To the Graduate Council:

I am submitting herewith a thesis written by Randall D. Whorton entitled "Research, Design, and Development of a Central Paste Wax Distribution System for Investment Casting Production." I recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Mechanical Engineering.

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RESEARCH, DESIGN, AND DEVELOPMENT OF A CENTRAL PASTE WAX DISTRIBUTION SYSTEM FOR INVESTMENT CASTING PRODUCTION

A Thesis

Presented for the

Master of Science

Degree

The University of Tennessee, Knoxville

Randall D. Whorton

December 1978

1373288

ACKNOWLEDGEMENT

The author wishes to express his appreciation to Dr. R.L. Young, Assistant Dean at the University of Tennessee Space Institute, for his comments, guidance, and very helpful advice during this design.

Sincere appreciation is due Southern Tool for their financial and labor support. This design and test would have been impossible without their very strong backing and encouragement. It is true satisfaction to be a part of their drive and ambition in exploring totally new areas of technology. The author also wishes to thank the various company's mentioned within this paper for their cooperation in making this a successful endeavor.

Special thanks are due the author's wife, Marcella, for her patience and understanding during the period of graduate work and for the typing of the manuscript. Thanks are also due the author's parents for their encouragement and support from the time he first began his college work.

ABSTRACT

Southern Tool's investment casting facility was experiencing an increased demand for precision castings made by the age old "lost wax" process. As production was stepped up in response to this demand, new and better methods of production were sought to increase both quality and efficiency. A basic part of producing castings by the "lost wax" process requires the making of a wax pattern having geometry and dimensions of the metal casting to be made. This wax pattern is made by injecting a special investment casting wax, commonly in the paste condition, into a metal die. In the process of making the wax patterns, liquid wax was commonly cooled to the paste temperature by pouring the liquid wax into a heated tank, allowing heat to be lost or transferred to the surroundings until the desired temperature was reached, and then maintaing the wax at this temperature. This method of cooling wax was very slow and cumbersome to the production process. Due to the difficulty of cooling by other methods and subsequent problems involved in transferring the paste wax

to the work areas, few significant developments had been made in this area.

A continuous production system capable of cooling the liquid wax to the non-Newtonian paste condition and supplying the wax to the desired location was designed and developed. Cooling was accomplished by means of a scraped-surface heat exchanger which had been previously used in similiar non-Newtonian applications. Flow data was taken and the resulting flow curve was plotted for paste wax at 145°F. The particular casting wax utilized for testing was Freeman Manufacturing Company's No. 5350-H with a melting point of 195°F. Procedures for calculating flow parameters in various pipe sizes were investigated and analytical procedures were established.

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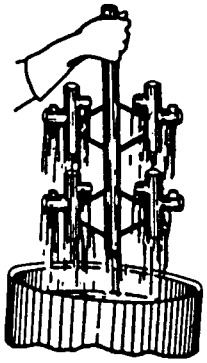
A	Cross-sectional area
CPS	Centipoise (viscosity)
Ckt	Circuit
D	Diameter
du/dy	Shear rate
H	Heat flow
L	Length
P	Pressure
ρ	Density
$\triangle P$	Pressure differential
Q	Flow rate
r	Radius
R_e	Reynolds number
RPM	Revolutions per minute
t	time
τ	Shear stress
τ_ω	Shear stress at wall
V	Flow velocity
μ	Absolute viscosity

I. INTRODUCTION

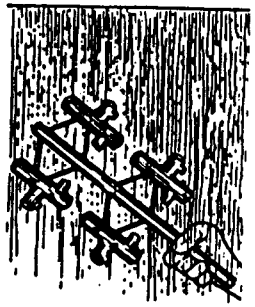
The basic process involved in the production of investment casting has been used for centuries. Historically the "lost wax" process dates before the great pyramids of Egypt with World War II marking the beginning of production parts utilizing this age old process. Today shortcuts which provide finished, precision parts without costly machining, welding, and assembly are needed more than ever. Investment casting is, in many instances, the answer to cutting production costs involved in complicated assemblies which formerly required many machining hours, fastners, welds and subassemblies. The production of modern investment casting has become a high technology business illustrated very simply in Figure 1 and explained in the following paragraphs.

1. Making of the Pattern (Figure 1a)

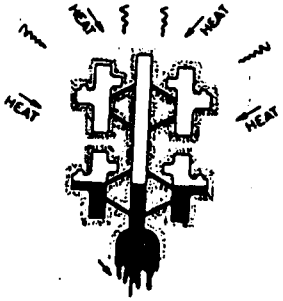
The process begins with fabrication of a one-piece heat dissolvable pattern. Although other materials have been utilized, a special investment casting wax is normally



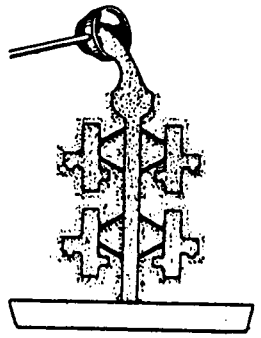
c. *Ceramic Slurry Coating*



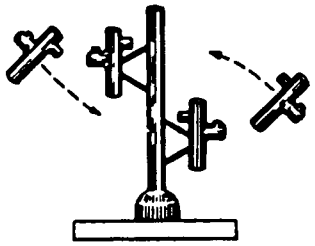
d. *Ceramic Sand Coating*



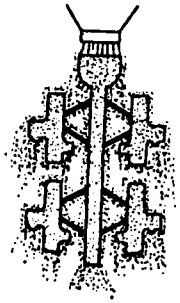
e. *Shell De-Wax*



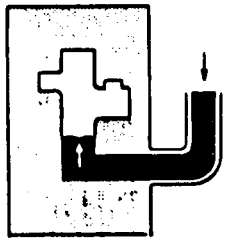
f. *Casting*



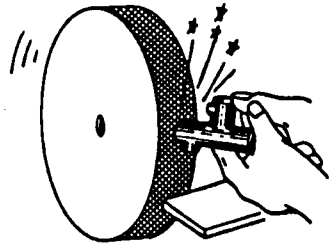
b. *Pattern Clustering*



g. *Cleaning*



a. *Pattern Fabrication*



h. *Finishing*

Figure 1. Investment Casting Process

used in this process. The pattern is made by injecting this special wax in liquid or paste form into a metal die and allowing the wax to solidify. Die complexity varies considerably depending upon the method of production (manual or automated), the production quantities, and the complexity of the part.

The wax patterns have the same geometry that is required in the finished product; however, they are made slightly oversize to compensate for shrinkage which occurs during pattern and metal solidification.

The pattern will have one or more "gates" which are normally located at or near the heaviest sections of the part. The gate or gates are required to: (a) attach the wax patterns to the "sprue" to form a cluster, (b) provide a draining passage for the pattern wax as it melts upon heating and (c) guide molten metal into the pattern cavity in the pouring operation.

2. Pattern Clustering (Figure 1b)

Wax patterns are fastened by the gate to one or more wax sprues which are in turn attached to a ceramic pouring

cup. Patterns, sprues, and ceramic cup comprise the "cluster" or "tree". For simplicity a single sprue is shown in Figure 1b.

3. Ceramic Shell Building.

The cluster (or tree) is then dipped into a ceramic slurry, removed, and allowed to drain (Figure 1c). After draining, the slurry-coated cluster is then coated with a fine ceramic sand (Figure 1d) and allowed to dry. After drying, the process is repeated again and again using coarser and coarser ceramic sand until a self-supporting shell is formed. This shell may range in thickness from 3/16 to 5/8 inches.

4. Shell De-Wax (Figure 1e).

Once the desired shell thickness is obtained and allowed to dry, the cluster is placed in a high temperature furnace or steam autoclave where the wax pattern melts and runs from the shell through the gates, sprues, and ceramic pouring cup. This leaves only a ceramic shell mold with desired geometry and dimensions which can be used in the foundry.

5. Casting (Figure 1f).

In the foundry, the ceramic mold is fired to burn out the last traces of pattern wax and to allow a degree of temperature compatibility between mold and molten metal. After this is accomplished, the hot mold is immediately filled with molten metal which enters the pattern cavity by way of the ceramic cup, sprues, and gates. Once the mold is filled with the desired metal alloy, the mold is allowed to cool prior to the cleaning process.

6. Cleaning the Metal Casting (Figure 1g).

As the ceramic mold filled with liquid metal cools, the mold will begin to crack away from the metal casting. The ceramic mold material which does not fall away from the casting on its own must now be removed. This is accomplished by vibration, shot blasting, and chemical processes.

7. Finishing (Figure 1h)

After all ceramic material is removed from the metal casting, individual castings are removed from the metal cluster by means of cut-off wheels and belt grinding.

Generally, the individual casting is then sand blasted to obtain a smooth finish. The casting is then ready for secondary operations such as heat treating, machining, plating, and inspection prior to shipment or use.

II. STATEMENT OF THE PROBLEM

A. Paste Wax Extrusion

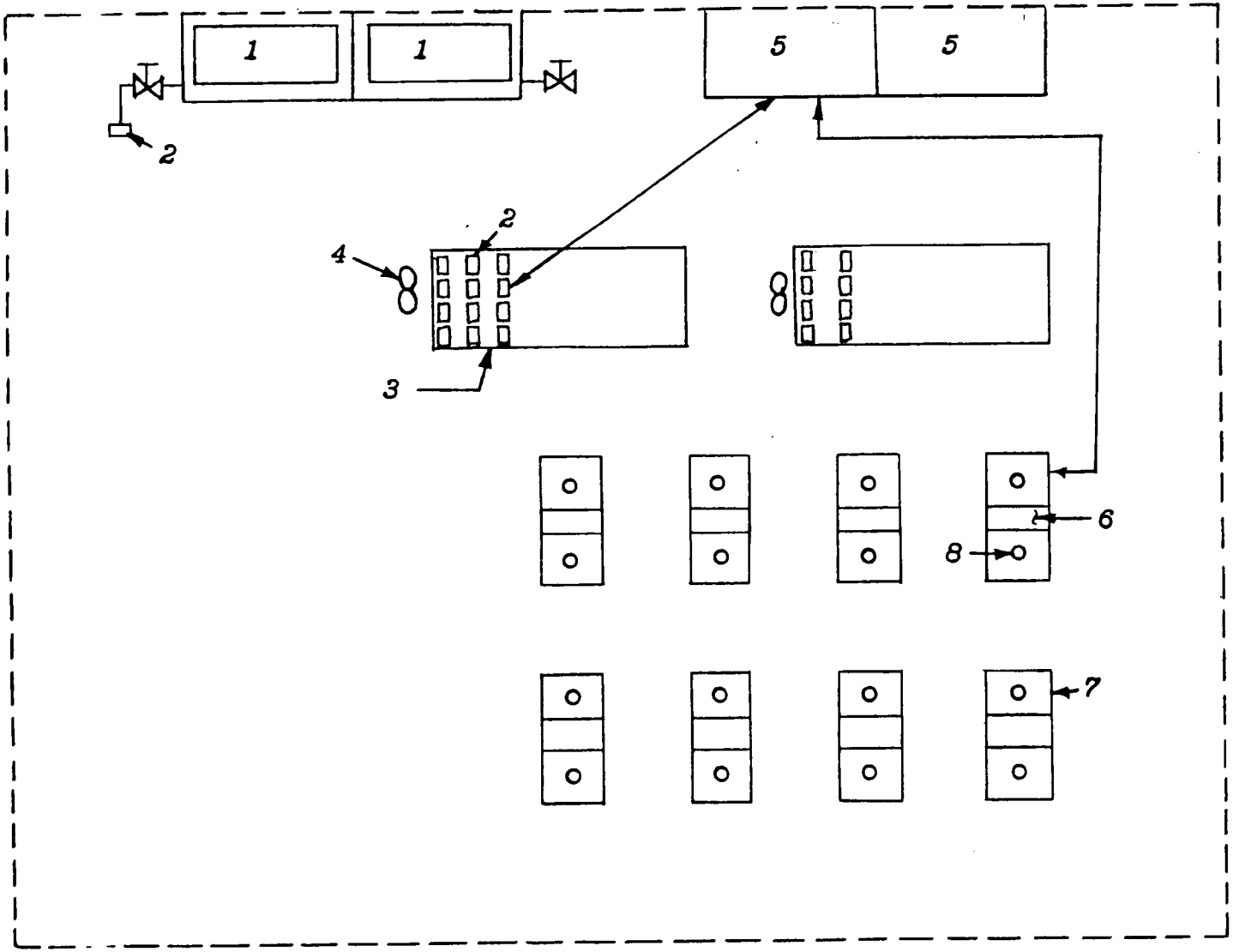
At Southern Tool's investment casting facility wax at a paste temperature of approximately 145°F is extruded into the metal die for fabricating wax patterns. Paste wax extrusion is preferred by Southern Tool over liquid wax injection for several very good reasons. First, liquid injection requires longer periods of cooling time after the metal die is filled with wax. Second, liquid injection yields greater volumetric shrinkage of the wax pattern. Longer periods of cooling time requires more production time. Some investment casting firms overcome this problem by employing water cooled metal dies and platens. These same facilities can be equally applied to paste extrusion with still shorter cooling periods and less production time resulting in less cost to customers. The more shrinkage involved in the process, the harder it is to control critical dimensions. The real advantage of liquid injection comes into view only when thin sections and, perhaps, large dies are required. It would be a

mistake to inject dies with liquid wax when it is not required and, although Southern Tool has the capability of liquid injection, currently all production parts are paste extruded with very good results.

B. Wax Flow with Existing System

The current method of transferring paste wax into the extrusion tubes of the wax press is the primany barrier to increased production at Southern Tool. Increased production could be obtained by increasing equipment, personnel, and facilities; however it is, by far, more desirable to eliminate these requirements through advances in technology whenever possible.

Figure 2 shows the flow of wax currently in use for production of wax patterns. Located within the wax room of the production facility are several wax melting tanks where investment casting wax is melted from a solid, at ambient temperature, to a liquid, at approximately 200°F. Tanks are commercially available in various sizes designed specifically for this purpose. Normally a minimum of two tanks are used. One tank which is in use



1—Wax Melting Tank

2—Wax Handling Pan

3—Cooling Table

4—Fan

5—Large Wax Holding Oven

6—Small Wax Holding Oven

7—Wax Press Work Station

8—Wax Press Extrusion Tube

Figure 2. Wax Flow Within Wax Room.

contains wax previously melted to the liquid state while the other is in the melting process. This gives one tank which is available for use at all times. Once the wax is melted, it is then drawn from the melting tank, by means of a valve, into small pans approximately $10\frac{1}{2}$ inches long, 5 inches wide, and $2\frac{1}{2}$ inches deep. The size of the pan is small to facilitate the many succeeding handling operations. The small pans are next placed onto a cooling table where a fan moves room temperature air across the table, cooling the wax to the desired extrusion temperature of 145°F. As many as 42 pans may be upon each cooling table and several tables might be in use depending upon the quantity of wax required for production rates. When the extrusion temperature is reached, the pans are transferred into large, wax holding ovens capable of retaining approximately 60 pans each. Here the wax is held at extrusion temperature for several hours to assure adequate temperature distribution within the pan. As operators of the wax presses require additional wax, the wax is removed from the large holding oven and transferred to the various work stations for extrusion. At each work station (or wax press) is a

smaller holding oven where the pans are held between extrusion cycles. As required, the pans are removed and wax is taken from the pan and placed into the extrusion tube of the wax press. The amount of wax removed from the pan depends entirely upon the size of the wax pattern being made and is a judgment which must be made by the wax press operator. Each time a wax pattern is made, the oven must be opened to remove wax from the pan.

C. Problems With Present System

Problems involved with the existing system of wax pattern making are easily identified.

1. Safety Hazards.

While draining the hot, liquid wax from the melting tank, workers are exposed to wax at 200°F. If care is not taken, burns to employees result. Once the molten wax is safely within the pan, it must now be hand carried to the cooling table. Although this distance is small, slips causing wax spillage are still a hazard. Even at the cooler temperature of extrusion, burns may still

result if care is not taken in handling the wax within the production area.

2. Working Conditions.

Providing comfortable temperatures within the wax room is difficult and costly. The melting tanks are radiating heat into the room, the fans circulating room air for cooling the hot wax are also adding heat to the room, opening of the large holding ovens adds heat into the room, and the constant opening and closing of the many smaller oven at work stations adds heat into the room.

3. Production Time.

Cooling of the wax from molten to paste condition is slow and the many handling processes involved have a direct effect upon productive time of employees. Each operator must place a small amount of excess paste wax into the extrusion tube to insure that the metal die is completely filled during extrusion. After several extrusion cycles, this wax becomes hard and must be removed from the tube. Doing this results in more unproductive time. The result is low labor efficiency.

4. Quality Control.

The quality of the finished metal casting is directly proportional to that of the wax pattern. It is impossible to make a quality casting from a poor mold. A major factor on pattern quality is the extrusion temperature. For the best possible patterns extrusion temperature should be precisely known and controlled. Every pattern should be extruded at the same temperature to insure consistent shrinkage. With the present system of handling the paste wax, this is impossible. An operator at one station may open the small holding oven, remove the pan, and place wax into the extrusion tube in half the time of another operator. This results in unknown extrusion temperatures resulting in different pattern shrinkage values. An operator may work faster during the morning than in the afternoon. Coffee breaks, idle chatter, and breaks for lunch, supper, or whatever all effect extrusion temperature since time out or in the oven is constantly changing.

5. Energy Consumption.

It is easily seen that energy efficiency is poor with

the present wax room set-up. Cooling of the work area is difficult due to the large heat additions, and oven temperatures are lost due to opening and closing. These result in greater cooling requirements and greater heat requirements at the same time.

D. Automation Problems

It would seem a small project to redesign the present system of wax handling to give automatic supply of wax by pumping the liquid wax from the wax melting tank, through a heat exchanger for cooling and finally into the extrusion tube of the wax presses for use. Problems involved in such a system become complex and require a great deal of testing and analysis. To illustrate only one problem at this point, consider that the wax in the paste condition is neither solid nor liquid. It falls into the little explored realm of non-Newtonian fluids. Since familiar fluid flow equations are derived only for Newtonian fluids, this complicates the determination of flow parameters such as flow rate and head loss. Each non-Newtonian fluid must be examined on an individual

basis. This causes many problems within the pipe network.

In order to design a workable, production oriented, automatic supply system, research must be conducted to determine operational requirements. The problems and solutions within the design phase of a research system become the initial task with analysis and design procedures the ultimate goal.

III. PRELIMINARY RESEARCH

A. Wax Data

The first step of the research project was to investigate the flow properties of the wax. Freeman Manufacturing Company (manufacturer of casting wax) was asked to supply viscosity data of a typical wax used in the making of wax patterns. In response, Mr. Richard Doenges, Research and Development Director, supplied data shown in Table 1. Data shown in Table 1 was taken using a recording Brookfield rotary viscometer with a No. 7 spindle. The speed of rotation was recorded in revolutions per minute and viscosity was recorded in centipoises. While questioning Mr. Doenges, it was learned that wax is a non-Newtonian fluid with peculiar flow characteristics. Freeman Manufacturing Company had run tests on wax in the paste temperature range but data was not recorded. Therefore, very little was already known. However, it was pointed out that the viscosity of the wax is time dependent.

To futher investigate the time dependency of wax flow, a simple lab experiment was set up. A beaker

Table 1. Shear Rate versus Viscosity of an Investment Casting Wax

TEMPERATURE (°F)	SHEAR RATE (RPM)	VISCOSITY (CPS)
190	100 2.5	150[1] 400
180	100 2.5	1800 400
170	100 2.5	2900 10,000
160	100 2.5	5100 36,000
150	100 2.5	8500 96,000
145	100 2.5	10,000 170,000
140	2.5	280,000

[1]*The values given for the viscosity coefficient at 190°F appear to be switched. However, the data is presented exactly as received from the wax manufacturer.*

containing solid wax at room ambient temperature was heated until the wax became molten and then allowed to cool while being stirred to approximately 145°F. When cooled, the beaker was turned up and wax began to flow down the sides. The same beaker was then reheated, allowed to cool as before, and placed into a laboratory oven at 145°F and held at this temperature for several hours. The beaker was then removed from the oven and turned upside down. The result was no flow. This proved that casting wax in the paste condition is not only a non-Newtonian fluid but also a time-dependent one.

Table 1 shows that at low rotational speeds viscosity is very high. At 145°F viscosity is 17 times larger at the low rotational speed of 2.5 revolutions per minute than at the high rotational speed of 100 revolutions per minute. Higher viscosity yields higher pressure losses and it will, therefore, take more pressure to initiate wax flow than to maintain it. This becomes very important when piping the paste wax from one location to another with unsteady flow requirements.

B. Time Dependent Non-Newtonian Fluids

Knowing that wax in the paste condition is a time dependent non-Newtonian fluid, an investigation into experiments and publications relating to these fluids was in order. It was found that these fluids are classified into two groups; thixotropic fluids and rheopectic fluids.

1. Rheopectic Fluids.

Rheopectic fluids exhibit a reversible increase in shear stress with time at a constant rate of shear and temperature. The shear stress will reach some limiting value depending upon the shear rate and temperature of the experiment.

A typical flow curve for a rheopectic fluid measured in a single experiment in which the shear rate is steadily increased from zero to a maximum value and then immediately decreased steadily toward zero would appear as shown in Figure 3. A rotary viscometer may be utilized for such experiments.

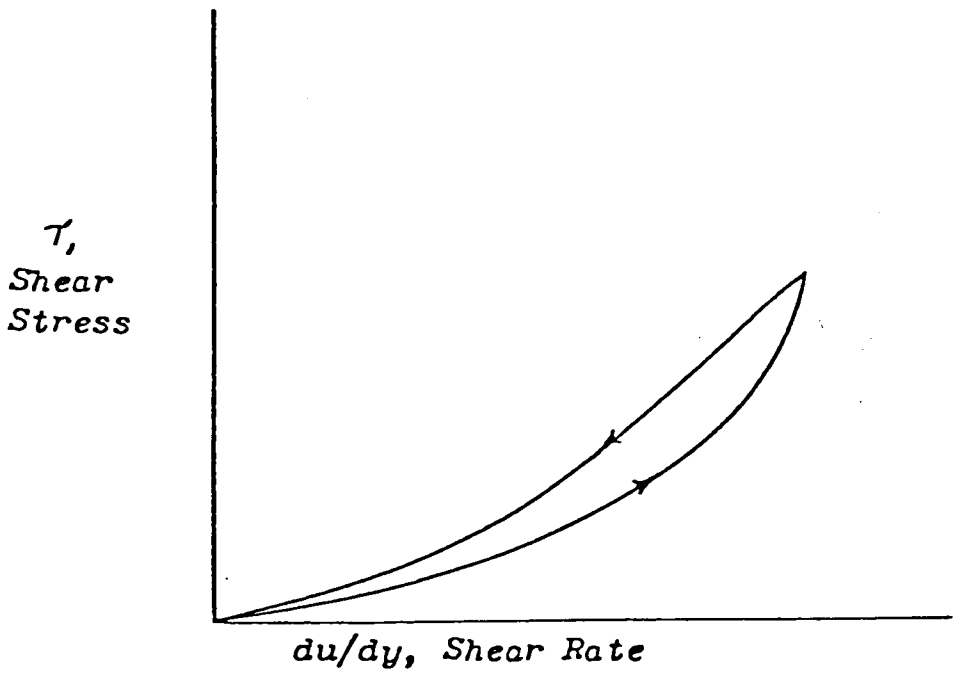


Figure 3. Typical Flow Curve of a Rheopectic Fluid.

Arrows shown in Figure 3 indicate the progress of the experiment. For the same fluid, the location of the loop would be different for a different time period and is also dependent upon the time the fluid has been at rest prior to the experiment.

2. Thixotropic Fluids.

Thixotropic fluids exhibit a reversible decrease in shear stress at a constant rate of shear and isothermal conditions. As in the case for rheopectic fluids, the shear stress will reach some limiting value depending upon the shear rate and temperature of the experiment.

A typical flow curve for a thixotropic fluid measured in a single experiment in which the shear rate is steadily increased from zero to a maximum value and then immediately decreased steadily towards zero would appear as shown in Figure 4.

Arrows shown in Figure 4 indicate the progress of the experiment. Again, for the same fluid, the location of the loop would be different for a different time period and is dependent upon the time that the fluid has been at rest prior to the experiment. Note that the direction

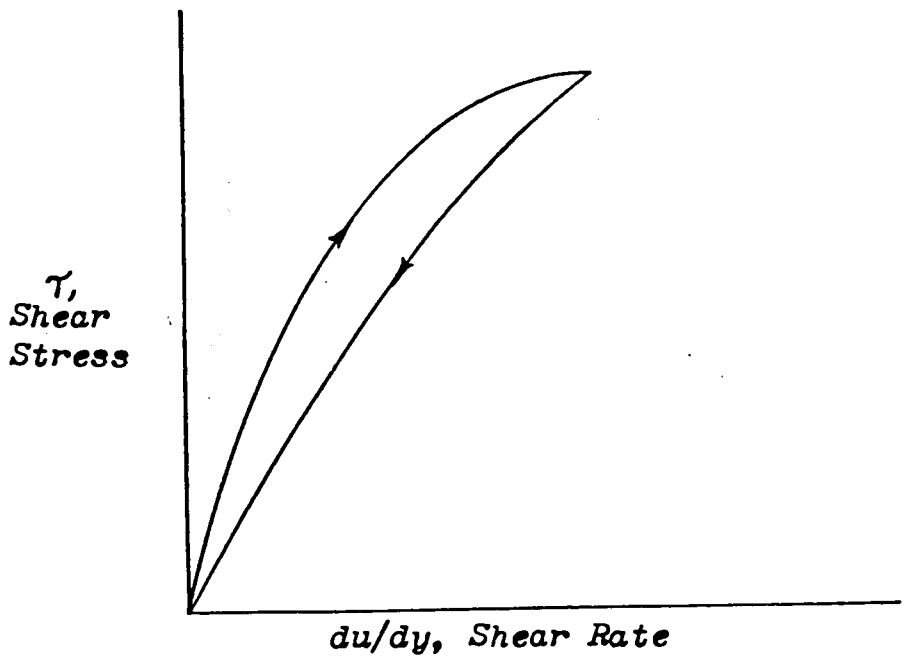
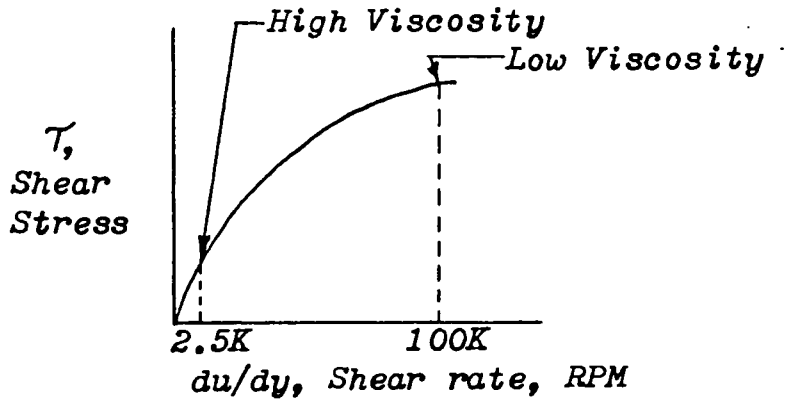


Figure 4. Typical Flow Curve of a Thixotropic Fluid.

of the arrows and the concavity of the curves are reversed from those shown for a rheopectic fluid in Figure 3.

C. Fluid Classification of Paste Wax

Table 1 shows data taken on casting wax using a recording Brookfield rotary viscometer. This data showed that at 145°F the viscosity was 17 times greater at the low RPM of 2.5 than at the high RPM of 100. In tests using rotary type viscometers, Skelland (1), Coleman, Markovitz, and Noll (3), and Holman (22), all give shear rate as a direct function of rotational speed. With this in mind, Table 1 shows that at low shear rates wax viscosity is high and at high shear rates viscosity is low. Since viscosity is defined by the slope of the curve given by shear stress versus shear rate, this curve must appear as shown below,



The "K" given on the preceding page is a constant relating shear rate to rotational speed and is a function of the type and component size of the particular rotary viscometer being used.

A comparison of the preceding curve with Figure 4 shows that the wax is behaving as a thixotropic fluid rather than a rheopectic fluid depicted in Figure 3.

D. Flow Investigation

Since the flow of paste wax is time-dependent, a major problem involves initiating flow after a long period of rest. It was first considered that flow of paste wax in production facilities where long pipe lengths are involved might not be feasible if pressures required to initiate flow became so large that conventional valves, pumps, pipe, and tubing could not be used.

In order to obtain some insight into this problem the crude system shown in Figure 5 was fabricated. One end of the insulated pipe assembly was capped while the other end of the pipe was filled with liquid wax. The pipe assembly was then placed into an oven and held at

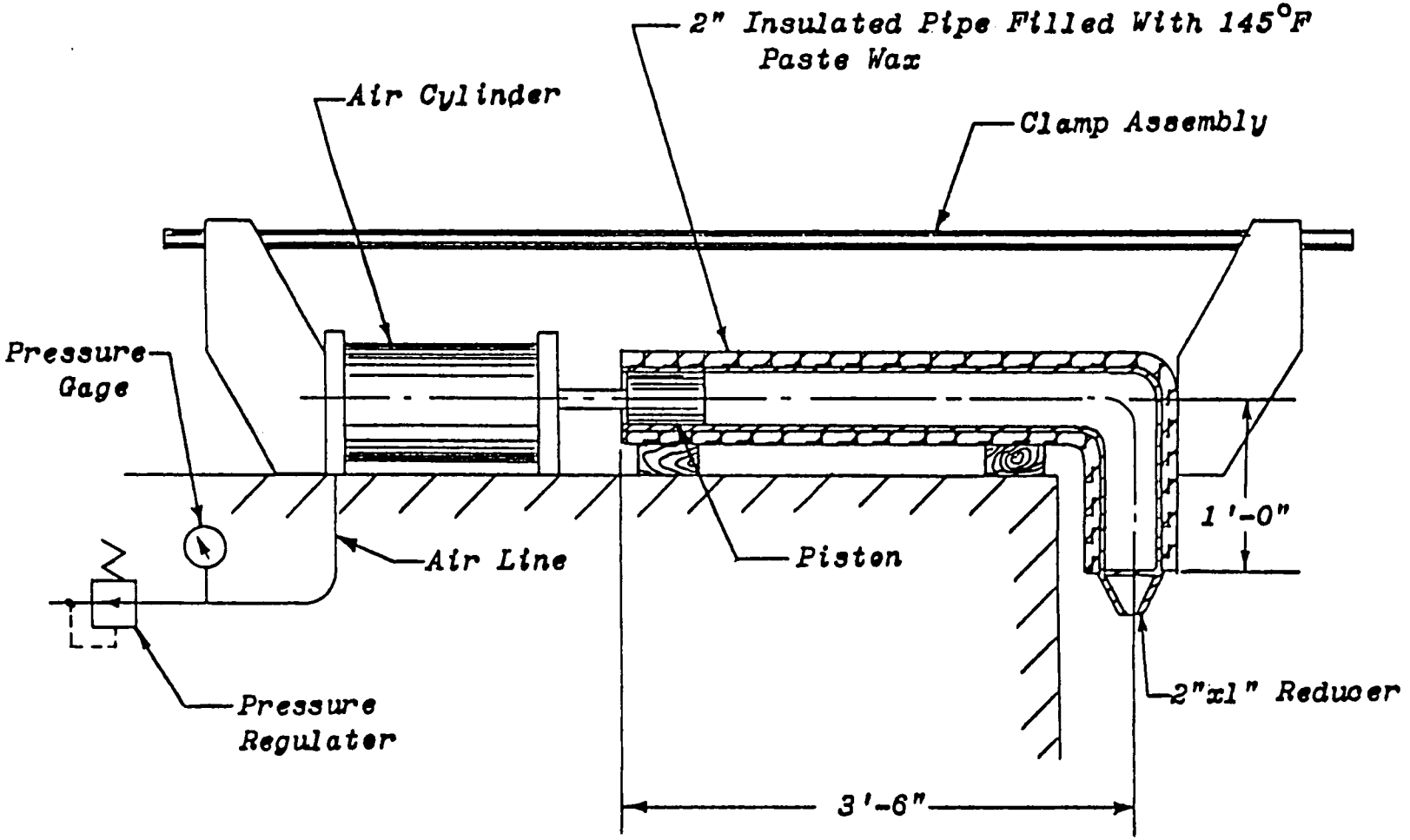


Figure 5. Test Apparatus For Preliminary Flow Investigation.

145°F for a period of 12 to 16 hours. After this period, the pipe assembly was removed and tested by inserting a piston connected to an air cylinder into one end of the pipe. By observing the pressure at which flow was initiated, some reassurance was gained. Flow could be initiated by approximately 15 lb/in^2 of gage pressure. When corrections for differences between cylinder bore and pipe internal diameter were made, it was determined that approximately 40 lb/in^2 was acting upon the wax. Using values given by Potter (18) for the equivalent length of the 2" nominal diameter elbow and the 2" x 1" elbow, an equivalent pipe length of approximately 10.5 feet was determined for the test system. For the same velocity, density, and flow rate to occur in a larger test system of approximately 80 feet in length would require 305 lb/in^2 of pressure. This pressure was calculated using standard equations for Newtonian fluids, although nothing had been proven at this time which would allow the use of Newtonian fluid flow equations. It should be pointed out that absolutely no idea of pressure requirements existed at this time and that this test was meant only to give some feel for pres-

sures which might be encountered in later, more elaborate test set-ups.

One source of error within this preliminary test set-up was the drag encountered between the pipe and the piston. Another source of possible error was pressure leakage between the pipe and piston. It was felt that the pressure requirement of 305 lb/in^2 calculated using this test system would be conservative and that the wax could be moved through pipe fittings such as 90° elbows and sudden contractions.

When conducting this experiment, it was noted that as wax began to flow it exhibited a core movement which immediately increases as flow begins. Also, an air line was connected to one end of the pipe in lieu of the cylinder and piston arrangement. When this was done and air pressure applied, the air simply caused an air cavity within the pipe to occur. The result was a small amount of wax and then air at the opposite end of the pipe.

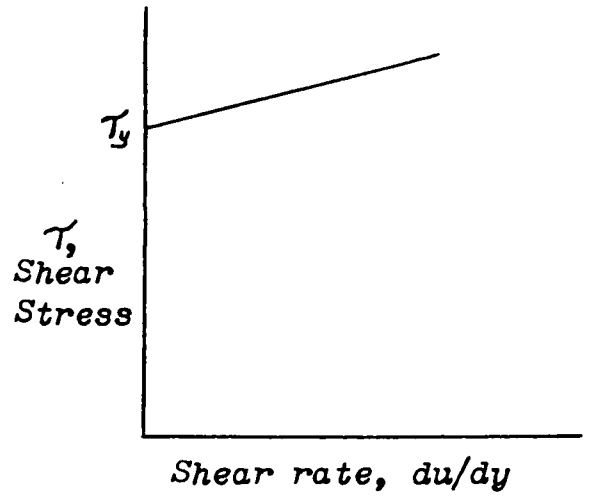
From this preliminary experiment some knowledge was gained into the requirements of a better and more sophisticated test system to follow.

IV. ESTABLISHING DESIGN AND ANALYSIS PROCEDURES

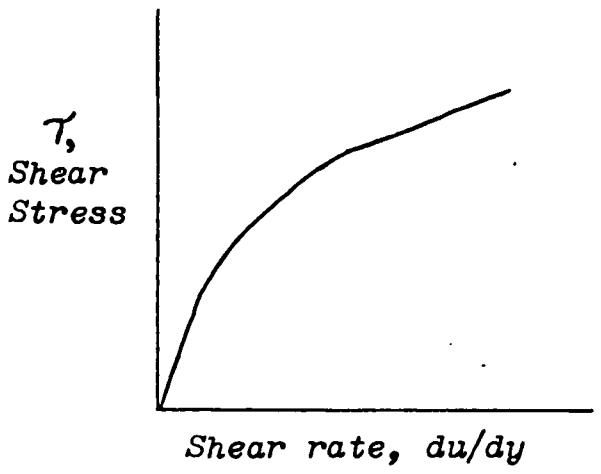
A. Required Design Approximations

1. Pipe and Pump.

Engineering design procedures for thixotropic fluids are virtually nonexistent. However, design methods for these fluids can be approximated if it is remembered that the time dependent characteristics manifest themselves only when flow is beginning. According to Skelland (1), a thixotropic fluid which has been flowing for some time in laminar flow in a tube of uniform cross section will have had its internal structure modified so that it behaves essentially like a Bingham plastic or a pseudo-plastic fluid. Bingham plastics are time-independent non-Newtonian fluids which exhibit a yield stress at zero shear rate, followed by a straight line relation-ship between shear stress and shear rate. A typical flow curve for a Bingham plastic fluid is shown on the following page.



Pseudoplastic fluids do not have a yield stress and are characterized by a progressively decreasing slope of shear stress versus shear rate. A typical flow curve for a pseudoplastic fluid is shown below.



Since pressure required to initiate flow in a pipe filled with paste wax will be greater than the pressure

required to maintain flow, the pump, pipe and other related wax handling equipment must be designed to overcome or withstand these higher pressures.

2. Contractions and Fittings.

Since wax flow at uniform shear behaves as a Bingham plastic or pseudoplastic fluid, experiments involving these fluids may be utilized. Weltman and Keller (2), performed experiments on both laminar and turbulent flow of a Bingham plastic slurry and a pseudoplastic slurry through sudden contractions and other fittings which included 90° elbows and four types of valve. According to Skelland (1), their data showed that the pressure losses in all cases were very near those obtained with Newtonian fluids and are in accordance with other investigations. It is assumed that Skelland is referring to the equivalent pipe length of the various valves and fittings and not to actual pressure losses which would depend upon the characteristics of the particular fluid whether Newtonian or non-Newtonian.

B. PIPE SCALE-UP PROCEDURE

Once flow has become steady the investment casting wax will behave as a plastic or pseudoplastic fluid which are both time-independent fluids. The general equation for laminar flow of a time-independent fluid in a cylindrical tube, assuming no slip at the tube wall is given by Skelland (1), as:

$$Q/\pi r^3 = 8Q/\pi D^3 = 8V/4D = (1/\tau_w^3) \int_0^{\tau_w} \tau^2_{rx} f(\tau_{rx})\, d\tau_{rx}$$

where

$$f(\tau_{rx}) = -du/dr$$

According to the analysis given by Skelland (1), for time independent fluids the value of the integral depends only on the limits. Therefore, $8Q/\pi D^3$ and $8V/D$ are functions of τ_ω only, regardless of shear rate. This implies that for the time independent fluid at isothermal and steady flow conditions, the relationship between $8Q/\pi D^3$ or $8V/D$ and τ_ω is independent of tube diameter and length for laminar flow. Flow in a pipe is laminar when the Reynolds number does not exceed 2100. The definition of the Reynolds number is given by:

$$R_e = (DV\rho)/\mu$$

When dealing with paste wax having a density of 56 lbs/ft^3 in 2" nominal pipe this reduces to:

$$R_e = (9.646V) / \mu$$

where V is velocity in ft/sec and μ is viscosity in lbs/ft.-sec. When dealing with wax flow with high viscosity and low velocities, it is evident that turbulent flow will never be encountered.

C. Design From Tube Viscometer Measurements.

For a specific non-Newtonian time independent fluid the relationship of $8Q/\pi D^3$ or $8V/D$ and τ_ω can be established from experiments conducted with a tube viscometer at the desired temperature and range of $8V/D$, and then used to calculate the pressure drop and any laminar flow rate in any size pipe when operating at the same temperature used in the test.

A diagram of a tube viscometer is shown in Figure 6. Several tube lengths and diameters are needed. The lengths may be measured by micrometer and the internal diameters should be precision bore for accurate calculations. Tube length to diameter ratios should be as large as possible to decrease entrance effects. For paste wax

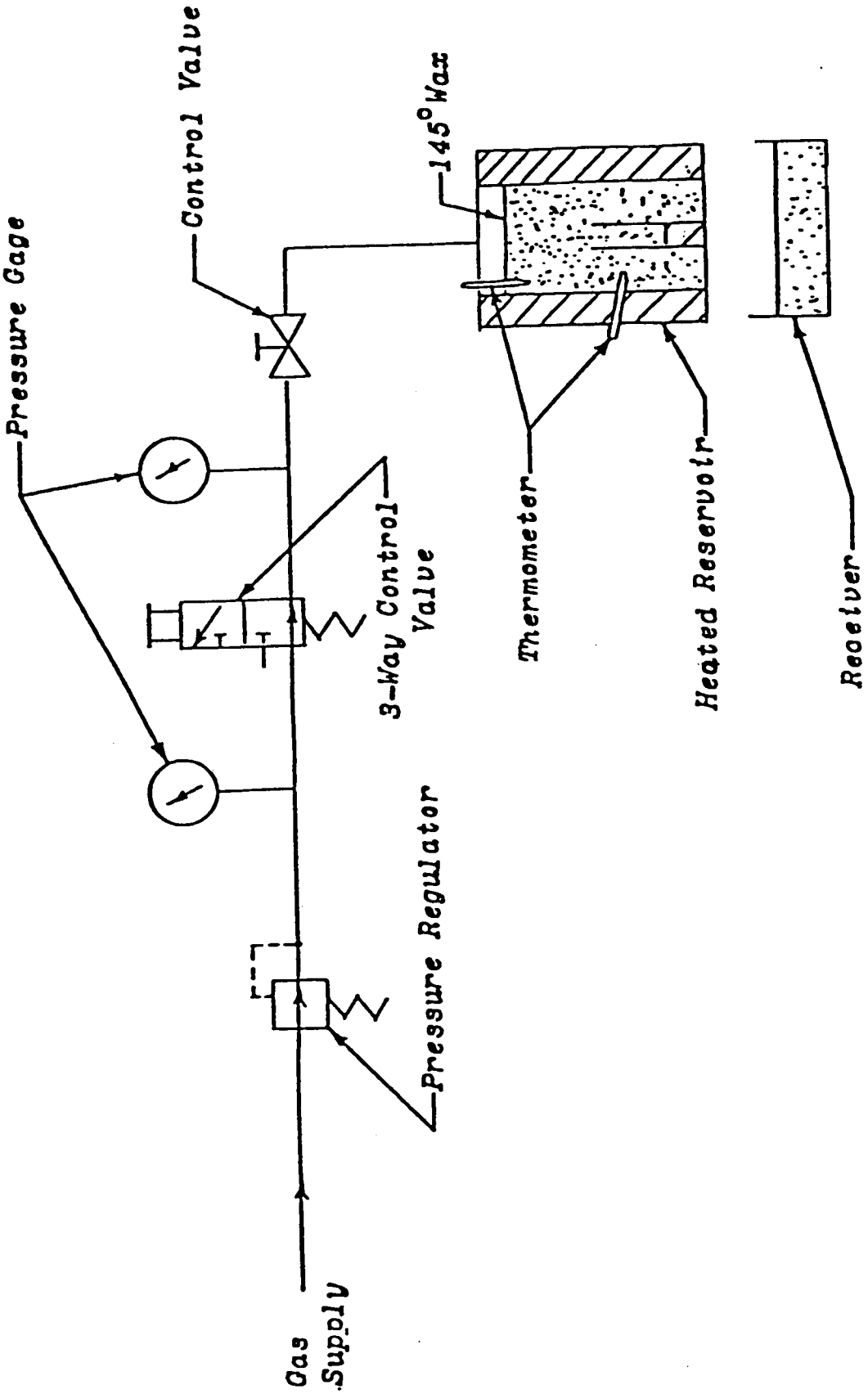


Figure 6. Typical Viscometer Test Set up

measurements the reservoir and tube should be maintained at the same temperature of the wax being tested.

Wax data is obtained by closing the end of the capillary tube with a stopper and filling the reservoir with liquid wax. The wax would then be allowed to cool to the desired temperature and then maintained at that temperature by controlling the temperature of the reservoir and tube. The wax should remain at test temperature for some time to allow stabilization of temperature and maximum time-dependent characteristics to become effective. Pressure could then be applied to the reservoir by the three-way valve. Pressure required to begin flow should be recorded. This will allow scale-up procedures to predict initial flow pressures in larger systems. Wax is then allowed to flow into the receiver in a recorded time and the test is over. The material in the receiver is weighed and the volumetric flow rate is calculated from a knowledge of the density of the wax. Then, by plotting τ_w *or* $D\Delta P/4L$ *versus* $8V/D$ *for various diameters and tube lengths, curves similiar to those shown in Figure 7 should result. A different set of curves will result*

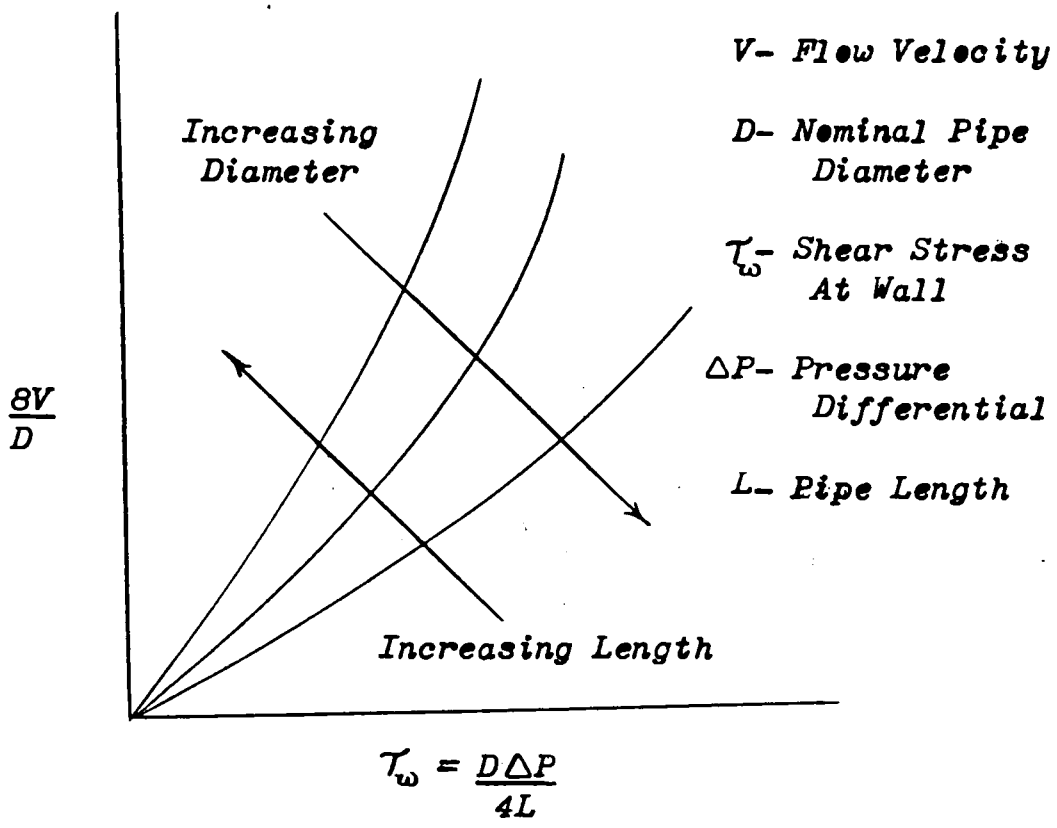


Figure 7. Typical Flow Data of a Thixotropic Fluid Such as Investment Casting Wax.

for experiments conducted at other temperatures. Separate curves will be obtained for each pipe diameter and length. The experimental plot can now be used to calculate pressure drop at any laminar flow rate as long as diameter and length are unchanged. Data recorded at initial flow can also be used to estimate pressure requirements.

In the case of thixotropic fluids, Skelland (1) says more structural breakdown and consequently lower effective viscosities are obtained with longer tube lengths or smaller diameters. This implies that if data taken on a 2" nominal diameter pipe 42.5 inch long is applied to a smaller diameter pipe or a longer pipe, the values thus obtained will be conservative. It should be remembered that applying the experimental data in this manner does not yield actual flow parameters.

At first observation of Figure 7, it appears that long slender tubes will yield best results with paste wax flow. Although the shear stress at the wall will be less (due to higher shear rates) in long slender tubes, the pressure losses associated with delivering the wax at equivalent flow rates to the desired location will also be large.

Three corrections must always be made to the measurements obtained on a capillary tube viscometer and a fourth correction is needed in some cases. According to Skelland (1), these corrections are for the following effects:

1. *Head of fluid above the tube exit*
2. *Kinetic energy effects*
3. *Tube entrance effects*
4. *Effective slip near the tube wall*

These corrections are discussed, and associated equations and calculations are given, in the works of Skelland (1).

Since the tube viscometer test arrangement deals only with very small lengths and diameters when compared to actual pipe installations, scale-up procedures from such measurements are impossible. Therefore, it was desirable to construct a larger scale system composed of the required pipe sizes. This larger system could then be used to supply wax to the desired location when testing was complete.

V. TEST SYSTEM DESIGN

A. Heat Exchanger

One of the basic problems of centralizing paste wax distribution is cooling the wax. It is desired to cool wax from approximately 200°F. to a selected temperature which is presently 145°F. This requires cooling wax from liquid to paste. Water cooling in a tube-type heat exchanger is normally utilized in this range of temperature. However, the use of such an exchanger is impossible in this application. In a tube type heat exchanger the liquid wax would be pumped through tubes surrounded by cooling water. As the liquid wax begins to cool, a solid layer of wax would form on the inside diameter of the tubes. Soon, as the layer builds, the wax flow would be stopped due to a clogged line. In order to assure that this solid layer does not form, the wax must be continuously agitated, or stirred in some manner.

Investigation into commercial heat exchangers yielded very good rewards. Units used in difficult cooling applications, such as wax, were found to be available

from two American manufacturers. The units are termed "Scraped Surface" heat exchangers and hold an amazing resemblance to an ordinary home ice cream freezer. A cut away view of the exchanger selected appears in Figure 8. This exchanger is widely used in the food processing industry and has been used in applications involving pastes, syrups, plastics, gums, glues, suspensions, tars, salves, and other difficult applications. The unit shown in Figure 8 is manufactured and patented by CONTHERM, Alfa-Laval Groups, Newburyport, Massachusetts.

Alfa-Laval was contacted and questioned as to the products applicability in the wax cooling process. Little doubt on Alfa-Laval's part proved promising. After establishing the requirements of the heat exchanger unit, Alfa-Laval agreed to design a complete cooling unit which would have the capability of controlling the exit temperature of wax to approximately $\pm$ 2°F while allowing the wax pump to be turned off without further decrease in temperature. The latter feature of the unit is termed "maintain status" and is very important if it is desired to interrupt the flow of wax through the heat exchanger.

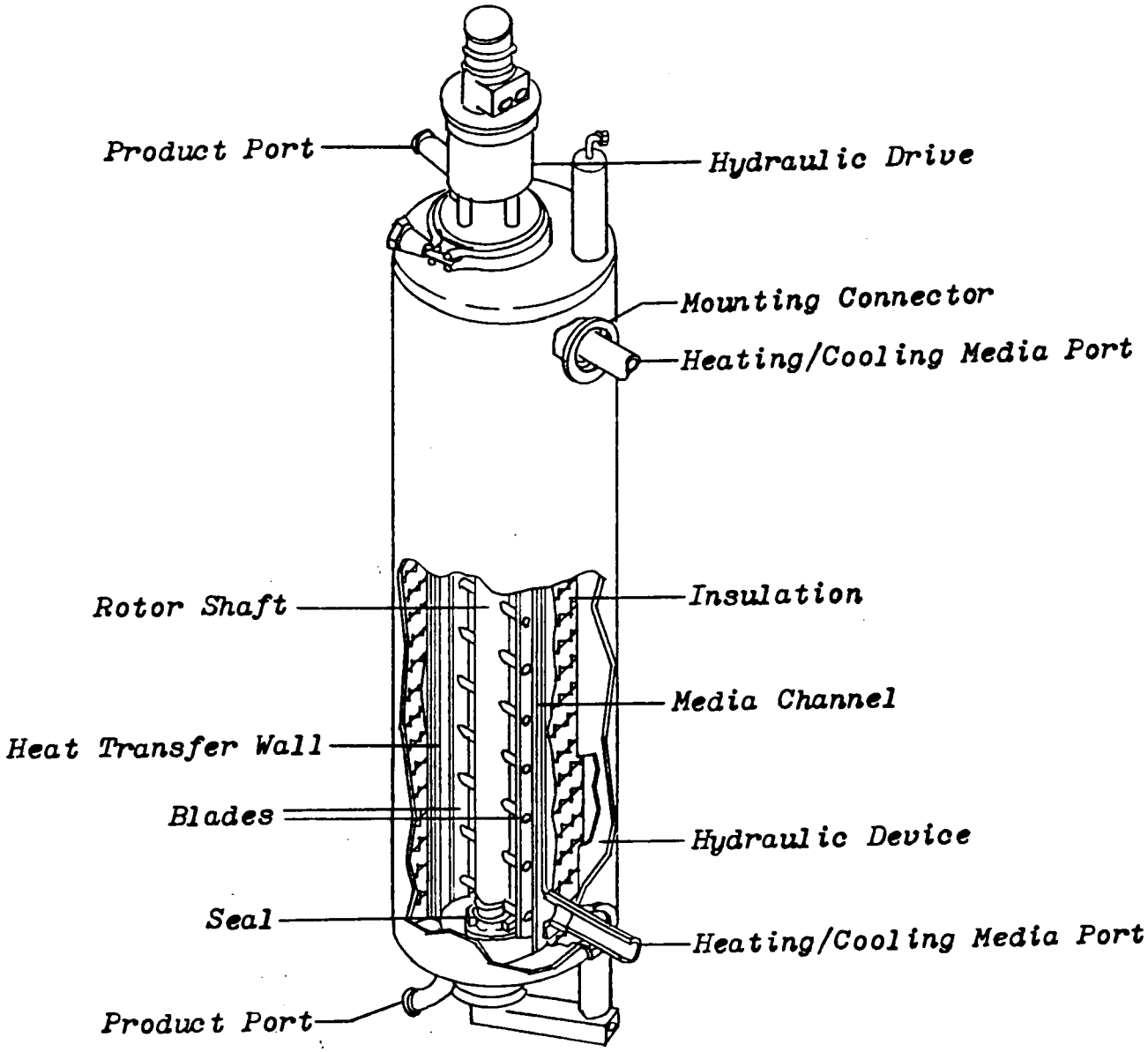
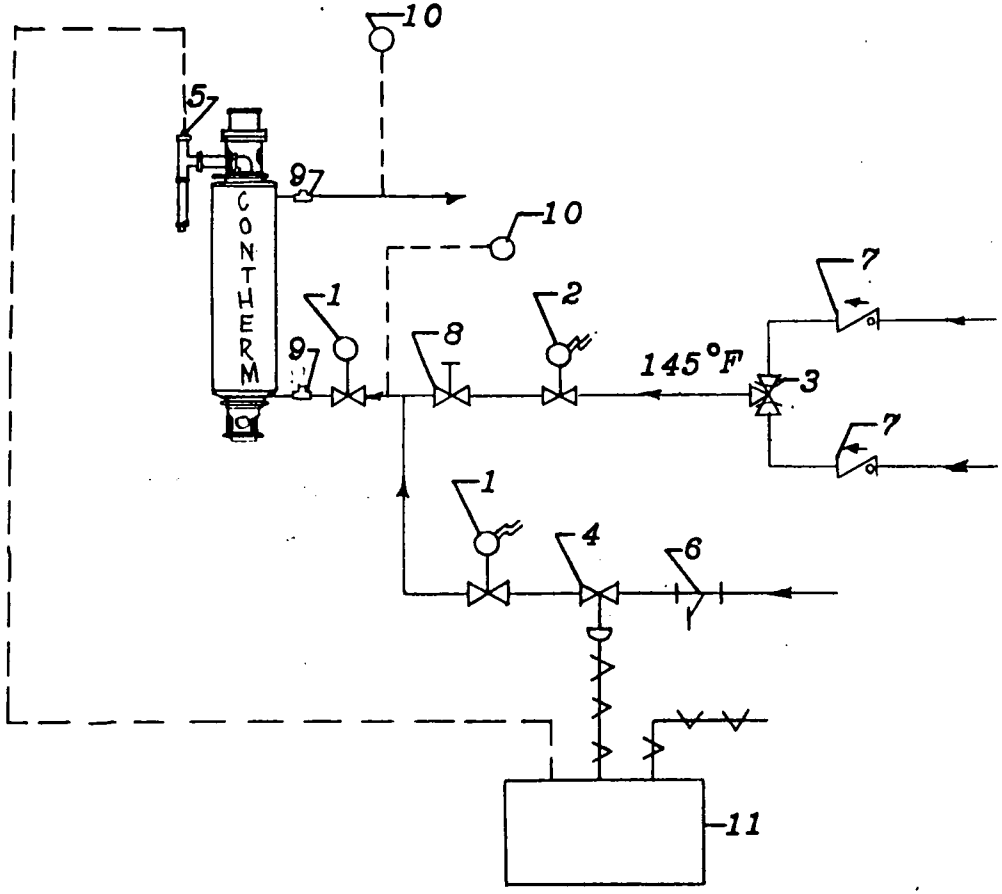


Figure 8. Scraped Surface Heat Exchanger

With the exception of motor starters and various other electrical hardware the Alfa-Laval supplied system is shown in Figures 9 and 10. In an enterprising effort, Alfa-Laval custom built the unit shown in Figures 9 and 10 on a rent with intent-to-buy basis. No other investment casting firm was known to be using such a system and neither of the companys manufacturing scraped surface heat exchangers knew of any investment casting firms using such equipment. Since little was known about the units performance with wax, a research program was conducted with Alfa-Laval guaranteeing their units performance.

B. Wax Piping System

Wax injection presses for injecting the paste wax into the mold were already in production. It was desirable to continue the use of this equipment for financial reasons. Therefore, the wax supply system had to be adaptable to this existing equipment. The double-head semi-automatic wax press is shown in Figure 11 with attention called to the injection tube and entry point for automatic wax supply.



1—Normally Closed Solenoid Valve
2—Normally Open Solenoid Valve
3—Thermostatic Mixer Valve
4—Air Operated Diaphragm Control Valve
5—Temperature Sensing-Control Bulb
6—In-Line Strainer
7—Check Valves
8—Throtting Valve
9—Pipe Tee
10—Panel Mounted Temperature Gage
11—Indicating Controller

Figure 9. Alfa-Laval Heat Exchanging System Schematic

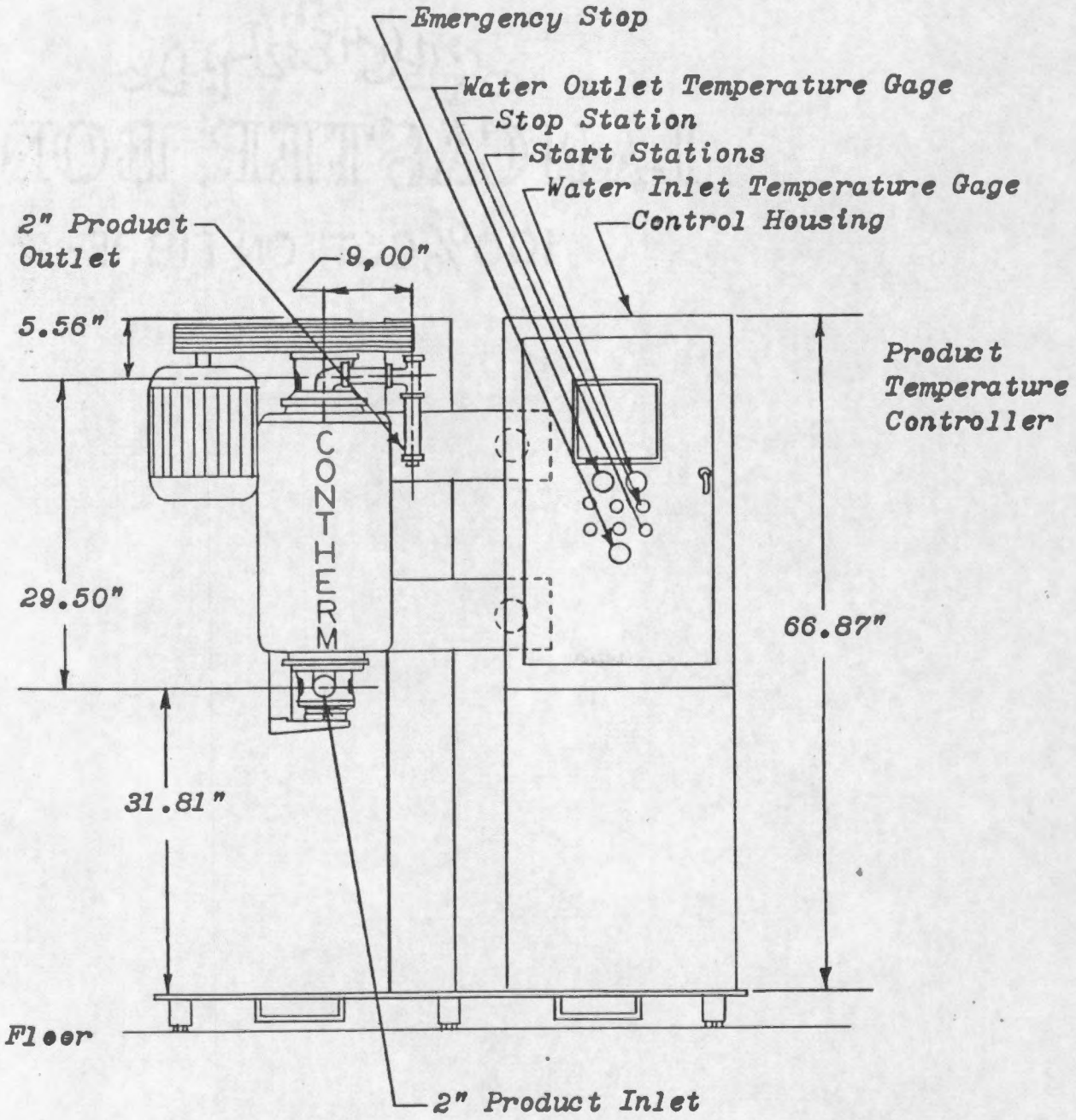


Figure 10. Basic View of Alfa-Laval Heat Exchanger System.

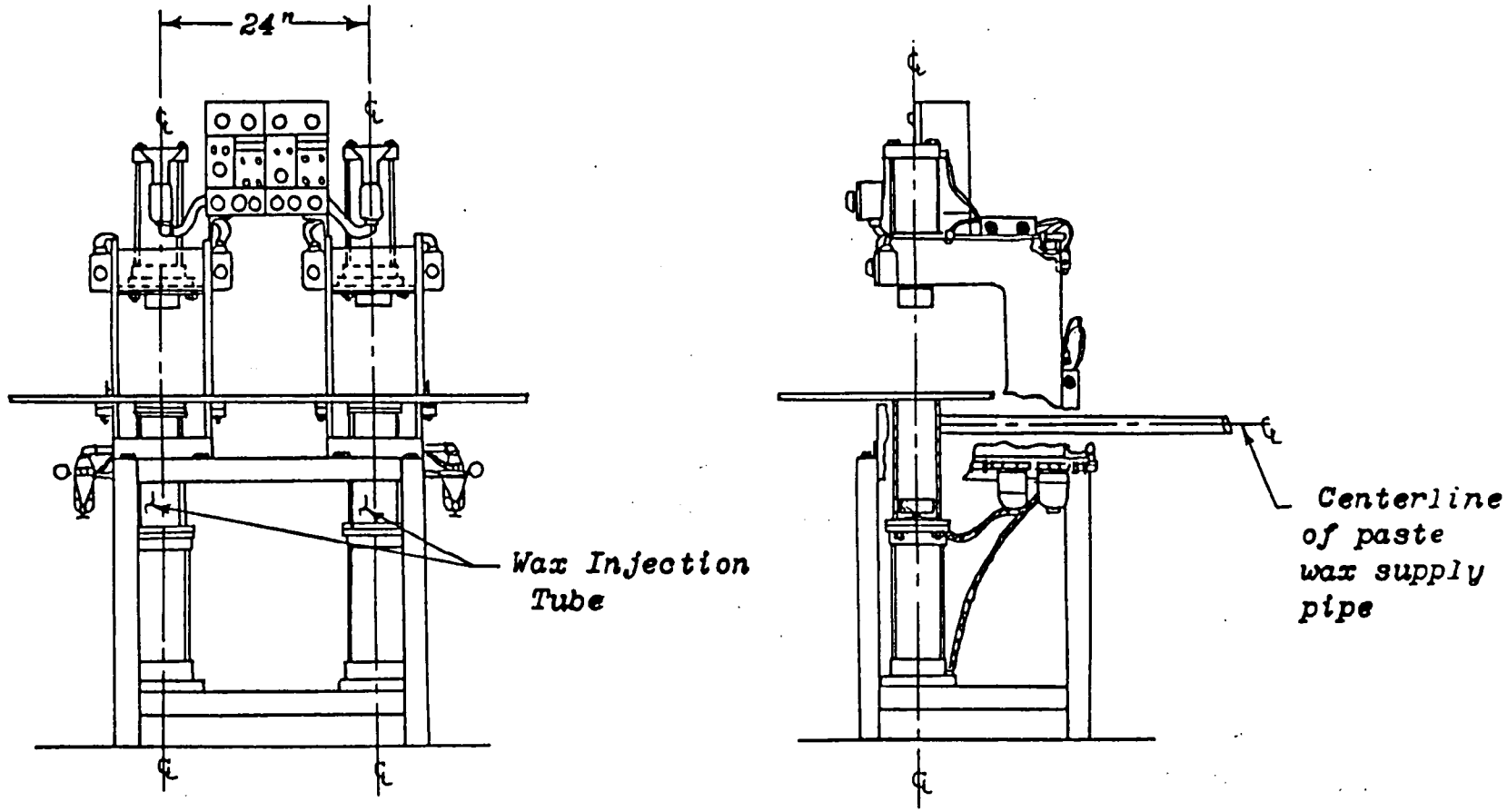


Figure 11. Double Head Semi-Automatic Wax Press.

Required spacing of the wax presses was obtained from production supervisors and the remainder of the test system was designed to yield pressure losses over various pipe lengths and fittings. It was necessary to gain enough pressure and flow data from the test system to allow scale-up calculations for a production system where greater pipe lengths and numerous fittings would be required. From present production requirements it was established that four of the wax presses shown in Figure 11 would compromise the initial production system. With this in mind, the basic system of piping required to supply four such presses was determined to be as shown in Figure 12.

1. Pipe Sizing.

The selection of pipe diameter came next. Since Alfa-Laval had experience in pumping non-Newtonian fluids such as casting wax, they were consulted for recommendations. The heat exchanger exit connection as supplied by Alfa-Laval was nominally a two inch size and this was the standard size used by Alfa-Laval. A large pipe diameter

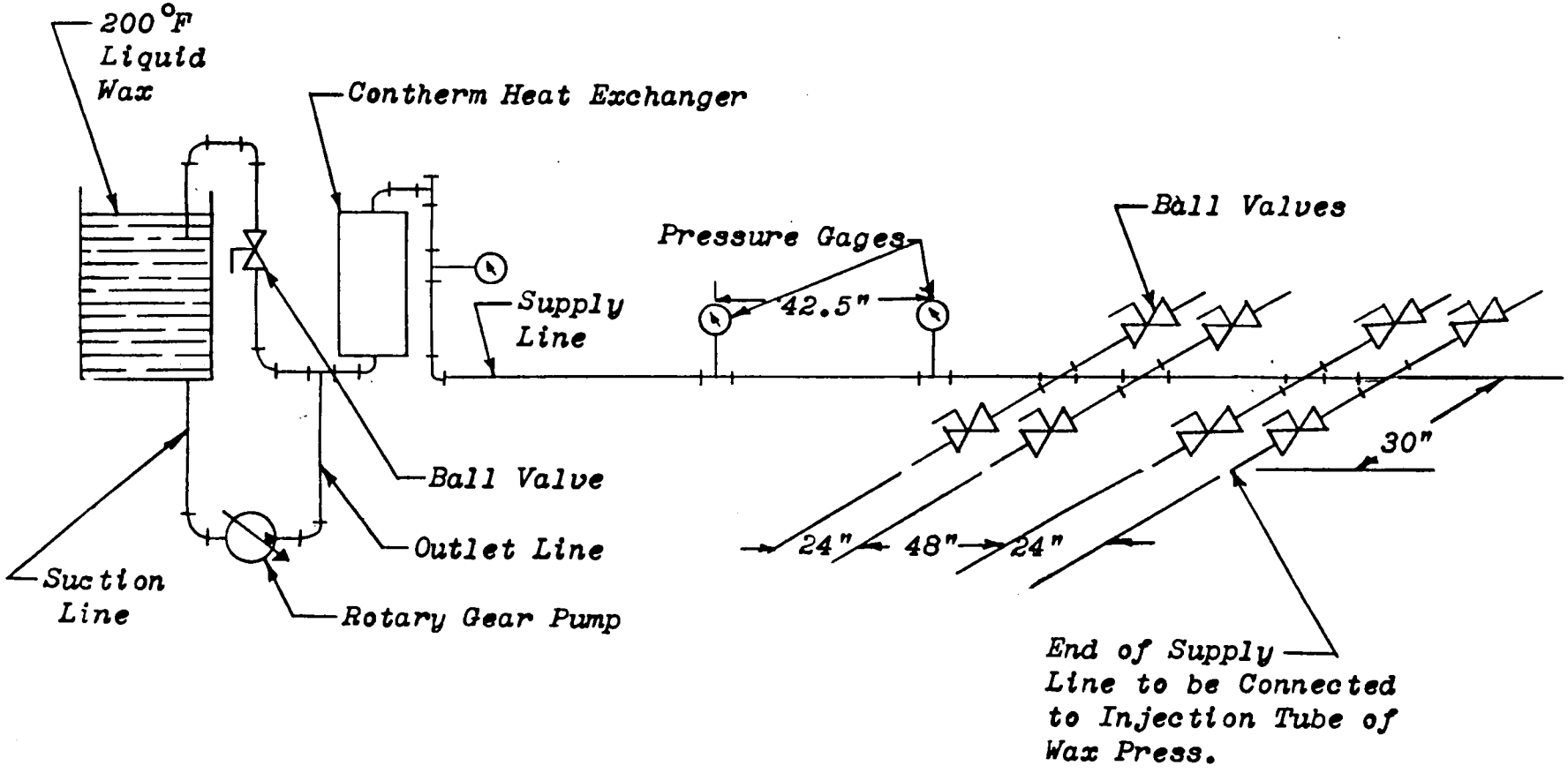


Figure 12. Basic Pipe System Required to Supply Four Semi-Automatic Wax Presses.

would lessen the effect of high shear stress due to high viscosity and would require lower pressures to iniate flow. For these reasons two inch schedule 40 pipe was chosen for the portions of pipe containing paste wax. The pipe did, however, have to be reduced in size for entry into the injection tube of the wax press since existing injection tubes were only three inches in diameter. Pipe sizes in sections of the supply system containing liquid wax could be made to agree with the standard pump connections. With the very low flow rates required, large pipe lines containing liquid wax would be a source of air entrapment because they would not be completely filled with wax.

2. Pipe Pressure Rating.

Based upon preliminary research and conversations with others in the wax industry concerning pressures which might be encountered within the system, seamless pipe meeting ASTM A106 standards was chosen. This permitted pressures within the pipe as high as 1500 lbs/in^2 and it was hoped that this would be three to four times the pressure actually required to deliver the wax to the point of injection.

3. *Flow Requirements.*

In an effort to determine flow requirements of the paste wax, a short time was spent in the production facility observing wax press operation and consulting with immediate supervisors. It was determined that over an eight hour period approximately 400 pounds of wax was being injected. This implied approximately 50 pounds per hour or 0.833 pounds per minute was being consumed. However, when the actual injection is in progress as much as 10 pounds per minute were required at a single injection point depending upon the size of wax pattern being produced. This flow would be unpredictable in a production situation since one wax press may be injecting two different molds and four wax presses might be injecting eight different molds with various injection times. Therefore, the piping system must be capable of taking out surges due to demand. The heat exchanger would therefore be subject to drastic changes in demand. When more wax is required, more coolant is required and although the heat exchanger system will respond to a variety of demands, such drastic changes are beyond its capability.

Therefore, in order to assure close control of temperature while responding to demand, some type of "surge" tank must be placed within the pipe system.

C. Surge Tank

Various types of surge tanks were investigated with the common bladder type being first. It was quickly recognized that subjecting the bladder to the paste wax temperature of 145°F would drastically reduce its life. The surge tank shown in Figure 13 was then considered, but after the air cavity problem encountered in preliminary research it was decided that the flow shown in Figure 13 would in actuality be as shown in Figure 14.

It was soon determined that only a piston type accumulator could be utilized. This proved to be a wise choice and yielded very good results. The basic piston type accumulator is shown in Figure 15. The charge pressure must be variable since the wax pump must overcome this pressure in order to fill the surge tank with wax. It is desirable to have no pressure on the charge side of the accumulator during filling. This was accomplished and is discussed in the following section.

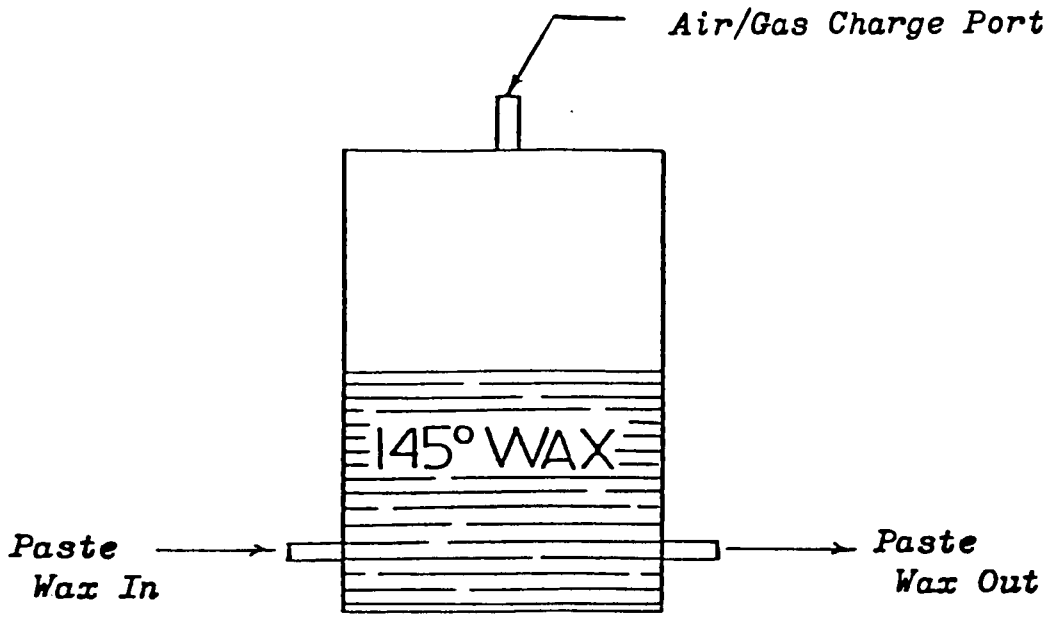


Figure 13. Typical Air/Gas Over Liquid Surge Tank

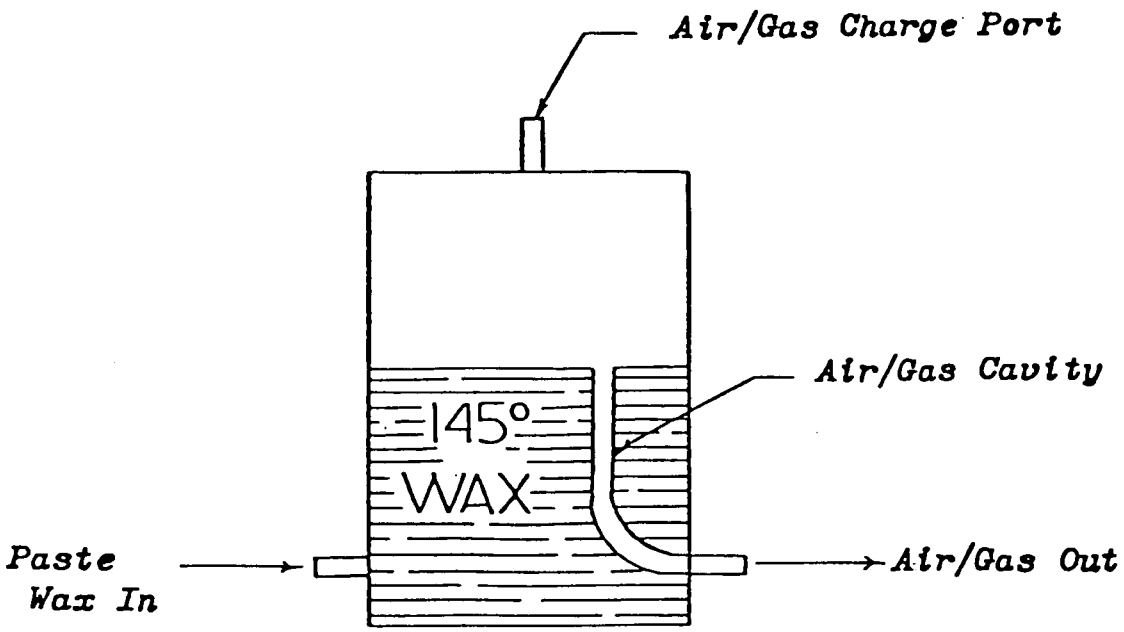


Figure 14. Cavity Flow With Air/Gas Over Liquid Surge Tank

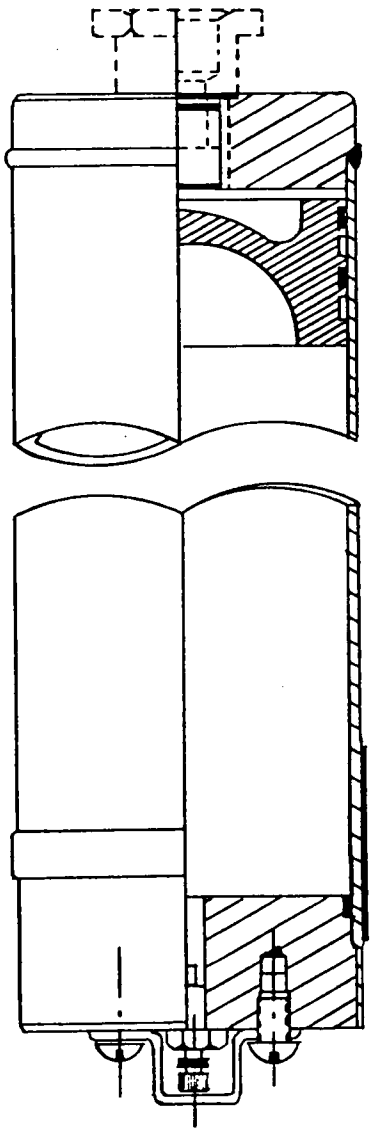


Figure 15. Hydraulic Piston Accumulator

D. Pump Selection

The pump required to move the wax into the surge tank was a rotary gear pump capable of delivering 0.5 gpm at 300 psig and 200°F. The flow rate of 0.5 gpm is consistent with maximum cooling capability of the scraped surface heat exchanger.

The system shown in Figure 16 was designed which allows the surge tank to give auxilliary pumping. During filling, the surge tank is under no charge pressure which would cause increased work on the supply pump. After the tank has been filled, the ball valve on the supply line is closed and the charge side of the surge tank is supplied with any desired pressure from the hydraulic power unit. This allows operation of the system without the supply pump. The relief valve shown is adjustable and will allow bypass of the hydraulic fluid back into the hydraulic reservoir when wax is not required. Operation in this manner allows for maintenance on the heat-exchanger, pump, and other equipment located in the system prior to the surge tank without stopping production. This is very important from the production stand point.

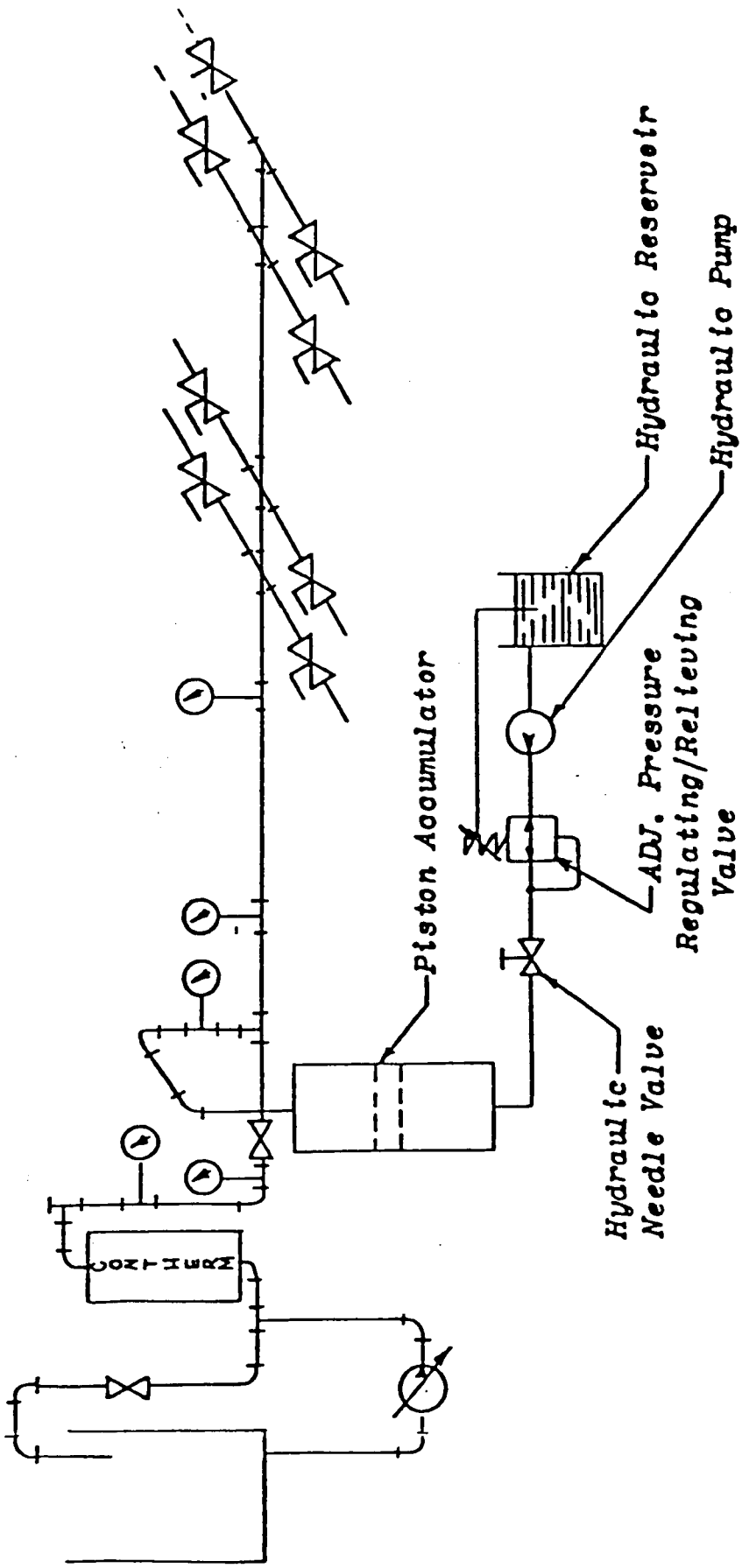


Figure 16. Pipe System With Auxiliary Pumping Capability.

E. Heat Tracing System

When pumping paste wax at 145°F in uninsulated and unheated pipe, a layer of solid wax forms on the internal pipe diameter due to temperature differences between pipe and wax. To solve this problem, the pipe and all wax handling components must be maintained at the same temperature as the paste wax. It is also desirable to heat-up all system components if a power failure should occur.

Several methods for heating and maintaining pipe system temperatures are: (1) liquid jacketed or traced. (2) steam jacketed or traced, and (3) electrically traced. Jacketed pipes heated with a fluid are expensive to install, maintain and operate. Temperatures in the paste wax system are far below the condensing temperature of steam and, thus, hard to control. Heated liquids (such as oils, water with antifreeze, etc.) are more flexible as to temperature range, but require pumps, heat exchangers, and controls. For ease of installation, maintenance, and control,

electrical tracing is the desired method of raising or maintaining pipe temperatures in a paste wax system.

Various manufacturers of dependable heat tracing system were contacted and given the requirements of the desired wax piping system. Heat-up of the pipe from 70°F to 200°F in a two hour period was the principle design parameter to be obtained. In case of power failure the entire pipe system must be functioning normally as quickly as possible. From production requirements two hours was determined to be a maximum delay. Maintaining the system at 145°F can easily be accomplished by means of temperature controllers if the system has the capability of heat-up to 200°F in two hours. For safety and insurance reasons the cable had to be both Underwriter's Laboratory and Factory Mutual approved. This requirement eliminated many suppliers of electric heating cable.

Thermon Manufacturing Company, San Marcos, Texas was awarded a subcontract for design and fabrication of the electrical heat tracing system. In order to guarantee performance of the system, certified drawings of the pipe system were required. The heat tracing system which

resulted is shown in Figure 17 and the electrical loading of this system is given in Table 2. Loadings listed in Table 2 were derived by Thermon through the use of computer programs which had proven accurate on many previous applications. A sample hand calculation of required wattage to heat up an insulated pipe containing wax is given in Appendix A. Calculations given in Appendix A are based upon steady state heat transfer and are probably conservative in regards to heat-up times. The heating up of the wax within the pipe actually involves unsteady state heat transfer. A more accurate method of calculating heat-up time would involve the thermal diffusivity of the wax as well as the unit surface conductance coefficient between the pipe and wax. This method of heat conduction is discussed by Kreith (10) in detail. One of the basic parameters involved in calculating the unsteady state heat-up time is the unit surface conductance coefficient between the wax and the pipe. Since this was not known, subsequent calculations were not possible. Table 6, which appears in Appendix A, was taken from reference 21 of the Bibliography. Table 7, which also appears in

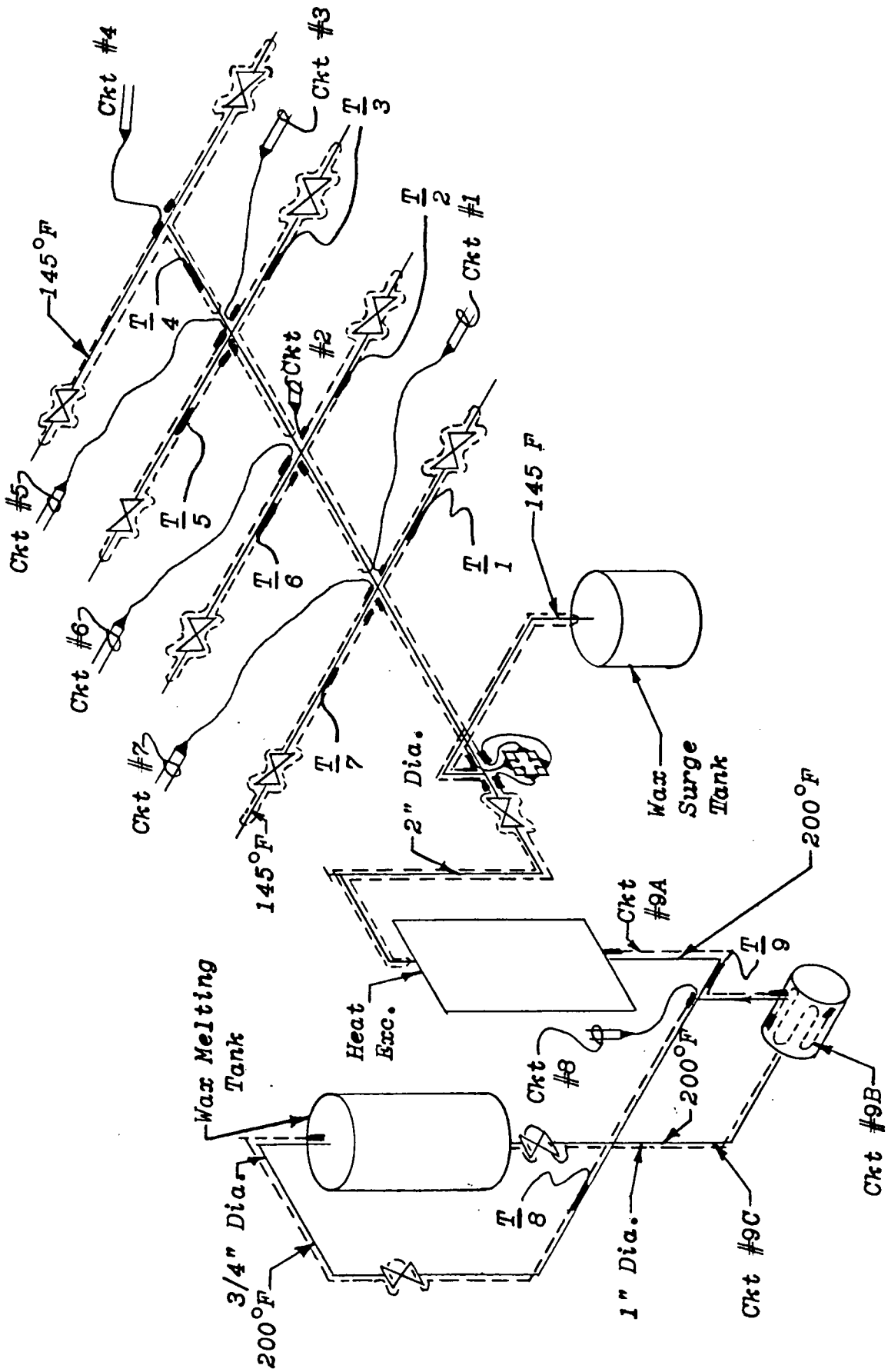


Figure 17. Heat Tracing System for Test Equipment.

Table 2. Electrical Loads for Heat Tracing System shown in Figure 17

CKT#	PIPE SIZE	LENGTH	VOLTS	AMPS	WATTS	WATTS/FT. OF CABLE	WATTS/FT. OF PIPE
1	2"	42'-2"	120	7.66	919.0	21.80	43.60
2	2"	11'-0"	60	3.44	237.0	21.51	43.02
3	2"	15'-0"	88	4.24	372.7	24.85	49.70
4	2"	18'-0"	88	4.46	392.7	21.82	43.64
5	2"	7'-0"	50	3.21	160.7	22.96	45.92
6	2"	7'-0"	50	3.21	160.7	22.96	45.92
7	1",2"	7'-0"	50	3.21	160.7	22.96	45.92
8	3/4"	7'-1"	30	3.07	92.2	13.02	13.02
9A 9C 9B	1",3/4"	7'-3"	30	3.99	114.0	15.66	15.66
	PUMP	3'-6"	30	3.75	113.0	32.11	32.11

Appendix A, was supplied by Emerson Electric Co, Pittsburg, Pennsylvania, manufacturers of "Chromalox" industrial heaters and controls.

The method of sensing and controlling pipe temperature was not supplied by Thermon Manufacturing. For this, a time-proportioning electronic temperature controller utilizing an iron-constantan (Type J) thermocouple.was chosen. This particular controlling system allowed selection of pipe temperature from ambient to 250°F with control in the ± 2°F range. The time-proportioning type of controller was selected to reduce the effects of off-on cycles on the life of the heater cable.

F. Surge Tank Temperature Maintenance

For the same reasons as given above, the surge tank must also be maintained at operating temperature. The easiest and most economical way of accomplishing this is to submerge the surge tank into a heated water or oil bath. This same water or oil bath may also be used to maintain wax within the Contherm heat exchanger at operating temperature when flow thru the exchanger is stopped. This

would allow the elimination of the hydrostatic mixing valve (shown in Figure 9, page 42) which is designed to supply coolant at 145°F.

G. Design Results

Figure 18 shows the final test system in schematic form. To fill the surge tank with paste wax: (a) valves 2 and 8 are open in the wax system, valves 19, 16, 41, 43, and 14 are open in the water system, and valve 22 in the hydraulic system is open, (b) the adjustable relief valve (23) is set for zero back pressure, (c) the water pump (21) is turned on and cooling water is supplied thru the water-to-water heat exchanger, and (d) the wax pump (3) is turned on. The hydraulic pump (24) is off and all other valves are closed. Temperature controllers supplying power to heaters on liquid wax lines are set at 200°F and those supplying power to heaters on paste wax lines are set at 145°F. The temperature indicating controller (36) is set at 145°F.

Once the surge tank is full, valve 4 is opened to allow continued pumping of liquid wax while stopping flow

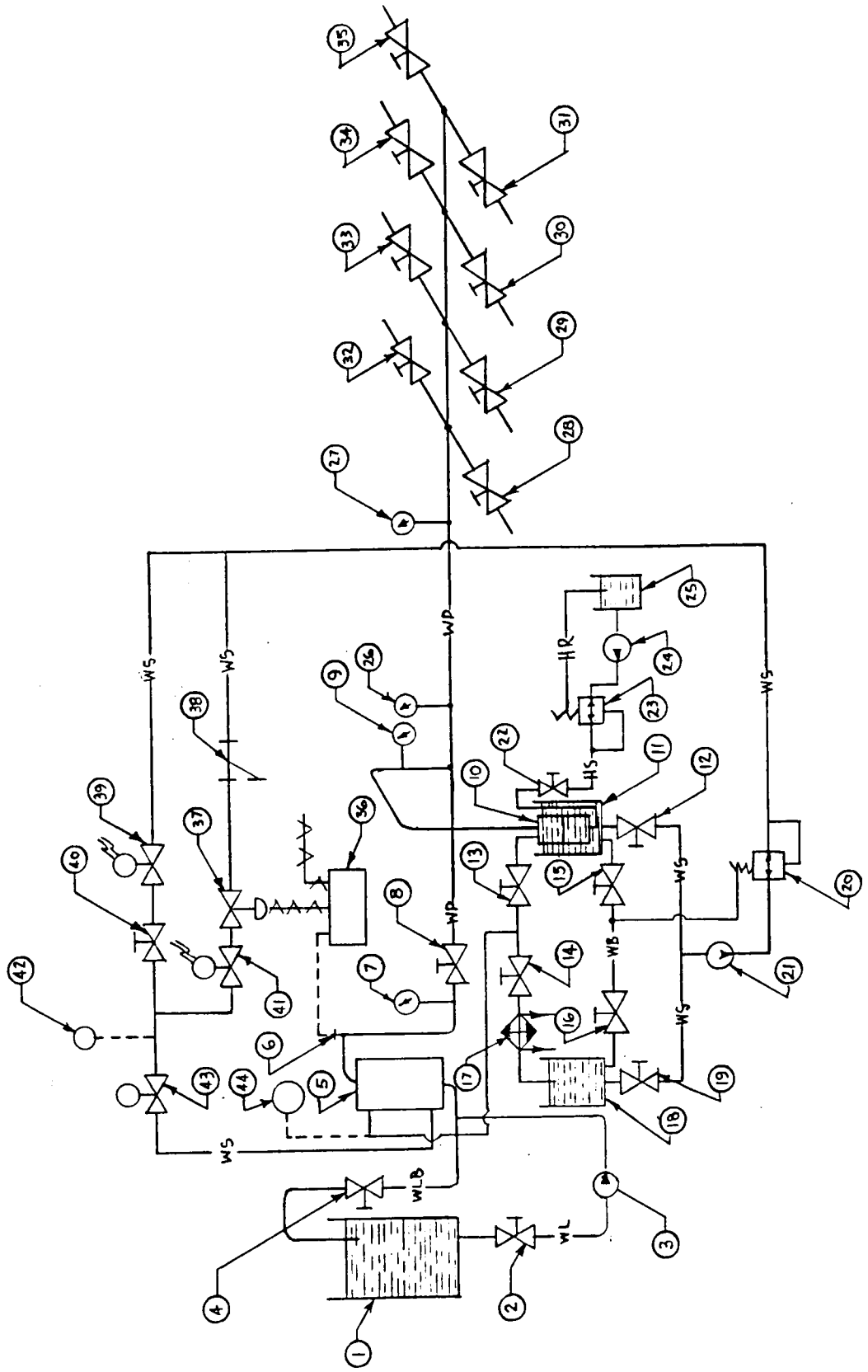


Figure 18. Test System Schematic.

1 - 200°F Wax Melting Tank
2 - 1" NPT Ball Valve
3 - Rotary Gear Pump
4 - 3/4" NPT Ball Valve
5 - Scraped Surface Heat Exchanger
6 - Thermocouple
7 - Pressure Gage
8 - 2" NPT Ball Valve
9 - Pressure Gage
10 - Hydraulic Piston Accumulator
11 - 145°F Water Reservoir
12 - 1/8" NPT Disc Valve
13 - 1/8" NPT Disc Valve
14 - 1/8" NPT Disc Valve
15 - 1/8" NPT Disc Valve
16 - 1/8" NPT Disc Valve
17 - Water-to-Water Heat Exchanger
18 - Cold Water Reservoir
19 - 1/8" NPT Disc Valve
20 - 1/8" NPT, 60 Psi, Relief Valve
21 - Water Pump
22 - Hydraulic Needle Valve
23 - Adj. Hydraulic Pressure Regulating/Relieving
24 - Hydraulic Pump
25 - Hydraulic Reservoir
26 - Pressure Gage
27 - Pressure Gage
28 - 2" NPT Ball Valve
29 - 2" NPT Ball Valve
30 - 2" NPT Ball Valve
31 - 2" NPT Ball Valve
32 - 2" NPT Ball Valve
33 - 2" NPT Ball Valve
34 - 2" NPT Ball Valve
35 - 2" NPT Ball Valve
36 - Temperature Indicating Controller
37 - Air Activated Diaphragm Valve
38 - In-Line Strainer
39 - Solonoid Valve
40 - 1/8" NPT Disc Valve
41 - Solonoid Valve
42 - Remote Temperature Gage
43 - Solonoid Valve
44 - Remote Temperature Gage
-WL- Wax Liquid Line
-WLB - Wax Liquid By-Pass Line
-WP - Wax Paste Line
-HS - Hydraulic Supply Line
-WS - Water Supply Line
-WB - Water By-Pass Line
-WR - Water Return Line

Figure 18. Continued.

thru the heat exchanger (5). It is now desired to stop cooling of the wax trapped within the heat exchanger (5). This has been previously referred to as "maintaining status". To do this: (a) the water pump (21) is momentarily turned off, (b) valves 19, 16, 41, and 14 are closed, (c) valves 12, 15, 13, 39, 40 are opened, and (d) the water pump (21) is turned on. This will allow water from the 145°F reservior (11) to circulate within the heat exchanger (5) and prevent further cooling of the wax within.

VI. TEST SYSTEM OPERATION

In order to take flow data and supply paste wax at 145°F at any of valves 28-35: (a) valve 8 is closed, (b) valve 22 is momentarily closed, (c) the hydraulic pump (24) is turned on, and (d) the desired pumping pressure is set by means of the adjustable relief valve (23). The system is now ready to supply wax flow at any desired rate by gradually opening the hydraulic needle valve (22). The needle valve (22) is opened only slightly for the initial data point. One of the valves 28-35 is now opened and flow is allowed to reach a steady state. Wax is then captured in a container in some timed interval while pressures at gages 26 and 27 are recorded. The captured sample is then weighed and the flow rate is calculated using this and the recorded time interval. The needle valve (22) is then further opened and data is recorded again.

By continually opening the needle valve (22), flow is increased. Opening the valve, then closing it and recording data will yield eroneous data since viscosity is a function of shear rate (flow) and time. In Section III, Part B

and Section IV, Part C, it was pointed out that flow must be steadily increased.

Data may be taken until the wax surge tank (10) is empty. At this time the entire process may be repeated.

VII. FLOW TEST RESULTS

Data, taken as outlined in the previous section, is recorded in Table 3. Very low pressure losses resulted with wax at 145°F. Flow could be established at any outlet with as little as 60 psig on pressure gage 26. When allowed to rest for 12-14 hours with no flow, it was found that by only opening a valve at any outlet flow readily occured.

Extensive data at temperatures other than 145°F was not recorded since this is the temperature at which the production system operates. However, to gain some knowledge about flow at lower temperatures, the surge tank was filled with wax at 125°F, the water reservoir (11) maintained at 125°F and all paste wax lines maintained at 125°F. The system was then allowed to rest for 12-14 hours. Pressures required to initiate flow at this temperature reached 300 psig in the wax line and 500 psig in the hydraulic system.

Table 3. Recorded Raw Data

TEST NO.	GAGE PRESSURE		TIME (SEC)	WAX WEIGHT (lbs)
	GAGE 26	GAGE 27		
1	72	49	117	.216
2	72	48	50	.379
3	73	49	44	.348
4	72	48	7	.203
5	79	50	6	.222
6	79	50	4.5	.204
7	80	50	4.25	.213
8	81	51	4.70	.255
9	83	52	3.40	.233
10	95	55	4.80	.568
11	98	55	3.90	.583
12	99	56	5.20	.764
13	98	56	7.50	1.196
14	100	59	5.90	1.052
15	102	55	5.90	1.447
16	111	61	4.10	1.477
17	120	70	3.70	1.407
18	120	72	5.10	2.355
19	110	71	4.10	1.846

VIII. FLOW DATA ANALYSIS AND APPLICATION

Table 3 was utilized to calculate the flow parameters 8V/D and DΔP/4L and the results appear in Table 4. These parameters were then plotted and are shown in Figure 19. A comparison of Figure 19 with Figure 7 shows that the wax is, indeed, a thixotropic fluid. The general shape and concavity of the curve shown in Figure 19 is very near that which was predicted by looking at other thixotropic fluids in Figure 7.

Using the data shown in Figure 19, flow parameters in pipe of 2" nominal diameter and 42.5" length may be established at any laminar flow rate. According to Skelland (1), more structural breakdown and consequently lower effective viscostity would be obtained with a longer pipe or a pipe of smaller diameter. Therefore applying the data shown in Figure 19 to a longer or smaller diameter pipe will yield conservative flow parameter values.

Table 4. Flow Parameter Data

TEST NO.	GAGE PRESSURE		TIME (sec.)	WAX Weight (lbs.)	ΔP (psig)	Q (lb/hr)	V (ft/hr)	$\frac{D\Delta P}{4L} \times 10^2$ (psig)	$\frac{8V}{D}$ (hr^{-1})
	GAGE 26	GAGE 27							
1	72	49	117.00	.216	23	6.6	4.8	28.1	221
2	72	48	50.00	.379	24	27.3	19.6	29.3	914
3	73	49	44.00	.348	24	28.5	20.5	29.3	954
4	72	48	7.00	.203	24	104.4	75.2	29.3	3498
5	79	50	6.00	.222	29	133.2	95.9	35.4	4464
6	79	50	4.50	.204	29	163.2	117.5	35.4	5469
7	80	50	4.25	.213	30	180.4	129.9	36.6	6045
8	81	51	4.70	.255	30	195.3	140.6	36.6	6545
9	83	52	3.40	.233	31	246.7	177.6	37.8	8267
10	95	55	4.80	.568	40	426.0	306.7	48.8	14,275
11	98	55	3.90	.583	43	538.2	387.5	52.5	18,035
12	99	56	5.20	.764	43	528.9	380.8	52.5	17,723
13	98	56	7.50	1.196	43	574.1	413.4	52.5	19,238
14	100	59	5.90	1.052	41	641.9	462.2	50.0	21,510
15	102	55	5.90	1.447	47	882.9	635.7	57.3	29,586
16	111	61	4.10	1.477	50	1296.9	933.8	61.0	43,459
17	120	70	3.70	1.407	50	1369.0	985.7	61.0	45,875
18	120	72	5.10	2.355	48	1662.0	1196.6	58.6	55,694
19	110	71	4.10	1.846	39	1621.0	1167.1	47.6	54,320

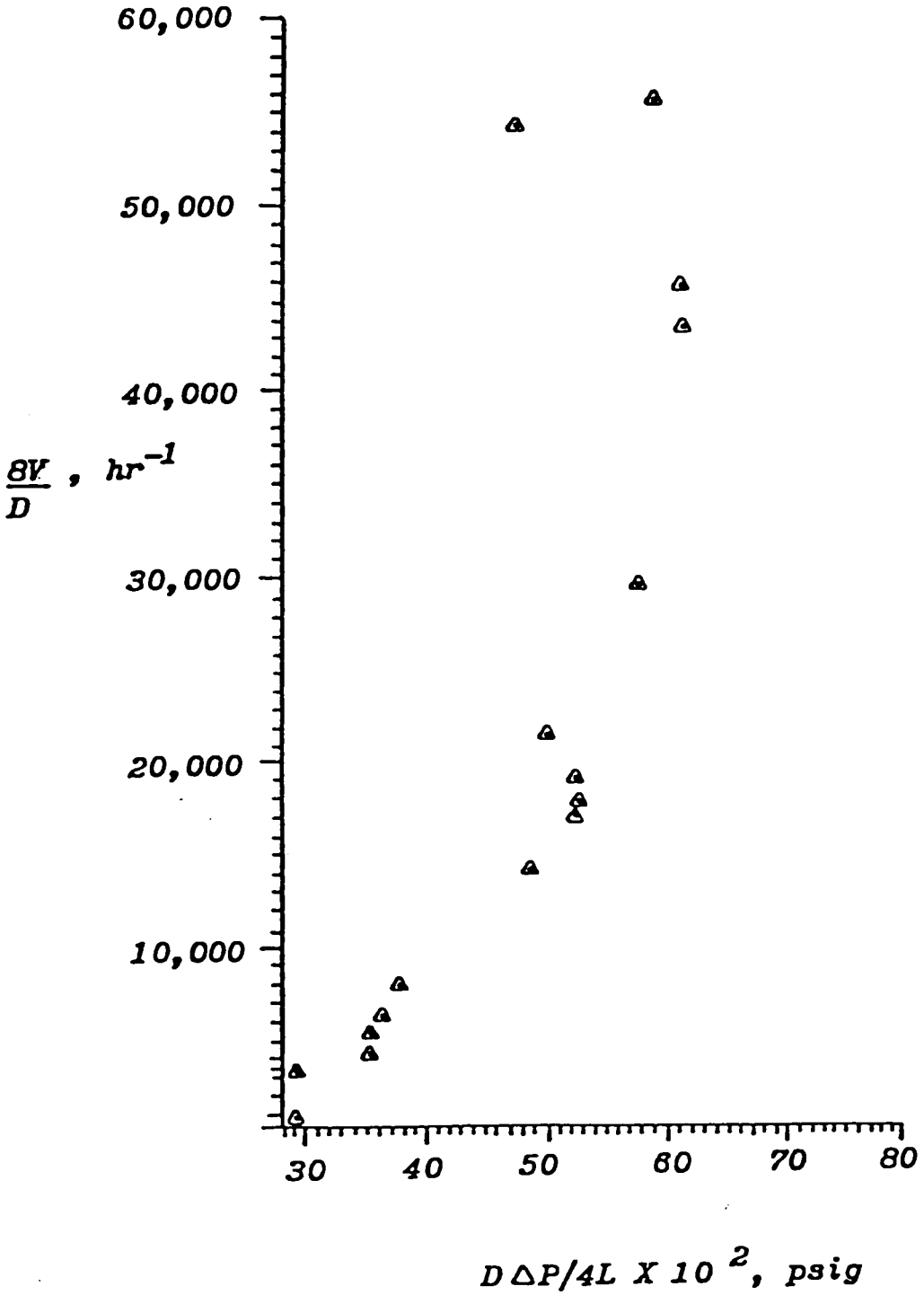


Figure 19. Flow Data Plot For 145°F Investment Casting Wax

IX. ELECTRIC HEATER OUTPUT

In order to verify design power of electric heater circuits, the current and load of each heater was recorded under the heat-up load and respective heater wattages calculated. Current and voltage data as well as power wattage is recorded in Table 5. Subsequent testing was then conducted to assure proper heat-up times. Because the thermocouple for controlling temperature was bonded to the exterior of the steel pipe, it was impossible to evaluate exactly when the hard wax in the center of the pipe became 200°F. The pipe heated up to temperature in approximately one hour and the thermocouple then maintained this pipe temperature. Since the wax has a thermal conductivity of approximately 0.14 BTU/hr/ft./°F (which is equivalent to many insulators), it was some time latter when wax in the center of the 2" nominal diameter became liquid at 200°F.

Table 5. Measured Heater Output of Heat Tracing System

CKT. NO.	VOLTAGE (VAC)	CURRENT (AMPS.)	POWER (WATTS)
1	115	7.3	839.5
2	60	4.4	264.0
3	80	4.2	336.0
4	82	4.6	377.2
5	50	3.8	190.0
6	49	3.5	171,5
7	50	3.7	185.0
8	30	3.2	96.0
9	30	4.2	126.0

X. CONCLUDING REMARKS

Many problems were encountered in the course of designing the wax supply and test system contained herein. Solving these problems yielded a very good workable system which is capable of production operation. Many design changes dealing with control must be initiated before the system is placed into production and many functions, performed manually during testing, must be automated.

Concluding recommendations and statements of test results are given below:

1. The normal procedure used by most, if not all, investment casting facilities for cooling liquid casting wax to injection temperatures is to place the molten wax in liquid state into a temperature controlled tank and allow cooling to take place through heat transfer with surroundings. This method is very slow and can be greatly improved upon through the use of a scraped surface heat exchanger. Using the heat exchanger, the wax can be cooled on a continuous production basis.

2. Air cooling of liquid wax results in non-uniform cooling while cooling with the heat exchanger system yields uniform cooling. It is felt by wax manufacturers that this will result in a possible change of

crystalline structure. All testing conducted to date has not shown this to be an undersirable condition. However, it should be pointed out that all recommendations concerning wax injection temperatures and pressures apply only to wax cooled in a nonuniform manner.

3. The pipe material selected in wax supply systems should be given careful consideration. Seamless black pipe used in a supply system, should be cleaned with a good detergent prior to use.

4. Pressures originally predicted as a result of testing outlined in Part D of Section III were never encountered. This is probably due to the supply pipe being heated and causing a thin layer of liquid wax near the internal diameter. In early experiments the pipe was not heated. Also correlation problems existed between pipe lengths as pointed out in Section IV, Part C.

5. While operating the test system, maintenance on the internal seals of the scraped surface heat exchanger was conducted. When placing the unit back into production the heat exchanger was not primed with wax. This caused air entrapment within the wax. Over a period of several days the air was removed from the system but could not be used for the making of wax patterns. It is strongly recommended that in any closed supply system containing wax, all components be filled with liquid wax during maintenance and prior to installation.

6. A satisfactory test system capable of production operation was designed, built, and extensively tested.

7. *A flow curve was generated from test data which allows calculation of flow parameters at various flow rates. Use of this data with smaller diameter and longer lengths was also discussed and illustrated.*

8. *Flow data was taken which proved investment casting wax to be a thixotropic fluid with flow characteristics similiar to those for other thixotropic fluids such as oil well drilling muds, greases, margarine, shortening, printing ink, and paints.*

9. *Flow within a pipe supply system can be easily initiated with relatively low pressure requirements at temperatures 50°F below the softening point when using Freeman Manufacturing Company's 5350-H casting wax.*

10. *Serious consideration is now being given to place the test system into production at Southern Tool's Investment Casting facility in Anniston, Ala. Various problems involving solidification of the resin component of the wax must be solved prior to production use. According to the wax manufacturers, this problem is associated with the particular wax now used by Southern Tool and would not be encountered with other waxes contining little or no resin components.*

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BIBLIOGRAPHY

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APPENDIXES

APPENDIX A

CALCULATION OF POWER REQUIRED TO HEAT UP WAX SUPPLY PIPE FROM 70°F TO 200°F IN TWO HOURS

I. For 2" Schedule 40 Pipe:

Given:

Pipe Data:
- I.D. = 2.067 in.
- Wt/ft = 3.653 lb.
- Internal Area = 3.356 $in.^2$
- Sp. Heat = 0.12 BTU/lb-°F

Heat-up Time = 2 hrs.
Ambient Temperature, T_a = 70°F
Process Temperature, T_p = 200°F
Product (Investment Casting Wax) Data:
- Sp. Gravity = 0.90
- Sp. Heat = 0.69 BTU/lb-°F
- Heat of Fusion = 75 BTU/lb.

Insulation: 1" Thk. Ceramic Fiber

Solution:

Step 1: Substract the ambient temperature, T_a, from the process temperature, T_p:

$$T_p = 200°F$$
$$-T_a = -70°F$$
$$\Delta T = 130°F$$

Step 2: Calculate the heat required to raise the temperature of one foot of pipe through a ΔT of 130°F: (H_{pipe})

$$H_{pipe} = (wt/ft \text{ of pipe}) \times (Sp. \text{ Heat of pipe}) \times \Delta T$$

$= 3.653\ lb/ft \times 0.12\ BTU/lb\text{-}^{\circ}F \times 130^{\circ}F$
$= 57.0\ BTU/ft\ of\ pipe$

Step 3: *Calculate the heat required to raise the temperature of the wax in one foot of pipe through a ΔT of 130°F: ($H_{product}$)*

$H_{product}$ = (wt. of wax in 1 foot of pipe) x (Sp. heat of wax) x ΔT
$= (3.356/144\ ft^2 \times 1\ ft \times 62.4\ lb/ft^3 \times 0.90) \times (0.69\ BTU/lb\text{-}^{\circ}F) \times 130^{\circ}F$
$= 117.4\ BTU/ft\ of\ pipe$

Step 4: *Calculate the heat required to melt the wax contained in one foot of pipe: (H_{melt})*

H_{melt} = (wt. of wax in 1 foot of pipe) x heat of fusion of wax
$= (3.356/144\ ft^2 \times 1ft \times 62.4\ lb/ft^3 \times 0.90) \times 75\ BTU/lb$
$= 98.2\ BTU/ft\ of\ pipe$

Step 5: *Calculate the heat required to raise the temperature of a one foot length of insulation through a ΔT of 130°F: (H_{Ins}), Refer to Table 6.*

H_{Ins} = Factor from Table 6 x ΔT
$= 0.079 \times 130^{\circ}F$
$= 10.3\ BTU/ft.\ of\ pipe$

Step 6: *Calculate the total heat required per foot of pipe: (H_t)*

$H_t = H_{pipe} + H_{product} + H_{melt} + H_{Ins}$
$= (57.0 + 117.4 + 98.2 + 10.3)\ BTU/ft.$ of pipe
$= 282.9\ BTU/ft\ of\ pipe$

Table 6. Factors for Calculating the Heat Required for Heating Up of Various Insulation Materials

Given: *pipe-Btu/ft-°F(ΔT)*
flat-Btu/ft²-°F(ΔT)

NPS Pipe Size	NOMINAL INSULATION THICKNESS								
	1"	1-½"	2"	2-½"	3"	3-½"	4"	4-½"	5"
½"	0.040	0.072	0.114	0.164	0.223				
3/4"	0.045	0.080	0.125	0.177	0.242				
1"	0.052	0.091	0.139	0.195	0.260				
1-¼"	0.061	0.105	0.157	0.217	0.287				
1-½"	0.068	0.113	0.169	0.234	0.304				
2"	0.079	0.133	0.194	0.265	0.343	0.432	0.530	0.631	0.745
2-½"	0.092	0.153	0.221	0.298	0.384	0.476	0.578	0.694	0.808
3"	0.108	0.176	0.253	0.338	0.430	0.535	0.646	0.765	0.896
4"	0.135	0.216	0.304	0.402	0.508	0.625	0.752	0.885	1.025
6"	0.191	0.292	0.415	0.544	0.675	0.821	0.975	1.134	1.303
8"		0.380	0.518	0.675	0.839	1.008	1.182	1.370	1.565
10"		0.461	0.640	0.814	1.003	1.205	1.400	1.620	1.850

Step 7: *Convert H_t to watts/foot:*
1 watt = 3.412 BTU

H_t = 282.9/3.412 watts/ft of pipe
= 82.9 watts/ft of pipe

Step 8: *Determine the heat loss through insulation per foot of pipe: (H_L), Refer to Table 7.*

H_L = (Factor from Table) x 1/1.25 x ΔT
= 0.109 x 0.60 x 0.8 x 130°F
= 6.8 watts/foot of pipe

Step 9: *Determine the watts per foot of pipe per hour required to heat up within the specified time of 2 hours: (WFPH)*

$$WFPH = \frac{H_t \text{ (watts)}}{time} + \text{heat loss}$$
$$= \frac{82.9}{2} + 6.8$$
$$= 48.3$$

II. *For 1" Schedule 40 Pipe:*

Given:

Pipe Data:
I.D. = 1.049 in.
Wt./ft. = 1.679 lb.
Internal Area = 0.864 in.^{2}
Sp. Heat = 0.12 BTU/lb-°F
Heat-up Time = 2 hours.
Ambient Temperature, T_a = 70°F
Process Temperature, T_p = 200°F
Product (Investment Cast Wax) Data:
Sp. Gravity = 0.90
Sp. Heat = 0.69 BTU/lb-°F
Heat of Fusion = 75 BTU/lb-°F
Insulation: 1" Thk. Ceramic Fiber

Table 7. Heat Required to Offset Losses in Pipelines

PIPE SIZE	PIPE DIA. (O.D.)	RECOMMENDED SIZE OF INSULATION	INSULATION THICKNESS AND FACTORS				
			1/2"	3/4"	1"	1 1/2"	2"
1/2	0.840	3/4	0.086	0.065	0.054	0.043	0.037
3/4	1.050	1	0.012	0.076	0.062	0.048	0.041
1	1.315	1 1/4	0.123	0.090	0.073	0.056	0.047
1 1/4	1.660	1 1/2	0.142	0.013	0.083	0.063	0.052
1 1/2	1.990	2	0.164	0.118	0.094	0.070	0.058
2	2.375	2 1/2	0.192	0.137	0.109	0.081	0.066
2 1/2	2.875	3	0.229	0.162	0.128	0.093	0.076
3	3.500	3 1/2	0.259	0.181	0.142	0.107	0.083
3 1/2	4.00	4	0.287	0.200	0.157	0.113	0.091
4	4.50	4 1/2	0.316	0.219	0.172	0.123	0.098
4 1/2	5.00	5	0.347	0.243	0.189	0.134	0.0107
5	5.563	6	0.417	0.284	0.219	0.155	0.121
6	6.625	7	0.472	0.322	0.250	0.174	0.136
7	7.625	8	0.526	0.357	0.275	0.192	0.151
8	8.625	9	0.571	0.397	0.305	0.212	0.166

1. *Find the temperature difference (ΔT), which is the difference between desired holding temperature and lowest expected ambient temperature.*

2. *To Obtain watts per foot necessary for holding temperature, multiply temperature difference by insulation thickness factor that corresponds to pipe size used (ΔT x factor = W/ft/loss).*

Notes:

a. *The values in this table include a 25% safety factor to allow for variables involved.*

b. *Theoretically during heat up, the heat loss through insulation will average approximately 60% of table value.*

Solution:

Step 1: *Substract the ambient temperature,* T_a *from the process temperature,* T_p*:*

$$\begin{aligned} T_p &= 200^\circ F \\ -T_a &= -70^\circ F \\ \hline \Delta T &= 130^\circ F \end{aligned}$$

Step 2: *Calculate the heat required to raise the temperature of one foot of pipe through a* ΔT *of* $130^\circ F$*:* (H_{pipe})

$$\begin{aligned} H_{pipe} &= (wt/ft \text{ of pipe}) \times (Sp.\ Heat \text{ of pipe}) \times \Delta T \\ &= 1.679 \text{ lb/ft} \times 0.12 \text{ BTU/lb-}^\circ F \times 130^\circ F \\ &= 26.2 \text{ BTU/ft. of pipe} \end{aligned}$$

Step 3: *Calculate the heat required to raise the temperature of the wax in one foot of pipe through a* ΔT *of* $130^\circ F$*:* $(H_{product})$

$$\begin{aligned} H_{product} &= (wt.\ of\ wax\ in\ 1\ foot\ of\ pipe) \times (Sp.\ Heat\ of\ wax) \times \Delta T \\ &= (0.864/144 \text{ ft}^2 \times 1 \text{ ft.} \times 62.4 \text{ lb/ft}^3 \times 0.90) \times (0.69 \text{ BTU/lb-}^\circ F) \times 130^\circ F \\ &= 30.2 \text{ BTU/ft. of pipe.} \end{aligned}$$

Step 4: *Calculate the heat required to melt the wax contained in one foot of pipe:* (H_{melt})

$$\begin{aligned} H_{melt} &= (0.864/144 \times 1 \text{ ft.} \times 62.4 \text{ lb/ft}^3 \times 0.90) \times (75 \text{ BTU/lb}) \\ &= 25.3 \text{ BTU/ft. of pipe} \end{aligned}$$

Step 5: *Calculate the heat required to raise the temperature of a one foot length of insulation through a* ΔT *of* $130^\circ F$*:* (H_{Ins})*, Refer to Table.*

H_{Ins} = Factor from Table x ΔT
= 0.052 x 130°F
= 6.8 BTU/ft of pipe

Step 6: Calculate the total heat required per foot of pipe: (H_t)

$H_t = H_{pipe} + H_{produce} + H_{melt} + H_{Ins}$
= (26.2 + 30.2 + 25.3 + 6.8) BTU/ft. of pipe
= 88.5 BTU/ft. of pipe

Step 7: Convert H_t to watts/foot of pipe:
1 watt = 3.412 BTU

H_t = 88.5/3.412 watts/ft. of pipe
= 25.9 watts/ft. of pipe

Step 8: Determine the heat loss through insulation per foot of pipe: (H_L) Refer to Table.

H_L = (Factor from Table) x 0.6 x 1/1.25 x ΔT
= 0.073 x 0.6 x 0.8 x 130°F
= 4.6 watts/ft. of pipe

Step 9: Determine the watts per foot of pipe per hour required to heat up within the specified time of 2 hours: (WFPH)

$WFPH = \frac{H_t \text{ (watts)}}{t}$ + heat loss
= 25.9/2 + 4.6
= 17.5

APPENDIX B

SAMPLE SCALE-UP CALCULATION

TO DETERMINE FLOW PARAMETERS

I. Find the pressure loss in a 1" nominal diameter pipe system with a length of 15 feet handling paste wax at 145°F. It is desired to pump the wax at a rate of 150 lb/hr. The wax has a specific gravity of 50.5 lb/ft.^{3}

Solution:

Step 1: Calculate the 8V/D at the desired flow rate:

$$\text{Flow rate} = 150 \text{ lb/hr} = AV$$
$$150 \text{ lb/hr} = (\pi \rho D^2 V)/4$$

$$8V/D = (32)(150) / (\pi \rho D^3)$$
$$= \frac{(32)(150)}{(50.5/1728)(1.049)^3 \pi}$$
$$= 45{,}292$$

Step 2: Enter Figure 19 at 8V/D of 45,292 and determine the corresponding value of $D\Delta P/4L$ from the curve. Read a $D\Delta P/4L$ of .61psig

Step 3: Solve $D\Delta P/4L = .61$ psig for the pressure drop.

$$D\Delta P/4L = .61 \text{ psig}$$
$$\Delta P = (.61)(4)(L) / (D) \text{ psig}$$
$$\Delta P = (.61)(4)(15)(12) / (1.049)$$
$$*\Delta P = 419 \text{ psig}$$

*Note: Since this pipe would be larger in diameter and longer in length than the one used in

gathering data, this represents a conservative pressure loss. This was pointed out in Section IV, Part C.

II. Find the distance that 1000 lb/hr of paste wax can be pumped with a maximum pressure loss of 100 psig in 2 inch schedule 40 pipe.

Solution:

Step 1: Calculate the 8V/D at the required flow rate:

Flow rate = 1000 lb/hr = AV

$$8V/D = (32)\ (1000)/(\pi \rho D^3)$$
$$= \frac{(32)\ (1000)}{(50.5/1728)\ (\pi)\ (2.067)^3}$$
$$= 39{,}466.7$$

Step 2: Enter Figure 19 at 8V/D of 39,466.7 and determine the corresponding value of $D\Delta P/4L$ from the curve.

Read a $D\Delta P/4L$ of 0.61 psig.

Step 3: Solve $D\Delta P/4L = 0.61$ psig for the maximum length:

$$D\Delta P/4L = .61 \text{ psig}$$
$$L = D\Delta P/\ (4 \times 0.61) \text{ in.}$$
$$L = (2.067)\ (100)\ /\ (4 \times 0.61 \times 12)$$
$$*L = 7.059 \text{ ft.}$$

*Note: Since this pipe would be longer in length than the one used in gathering data, this represents a conservative pressure loss. This was pointed out in Section IV, Part C.

VITA

Randall Whorton was born May 12, 1950 in Gadsden, Alabama. He graduated from Cherokee County High School, Centre, Alabama, in 1968. In September of that year, he entered Jacksonville State University taking pre-engineering curriculum. After completing pre-engineering courses at Jacksonville, he entered Auburn University in June of 1970 where he graduated in 1972 with a Bachelor of Science degree in Mechanical Engineering, and was commissioned a Second Lieutenant in the United States Army Ordinance Corps on a reserve status. Upon graduation, he was employed by Arnold Research Organization, Arnold Air Force Base, Tennessee, as a mechanical design engineer. In January of 1975 he began part time work on his Master of Science degree at the University of Tennessee Space Institute. After meeting all residency requirements for the Master of Science degree he was employed by the Research and Development division of Etowah Manufacturing Company, Gadsden, Alabama as a project engineer in April of 1977. In August of 1977 he was employed by Southern

Tool, Anniston, Alabama, as plant engineer. He is presently with this firm and is serving as a Captain in the United States Army Ordinance Corp Reserve. Mr. Whorton is married and has two children.