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TITLE

DETERMINATION AND DEMONSTRATION OF THE POTENTIAL FOR CATALYTIC HEAT SOURCES FOR PERSONAL ACTIVE THERMAL PROTECTION

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FINAL REPORT:

DETERMINATION AND DEMONSTRATION OF THE POTENTIAL FOR CATALYTIC HEAT SOURCES FOR PERSONAL ACTIVE THERMAL PROTECTION

This report was prepared solely for the purpose of satisfying, in part, the requirements of the Department of National Defence Contract #: W7711-2-7183/01-XSE

Submitted by: Rod Sprules
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Submitted to: Dave Eaton
Defence and Civil Institute of Environmental Medicine

Date Submitted: December 2, 1994

EXECUTIVE SUMMARY

With the support of the Defence and Civil Institute of Environmental Medicine, Exotemp Systems Inc. has developed a portable, pocket-sized, catalytic propane burning heat source for personal active heating during cold climate operations. This device heats fluid which can be pumped through the flexible tubing in either off-the-shelf or custom liquid-circulating textile products. There are many potential applications for such a system - heating a survival bag, maintaining the temperature of a medical pannier, actively heated casualty wraps to treat or prevent hypothermia, or even a ration heater. This unit is the first of a family of such devices which will serve as heat sources for liquid-circulating textile products. The heater is only 4.2"x7.2"x2.4", weighs approximately 2 lbs and has a heat output of 200 Watts. It can be started in temperatures as low as -30°C, but can also be used in colder conditions if the propane is warmed.

The impact on defence operations in cold environments may be considerable. The technology may have the most impact in unsupported operations, of 2 to 5 days length, by dismounted individuals or small groups. It will be practical to reduce or eliminate removable passive insulation for winter operations. Sleeping bags and tents may become obsolete for certain missions. Stoves for heating rations and melting snow may be discarded for some missions. Snow would be more easily melted in a plastic bag in a heated pocket, and rations would be warmed in the same way or eaten cold. Ideally, this system will reduce the amount of equipment required by defence personnel during cold weather missions, and reduce time spent in making and breaking camp.

TABLE OF CONTENTS

1 INTRODUCTION

1.1 Background

As a result of research funded by the Defence and Civil Institute for Environmental Medicine (DCIEM), a prototype catalytic propane liquid heater has been developed for use in active thermal protection by Exotemp Systems Inc.

1.2 Objectives

The objective of this contract is to develop a catalytic heat source for use in personal active thermal protection. One of the main features should be a relatively small size to allow for portability. In addition, it should be durable, user-friendly, reliable, and have a high heating capacity per unit weight. It should produce approximately 200 Watts of heat to supplement a human's heat loss. Ultimately, it may enable the user to reduce the equipment required during cold climate operations.

2 POTENTIAL APPLICATIONS FOR ACTIVE HEATING DEVICES

This portable heat source will have the most impact on remote unsupported missions, especially those carried out by individuals or small groups and spanning over a few days. The following is a brief description of the applications of this heating device determined through discussions with possible end-users.

Personal Heating	- Due to the small size of this heater it is practical to incorporate it into the user's clothing. This may reduce the thickness and increase the comfort of clothing, providing increased mobility, and lighter overall weight. The time required to make and break camp would also be reduced.
Casualty Bags	- Such a heater could provide supplemental heat for casualty bags used by Medics in cold climate operations.

Intravenous Heater	- The device could be used to heat intravenous supplies on site. The current techniques involve the thawing of frozen bags by using the body heat of the technician.
Survival Bags	- The heat source could also be integrated into casualty wraps for either prevention or treatment of hypothermia. Search and Rescue Technicians currently warm the victim by climbing into a passively insulated bag with them.
Medical Panniers	- It could be incorporated into medical panniers to provide a constant temperature environment for intravenous solutions and other temperature sensitive medications.
Water Heater	- A pocket could be added into the user's parka to melt snow and ice for drinking water. This would eliminate the need to stop travel and start a fire or stove.
Ration Heater	- This is similar to the water heater. The user could heat meals while travelling, reducing or eliminating cooking equipment.

In addition to potentially reducing the amount of supplies and equipment required for cold climate operations, the current survival and rescue techniques could be made more efficient and effective.

3 DESCRIPTION OF DESIGN FEATURES

3.1 Introduction

This section contains a description of each feature of the heater, and an explanation of why each is included in the system.

3.2 Overview of the Design

The design is based on the catalytic combustion of propane. The propane is either supplied through a refillable tank or from standard disposable containers - both supplies are regulated. This system transfers approximately 200 watts of heat into the transfer fluid. Some of the generated heat is converted to electrical power via thermoelectric coolers (T.E.C.'s). This electrical power is used to operate an automatic control system and a pump which distributes the heat through a liquid circulating garment. Various features are included in the control system for safety, reliability and user-friendliness. The heater is small enough to be easily carried on a belt or in a pocket.

3.2 Catalytic Propane Combustion

3.2.1 The Catalyst

The heat for this system is generated by catalytic combustion of propane. One of the main characteristics of catalytic combustion is that no flame is required to burn the fuel mixture. This means the combustion is orientation independent - ideal for portable applications. Another advantage to using catalysts is the tolerance towards variations in the air/fuel mixture. The device is insensitive to fuel vapour pressure fluctuations or a momentary lack of air supply. In fact, if the gas flow across the catalyst is momentarily ceased, the combustion can be continued simply by initiating the gas flow. However the combustion will extinguish if the temperature of the catalyst decreases too much.

The catalyst used is coated onto a metal screen which is cylindrical in shape. The mass of the screen is relatively small which permits heating of the catalyst by a piezo-electric spark igniter.

3.2.2 Propane as a Fuel

The low boiling point of propane (-42°C) is a significant feature of this heater in that the vapour pressure at -30°C is enough to supply and mix the fuel for combustion (*i.e.*, no fuel pump is required). The fuel can be purchased in disposable tanks at a relatively low cost. Propane is also a common fuel used for camping equipment, and thus is - in some cases - already part of the user's standard supplies. If treated properly, this fuel is safe, efficient and ideal for this system.

The exhaust created by the combustion of propane is relatively clean. The products of combustion are H_2O, CO_2, and N_2 - none of which are harmful. However, in cold climate operation, the water in the exhaust may condense then freeze in the exhaust pipe, causing blockage. This is unacceptable, and is prevented by ensuring that the exhaust temperature is above 100°C. The consequence of maintaining a high exhaust temperature is a slight decrease in system efficiency.

3.2.3 Fuel Mixture

The fuel is mixed with air by means of a high speed jet. A vacuum is created in the air intake throat by forcing the jet into a mixing section. At the outlet of this section a diffuser is added to recover enough head to force the air/fuel mixture through the manifold. This ensures that the required air is mixed with the propane prior to entrance into the catalyst. By only using primary air as opposed to secondary air (air in the combustion chamber), the combustion is quite stable. Therefore, any back-pressure, caused by restriction of exhaust exit, or wind conditions, does not critically affect the combustion.

An air fuel ratio with approximately 10 to 30% excess air significantly reduces the temperature of the catalyst, and ensures that the minimum amount of carbon monoxide is produced. Using the exact stoichiometric ratio would mean the highest combustion temperature causing the performance of the catalyst to deteriorate at a quick rate.

3.2.4 Ignition

Ignition is relatively easy with the use of a catalyst since it can be preheated by method of choice. The two techniques investigated in this research are a hot-wire and a spark ignition. The hot-wire is powered by batteries, and is wrapped around the catalyst, whereas the spark ignition relies on a flame front to preheat the catalyst. It has been determined during testing (see section 5) that a piezo spark based ignition is less intricate and more reliable since the dependence on batteries is eliminated.

Since the mass of the catalyst is small, it can be preheated by a simple flame front. This is the preferred method. Although, the use of a hot-wire ignition can be (and has been) incorporated into a completely automatic system where the user must only supply the fuel and throw a switch. However, this system is dependent on the undesirable characteristics of rechargeable batteries when at cold temperatures.

3.3 Thermoelectric Power Generation

There are different methods of supplying electricity to the pump. The most common method would be a rechargeable battery, but this defeats a major objective of the project - good endurance (propane has a much higher energy capacity than batteries). If batteries are the sole source of electricity for the pump, the user must supply fuel in addition to charged batteries, which is not practical. Therefore, thermoelectric coolers are used to generate enough electrical power to supply the pump and control system.

Thermoelectric coolers are based on the Seebeck effect [5]. Usually, power is supplied to the T.E.C. to pump heat, but creating a heat flux across the T.E.C. will produce electrical power. Exotemp has determined that each T.E.C. requires approximately 25 to 30 W of heat to generate about 1 W of electric power. Since this system is designed to transfer 200 W of heat into the water, the heat used for power generation is not wasted.
By implementing thermoelectric coolers into the system, the endurance is solely dependent on the amount of propane supplied, not on the life of a battery. Therefore, such a system may be a practical power supply for remote applications with a long duration where a supply of charged batteries is impractical.

3.4 Heat Transfer Characteristics

In the highest mode, this system transfers approximately 200+ Watts of heat into the circulating fluid. This heat may be enough to supplement the heat loss experienced during extreme cold climate exposure. Improved efficiency would be attained with the addition of some passive insulation.

The plate on the hot side of the thermoelectric coolers has black anodized aluminum fins. This enhances both the radiative and the convective heat transfer into the T.E.C.'s. On the cold side of the T.E.C.'s, a liquid-cooled aluminum plate is used. The fins and the liquid-cooled plate are flattened with a variance of 0.002 inch. This is critical to reduce the contact resistance between the plate and the T.E.C.'s. To improve overall system efficiency, one of the walls of the combustion chamber is also liquid-cooled.

3.5 Control System

To control the fluid temperature at the outlet of the heater, two automatic control systems have been constructed and tested. The existing control system uses a piezo spark ignition, and the prior system was dependent on Nickel-Cadmium batteries for startup. Both systems use CMOS logic and thermistors for control. The system which uses batteries includes safety features such as high water temperature, prevention of gas flow when no combustion present, and hot-wire ignition shut-off when no gas is present. Although this battery-operated system has more safety trips, it is intricate and relies heavily on its batteries for ignition. However, when a safety feature is initiated, the gas flow is shut off automatically. In the spark ignited system, only a buzzer is sounded and the user is responsible for turning off the gas. Both systems have a potentiometer to allow the user to adjust the temperature of the outlet fluid. This is used in conjunction with a ten-step LED display to show the set point and process temperature.

3.5.1 Control System with Batteries

This system initiates combustion using a hot wire. The user simply throws the main power switch then adjusts the temperature setpoint. There are two solenoid valves that control the gas flow. One is the main valve, and the other is a by-pass to toggle the gas flow between high and low settings. The by-pass valve is initially open upon system startup. When the temperature of the output fluid reaches the setpoint, the power to the by-pass valve is shut off, reducing the gas flow by forcing it through a restriction. In the event that one of the safeties is violated, the power to the main valve is cut. The user must then push a reset button to restart the flow. Although the flow rate through the solenoid does not vary with respect to voltage, the effect of the excess propane between the valve and the combustion chamber causes a gradual decline in gas flow. In effect, this is a closed loop control system with a maximum and minimum gas flow, and temperature feedback. Both a system schematic and a wiring schematic for this control system can be found in Appendix A.

The power consumption of the control valves is minimal. The valves' power consumption is reduced by decreasing the voltage from 2.5 volts down to 1.2 volts after approximately 1 second every time they are turned on. The value of 2.5 volts was determined to be the minimum voltage required - at a gas pressure of 30 psi - to open the valves, and only 1.2 volts are required to keep it open.

Analogous to an automobile, the batteries are being charged while the system is running. A special module is included in this control system to ensure that the batteries will charge. When the water outlet temperature rises above the set point, the gas is switched into the low position. If the response time for the decrease in water temperature is long, the gas flow would normally stay low until the water temperature reaches the set point. This causes a decrease in the electrical power generated by the thermoelectric coolers. The pump then slows down along with the water flow, and the water temperature increases. To combat this problem, the gas is switched to high in order to generate the required electric power whenever the voltage falls below a pre-determined value.

3.5.2 Control System with Piezo Ignition

This control system is used in the prototype. It is not as complex as the alternate system, but it is more reliable. Instead of controlling the main gas flow with a solenoid valve, this system relies on the user to turn the gas on and off manually. The gas flow is toggled between high and low with a solenoid valve in the same way as the first system. However, this by-pass valve is normally open. Therefore, the gas flow is automatically in the high position upon startup.

If the gas flow is kept in the low position too long, the heat flux through the T.E.C.'s decreases; causing the output voltage to decrease. As the voltage decreases below a minimum value, the valve will open due to the lack of available power. In effect, the system has a minimum heat output; determined by the minimum heat flux through the T.E.C.'s which is necessary to generate enough electrical power to run the control system and the pump. Since this system uses less electrical power (it does not have batteries to charge, or a solenoid valve to hold open) the minimum heat output is lower than the minimum output from the system with the hot-wire ignition. Both a system schematic and a wiring schematic for this control system can be found in Appendix A.

3.6 Options and Specifications

The heater is encased in a black pouch that fastens to a waist belt. The dimensions of the protective case are 4.2" x 7.2" x 2.4". The weight is approximately 2 lbs. There is an optional thermistor to allow remote temperature sensing. Remote sensing is useful in systems where it is not advantageous to control the temperature of the fluid at the output. For instance, the user may want to control some other parameter like in an intravenous heater where the temperature of the solution entering the body is critical.

4 PERFORMANCE TESTING

4.1 Introduction

Two separate tests were performed in a miniature cold chamber to determine the advantages and disadvantages of the control systems. The heater was tested in a miniature cold chamber twice; once for each control system. The results are discussed, and some conclusions are presented.

4.2 Test Apparatus

The heater was in series with a reservoir which was open to the atmosphere. The working heat transfer fluid consisted of approximately 50% water and 50% alcohol. To measure the fluid temperature, thermocouples were inserted at the inlet and outlet of the heater. A tube was attached to the heater in order to direct the combustion exhaust outside of the chamber.

For the fuel supply, a 400 gram propane tank was attached to the regular propane tank to allow for an extended experiment if required. A pressure gauge was used to indicate the gas pressure behind the orifice and to allow the experimenter to check for gas flow.

The cold chamber consisted of an insulated box with a plexi-glass viewport to allow visual inspection. Several copper pipes, which were capped at the bottom, penetrate the top of the chamber to form a tube bank. A brushless DC fan was used inside the chamber to circulate air over the tube bank. In each tube, a mixture of methyl hydrate and dry ice was allowed to bubble, enhancing the heat transfer coefficient on the inside of the pipes. The chamber was capable of reaching temperatures of approximately -45°C. There was no humidity control mechanism.

4.3 Procedure

4.3.1 Test #1: Hot-Wire Ignition Control System

The entire system, including a coolant reservoir and fuel tank, was placed inside the cold chamber. The temperature of the chamber started at 19.5°C. Dry ice was added until the chamber reached -39°C which took approximately 25 minutes. The chamber was then allowed to heat up to -25°C at a time period of 40 minutes. The system tests were conducted at -25, -20, and -15°C.

4.3.2 Test #2: Piezo Spark Ignition Control System

The system was placed in the chamber and was taken down to a temperature of -39°C. The chamber temperature was then allowed to slowly increase to -30°C. After approximately 45 minutes at -30°C the gas was turned on, and the spark was actuated to start the combustion.

4.4 Results and Discussion

4.4.1 Test #1: Hot-Wire Ignition Control System

At -25°C, the system did not start, because there was no gas flow. The primary cause of start-up failure was due to the characteristic voltage decrease in the batteries. At low temperatures, the voltage of Ni-Cad batteries decreases as load is added. This system uses three 1/2AA cells for the control system, and three 1/2AA cells for the electric ignition. The CMOS electronics require a minimum of 3 Volts to work, but the battery voltage fell from 3.6 to below 3.0 Volts when the control system was turned on. The transistors which power the solenoid valves could not open at this low voltage. The batteries were replaced by sub-C cell batteries. This provided adequate voltage to run the control system.

When the chamber reached -20°C, the control system worked but the hot-wire was not igniting the catalyst. The batteries for the ignition were replaced by a variable voltage supply to determine if the hot-wire required more current. This was not the case. It was determined that either the fuel was not completely vaporized prior to contact with the catalyst, or perhaps the catalyst was covered with water condensation (frost) due to the lack of humidity control in the chamber. The latter is unavoidable even in actual climatic conditions.

For a temperature of -15°C, the Ni-Cr wire, again, did not provide enough heat for the catalyst to initiate combustion. The catalyst was then preheated with a butane torch. The catalysts ignited and within a minute there was enough electrical power to run the pump and the controls.

There were also some unpredictable difficulties with this control system at the low temperatures. This was probably due to moisture condensing on the bottom of the control board. Adding a sealant would eliminate this problem.

4.4.2 Test #2: Piezo Spark Ignition Control System

At -38°C, the system did not start, because liquid propane was contacting the catalyst. This was probably due to a combination of the throttling of the air/fuel mixture and the cold temperature of the manifold. In effect, this was extinguishing any combustion that was happening. Consequently, any propane that was vaporized in the combustion chamber did not ignite when sparked since the fuel/air ratio was too high.

To initiate combustion, the catalyst must reach a minimum temperature. The colder the heater is upon startup the more times it had to be sparked, but eventually it did start. At -30°C, the combustion was fully established after approximately 4 strikes on the piezo crystal.

4.5 Test Conclusions

It is concluded that the system which uses hot-wire ignition for startup is too dependent on the undesirable characteristics of Nickel-Cadmium batteries at sub-zero temperatures. The lowest startup temperature without preheating of the fuel was -25°C. Additionally, the prototype control board is complex and requires significant calibration. The batteries must be charged enough after ignition, or else there is a possibility that there may not be sufficient power available for the following use. When trying to start the system, the batteries may run out of power before the catalyst is hot enough.

The system which uses the piezo spark ignition will start at low temperatures (about -30°C) unless the propane is condensed before reaching the catalyst. This is dependent on the temperature of the propane tank at the time of combustion, but the propane can be preheated before the system is started. There are two disadvantages to this system as it now stands. First, it does not have a cut-off valve for the gas when the water temperature gets too high. Second, although the pump always starts when the unit is cold, it might not start immediately after the system has been turned off.

It is apparent that the less intricate version of control, which greatly relies on the mechanical characteristics of the heater, is more reliable. However, like many camping appliances, the shut down of fuel flow is not automatic, but instead relies on the user.

5 CONCLUSIONS

Substantial progress has been made towards the objectives described in section 1.2. A catalytic propane heat source has been developed. It is small in size, durable, and easy to use. Future generations of this device are expected to reduce the amount of equipment required during cold climate operations, and to make the current survival and rescue techniques more efficient and effective.

6 RECOMMENDATIONS

In recognition of the main objective of this contract - to develop a field safe, catalytic propane heater for use in active thermal protection - and from the outcomes of the performance tests the following features are recommended for future designs:

- A piezo spark ignition should be used. This is a safe and reliable method of startup which does not require charged batteries.

- The specified minimum starting temperature should be -30°C or warmer. Systems designed to start at lower temperatures would be unduly complex since the fuel must be preheated. Because of the small size of the system, it should be practical to preheat both the heater and the fuel to a temperature above -30°C by using body heat.

- In future designs, careful consideration should be given to startup, safety, and control features. Almost all propane fuelled devices present some danger when misused. For this device, a judgement will have to be made as to whether certain protective features are warranted or even desired. More complex designs tend to be less reliable, and since this unit may be used for survival, certain safety features might actually detract from the user's safety in real life conditions. We assume that the user is alert when starting the unit, has been given basic training in its operation, and will not be alert at all times after the unit has been started: Our present opinion is that a general purpose unit should incorporate the following safety features:
    - Piezoelectric ignition should be used. This is a reliable and safe method if applied with a minimum of care.
    - Fuel flow should be tripped automatically if the hot plate inside the unit becomes too hot or too cold after startup.
    - There should be an audible alarm prior to a high temperature trip.
    - The LED display should be replaced by a simple dial for the potentiometer.

- Future systems should employ a simple manual means of de-aerating the circulating liquid.

- This work has shown that easily portable warm liquid circulating units will be feasible for defence use. A technology base has been created which will allow the straightforward development of units for either general or specific uses.

- There are many possible applications for this device. It could drastically improve the performance of defence personnel during cold climate operations. Although this is a useful product, it is only a prototype and has much room for innovation. It needs to be developed into a machine which would comply with the characteristic features and standards of field-use military equipment. It is highly recommended that the development of this device be pursued further.

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APPENDIX A

NOTES:

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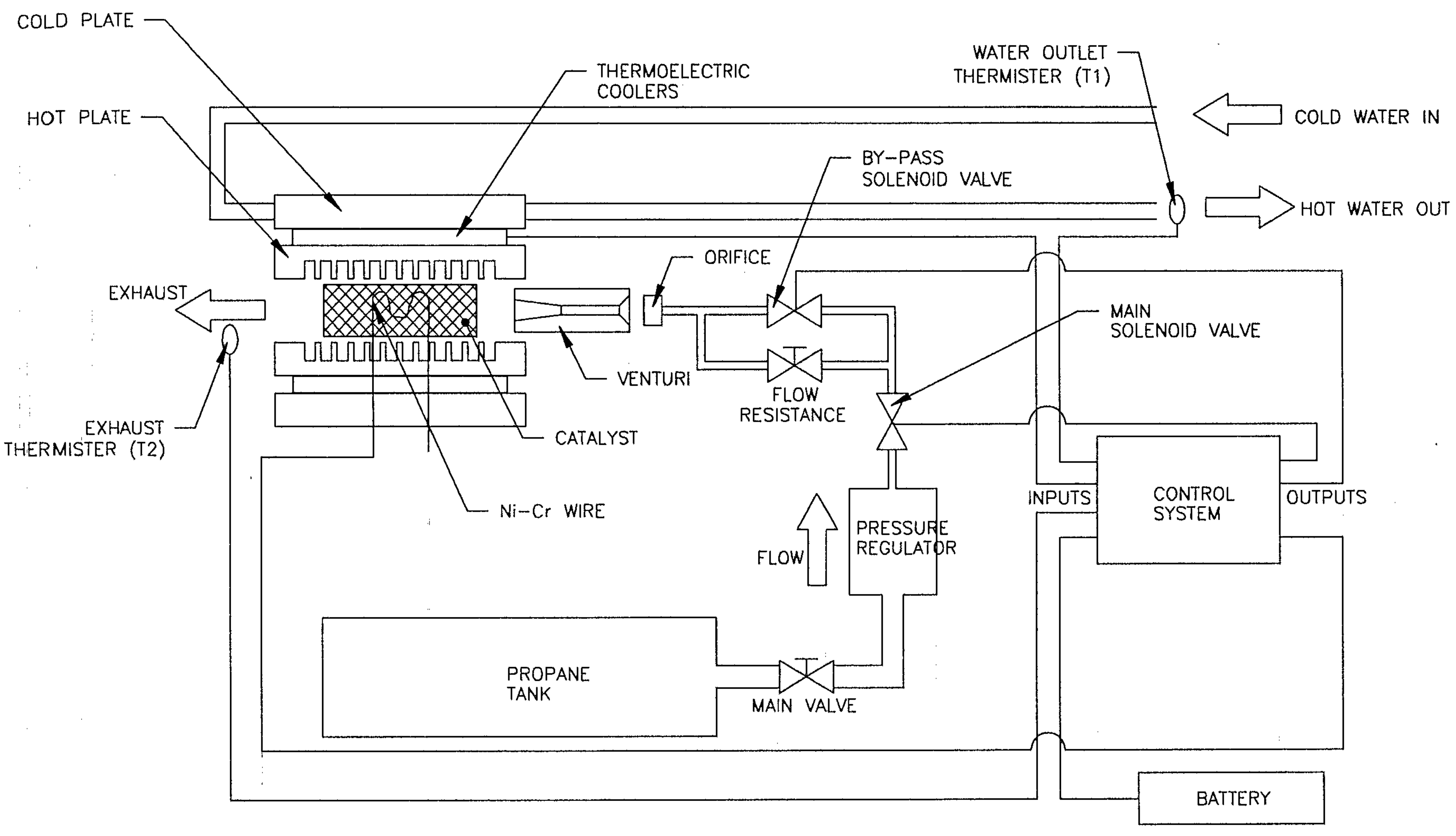

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SYSTEM SCHEMATIC FOR HOT-WIRE IGNITION

SIZE	NSCN	DRAWING NO.	
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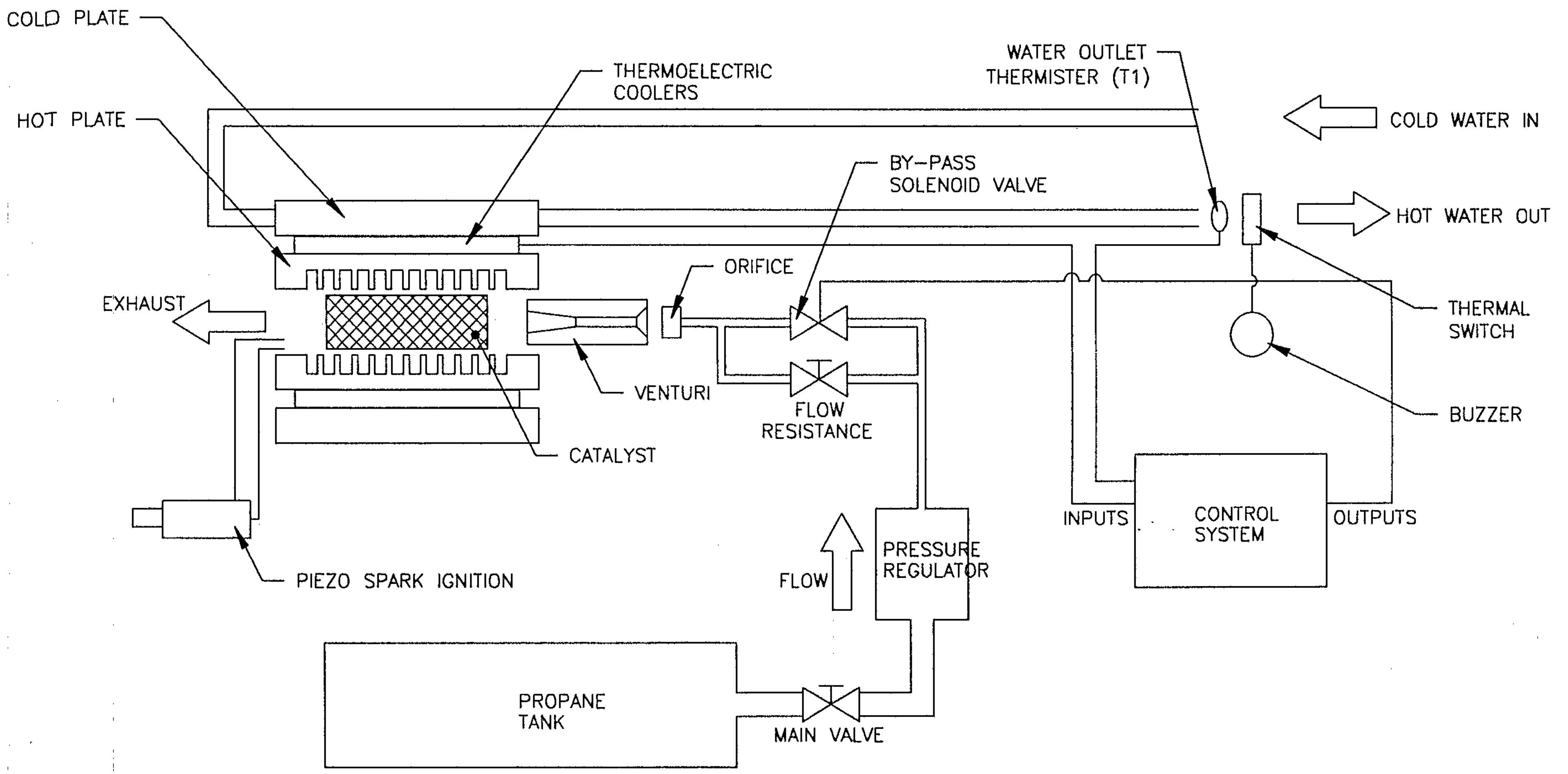

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SYSTEM SCHEMATIC FOR PIEZO IGNITION

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SCALE 1/1 UNIT WT. SHEET 1 OF 1

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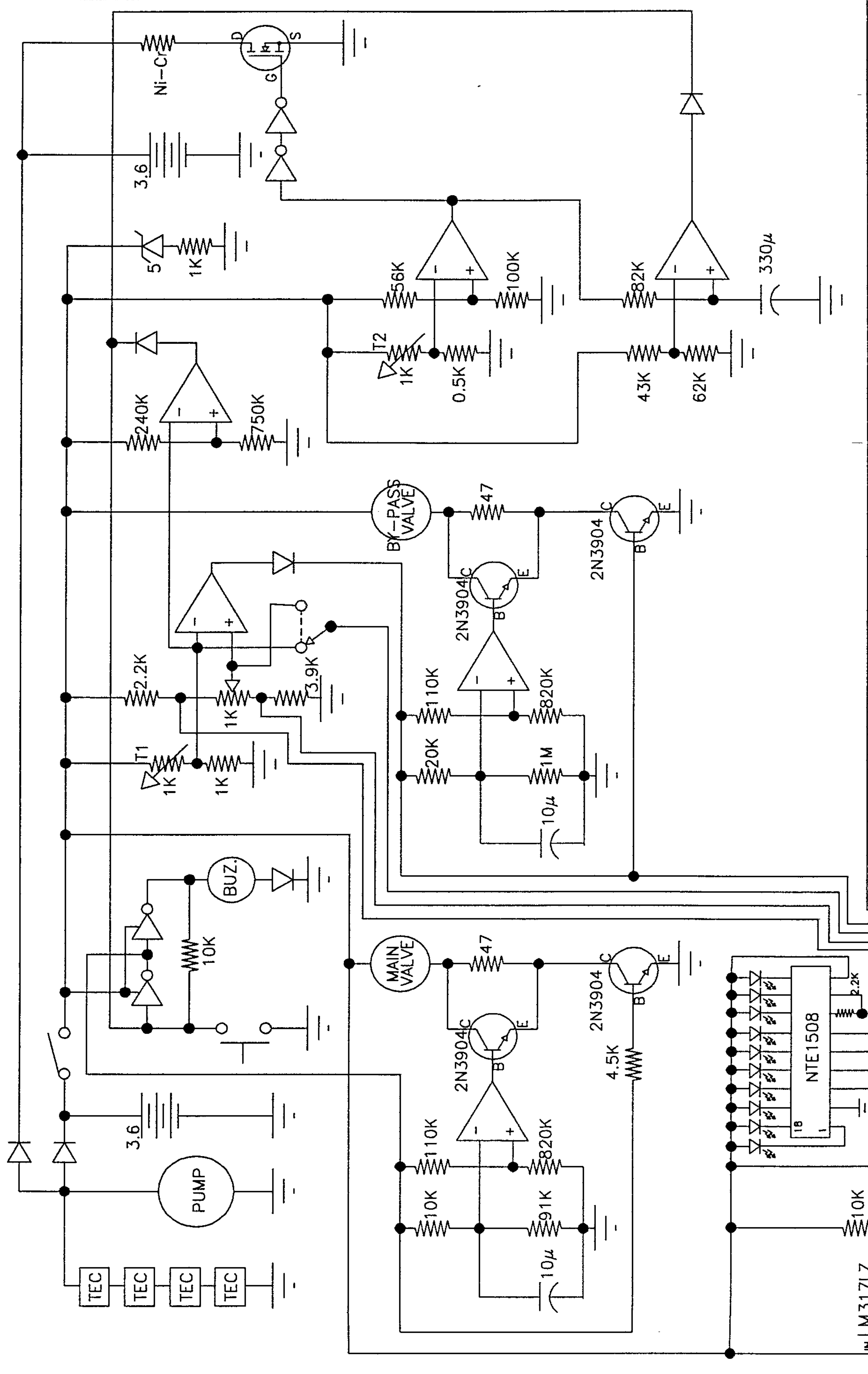

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WIRING SCHEM. FOR
HOT-WIRE IGNITION

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