Centrifugal Water Pump

MAE 364

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Abstract:

The centrifugal water pump is custom built for the military. The pump provides the flow for the cooling system of the gun mounted on naval vessels. The pump was designed for an unusually high flow rate. The rotations per minute of the pump will need to be accommodated with special design considerations.

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Introduction

The department of the Navy is accepting proposals for centrifugal pumps to cool surface to air rapid-fire 20millimeter machine gun system on board of their guided missile destroyers. The pump should be able to withstand high temperature, high pressure cycling. The most important function is that it does not malfunction when it is being used. A failure of this pump can cause the death of American servicemen and the destruction or the seizure of a multi-million dollar artillery unit. Because of its application you will see that many of the parts and techniques enhance the safety and reliability of the pump. SJPJ is a pump manufacturer out of Buffalo, New York and is competing for this multi-million dollar contract. The purpose of a centrifugal pump is to supply pressure to a source. Figure 1 shows a very basic centrifugal pump. The water is fed into the center of the impeller. The impeller causes the water to be accelerated outwards through centripetal motion. Notice the distance between the casing walls. This increase in distance slows down the fluid and increases pressure. The pump that we will be designing is a single stage centrifugal pump.

Casing

There are two major components in our pump housing, the inner and outer liner. To cut down on cost our design team opted to manufacture a ceramic inner liner instead of making the whole casing out of high carbon steel. Because most of the heat will be produced in the impellor section a ceramic liner will separate the casing and the hot zone. Zirconia, a ceramic oxide will be produced through injection molding. This inner casing will be able to withstand the intense heat produced by the pump. Zirconia has a low

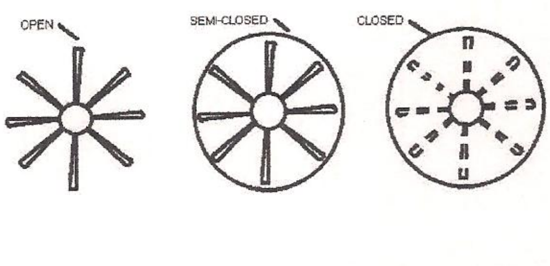
thermal expansion which is important to the overall performance of the pump. If the casing was to expand or contract it cause clearance problems between moving part which can lead to a premature failure. Another problem that could occur is misalignment between piping and pump. After the material is dried and fired it will be machined (ultrasonic) with a very fine grain abrasive to reduce surface roughness and remove surface defects. After machining it will be glazed this improves strength and also act as a sealant. The sealant is important because our outer casing is manufactured using powder metallurgy and leakage is inherent in powder metallurgy because of its porosity. The outer casing will be made out of an aluminum alloy. Aluminum was picked because of its high thermal conductivity which will help in the cooling of the casing, its high strength to weight ratio which can be beneficial in installation/maintenance and most important its machine ability. The casing will house the guts of the pump. One major concern is heat dissipation. The bearings and shaft are of major concern so we equipped the outside of the casing with fins to increase heat transfer from the bearings to the outside air. There will also be water jackets incorporated in the pump that will help assist cooling at high temperature locations. The first step would be to produce a mold in which the other parts will be made. Because of the low production run the mold will be produced using a rapid prototyping method called selective laser sintering. The mold is made when a laser cuts the shape of the product into a thin layer of powder which is sintered as the laser shapes the part. A motor raises the powder to form the next layer of the part. The actual part will be made through powder metallurgy because of the close dimensional accuracy and the near elimination of machining. We want to limit machining in order to reduce human error. The casing will be made out of two

symmetrical parts which will reduce complexity during assembly and finishing after sintering. After the particle size has been chosen the powder will be put into the mold and be compressed into its shape. The mold and the powder will be put into a furnace in which the bonding of the powder will join via diffusion. During diffusion the strength, density, ductility and thermal conductivity will all increase considerably. The next step is heat treatment to increase strength. Because aluminum is a non-ferrous metal we will use precipitation hardening. Precipitation hardening is when a material is heated at a certain temperature and for a specific time. As time increases new grains start to form, increasing strength. Next the part will be machined to the desirable tolerances and reduce any burrs or rough edges. The last step is to powder coat the exterior of the casing blue to increase the aesthetic appeal.

Impeller

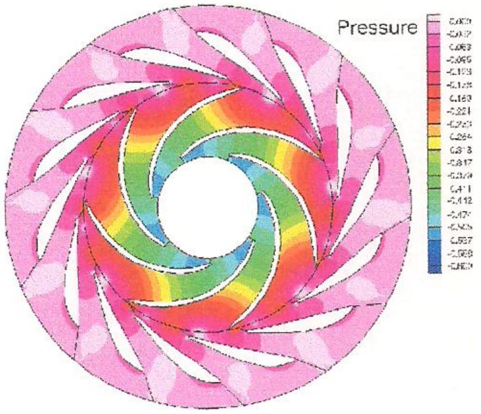
The impeller of a pump is one of the most important parts, as it is what actually transmits the work from the drive motor to move a fluid. The impeller performs very differently with various designs and thus with each new task a pump must perform, generally there will be a unique impeller. Some of the numerous ways that a pump impeller may be modified are through dimensions and blade geometry.

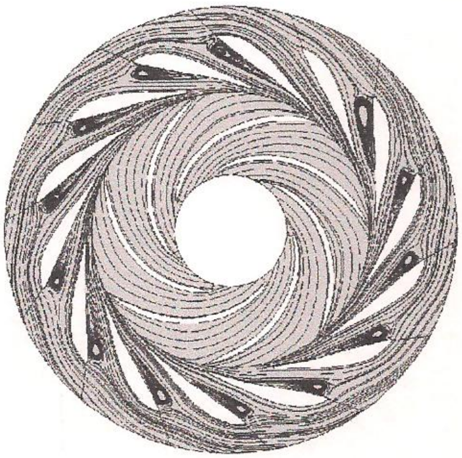
There are several types of impellers, including open, semi-closed, and closed.



The blades in all of these designs are submitted to large pressures and forces at higher speeds, but none more than the open design. With the open design, the blades stick out like a fan, but in a closed or semi-closed design, the backer(s) acts as mechanical support to aid in maintaining structural integrity.

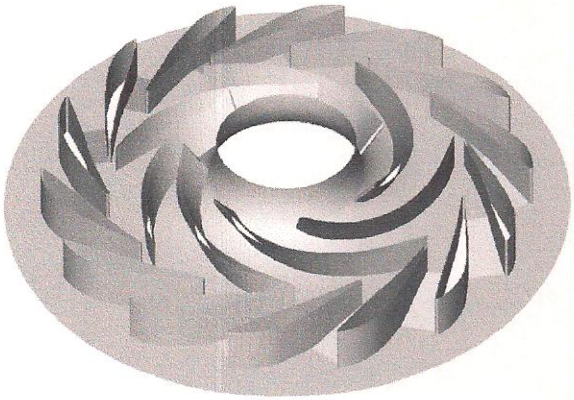
Typical pressure and velocity distribution in impeller/diffuser:





In the pump that is being designed for the cooling jacket of the weapon, there were several design requirements to be satisfied. Since it requires high speed, the impeller design to be used is the semi-closed impeller design. This design is much more maintenance friendly than the closed impeller. It has other advantages as well, which include less efficiency loss for inaccuracy of tolerances than the closed impeller.

The blade geometry is one of the final considerations and can range from straight to a flowing curved design. In this pump, the blades will be steeply raked and curved to account for the high rpm of the pump and to minimize cavitations. (shown below)



To manufacture this impeller, AISI 304 stainless steel will be used as the material to create it and the process will be rapid prototyping to investment casting. The high pressures in the pump, due to flow conditions, tend to be located on one side of a blade where as the opposite side is subjected to a low pressure. The stainless steel used is very strong and will resist deformation from pressures and corrosion that would occur due to the coolant used.

Several patterns for the impeller will be made at the same time by use of rapid prototyping. They must be modified reproductions in the sense that molten metal in investment casting does not flow well around sharp corners. Therefore, these patterns must have rounded excess edges instead of sharp and immediate corners. The patterns will be cut out of wax and then mounted onto a series of hollow rods to make an "impeller tree mold." This unit is then dipped into a slurry mixture to take the form of the patterns. It is then baked at high temperature until all the wax has melted out or vaporized, leaving a hollow core for the molten stainless steel to flow into. The molds

are then preheated to help the metal flow and prevent rapid cooling before the mold is completely filled.

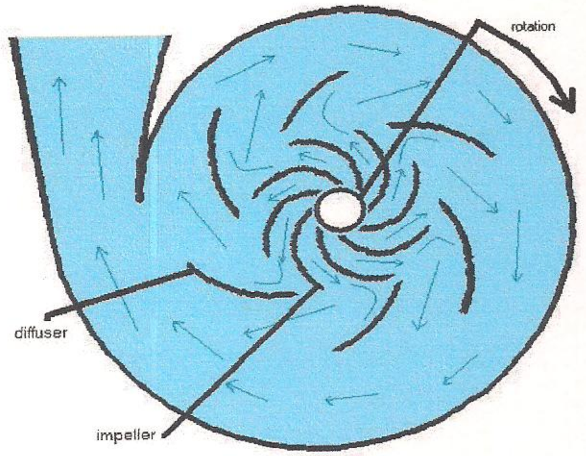
Once the steel has had time to cool, the slurry is then broken away leaving all of the unfinished impellers. These are then broken off the tree and the trees can be recycled by reusing the material in the molten stainless for the next batch. Since an investment casting method was used, the dimensions are close to final spec, but not finished. A small machining process is necessary to give the piece its final sharper edges and tolerances.

The final finish on the blades will be CNC milled and can be removed at a rate of 300 feet/minute for AISI 304 stainless steel when done slowly. The chip formation and material removal rate will be kept low in order to maintain very high surface integrity and finish. Since stainless steel has a high strain rate sensitivity, with the use of coolant, the material removal rate will be kept low. Due to the high forces and pressure, any imperfections in surface finish will be exploited and lead to failure. Therefore, the surface finish of the blades will be made almost mirror-like to reduce any restrictive forces on flow by the surface defects. The final machining will be accurate to 0.002" on all edges mating with another surface since for every two-thousandth of an inch inaccuracy, the pump will lost approximately one percent of its capacity. Finally, the hole and notch will be bored and finely machined to a sufficient tolerance. This will allow the impeller to mount onto the shaft and lock into the supplied groove on the shaft.

Once the final pieces are completed, they will be coated with Teflon to protect the surface against excessive wear from cavitations. This is a temporary protective finish and will allow simple maintenance as parts may be removed, recoated and then replaced.

Diffuser

The diffuser is a non-rotating piece of the pump that sits around the impeller. It has blades of near identical shape to the impeller, but they face the opposite direction. The diffuser serves primarily as a redirector of water flow to create a fast current that exits the pump from the discharge nozzle.

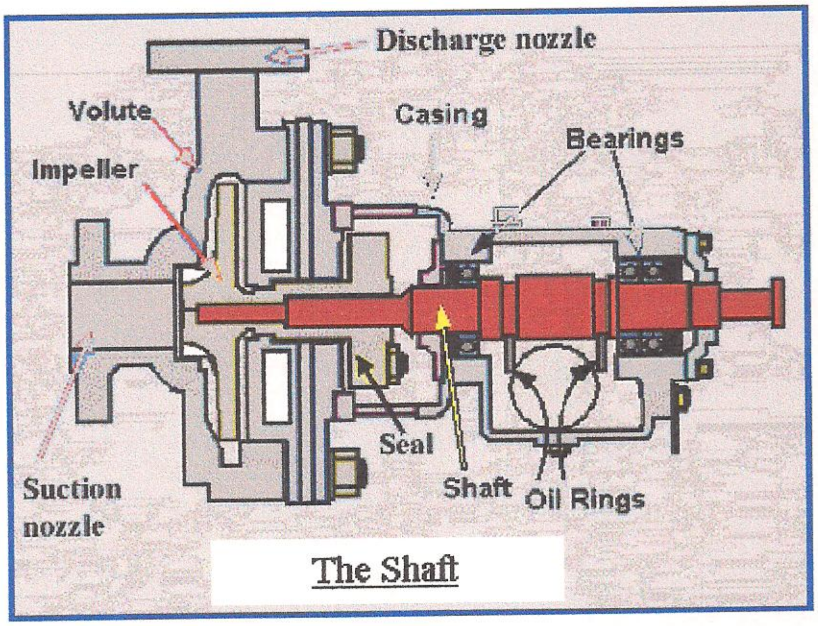


There is generally less diffuser blades than there are impeller blades. This is to prevent flow problems from forming where a diffuser blade and impeller blade are tip to tip at every point they cross. If this situation did occur, there would be severe knocking and buildup of pressure.

Since this part of the pump is subjected to the same pressures from the fluid as the impeller, but not the centrifugal forces, as it does not move, it can be made of a lighter grade AISI 303 stainless steel. The manufacturing processes followed to create this piece will be identical to that of the impeller until machining. AISI 303 stainless steel can be machined at approximately 140-150 feet/minute. The surface finish will be polished and easier to attain with the softer metal.

The diffuser will be coated in Teflon, like the impeller and will allow it to be a more permanent part with a replaceable finish.

Shaft



The Shaft

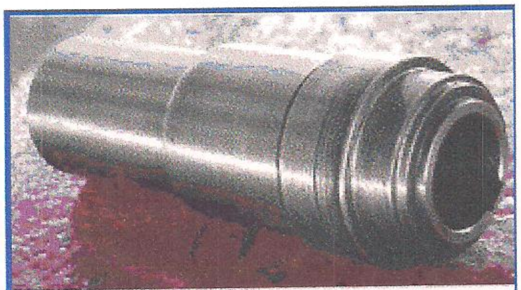
The shaft is a rod running the length of the pump, which has two primary functions. The first is to transmit torque to the impellor. The second function is to keep the rotor aligned properly without compromising its design tolerances.

As a torque transmission device, the shaft must be able to overcome a variety of stresses. These include the regular torque supplied to the moving impellor, and the highly variable and much larger stresses incurred when the pump is activated and deactivated. By maintaining the alignment of the rotor, and supplying all the support to the impellor, the shaft undergoes alternating bending stresses as well.

Shafts also must be designed to eliminate the problems associated with the critical speed, that is the speed where the frequency of the shaft's rotation is close to the natural frequency of the shaft (or one of its harmonics). Operation at or near these speeds will produce strong vibrations, and resulting bending stresses. Since this is to be a high-speed pump, the shaft must be able to withstand a period of high alternating bending stress as it

accelerates to its operating speed. Such a part must be made from a high-strength steel, such as a chrome-alloy steel.

To manufacture this, a drawing process can create the basic form of the shaft. A steel-alloy ingot can be purchased from a low-cost supplier and drawn from a die. This process will increase the strength and hardness of the shaft material, while it also brings the shaft closer to the final form of the product. We will also add a lubricant to reduce friction. This will allow a larger reduction of the shaft size as well, which compacts the grains and increases the hardness and strength of the material. This piece will then need some heat treatment to reduce the residual stresses, but to maintain some of the work hardening. The piece will then be machined on a lathe to remove excess material and create the special features at the shaft's end, which allow the impellor and the power input to be attached. Finally, it will be machined to raise the final tolerances of the part so it fits within its bearings properly.

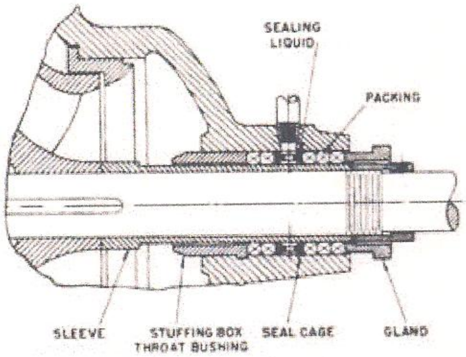


Shaft Sleeve

The shaft sleeve is a piece of metal that covers the shaft to protect it from wear and erosion, and to locate parts on the shaft. This piece is usually the first part of the pump to wear out and requires replacement most often. (p. 134) As the shaft sleeve needs replacement often, more of these than the other components will need to be manufactured. To produce one of these, the form of the part will be investment cast,

because this can create very accurate parts and the process is inexpensive. The part will then be machined with a lathe to make the exterior of the part conform with dimensional accuracy. The hole for the shaft will be bored and reamed in order to fit the shaft properly.

Stuffing Box



The Stuffing Box

The stuffing box is the entire unit of the pump that seals the impellor chamber from the rest of the pump. Its primary purpose is to prevent (or at least control) leakage of fluid either into or out of the pump chamber. It consists of a seal chamber filled with a packing material and a gland that holds the packing material in place and compresses the packing material. Also included in the stuffing box is some sort of cooling mechanism, being either fluid leaking through the stuffing box, cooling-water jacketing, or both.

The packing material must be selected carefully. It needs to be somewhat of a plastic nature because it needs adjustment to optimize the operation of the pump. Also, it is required to absorb energy without damaging the shaft or the shaft sleeve, and without failing. Typical materials include plastics, synthetic fibers, graphite foil, and metallic strands. Our pump will be stuffed with Teflon (PTFE) fiber packing, because it can withstand higher pressures, velocities, temperatures, and all levels of acidity. (P.150) We will purchase this element, but we can install it and shape it in house.

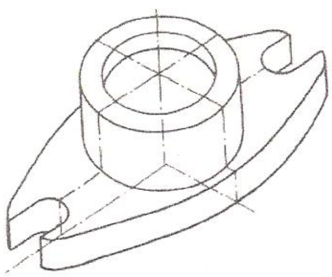


Fig. 8.22 Solid stuffing box gland.

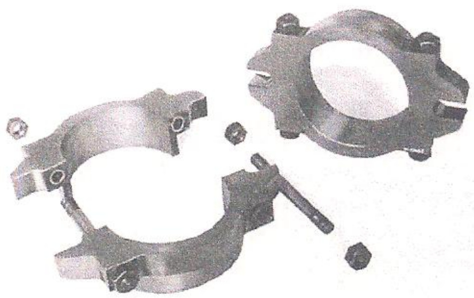


Fig. 8.23 Split stuffing box gland

There are two basic gland designs: solid and split. The solid gland is made from a single piece of metal that wraps around the shaft. A split gland is made from two pieces that are bolted together around the shaft. These are used generally in larger pumps. The solid gland however should have superior properties, as it is one piece. These are usually made from bronze, and that is what we are going to do.

The way to make this is by impression-die forging. A piece of bronze will be carefully inspected and cut to the correct size using a saw, because bronze is not very hard. Then, it will go through a bunch of forging and re-heating phases until the piece is the correct shape. The forging operation will make the gland stronger and it is a simple operation that does not cost too much if productivity is high enough. Some final machining will put the piece in the correct tolerance. This will include cutting to remove the flash, and boring and reaming to finish the hole.

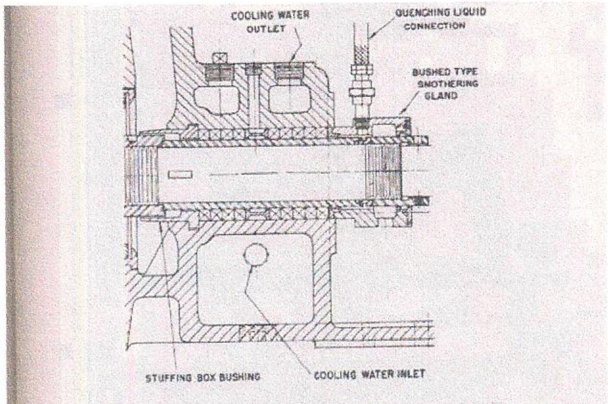


Fig. 8.13 Jacketed stuffing box with cored cooling passage cast in casing.

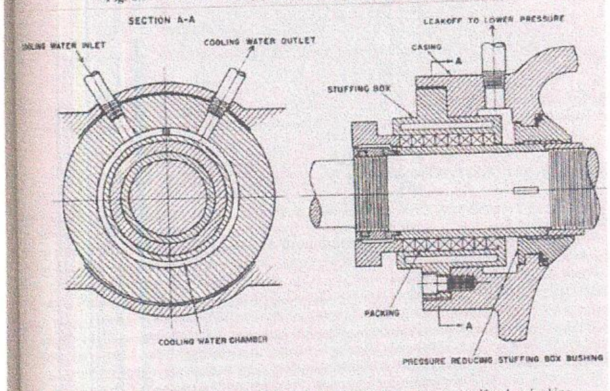
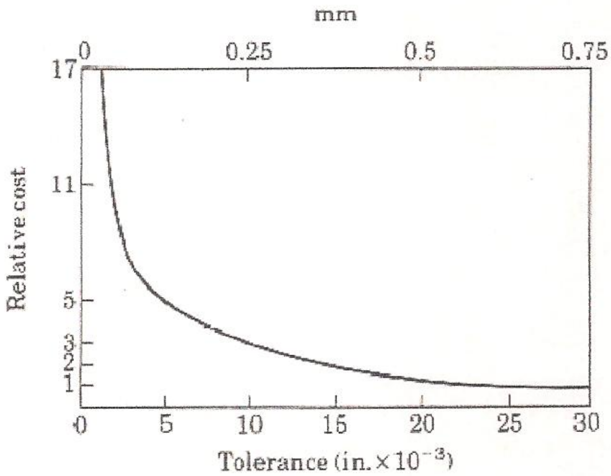


Fig. 8.14 Separate jacketed stuffing box assembly with pressure-reducing stuffing box bushing.

Also, in the stuffing box there will be channels for cooling fluid. These will be machined out of the gland and connecting ports can be attached via threading in the gland.

Purchased Parts

- Bearings: 3 Bearings total are needed to stabilize the drive shaft. The bearing will experience both axial and thrust loads. The bearings will able to withstand shock and vibration, which the military gun will produce during its operation. The casing is going to have very high tolerances were the bearing will be housed to stabilize the outer ring. Stabilizing the outer ring will increase the L_{10} life of the bearing. The shaft will also have high tolerances on the contact of the inner bearing. These high tolerance need to be within .0025in that allow for the high rpm operation and minimize the amount of vibration. As you can see from this graph that the cost of the tight tolerance in terms of relative cost is at a very high factor of 8.

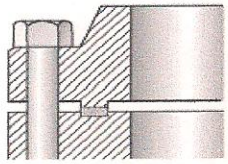


- Seals: The seals are going to need to withstand high pressure and high temperature. A need to withstand salt water environments is necessary. The tongue and groove style seal is very effective at retaining high pressure. The style requires an extra milling operation in the casing resulting in increased cost. The depth of the cut is directly related to the type of seal used. The polyurethane seal

is going to be used because of its high tolerance to heat. Some basic dimensions of the tongue and groove are presented below for a visual aid.

Tongue and Groove

Fully Confined Gasket



- Groove depth is equal to or less than tongue height
- Groove usually not over 1/16" wider than tongue
- Gasket dimensions will match tongue dimensions
- Joint must be pried apart for disassembly

➢ Nuts/Bolts: The strength of the bolts should at least grade 6 on the SAE scale. There also will be one nut holding the impellor on to the shaft. The bolts will compress the gasket and make the two halves of the casing flush. Making the casing flush will increase the strength of the pump and reliability.

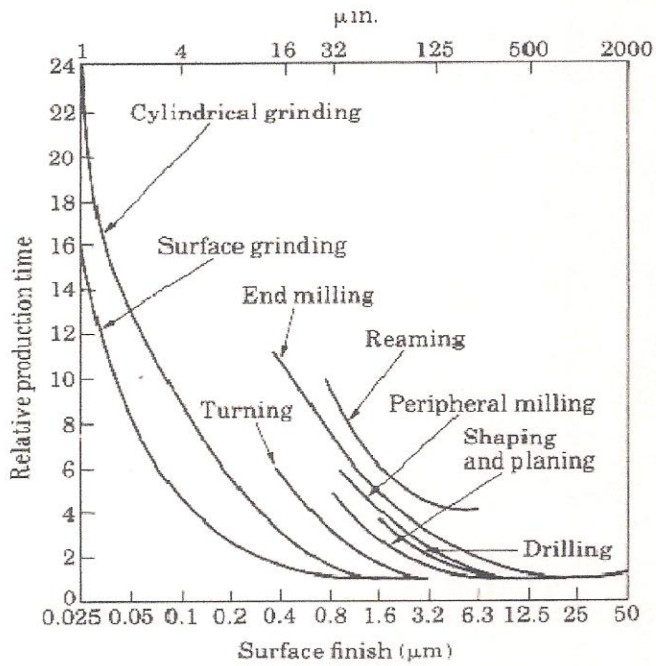
➢ Gaskets: The casing and the stuffing box is going to experience very high pressure levels. The standard gasket will not provide sufficient pressure rating. In this custom job the gasket will have to be made of a rubber coated metal. This style of gaskets is more expensive but the trade off is increasing internal pressure rating and reduce the blown out factors.

1 - Gasket for the stuffing box to the casing

1 - Gasket for the stuffing box to the nozzle fixture

The mating surfaces of the parts were the gaskets are going seal are required to have a smooth finish. The smooth surface is necessary for the seals to withstand the high pressure from the operating rpm level of the shaft and impellor/diffuser assembly. The quality of the surface finish is increased relative to the increased time spent on the process which is demonstrated by the graph located below. The

end milling process will provide a smooth surface finish of 0.8um with a relatively short time period as the graph below show's. The process used will decrease the cost of the surface finish of the mating parts.



- Lubrication Fluid: SAE 90 viscosity rating, for the lubrication of the shaft and bearing inside the casing.

Assembly

Assembly of the pump was focused on the ability to repair internal parts. The assembly is preformed by human hands. Computer automated systems is not reasonable in the situations due to the low production rates. The total revenue of the high production project would fund the set-up and control of the computer system. If the production rate was high enough computer automated assembly is more reasonable.

All the connection will have non-permanent connection. This helps the maintenance personal to replace individual parts in the unit at the location of operation.

The pump will also be powered by a separate electrical motor (sold separately) which also allows for quick replacement without touching the electric motor.

Cost Analysis

There is an order for 100 units from the government to be called for naval service. The number of production units is small which drives the cost up significantly. Since there is no welding necessary, the cost is reduced because it reduces the number of machines used and the personal training is expensive to train a welder. Basic assemblers in low production jobs are cheaper than the alternative computer automated assembly and welding sub-assemblies. The high tolerances are the main reason for the high machining cost. The following is a basic brake down of the total cost a unit.

Parts with nested costs per unit

➢ Casing		
	Material: Aluminum, Ceramic	$600
	Powder Metallurgy	$1000
	Machining Cost	$210
➢ Impellor / Diffuser		
	Material: Stainless Steel, Teflon coating	$500
	Rapid Prototyping aiding Investment Casting	$1250
	Machining Cost	$350
➢ Shaft		
	Material: Steel alloy	$200
	Drawing	$50
	Machining Cost	$280
➢ Stuffing Box		
	Material: Teflon, aluminum	$150
	Machining Cost	$200

- Buy Outs

Bearing: 3 unit	$130
Seals:	$50
Nuts, Bolts:	$10
Gaskets:	$30
Machining Cost:	$0
Fluid	$9

- Assembly Cost

$15 per hour at 30 hours	$450

- Engineering Cost

$25 per hour at 2000hours divided by number of units produced	$500

Total	**$5969**
15% mark up price for profit (from $5969)	$895
10% Covers overhead for tooling and machine maintenance (from $5969)	$597
Total Retail Unit Price	**$7461**
Total Revenue of 100 units sold	$7,461,000

Conclusion

The centrifugal pump was made successful to withstand the high rpm range needed to sufficiently cool the military weapon. The methods of manufacturing that were used are rapid prototype, investment casting, powder metallurgy, drawing and machining. Through a series of carefully organized manufacturing steps of these processes, the parts were manufactured to high tolerance clearances and cost effectiveness. The pumps were expensive with a trade off of very high strength tolerances and high rpm capability.