, power greater than most commercial buildings are equipped with.
Another cost not to be overlooked is that of preventing the high-frequency generator from radiating energy into space and causing interference with communications. This can be controlled by one of two means: (1) incorporating equipment within the generator to keep it within the narrow wave bands allocated by the FCC for dielectric heating (at 13, 27, and 40 megacycles), both for fundamentals and harmonics; or (2) shielding the entire room within which the machine is installed and adding devices to prevent radiation from the power input, thus reducing the overall radiation to meet FCC requirements.

The third basic factor to be considered before starting design is the availability of materials and fabrication facilities. With adequate time, practically any specialized material that would be desirable from a performance and economic standpoint could be specified and used. Similarly, jobbing of the fabrication could be distributed throughout the country to the most advantageous vendors. Due to the shortage of time, however, the choice of materials was limited to those obtainable from Portland stocks, and the fabrication was done almost entirely in the shops at Oregon State College.

IV.
PRELIMINARY DESIGN

A study of the heat balance of a mass of material
heated by dielectric energy reveals that the heat input is, under proper conditions, uniformly distributed throughout the mass. The heat gain or loss by conduction, convection and radiation to the surrounding medium, be it air or liquid, affects primarily only the surface of the material. In other words, while the dielectric field supplies sufficient energy to raise all the mass to the desired blanching temperature, the surrounding medium, if it is not maintained at a temperature approaching that required for blanching, will act as a quenching agent and prevent the surface of the mass from reaching the required temperature. This difficulty has been encountered previously in other applications of dielectric heating; e.g., ovens designed to bake bread continuously by dielectric means had to have infra-red lamps added to bake the crust, which otherwise remained doughy.

Another problem to be solved is that the power density or heating effect between the electrodes is not entirely uniform either horizontally or vertically, even for homogeneous materials. The most obvious solution is to agitate or rotate the material as it is passed through the dielectric field.

One solution that would simplify the problem of keeping the surface of the material as warm as the interior would be to package the food and then heat by means of radio-frequency power. The two known difficulties to this
solution are: (1) rapid cooling after heating, essential to good flavor of foods, is no longer possible; and (2) no packaging material is known that is both economically feasible and dielectrically satisfactory.

Another very desirable solution would be to pass the material through the dielectric field on a canvas or plastic belt, surrounded by hot air, and cool with a blast of refrigerated air. The main obstacle to this proposed solution is the occurrence of arcing as heating progresses. Steam arising from the vegetables evidently provides a path of lower resistance. Directing a stream of air across the vegetables helps, but does not solve the difficulty. The high power or heat intensities required for a feasible continuous process would be impracticable with air surrounding the vegetables.

Consequently, the only choice appears to be to float the vegetables through the dielectric field in water. The water could be preheated to avoid cooling the surface of the material, and turbulence induced to insure uniform heating. The disadvantages are several, though. If the water carrying the vegetables is recirculated in order to save its sensible heat, its heat absorption from the dielectric field will steadily increase, due to its increasing salt concentration from contact with the vegetables. Hence the water probably cannot profitably be used more than once.

Another disadvantage is that some of the water-soluble
vitamins will be lost. This loss may be kept at a minimum, though, by keeping the vegetables in contact with the water as short a time as possible. Despite these shortcomings, it was decided to float the vegetables in hot water through a horizontal length of glass tubing. The electrodes could be applied two different ways, which will be discussed later. As an added precaution against arcing difficulties, provision would be made to allow distilled water or transformer oil to surround the electrodes and glass tube.

With the surrounding medium decided upon, the minimum required capacity of the radio-frequency generator could now be determined. The following assumptions were made for these preliminary calculations:

1. Nominal weight of a single unit of the largest vegetable to be tested (corn-on-the-cob) equals 0.5 pound.
2. Specific heat of the vegetable equals 1.0 (water content of corn equals 85 per cent).
3. Temperature change is from 60 to 180°F.
4. Maximum time of heating equals 20 seconds.
5. No electronic heat absorption by the surrounding water (including the air or liquid outside the glass tube).
6. Negligible heat conduction between the carrying water and vegetable.
7. Entire generator capacity absorbed by the ear of corn.

The calculations for the required generator output, expressed
in Btu per hour, are as follows.

Output \[= \frac{\text{weight of material being heated}}{\text{specific heat}} \frac{\text{(temperature change, } ^\circ F\text{)}}{\text{time}}\]
\[= (0.5)(1.0)(180-60)(3600/20)\]
\[= 10,800 \text{ Btu/hour}\]
\[= 3.2 \text{ kilowatts}\]

However, batch experimentation with the one kilowatt generator in the Food Technology laboratory indicated that a large portion of the energy output is absorbed by the water surrounding the vegetables. Due to equipment limitations, it was not possible to determine an applicable ratio of heat absorbed by a particular vegetable to that by the water.

Even the minimum amount of surrounding water is substantial. Not including the possible distilled water or transformer oil surrounding the electrodes and glass tube, the weight of water carrying an ear of corn through the minimum size of glass tubing equals approximately 3.3 pounds, calculated as follows:

Minimum rate of flow = 1 inch/second (by experiment)
Glass tube inner dia = 2.6 inches
Wt of water/cu in. = 0.036 pound
Wt of water/ear of corn = \(\frac{\text{lb/cu in.}}{\text{cu in./20 sec}}\) - (wt of water displaced by corn)
Wt of water/ear of corn = \((0.036)\left(\frac{\pi}{4}\right)(2.6)^2(20) - (0.5)\) 

\[= 3.2 \text{ pounds of water}\]

It should be pointed out that an increase in generator output above the required minimum would allow a closer spacing between the vegetables, thus decreasing the amount of water per unit of vegetable and increasing the overall efficiency.

In view of the above conditions, at least a ten kilowatt output generator for the continuous-process blanching pilot plant would probably be required.

By logically combining the foregoing fundamentals and design features, one could visualize the basic design as shown in figure 2, p.16. Due to the many unknowns and to the different characteristics of the various vegetables to be blanched, maximum flexibility of operation was highly desirable. This flexibility was to be attained by incorporating the following variables in the design:

1. Temperature and velocity of water carrying the food.
3. Diameters of both metal and glass tubing through which the vegetables flow.
4. Area and intensity of electronic field.
5. Temperature of the medium (either air, distilled water, or oil) surrounding the glass tube and electrodes.
(6) Velocity of the inlet feed mechanism.
(7) Angle and velocity of the conveyor belt.

V.

DETAIL DESIGN AND CONSTRUCTION

A. Vegetable Handling

The design problem of floating the vegetables through a horizontal length of glass tubing can be broken down into three parts: (1) injecting the vegetables into the tube; (2) controlling the vegetables' rate of flow through the high-frequency field; (3) discharging food from the tube, removing it from the water, and quenching.

The continuous insertion of vegetables of different sizes, shape, and density (some lighter than water, some heavier) into a submerged round glass tube appears not too difficult at first consideration. It was originally thought that the vegetables could be directed into the tube by sliding them down a chute (into which they would be dumped from a conveyor belt) and into a funnel, using their momentum to force them beneath the water's surface and into the tube. The water surface had to be maintained above the top of the tube; air in the tube would increase arcing difficulties.

The variable-angle jet on the right in figure 4, p.18, plus the general movement of the main water flow was expected to help start the vegetables on their trip through the glass tube. However, doubt that gravity and water flow alone
Figure 2

SCHEMATIC of PILOT PLANT

Quench Tank
Air, Water, or Oil

Cold Water

Temp. Regulator
Counterflow Heat Exchangers

discharge

Steam
Heating Tank

Figure 4
SKETCH of INLET TANK & FLOW TUBE ASSEMBLY
Figure 5

VIEW OF INLET FOR VEGETABLES
Figure 6

INLET VIEW WITH PART OF INJECTION MECHANISM REMOVED
Figure 8

REAR VIEW OF PILOT PLANT
would be sufficient prompted the addition of a positive, mechanical-type of injection, as shown in figures 5 to 7, pp.19-21. The rear view of the machine, figure 8, p.22, shows the V-belt drive of the injection mechanism from the speed reducer.

At the top of the inlet slide, a perforated pipe spread a sheet of water for the vegetables to slide on since it was found that corn-on-the-cob would not slide on a dry surface, regardless of the angle of that surface. As indicated in figure 4, the slide as well as practically all of the machine which contacted the food was constructed of aluminum. That metal was chosen in place of stainless steel, due to lower cost, far better machinability, easier formability, and lighter weight. The aluminum alloy 61S was chosen because of its good combination of properties. Strength and formability are well compromised, corrosion resistance good, and it is weldable. Other metals were used only when special requirements dictated their choice (e.g., wear or weight).

As shown by figure 4, the inlet funnel assembly is composed of an elliptical-type cylinder intersecting a round tube at an angle. Since the inner surface had to be quite smooth, and since a foundry capable of producing quality castings was not available nearby, the funnel assembly was welded together from six machined parts. The path of the bottom tip of the injection finger assembly (figure 7,
Bushings for the lower two solid aluminum pulleys of the injection mechanism (Fig. 5) are fabric-phenolic plastic, bearing on brass shafts. That choice was made due to the corrosion requirements (steam arising from the hot water), the location of the pulleys (directly over the food), and the slow speeds. The upper pulley shaft, not being over the food area, bears against two Oilite bushings, pressed into the tubular steel housing.

The finger assemblies are designed to swing freely until they enter the inlet funnel, at which time a projecting "ear" (-3 of Fig. 7) ordinarily enters a cam slot (-2 of Fig. 6). Should a vegetable strike it the instant before the ear enters the slot, the finger assembly will be knocked up parallel to the belt and kept in that position by contact of the ear with the lower cam surface. Horizontal and vertical adjustment of the injection mechanism frame, of the finger assembly, and vertical adjustment of the cam assembly insure proper alignment in operation.

By means of clamping plates (-1 of Fig. 6) and oversize holes in the frame, the position of the injection mechanism driving pulley can be shifted plus or minus $\frac{1}{2}$ inch, vertically and horizontally. An inspection of figure 8, p. 22, indicates the necessity for so much adjustment. The driving pulley (-5 of Fig. 8) of the conveyor belt in the separation tank can be moved to adjust the conveyor belt tension, and elongated slots in its mounting plate allow the speed reducer
(-2) to follow that movement as well as maintaining proper V-belt tension, and the injection mechanism pulley (-1) must follow those movements, plus keeping V-belt tension between it and the speed reducer.

The situation is not ideal, but it allows the use of a single variable-speed drive combination. A \( \frac{1}{2} \) hp motor (-4 of figure 8) drives a speed-changer (-3) with a change ratio of 6.3:1. This particular variable-speed mechanism, manufactured by the DoAll Company, was chosen for its simplicity and inexpensiveness. A pivoted motor mount was required in order to use this type of speed-changer. The worm-gear speed-reducer (-2) had a ratio of 48:1.

As soon as the vegetable reaches the horizontal portion of the inlet funnel, its velocity will be controlled by hydraulic action. The main water flow entering the bottom of the inlet tank (figure 4) and the two ball-nozzle assemblies each have separate valves. The purpose of the variable-angle ball nozzle assembly, located in the inlet flow tube (figure 4), is to produce a helical water flow through the glass tube, thus insuring a uniform exposure of the vegetables to the high-frequency field and reducing the tendency of the vegetables to stop or move intermittently (due to frictional drag). Irregular motion would not only produce an unpredictable amount of heating but for vegetables shaped like corn-on-the-cob, would create jamming as the following vegetables would be shoved in
regularly by the injection mechanism.

The seal used for the ball-nozzle assembly is the same type that is used throughout, as shown in figure 4. They are called O-ring seals, and were molded from a special rubber compound that does not affect the flavor of food.

The unit component type of construction, as shown by figure 4 and figure 10, p. 28, was necessary because of the desired variance in tube size. The tanks were built to be able to use tubing from 60 to 100mm (approximately 2.6 to 4 inches). Since the water level had to remain the same, the top of the tubing also did not change, thus eccentrically locating all tubing except the largest size. Pending results of preliminary tests, inlet funnels and inlet and outlet flow tube assemblies were built only for the two smaller sizes.

The thermometer wells to determine water temperatures before entering and after leaving the high-frequency field are shown in figure 10. They were built by end-milling slots in the sides of the flow tubes and welding a bored-out block over the slots. Mercury thermometers would then have a constant flow of water around them.

The ring between the inlet flow tube, figure 4, and the glass tubing was made separate for assembly purposes, so that, by withdrawing it via the heating tank side, the inlet flow tube could be removed without changing position of the
Figure 9

BALL NOZZLE ASSEMBLIES
Figure 10

OUTLET AND INLET FLOW TUBE ASSEMBLIES
Figure 11

VIEW OF DIELECTRIC HEATING AREA WITH SOLID CIRCULAR ELECTRODES
Figure 12

VIEW OF SEPARATION AND QUENCHING TANKS, WITH FLOW TUBE ADAPTOR FOR LARGE VEGETABLES
Figure 13

VIEW OF SEPARATION TANK WITH FLOW TUBE ADAPTOR FOR SMALL OR DICED VEGETABLES
Figure 14
SKETCH of WATER OUTLET ASSEMBLY
inlet tank. This operation would be necessary when changing the tubing size.

Figure 11, p.29, shows two ears of corn passing through the glass tubing, and figure 12 illustrates them emerging onto the stainless-steel wire-mesh conveyor belt. The flow tube adaptor, illustrated in figure 13, prevents small or diced vegetables from floating or sinking away to one side before the conveyor belt picks them up. A special L-section rubber extrusion is stapled to the wire-mesh belt, crosswise to pick-up the vegetables and along the edges to form sides. The staples were extra-long, heavily plated for corrosion resistance (stainless steel staples are not a standard item), and individually clinched by hand to the wire adjacent to the extrusion. Staples machine clinched over the entire mesh will loosen from flexing while going over the pulleys.

In order to encourage the placement of the vegetables directly upon the conveyor belt, the water outlet in the separation tank was located between the belt surfaces, as shown in figure 14, p.32. Adjustment was designed into the outlet assembly to allow for both water level and conveyor belt variance. In order to bend the one inch aluminum pipe, it was necessary to anneal it, and then heat both it and the dies to about 300F before bending. Even so, the 90° bend produced visible evidence of yielding.

In order to determine the optimum belt angle, the
angle of the conveyor belt was made variable by means of slots in the supports (-2 of figure 13) for the assembly. One of the bars (-1) which supports the driving pulley and absorbs the reaction of the belt tension had to be offset to provide clearance for the water outlet (-3). The stainless steel shaft of the driving pulley rotated in the flanged Oilite bushings, pressed into the bars. Due to the small diameter of the driving pulley, it was necessary to cement a continuously-wound rubber strip around it, so as to provide sufficient traction for the conveyor belt. The flange on both the driving and idler pulleys was spun from stainless steel sheet and then silver-brazed to the assembly.

The conveyor belt dumped the vegetables directly into a cold-water quench tank (on the left in figure 12), which was kept cold by a water inlet in the bottom and an overflow, and which had a zinc-plated rectangular wire basket for removing the vegetables. The wire basket was first obtained from a hotel supply house and the dimensions of the quench tank determined from it.

B. Hot Water Supply

The purpose of the hot water supply system is to furnish hot water to surround the vegetables and float them through the high-frequency field, at a variable temperature (determined by the particular vegetable being tested), and with a minimum expenditure of heat. Since the water could
be used only once, as previously discussed, it is necessary to recover as much of its heat as practical. Consequently, heat exchangers were chosen, as shown in figures 2 and 3; the first to preheat the incoming fresh water by means of the discharged water, and the second heat exchanger to add the required heat to bring the water up to the desired temperature.

Since most food-processing plants are already equipped with steam, that was the source of heat used in the final heat exchanger. Both heat exchangers were purchased from the Graham Manufacturing Company, since their products' cost and weight were only a fraction of those of the standard type of counterflow heat exchanger. Basically, their construction consists of coiled copper tubing enclosed between plates; one fluid inside the tubing, the other flowing in the opposite direction in the space between the coils and the plates. The required capacities of the heat exchangers were calculated on a basis of fifty percent heat recovery, maximum anticipated water flow at 200°F, and 40 psig steam pressure. The discharged water's small head of only 3 feet also affected the requirements of the first heat exchanger.

C. Application of High-Frequency Power

The electrode design shown in figure 11, p. 29, shows the arrangement which proved most successful in laboratory
tests with the small one kw generator. Every other electrode is connected in parallel, thus giving heating throughout the length of the tube except for the spaces directly under the electrodes. (Note that the tank ends also act as ground electrodes). Varying the number and spacing of the electrodes will, of course, vary the intensity of the high-frequency field.

It is advantageous to have as little air space as possible between the copper electrodes and the glass tube, so that the voltage gradient (see p. 6) within the glass tube will be a maximum and the arcing probabilities between electrode and glass will be reduced. The principle of dielectrics in series is that the voltage appearing between opposite faces of each dielectric is dependent upon the thickness and dielectric constant of each material. The following equation and example will illustrate this principle.

\[ E_1 = \frac{E}{1 + (s_2/s_1)(\varepsilon_1/\varepsilon_2)} \]

\( E_1 \) = voltage across dielectric (1)
\( E \) = total electrode voltage
\( s_1 \neq s_2 \) = thicknesses of dielectrics (1) & (2) respectively
\( \varepsilon_1 \neq \varepsilon_2 \) = dielectric constants of dielectrics (1) and (2) respectively
Example:

\[
\begin{align*}
E_1 \text{ of water} &= 80 \\
E_2 \text{ of air} &= 1 \\
s_1 = s_2 &= 1 \\
E &= 100 \\
E_1 &= \frac{100}{1 + (\frac{1}{2})(80)} \\
&= \frac{100}{87} \\
&= 1\frac{1}{4} \text{ approx. voltage drop across water} \\
E_2 &= 100 - 1\frac{1}{4} \\
&= 98\frac{3}{4} \text{ approx. V drop across air}
\end{align*}
\]

The foregoing principle proved quite true in our preliminary tests, demonstrating that the solid-type electrodes shown in figure 11 were unsatisfactory. They were built by bending copper tubing around a form and silver-brazing to a small plate between the ends. Since the glass tubing is not a perfect circle, the electrodes’ required clearance usually left several thousandths air gap. Consequently, flat strip electrodes (0.010 inch thick) which could be drawn tightly around the tubing were made and successfully tested. The same type of copper strip stock was also arranged on opposite sides of the glass tubing, running parallel and taped tightly to the tubing. This arrangement, which did not permit variance of the field intensity (by changing the spacing between electrodes), produced
arcing under the same conditions which proved satisfactory with the other arrangement (alternate circular strips).

The grounding problem for high-frequency power requires a somewhat different solution than for low-frequency power. Instead of running leads to a water pipe or metal rod in the ground, the best procedure appears to be to connect the copper-strip leads to a large metal plate which is flat on the ground.

In regards to safety precautions, the best solution would be to physically prevent contact with the energized leads by means of guards. Since this is quite cumbersome for experimental work, the next-best solution was adopted, that of warning the operators when power has been applied. This was accomplished by clipping a fluorescent tube (not shown in the photographs) to the front of the heating tank and taping miniature neon lamps to the leads.

D. Measurements

Mercury thermometers were chosen for their accuracy to measure water temperatures. Those measuring the temperature of water under pressure were contained in brass thermometer wells. Sealing of the thermometer in the well was done with an O-ring seal, compressed with a beveled ring, and proved quite satisfactory.

Water temperatures were measured at the following points: incoming, after the first heat exchanger, after the second heat exchanger and before entering the high-frequency
field, after leaving the glass tube, after the discharge water has passed through the first heat exchanger, the quench tank, and the heating tank (if filled with distilled water or transformer oil). Incidentally, the length of aluminum tubing in the heating tank shown in figure 11 is connected to the steam line in order that equilibrium conditions may be reached immediately by any fluid in the tank.

The temperature of the vegetables before and after dielectric heating can be measured with thermocouples, particularly those having a needle type of hot end which can be readily thrust into the vegetable. The steam pressure, although not a critical item, could be measured with a simple Bourdon-type gauge.

The water volume (and its average velocity, by calculation) could be determined by weighing the amount discharged within a given length of time. The turbulence and local water velocity could and was observed by inserting a small portion of a red dye powder into the flow at the inlet funnel.

E. Miscellaneous

Most calculations have been omitted, since they were elementary and obvious to those experienced in the field of machine design (e.g., pulley diameter calculations, required heat capacity of heat exchangers). Due to the nature of the machine, the only parts which required a stress analysis
were the long angles of the frame (—1 of figure 3). The angle section chosen was one which was capable of supporting a man's weight at the center with a 3G loading condition.

Steel angles were chosen for the frame instead of aluminum for reasons of cost and ease in welding (all of the aluminum arc-welding was done in an inert atmosphere of helium with special equipment). The extra weight is not important, as the machine can be split into two parts and readily handled by two men. Unions in plumbing lines and a bolted frame assembly allow separation of the lower from the upper half of the machine. Complete assembly or dis-assembly can be accomplished by one man in about an hour, depending upon his knowledge of the components.

In regard to the plumbing, the standard threaded type was chosen because of the short runs and the many standard connections incorporated in the purchased parts. Galvanized steel pipe and fittings were used from the cold water supply to the first heat exchanger, and brass to carry the hot water from there to the inlet tank. The use of brass quite possibly would not be necessary. The galvanized pipe was also used on the steam line, discharge line, and drain lines from all tanks. The largest pipe size compatible both with water lines ordinarily found in buildings and the smaller heat exchanger (½ inch) was chosen for the incoming fresh water lines. Choice of a larger size would have reduced the pressure drop but slightly.
It should be mentioned that, except for the cadmium plating and bending of the 1 inch aluminum pipe, all of the fabrication was done in the college shops. With such close proximity to the fabricating facilities the detail design was readily adapted to the limitations of the available equipment. Maintaining close tolerances in machining was a minor problem. Except for parts which had to fit purchased parts (such as Oilite bushings), dimensions could be expressed in fractions and the clearances in the required thousandths.

VI.
PRELIMINARY TESTS

In order to demonstrate the workability of the design and to detect and correct any malfunctions, preliminary tests were made in the Forest Products Laboratory. The high-frequency generator located there (manufactured by the no defunct Vetrie Company) has an output capacity of approximately eight kw and variable frequency (from two to thirteen megacycles). The generator was placed close to the electrodes of the pilot plant, as shown by figure 15, p.43.

The first difficulty noticed was occasional failure of the discharge drain to handle maximum water flow. Since closing and reopening the discharge line valve (located beneath the first heat exchanger, figure 8) restored the proper discharge flow, it was surmised that air was being trapped, probably between the heat exchanger and valve.
The most feasible correction of the difficulty would be to add another discharge drain to the separation tank, as indicated in figure 14, p.32, and by-pass the heat exchanger (the second or steam heat exchanger has sufficient capacity to do all the heating). The addition of the top round plate and flared entrance would increase the capacity of the proposed discharge line considerably.

The hot water supply system functioned satisfactorily. For one particular setting of the temperature regulator, the first heat exchanger raised the incoming fresh water from 65 to 115°F, and the second heat exchanger boosted it to 180°F.

Fresh peas, corn-on-the-cob, whole and diced potatoes were tested. Feeding the peas into the inlet funnel proved more difficult than anticipated. Some of the peas would float, and the following peas would (after rolling down the slide) strike them and bounce outside of the inlet funnel. This could be corrected by either reducing the velocity of the peas or raising the sides of the inlet funnel to confine them.

The major difficulty encountered was the poor flow of the vegetables through the glass tube. An insufficient rotary or swirling action allowed the vegetables to drag and hang-up too easily on the glass surface at the desired rate of flow. Increasing the rate of flow and length of tubing (the reason for the latter would be to retain the
same heating effect) does not appear to be the best solution. The most practical solution for this pilot plant appears to be the addition of a small single-stage centrifugal booster pump between the main hot water supply and the top variable-angle jet (figure 4). A higher water level would also be desirable. The present level of \( \frac{1}{2} \) inch above the top of the tube allows air to be sucked in too easily.

Tests with the larger vegetables indicated that the 70mm tube size would be required. The 60mm size would, of course, be satisfactory for smaller vegetables. As anticipated, the tests demonstrated the particular advantages of dielectric heating for diced potatoes. By floating them through the high-frequency field in water much cooler than the final blanching temperature, a thin but firm outer surface was achieved, thus avoiding overcooking of the surface and consequent disintegration produced by the usual blanching or cooking methods.

Probably the greatest doubt about the feasibility of floating vegetables through the dielectric field was the fear that the water would absorb too large a portion of the high-frequency power in comparison with the vegetables. To determine the ratio of energy absorption for water and vegetables, several test runs were made, using potatoes cut to a cylindrical shape and shoving them through by use of the injection mechanism. For the sake of simplification, the rate of water flow was pre-determined, the water was
not heated (the average temperature of the potatoes was assumed equal to the internal temperature, thus neglecting cooling effect of the water), the time the vegetables were exposed to the high-frequency field was the same for all runs (one minute), and the volume or mass ratio of vegetables to water was kept constant at two pounds of water to three of potatoes. It is doubtful if less water per pound of vegetable would be possible in practice with a hydraulically-controlled flow.

The frequency of the generator was between ten and thirteen megacycles, the maximum rate of energy absorption by the water and vegetables was $6\frac{1}{2}$ kw, and the water was Corvallis tap water (quite soft). Results of the first three test runs, with air surrounding the five flat-band electrodes, checked closely. For a 40% water ratio by weight, the water absorbed 20% of the energy. Conversely, the potatoes absorbed 80% of the power.

The effect of having distilled water surround the glass tube and electrodes could not be determined; the mass of water was relatively so great (approximately 80 pounds) that the temperature rise was too small to measure accurately. As previously mentioned, arcing interrupted the test with parallel and horizontal electrodes. The energy absorption ratio, though, was similar to that obtained with the other electrode arrangement. Table I on p.47 is a summary of the six test runs.
The results to date indicate that continuous-process high-frequency blanching is quite possible and that completion of this investigation is definitely warranted. Only further research will reveal the economic feasibility of the process. Incidentally, specific recommendations of redesign to achieve the optimum operating results have been furnished the Food Technology department, who will complete the investigation.
<table>
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<tr>
<th>TEST NO.</th>
<th>Electrode Arrangement</th>
<th>WATER</th>
<th>POTATOES</th>
<th>ENERGY ABSORPTION, %</th>
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</thead>
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<td></td>
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<td>WT.</td>
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<td>1</td>
<td></td>
<td>70 82</td>
<td>584 BTU</td>
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<td>72 79</td>
<td>42 BTU</td>
<td>70</td>
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<td>73</td>
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<td>Parallel, Air</td>
<td>69 72.5</td>
<td>18 BTU</td>
<td>77</td>
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</table>

1. Table is based on a volume ratio of 2# water to 3# potatoes.
2. Does not include heat absorbed by the distilled water in the heating tank.
3. Aroed before completion of test.

**TABLE I**

**DIELECTRIC HEAT ABSORPTION RELATIONSHIP OF POTATOES AND WATER**
BIBLIOGRAPHY


