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TECHNICAL REPORT
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NONPOWERED INSTANT WATER HEATER

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The technical feasibility of a nonpowered instantaneous water heater based on the use of a condensing steam ejector pump has been established by test of a commercially available ejector. Using steam at approximately 25 PSIG pressure, it has been demonstrated that water can be simultaneously heated and pumped to pressures up to two times the steam pressure. The overall system concept is that of a lightweight, portable heater package that is fired with a constant-run, manually-controlled burner. The concept can accommodate the operation of a constant-run burner with only intermittent water delivery, as in a kitchen use, by recirculation of heated water back to the supply tank/barrel. With outlet water pressure greater than the inlet steam pressure, the unit can incorporate automatic feed of makeup water to the steam generator. The system concept can be implemented in a range of outputs. At 100,000 Btu/hr burner output and 50% efficiency, system capability would be at about 0.8 GPM continuously with a 100^{O}F temperature rise, 1.5 GPM continuously with about a 50^{O} rise, or 1.5 GPM intermittently at 100^{O}F rise and 50%/50% on-off delivery duty cycle.

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Preface

This report describes a project carried out by Yankee Scientific to assess the feasibility of developing a nonpowered instant water heater for use in Army field kitchens. This SBIR Phase I project was carried out under the sponsorship of the U.S. Army Natick Research Development and Engineering Center, (Army Contract No. DAAK60-93-C-0022.)

The information contained within this report will be useful to persons responsible for identifying new methods for supplying heated and pressurized water to troops in the field without requiring the use of electric power or large engines. The general class of equipment developed during this investigation could find application to both military and civilian situations.

The author additionally thanks Penberthy, Inc. for allowing the reproduction of illustrations and information from Penberthy's technical literature.

NONPOWERED INSTANT WATER HEATER

Section 1

Introduction and Background

Introduction

The United States Army has a need for a nonpowered, pressurized hot water source for field sanitation purposes, including cooking, cleaning, laundry, and showers, as well for other purposes such as decontamination and equipment maintenance. Current water heating is done in a non-pressurized batch mode with antiquated immersion heaters or in open sinks. These units have no provision for filling from the water source and cannot provide a pressurized flow for effective use of the hot water. When a continuous source of pressurized hot water is required, electrical or engine-driven pumps are required.

Project Objective and System Requirements

The objective of this project is to develop a nonpowered system that can provide a pressurized flow of hot water in field situations. It is desired that the system operate essentially as an "instantaneous" heater and not employ substantial hot water storage capacity. Specific preferences for this system include:

1) Compatibility with current burner systems, such as the M2 or M3 burner

2) Variable flow, pressure, and temperature capability in the range of two to five gallons per minute

3) Delivery pressure over 20 PSIG

4) 50 to 100 °F water heating capability

5) Man portability, minimum size and weight

6) Controlled delivery temperature and pressure

Technical Approach for Nonpowered Instantaneous Water Heater (NPIWH)

The technical approach that has been used to develop the required nonpowered instantaneous water heater, referred to as the "NPIWH" in this report, is to use a direct-contact, steam-driven water pump. In this concept, the burner is used to heat a small steam generator which, in turn, will operate a steam-driven ejector-type water pump. The steam pumps the water to pressure while simultaneously heating the water. The concept is adaptable to essentially any type of fuel burner that the Army may prefer to use with this system.

Section 2

Direct-Contact, Steam-Driven Water Pumps

General Principles

Direct-contact, steam-driven water pumps fall into to the general category of so-called *jet pumps* or *ejectors*. They are also referred to as eductors and injectors. Such steam operated ejectors provide a pumping action as a result of the transfer of momentum, by mixing, from a relatively a high pressure and velocity primary flow (steam) into a lower pressure and velocity secondary flow stream, in this case water. Because this type of pump operates by mixing and entrainment effects, their efficiency in converting mechanical energy in the primary flow to mechanical energy in the secondary flow is low typically only about 10 to 20%.

For most ejectors, including many that are designed to pump water with steam, the discharge pressure is limited to some moderate fraction of the pressure of the driving primary (steam) flow. However, in the particular case of steam-driven water pumps there is the special opportunity to take advantage of the dynamic effects produced by condensation of the steam. The significant advantage of these so-called "condensing" ejectors is that it is possible for the discharge water pressure to actually be higher than the inlet water pressure. This advantage allows for achieving the desired water pressure at lower steam pressure. The fact that the ejector discharge pressure can be greater than the inlet steam pressure also allows for the use of some of the ejector discharge water flow as makeup water for the steam generator.

Standard Steam-Driven Ejectors

Standard steam-driven, ejector-type water pumps are widely used in industry. Figure 1 is a typical configuration. Pressurized steam is provided at the primary flow inlet, water is inlet at the suction port, and the discharge is a pressurized flow of water that is heated

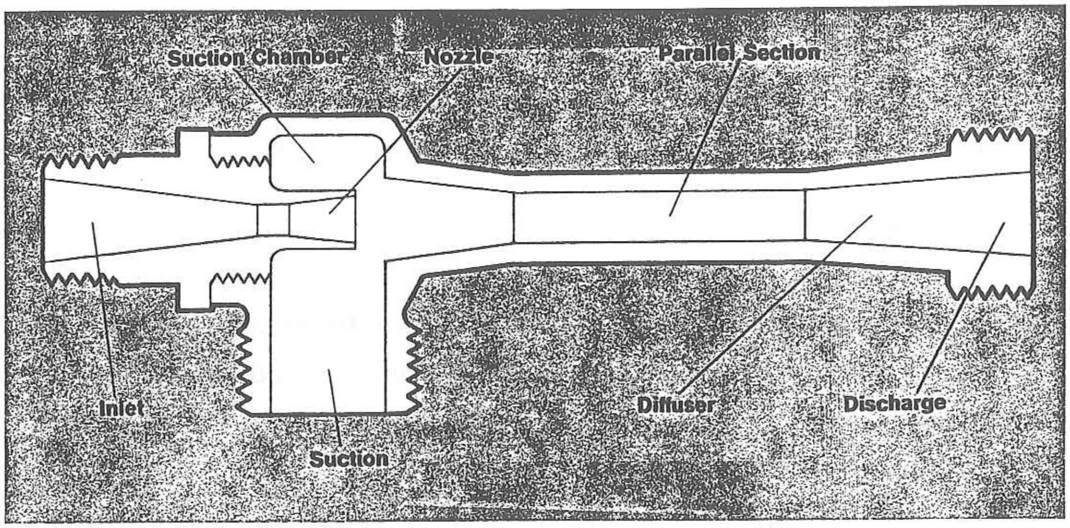


Figure 1. Standard Steam-Driven Ejector Water Pump

as a result of the condensation of the steam by the water.

For this application, performance quotations where solicited from several vendors. Stated inlet conditions were 50 PSIG saturated steam and atmospheric pressure water. Maximum discharge pressures of about 20 PSIG were quoted. Steam consumption is about 0.5 pounds of steam per gallon of water pumped. These standard-type ejectors are available at any desired flow capacity.

The general literature of direct steam-driven ejector-type water pumps has been reviewed in Reference 1.

Condensing Steam Ejectors

The condensing ejector is similar to the standard ejector in that steam is directly contacted with water to provide a simultaneous pumping and heating effect. However, the unit is designed to take advantage of the additional mechanical energy that can be recovered as a result of the condensation of the steam. Like the standard ejector, the condensing ejector is generally composed of a pair of inlet nozzles, a mixing section, and a diffuser.

In the condensing ejector, the fluid streams are accelerated in the nozzles at the exit planes of which the vapor is at a high temperature and velocity compared to the temperature and velocity of the liquid. The streams come into contact in the mixing section. Due to a large temperature difference and the relative velocity between the streams, a high rate of heat transfer is established. Vapor condenses onto the liquid stream and the momentum of the liquid increases. For the proper inlet and exit conditions, it is possible to cause all the vapor to condense within a short axial distance in the mixing section. The condensation process by which the two-phase flow is rapidly transformed into a single-phase liquid stream, with a resulting rise in pressure, is called a condensation shock. It is this condensation shock effect that allows for the discharge pressure to be greater than the inlet steam pressure.

Applications for condensing ejectors include boiler feed pumps and other industrial pumping duties where the simplicity is desired, the higher delivery pressure is required, and the moderate level of energy efficiency is acceptable. Applications that have been considered for this type of pump are reported to include underwater propulsion systems (2), space power systems (3,4) and active environmental control systems (5).

The phenomena occurring in a condensing steam ejector are complex and there is a very limited technical literature concerning their design and performance. Two vendors of such "condensing" ejectors steam-driven water pumps have been identified. These are Penberthy Co. in Illinois and Vicjet in Pennsylvania. Penberthy Co. makes condensing ejectors, referred to as automatic injectors, in the size range of interest (1.5 GPM and larger) while Vicjet appears to specialize in larger units. Senior technical personnel at Penberthy Co. state that their design is very old and was originally developed for use as a boiler feed pump for steam locomotives. It is also stated there is limited performance information available on existing units and that the original engineering and design basis for the existing units is not available to them. Some studies of condensing ejectors at university research laboratories have been reported (6), but the designs considered in these works appear to have limited relationship to what is available as a commercial product.

The Penberthy™ Model 00-526 Automatic Injector

The Model No. 00-526 low pressure automatic injector (i.e., condensing ejector) of the Penberthy Co. was selected for application to the NPIWH. The configuration of this injector is shown in Figure 2. The capacity of this ejector is given by the manufacturer as indicated in Table 1. Steam consumption was reported to be 38 and 32 lbs/hr at 40 and 60

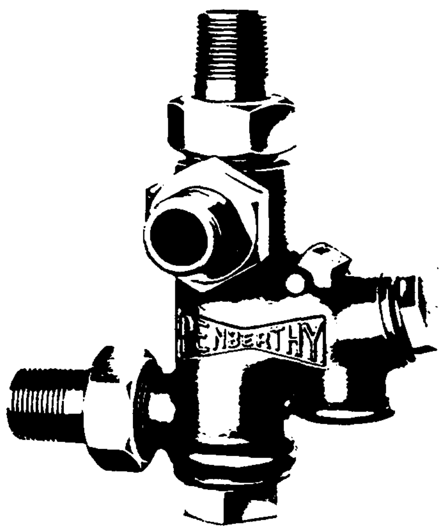


Figure 2. Penberthy Condensing Ejector

PSIG steam pressures, respectively. At the capacities given in Table 1, this translates to approximately 0.5 pounds of steam per gallon of water pumped, which is essentially the same performance as the standard-type, steam-driven ejectors described above. No other performance data are available. This ejector has a small physical size, being only about 5 inches tall and having 3/8 inch NPT pipe connections. It is made from a bronze casting.

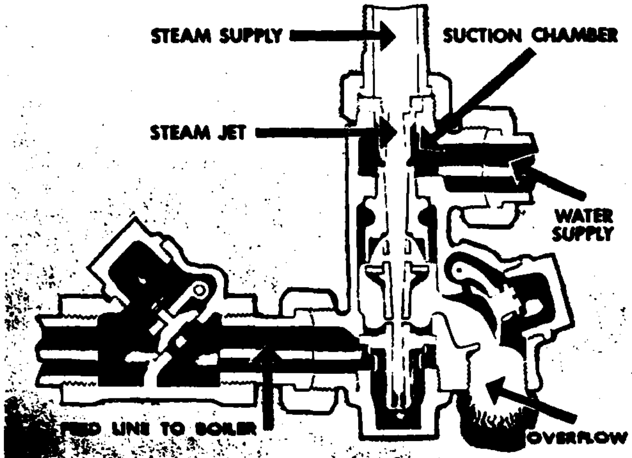
Table 1. Capacity of No. 00-526 Condensing Ejector

Steam Pressure	Gallons per Hour*
20	55
40	80
60	75
80	65
100	55

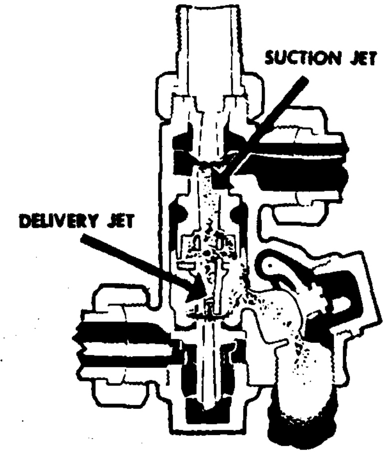
* at 3 feet of suction lift and 74 °F water temperature

The operation of the Model 00-526 is illustrated in Figure 3. Steam flow is first provided to the ejector. Then the water inlet line is opened. The ejector automatically sequences through venting and startup as described in Figure 3.

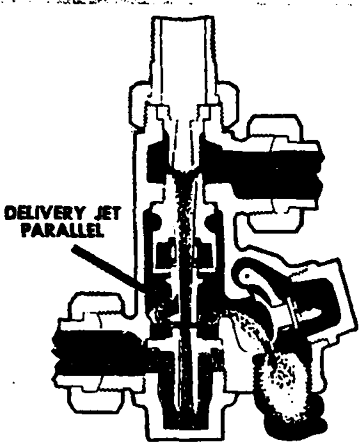
Although the basic performance of this ejector appeared attractive, further test data were needed to confirm applicability. For this reason, one of the Model 00-526 automatic injectors was acquired, installed in a test stand, and tested as described in the following section of this report.



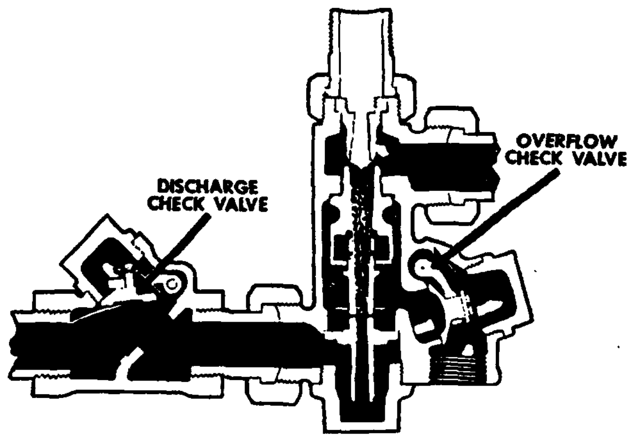
When steam supply valve is opened, steam passes through steam jet into suction chamber, proceeds through suction jet and out of the overflow. Steam, which attains a velocity of approximately 2500 ft per second as it leaves the steam jet, entrains the air in suction chamber and creates a vacuum.



The vacuum created in suction chamber begins to draw in water from supply line. The water is now entrained by the steam and a high velocity mixture of water and steam passes through the suction jet and out of the overflow.



When the amount of steam and water reach the proper proportion, the steam gradually condenses as the mixture advances through injector. Upon reaching delivery jet parallel the mixture is fully condensed.



The energy contained in the water passing through delivery jet is sufficient to build up a pressure, greater than the boiler pressure, causing water to flow through the discharge check valve into the boiler. When flow into the boiler is established the overflow valve closes automatically and prevents the entrance of air which would disrupt operation of injector. Total operating cycle requires only a few seconds.

* Formerly Penberthy Injector Co.

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Figure 3. Operation of Penberthy Condensing Ejector

Section 3

Test of Condensing Steam Ejector

Description of Condensing Ejector Test Apparatus

A Penberthy Model No. 00-526 low pressure automatic injector was installed in a test stand as depicted in Figure 4. The apparatus included a steam pressure regulating valve for step-down controlled steam pressure from the available 200 psig supply. Regulated pressures in the range of 10 to 50 psig were available. Pressure gauges were located on the steam inlet and water outlet lines and a compound vacuum-pressure gauge was located on the inlet water line. All lines were valved. The water feed was from a standing 55 gallon tank at atmospheric pressure. Water delivery was to another 55 gallon tank located on a weighing scale. Temperatures were measured with a Type K thermocouple in the supply tank and in the delivered water flow.

Figure 5 includes photographs of the test apparatus. The apparatus was assembled in the Yankee Scientific, Inc. mechanical laboratory and installed in the Mechanical Engineering Test Laboratory at the Massachusetts Institute of Technology.

Operation of Condensing Ejector Test Apparatus

The basic ejector test is that of measuring the flow rate and temperature rise of the water as a function of the inlet steam pressure and the outlet water pressure. Each test begins with introduction of steam at the ejector inlet at the pressure controlled by the steam regulator valve. Initially the steam flows through the ejector and out the ejector vent. Then the water inlet valve is opened quickly. Generally, within a few seconds, flow of water at the water outlet begins and the outlet valve is adjusted to attain the desired outlet pressure. Restricting the outlet flow causes a rise the in the outlet pressure at the ejector. The flow stabilizes quickly and the time required to attain a certain of amount of mass flow of water

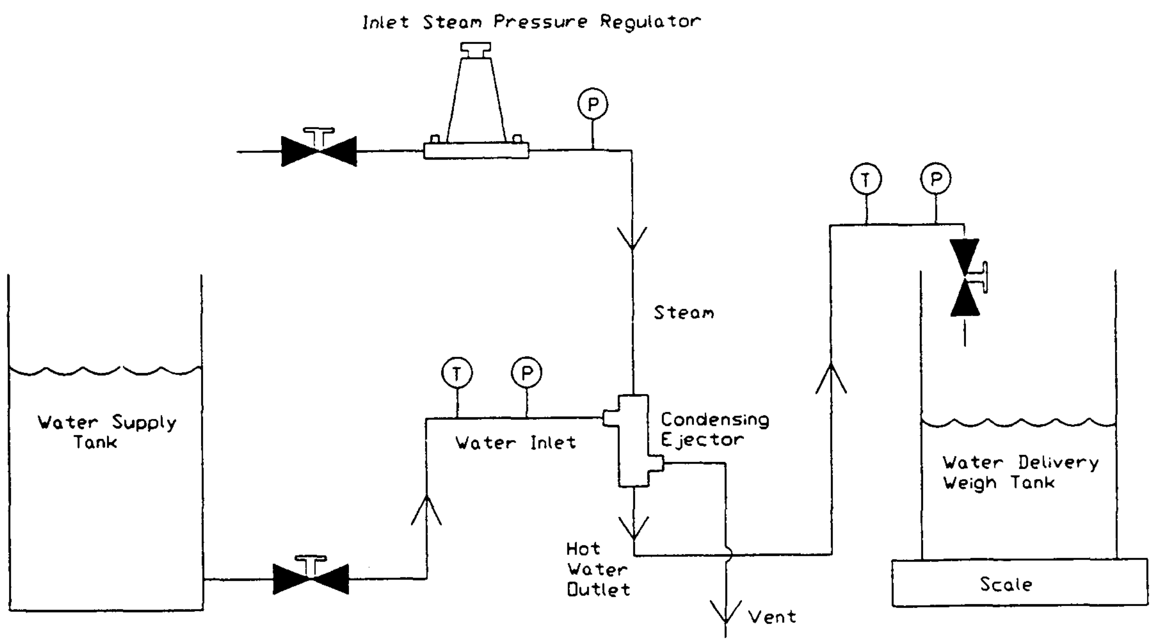

Figure 4. Schematic of Condensing Ejector Test Stand

as recorded by the weight scale is measured. The temperature of the water in the inlet supply tank and the outlet pipe are also measured.

The change in weight of the delivery tank per unit time yields the total flow rate of steam and water through the ejector. From the temperature rise of the water, the amount of steam condensed can be calculated. Thus, the steam flow rate is established.

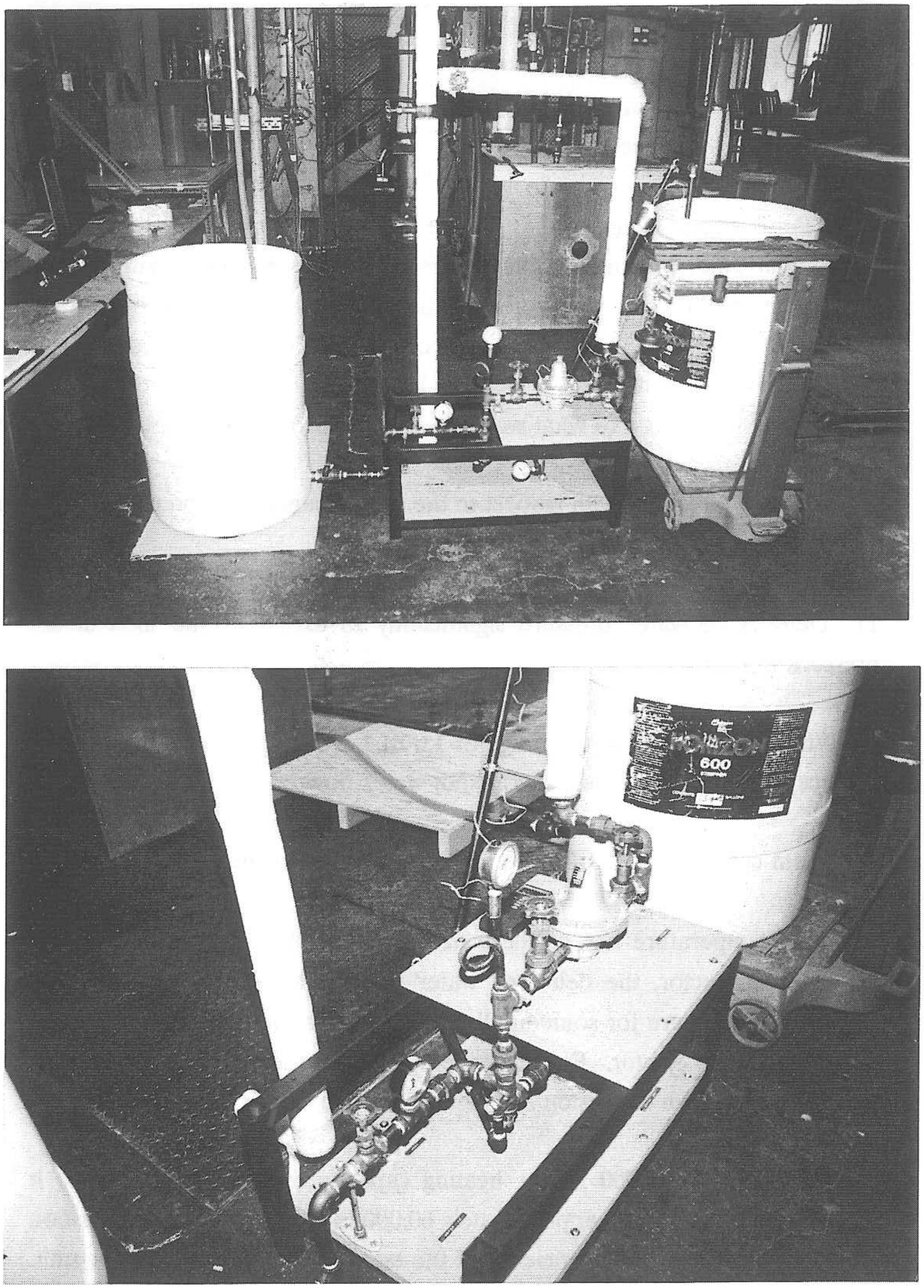

Figure 5. Photographs of Condensing Ejector Test Stand

Test Results

Overall, the performance of the Penberthy low pressure automatic injector was excellent and in line with expectations.

Basic Performance Characteristics The ejector performance as a function of the ratio of the outlet water pressure to inlet steam pressure is given in Figures 6 through 9. The pumping rate, steam consumption, heating rate, and water temperature rise are all given as a function of this pressure ratio. Performance at 18 PSIG and 29 PSIG steam pressures is given in each case. The 18 PSIG is near the lower limit of operation of the condensing ejector while 29 PSIG is close to what would be an actual desirable operating pressure.

Important observations with respect to the performance data presented in Figures 6 through 9 for the Model 00-526 ejector are as follows:

1) Delivery of water pressure significantly in excess of the inlet steam pressure is achievable.

2) With delivery rates in the range of 1.0 to 1.5 GPM, this ejector provides an acceptable minimum capacity for hot water flow.

3) Steam consumption is close to that stated by the manufacturer.

4) With temperature rise of the water of about 40 to 50 °F as it passes through the ejector, the delivered water may be adequately heated from ambient temperature for some applications, such as showering, with a single pass through the ejector. For higher temperatures the water would need to be recirculated (see discussion in following section of this report).

5) The 30,000 to 40,000 Btu/hr heating capacity of this ejector makes it consistent for use with an approximately 60,000 to 100,000 Btu/hr combustion system, depending on the efficiency of the burner and steam generator unit.

Startup and Operating Characteristics The ejector started reliably by the sequence of admitting the steam first and then the water. Starting is assisted by the "jogging" of the inlet water valve after about 30 seconds of steam flow through the ejector. Up to a pressure ratio (outlet water pressure/steam pressure) of about 2.0, operation of the ejector was

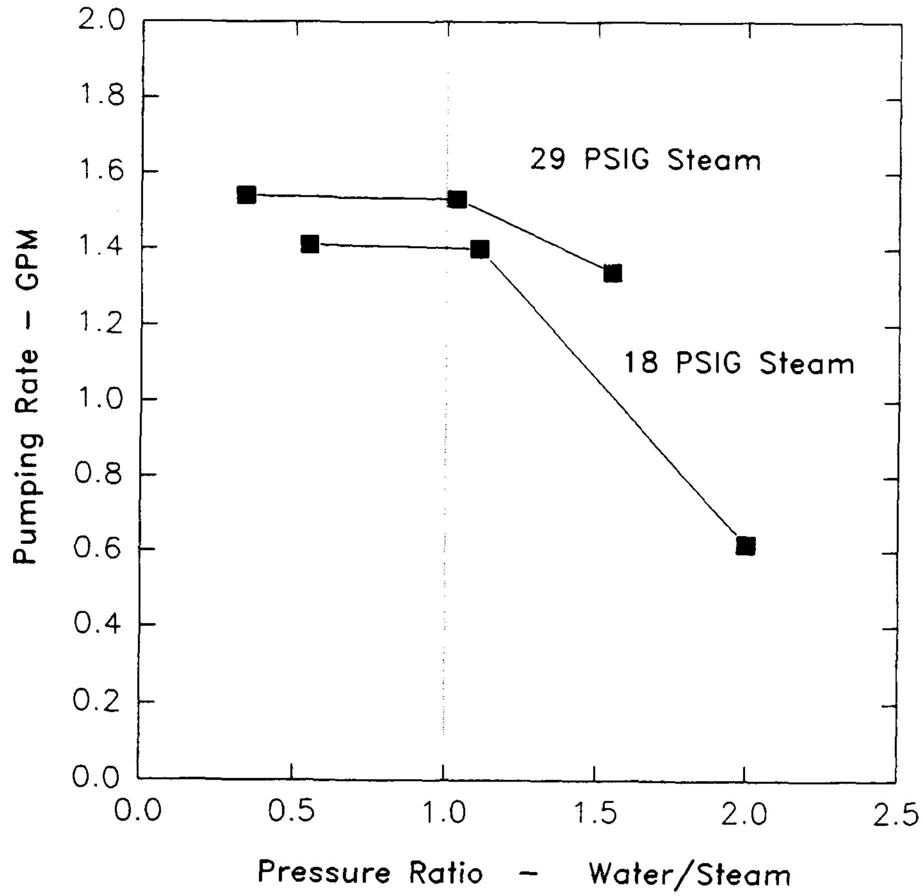

Figure 6. Condensing Ejector Pumping Performance as Function of Operating Pressure Ratio

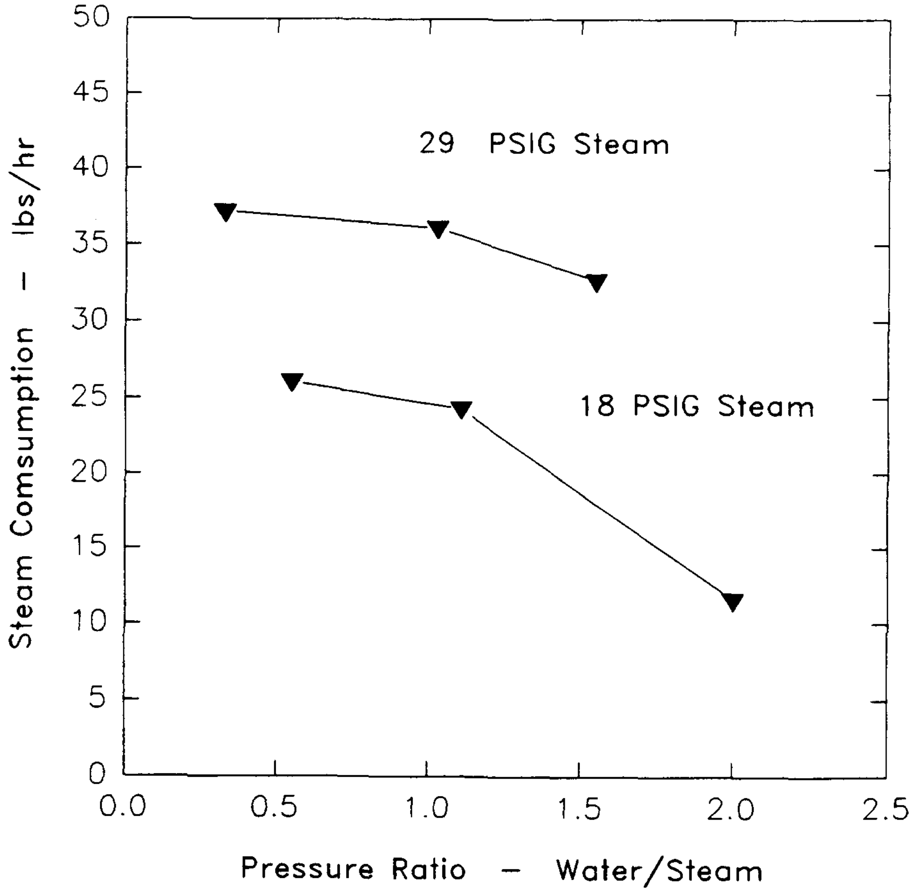

Figure 7. Condensing Ejector Steam Consumption as a Function of Operating Pressure Ratio

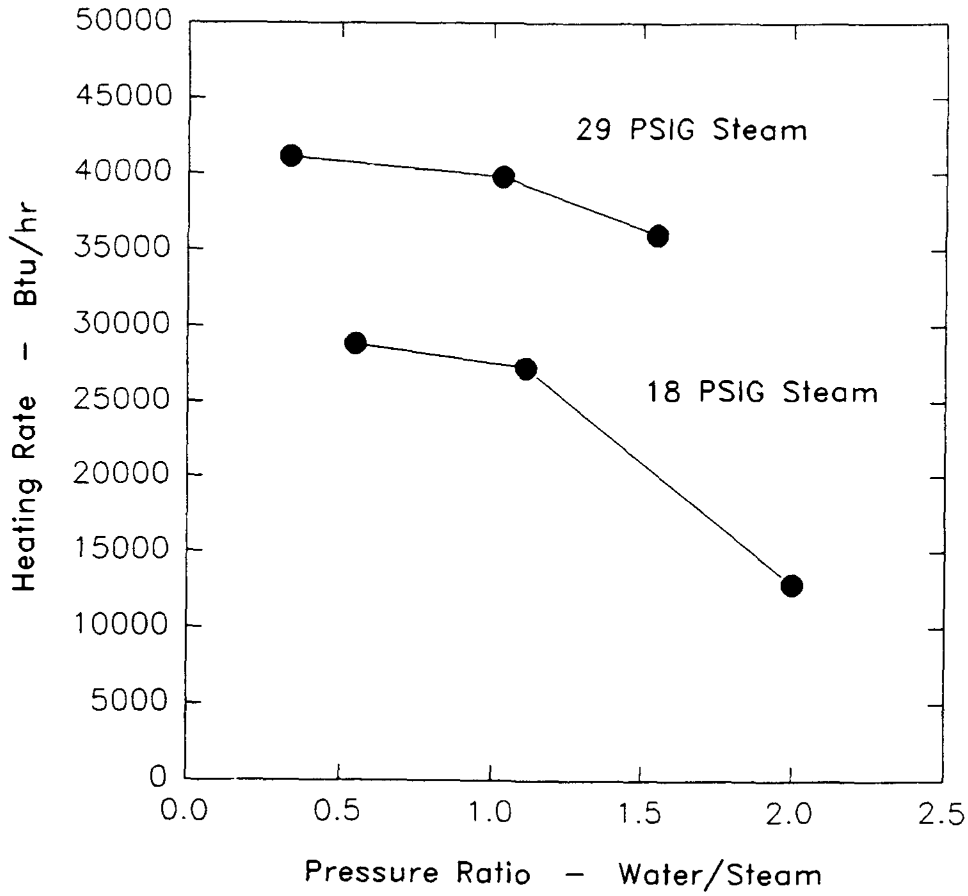

Figure 8. Condensing Ejector Heating Rate as a Function of Operating Pressure Ratio

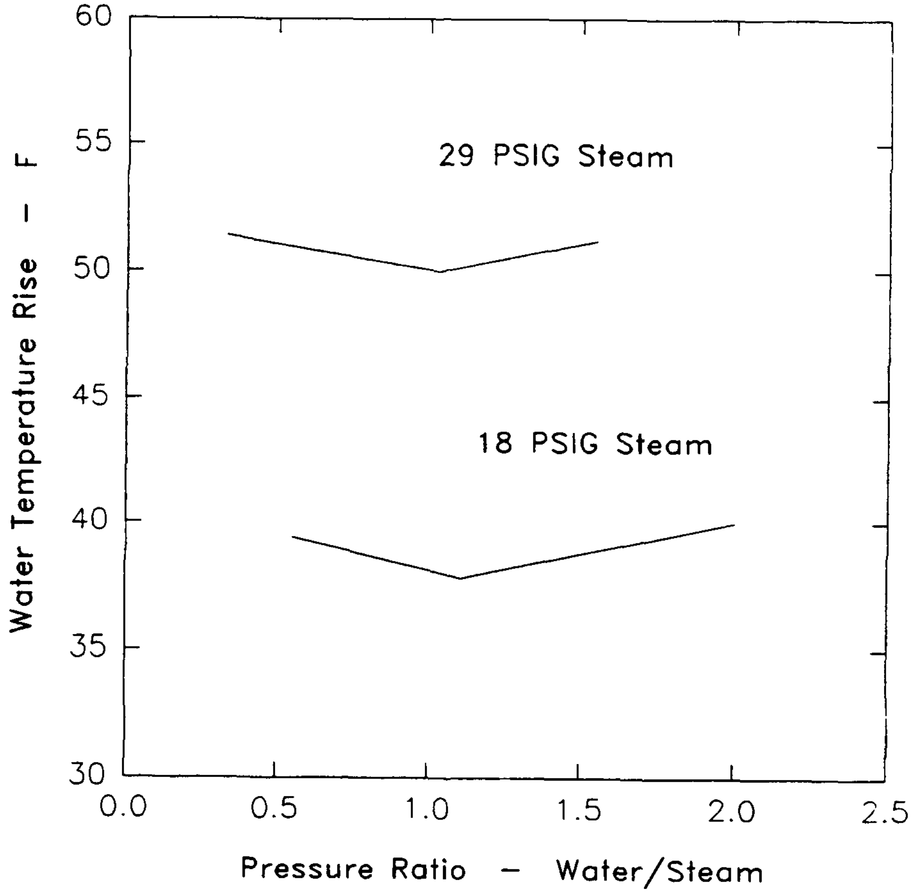

Figure 9. Condensing Ejector Water Temperature Rise as a Function of Operating Pressure Ratio

smooth, without pulsation. The operation of the ejector is also quiet.

Control of the water flow was best achieved by valving at the outlet water line. A delivery spray nozzle with on-off valving action proved to be effective, with instantaneous response by the ejector. Delivery of pressured water with the repeated and rapid opening and closing of the delivery nozzle was essentially identical to that normally experienced with pressurized tap water. Regulation of the water flow by the inlet water valve was not as effective.

The minimum operating steam pressure was 16 PSIG. Below this level operation was erratic, with loss of outlet pressure capability. Figure 10 is the flow - pressure characteristic at constant steam pressure. Figure 11 shows the effect of steam pressure on delivery flow at a pressure ratio of 1.0.

<u>Effect of Inlet Pressure/Vacuum</u> The ejector was tested for operation with different inlet water pressures. First, variation in the supply tank level with the flooded-inlet configuration and the inlet valve wide open had no measurable effect on the operation. Variation in the level of the inlet tank was approximately 2.5 feet and over this range the inlet pressure measured by the compound pressure gauge (pressure and vacuum) at the ejector inlet would remain at zero. Also, the ejector inlet pressure was reduced to vacuum levels by partially closing the inlet water valve. At inlet vacuum pressures of 10 inches of mercury, there was about a 30% decrease in flow capacity. Thus, while the unit does have suction lift capability (up to at least 10 feet of elevation), better performance is achieved with the flooded inlet condition.

<u>Effect of Inlet Water Temperature</u> The ejector was also tested to determine the effect of inlet water temperature on the ability to sustain the outlet pressure. At a constant inlet steam pressure, testing indicated no change in delivery pressure over the range of inlet temperatures from 80 to 130°F. With the temperature rise remaining constant at about 40°F, independent of inlet water temperature, the outlet water is about 170°F at the 130°F inlet water temperature. This ability of the ejector to operate with elevated inlet water temperature confirmed the possibility of achieving, as desired, a full 100°F heating capability with the ejector through the use of hot water recirculation or bypass back to the storage/supply tank or barrel (see discussion in next section).

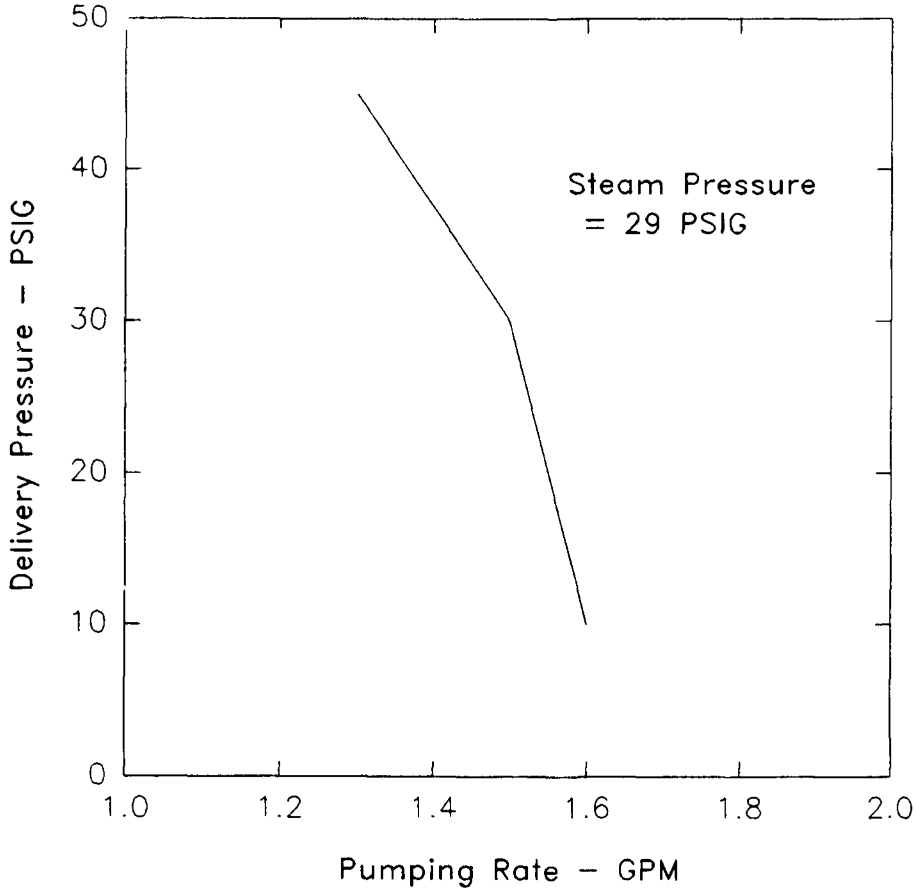

Figure 10. Pumping Performance Curve for Condensing Ejector

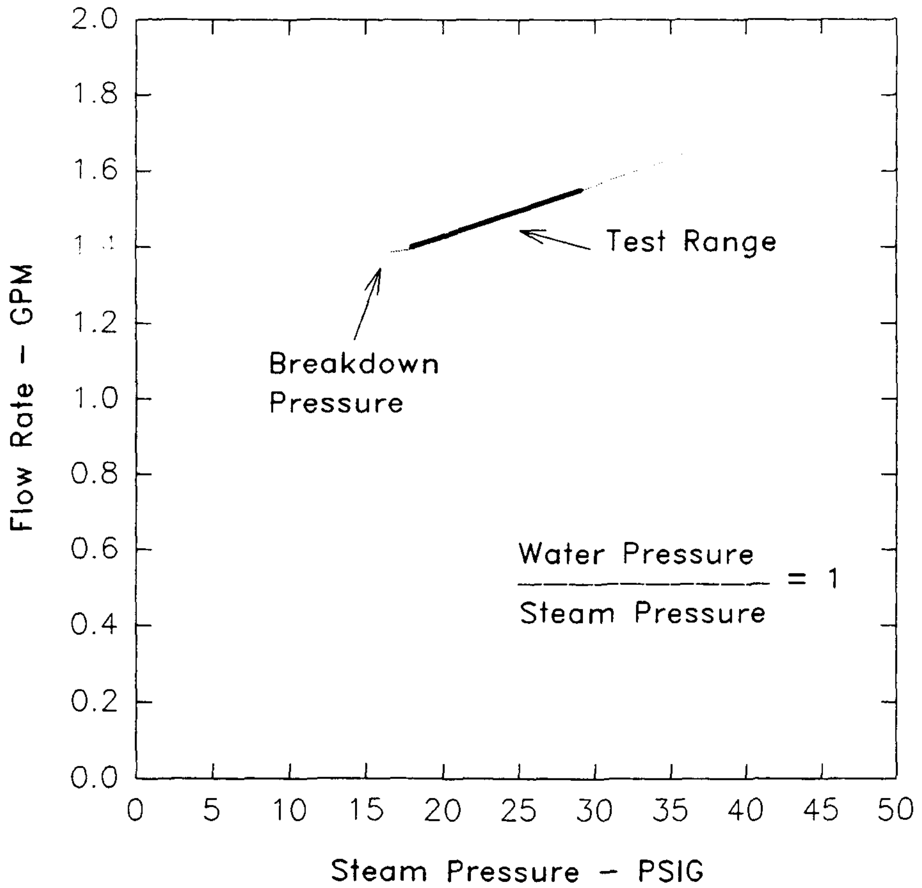

Figure 11. Condensing Ejector Pumping Rate as a Function of Steam Pressure at Pressure Ratio = 1

Section 4

Design Options for Nonpowered, Pressurized, Instantaneous Hot Water System Using Condensing Ejector

Introduction

In this section, the basic strategy for designing a nonpowered instantaneous water heater (NPIWH) is discussed. This presentation focuses on 1) the basic thermal design problem of achieving the desired hot water delivery characteristics with a burner of limited capacity and 2) the configuration and components needed to implement the condensing ejector concept.

The discussion in this section summarizes the range of design options that should be feasible within the general concept of the nonpowered water heater using the condensing steam ejector. The common elements of all design options of this system are the burner, the steam generator, and the condensing ejector.

The thermal output of the available burner defines the limit of the time-averaged output of any water heating system. Thermal storage is often used with water heaters to provide instantaneous hot water delivery capacities that are in excess of the time-averaged limit. Consideration of the role thermal storage can play in this application is an important part of defining the NPIWH system design options and performance potential.

In addition to the fundamental thermal limitation of the heat source, a water heater using a steam ejector for both pumping and water heating must, of course, function within the limits of performance of the ejector itself. In this section, the limits of thermal and ejector performance are reconciled in light of Army requirements.

NPIWH Design Basis

Thermal Capacity

This analysis assumes the availability of an M2 or M3 burner, as the use of available components for the burner has important developmental and logistical advantages. Nominal firing rate of the M2 or M3 burners is 60,000 Btu/hr. However, it is understood that firing to 100,000 Btu/hr may be possible.

Nearly any type of fuel burner could be used to operate the steam generator that is an essential element of the NPIWH. However, it is assumed that the burner will not have any automatic firing controls and that the system must be designed to accommodate constant-run burner operation.

Heating Efficiency

With good design of the arrangement of the burner and the steam generator, it should be possible to achieve at least a 50% steady-state recovery of the available combustion heat into the steam generator. This efficiency of 50% is used in the following analysis. Thus, net steam output of the steam generator using the above mentioned 60,000 Btu/hr and 100,000 Btu/hr burner capacities are approximately 30,000 and 50,000 Btu/hr (or about 24 and 40 lbs/hr of steam), respectively. Note that 50,000 Btu/hr is the thermal energy needed to heat a continuous flow of 1 gallon per minute of water through a temperature rise of 100 Fahrenheit degrees.

Ejector Performance

As discussed previously, two types of ejectors have potential application for application in the NPIWH system. One is the conventional venturi-type steam-driven water pump or ejector and the other is a so-called "condensing" steam-driven water pump or ejector. The major difference between the two types of systems is the pressure capacity at the discharge flow.

The condensing ejector is preferred for this application because it is capable of producing a delivery water pressure that is greater than the inlet steam pressure. For the conventional ejector, the delivery pressure of the water will be limited to about 40% of the inlet steam pressure. The condensing ejector thus has an obvious practical advantage with respect to the design pressure requirements for the steam generator and also provides the capability of automatically providing feed-water flow to the steam generator.

Another practical aspect with respect to ejector operated systems is the available sizes of ejectors. For the simple conventional ejector, the unit can be designed as needed, with the required size procured as a catalog item or custom manufactured. However, for the condensing ejector, only limited sizes are available. The Penberthy Model No. 00-526 which was tested as reported in Section 3 is the smallest available unit. The performance data presented in Section 3 for this condensing ejector is used as the basis for the following analysis of system configurations.

Basic System Configuration

The basic configuration of the proposed condensing ejector NPIWH system is that shown in Figure 12. The main components are:

1) a water supply/storage tank or barrel;

2) the heater assembly containing a burner, steam generator, and ejector; and

3) the delivery nozzle.

The supply/storage tank is an unpressurized container (open or closed) that can supply water to the heater assembly by gravity (or suction) flow.

In this system configuration, water is be pumped to the delivery nozzle by the ejector in the heater assembly when the delivery nozzle is open. When the delivery nozzle is closed, the ejector provides a continuous use of the available steam by recirculating water back to the supply/storage tank. The water is heated when it passes through the steam driven ejector. When the delivery nozzle is closed, the heated recirculated water raises the average temperature of the supply tank. The system can be operated until the supply tank is empty. The pressurized water flow from the ejector simultaneously provides the small flow of water

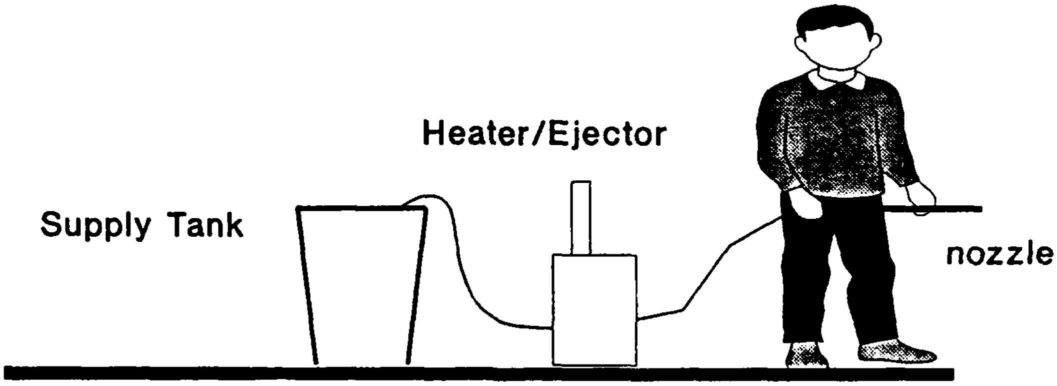

Figure 12. Condensing Ejector Hot Water System

needed for automatic supply of feed water to boiler.

The configuration as shown in Figure 12 is preferred, because

1) it can be operated with any available atmospheric-pressure water tank or barrel (metal or plastic, small or large),

2) it is simple and compact,

3) it provides the required delivery rate and temperature capability with the smallest components, and

4) it inherently accommodates the use of a nonpowered, constant-run burner

(i.e. a burner that has manual on-off control, has only manual adjustment, and may require somewhat involved ignition procedure).

This configuration provides for the greatest output capability with the minimum-sized burner. Hot water delivery flow rate will be at the maximum pumping capacity of the ejector. The time-average thermal capacity is governed by the size of the burner and steam generator, with the instantaneous thermal output of hot water dependent on the relative duration of delivery and standby periods of operation. The following discussion of the overall thermal balance of the proposed NPIWH provides the specific rational for this system configuration. The configuration shown in Figure 12 forms the basis for the detailed design alternatives described later in this section.

A similar arrangement to that shown in Figure 12 would be the same type of atmospheric-pressure tank system, but with water maintained at constant level in the tank by gravity flow from a local water supply tank or other water container. Overall thermal behavior limitations would be similar, with specific water temperature delivery variations dependent on extent of mixing within the tank.

An alternative arrangement would be to utilize the ejector to pump heated water into a sealed pressure tank. The tank could initially be filled with air or have a pressurized air-filled membrane bladder which would allow for a somewhat smaller tank with more constant delivery pressure. Using a pressure tank of either kind, water would be heated by the ejector and pumped into the tank on a continuous basis, up to the capacity of the tank. Then, delivery rate would be relatively unlimited since flow would be sustained by the pressure in the tank. This is similar to operation of holding tanks for common domestic well water systems. The fundamental advantage is that supply flow capacity is separate from pump flow capacity. Disadvantages are that a larger, dedicated tank of pressure capability is required. Because of interest in maximizing compactness of the hardware and minimizing the amount water storage within the NPIWH itself, this configuration is not considered further in this work.

Overall Heat Balance

The thermal output of the steam generator and burner needs to be matched to the performance characteristics of the condensing ejector. The key parameter in this regard is the steam consumption of the ejector. The Penberthy Model No. 00-526 automatic injector (ejector) has a steam consumption in the range of 30 to 40 lbs/hr at the conditions of interest (approximately 25 PSIG steam pressure) while pumping at approximately 1.5 gallons per minute. At 50% combustion efficiency, this would correspond to a burner input of approximately 100,000 Btu/hr.

The ratio of steam-flow to water flow for heating water through a 100°F temperature rise is about 0.83 lbs of steam per gallon of water. This steam flow amount is greater than the amount of steam flow used by the ejector for pumping. Specific steam consumption for the ejector is in the range of 0.35 to 0.50 lb steam per gallon of water pumped. With once-through flow of water through the ejector the temperature rise is typically about 40 to 50°F as seen in Figure 9 in the prior section of this report. For many applications this may prove to be satisfactory (such as summertime showering).

However, to achieve the needed 100°F temperature rise the ejector system would need to be operated in some other manner than simply once-through flow. The time-averaged rate of delivered water flow needs to be reduced below the 1.5 pumping capacity of the ejector. At the 40 lb/hr of steam flow consumption of the ejector, the time-averaged water flow can only be about 0.8 GPM to achieve a continuous flow of water heated through a temperature rise of 100 F. This reduced flow could be achieved by the use of a throttling valve at the water discharge or by the use of a bypass loop that feeds part of the ejector discharge flow back to the ejector water inlet. Of the two approaches, the use of a bypass recirculation directly back to the ejector inlet would be preferred. As shown in Figure 10, the pressure-flow curve for the ejector is very steep. Recirculation of part of the discharge back to the inlet would allow for a more constant delivery pressure over a range of flow rates. However, in either case, water delivery at this 0.8 GPM rate, while of some usefulness, is somewhat low in comparison to normal tap water delivery rates of about 2 GPM. Other design approaches are preferable.

With respect to achieving the desired 100°F heating capability, the concept of using the supply tank also as a thermal storage and buffer tank is preferred. With this concept, water would be first partially heated and recirculated back to the storage tank. This would be done for a period of time sufficient to heat the tank inventory approximately 50°F. Then, the recirculation would stop with the opening of the delivery nozzle. Partially heated water from the tank would be pumped and heated an additional 40 to 50°F by the ejector to achieve the full 100°F heating at the point of delivery.

This approach allows for intermittent delivery flow rates up to the pumping capacity of the ejector. It is a simple approach to reconciling the performance characteristics of the ejector, the desire for flow rates typical of hot water faucets, the desire for 100°F heating capability, and the thermal power limits imposed by a 100,000 Btu/hr burner. This approach is of benefit with respect to allowing for intermittent delivery of water to the point of use while accommodating operational needs of the constant-run burner. This concept is the basis for several specific configurations described in the following paragraphs.

Proposed NPIWH Designs

Three different arrangements of control components for the basic NPIWH configuration shown in Figure 12 are presented in Figures 13 through 15. The three different arrangements are:

Figure 13 -- Manual Pressure Control
Figure 14 -- Steam Pressure Control
Figure 15 -- Water Pressure Control

The systems would all have the basic capabilities of providing delivery flow at the maximum pumping rate of the ejector and provide for recirculation back to the storage tank to allow for full 100°F heating capacity and accommodation of a constant run burner. All three systems provide for automatic feed of water to the steam generator from the ejector discharge.

Manual Pressure Control The arrangement shown in Figure 13 is the simplest. Operation of the system would rely on the operator adjustment of valves to set and sustain the desired delivery rates. The largest component of the system is the steam generator. Water level is controlled in the steam generator by a float valve. A check valve on the boiler feed would prevent outflow from the boiler in the event that the ejector discharge pressure drops below the boiler pressure during some transient operating conditions. Initial starting would require manual filling of the steam generator with water. The steam generator pressure is limited by a pressure relief valve. A valve on the water supply to the ejector would be used to initiate pumping once steam flow commenced. Because the ejector has suction pumping capability, the supply line may be in the form a hose that feeds over the rim of an open barrel. In practice, the ejector water feed (suction) line can be tied together with the bypass/recirculation line so that there is one two-line hose that couples the water supply with the heater assembly.

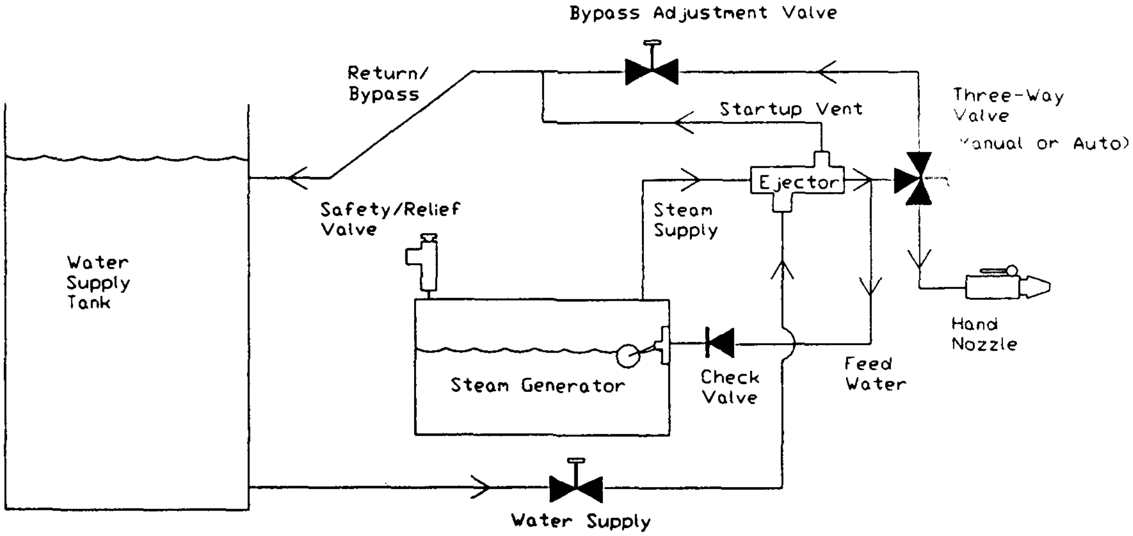

Figure 13. Condensing Ejector Hot Water System with Manual Pressure Control

A three-way valve at the ejector discharge would route the discharge flow either to the delivery nozzle or the supply tank. This can be a manually operated valve or an automatic valve. An automatic valve would divert flow to the delivery nozzle when the nozzle is opened as a result of the drop in pressure sensed by the valve (typical of common household kitchen sink hand-spray devices). Use of a three-way valve allows the ejector to operate whether or not the delivery nozzle is open and thus provides for continued steam generator feed water capability and utilization of steam from the steam generator and its constant-run burner.

The bypass valve would be adjusted such that the ejector outlet pressure is greater than the boiler pressure to ensure automatic feed of water to the steam generator.

The operating sequence would be as follows:

1) manual initial fill of steam generator and ignition of burner,

2) boiler pressure rises and steam flows thorough the ejector,

3) operator opens water supply line and pumping begins, with bypass flow back to the storage tank; the bypass valve is adjusted to sustain ejector discharge pressure at desired level, and

4) when delivery of heated water flow is desired, the handle nozzle is opened (assumes automatic three-way valve).

With initial adjustment of the bypass valve and delivery nozzle, delivery pressure would vary depending on the steam pressure in the steam generator. With a steady operating burner, the system should operate with a minimum of pressure fluctuation and require a minimum of operator attention. This is because the pumping rate of the ejector is not a strong function of pressure. However, the dynamics of such a system could be firmly established only after testing of an actual system. This manual control configuration is similar to that used without difficulty with the ejector test apparatus described in Section 3.

In the operation of this system, the operator could intentionally use the bypass mode to preheat the supply tank inventory to achieve a high final delivery temperature. Otherwise the bypass mode would serve to simply sustain system operation when the delivery nozzle is closed. Delivered water temperature should be reasonably steady since the ejector provides a constant flow rate and heating rate at a particular operating point. Flow rate and heating rate are relatively insensitive to reasonable variations in steam pressure. Delivery temperature would, of course, be directly related to the supply tank temperature. Delivery will be about 40 to 50°F above the supply tank temperature. Whether preheated by bypass operation or at ambient temperature, the supply tank temperature itself would be nearly steady over the 15 to 20 minute period of delivery operation that would be possible from a single 32 gallon supply barrel. Continuous operation can be sustained by moving the suction line from one tank/barrel to another.

Steam Pressure Control This system is similar to the manual pressure control system with the exception that the steam generator pressure is controlled by a back pressure regulator valve. This valve, which is commercially available, senses the upstream pressure and opens as needed to control the upstream pressure to a set value. In the NPIWH steam generator application, this valve would be used to vent excess steam into the bypass line for condensation in supply tank/barrel. The valve would thus act to provide high-side regulation of steam pressure and a more constant steam pressure supply to the ejector. This should have the resultant effect of a more steady pressure and flow at the delivery nozzle. The specific operational advantage over the manual control system would need to be verified by

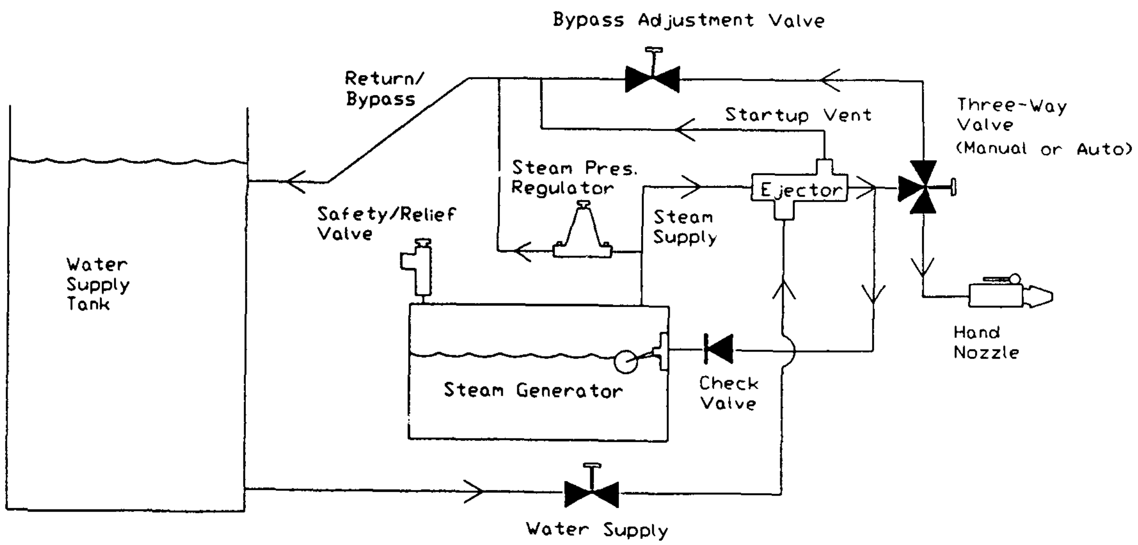

Figure 14. Condensing Ejector Hot Water System with Steam Pressure Control

test. An advantage of this approach is that there is direct control of the steam pressure and thus less reliance on the balance between the steam generation rate and steam utilization rate as a pressure regulating mechanism. The expected operating behavior of the steam generator with this type of control system is illustrated in Figure 16.

<u>Water Pressure Control</u> This system is again generally similar to the manual control system with the exception that the three-way valve is eliminated and a back pressure regulator valve is used to control the ejector outlet pressure. In this system, if the hand nozzle is closed, the buildup of pressure at the ejector discharge causes the regulator valve

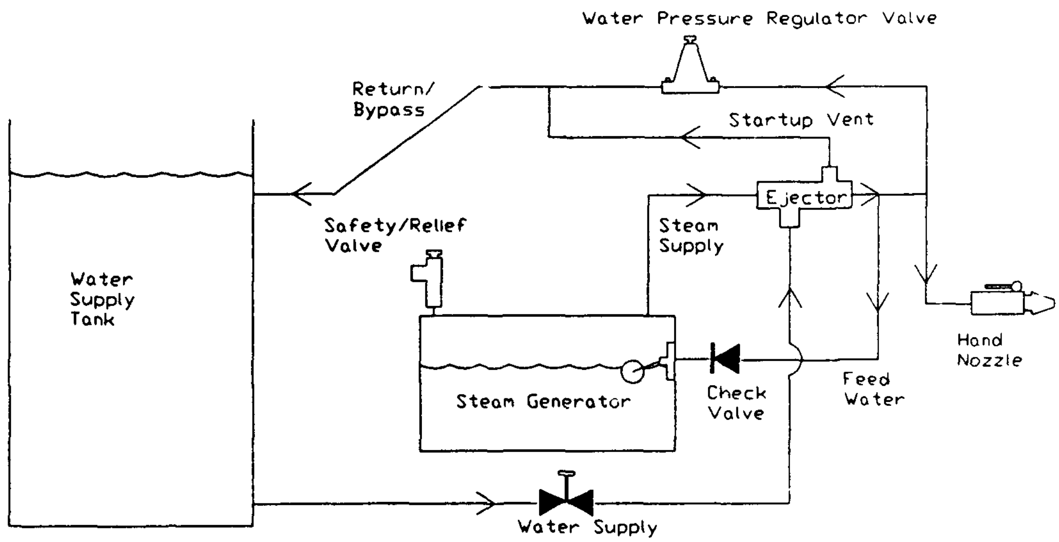

Figure 15. Condensing Ejector Hot Water System with Water Pressure Control

to open, regulating the ejector discharge pressure to a set level. Thus, flow through the ejector would be automatically sustained at any time the delivery nozzle is closed. Also, on partially opening of the delivery nozzle, water pressure at the nozzle would remain constant. The fundamental advantage of this system over the steam pressure control system is that the actual delivery pressure is regulated (high-side).

Component Design/Selection

With the performance of the condensing ejector verified as reported in Section 3, the

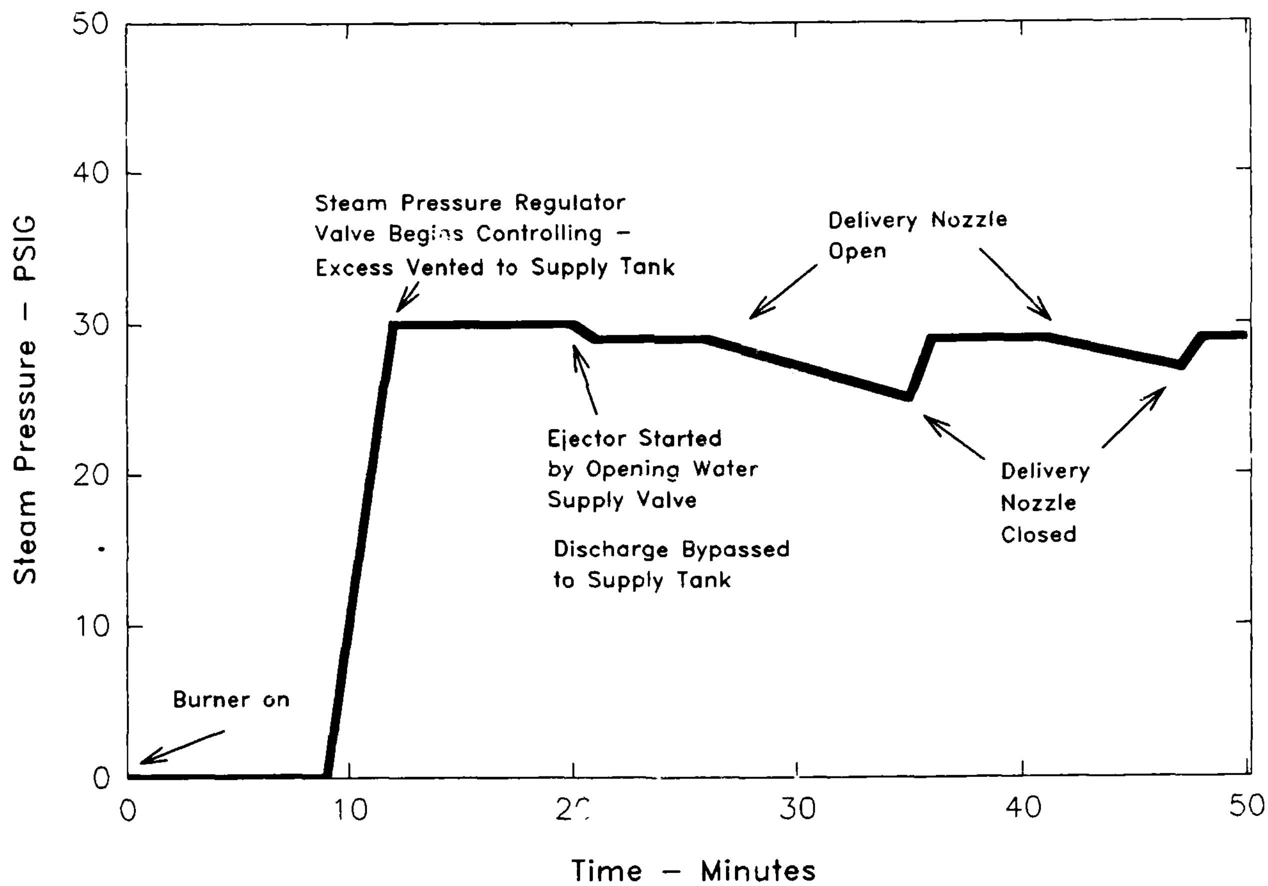

Figure 16. Predicted Operating Behavior of Condensing Ejector Hot Water System with Steam Regulating Valve

design of the proposed NPIWH system can be implemented with a high degree of certainty in attaining the desired performance. There are no significant materials performance or other factors that present major difficulties in development of the system concept. Some considerations relevant to the design and selection of the system components are described in the following paragraphs.

Burner As discussed previously, this system concept can be made to work with essentially any type of burner. It is preferable to use an existing Army burner such as the M2 or M3. Close coupling of the burner flame with the steam generator will be important to attaining reasonable thermal efficiency. Final burner selection will be made in the initial stages of the prototype design.

Steam Generator It will be desirable to design the steam generator ("boiler") for light weight and compactness. Low weight will be best attained using a wrought stainless steel for the material of construction. A water tube design with steam drum would likely be the preferred design. Tubes that have extended surfaced (i.e., fins) on the combustion gas side would be also be preferred. Design should follow ASME Boiler and Pressure Vessel Code. Based on comparison to small commercially-available steam boilers an overall required physical size of the heater assembly that includes the steam generator, burner housing, ejector, and valving should be no greater than about 24 inches high by 24 inches long by 15 inches wide. A short draft stack would be desirable for achieving good heat transfer performance.

Ejector The design concept is based on the use of a Penberthy Model 00-526 low pressure automatic injector. The size tested is compatible with a 100,000 Btu/hr burner yielding 0.8 GPM continuous 100°F heating (or 1.5 GPM at 50°F temperature rise continuously or 1.5 GPM at 100°F rise intermittently). Penberthy is the only know supplier. Other ejector sizes are available that have capability of 2 and 4 times the Model 00-526, with even larger units up to 60 times the capability of Model 00-526 also available. The Model 00-526 has 3/8 inch NPT connections.

Valves and Piping All valves and piping for the heater would be commercially available items. Tubing with welded or soldered fittings may be preferred to minimize weight. The valves and piping would be secured to the steam generator. It should be possible to mount the piping and valves, including the ejector, in a compact close-fitting arrangement with the steam generator since these components, with one exception, are small relative to the steam generator. The exception is the steam pressure or water pressure regulating valve shown in Figures 14 and 15. A number of different vendors can supply this valve, but the smallest unit has a weight of about 9 pounds, which would be a significant addition to the weight of the system. Also, such regulator valves are costly (about $400). Thus, weight and cost factors with the respect to automatic pressure regulator valves motivate a first experimental test with the manual control system as shown in Figure 13.

Suction and Supply Lines The suction/bypass line would be a double hose, with one line for gravity or suction flow of water from the tank and the other for the bypass/recirculation line. Flexible low-pressure rubber hoses of 0.5 inch ID would suffice for the suction/bypass line for the 100,000 Btu/hr unit. The delivery hose would be a flexible rubber hose of 0.5 inch ID capable of moderate pressure (up to 75 psi) hot water (up to 200 °F). The deliver nozzle can be designed for the specific tasks of interest to Army. It should be insulated so that it can be handled with hot water flow and provide toggle on-off and flow/spray adjustment capability.

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Section 5

Conclusions

In this project, a of range options for using steam to heat and pump water by direct contact means has been explored. Focus has been on the use of steam-driven water jet pumps or ejectors. Both standard conventional steam-driven water jet pumps and less-widely utilized condensing ejectors have been considered. The focus has been on the condensing ejector technology because of the high pressure output and the design and operational advantages that stem from the use of automatic boiler feed water supply. Standard steam-driven direct contact water pumps are only capable of pressures of about one-half the inlet steam pressure and thus were not found to be as attractive for this application.

The technical feasibility of a nonpowered instantaneous water heater based on the use of condensing steam ejector pump has been established by test of a commercially available ejector. Using steam at approximately 25 PSIG pressure, it has been shown that water can be simultaneously heated and pumped to pressures up to two times the steam pressure. The condensing ejector is small, lightweight, and has no moving parts (except for a check valve). Water is heated approximately 50°F as it is pumped in the steam-driven ejector.

The overall system concept is for a lightweight, portable heater package that is fired with a constant-run, manually controlled burner. The heater package will contain the steam-generator, ejector and appropriate valving. It is to be connected to the water supply and delivery point by flexible hoses. Water supply can be by gravity flow or by suction up over the side of an open tank or barrel. The connection to the supply will be a two-line hose - one for water supply and the other for operation in a bypass/preheating mode. The concept allows for accommodating the operation of a constant-run burner with only intermittent water delivery, as in a kitchen use, by recirculation of heated water back to the supply tank/barrel.

The system concept can be implemented in any size of interest to the Army. As with all water heaters, delivery capacity is limited by the thermal output of the burner. At

100,000 Btu/hr burner output and 50% efficiency, system capability would be at about 0.8 GPM continuously with a 100°F temperature rise, about 1.5 GPM continuously with about a 50°F rise, or about 1.5 GPM intermittently at 100°F rise and 50%/50% on-off delivery duty cycle. At higher burner capacities, hot water output capability would be proportionately higher.

Manual and self-operated automatic pressure control valves have been considered for control of the ejector system. The manual valving is preferred for weight and cost considerations. The practicality of manual control needs to be verified in prototype testing.

With selection of a nonpowered fuel burner of Army preference for this system, there are no significant technical impediments to the development of this system concept. Development of field trial units is recommended for Phase II of this SBIR project.

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