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INTEGRATED PUMP ASSEMBLY - AN ACTIVE COOLING SYSTEM FOR MARS PATHFINDER THERMAL CONTROL

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ABSTRACT

The Mars Pathfinder spacecraft which will be launched in December 1996 features an active cooling system for controlling the temperature of the spacecraft. This will be the first time that such a mechanical pump cooling system is used on an interplanetary or long duration flight (over two weeks) in space. The major element of the cooling system is the Integrated Pump Assembly (IPA). It uses centrifugal pumps to circulate liquid freon to transfer heat from spacecraft electronics to an external radiator. The IPA consists of redundant pumps, motor control electronics, thermal control valves, check valves, and an accumulator. The design and flight implementation of this pump assembly were accomplished in less than two years. This paper describes the design, fabrication, assembly, and testing of the IPA.

INTRODUCTION:

A thermal control system featuring a new mechanical cooling loop technology has been designed, built, and installed on the Mars Pathfinder Spacecraft. This thermal control system, called the Heat Rejection System (HRS), employs single-phase freon liquid to transfer excess heat from the spacecraft electronics and other equipment to an external radiator. The major element of the HRS is the Integrated Pump Assembly (IPA) which circulates and controls the flow of freon in the mechanical loop. The IPA consists of mechanical centrifugal pumps, control electronics, and valves and is the only active component of the Pathfinder thermal control system. The design and flight implementation of the IPA is described in this paper.

The Mars Pathfinder spacecraft is scheduled to be launched in December 1996. It is the first of a series of spacecraft designed to explore the planet Mars; at least two spacecraft are planned to be sent to Mars every two years for the next fifteen years by the United States, the European Space Agency, and Russia. The major objectives of the Mars Pathfinder are to demonstrate low cost entry, descent, and landing technologies for use in the subsequent flights to Mars. Further, the Pathfinder includes a lander that will operate for one month on the Martian surface conducting surface science studies assisted by a microrover.

The temperature control requirements of the spacecraft during launch, cruise, and Martian surface operation necessitated the design of the Heat Rejection System. A description of the design of HRS is given in a companion paper (Reference 1). When the decision was made in May of 1994 to use a heat rejection system on Pathfinder, there were only eighteen months available to design, fabricate, flight qualify, and install the HRS on the spacecraft. Initial design studies of HRS showed the IPA to bc not only the major element of the I IRS but also consisting of technologies that were new and never flown in space for long duration. Further, the experience base at the Jet I'repulsion 1 ,aboratory (JPL) on these types of pump systems was practically nonexistent. in addition, because of the Discovery class mission status of Pathfinder, the cost and schedule were capped and could not be exceeded. The challenge was how to design and flight implement the IPA with all these constraints.

IPA IMPLEMENTATION APPROACH:

An initial trade-off of the constraints on schedule, cost, and JPL in-house experience for the IPA showed that industry participation was imperative. An industrial survey was made of companies and other organizations who had expertise in mechanical pumped cooling loops for aerospace applications. NASA's Goddard Space Flight Center had extensive experience in developing capillary pumped loops for the spacecraft applications and some experience in using mechanical pumps as boosters, Other mechanical pumped loop space applications included the cooling system for the Space Shuttle bay, cooling for the space suits used by the shuttle astronauts, and cooling of avionics and lasers used in fighter planes. The only other space-based mechanical pump effort was at the European Space Agency where some developmental efforts were being made (Reference 2). Based on this survey and other trade studies, it was decided to have the IPA procured from an experienced vendor.

The flight implementation of a new technology flight hardware usually consists of developmental units for proving the engineering concepts, engineering model units for flight qualification, and final fabrication of the flight units. 1 lowever, in the Path finder's case, because of the schedule and cost constraints along with the limited experience in the use of mechanical pumped cooling loops in the space industry, a new implementation approach was used for the I} 'A. In this approach, it was decided to proceed with the developmental and the flight units at the same time and to skip building the engineering model units for qualification and to qualify the flight units at the protoflight test levels. One of the risks in this approach was that any significant design change to address the problem observed in the developmental units would affect the flight unit schedule and cost. The other risk to the flight system design was that any problem encountered during the protoflight tests could require design changes that would affect the schedule and cost.

It was decided early in the design of the system that the risks could be minimized with a careful design of the developmental tests and a thorough review of the flight system design before the start of fabrication. It was also understood that in order to minimize the risks, J])l, had to work very closely with the selected vendor ofthc IPA. The whole approach was success-oriented and expected a close working relationship amongst all the parties involved,

initial specifications were developed in May of 1994 and Request for Information was sent out to the industry. The final detailed specifications were developed and sent out in September 1994 and the vendor was selected and contract awarded by December 1994,

IPA SPECIFICATIONS:

The IPA design specifications were developed based not only on the spacecraft thermal control considerations but also on the spacecraft system level considerations of reliability, mass, power, and cost. As a consequence, the overall system consisted of redundant pump systems: each unit consisting of its own pump/motor, motor control electronics, check valves, and thermal control valve to bypass the flow. The only non-redundant component in the IPA is the accumulator-. The specified arrangement of the components in the IPA is shown in Figure I.

The specifications developed for the IPA for the Request for I'reposal consisted of the following topics: 1) Hydraulic and electrical performance, 2) Component description, 3) Mechanical and electrical design, 4)Electronic and mechanical parts, 5) Electromagnetic compatibility, 6) Operating anti non-operating environments, 7) Fabrication and assembly requirements, and quality assurance provisions. The key specifications arc listed in "l'able 1.

"1'able 1. Integrated Pump Assembly Specifications

Section	Specification Detail
THERMAL & HYDRAULIC	
Flow Rate and Pressure rise	Freon flow rate of 0.2 gpm, at 4 psid in the operating temperature rang of -20 to 30 C
Max. Operating Pressure	100 psia
Operating Temperature Range	-30 C to40 C
Bypass ratio	O C above, 100°/0 radiator flow -7 C below, 1 OO°/. bypass flow
Leak Rate	1 lelium leak rate of 10-7 scc/sec for the gas and 10-'1 scc/sec for the liquid side
Storage temperature	-'40 c to 50 (
PHYSICAL	
Mass	Maximum of 8 kg dry
Size	10 inch by 10 inch by 6.5 inch
Service Valves	One for gas charge and two for liquid fill and purge
Mounting	Mounted on a base plate
OPERATION	
Life	10,000 hours continuous, 3 calendar years
Start/stops	1000
ELECTRICAL	
input Voltage	To operate in 27 Vdc to 36 Vdc
Power	10.6 Watts maximum
Isolation	One megohm electrical isolation
Electronics parts	MIL-STD-975 Grade 2, MIL-STD-883C Grade B for microcircuits, withstand a radiation environment of 500 Rads (S1), CMOS and MOSFETs meet single event effect parameters
ACCEPTANCE TESTS	IPA hydraulic performance, Sinusoidal and random vibration, thermal vacuum test, proof pressure.arid leak rate tests

DESIGN AND FABRICATION:

DESIGN - The detailed mechanical and electrical design of the IPA was developed by the vendor based on the specification provided by JPL. The mechanical design consisted of three major components mounted on a base plate. These components are: 1) accumulator, 2) pump/thermal control manifold, 3) electronic box housing all the motor control electronics, and 4) front panel housing the service valves. A schematic of the IPA envelope is shown in Figure 2. The materials used for the I PA are 3041, stainless steel and aluminum. Stainless steel is used for all the wetted paths of the IPA whereas aluminum is used for the baseplate and the electronic box. The electronic box is designed as modular unit so that it can be removed from the pump assembly during welding of the pump assembly to tubing that that would circulate freon in the spacecraft.

The accumulator feature a welded Inconel 718 bellows to contain the freon liquid with the pressurant gas (nitrogen) on the outside of the bellows. The stroke volume of the bellows is 24 cubic inches. A service valve is mounted on the housing to provide access to charge the accumulator with gas to the required pressure. A strain gauge type pressure transducer is welded to the accumulator housing to measure the gas pressure during ground operations and testing. The pump manifold is machined from wrought stainless steel, which houses the check valves, thermal control valves, pump/motors, and the inlet and exit ports.

A centrifugal pump was chosen over other types of pumps based on life and reliability data on pumps and the suitability for the current application. The hydraulic performance and electrical power requirements of the Pathfinder' HRS favor the centrifugal type pump. The Pathfinder HRS requires a small pressure rise at large flow rate and had very small power available for the pumps. At the required performance point of 0.2 gpm at 4 psid, the specific speed of 1267 predicted a pump head efficiency of 10% for a centrifugal pump, meeting power requirements. Use of a positive displacement pump rejected due to a lower service life and material restrictions. The selected pump featured a radial vane Barsky type impeller, driven by a brush less DC motor with hall effects sensors embedded in the stator. The impeller is a four-vane design without side shrouds to minimize viscous losses, and is attached directly to the motor shaft. The motor rotor which rotates about 12,000 rpm, is supported by two carbon graphite journal bearings, lubricated by the working fluid. The rotor consists of permanent magnet poles made of Samarium Cobalt. A stainless steel sleeve isolates both the rotor and stator from the working fluid. This wet design negated the need for a shaft seal, improving, the pump life. The vendor used this design a few years earlier for a developmental unit for another program. This unit was ground tested and had run for about 3000 hours and experienced over 300,000 start/stops. The clearances in the pump vary from about 6 micron in the journal bearings to 125 micron in the bypass loop for wetting the journals. A schematic of the pump/motor is shown in Figure 3. Two developmental pumps were first built for the Pathfinder program as life tests unit pumps. These pumps went through thermal cycles and random vibration tests and one of the units is currently being life tested. One of the pumps has operated for over 5,500 hours as of May 1996 and still continues to operate. Details of these tests are given in Reference 1.

The check valves used were made of stainless steel with a cracking pressure of 0.2 psi. These valves used Teflon 0-rings as seals. The thermal control valve is an assembly of a wax actuator which provides an actuation of 20 roils over a temperature range of -7 to O C. The actuator moves a spool in the valve that opens or closes the bypass port depending on the temperature of the freon flowing through the valve, The wax is hermetically sealed from the working fluid by a stainless steel bellows, preventing wax loss through a dynamic seal as is common to most wax actuator designs. The original design consisted of stacked bimetallic discs. However, after some developmental tests, it was found that the disc material were not compatible with freon and that they did not produce smooth linear motion due to stiction. Because of this a new development effort was undertaken to build a wax actuator which would meet the Pathfinder needs,

The motor control electronics is enclosed in a wrought aluminum box housing the circuit card assemblies of both the pump/motors. A connector is mounted on one end of the box for the input power and another connector on the bottom box connects the motor controller to the pump/motors. The circuit cards are multilayer boards with lead-in components soldered to the boards. The circuits are designed to meet the Pathfinder fault tolerance requirements for radiation susceptibility. The parts used met the reliability requirements (MIL-STD-975 Grade 2 and MIL-STD-883C Grade B). The single event effect sensitive parts used were JPL-approved rad hardened parts. EMI filters were included to meet the conducted and radiated emissions and susceptibility requirements of the Pathfinder spacecraft.

FABRICATION - The fabrication was done in three major subassemblies before the whole unit was put together. The three assemblies are 1) Accumulator assembly, 2) Pump manifold assembly, and 3) Motor controller electronics subassembly. The accumulator and the pump manifold are all welded stainless steel units, whereas, the controller electronics is in a hogged out aluminum box with a bolted-on lid. The welds were made to qualified weld schedules by MI I ,-S'1'1)-1 595 certified weld operators. The sample welds were made on the day of the flight weld and inspected under high magnification for sound weld quality (depth of penetration, porosity, cracks etc.) before welding the actual hardware. The unit was leak tested before proceeding with the next series of welds.

The accumulator assembly consisted of the machined housing, the bellows, service valve, pressure transducer, and purge tubing, All the parts were cleaned thoroughly to remove the particulates above 25 microns in size before the parts were assembled, tested, and welded. "l'he unit was tested for leak rate and bellows performance between each series of welds. Electron beam welds were used for all the welds in the accumulator subassembly. After completing the assembly, the pressure transducer output was calibrated against pressure **gage** readings.

All the motor assemblies, valves, and inlet and outlet tubing are assembled into the wrought stainless steel pump manifold, All these parts arc welded into the block using laser welding. Because of the magnetic properties of the motors, electron beam weld could not be used for this assembly. As in the case of the accumulator fabrication, the pump manifold par ts were cleaned and the unit tested between each series of welds. The tests consisted of checking the performance of each pump, thermal control valve, and the check valves before the next series of welds were made.

Electronic box fabrication consisted of fabricating, the circuit cards and populating them with parts. The multi layer circuit cards were fabricated to Mil-P-551 10. All the lead-in components were soldered to the boards per the MI I ,-STD-2000. The boards were conformably coated before they were installed in the box.

The final dry mass of the IPA before it was installed on the spacecraft came out to be 8.0 kg.

PERFORMANCE TESTS:

Three types of performance tests were done on I PA: 1) 1 lydraulic, 2) Electrical, and 3) System proof and leak. The hydraulic performance tests were conducted to verify that IPA met the specification requirements. These requirements related to the flow rate and pressure rise at various temperatures. The IPA flow rate at various pressure rises is shown in Figure 4 for the IPA with one pump operating,

in the electrical performance tests, the current draw of the IPA at various flow rates was measured. 'l'he input voltage to the IPA was varied between 27 Vdc and 36 Vdc and the IPA current draw was measured. The IPA electrical pet formance is shown in Figure 5.

In order to verify the integrity of the IPA fabrication, the unit was proof tested and leak checked. The unit was successfully tested to a proof pressure of 185 psig. Two leak rates were specified for the I PA - onc for the gas side of the accumulator anti a second for the rest of the unit which is the liquid side. For the gas side, the maximum leak rate was specified at ? .X i 0¨ scc/sec of helium, whereas for the liquid side, it was specified as 1 X 10-"' scc/sec helium. The leak rates for each weld and valve were computed based on these total leak rates and were tested to the computed levels during, the leak check of the assembly.

QUALIFICATION TESTS:

Three types of qualification tests were clone on IPA besides the performance tests. These arc vibration tests, thermal vacuum tests, and Electromagnetic compatibility anti susceptibility tests, The levels to which the unit was tested were protoflight levels since the flight unit was used instead of an eng ineering model to flight qualify the IPA. The order of the acceptance tests arc given in Table ?.

Table 2. Acceptance Tests for the i PA

Type of test	Verification Purpose
Performance tests	Performance of the IPA before the start of the qualification tests
Sine Vibration tests	Design for the protoflight launch loads
Random Vibration tests	Design for the protoflight launch loads
Functional tests	Functionality of the unit after an acceptance test
Thermal Vacuum test	Design for the protoflight temperature range
Functional test	Functionality of the unit after an acceptance test
Proof pressure test	Design for the operating pressure
Leak Detection test	Leak rates of the IPA
Performance tests	Performance of the IPA at the completion of qualification tests

The test requirements for the Sine and Random vibration are given in Table 3. The IPA successfully underwent these tests while both the pumps were operating. The performance was monitored during the actual vibration. The sine vibration test consisted of sweeping at the specified sinusoidal amplitude levels from the lowest frequency to the highest frequency and back to the lowest frequency at a rate of2 octaves/minute in each of the three orthogonal axes. The random vibration tests was conducted one minute per axis. Accelerometers used to monitor the responses during both the tests,

Table 3. Sine and Random Vibration specification for the IPA

Axis	Protoflight Test Level	Frequency Band
SINE VIBRATION:		
All	1.27 cm double amplitude 10.0 g (Acceleration O-to-peak)	5 - 20 Hz
RANDOM VIBRATION:		
All	+6dB/octave 0.2g2/Hz -12 dB/octave 13.2 g_{rms}	20 - 80 Hz 80-700117, 700-2000117, Overall

The thermal vacuum test on the IPA consisted of two types of tests. The first test was done on the motor controller electronics separately. The electronic box was mounted on a base plate which maintained at 70 C while both pumps were continuously on for a seven-day period, Electrical simulated loads were used for the pumps in this test. The second thermal vacuum test was conducted on the whole IPA and consisted of one-day cold and two-day hot soak, The tests requirements are shown in Figure 5.

The EMI qualification tests for conducted emissions and Susceptibility were done on a separate life test pump/motor unit which was of the same design as the flight pump/motor unit and the flight electronics. The EMI tests performed for the power line ripple and power line transients for both emissions and susceptibility, The EMI qualification tests for radiated emissions ant] susceptibility were performed at the spacecraft level. The IPA went through the tests and satisfactorily met the spacecraft requirements.

PRESENT STATUS:

The IPA has been integrated with the rest of the HRS on the Pathfinder spacecraft. The spacecraft went through an acoustic test to simulate the launch vibration conditions. The IPA has been performing well. The spacecraft will undergo a solar vacuum test in April 1996 to simulate the mission cruise conditions of solar flux and the space thermal environment. During this test, the IPA will be operated in flight-like conditions. The temperatures of the entire HRS will be monitored along with the accumulator flight-like conditions. The temperatures of the entire HRS will be monitored along with the accumulator gas pressure. The performance of the HRS and IPA will be evaluated and compared to tbc earlier analytical predictions.

CONC1,LJS1ONS AND RECOMMENDATIONS:

The design and flight implementation of the Integrated Pump Assembly for the Heat Rejection System of Mars Pathfinder spacecraft was successfully accomplished in less than eighteen months. This quick turn around for a new spacecraft technology was achieved by employing non-traditional techniques such as parallel work on the developmental and flight units, flight qualification to protoflight levels, trading off schedule and cost against risks during the implementation, and quick decision on the design changes to fix problems encountered during the design verification.

The modular design of the I PA made it easier to fabricate and test electronics and the mechanical parts of the assembly independently and expeditiously. A new wax actuated thermal control valve was developed for the IPA for bypassing the radiator for fluid temperature below O C. The If'A was successfully assembled using extensive electron beam and laser welding. The high level of cleanliness required for the IPA during assembly and test was achieved by employing careful handling procedures. The IPA has been successfully installed in the spacecraft heat rejection system and tested.

Because it was the first time an active cooling system was being implemented on a spacecraft, several lessons were learned from the flight implementation of the IPA on the Pathfinder. These are in the areas of design, fabrication, and testing of the pump assembly and integrating it on the spacecraft. Some of these include design modifications to make the welding process easier, elimination of some intermediate cleaning processes by better handling of the hardware, and using liquid nitrogen to perform some of the cold tests. Further, the cooling system design itself can be improved for future spacecraft by employing more advanced concepts for IPA such as variable speed motors, advanced thermal valves, feedback systems for flow control, and low mass accumulators.

ACKNOWLEDGMENTS:

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'I'he design and flight implementation of the I PA could be accomplished under a very tight schedule (under two years for new technology flight item) due mainly to extreme cooperation and support of many people. The authors would like to acknowledge the following persons. At JPL, Bill layman, Ed Litty, Greg Rosalia, Richard Rainen, Andre Yavrouvian, and Rob Menke for their support for the IPA task; Chris Mirate, Jack Patzold, Richard Fleischner, and Jay Dettinger for the implementation of the 11'.4 into the spacecraft; Yi-Chien Wu, the Thermal subsystem task manager, for his constant support and faith in us; and finally, Brian Muirhead, the Pathfinder Spacecraft Manager, for his leadership in choosing the active cooling loop for Mars Pathfinder and support during the design anti flight implementation of the I} 'A. At Howden Fluid Systems: Scott Forbes, Chief IPA technician, for ably taking care of the entire fabrication anti testing of the IPA from the beginning. Richard Fischer, Director of Engineering, Bill Young, Chock Forbes, Mitch Frey, and Rich Densmore for their support for the design and testing of the IPA; Larry Nowlin, the Program Manager for Ii'A, for expeditiously resolving many difficult problems during the execution of the task.

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2. De Paolis, M., "A controlled Pump Assessment for Spacecraft Cooling," Thermal Control and Heat Rejection Section, ESTEC, The Netherlands, PP 141-162, Vol.18, ESA Journal, 1994.

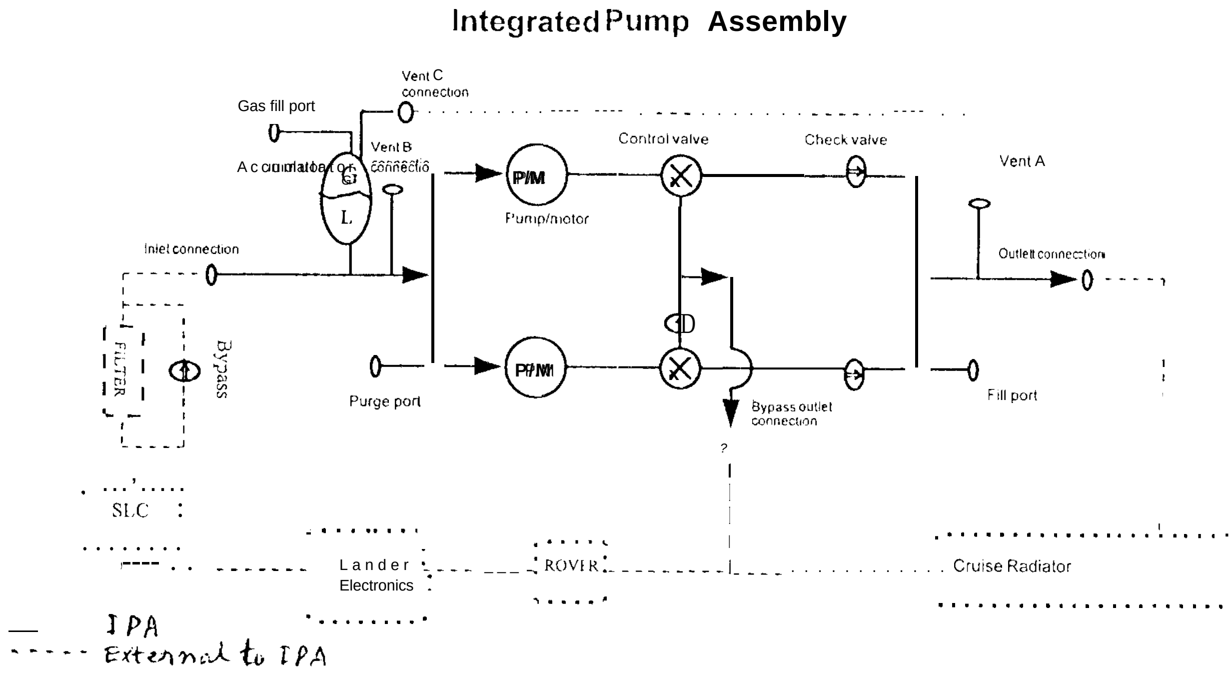


Figure 1. Integrated **Pump** Assembly Hydraulic Schematic

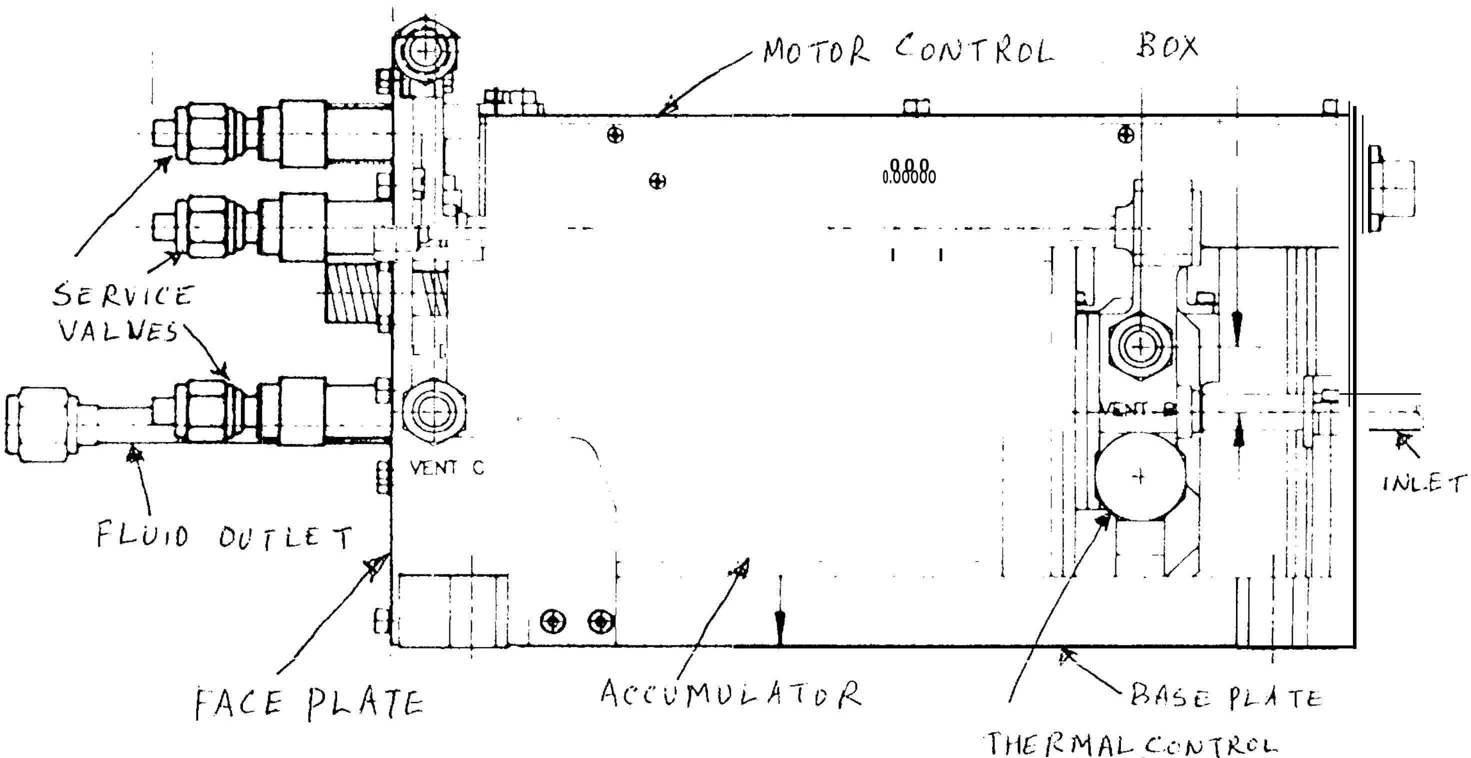


Figure **2. IPA** Mechanical Design

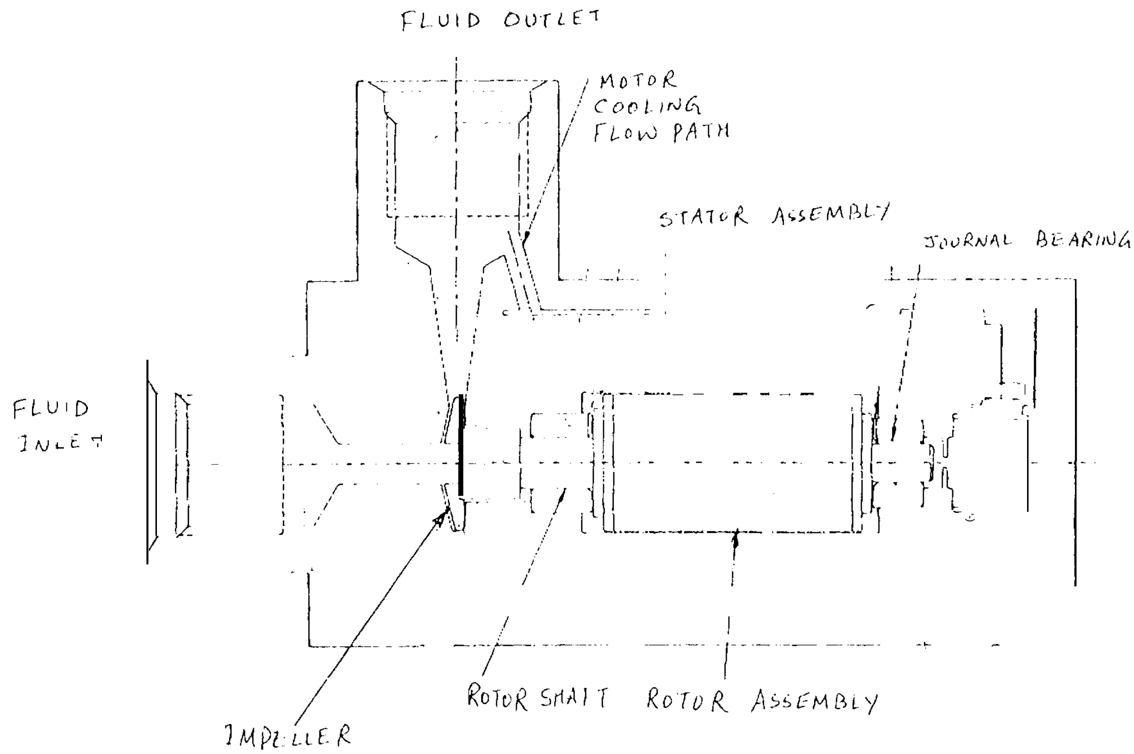


Figure 3 IPA Pump/Motor Schematic

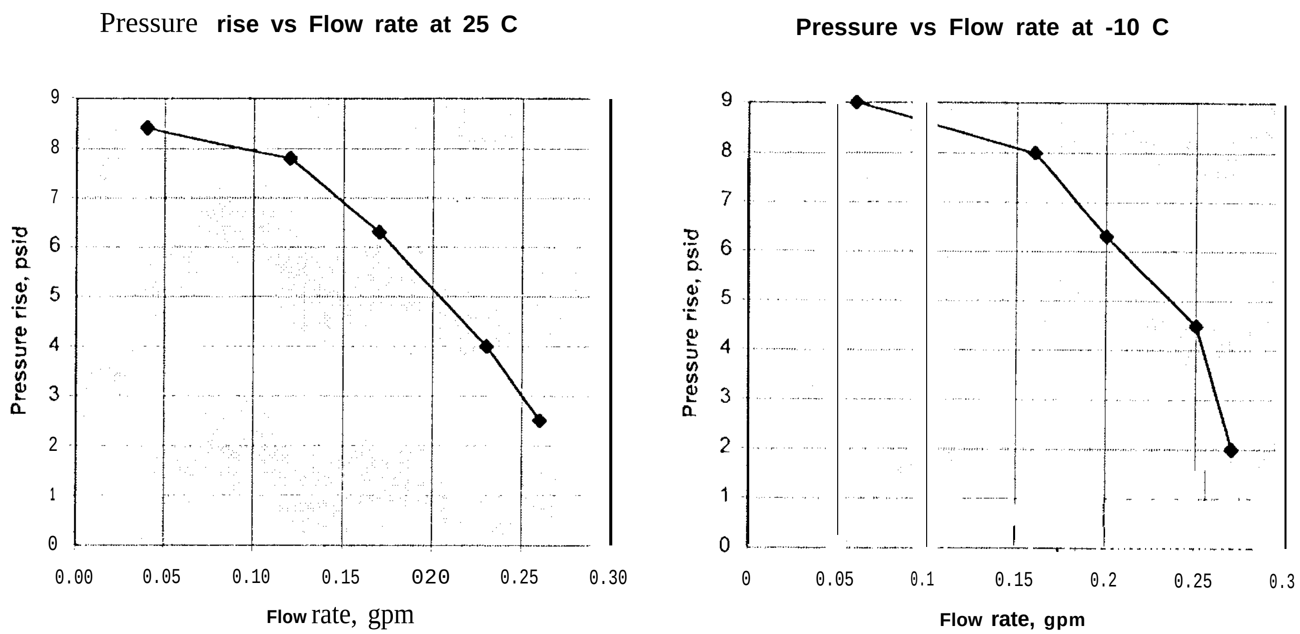


Figure 4. Hydraulic Performance of the IPA Pump

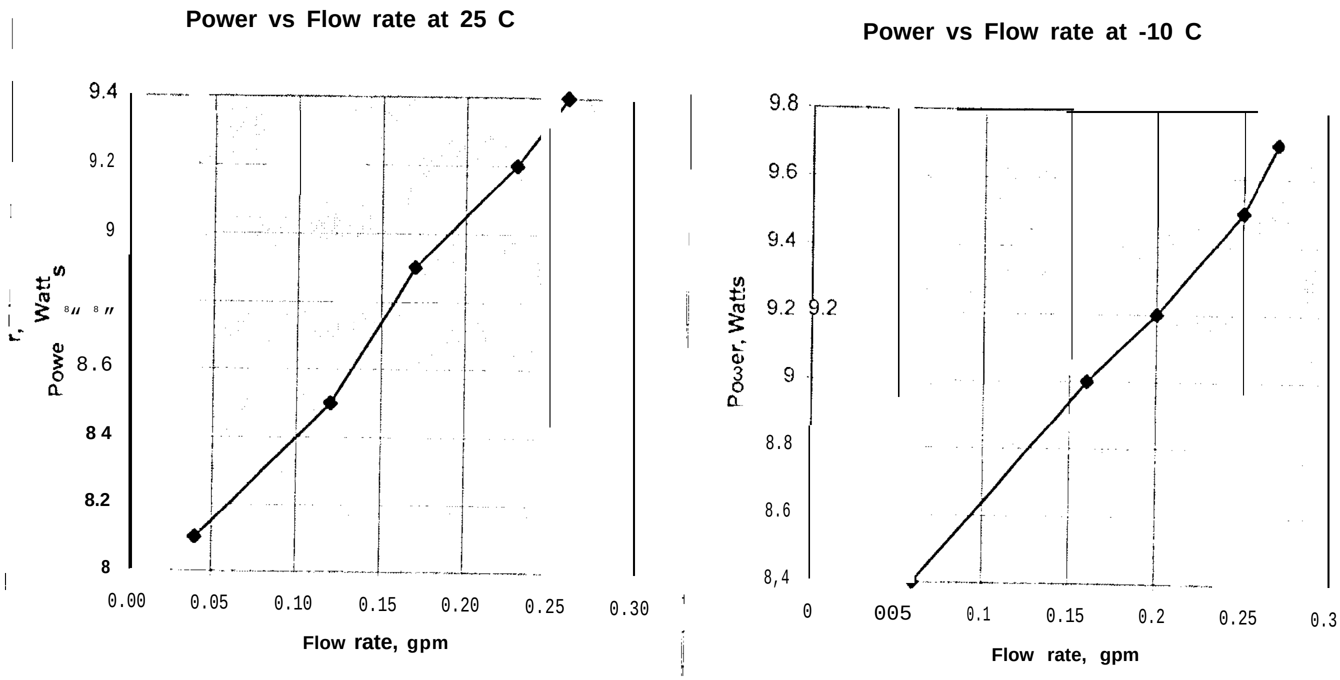
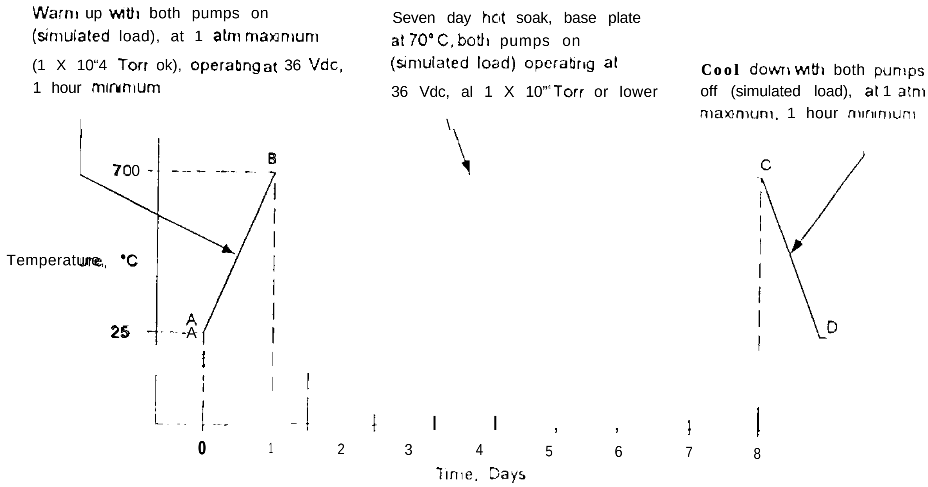
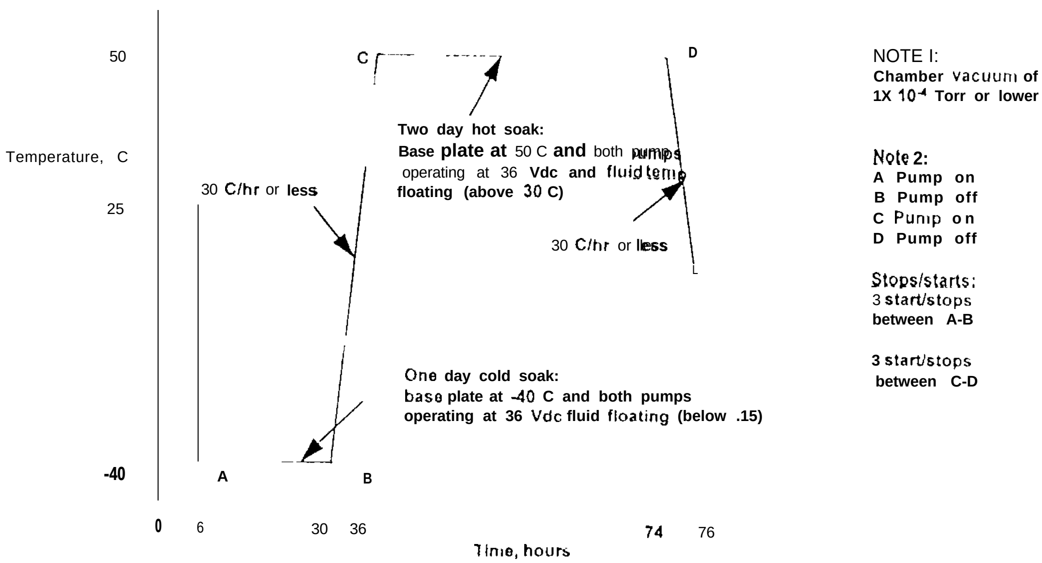


Figure 5. Electrical Performance of the IPA Pump



a) Thermal Qualification Test for the Motor Controller Electronics

Thermal/vacuum test for Integrated Pump Assembly



b) Thermal Qualification Test for the 1 PA with Electronics

Figure 6. IPA Thermal Qualification Test Cycle