7-6-1983

Domestic Water Heating with Microwave Radiation

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Abstract

Purpose of the Study

1. To determine if microwave radiation can be safely employed in a domestic water heating system.

2. To determine if microwave radiation can be efficiently and economically employed in a domestic water heating system.

3. To determine if microwave radiation can be effectively employed in a domestic water heating system.

Domestic Water Heating with Microwave Radiation

Industrial Technology
Research Paper

A Research Paper for Presentation
to the Graduate Faculty
of the Department of Industrial
Technology
University of Northern Iowa

In Partial Fulfillment of the Requirements for
the Non-Thesis Master of Arts Degree

by
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July 6, 1983

Approved by:

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ACKNOWLEDGMENTS

I wish to thank Dr. Rex Pershing, advisor, for his suggestions, guidance, and encouragement not only for this study, but throughout my time as a graduate student. A special appreciation is extended to Dr. Michael R. White, graduate faculty member, for his aid and constructive criticism toward the completion of this study.

I wish also to express my indebtedness to my wife, Judy Merchant, for the typing of this research paper, and also for her patience and understanding without which this study could not have been completed.

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CHAPTER 1

Introduction

Significance of the Study

Water heating has become so common place in American homes that having a system that produces an almost endless supply of hot water is considered to be a necessity. As can be seen in Table 1, energy usage for water heating is second only to that used for heating of space. Although almost 60 percent of the energy used in American homes is used for heating space, over one-fourth of that amount is used in water heating. This is slightly less than the combined energy usage of the next three categories.

Table 1

Energy Usage in American Homes

Area of Usage	% of Total
Heating of space	57.5
Water heating	14.9
Refrigeration	6.0
Cooking	5.5
Air conditioning	3.7
Lighting	3.5
Television	3.0
Food freezer	1.9
Clothes dryer	1.7
Other	2.3

(Campbell, 1978, p. 4)

Americans use and waste appalling amounts of hot water. As with many other resources, Americans use and consume many times the amount of heated water than is necessary for normal cleanliness. According to John Murphy in the Homeowners Energy Guide:

> We use up hot water in approximately this way: Everytime we take a shower we use about 10 gallons of hot water. An average clothes washer uses 22 gallons of hot water per regular washing cycle, and an automatic dishwasher uses about 15 gallons. (Campbell, 1978, p. 1)

Americans have come to depend on the availability of hot water with almost the same expectation as they have with the sun rising in the morning. This usage translates into a phenominal amount of hot water used by a family each year. According to Campbell (1978), that usage "averages out to 2,500 gallons of hot water a month for a family of 5 or 30,000 gallons a year" (p. 2). This amount of hot water could be reduced in many ways, but that is not the purpose of this study. Rather, this study will investigate a way of providing that hot water less expensively.

Energy is also wasted as the hot water is sitting in the pipes between the water heater storage tank and the faucet. Even if these pipes are insulated, though most are not, the sitting water loses some of the heat it once had. Campbell (1978) said that in "just testing the temperature of our shower water, ½ to 2 gallons of hot water is wasted per test" (p. 1). Great quantities of hot water are poured down the drain just to get the water to the right temperature for washing the hands, face, dishes, or, as stated above, to test the shower water.

Not only is energy wasted in the pipes between the storage tank and the faucet, but even more is lost from the storage tank alone. The amount of heat lost during storage is proportional to the surface area of the storage tank, the insulation surrounding the tank, and the temperature difference between the hot water and the air of the room in which the storage tank sits. The central factor of these four, however, is the R-value, or the thermal insulative value, of the insulation that surrounds the water heater storage tank.

> If you read that the R-value of a particular insulation is 20, that means that 1/20 (0.05) of a BTU of heat will pass through one square foot of the material in one hour if the temperature differential is one degree Fahrenheit. (Campbell, 1978, p. 65)

In reference to the above quote, the heat lost can be calculated from the surface area (A) of the tank, the R-value (R) of the tank insulation, and the temperature differential (T) between what the water heater thermostat is set at and the temperature in which it sits. Using the water heater of the test home in the study, it is calculated that a 50 gallon (189.11 liter) storage tank, which is 16 inches (0.406 meter) in diameter and five feet (1.52 meter) tall has a surface area of 23.7 square feet (2.20 square meters). The tank is insulated with urethane foam which has an R-value of 6.3 per inch (2.54 centimers, cm) of thickness. Since the tank is insulated with a two inch (5.08 cm) layer of this foam, the R-value of the insulation surrounding the storage tank is 12.6. In this example, the mean temperature of the room in which the storage tank sits was 60° Fahrenheit (F) (15.5° Celsius, C). With the water heater thermostat set at 120°F (48.9°C), this was a temperature differential of 60°F (15.5°C). Substituting the above values in the following formula: BTU's lost/hour = 1/R x T; it was found that 112.9 BTU's (0.03 kilowatt·hour, kWh) were lost per hour, or 2,708.6 BTU's (0.79 kWh) lost per day.

The lost heat in the above example may be more meaningful if it is converted back into heated water. "It takes 8.33 BTU's to heat a gallon of water one degree Fahrenheit" (Campbell, 1978, p. 3). If the source water is 54°F (12.2°C), as it is in the test home of this study, then the water must be heated 66°F (18.9°C) to reach the thermostat shut-off temperature. One gallon (3.78 liters) of 54°F (12.2°C) water heated to 120°F (48.9°C) uses 549.8 BTU's (.16 kWh) of heat (8.33 x 66). Using Campbell's daily water usage for the family of five, 2,775 gallons (10,389.5 liters), it is calculated that enough heat is lost in the above example to heat five gallons (18.9 liters) of the 54°F (12.2°C) to 120°F (48.9°C), (2,708.6 BTU's lost/day ÷ 549.8 BTU's/gallon = 4.93 gallons/day). This means that if all that lost heat could be saved, every two days the hot water used during a shower would have been heated free. In a year it could mean the savings of enough energy to heat 1,825 gallons (6,898.5 liters) of hot water or almost three-fourths the amount of hot water used in one month by the family of five, as stated by Campbell.

If the water heater storage tank could be eliminated, as well as the long runs of pipe between the tank and the faucet, then a considerable savings of energy could be realized. It is to this end that this study is aimed. This study will investigate if microwave radiation can be used safely, effectively, efficiently and economically to heat water for domestic application.

Statement of the Problem

How can microwave radiation be utilized in a domestic, non-storage water heating system?

Purpose of the Study

1. To determine if microwave radiation can be safely employed in a domestic water heating system.

2. To determine if microwave radiation can be efficiently and economically employed in a domestic water heating system.

3. To determine if microwave radiation can be effectively employed in a domestic water heating system.

Assumptions

1. It was assumed that impurities, if any, in the source water will not have a significant effect on the results of this study.

2. It was assumed that the water will absorb all of the microwave radiation generated by the magnetron.

Limitations

This study was limited by the funds available with which to build a test apparatus which would test magnetrons of different power ratings.

Delimitations

1. The frequency of microwave radiation used in this study was 2.45 gigahertz.

2. The distance between the water in the heating chamber from the microwave radiation source did not vary in this study.

3. This study was delimited to using only one size of magnetron, 700 watts (per FCC one liter test).

Definition of Terms

British Thermal Unit (BTU) is the amount of heat needed to raise one pound of water one degree Fahrenheit. One BTU is equal to 2.93×10^{-4} kilowatt·hour.

Electromagnetic waves are formed by simultaneous periodic variations of electric and magnetic field intensity. Included in the electromagnetic spectrum are radio waves, infrared radiation, visible light, ultraviolet radiation, X-rays, and gamma rays.

Giga is a prefix denoting one billion (10^9).

Hertz is a unit of frequency of a periodic nature and equal to one cycle change per second.

Kilowatt·hour (kWh) is a unit of energy denoting the expending of 1,000 watts for a period of one hour.

Klystron is a vacuum electronic tube used as an oscillator to generate microwave frequencies. It is usually employed in low-power applications.

Magnetron, also known as a cavity magnetron, was the first high-power microwave oscillator to be developed. The microwave frequencies are produced by an electron, under a strong perpendicular magnetic field, passing by a cavity in the cathode of the tube.

Microwave radiation is electromagnetic waves with frequencies between one gigahertz and 30 gigahertz.

Non-storage water heating system is a hot water producing apparatus which produces hot water as it is used and therefore eliminates the need of a storage tank.

Radiation field intensity is a term used to denote the strength of electromagnetic waves exposed to a given surface and is measured in milliwatts per square centimeter (mW/cm^2). Five mW/cm^2 is the maximum allowed by the Federal Communications Commission (FCC).

Source water is a term used in this study to designate the normal supply water to the test home.

Stabilization period is a five minute time period during which water is flowing through the test apparatus with or without power to the magnetron. At the end of the period the temperature of the discharge water from the test apparatus is read from the thermometer.

Sublimation is the point at which ice converts directly into water vapor without passing through the liquid stage.

CHAPTER 2

Review of Literature

Microwaves are electromagnetic waves similar in nature to any other electromagnetic waves, except for their high frequency and characteristics associated with these high frequencies. Like other electromagnetic waves, such as radio waves or even light, certain substances are transparent to microwaves, while other substances are opaque. Microwaves are found in the "frequency spectrum ranging approximately from 1 Giga Hertz (10^9 Hertz) to 30 Giga Hertz" (K. Gupta, 1979, p. 1). This means that the electromagnetic waves in this portion of the spectrum change polarity direction from one billion to 30 billion times per second. It was not until the "late 1930's, with further development during the Second World War,... that the development of the cavity magnetron led to the possibility of using even high frequencies for heating processes" (Barber, 1981, p. 401). The first application of microwave radiation was primarily in communications and radar detection applications. Since that time, applications for microwave radiation have been found in "physical research, in medicine, and in industrial measurements and also for heating and drying of agricultural and food products" (K. Gupta, 1979, p. 2). It is in these areas that further discussion was limited.

Microwave radiation does not heat substances in the same way as convential methods of heating. In the latter, "heat is transferred to the surface of the material to be heated by conduction, convection, and/or radiation and into the interior mainly by thermal conduction" (K. Gupta, 1979, p. 231). Heat produced by exposure of a substance to microwave radiation is produced directly within that substance. This principle takes advantage of the polar make-up of certain molecules. If a polarized substance (one side of the molecule is positively charged and the other negatively charged) is exposed to the electromagnetic field of microwave radiation, the molecules attempt to align themselves to that field. While attempting to align themselves within that field, at the frequencies of microwaves, the molecules are opposed by the viscous drag of the substance. The friction of these rapidly vibrating molecules actually generate the heat which is referred to as microwave heating.

The most common mechanisms for producing microwave radiation are "special oscillator tubes known as magnetrons and klystrons" (Copson, 1962, p. 7). Magnetrons are microwave oscillators with a high power output. Because of this, they are the most common source of microwave radiation for microwave heating. The ability to be able to vary the output power of the magnetron, coupled with the ability to exactly control the exposure time has made microwave heating very attractive to industry.

In the plastics industry, microwave radiation has been used to fuse plastics that can be heated by microwaves more effectively and efficiently than can be done by conventional methods of heating. Not only is microwave heating used in melt-fusing of plastics, but it can also be used in curing thermoset plastics. In one instance, it was reported the "cure times for thermosetting resins can be reduced 30-fold using microwave heating rather than ovens or presses dependent on thermal conductivity" (Strand, 1980, p. 64). The application of microwave heating to this type of process is very advantageous, since most plastics are poor thermal conductors. The "fastest cure that was able to be obtained in a 350^{o}F oven was 15 minutes,... but it was found by using microwave heating , that complete cures were obtained at 2.25kW in 45 seconds" (Strand, 1980, p. 67).

Time is not the only savings in using microwave heating in the plastics industry. The molds used in the processes referred to above were invisable to microwaves and the only item heated was the thermosetting plastics. The traditional method of heating the curing plastic involved heating the mold as well as the interior of the oven, consuming a great deal more energy than was necessary to cure the thermoset part. Strand (1980) reported that in using microwave heating rather than conventional methods "energy consumption in production (one of the prime contributors to processing costs) can be reduced by one third or more" (p. 67). He went on to say that this "provides these savings despite the fact that facility expenses are relatively high ($1,500 to $1,800 per installed KW of capacity" (Strand, 1980, p. 67).

The plastics industry is not the only industry to utilize microwave heating to accelerate the curing process of production items. Some foundries have found this application of microwave heating advantageous in curing cores and molds. Although there is no real energy savings from using microwave curing as opposed to conventional methods, it was found that the strip time of a mold or core, which normally had a cure time of ten minutes before being stripped from the pattern, could be greatly reduced. "Through microwave acceleration...the strip time would be cut in half" (Lukacek, 1981, p. 55). This savings in time would enable an increase in production with no, or only minimal, increases in energy costs.

Heavy industries do not have a corner on microwave heating applications. The textile industry has found that the application of the same principles can be profitable. The Peidmount Processing plant of Belmont, North Carolina, "formerly used only pressure dryers and port dryers to dry yarns following dyeing" (Richardson, 1981, p. 103). However, by realizing how readily water is heated by microwave radiation, the application of microwave heating proved to be very compatible with the drying of yarns. "The real advantage of the wave dryer is not so much the energy consideration, but rather quality consideration... Since it heats the water content of the package and not the yarns themselves, it can't over dry the good" (Richardson, 1981, p. 103).

The nuclear processing industry has even found an application for microwave heating. "Initial work has shown that microwave energy could be used to replace conventional heating in some processes,... with potential advantages particularly in fuel manufacture and waste treatment" (Simpson, 1982, p. 613). These advantages, again, are due to the principle of direct heating of a substance by microwave radiation, rather than the traditional method of heating by thermal conduction of the substance.

Industrial application of microwave heating has been carried over to medicine. A general explanation of the principle used in applying microwave heating in medicine is included here.

> The rate of microwave power absorption in most materials is proportional to its water content... Because the microwave signal penetrates most non-conductors, microwave power provides a most efficient means of applying heat uniformly throughout a body substance ... Because the heat does not have to be conducted through but is generated inside the body, microwave heating reduces the time needed for heating a body to a uniform temperature. (Baden Fuller, 1979, p. 5)

Though the use of microwave radiation in medicine is not limited to its application in heating, the following discussion will dwell only on the use of microwave heating in medicine as it relates to diathermy and hyperthermia. Diathermy is a treatment "where heat is produced to provide relief in afflictions situated in deep tissue" (C. Gupta, 1981, p. 403). Diathermy treatment, by producing a local temperature rise in tissue, produces an "increase in blood flow rate, cell membrane permeability and metabolic rate" (C. Gupta, 1981, p. 403). This process enhances healing and provides relief from pain. Effective diathermy treatment requires the tissue to be heated to a temperature of about 44^{o} Celcius. Surface heating to reach that temperature would be beyond the limits of toleration of the skin. "This problem can be overcome by selectively generating heat in the affected areas by controlled microwave radiation" (C. Gupta, 1981, p. 403). Because of the ability to selectively focus the microwave radiation to the area desired, the application of microwave heating makes it well suited for use in diathermy and hyperthermia.

Hyperthermia is a treatment in which tumor cells are "cooked" to damage and impede their growth without significantly affecting the surrounding healthy tissues. Because "cancerous tissues are dense and have less blood vessels per unit volume" (C. Gupta, 1981, p. 404), the radiated tumor does not as readily cook and lethal temperatures (to the cancerous tissue) can be generated.

Though the direct use of microwave heating to healing applications is a fairly recent adaptation to medicine, the principle of heating tissue with microwave radiation can be traced back to 1945. Ovens, where heat generation within the oven was by microwave radiation, "have been produced... since 1945" (Copson, 1962, p. 261). The normal frequency of microwave radiation used in microwave ovens is 2.45 gigahertz. Cooking at this frequency, also common to the frequencies used in many applications in industry and medicine, uses the same principles that are used to heat plastics, cure molds and cores, and warm body tissue. Most conventional means of cooking require the container to be first heated, then through thermal conduction, the food is cooked. More energy than needed is expended in cooking the food this way. "Compared to electric range cooking the microwave oven costs at least 25 percent less to operate as far as the consumption of electricity is concerned" (Copson, 1962, p. 314). As with the other applications of microwave heating, energy is not the only savings. Time savings is a plus also. One example of this is that "a frozen meal cooks in 1½ to 4 minutes in a microwave oven compared to 30 to 40 minutes cooking time in a regular oven" (Copson, 1962, p. 308).

Another application of microwave heating to tissue is in freeze-drying. Freeze-drying is the process of removing the water from a frozen substance by lowering the air pressure surrounding the frozen substance to the point where sublimation occurs. The problem of freeze-drying arises from the need to keep the substance frozen and yet provide the heat fusion and the heat of vaporization (675.6 calories per gram) to allow the ice to sublime without causing any melting of the substance. Although many methods of providing this heat have been tried, directly heating the substance, by using microwave radiation, has been one of the best ways to provide that heat. "This is due to the direct delivery of energy to the subliming region" (Copson, 1962, p. 235).

Microwave heating, then, saves energy and/or time in its application in different processes. The application of these principles to a domestic water heating system was the scope of this study. It investigated if the energy of microwave radiation can be efficiently and effectively transferred to water in a domestic water heating system. Also investigated will be the consideration of whether or not the time to heat adequate quantities of water, for domestic use, can be reduced by implementing microwave heating. If this is so, then it may be possible to eliminate the need for a storage tank, which is common to most domestic water heating systems. The elimination of that storage tank could possibly save considerable energy, as was shown in the example given in the Significance of the Study section. It is to these ends that this study was addressed.

CHAPTER 3

Methodology

Instrumentation

Certain instruments were necessary for the measurement of different variables in this study. These instruments were used in determining flow-rate of water through the test apparatus, detecting microwave radiation leakage, measuring temperature, determining electrical power consumption of the microwave generating source, and in determining water usage and electrical energy consumption of the test home system.

Flow-rate. Though there was no flow-rate meter used, per se, in this study, two instruments were used to determine the flow-rate. A graduated cylinder, calibrated in ounces, and a stop water, which timed to the tenth of a second, were used to calculate the rate of flow.

Radiation leakage. Since determination of whether or not microwaves could be safely used in this study was of primary importance, it was necessary to have an instrument that could detect the presence of microwave radiation at levels that would be harmful to people. A microwave radiation detection meter was built for that purpose. Its design was similar to that shown in Appendix A.

Temperature. Temperature determination was accomplished by a standard photographic Fahrenheit thermometer. The thermometer and calibration scale were encased in glass, allowing for complete immersion of the instrument.

Power consumption. The measurement of electrical power consumption was not measured directly, but was calculated from the voltage of the test home electrical supply and the amperage of the microwave radiation source. The voltage was measured by a standard commercial alternating current (AC) voltage meter. The amperage was measured by a standard commercial AC ammeter.

Test home system. It was necessary to have a point of comparison to determine the efficiency, effectiveness, and economy of the test apparatus. This was done by comparison to the water heating system of the test home. To make these comparisons, data were collected as to the amount of water that flows through the test home system for a given period and the consumption of energy to heat that water. These data were collected by using a standard water usage meter to measure the amount of water used and a standard kilowatt·hour meter to measure the consumption of energy to heat that water. The kilowatt·hour meter was installed in such a manner as to measure only the power consumed by the water heater.

Test Apparatus

The test apparatus was made from the following components: a source of microwave radiation, a heating chamber housing, a heating chamber, a holding basin, and a catch cup. A schematic depiction of the entire test apparatus is shown in Figure 1.

<u>Holding basin</u>. The holding basin was a five gallon (18.9 liters) container with an overflow hose on the side, 2.5 inches (6.35 cc) down from the rim and a shut-off valve 1.25 inches (3.18 cm) from the bottom on the front side of the container. The purpose of the holding basin was to provide a constant supply of source water without the problem of dealing with the pressure of the source water system.

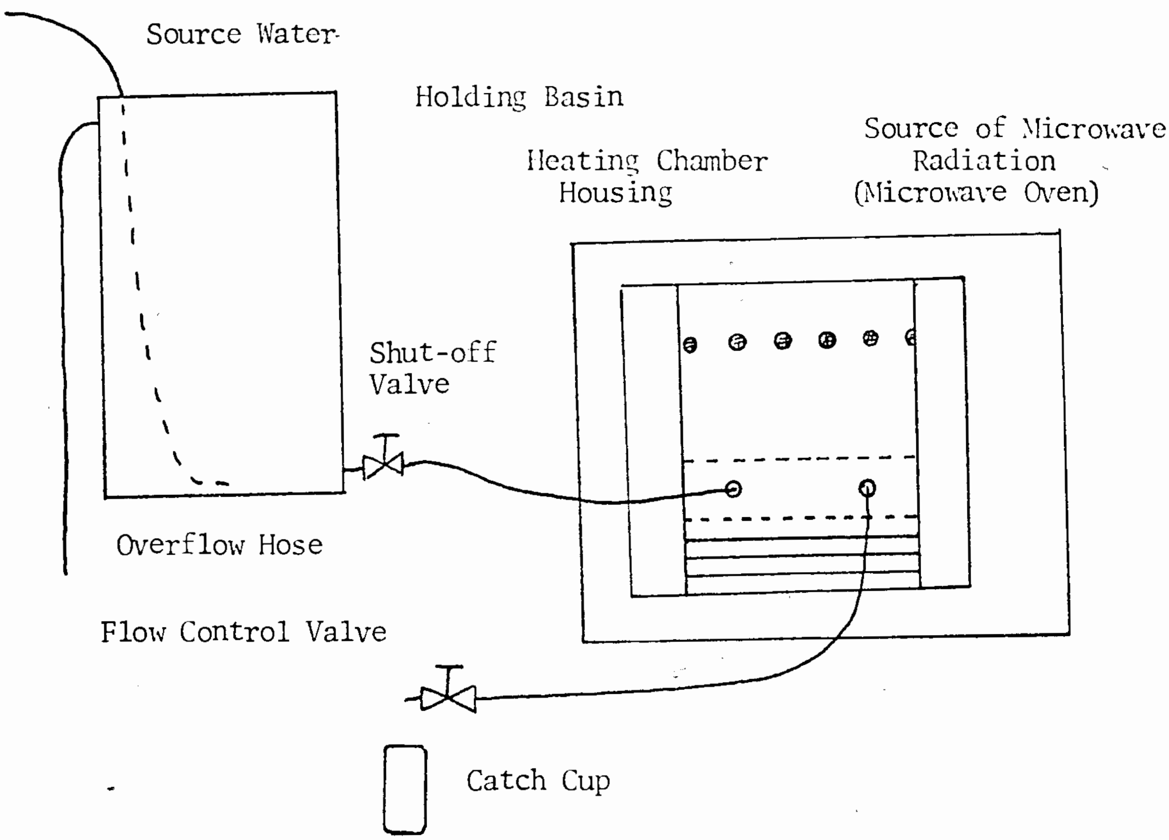

Figure 1. The testing apparatus used in this study.

Microwave source. The source of the microwave radiation was a 700 watt (per FCC one liter test) magnetron from a domestically available microwave oven (Amana Radarange, model RR-700). The microwave oven was modified so that the magnetron could be powered with the oven door open. The plastic "splatter shield", which covered the roof of the oven chamber, and the glass tray at the bottom of the oven chamber were removed to facilitate the mounting of the heating chamber housing to the roof of the microwave oven chamber.

Heating chamber housing. The heating chamber housing was a cylindrical aluminum container 10.5 inches (26.67 cm) in diameter and 7.5 inches (19.05 cm) deep. The properties of aluminum allow it to contain and reflect microwaves within the housing, with only negligible absorption of any of the microwave radiation.

Two inches (5.08 cm) down from the rim, half inch (1.27 cm) vent holes were drilled around the entire circumference of the housing. To prevent microwave radiation from escaping through these vent holes, the holes were covered by a strip of 18 x 16 mesh (i.e., 18 horizontal strands of wire per vertical inch (2.54 cm) and 16 strands of wire per horizontal inch) aluminum window screen. The screen was held in place with adhesive-backed aluminum tape.

Two brass fittings, an inlet and an outlet, were threaded into the housing side, two and a half inches up from the bottom, six inches apart. Within each fitting was an insert of the same type of aluminum screening as mentioned previously. The purpose of the screening was to prevent microwave radiation from escaping, while still allowing the flow of water into and out of the heating chamber.

The heating chamber housing was mounted on blocks of polystyrene foam to bring the rim of the housing in tight contact with the roof of the microwave oven chamber. To assure the containment of the microwave radiation within the heating chamber housing, adhesive-backed aluminum tape was used to seal the crack at the point of contact between the oven roof and the housing rim. Figure 2 shows a detail of the heating chamber housing.

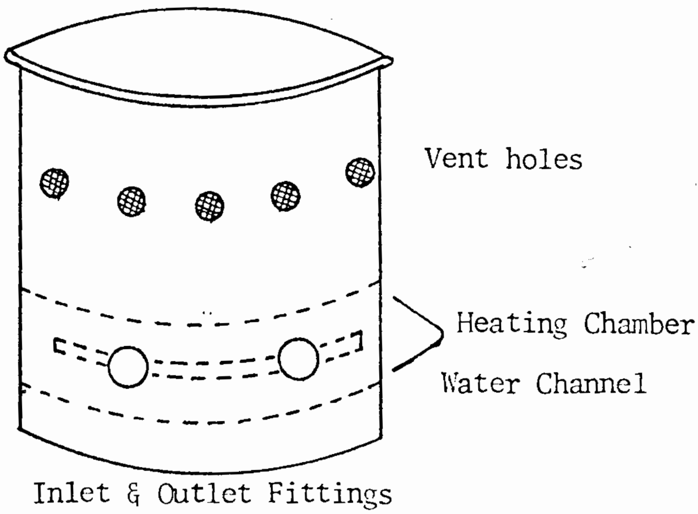

Figure 2. Detail of heating chamber housing.

Heating chamber. Contained within the housing was the heating chamber. The heating chamber was made of two circular pieces of one inch (2.54 cm) thick, closed-cell, rigid polystyrene foam sandwiched together. Polystyrene foam was chosen due to its transparency to microwave radiation, with only negligible absorption. A channel was cut into the bottom piece of rigid foam. The top and bottom pieces were then sealed together with hot-melt glue.

The design of the channel in the chamber was one of two designs. One design was a serpentine type channel 5/16 inch (0.79 cm) deep and 3/4 inch (1.90 cm) wide, as depicted in Figure 3. The channel of this type design held six ounces (177.28 milliliter, ml) of water.

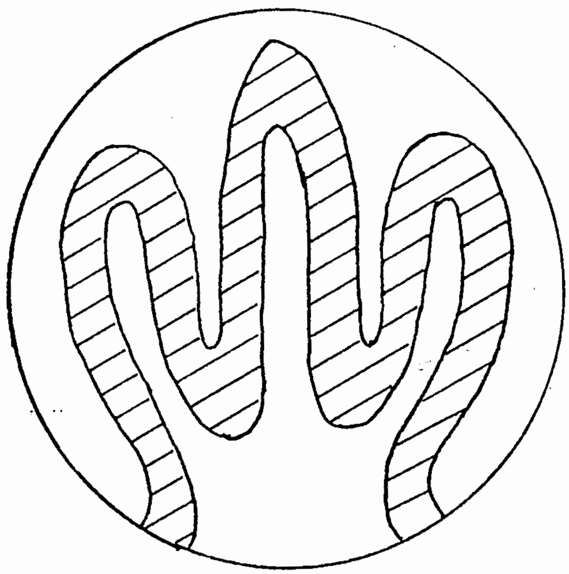

Figure 3. Serpentine channel design of heating chamber. (Shaded area is channel, cut in the foam.)

The second channel designed was two semi-circles 3/16 inch (0.48 cm) deep, with a 4¼ inch (10.80 cm) diameter. This type of channel held eight ounces (236.4 ml) of water. The two semi-circles were then connected by a three inch (7.62 cm) wide connecting channel as shown in Figure 4. The chamber covered the bottom of the housing and was connected and sealed to the hose fittings with hot melt glue.

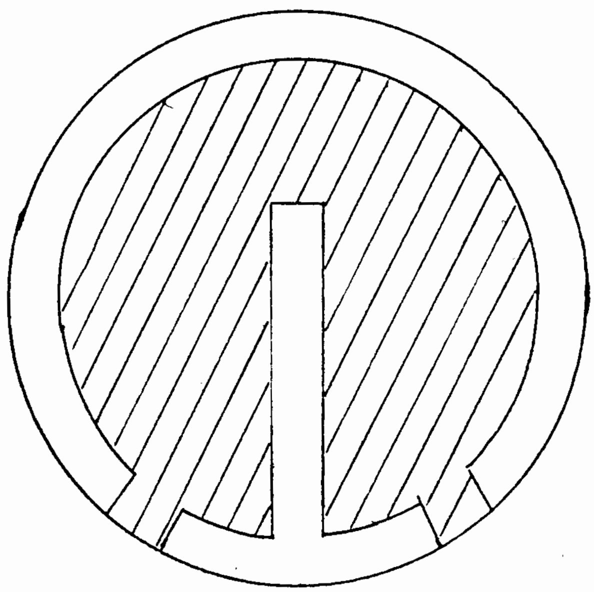

Figure 4. Double semi-circle design of heating chamber. (Shaded area is the channel that was routed in the rigid foam.)

Flow control valve and catch cup. At the discharge end of the outlet hose was the flow control valve. Its purpose was to regulate the flow rate of water through the test apparatus. The discharge water from the flow control valve flowed into the catch cup. This cup was a tall, small diameter cylinder in which the thermometer sat, halfway immersed. The volume of the catch cup was four ounces (118.2 ml).

Procedures

Test apparatus. The following procedures were used to gather data from the test apparatus. Water from the source flowed into the bottom of the holding basin through a hose. This assured that 54°F source water would flow into the test apparatus. If any water would have absorbed heat from the surroundings it would rise to the top and be discharged through the overflow hose. After allowing the holding basin to fill and begin to overflow through the overflow hose, water was allowed to flow through the heating chamber by opening the shut-off valve. A five minute stabilization period passed while the water flowed through the entire system. During this time, the power was off to the magnetron. This step was to determine whether the water would absorb any heat from the test apparatus. At the end of this stabilization period the thermometer was read and recorded.

A preliminary trial was conducted with the serpentine type heating chamber. The goal of this trial was to determine a water flow that would allow the discharge water temperature to reach and maintain 120°F (48.9°C). The flow-rate was controlled by opening or closing the flow control valve. The rate of flow was calculated from the time it took to collect an eight ounce (236.4 ml) sample. Since, for each flow-rate determination, the same sample volume (eight ounces, 236.4 ml) was taken, the only variable that would change was the time to collect the sample. Because of this, the change in flow-rate was indicated by the change in the sample collection time (SCT). At each change of flow-rate, at least three sample collections were taken and timed. This was to assure the accuracy of the time recorded for collecting the eight ounce (236.4 ml) sample. Samples continued to be taken until the SCT for three different samples fell within .3 seconds of each other. The average of these three collection times was then taken as the SCT of the flow-rate of that trial.

With each new flow-rate, at the end of the trial stabilization period (five minutes), the temperature of the discharge water was read and recorded from the thermometer in the catch cup. This was done to assure accuracy and consistency of the temperature readings that were taken for each flow-rate. After eight flow-rate changes the goal temperature (at least 120°F, 48.9°C) was reached and maintained. Since the flow of water at this flow-rate, for this final trial, was only a trickle, it was decided to conduct another series of trials with a heating chamber of a different design, which could possibly allow a more desirable flow.

The second heating chamber design was the double semi-circle. The same procedures, as were used in the trials with the serpentine design, were followed with this design. These, again, were as follows:

1. With power off to the magnetron and both the shut-off valve and flow control valve opened fully, an eight ounce (236.4 ml) sample was taken; and the time to collect that sample (SCT) was timed with a stop watch. From this the flow-rate could be calculated.

2. With the power then on to the magnetron, the water was allowed to flow through the test apparatus into the catch cup, which held the thermometer, for a five minute stabilization period. At the end of this period, the temperature was read and recorded, and the power shut off to the magnetron.

3. The discharge flow from the flow control valve would be reduced so that the SCT, for the eight ounce (236.4 ml), would be increased by two to two and a half seconds over that of the previous trial. This procedure was followed for the next seven flow-rate changes. For the five final flow-rate changes, the flow-rate was changed so that the SCT would be increased by five to six seconds over that of the previous SCT.

4. Step Two above was repeated, followed by Step Three, until the discharge water reached the goal temperature of 120°F (48.9°C).

While power was on to the magnetron, the electrical current flow of the microwave oven was monitored with an AC ammeter. The voltage of the receptible into which the microwave oven was plugged was monitored during the operation of the oven. The power consumption of the microwave oven was calculated from the measured amperage and voltage.

A microwave leakage detector (See Appendix A) determined the safety of utilizing microwave radiation in water heating application. At the beginning of each procedure Step Two, and periodically during each five minute stabilization period, the leakage meter was used to determine the amount of microwave radiation leakage.

Test home system. The following procedures were used to gather data about the water heating system of the test home. For a three week test period, the amount of water that flowed through the system was measured by a water usage meter. During this same test period, the amount of electrical energy consumed to heat this quantity of water was being measured by a kilowatt·hour meter. At the end of the test period both the gallon usage and electrical energy consumed was recorded.

CHAPTER 4

Analysis of Data

Safety

The data collected in this study were to provide a basis for determining the feasibility of using microwave radiation in a domestic water heating application. The first concern was to the safe use of microwave radiation in such an application. This was determined by the use of the microwave radiation leakage meter as described in Appendix A. In using this meter, the maximum needle deflection of the 50 micro-ampere meter movement, used in the leakage meter, was indicating 25 micro-amperes. By the conversion scale given in Appendix A, this translated into a radiation field intensity of 3.7 mW/cm^2. Five mW/cm^2 is the maximum safe level allowed by the Federal Communications Commission.

Efficiency

After the collection of data dealing with the determination of the degree of safety of such application of microwave radiation, all other data collected were related to determining the efficiency, effectiveness, and economy of using microwaves in heating water for domestic use. The source water temperature was 54°F (12.2°C). After allowing for the water to flow through the test apparatus for the five minute stabilization period and then reading the thermometer, it was found that the temperature of the discharge water was 54°F, the same as the source water.

The electrical power consumption was found to be 1,265 watts (W). This was calculated by using the formula for electrical power: P = I x E, where P is the power, I - the current, and E - the voltage. The measured current, while the magnetron was on, was 11 amperes. The voltage at the receptible, into which the microwave oven was plugged, was 115 volts.

Data were gathered from the two different designs of heating chambers. Each chamber had the same maximum flow-rate of 2.5 ounces (73.88 ml) per second. The capacity of the serpentine designed channel was six ounces (177.3 ml), while that of the double semi-circle (DSC) was eight ounces (236.4 ml).

With this background data in mind, the data collecting proceded to measure the temperature changes as the flow-rate was varied. Though the flow-rate was not measured directly, but was calculated from the time (sample collection time, SCT) required to collect an eight ounce (236.4 ml) sample, the only data necessary in determining the flow-rate was the SCT. Table 2 shows the resulting temperature for each flow-rate change, compared to the SCT for an eight ounce (236.4 ml) sample at that flow rate, for the serpentine heating chamber. Table 3 shows the same data, but for the DSC heating chamber.

Table 2

Resulting Temperature Versus the SCT for an Eight Ounce (236.4 ml) Sample for the Serpentine Heating Chamber Design

Trial #	Temperature		SCT
	°F	°C	sec.
1	74	23.3	15.5
2	78	25.6	18.5
3	82	27.8	21.0
4	85	29.4	25.5
5	91	32.8	34.0
6	94	34.4	38.0
7	100	37.8	41.5
8	123	50.6	58.0

Table 3

Resulting Temperature Versus the SCT for an Eight Ounce (236.4 ml) Sample for the DSC Heating Chamber Design

Trial #	Temperature		SCT
	°F	°C	sec.
1	59	15.0	5.5
2	63	17.2	7.5
3	67	19.4	10.0
4	77	25.0	12.0
5	82	27.8	15.5
6	86	30.0	18.0
7	89	31.7	20.0
8	92	33.3	26.0
9	104	40.0	31.5
10	110	43.3	36.0
11	118	47.8	40.0
12	124	51.1	45.0

Tables 4 and 5 show similar data, but in these tables the temperature is shown compared to the flow-rate as calculated by dividing the sample volume by the SCT.

The data of Table 4 and 5 have been combined and represented graphically in Figure 5. From this, it can be seen that the DSC heating chamber design is a better design, since the water reaches a higher temperature at a greater flow-rate than it does in that of the serpentine design.

Table 4

Resulting Temperature from Varied Flow-Rates in the Serpentine Heating Chamber Design

Trial #	Flow-Rate		Temperature	
	oz./sec.	ml/sec.	°F	°C
1	0.52	15.37	74	23.3
2	0.43	12.71	78	35.6
3	0.38	11.23	82	27.8
4	0.31	9.27	85	29.4
5	0.24	7.09	91	32.8
6	0.21	6.21	94	34.4
7	0.19	5.70	100	37.8
8	0.14	4.14	123	50.6

Table 5

Resulting Temperature from Varied Flow-Rates in the DSC Heating Chamber Design

Trial #	Flow-Rate		Temperature	
	oz./sec.	ml/sec.	°F	°C
1	1.45	42.85	59	15.0
2	1.07	31.62	63	17.2
3	0.80	23.64	67	19.4
4	0.67	19.80	77	25.0
5	0.52	15.37	82	27.8
6	0.44	13.00	86	30.0
7	0.40	11.82	89	31.7
8	0.31	9.16	92	33.3
9	0.25	7.39	104	40.0
10	0.22	6.50	110	43.3
11	0.20	5.91	118	47.8
12	0.18	5.32	124	51.1

Because the DSC heating chamber was a superior design to that of the serpentine design, further discussion will be limited to data that relates to the DSC design. The next area of consideration is the degree of temperature change in relation to the energy expended to produce that change in an eight ounce (236.4 ml) sample. The expended energy is calculated in the following way. Since energy can be expressed in either watt·seconds (Ws) or BTU's, both will be shown. Watt·seconds are calculated by multiplying the power consumed by the microwave oven (1,265 W) times the seconds of the SCT. From the resulting answer in Ws, the energy expended in units of BTU's can be derived by multiplying the answer in Ws times the conversion factor of 9.484×10^{-4}. Table 6 shows the degree change in temperature, from the temperature of the source water, compared to the energy expended for each temperature change.

Not all the energy expended, in the form of microwave radiation, was abosrbed by the water. To calculate the amount of energy absorbed, the weight of the sample in pounds, was multiplied times the Fahrenheit degree change of the water temperature for that trial from the source water temperature (BTU's absorbed = sample weight x ^{o}F). The weight of the eight ounce sample was 0.52 pounds (2.32 newton). Table 7 shows a comparison of the energy expended to that which was absorbed.

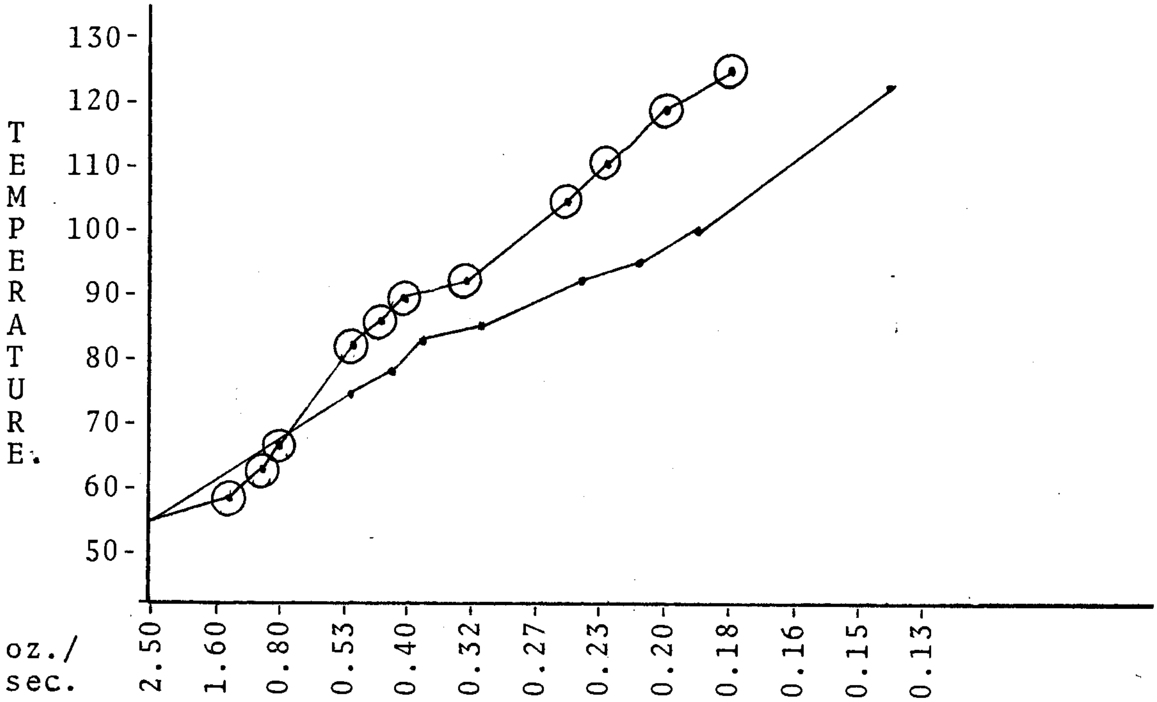

Figure 5. A comparison of temperature/flow-rate of the Serpentine and of the DSC heating chamber designs.

Table 6

Change in Temperature Versus Energy Expended per Eight Ounces (236.4 ml) of Heated Water for the DSC Heating Chamber Design

Trial #	Temperature from 54°F (12.2°C)		Emergy expended	
	°F	°C	Ws	BTU's
1	5	2.8	6,957.5	6.6
2	9	5.0	9,487.5	9.0
3	13	7.2	12,650.0	12.0
4	23	12.8	15,180.0	14.4
5	28	15.6	19,607.5	18.6
6	32	17.8	22,770.0	21.6
7	35	19.5	25,300.0	24.0
8	38	21.1	32,890.0	31.2
9	50	27.8	39,847.5	37.8
10	56	31.1	45,540.0	43.2
11	64	35.6	50,600.0	48.0
12	70	38.9	56,925.0	54.0

Table 7

Energy Expended Versus Energy Absorbed per Eight Ounces (236.4 ml) of Heated Water for the DSC Heating Chamber Design

Trial #	Energy in 10^{-3} kWh Expended/Absorbed		Energy in BTU's Expended/Absorbed	
1	1.93	0.76	6.6	2.6
2	2.63	1.37	9.0	4.7
3	3.51	1.98	12.0	6.8
4	4.22	3.51	14.4	12.0
5	5.45	4.27	18.6	14.6
6	6.33	4.88	21.6	16.7
7	7.03	5.32	24.0	18.2
8	9.14	5.79	31.2	19.8
9	11.07	7.63	37.8	26.1
10	12.65	8.54	43.2	29.2
11	14.06	9.77	48.0	33.4
12	15.81	10.67	54.0	36.5

As can be seen from Table 7, a considerable amount of energy was lost from that which was expended to that which was absorbed. Table 8 shows the amount of energy lost for each trial and the corresponding efficiency of each trial.

It is interesting to note that the efficiency increased to a point, then gradually began to decline. When the percentage of efficiency, for each trial, is graphed against the change in water temperature from that of the source water, an interesting curve results (See Figure 6).

Table 8

Energy Lost of that Expended per Eight Ounces of Heated Water for the DSC Heating Chamber Design

Trial #	Energy lost (Expended-Absorbed)		Efficiency of conversion (Absorbed÷Expended)
	10^{-3} kWh	BTU's	%
1	117	4.0	39.4
2	126	4.3	52.2
3	153	5.2	56.7
4	71	2.4	83.3
5	118	4.0	78.5
6	145	4.9	77.3
7	171	5.8	75.8
8	335	11.4	63.5
9	344	11.7	69.0
10	411	14.0	67.6
11	429	14.6	69.6
12	514	17.5	67.6

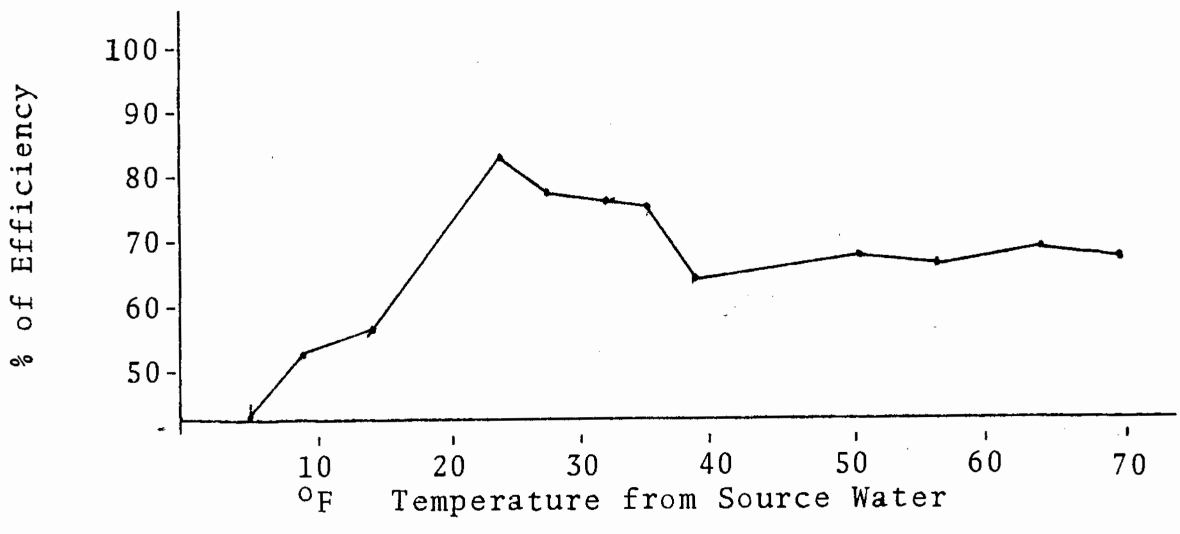

Figure 6. A comparison of the efficiency, of energy conversion from microwave radiation to heat, to the change in temperature from the source water temperature.

Economy

Economy is another area where determination is made by comparison to the test home. For the purpose of this study, the criteria was that the test apparatus must be at least as economical as the water heating system of the test home. During the test period 1,715.9 gallons (6,486.1 liters) of water flowed through the water heating system and 319 kWh of energy was consumed in heating this quantity of water. This means that .186 kWh per gallon (3.78 liters) of heated water was required, or 1.45×10^{-3} kWh per ounce (29.55 ml). From Table 7 it can be calculated that the test apparatus used 1.97×10^{-3} kWh per ounce (29.55 ml) to heat the water to 124°F.

Effectiveness

The data reported thus far have been related to the determination of the efficiency of the test apparatus in heating water. It is more difficult to collect data related to the effectiveness of the test apparatus. Effectiveness, for the purpose of this study, will be defined as a water heating system that produces at least the same amount of hot water as does the test home system under the following conditions:

1. The flow-rate must be equal to that of the shower set at its minimum flow-rate: 3.01 ounces (88.95 ml) per second, of which 1.89 ounces (55.85 ml) per second is hot water.

2. The temperature of the hot water must be at least 120°F (48.9°C).

By comparing the above conditions to the data contained in Table 5, it becomes evident that the test apparatus would not be accepted as being effective. A more indepth analysis of the data, as it relates to the efficiency, economy, and effectiveness, will be given in the Discussion section of Chapter 5.

CHAPTER 5

Summary/Discussion/Conclusions/Recommendations

Summary

Statement of the problem. How can microwave radiation be utilized in a domestic, non-storage water heating system?

Purposes of the study. To determine if microwave radiation can be (a) safely, (b) efficiently, (c) economically, and (d) effectively employed in a domestic water heating system.

Methodology. The test apparatus was made up of two basic parts: the microwave radiation source and the water heating chamber. The microwave source was a 700 watt (per FCC one liter test) magnetron from a domestically available microwave oven (Amana Radarange, model RR-700).

The water heating chamber was made up of two circular pieces of one inch (2.54 cm) thick, closed-cell, rigid, polystyrene foam. In one of these pieces a channel was routed to allow a path for the water to flow. After the channel was made, the two pieces were "sandwiched" together with the seam (where the two pieces joined each other) being sealed with hot-melt glue. This chamber was then horizontally mounted in a cylindrical aluminum container, the heating chamber housing. Into the front side of this container were mounted two hose fittings, which also reached the channel that had been cut into the one side of the heating chamber. Hot-melt glue, again, was used to seal around these fittings so that no water would leak as it flowed through the inlet fitting into the chamber and out the outlet fitting. The heating chamber housing, with the heating chamber mounted inside, was mounted into the modified oven as described above.

Source water, whose temperature was 54°F, was allowed to flow through the test apparatus at varying flow-rates while the magnetron was radiating microwaves. This microwave radiation was absorbed by the water, causing it to be heated. The temperature of the heated water was recorded for each different flow-rate. The electrical power consumption of the microwave oven was also monitored and recorded, as was any leakage microwave radiation. The determination as to the safety, efficiency, economy, and effectiveness of the test apparatus was then made from these data that were gathered.

Discussion

The primary concerns of this study were to collect data that could be used to determine whether microwave radiation could successfully be employed in a domestic, non-storage water heating system. Since microwave radiation of the frequency used, 2.45 gigahertz, can be harmful to humans by causing severe burns, the question as to the safety of such an application of microwaves must first be answered. In measuring the radiation field intensity of the leakage microwave radiation, it was found to be 3.7 mW/cm^2. This is well within the minimum safe level of 5 mW/cm^2 allowed by the FCC.

With the question of safety answered, it was necessary to proceed to determine the degree of efficiency of the test apparatus in using microwaves to heat water. As seen in Table 8, the greatest efficiency was 83.3 percent. However, at that level of efficiency, the water was being heated to only 23°F (12.8°C) above that of the source water, or to 77°F (25°C). Since the goal temperature of the study was at least 120°F (48.9°C), one must consider the efficiency of the test apparatus at the temperature of 124°F (51.1°C) reached in Trial #12. At that point the efficiency was only 67.6 percent. To make a comparison to the efficiency of the test home system it is necessary to calculate that efficiency from the data gathered on the system. During the test period, the test home system used 319 kWh to heat 1,715.9 gallons (6,486.1 liters) of water to 120°F (48.9°C). The following calculations were made to make that efficiency determination about the test home water heating system.

1. The weight of the hot water used during the test period = 1,715.9 gal. x 8.33 lbs./gal. = 14,293.45 lbs.

2. The temperature differential between that of the water heater thermostat setting and that of the source water = 120°F - 54°F = 66°F.

3. The minimum BTU's required to heat 1,715.9 gallons of water to 120°F = 14,293 lbs. x 66°F = 943,367.5 BTU's.

4. To convert BTU's to kWh = 943,367.5 BTU's x .0002927 BTU's/kWh = 279.12 kWh.

5. The efficiency of the test home system = 276.12 kWh ÷ 319 = 86.6%.

Since the test apparatus was a non-storage water heating system, the efficiency of such a system must be greater than that of a storage-type system, as was the test home system, or it is not acceptable. To produce 120^{o}F (48.9^{o}C) water, the test apparatus falls far short with consideration to efficiency.

Economy is the next consideration to be addressed. As with efficiency, economy is determined by comparison to that of the test home system. To be acceptable, the test apparatus must be as economical to operate as the water heating system of the test home. In the section entitled "Economy" of Chapter 4, it was reported that the test home system required 1.45 x 10^{-3} kWh per ounce (29.55 ml) to heat water to at least 120^{o}F (48.9^{o}C). The test apparatus used 1.97 x 10^{-3} kWh per ounce (29.55 ml) to heat water to 124^{o}F (51.1^{o}C) or 1.75 x 10^{-3} kWh per ounce (29.55 ml) for 118^{o}F (47.8^{o}C) water. At first consideration, there does not seem to be too much difference between the value given for the test home system or either of the other two values given for the test apparatus. However, if the lesser test apparatus value was used to heat a quantity of hot water comparable to that which was used during the test period, one finds that the small difference results in a considerable amount (1,715.9 gal. x 128 oz./gal. x 0.00175 kWh/oz. = 65.36 kWh). At the present rate per kWh (5.45¢/kWh) for the test home, this translates into an extra cost of $3.56, had the test apparatus been used to heat the water used in the test home during the test period. Although this is not a great amount of money, the test apparatus does not fulfill the requirement of being at least as economical as the water heating system of the test home.

The last consideration was the effectiveness of the system. As with the previous two considerations, effectiveness was defined by comparison of the test apparatus to the test home system. To be considered minimally effective, the test apparatus must have produced 120°F water at the flow-rate of 1.89 ounces (55.85 ml) per second (See the section entitled "Effectiveness" in Chapter 4 to understand how the above standard, 1.89 oz./sec. at 120°F was arrived). The greatest flow-rate that the test apparatus was able to produce, with water of at least 120°F (48.9°C), was 0.18 ounces (5.32 ml) per second. In considering the effectiveness of the test apparatus, it is evident that here too it falls far short of the minimum requirement.

Conclusions

1. Microwave radiation can be safely used in applications to domestic water heating systems.

2. The design of the test apparatus used in this study

does not allow for an efficient absorption, by the water, of the microwave radiation. At certain flow-rates, there was considerable loss of energy expended to that which was absorbed.

3. The test apparatus could not provide an effective flow (as defined in this study) of water heated to at least 120°F (48.9°C).

4. The test apparatus did not prove to be an economical method of heating water for domestic application, since the energy required per ounce of 120°F (48.9°C) water was 10.17 times greater than the standard electrical, storage-type water-heating system of the test home. A consideration, also, to the initial installation expense ($1,500--$1,800 per kilowatt for industrial application) that could be considerably greater than any presently available domestic water-heating system, points to the economical unacceptability of the designed application of microwave radiation in this study.

5. There seems to be a relationship between the efficiency of microwave radiation absorption in water to the flow-rate of the water through the test apparatus. This is pointed out in Table 8, where the flow-rate of Trial #4 provides the most efficient absorption of microwave radiation, with the efficiency declining from this point with either an increase or decrease of flow-rate.

Recommendations

The following are suggestions for further study in investigating the feasibility of microwave heating of water for domestic applications:

1. A magnetron of greater power could be used to determine whether a more effective flow-rate could be obtained.

2. The possible benefits of ganging two or more magnetrons, of the same power rating as the one used in this study, into stages, should be investigated. If the flow-rate, that would allow for the most efficient absorption of microwave radiation, could be found, the ganging of stages may produce a flow-rate that would be acceptable.

3. A greater amount of microwave radiation absorption might be realized by using a heating chamber design that would allow for a thinner sheet of water with a greater surface area.

4. A heating chamber design, in which the water is atomized into the chamber, may prove to be a way of providing a more effective surface area for the absorption of microwave radiation.

5. Further investigation could be done to determine if the distance that the heating chamber is place from the source opening of the microwave radiation has any effect on the efficiency of absorption.

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