To the Graduate Council:

I am submitting herewith a thesis written by William Scott Klein entitled "The Design of Mechanical Components for Two Water Exercise Machines". I have examined the final copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Mechanical Engineering.

Dr. Frank H. Speckhart, P.E., Major Professor

We have read this thesis and recommend its acceptance:

Dr. Jack F. Wasserman, P.E.

Dr. Andrew J. Edmondson, P.E.

Accepted for the Council:

Associate Vice Chancellor and
Dean of the Graduate School

The Design of Mechanical Components for Two Water Exercise Machines

A Thesis
Presented for the
Master of Science
Degree

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William Scott Klein

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I would like to thank Dr. Andrew Edmondson for agreeing to be on my examining committee on short notice, and remember well many examples of practical and useful information he provided me in various courses.

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Special thanks to Betty Carmon, Bobbie Kennard and Marva Anderson in the Mechanical Engineering Department office for putting up with me and helping me smooth out the administrative rough spots to get things done right.

Abstract

This thesis is a presentation of the sequence of ideas, iterative changes and challenges encountered in the process of designing specific components for two different personal exercise machines. These machines function partially submerged in a swimming pool environment and will be commercially manufactured by a new start-up company in Knoxville, Tennessee. They are expected to be of world-class design and construction. A number of different components of these machines were designed by the author with the aid and oversight of Drs. Speckhart and Wasserman, and the difficulties and successes of the main ones are presented here.

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Chapter 1

Introduction

The design tasks presented in this thesis attempted to solve problems which to the author's knowledge had not previously been undertaken. The overall project involved the design, development, and prototype manufacture of two entirely new pieces of exercise equipment. The project was undertaken via a contract between the University of Tennessee and the principals of a company formed for the purpose of commercializing the venture, HydroForce, Inc., headquartered in Basalt, Colorado. These machines are to be used in recreational and rehabilitative swimming pool environments for both pleasure and restoration of muscle function to individuals with diminished abilities. Figure 1 shows both machines, from the Internet site of the company, at www.hydro-force.com. Development of a product design specification illuminated problems not normally encountered in the manufacture of exercise equipment: the environmental parameter of water submersion established material requirements which do not exist for land-based units; all materials had to be able to survive and function satisfactorily in very corrosive chlorinated pool water. This meant all metals used had to not only withstand submersion indefinitely but also be cost-effective for the machines to be commercially competitive. Metal choices were thus limited to stainless steels, aluminum or brass; all aluminum had to be anodized as the pool environment proved to be too corrosive for the unprotected base metal. Even one zinc-plated carbon steel bracket was unable to withstand the corrosivity of the water and had to be replaced with a plastic one. Various plastics were used, the primary ones being acetal for its low moisture

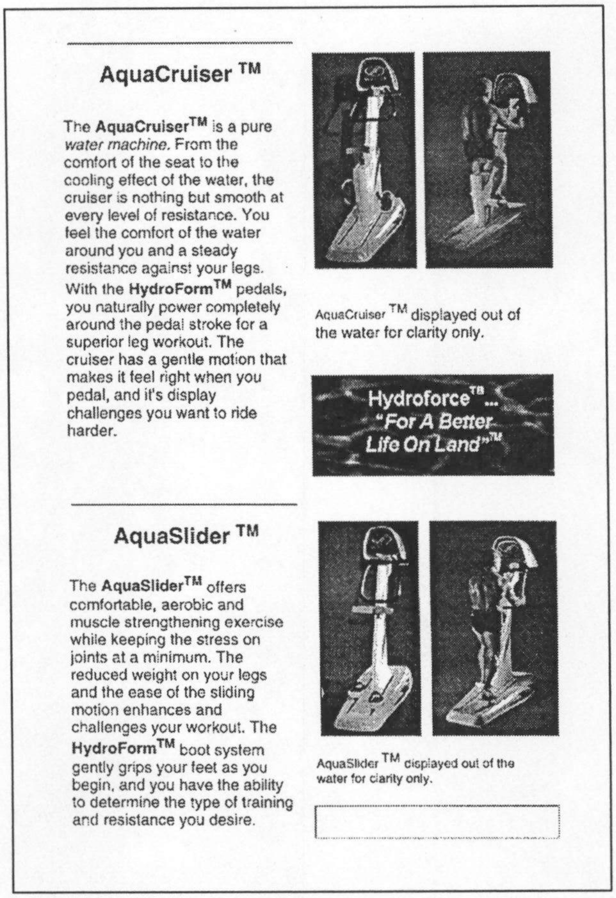

Figure 1. The "AquaCruiser" and "AquaSlider", from HydroForce, Inc.'s internet site

absorption and inherent lubricity, PVC (polyvinyl chloride) for its low price and favorable structural qualities[1], and some nylon. UHMW (ultra-high molecular weight polyethylene) was used for the sandal supports on the "ski" machine. An additional design constraint was the necessity of keeping production costs low. It was intended to produce a few units initially, scale the number up to about 250 for each machine, then based on orders received from early sales efforts to begin full scale production of an unknown number of units. This approach prevented the use of such high-volume cost-effective part production methods as

1 Information on PVC piping can be found on page 53 of the appendix.

injection molding, blow molding or rotational molding for plastic parts, or casting, forging, heavy machining or others for metal parts. All parts were thus designed in ways which would involve a minimum of processing and labor. This was a serious constraint since a problem which might easily be solved with a high-volume design was not feasible with this method. Other important considerations were those of customer comfort and satisfaction with the equipment. The customer here not necessarily being the end user, but since these are relatively expensive machines, the health clubs and spas which are forecast to purchase multiple units. These customers will have different requirements for satisfaction than an individual user might.

The product design specification was then:

- Low material cost
- Ability of construction materials to survive in the corrosive environment
- Low production cost
- Cost-effective fabrication methods using small initial production lots
- Ability of materials to be lubricated either by the water environment or molecular composition
- Long life (5+ years)
- Minimal maintenance requirements
- High user comfort
- High customer satisfaction with equipment
- World-class look, feel and function
- User-friendly controls
- Minimum number of parts
- Non-polluting materials
- Light-weight materials to reduce load on pool decks

Two machines were initially designed and built, one simulating a cross-country skiing exercise and one simulating a bicycling exercise. Both machines were designed to use the cooling, hydraulic, lubricating and buoyant features of water to provide their function. Both use hydraulic pumps to provide resistance to the user's muscle action: the "ski" featuring piston-type pumps and the "bike" featuring a turbine pump. Both of the machines have a pair of unique self-adjusting foot-holding devices which maintain positive placement of the user's foot in comfort, while providing quick release when exercise ceases. Development of this foot-holding device proved to be the most difficult part of the entire project. It was this area of design and development for which the author was initially engaged on the project and it was here he devoted the majority of his efforts. Although this was the primary area of responsibility, the author was involved in the design of many other components for these two machines, hence the title of this thesis. Throughout this thesis the author refers to the team rather than himself, since this was a team effort even though the author was primarily responsible for the items covered here.

An unforeseen factor in the design and development process was the continued interaction of the company owners and the changes in components due to changes of mind as to how the project should proceed. This was not necessarily negative, as the author believes the overall quality, function and appearance of the product improved substantially as a result of their personal involvement. There were considerable delays in the development process due to this interaction,however, and to the fact the owners were not continuously on site.

While it is certainly not a new concept, it proved very instructional to the author to observe that after all iterations had been exhausted, the simpler designs generally proved to be the best, both in function and appearance.

Chapter 2

Development of a Self-Adjusting Footpiece

1 Proof of Concept

By far the most difficult design challenge encountered both by the author and his team members was the requirement to provide a foot-holding device which could be used on both exercise machines (as well as possible future others). This device was required to function without having to be physically manipulated by the user (since this would probably require the user to have his/her head under water). It would hold the user's foot securely during exercise and would release swiftly upon cessation of exercise. This would allow extraction of the user's foot and prevent any panic sensation on the user's part should he or she desire to extract their foot and be unable to. In addition, the device would be required to accommodate a wide range of foot sizes, from a small female to a large male.

An early decision was made to use an inflatable bladder of some type, if this could be made to work, as it was believed this would provide a tenable solution to several of the design problems. The use of an inflatable[2] bladder would allow for accommodation of a range of foot sizes, would possibly allow rapid filling and exhausting, would be inexpensive, and by proper design would have good appearance and long life. Because many of the design challenges presented here had not been attempted previously by others, there was no existing body of information to draw on and many of the specific requirements such as

[2] The term "inflatable" is used for brevity; there are no actual gases present as the bladder is filled with fluid.

flow into and out of the bladder had to be estimated or approximated. Some information was available on foot sizes [1], and several different types of beach sandals were examined as starting points for a design of the "shoe". Additionally and more importantly from a design standpoint, the very nature of the problem prevented the creation of an analytical model due to the many unknown factors involved. A good analytical model would almost certainly have speeded up the design process by eliminating much of the trial-and-error effort. Figure 2 shows the first actual prototype built, which consisted simply of a bladder attached to a wooden platform. This was designed to test whether a suitably-sized bladder would perform the desired functions. The test was deemed satisfactory, and it was at this point that the author became involved with the project.

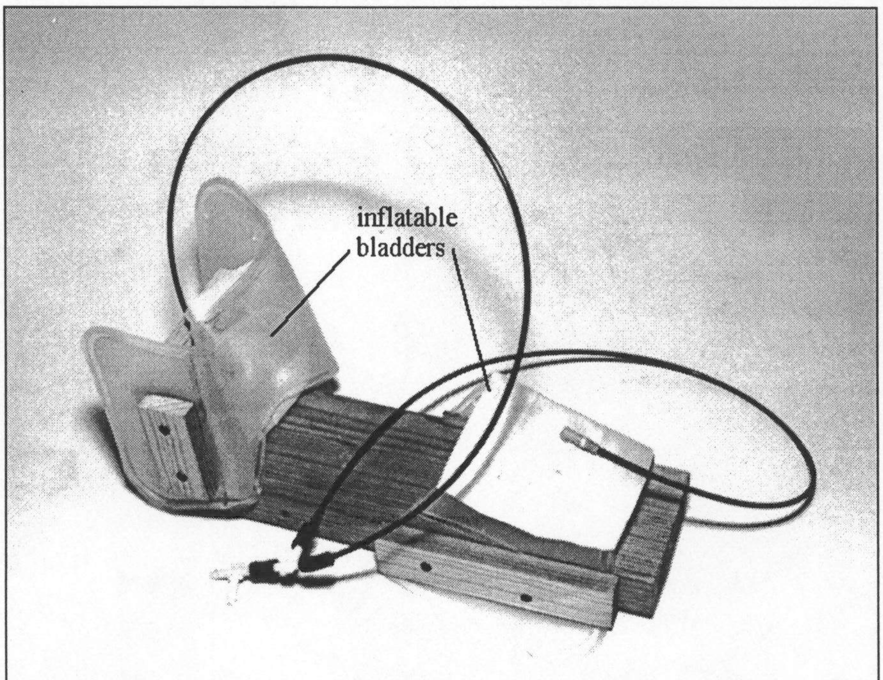

Figure 2. The first footpiece prototype, built to test the concept of an inflatable bladder

2 The First "Sandal"

The author's first design attempt, shown in figure 3, involved constructing a foot covering of 70-denier nylon, coated on one side with polyurethane (a standard bladder material), with a somewhat rigid polypropylene insert between the bladder layers for structural support, and attached to a wooden foot-shaped base to simulate the desired device. This bladder had a single fitting for both inlet and exhaust but was otherwise a sealed chamber.

This design was crude, but was of the general size and shape necessary and although unsatisfactory, did provide a reasonable range of adjustment for holding various sizes of feet. This range of adjustment problem cannot be overemphasized, as it involved not only

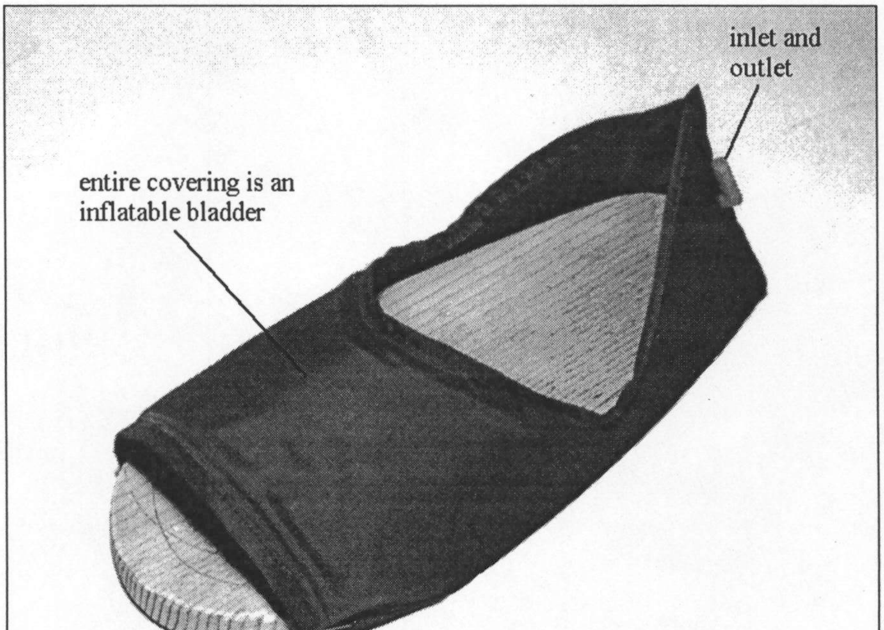

Figure 3. The author's first attempt at designing a self-adjusting footpiece

a problem of adjusting for length, but of adjusting for height and volume as well. If the heel is taken as a reference point, as was done on the "ski" machine, then there is an infinite variety of possibilities for the volume displacement necessary to accommodate even a few different sizes of feet, not to mention the full range of sizes necessary for this application. The requirement ranged from provision for a small female foot to a large male foot. The volume displacement spoken of here refers to the product of the distance from the underside of a necessary upper restraining piece to the supporting upper surface of the lower platform, the distance from the front-to-rear portion of this same piece, and the distance across the width of the platform, all of which are continuously varying with different users. This first attempt by the author was totally unacceptable to the company's owners, for reasons of appearance and feel, and a different direction was taken from this point.

3 Combined Bladder and Strap Design

The team, consisting basically of the author's two main committee members, the author, and the company's owners, decided to attempt the use of a strap in conjunction with a base of some type to support the user's foot both laterally and vertically. It was also decided to split the design into two separate ones as the ski machine required a heel support of some type whereas the bike needed a position locator in the area of the ball of the foot. The pumps used to fill the bladders also differed by machine, and it was unknown at this time whether a single bladder would function in both situations.

It was at this point that the first strap design was executed. This consisted of a double chamber, which offered the ability for relatively large displacements perpendicular to the longitudinal axis of the bladder, with separate intake and exhaust ports at either end of the bladder. The two chambers were connected internally to allow flow between them. The two-chamber bladder is shown in figures 4 and 5.

A problematic area of the entire bladder design and implementation was that of determining the correct amount of outflow bleed allowance. This was necessary to achieve the rapid release of the user's foot when exercise stopped. Flow at the beginning and during the exercise had to be sufficient to overcome a constant outflow which would in turn have to be sized so as to allow rapid collapse of the bladder when this flow stopped. As it was not possible to calculate this, it had to be determined by experimentation. This was done

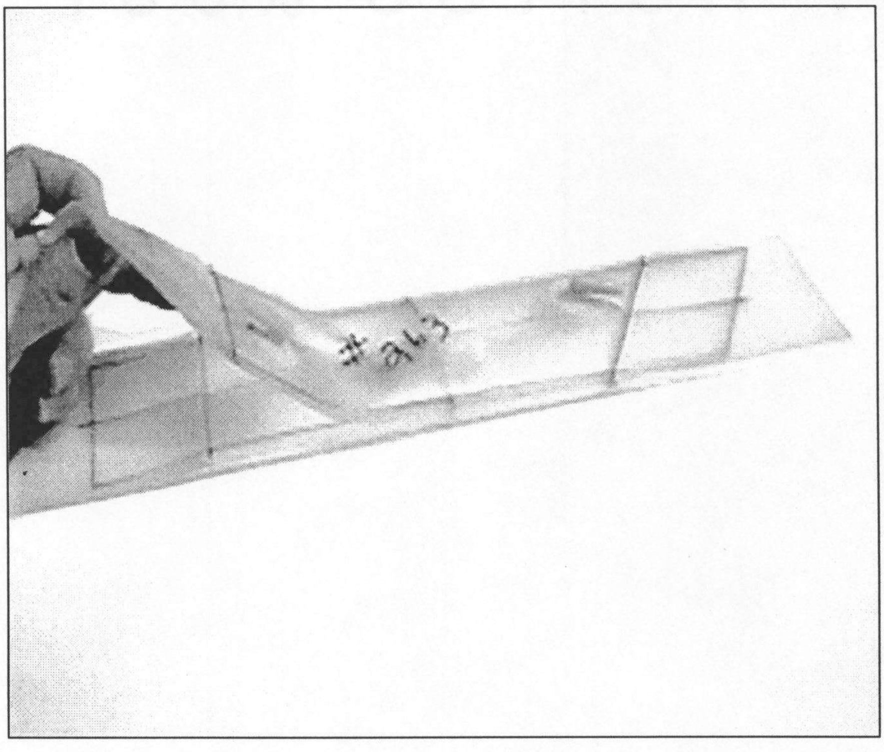

Figure 4. Two-layer construction of the second bladder

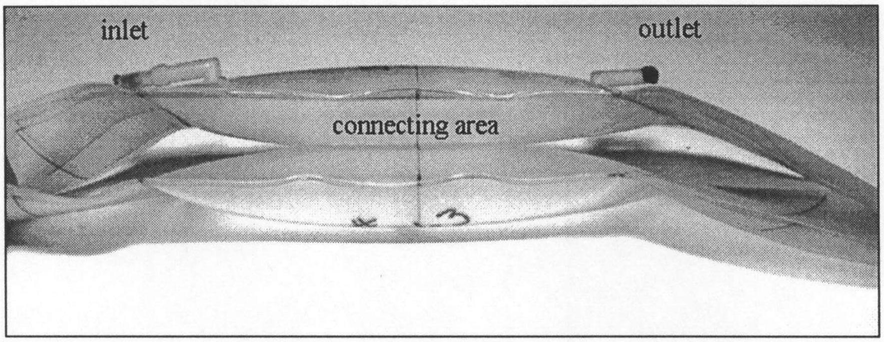

Figure 5. The two-layer bladder inflated

initially by using a small petcock on the output to restrict flow. There being no practical way to determine the required orifice, however, the author measured the pump output and pressure experimentally and then used this information to duplicate the bladder performance with a sized orifice (a comfortable user pressure within the bladder was on the order of approximately 2 psi). This occurred almost by chance, though, as the ultimate solution was to use a small brass reducer (shown in figure 6), originally intended to connect two different sizes of tubing. The smaller opening of this reducer happened to provide a successful solution to the problem. This brass piece will probably be replaced at some point with a simple plug, drilled to the correct bleed orifice, if this can be done less expensively than purchasing the commercially available reducer.

4 Rigid Formed Base Design

The successful two-chamber strap design was next attached to an ABS plastic platform used as a base for the bike pump. Development of the ski system was delayed pending a successful test of the bike piece, as the plumbing hookup was more complicated on the ski

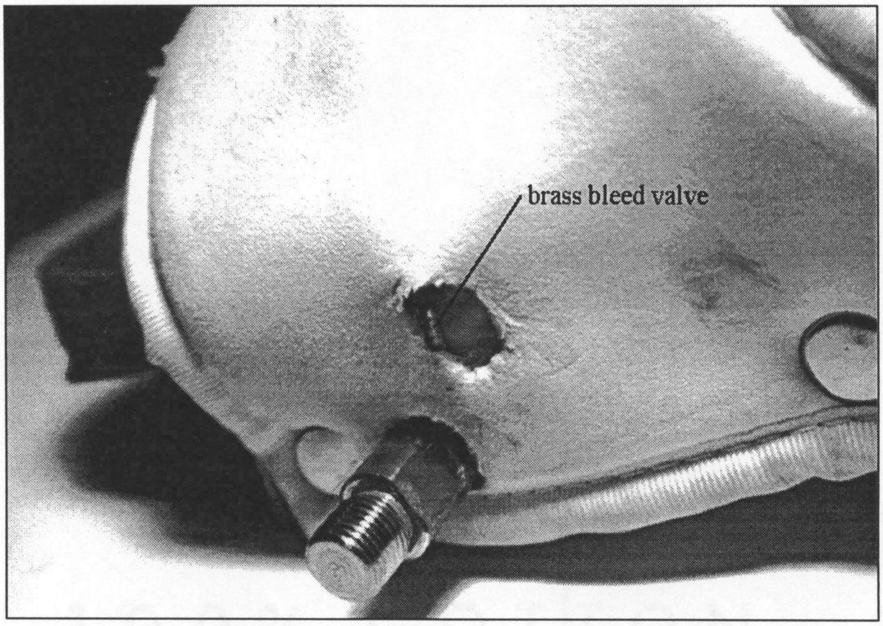

Figure 6. The brass tubing reducer used as a bleed orifice

since the footpiece moves relative to the pump, whereas on the bike the pump and footpiece are one unit. The bike pump (shown in figure 7) was fully functional and consisted of a cam attached to a shaft rotated by the user's pedaling action, a piston actuated by the cam and returned by an internal spring, and two check valves to direct the pump flow. This strap design was tested satisfactorily, but its appearance and physical feel were less than desired. It was decided to cover the bladder/strap with a fabric material in an attempt to improve these areas, and this was done, but presented other problems. A major concern was how to make the functioning device have both a pleasing appearance and be comfortable in use. The uncovered material of the bladder had an undesirable tendency to pinch the user's foot and was not particularly appealing to look at. Covering the bladder improved the feel, but presented additional problems of how to cost-effectively manufacture and assemble the

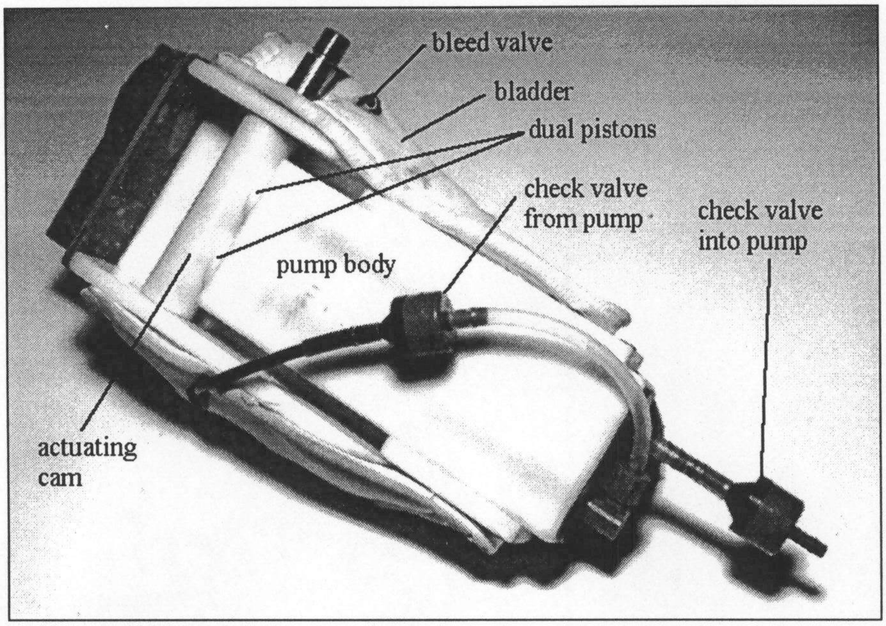

Figure 7. A later two-piston pump showing the two check valves and connections

device. The bladder would be obtained from a bladder manufacturer and would have to be inserted into the fabric sleeve. This sleeve would then have to be attached to the footpiece and the edges trimmed somehow for appearance. These problems of fastening, assembly and trimming were not thought to be simple enough to solve at this point, and a different direction was taken. As it later turned out, this design was relatively close to the final approved product.

Primarily for purposes of appearance and comfort, it was next decided to fabricate the footpiece base as a vacuum-formed part and attach the strap through slots in the surface of the piece. A local sign manufacturer was consulted for feasibility and agreed to fabricate some test pieces for the team (see figure 8). These were made of ABS plastic sheet, 3/16-inch thick, and formed over a handmade mold of the author's construction. The result was

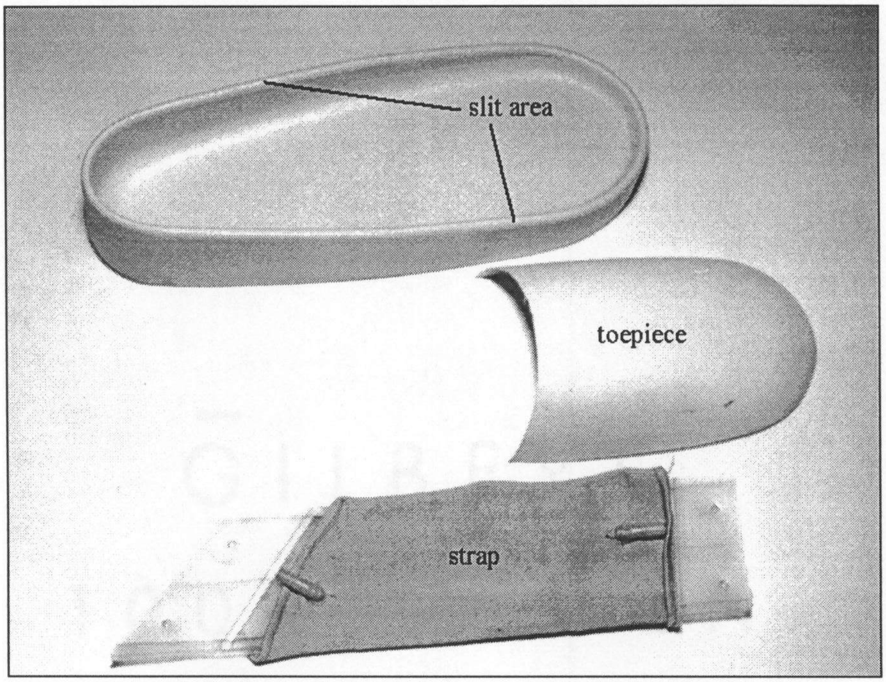

Figure 8. Vacuum-formed base with strap and later toepiece. The strap insertion slots are not shown here.

a base which was reasonably appealing in appearance, was comfortable, and lent itself to at least hiding the attaching edges of the bladder/strap. New bladders were constructed, fabric covers made, and the whole assembled to the vacuum-formed base. The sides of this base piece were raised about 1/2-inch to provide lateral support, and it was through these raised edges that a slot was cut for insertion of the bladder.

A remaining problem of this particular design was that of how to trim the portion of the fabric sleeves adjacent to the edges of the insertion slots so that they would have a finished look. The entire vacuum-formed piece with attached strap was solvent-welded to a supporting baseplate of 1/2-inch ABS plastic, which was in turn fastened with screws to an angled metal plate on the ski machine. This particular iteration was not tried on the bike, but it was felt that the method of attachment would be the same, since the bike pedal pump unit was essentially a flat platform on its upper surface. This points out another problem encountered, that of simultaneously attempting to design and develop two different pieces at the same time. This led to some confusion during discussion in meetings, but did not seriously hamper the overall development process.

5 The "Frankenstein Boot"

At this point, it was determined to attempt covering the entire front of the "shoe" in an effort to simplify the various problems encountered with the strap design and its appearance. This was a major departure from the previous design, although it was not seen to be so at the time, and resulted in much wasted time and effort. Another vacuum-formed piece was constructed by the author using a small fabrication unit recently purchased by the university for experimental purposes. This piece was attached to the prior vacuum-formed lower piece by solvent welding. Rather than using the strap with this change, it was decided to replace it with a pouch-type bladder of a larger contact surface which would essentially cover the main portion of the underside area of the upper toepiece. New bladders were constructed of the same 70-denier nylon as the very first attempt, without any reinforcing material and of a single stage, since the increased lateral area of the larger bladders would give an equivalent or better downward displacement compared to that of the two-stage narrower ones (figure 9). The new bladders were made with the inlet and outlet ports such that they would protrude through the top of the toepiece, and angled so as to hold the bladders in place. This complete change in design of course brought on an entirely new set of problems. There was now

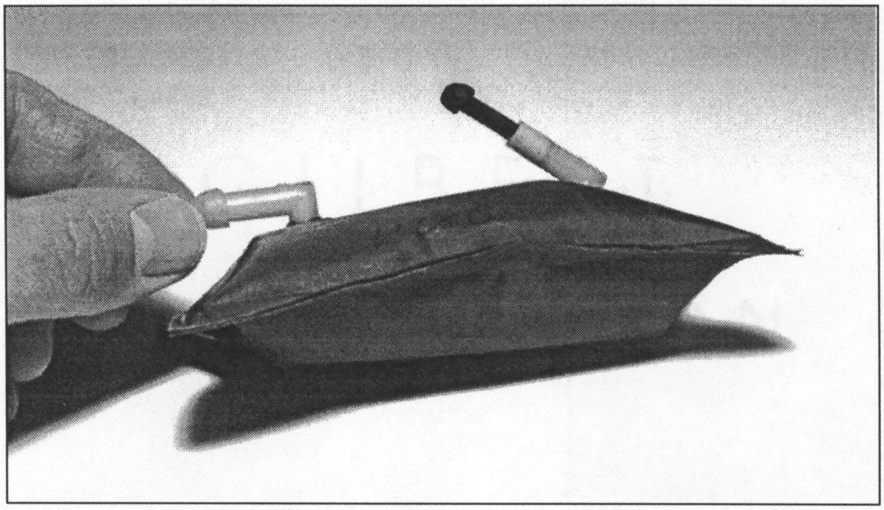

Figure 9. The small 70-denier nylon bladder inflated

good displacement of the bladder over the required range of operation, but the hard surface of the ABS plastic made the entire footpiece less than comfortable. There was also a new problem of trimming the edge of the upper toepiece so that the bladder would remain in position and so that it would not be visible. The author felt it would be feasible to solve the comfort and trim problems with an insert of some rubberized material, and proceeded in that direction. Construction of this insert was the most difficult fabrication encountered by the author on this project. A three-piece mold was made of Hydrocal, a professional mold-making material similar to plaster of paris, and a two-part silicone rubber (General Electric RTV 866 A & B) was used to fill the mold (figure 10) and produce the rubber inserts (figure 11). A reasonably good simulation was obtained by this method, though air bubbles induced into the silicone rubber material during mixing and pouring caused numerous voids in the finished parts. Nevertheless, the inserts were placed in the vacuum-formed shells and tested on the equipment. The function was better and the rubber did serve to trim the exposed

Figure 10. The mold used to make the rubber inserts

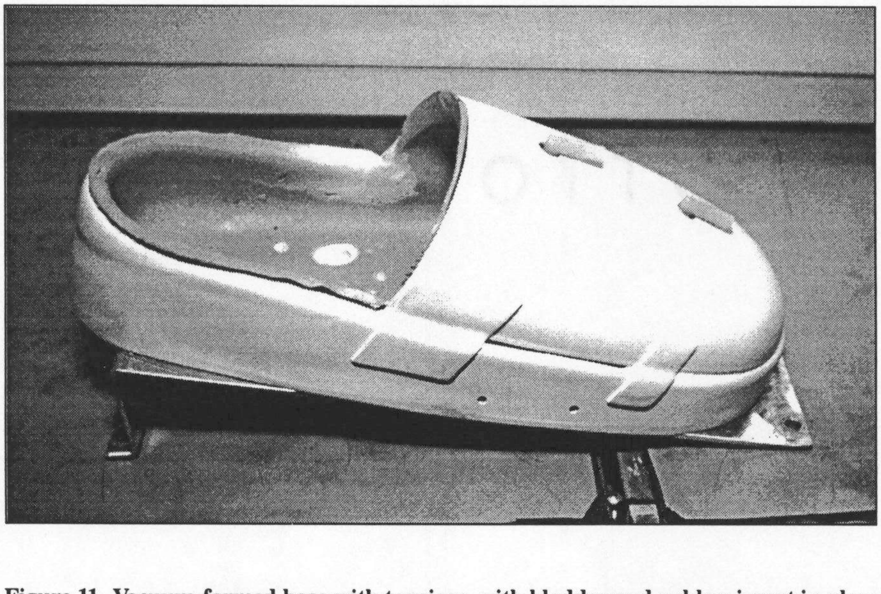

Figure 11. Vacuum-formed base with toepiece, with bladder and rubber insert in place

areas to some degree. The appearance of these pieces, however, was again unacceptable to the company owners, with good reason: they were referred to by team members as the "Frankenstein boots".

6 Re-evaluation, the Snap Sandal Design

It seemed to everyone that the design was going in the wrong direction, and an intensive session with the major participants yielded a decision to return to a simpler sandal type design. The team decided to attempt making a lightweight sandal designed around the more square bladder used in the previous enclosed footpiece. A sandal was constructed by the author and David Michael, another engineer on the team. This design consisted of a flat base which was foot-shaped in plan view, with a flat surface, and made from 3/8-inch sponge rubber with two thicknesses of 1/4-inch thick sponge rubber forming a strap. Within the two thicknesses of 1/4-inch thick rubber was placed the bladder from the previous design iteration. The base was adhesively mounted to a 1/4-inch thick piece of ABS plastic for structural support. In appearance this was nothing more than a simple beach sandal (figure 12). The comfort level of this piece was the best yet, and the bladder functioned well within the sponge rubber. One problem was the very low tensile strength of the rubber, which led to failure on testing. The failure was due to the user having a tendency to raise the heel of his foot when moving the ski track rearward. This action caused the sandal strap to separate from the base due to a lack of material strength.

This general effort was felt to be a major step in the right direction, however, and it was decided to pursue this foam rubber approach. This was not entirely coincidental as a poly-

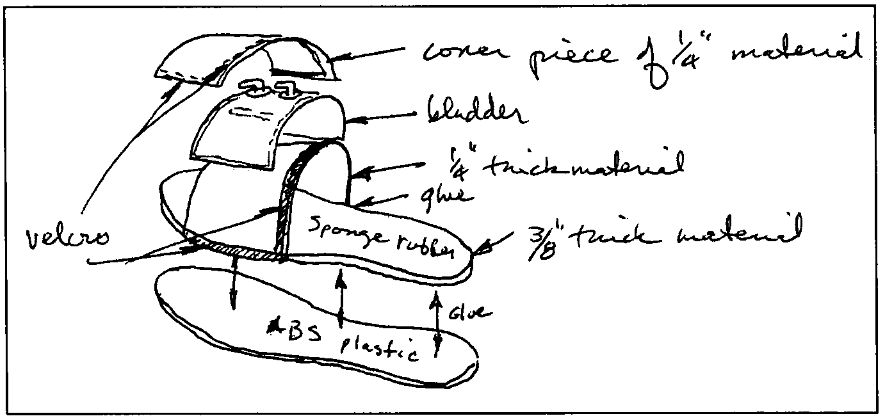

Figure 12. The "beach sandal" design, which proved to be in the direction of the final result

ethylene foam fabricator had previously been contacted with respect to producing padded components for other areas of both machines. It was felt additional pieces directed to this manufacturer would give better overall price negotiating advantage. Another problem was that the bladder tended to displace the foam strap equally outward away from the foot as well as inward toward the foot. It was obvious the efficiency of the bladder could be improved by limiting this displacement to the inward direction. Various methods of doing this were discussed with the team and experimented with by the author. The first attempt used a plastic scrim, a material which is best described as a screen with large spacing between the adjacent filaments, similar to common window screen, but of plastic and with large holes. This material was heat bonded to a piece of the polyethylene foam and used as an outer support. The attempt was less than satisfactory as the available material was more rigid than necessary and presented additional difficulties in having it encapsulated within layers of foam. This overall design also had no provision for a heelpiece for ski usage or forward locator for bike usage.

The sponge rubber sandal design was improved by moving the bladder inlet and outlet away from the top center of the strap to positions at either end and reshaping the bladder to best gain advantage of the sandal design. A new footpiece was made up using polyethylene foam to best simulate what might be expected from the commercial fabricator. Two layers of 2 lb density, 1/8-inch thick foam were used to construct a strap enclosing the redesigned bladder, and a single piece of 1/2-inch thick 4 lb density foam was used to make the base (figure 13). The bladder was covered with a sheet of nylon fabric cut to the proper shape in order to give the strap the structural properties lacking in the previous design. The nylon also served to prevent the bladder from expanding outward away from the foot, as the nylon layer extended beyond the bladder into the area of attachment of the strap to the base. This allowed the bladder to expand into the unrestricted space above and toward the foot, but prevented it from expanding outward away from the foot. Identical straps and bases were

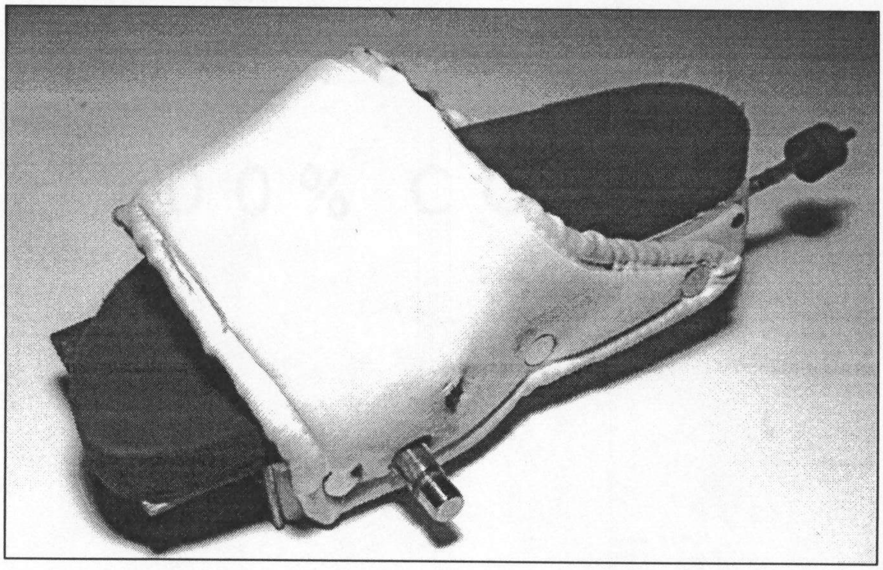

Figure 13. Foam strap sandal with nylon bladder insert and snap attachment

made for both the bike and the ski to keep the overall design and development process moving in parallel. Polyethylene foam is not readily bonded by most adhesives, so an edge trim of nylon bias tape was sewn completely around the strap edge for appearance and binding of the edge. Bonding of this foam is done by the commercial fabricator using heat provided by an oven to partially melt the layers of foam together. The process is carried out within a mold made to the desired finished shape into which the necessary layers of foam are placed, then the whole is placed into an oven at approximately 600° F. The process is controlled so that the foam itself never goes much above 250° F. This strap was attached to the ski platform and to the bike pump housing with common metal clothing snaps.

This design worked very well and was considered to be acceptable in feel and function, though not in appearance or ease of production. The owners additionally did not want to use any type of metal snap, even stainless, as their previous experience with these fasteners had been unfavorable. Their experience had been that this type of fastener tends to tear away from the fabric it is attached to, and also tends to lock up with time, preventing easy disassembly. Some research into the area of bonding polyethylene foam was done by the author and an effective adhesive was located which would provide a flexible bond, remain strong when submerged, and give a bond as strong as or stronger than the foam itself. This adhesive (Eclectic Products E-6000)[3] [2] did indeed work very well, and was used successfully on the final design prior to release to commercial manufacture.

[3] Manufacturer's advertisement for this material can be found on page 54 of the appendix.

7 Final Successful Design

The final successful strap design consisted of a shape-optimized bladder (figure 14), with inlet and outlet ports moved rearward as far as possible, inserted into an adhesively bonded foam sleeve constructed of an outer layer of 1/8-inch thick 4 lb density polyethylene foam and an inner layer of 1/4-inch thick 2 lb density polyethylene foam. The bladder was constructed such that the material of the bladder itself, being nylon, provided the necessary tensile strength to prevent the foam pocket from tearing when force was exerted on it by the user. This was achieved by designing the bladder with extensions on either end through which a 1/4-inch diameter PVC rod could be inserted for retention of the bladder. This bladder was also chambered to prevent the previously encountered kinking of a single large chamber on filling. This allowed the bladder also to conform better to the shape of the user's foot, as the bladder chamber separations were designed to allow the bladder to flex without

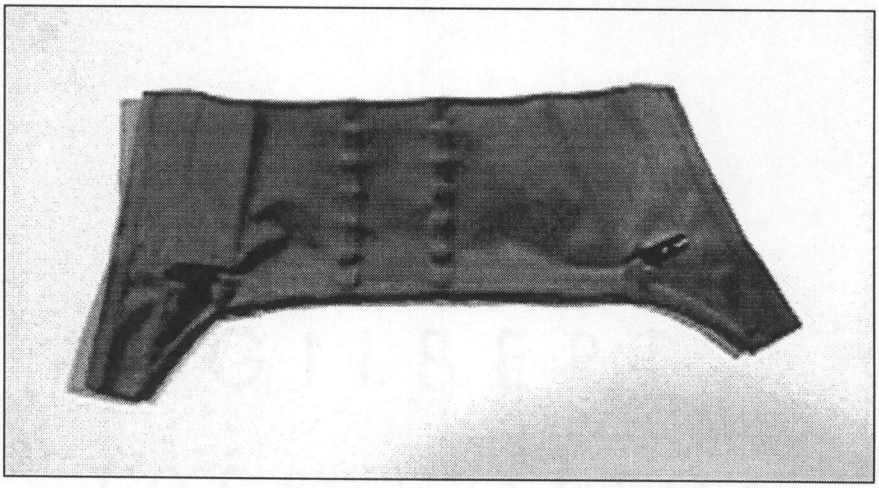

Figure 14. The final bladder shape, in 70-denier nylon, deflated

kinking at natural points of bending around a user's foot (figure 15).The retention rod with bladder attached was inserted into a slot formed parallel to the axis of the rigid base of the sandal support. This slot had a hole large enough for the rod and bladder to pass through, but its open upper side was made smaller than the diameter of the rod so that the rod could not pull out of the slot in a direction perpendicular to that of its insertion; i.e., a keyhole (figure 16).

An industrial designer was utilized to achieve a professional look to the overall piece, and the final result was very appealing and functioned as designed (figures 17 & 18). An insert of approximately 1/2-inch thick molded foam was used as the lower part of the sandal, with a heel support piece molded in for the ski machine and a toe locator piece molded in for the bike. These molded pieces were simulated on the prototype by machining them on a CNC mill from a rigid foam used for prototyping purposes. The edges of the slot for the

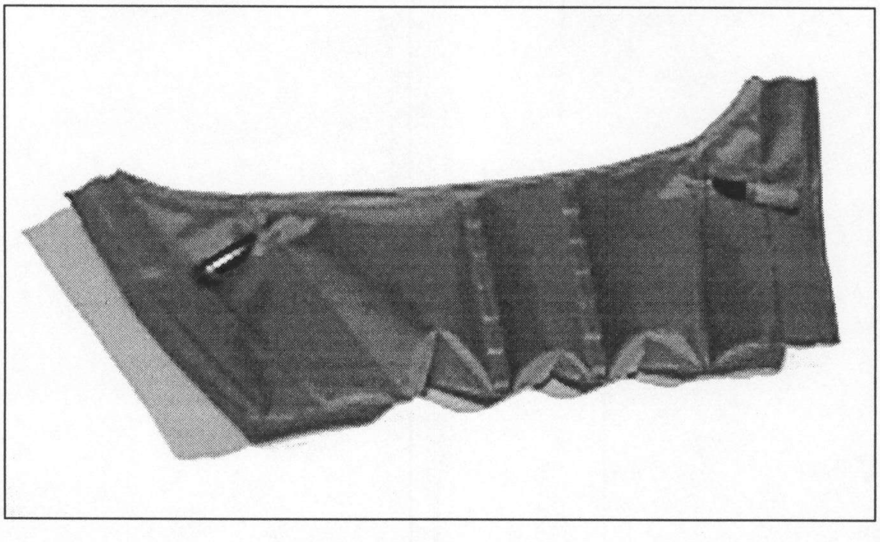

Figure 15. The final bladder, inflated. Note individual chambers connected by cross-flow channels.

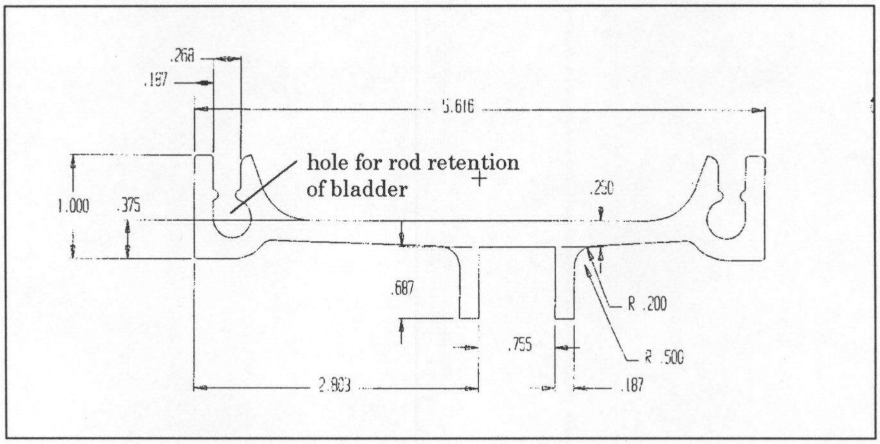

Figure 16. Cross-section view of the sandal base showing the formed slot for the upper strap attachment

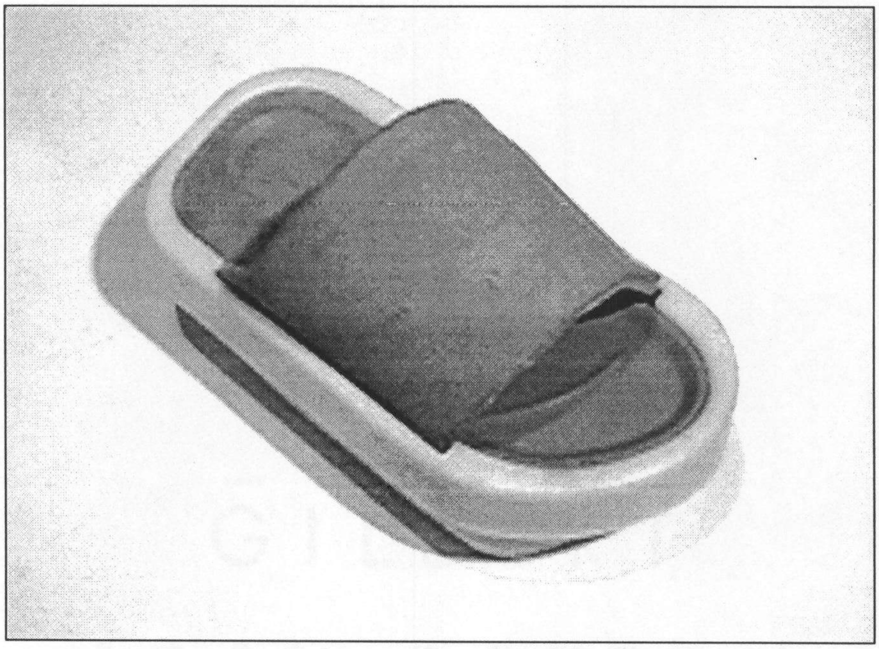

Figure 17. The final footpiece prototype. Note toe locator strip near front and trim piece around perimeter of footpiece, which hides all connections.

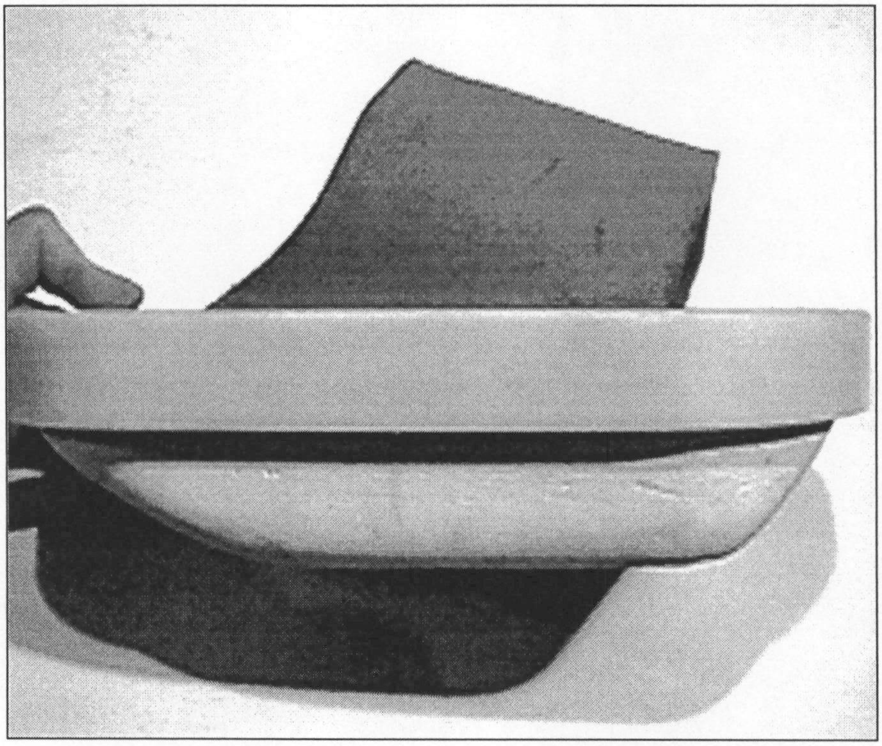

Figure 18. Side view of final design. bottom section is a trim piece to hide internal elements.

bladder attachment rod were trimmed by covering the entire outer edge with a piece of ABS plastic machined to simulate a vacuum-formed part for this purpose.

The simplicity of this design lends itself to cost-effective commercial manufacture and will almost certainly be more robust for the same reason. The tubing attachments to the bladder were chosen to be push-on connectors[4] for ease of assembly. While these connectors are more expensive than others, it was felt by the author that the labor savings of using these as opposed to cheaper threaded fittings would more than offset their additional cost. Further analysis may prove this not to be the case, but as far as ease of assembly is concerned they

[4] Manufacturer's information on these connectors can be found on page 55 of the appendix.

are very efficient.

The greatest difficulties encountered in the transition from earlier designs were the problems of how to enclose the bladder in an attractive covering of some type, how to fasten the bladder and/or covering to the base of the footpiece, how to provide for filling and purging the bladder with hidden lines, how to trim the edges of mating pieces and how to make the whole piece strong, comfortable and adjustable. An attempt was made to have the foam fabricator mold the bladder and covering in one operation, but this failed due to melting of the bladder inner surfaces to one another. The fabricator suggested using a removable insert to mold the bladder enclosure as one piece, into which the bladder would then be inserted, relieving it from the necessity of being exposed to high oven temperatures. The same problem of melting was also encountered when attempting to have the PVC rods molded in. Several iterations of strap retention were explored prior to the final choice. The dilemma was how to make the assembly process feasible and inexpensive. This required simple solutions, with a minimum number of both parts and assembly steps. The entire process of this final design took approximately one year, though work was on a part-time basis. Since much thought was involved in the design process as well as actual construction, it is questionable whether this process could have been speeded up considerably by a full-time effort. The generation of ideas and their natural iterative improvement with regard to a given design often takes more time than the actual construction, as this thinking process simply takes time to incubate.

Additional plumbing issues for the ski machine will be discussed in the following chapter.

The plumbing for the bike simulator was relatively simple, since the sandal was attached directly to the pump itself. Figure 19 shows an exploded view of the final combined sandal and pump design for this machine.

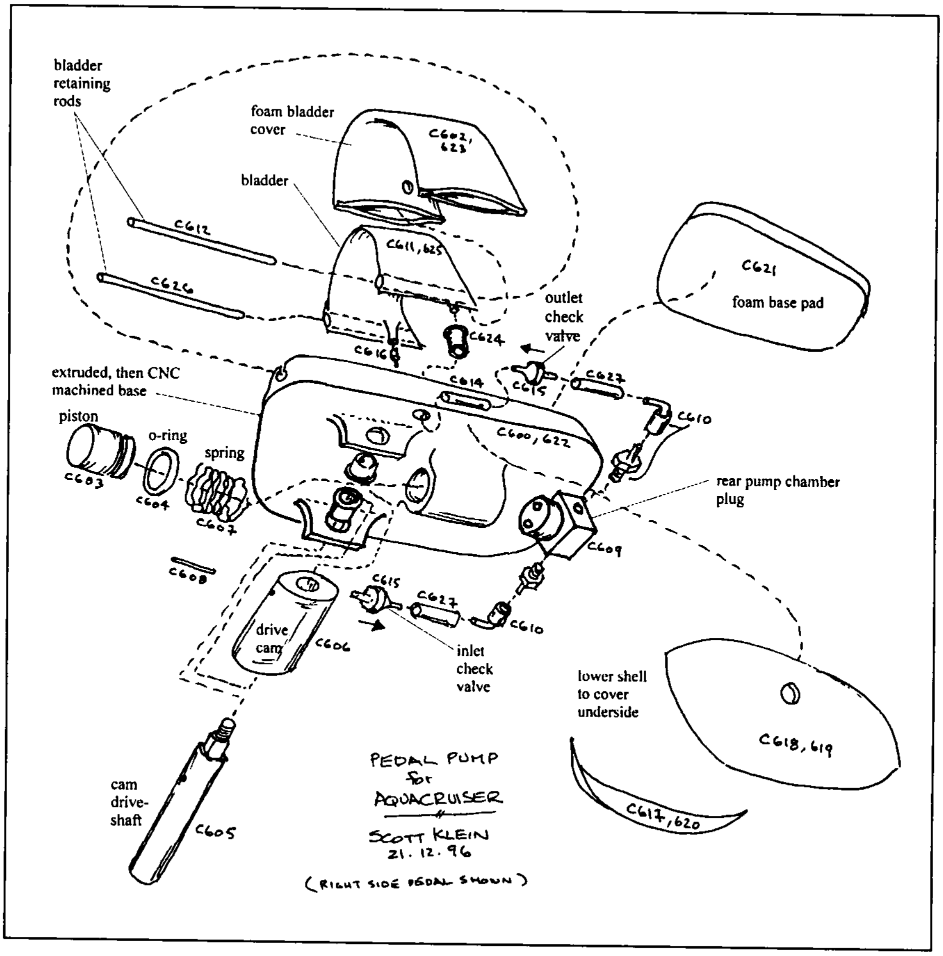

Figure 19. Exploded view of parts and assembly for the final bike pump sandal

Chapter 3

Development of a Functional Resistance Mechanism for the "Ski" Machine

1 Plumbing Considerations

The original concept of operation for the ski machine provided for a simple piston pump operated by the back-and-forth leg action of the user. It was intended to use commercially available and inexpensive common PVC water pipe for all plumbing. The first execution of this design involved using a specially-designed valve to both direct the flow of water and provide a variable resistance to the user's efforts. This valve incorporated an o-ring which was forced to slide on a machined slot, a condition determined to be detrimental to the life of the o-ring. There were also problems sealing the valve portion and easily manipulating the valve position. This was the point the author became involved with the project, and together with the other team members, it was decided to see if it might be possible to provide the functions of flow direction control and flow restriction control using commercially available plumbing pieces. A flow schematic was drawn and parts purchased to accomplish this using one-way check valves for directional control and a ball valve for flow restriction. The piping was all sized to 1-1/2 inch diameter I.D. The action of the system was provided by a piston rod of PVC pipe, with a piston head made from an end cap and machined for proper fit within the outer cylinder (1-1/2 inch I.D.). The piston head was also grooved to accommodate a rubber o-ring. The opposite end of the piston rod was attached to the user footpiece and moved as the user took strides forward and backward to simulate the skiing exercise. This system was plumbed on the first prototype and tested in the university pool. No plumbing to the sandal bladders (or even the bladders themselves) was in place at this time. This system worked reasonably well in that it provided the necessary resistance and was controllable by the valve. The check valves[5] were connected and oriented such that the flow of water was directed from one cylinder into the other, and then back again, as the user operated the machine. The ball valve was placed in this flow to restrict the entire flow both forward and backward (the final plumbing layout is shown in figure 20, and does not differ significantly from the initial effort).

2 Flow Control Problems

The main problems plaguing the development were non-linearity of the ball valve operation, fit of the pistons to the cylinders and check valve operation. It should also be noted here that much of the testing was of a subjective nature regarding feel of the operation of the machine to the user; no instruments were connected to the machine. As it turned out later when some pressure measurements were taken, the back-and-forth operation of the machine and inability of a user to provide a continuous motion prevented the taking of any particularly useful machine data (data was successfully recorded regarding the user's heartrate and O_2 consumption). The problem of the ball valve non-linearity was addressed by researching the existing literature regarding hydraulic valve operation, and yielded through further discussion with valve vendors the fact that there are almost no inexpensive solutions to the

[5] Information on the final specified check valves can be found in the appendix on pages 56 and 57.

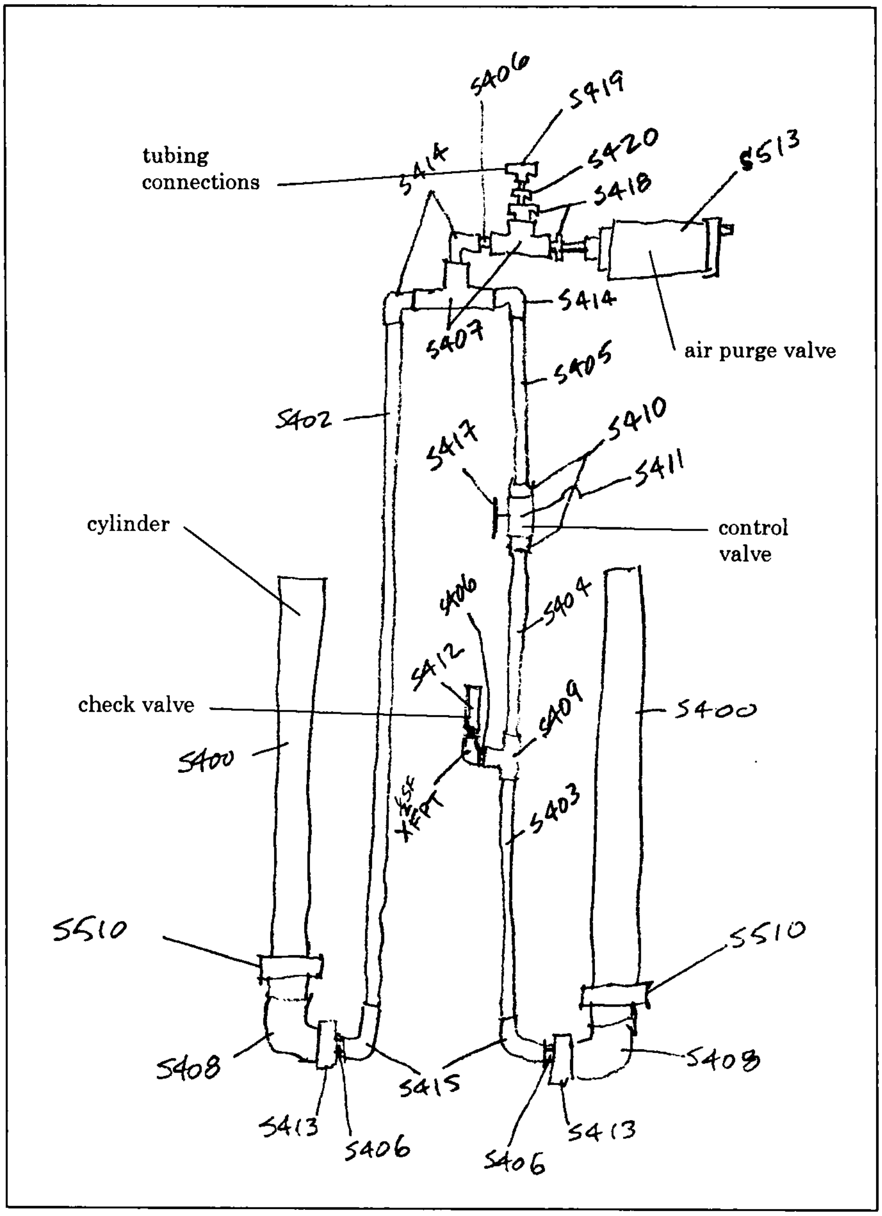

Figure 20. Schematic of the ski machine plumbing layout. This does not show the pistons, which operate within the cylinders.

problem. Plastic globe and other ball valves were tried, as well as a needle valve, but all were either too flow restrictive, expensive or non-linear in operation. A solution was finally found in the use of a brass butterfly valve which, though non-linear, provided a large enough linear range of operation through partial use of its total range. This amounted to using approximately half of the valve's possible range of operation. The non-linearity of the control valve's operation presented a problem in that it prevented the design of a simple means for the user to easily move from one resistance setting to other incremental settings which would provide a linear response to the user's exercise efforts.

3 Pump Difficulties

The problem of feel was mainly one of properly locating and orienting the check valves and correcting o-ring sizing problems. The number of check valves was reduced from a beginning count of three to only one in the final design. The purpose of these was to provide for filling of the system and flow between the cylinders; it was determined through experimentation that only one valve was necessary to fill the system, and this due to the fact that this was a closed system. The piping size was reduced as the design developed and the final design used 3/4-inch schedule 40 PVC as the pump cylinder, with the piston rods being 3/8-inch schedule 80 PVC. The piston rod diameter turned out to be the restricting factor in this size reduction, as this piece is a long thin cylinder which is subject to buckling under the stresses of operation. This problem was never actually encountered, but was anticipated and corrected by inserting a solid rod of 6061-T6 aluminum into the open center of this piece as a preventive measure. Earlier pistons had o-rings which fit too tightly to the cylinders and caused excessive friction and wear of the ring. Even though o-ring manufacturer's guidelines for the sizing and choice of materials for this application[6] [3] had been followed, the tolerance variance in the PVC pipe I.D. caused sizing problems. This inconsistency of diametral tolerance exists between individual pieces of PVC pipe, whether from the same or different manufacturers[7] [4]. It was decided that there was no cost-effective way to easily overcome this problem, and the best solution would be to inspect the pipe prior to purchase and measure it for acceptable tolerance. It was also discussed that this could be accomplished by requiring the pipe vendor to pre-select shipments; this was verified with a local vendor as a possibility. Another possible problem with the use of this pipe in this application (for which it was never intended) is that of the existing waviness and roughness of the interior walls of the cylinders causing excessive wear of the o-rings. As of the date of publication of this thesis this has not been determined, but life testing of the entire machines is scheduled.

4 Connection of the Pumps to the Sandal Bladders

On the ski machine, since the sandal bladders were moving relative to the pumps, a condition which did not exist for the bike, it was necessary to design and develop a means to provide a flexible connection of some type which would allow this movement. The author's first attempt was a "Rube Goldberg" type apparatus which externally suspended pulleys from the machine's upper frame by a length of wire. Flexible tubing was directed around these pulleys and the pulley motion controlled by springs also attached to the machine frame.

[6] These specifications can be found on pages 58, 59 & 60 of the appendix.
[7] Standard specifications for PVC pipe can be found on page 61 of the appendix.

This whole apparatus was intended only as a means of testing the hookup on this machine. Surprisingly, this setup worked well (figure 21).

The author then undertook to see if the design could be reduced in size and positioned so as to fit within the confines of the aluminum ski rail extrusion which also contained the pumps and "skate" mechanism. This "skate" was so-called for its resemblance to a common roller skate. As a functional description, this skate was attached to the piston rod which by motion of the user's foot developed pressure within the pump cylinders which were stationary. The challenge was to somehow direct the pressure and flow of a portion of the water within the stationary pumps into the moving bladders of the sandals attached to the skates and pistons. This was done successfully by using a length of commercial cable carrier[8] [5]. This product is segmented and pivoted at either end of each segment so as to allow it to change direction within a small radius while maintaining its motion within a plane. Larger versions of this type of cable carrier are used extensively in industry for this type of application, mostly to carry electrical cables between moving and stationary portions of a piece of machinery. In our application a section of 1/4-inch diameter tubing was threaded through the cable carrier to connect the pump cylinder to the bladder. One side of the machine also carried an electrical cable to connect a Hall effect sensor attached to the skate for speed and motion sensing. This solution was very successful, and worked flawlessly, but was an expensive solution due to the cost of the cable carrier. Due to the many other items under development, and their greater priorities, no further work was

[8] The cable carrier manufacturer's information for the carrier used can be found on pages 62 and 63 of the appendix.

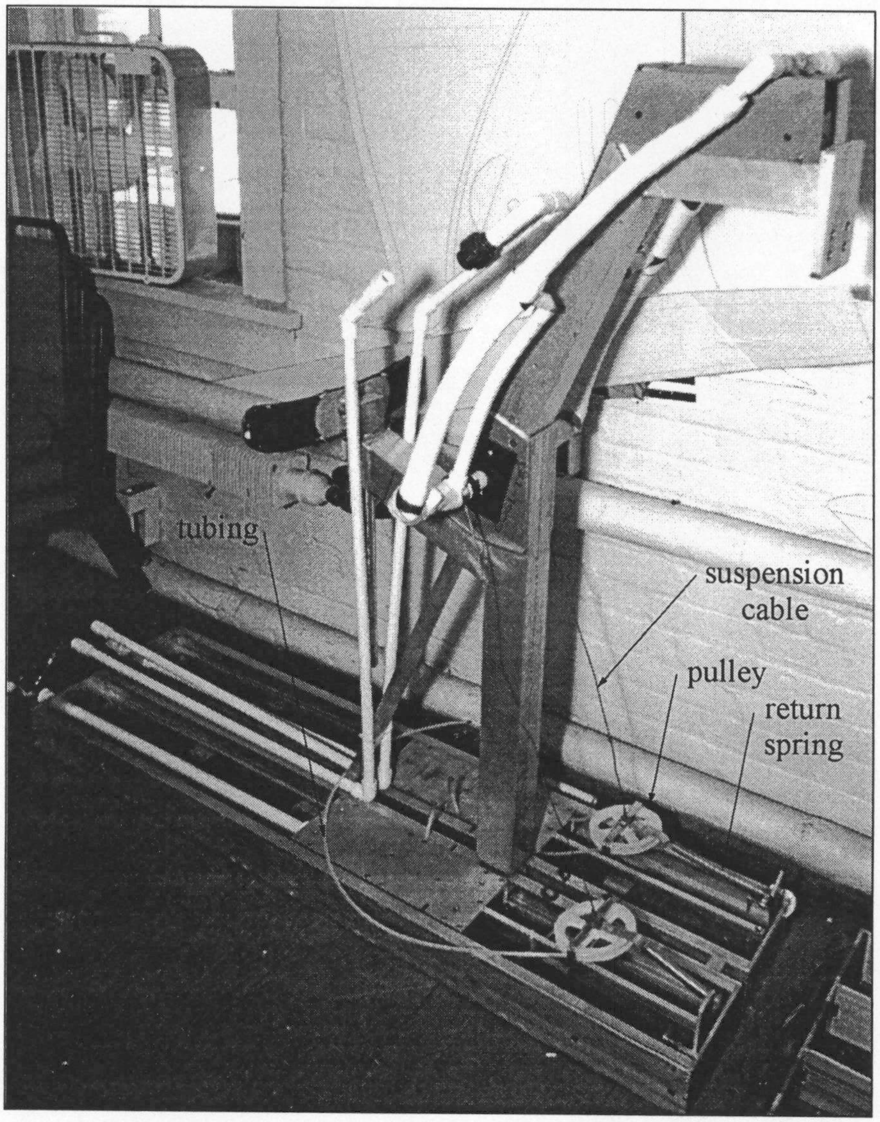

Figure 21. The first functional ski machine prototype. This machine had been partially disassembled when this photo was taken, but the pulleys and cables described in the text can be clearly seen.

done on this design during the author's involvement. The author did design what he considers to be a more elegant solution, however, after leaving the project. This was passed on to the other team members on his departure.

The newer design involves the use of brass or copper pipe as piston rods, rather than the PVC presently in use. A small hole would be drilled in the head of the piston to allow the pressure within the cylinder to enter the hollow piston rod. The opposite end of this hollow rod would be inserted into a solid aluminum block drilled for passage of the fluid to the moving portion of the skate (the piston rod is also of course moving, since it is attached to the skate). A drilled and tapped hole in the aluminum block would allow the flow to exit into a short section of tubing attached to the bladder. This design would completely eliminate the cable carrier, most of the present tubing, several tubing connectors (which are also expensive), and the present section of 6061-T6 aluminum rod used as buckling prevention within the PVC piston rod. The author has not at this time conducted an exhaustive analysis of this design, but firmly believes it would provide a successful cost-effective solution. Figure 22 shows the portion of the improved design which would be attached to the skate body.

The electrical connection for the Hall effect sensor could be altered such that the wire does not move at all by mounting the sensor to the extruded rail which encloses the skate assembly. Several magnets would then be mounted at the appropriate positions along the skate body to trigger the sensor as they passed by. This would not require a large number of magnets, since the present system allows for a full rotation of the skate wheel between

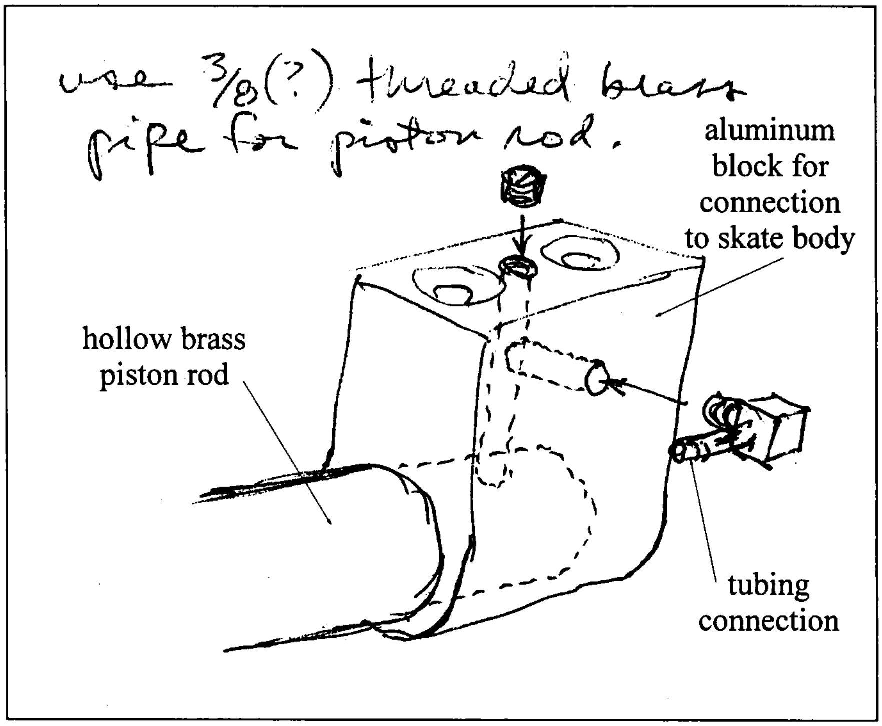

Figure 22. The proposed simplification of the fluid connection between the stationary pump cylinders and the moving sandal bladders

triggering events, and this would translate into about five of six magnets in the new layout. Since these magnets are relatively inexpensive, the author believes this would be a cost-effective solution.

5 "Skate" Wheel Development

The wheels of the moving chassis of the pump piston carrier were originally designed of solid acetal polymer, drilled through their centers, and attached to the chassis by individual socket head machine screws. There were six of these which ran in a restricted channel constructed of strips of 6061-T6 aluminum held to the outer frame by screws. This design worked well except for a tendency of the screws attaching the wheels to become loosened and bind against the frame during testing. This was also a very expensive method of construction and assembly. Dr. Frank Speckhart reasoned that the entire portion of the frame rail assembly surrounding the moving chassis might be better and more economically constructed as a single extruded piece. This was investigated and was indeed more economical, and a design was developed with other team members to accomplish this improvement. At the same time, the author, working with Dr. Speckhart, questioned whether the skate assembly could not also be significantly improved. The author designed a wheel and axle assembly which worked in concert with the aluminum extrusion and significantly reduced the number of parts and cost of this portion of the machine. The wheels were designed as a simple solid piece cut from a section of acetal rod of the correct diameter, then drilled concentrically to accept an axle and the outer edges beveled slightly. These fit onto a cylinder (axle) of PVC rod inserted through the skate body, which the author designed as a section of 6061-T6 aluminum stock channel. These pieces were sized such that with the clearances minimized, the wheels and axles were held captive between the aluminum channel skate body and the outer aluminum extruded piece. This eliminated the need for any further method of retention of the axles or wheels and significantly facilitated assembly of the parts. (Figure 23). In a further attempt at cost reduction, the author changed the specification of the wheel material from acetal to PVC. Since the axles were already PVC and the strength of the materials were similar, this was not thought to be a big step, but one which would provide good cost savings. An unanticipated problem arose, however, when this change was implemented and tested: the PVC wheels exhibited much greater friction

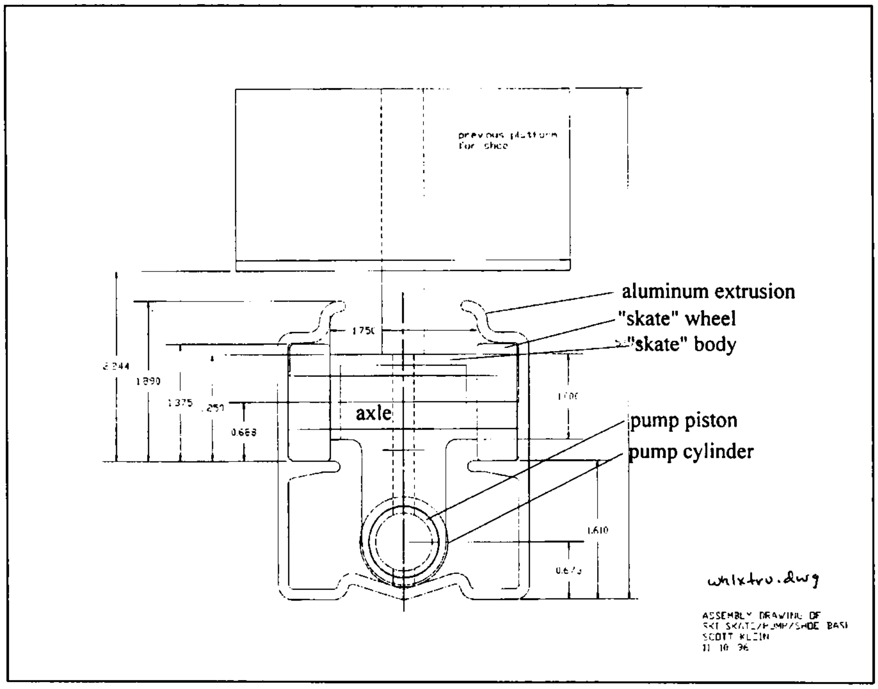

Figure 23. Cross-sectional view of the "skate", the enclosing extrusion, the pump cylinder and piston

between the walls of the aluminum extrusion than the previous acetal ones and this resulted in greater user effort and machine noise. This was an unanticipated problem because the clearance between the wheels and the outer extrusion was only on the order of 0.010-0.020 inch, and it was not anticipated that the wheels would be able to develop enough side friction to cause a problem. There was no difference in the rolling action of the wheels as long as no side force on the chassis was present, but when the user pushed to either side there was much greater friction and noise than that evident with the acetal wheels.

The previously mentioned sensor was used to detect motion of the skate chassis.This signal was converted electronically into information about the machine's speed and subsequently the user's effort, when combined with information about the valve position. The electronic pickup was accomplished by mounting a 1/8-inch diameter by 1/4-inch length magnet parallel to the skate wheel's axle, in a single wheel, and sensing the magnet's passage as the wheel rolled by means of the Hall effect sensor mentioned. This gave the number of rotations of the wheel, and combined with a time measurement and the wheel dimensions, the carriage speed. This support was provided by Mark Holdoway, a recently graduated electrical engineer hired for this purpose.

Chapter 4

Development of a Resistance Mechanism for the "Bike"

1 Pump Design

The "bicycle" resistance mechanism consisted of a turbine revolved by the pedaling action of the user. This was a radial turbine, with essentially flat outer sides and radial vanes which pumped water in through openings on either side of the turbine near its central hub and out via the radial vanes to exit at the turbine radial periphery. The flow control consisted of a double acting valve mounted on the same shaft as the turbine, which slid open and closed to allow or prevent flow through the openings in the turbine faces. These parts were designed by Dr. Frank Speckhart, and the author became involved at the point of initial mounting and testing of them. This turbine was successful from the beginning and remained essentially unchanged; there were minor adjustments in the design to increase the width and diameter, and the overall design was optimized for production by reducing the wall and vane thickness of the turbine. The turbine was intended from the outset to be a vacuum-formed part if this proved feasible. This was successful and the design was further optimized by vacuum-forming each face of the turbine to incorporate the vanes in such a way that half the vanes were formed on each interposing face of the turbine. This allowed for a reduction in the number of parts and facilitated the production and assembly of the turbine by making each face of the turbine identical, thus reducing this portion from two parts (identical faces, vanes) to one (single face with incorporated vane). The action of the turbine was very smooth, and allowed for increased resistance (and exerted effort on the user's part) by incremental opening of the turbine valve to increase pump flow (since greater flow required greater shaft torque).

2 Control of the Turbine Valve

The valve actuator was designed by the author with Dr. Speckhart, and consisted of a yoke which engaged a grooved collar attached to the valve itself. This yoke was pivoted on a mounting bracket attached to the machine frame and designed to allow actuation perpendicular to the motion of the valve. The action of the valve was parallel to the turbine shaft but any controls would be mounted higher on the machine and space constrictions around the turbine prevented actuation parallel to the shaft. This yoke design was successful from the outset and was not changed except for material of construction and minor point-of-actuation accommodations (figure 24). The initial material for the yoke was ABS plastic, which performed successfully, but due to concerns on the author's part about the long-term durability of the part and possible overstressing, this was changed to aluminum. Several different methods of moving the yoke were tried before a final solution was determined. The first attempt was at actuation by use of a length of plastic tubing; due to stretch of this material and movement of the entire piece of tubing perpendicular to its direction of engagement, this attempt could not provide a positive, repeatable solution and was abandoned. The possibility of using a cable to move the yoke was discussed, but due to inexperience and lack of knowledge in this area on the author's and others parts, this was not tried at this time. The first successful controller used steel rods with model airplane

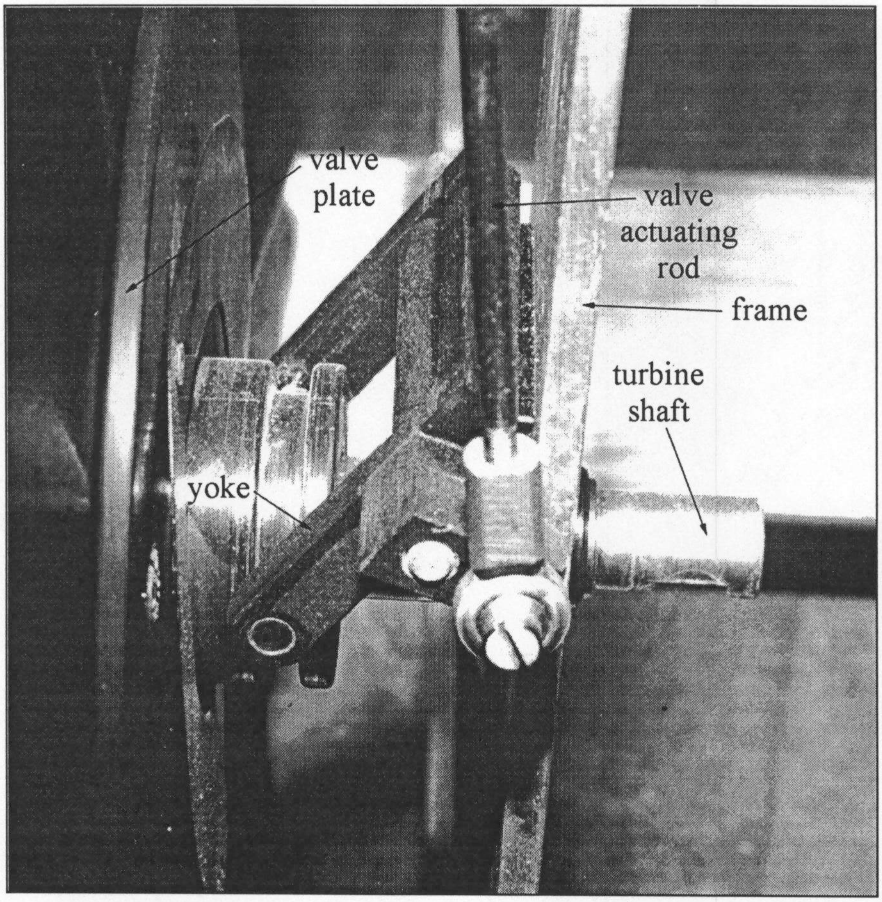

Figure 24. The bike valve control mechanism. Motion of the vertical rod moves the valve horizontally in or out.

rod ends as connectors to move the actuation point from the yoke itself to a point above the water line where the control could be engaged by the user. These rod ends were plastic and lacked sufficient strength to perform long-term, but did prove this method as feasible. The next step was to procure some commercial stainless steel rod ends and use stainless steel rod to connect them to a newly-designed ball-detent lever. This was the first control to allow the team to make relatively fine differentiations in the valve movement in order to provide information about possible desired settings for the final valve positions. This control lever, shown in figure 25, was relatively crude and was never intended as a final solution; it did prove useful as a testing piece, though. In an attempt to satisfy the company's owners, the next control design used a rotary knob to move the yoke. This was designed by the author and used a spring-loaded mechanism to force the knob into detent positions which were predetermined by dividing a roughly 90° designed range of motion into five positions. This design worked well but was unsatisfactory in appearance and feel to the owners. The ski machine had been developed also by this time to a point where it was feasible to develop identical controllers for both machines; this was done beginning with this

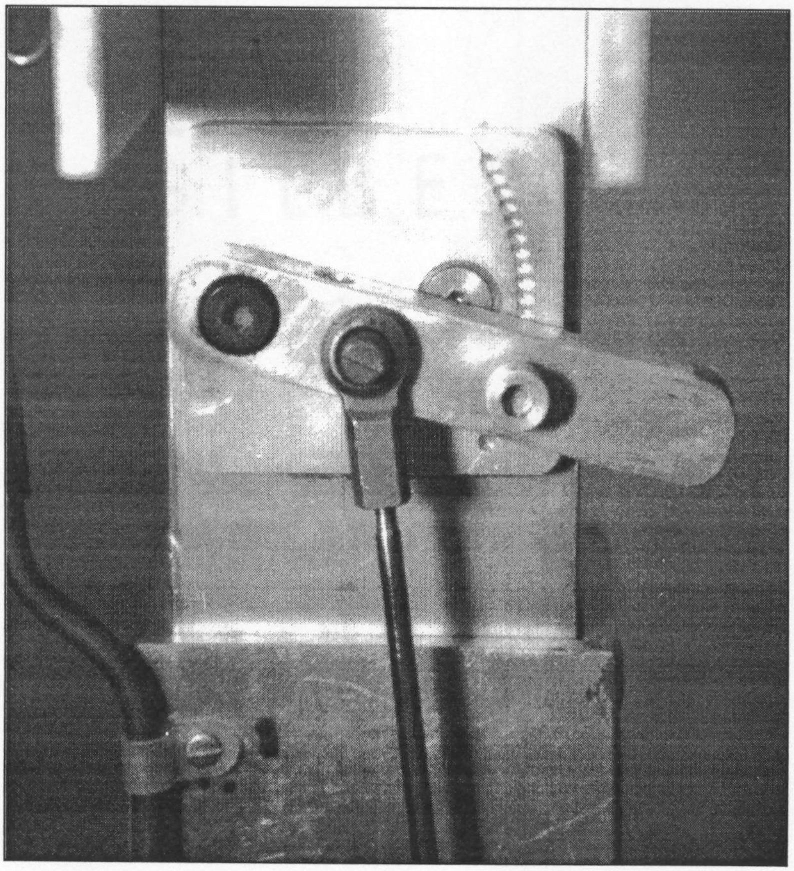

Figure 25. The first operational valve control for the bike

rotary knob control. The appearance of these knob controllers was good, but was not what was sought (figure 26).

At this point the owners decided to use a lever control similar to that used in aircraft. Dr. Speckhart thought this was a good time to try using cable actuation also, since the stainless ball ends were very expensive, and there was other machining being undertaken in the production of parts to provide the desired range of motion of the valves on both machines.

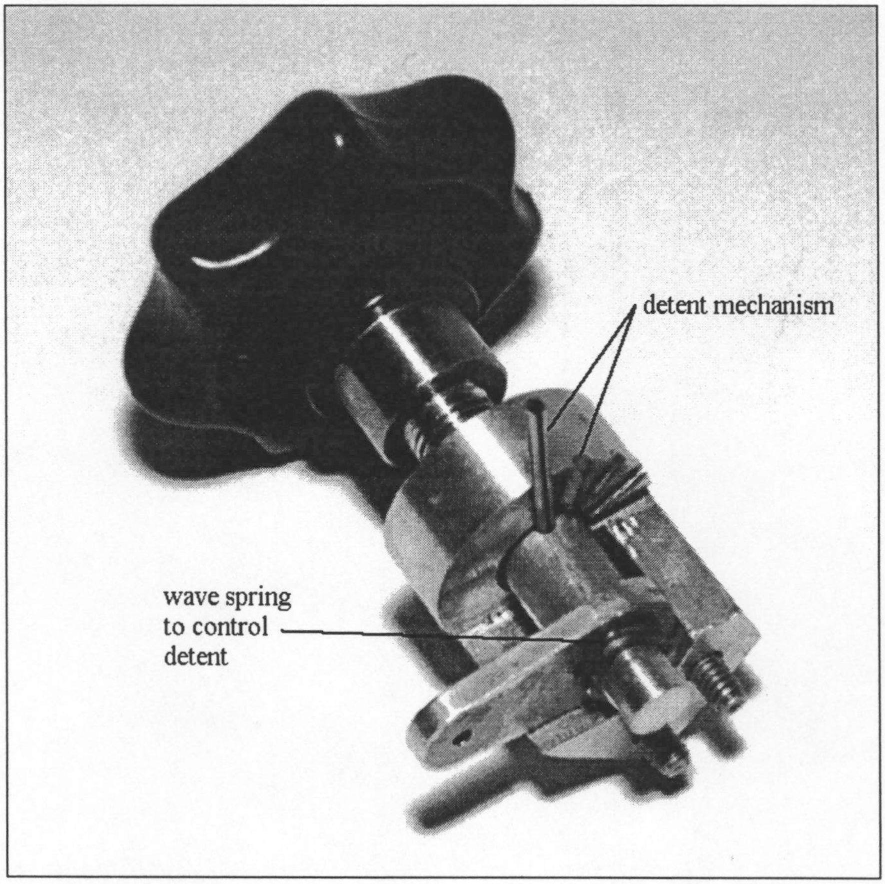

Figure 26. The knob-handled valve controller, used on both the bike and the ski

The cable controllers were designed by Dr. Speckhart and the availability and specifications of stainless mini cable was researched by the author. Such cable was determined to be readily available, and sample quantities were obtained. A small drum was designed by Dr. Speckhart as part of the controller and used to wrap the cable. The drum diameter was sized to provide the correct movement of the cable to give full range of motion to the valve. Resistance was provided to the control handle via Belleville washers mounted at the control pivot point. This prevented the cable from moving the control due the closing spring force of the valve (figure 27). These controllers worked well and provided continuous rather

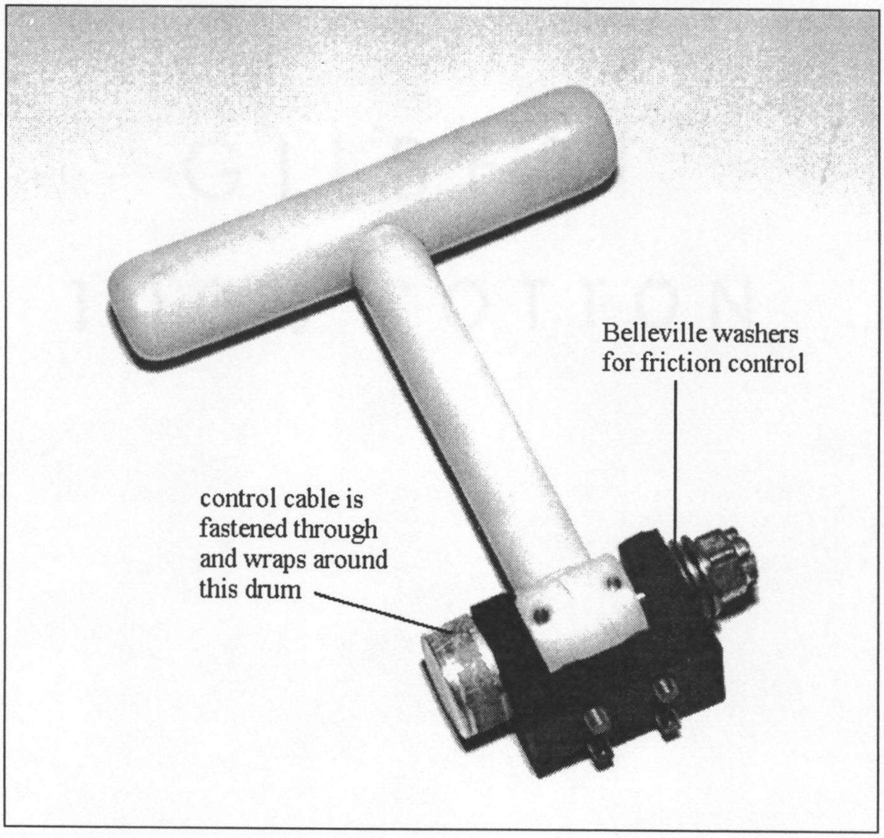

Figure 27. The T-handle aircraft-style control designed by Dr. Frank Speckhart

than incremental motion for actuation of the valve.

Here the owners again changed their minds and wanted to try a thumbwheel-type control. The author designed a control using a 2-inch knurled wheel for thumb or finger control, and using plastic gears to obtain a high mechanical advantage to compensate for the lack of leverage which had been available with the previous designs. Again, this controller worked well, with a slightly greater number of rotations than might be desirable, but still did not meet the nebulous desires of the company's owners (figure 28).

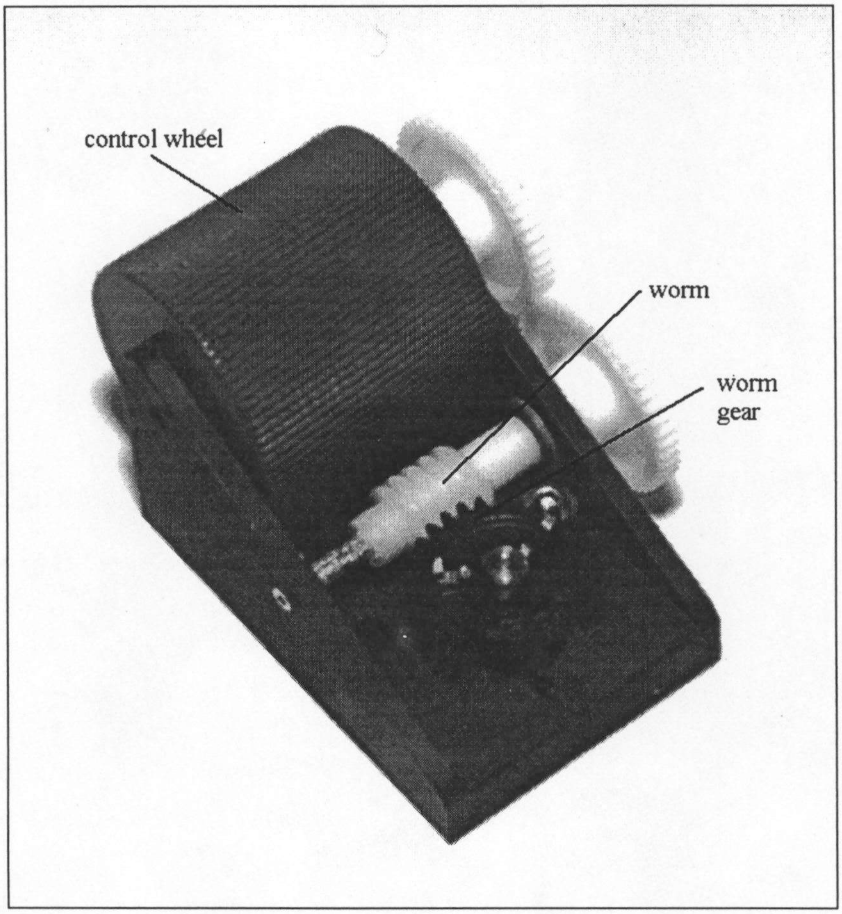

Figure 28. The thumbwheel controller for the valves on both machines

It had been discussed in the beginning whether it might be possible to use electronic control for the valves on both machines, but it was felt at the time to be a more expensive and less feasible solution. Little was known (by the team members) about the availability of required components which might survive the water environment. This option was reevaluated at this point and was believed to be the best overall solution now that more was known about the requirements and possibilities for mounting. It was even discussed whether a stepper motor could be obtained which might be mounted submerged, but this was felt to be too severe and unpredictable an environment, even though motors were available for washdown environments in chemical and food processing situations. It was decided to use a stepper motor with the previous cable and drum arrangement to move the valves on both machines. This would provide more options for future development and addition of possible enhancements to the machine's function. The stepper motor was attached to a worm reduction gearbox and the cable drum was attached to the output shaft of this same gearbox. A magnet was mounted in the side face of the drum, and the drum sized for less than one revolution, in order to provide actuation of a Hall effect sensor mounted to a small circuit board attached to the same side of the gearbox.

Chapter 5

Conclusions

The author is very grateful to have been a participant in this project, and feels it provided him with the best possible experience in his field of interest, that of machine design. The very fact that the owners of this company were unsure of exactly what they wanted, combined with the natural progression of successive design iterations, provided a real-world design experience unlikely to be duplicated by an academic-only project. The continual changes, the off-site location of the owners and the part-time nature of the team participants did serve to make the development of the final design a more protracted situation than might have been the case with a full-time, on-site, pre-determined goal scenario.

A number of additional design challenges were encountered and undertaken during the course of this project, and are not mentioned in this thesis. Among these were the design of a functional pool-edge mounting system for the machines, the design of a suitable means for inserting and extracting the machines from the pool, means of mounting the machine coverings to the frame, determination of a suitable hinge for the front cowling and storage area of both machines and selection of various fastener types and materials. The author was involved to varying degrees with other team members in each of these areas.

The author feels the concept and execution of these machines will be successful in the marketplace, provided sufficient testing is undertaken to ensure proper functioning of all parts of the machines for an extended period of time with different users. This is planned by the company's owners, but it appears to the author the project is being rushed to market before this work has been adequately performed. There are many areas of both machines which have only been fabricated and tested in single-unit prototype form, and those custom-made for correct function. Whether these machines can be mass-produced with unskilled labor and have the world-class look and feel the owners are seeking remains to be seen. The author feels both of these machines are good designs in that they are conceptually and functionally sound, have had their number of parts minimized as far as is reasonably possible and should be robust in that they should be able to be assembled under the conditions mentioned and maintain their function within a good tolerance range for the life of the machines.

References

References

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[5] *IGUS Energy Chain Systems Product Catalog*, IGUS, Inc., P.O. Box 14349, East Providence, RI 02914-0349

[6] *Thermoplastic Piping Systems Technical Manual*, R & G Sloane Manufacturing Company, Inc., 7660 N. Clubourn Avenue, Sun Valley, CA 91352

Appendix

Appendix

PVC

Polyvinyl Chloride

PVC has relatively high tensile strength and modulus of elasticity and therefore, is stronger and more rigid than most other thermoplastics. The maximum service temperature is 140°F for Type I. PVC has excellent chemical resistance to a wide range of corrosive fluids, but may be damaged by ketones, aromatics and some chlorinated hydrocarbons. It has proved an excellent material for process piping (liquids and slurries). water service and industrial and laboratory chemical waste drainage.

Advantages of Polyvinyl Chloride (PVC):

- High Chemical and Corrosion Resistance
- Lower Installation Cost
- Heavy Duty
- Maintenance Free Internal and External Surfaces
- Shorter Laying Length (Exclusive with GSR)

GSR Schedule 80 PVC Pipe and Fittings Feature...

Outstanding Chemical Resistance.

PVC thermoplastic is highly resistant to acids, alkalis, alcohols, and many other corrosive media. They are ideal for moderate temperature process piping installations and most service piping applications.

Lower Installed Cost.

Solvent cemented or threaded connections contribute to lower installed cost than carbon steel, steel alloy or other conventional materials. Handling during installation is greatly simplified, since PVC pipe and fittings weigh about *one-sixth* as much as steel.

Maintenance Free Service.

PVC will not rust, scale, pit or corrode on interior or exterior surfaces — nor is it subject to electrolysis. You are assured of many years of leak-free, maintenance-free service. For buried applcations, PVC is *not* affected by soil conditions. Painting is not required for indoor non-exposed installations For outdoor sunlight exposed installations, painting with two coats of white colored water base latex paint is recommended.

Non-Toxicity.

PVC thermoplastic and GSR pipe and fittings are listed with the National Sanitation Foundation (NSF) as suitable for use with potable water.

Versatility and Dependability.

PVC pipe and fittings have been found suitable for more than 75 percent of the process, service and drainage piping used by the process industries — as well as hundreds of other corrosive and non-corrosive applications.

The shorter laying lengths of GSR fittings are definite time and space savers when piping at close quarters.

To ensure a positive seal when assembled in the field, all female thread sockets are individually tapped at the factory. You can be sure that each and every connection will meet standard specifications and tolerances.

Less Expenditure of Energy.

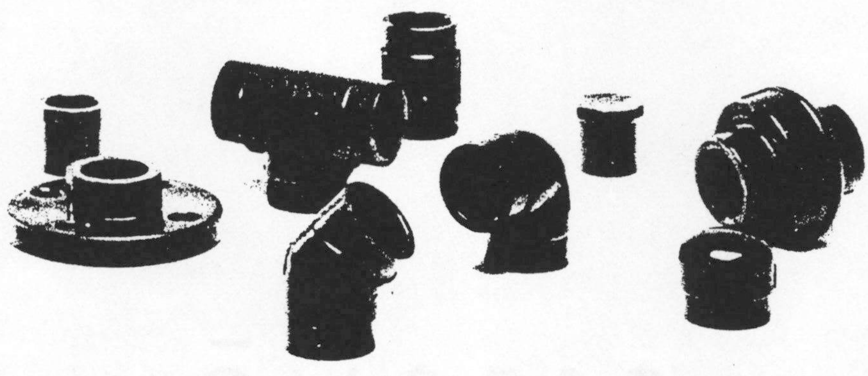
The manufacture of PVC thermoplastic requires *less than 50 percent* of the energy expended to produce carbon steel and steel alloys.

Higher Flow Rating.

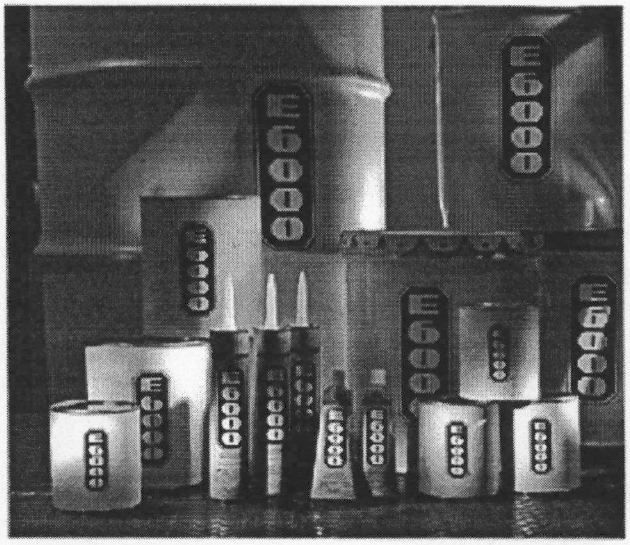
Smooth interior walls result in lower pressure loss and higher volume. (Hazen & Williams C factor = 150).

Usage.

PVC thermoplastics are used in Chemical and Food Processing, Industrial plants and Petrochemical Industries, Atomic Energy, Military, Naval and Civil Defense, Photo Engraving, Photo Labs, etc.



E-6000 comes in a handy container for any size job.



Technical Specifications

Colors: Clear, Black, White, Gray
Hardness: 75 to 85 Shore A
Elongation: 700%
Recovery at 300%: 95%
Temperature Range: –120˚F to 210˚F
Tensile Strength: 2,900 p.s.i.
Viscosity: Self Leveling
(various grades available)
Tack Free Time: 10 minutes (outer surface)
Cure time: 8 hours as a sealant – 24 hours as an adhesive at 70˚F. Curing time may be affected by temperature fluctuations. Material will cure faster at temperatures above 70˚F and will cure slower at temperatures below 70˚F.
Thinner And Cleaner: Eclesolv
Shelf Life (unopened tube): 5 years
Chemical Resistance: Excellent

Resistivity and Dielectric Properties

Surface Resistance: 3.7×10^9 ohms
Dielectric Constant Strength (ASTM D 149): 400 V/mil

Adhesion Data (Peel) (ASTM D 903)

Glass	34 p.l.i.
Aluminum	32 p.l.i.
Steel	34 p.l.i.
Concrete	26 p.l.i.
Fiberglass	34 p.l.i.
PVC	31 p.l.i.
Neoprene	32 p.l.i.
Pine Wood	32 p.l.i.
Brass	32 p.l.i.
Polycarbonate	30 p.l.i.

Note: Shear adhesion results on the above substrates range from 400 to 600 p.s.i.

E-6000 outperforms all other adhesives.

Peel Resistance of Cotton Tape Bonded To Various Substrates* (p.l.i.–Summary of Averages)

	Concrete	Glass	Wood	ABS	Lexan	PVC	Urethane
E-6000	**26.8**	**33.7**	**32.2**	**31.4**	**35.8**	**30.9**	**43.8**
Devcon Cement	2.0	1.0	5.4	15.1	2.3	0.4	13.2
Dow Silicone	15.3	13.6	9.8	9.9	13.4	2.0	11.7
Duro Cement	4.5	0.2	2.2	22.3	5.8	15.4	21.9
GE Silicone	3.8	13.3	3.2	1.4	0.2	0.4	2.6
Permatex	3.3	0.2	0.9	7.8	8.3	11.2	21.4
3M	6.8	17.7	20.5	17.9	15.7	15.0	11.0

*Test conducted by United States Testing Company, Inc.

AMAZING GOOD ADHESIVES®

Manufactured by Eclectic Products Inc.
P.O. Box 4566, Carson, CA 90749-4566
Phone 1-800-767-4667

93102E610

LF 3000 Instant Fitting System

Time Savings:
- Tube fitting time is substantially reduced. Assembly time savings are, on an average, 75% of conventional compression fittings.
- All check tightening time is eliminated. The LF 3000 Instant Fitting System provides a 100% lock and seal the first time.
- No assembly tools or skills are needed.
- Fittings are easy to assemble and disassemble.

Reusability:
- The LF 3000 can be used dozens of times.

Full Flow:
- LEGRIS fittings require no support ferrules or I.D. tube supports. (DOT Fittings an exception)
- Compare the orifice in any of our fittings. We have a larger unrestricted passage as we use the full I.D. of tubing. There are no system worries about the C_v factors.
- 5/32" LF 3000 has the same flow as 1/4" conventional fitting-savings on space and tube size.

Swivel Feature:
- All male elbows and tees can be swiveled 360° on an 'O' ring seal allowing closer assembly. This feature is a great time saver in areas of poor accessibility and allows proper orientation of the fitting.

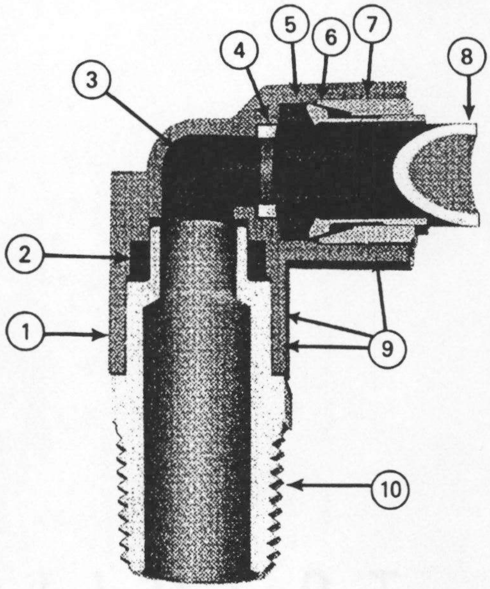
Tubing Requirements:
The LF 3000 Instant Fitting accepts many types of plastic tubing including nylon, polyethylene, teflon, etc.

Working Temperature:
- Sub zero F to +160°F.

Working Pressure:
- Vacuum to 250 PSI at working temperatures.

Materials:
- Fitting Body –
  Brass - Free Machining Type
  Plastic - Acetal Copolymer and/or Nylon 6.6
- Cartridge Parts –
  Free Machining Brass
- O-Ring –
  Buna N-Nitrile

LF 3000 Advantages

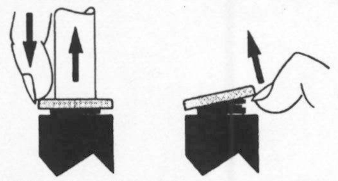


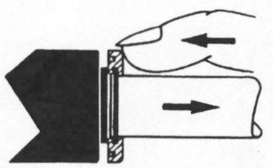
Covered by Patent No. 3653689

1) Acetal Copolymer, and or Nylon 6.6 precision molded into bodies to form tees, 90° elbows and many other fitting configurations.
2) 'O' Ring seals the threaded base into the fitting body.
3) Shows full flow capacity of fitting in relationship to the ID of tubing.
4) Cutaway of tubing showing the tubing's ID in relationship to the fitting's ID flow capacity.
5) 'O' Ring seals on the tubing OD. This 'O' ring makes and instant seal immediately upon receiving the tubing.
6) Slotted collet, the mechanism locking the tubing into the fitting.
7) Sleeve, the housing for the slotted collet whose inside configuration is beveled to match the outside configuration of the slotted collet. When pressure (or vacuum) is introduced into the system the collet and tubing move slightly backward, the slotted collet is compressed and causes the sharp gripping ridges, machined into it, to bite into the tubing's OD. The greater the pressure the stronger the grip. The connection is permanent. The disconnect must be made deliberately by simultaneously pushing in on the collet and pulling out on the tubing.
8) Push the plastic or soft metal tubing* into the fitting and there is an instant connection and a 100% seal. Can be connected and disconnected dozens of times. (See point 7)
9) Gripping ridges which lock the components into the fitting body.
10) Threaded bases - available in 1/16" to 1/2" NPT (dry seal threads) and 10 - 32 in some configurations.

Type of fitting	Average time each connection	Possible connections per hour
LF 3000 Typical Plastic Tube	3 Sec.	1200
Fitting Typical compression	12 Sec.	300
Fitting	19 Sec.	180
Typical Flare Fitting	49 Sec.	73

Disconnection of plastic tube
Depress the manual release button. This holds the collet off the locking slope and allows the tube to be drawn out of the fitting. In places not easily accessable it may be necessary to use our disconnection tool shown on page 13.





LF3000 instant fittings are sold complete with assembled gray manual release buttons. However, it is possible:
- to flick off the release button if for reasons of security it is not required.
- to replace the gray buttons with other colors. See page 14.

All dimensions in this catalog are in decimal inches unless otherwise stated. We reserve the right to change any dimensions or specifications without prior notification.

MINIATURE PRECISION COMPONENTS, INC.
P.O. BOX 1901
100 WISCONSIN STREET
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AUTOPARTES de PRECISION de SANTANA S.A. de C.V.
AVENIDA SIERNA Y CALLE 15
SANTA ANA SONORA MEXICO
PHONE: 632 4 15 83
FAX: 632 4 14 86

Quotation

University of Tennessee
414 Dougherty Hall
Knoxville, TN 37996
Attn: Mr. Scott Klein

Quote Number: UN36-001

Date: December 4, 1996	Ship Via: Best Way	FOB: Wisconsin	Terms: TBD

Quantity	Unit	Description	Unit Price	Amount
50-499/yr.	Each	MPC part number: A306 3/16" x 3/16" Check Valve Diaphragm: Epichlorohydrin Housing: Nylon	$ 1.950	
50-499/yr.	Each	MPC part number: A961 3/16" x 3/16" Two Port Inline Check Valve Diaphragm: Fluorosilicone Housing: Nylon	$ 1.825	
		Lead time: 4-6 weeks after receipt of purchase order.		

This quotation is firm for 90 days. Thereafter, prices will be subject to change due to material, labor and energy cost increases. The lead times are contingent upon availability of material and/or tooling capacity and will be confirmed with acknowledgment of your purchase order. We wish to thank you for your inquiry and hope we may have the opportunity of serving you.

Respectfully Submitted,

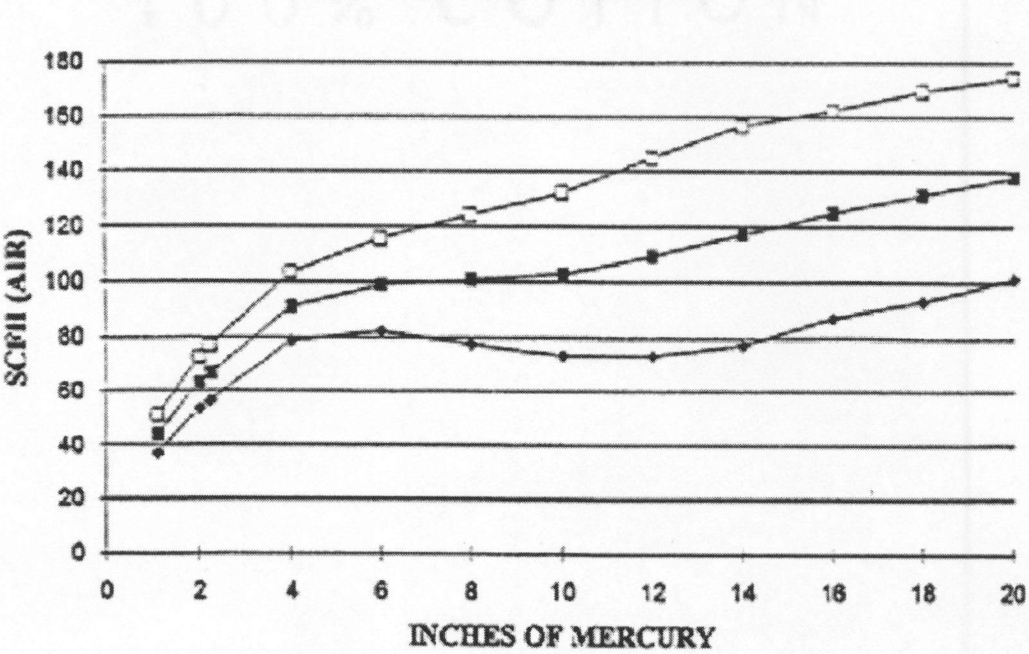
Daniel R. Brost

Daniel R. Brost
Sales Engineer

A119 (A961)

	INCHES OF WATER PRESSURE			INCHES OF WATER VACUUM	
Sample #	Average Open	Average Close		Average Open	Average Close
1	0.28	0.15		0.22	0.18
2	0.19	0.07		0.30	0.09
3	0.37	0.30		0.41	0.28
4	0.41	0.34		0.36	0.33
5	0.95	0.82		0.91	0.73
6	0.48	0.37		0.50	0.47
7	0.17	0.17		0.27	0.26
8	0.55	0.51		0.61	0.51
9	0.51	0.43		0.54	0.43
10	0.38	0.28		0.27	0.20
11	0.26	0.16		0.41	0.18
12	1.50	1.10		1.50	1.10
Average	0.50	0.39		0.53	0.40
3σ	1.13	0.90		1.08	0.85
High	1.50	1.10		1.50	1.10
Low	0.17	0.07		0.22	0.09

PRESSURE FLOW–A119



O-ring glands for industrial reciprocating seals

Design chart A6-5, on the next page, provides a reasonable basis for calculating reciprocating O-ring seal glands. Table A6-5, which follows it, contains recommended gland dimensions for the standard O-ring sizes. The major difference from the military gland dimensions (table A6-4) is the use of standard cylinder bore and standard rod dimensions.

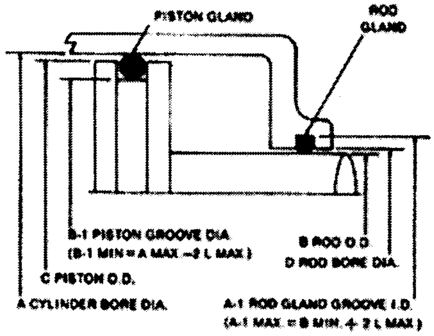
Although these dimensions are suitable for most reciprocating designs, it is often desirable, or even necessary, to deviate from them. Chapters A2, A3 and A4 are helpful in determining when such special designs are indicated and provide useful data for such modified designs.

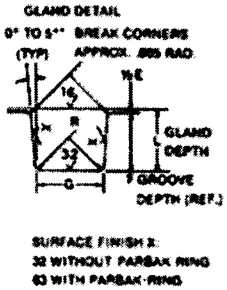
Procedures for using table A6-5 are outlined in the following guide.

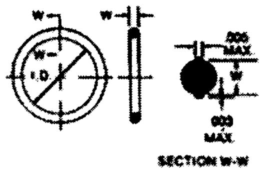
GUIDE FOR TABLE A6-5

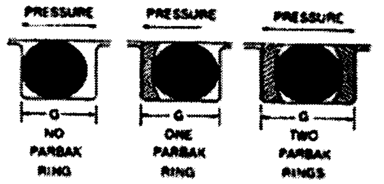
IF DESIRED DIMENSION IS KNOWN FOR	SELECT CLOSEST DIMENSION IN COLUMN	READ HORIZONTALLY IN COLUMN	TO DETERMINE DIMENSIONS FOR
Bore Dia of cylinder	A	B-1	Groove Dia of piston
		C	OD of piston
		G	Groove width
OD of piston	C	A	Bore Dia of cylinder
		B-1	Groove Dia of piston
		G	Groove width
OD of rod	B	A-1	Groove Dia for rod
		D	Bore ID for rod
		G	Groove width
Bore Dia for rod	D	A-1	Groove Dia for rod
		B	OD of rod
		G	Groove width

After selecting gland dimensions, read horizontally to determine proper O-ring size number. Specify compound.
Refer to table B1, B5 or B10 to select the proper compound. The effective part number for an O-ring consists of both a size number and a compound number.









Refer to design chart A5-5 (below) and table A5-5 for dimensions.

Dynamic

DESIGN CHART A5-5 FOR INDUSTRIAL RECIPROCATING O-RING PACKING GLANDS

O-RING SIZE PARKER 2-	W CROSS SECTION NOMINAL	W CROSS SECTION ACTUAL	L GLAND DEPTH	SQUEEZE ACTUAL	SQUEEZE %	E (a) DIAMETRAL CLEARANCE	G GROOVE WIDTH NO PARBAK RINGS	G GROOVE WIDTH ONE PARBAK RING	G GROOVE WIDTH TWO PARBAK RINGS	R GROOVE RADIUS	ECCENTRICITY MAX. (b)
006 through 012	1/16	.070 ±.003	.055 to .057	.010 to .018	15 to 25	.002 to .005	.093 to .098	.138 to .143	.205 to .210	.005 to .015	.002
104 through 116	3/32	.103 ±.003	.088 to .090	.010 to .018	10 to 17	.002 to .005	.140 to .145	.171 to .176	.238 to .243	.005 to .015	.002
201 through 222	1/8	.139 ±.004	.121 to .123	.012 to .022	9 to 16	.003 to .006	.187 to .192	.208 to .213	.275 to .280	.010 to .025	.003
309 through 349	3/16	.210 ±.005	.185 to .188	.017 to .030	8 to 14	.003 to .006	.281 to .286	.311 to .316	.410 to .415	.020 to .035	.004
425 through 460	1/4	.275 ±.006	.237 to .240	.029 to .044	11 to 16	.004 to .007	.375 to .380	.408 to .413	.538 to .543	.020 to .035	.005

(a) Clearance (extrusion gap) must be held to a minimum consistent with design requirements for temperature range variation.
(b) Total indicator reading between groove and adjacent bearing surface.

"C" preferred

Squeeze is o-ring radial height divided by original cross-section diameter. maintain 8-9% squeeze minimum

TABLE A6-5 GLAND DIMENSIONS FOR INDUSTRIAL RECIPROCATING O-RING SEALS, 1500 PSI MAX.†

O-RING SIZE PARKER NO. 2-	DIMENSIONS ID	±	W	MEAN OD (REF)	A BORE DIA. (CYLINDER) +.002 −.000	A-1 GROOVE DIA (ROD GLAND) +.002 −.000	B OD (ROD) +.000 −.002	B-1 GROOVE DIA *(PISTON) +.000 −.002	C OD (PISTON) +.000 −.001	D BORE DIA (ROD) +.001 −.000	G† WIDTH GROOVE +.005 −.000
006	.114	.005		.254	.249	.234	.124	.139	*.247	.126	
007	.145	.005		.285	.280	.265	.155	.170	*.278	.157	
008	.176	.005		.316	.311	.296	.186	.201	*.309	.188	
009	.208	.005	.070	.348	.343	.328	.218	.233	*.341	.220	.093
010	.239	.005	±.003	.379	.374	.359	.249	.264	*.372	.251	
011	.301	.005		.441	.436	.421	.311	.326	*.434	.313	
012	.364	.005		.504	.499	.484	.374	.389	*.497	.376	
104	.112	.005		.318	.312	.300	.124	.136	*.310	.126	
105	.143	.005		.349	.343	.331	.155	.167	*.341	.157	
106	.174	.005		.380	.374	.362	.186	.198	*.372	.188	
107	.206	.005		.412	.406	.394	.218	.230	*.404	.220	
108	.237	.005		.443	.437	.425	.249	.261	*.435	.251	
109	.299	.005		.505	.499	.487	.311	.323	*.497	.313	
110	.362	.005	0.103	.568	.562	.550	.374	.386	*.560	.376	.140
111	.424	.005	±.003	.630	.624	.612	.436	.448	*.622	.438	
112	.487	.005		.693	.687	.675	.499	.511	*.685	.501	
113	.549	.007		.755	.749	.737	.561	.573	*.747	.563	
114	.612	.009		.818	.812	.800	.624	.636	.810	.626	
115	.674	.009		.880	.874	.862	.686	.698	.872	.688	
116	.737	.009		.943	.937	.925	.749	.761	.935	.751	
201	.171	.005		.449	.437	.427	.185	.195	*.434	.188	
202	.234	.005		.512	.500	.490	.248	.258	*.497	.251	
203	.296	.005		.574	.562	.552	.310	.320	*.559	.313	
204	.359	.005		.637	.625	.615	.373	.383	.622	.376	
205	.421	.005		.699	.687	.677	.435	.445	.684	.438	
206	.484	.005		.762	.750	.740	.498	.508	.747	.501	
207	.546	.007		.824	.812	.802	.560	.570	.809	.563	
208	.609	.009		.887	.875	.865	.623	.633	.872	.626	
209	.671	.009		.949	.937	.927	.685	.695	.934	.688	
210	.734	.010		1.012	1.000	.990	.748	.758	.997	.751	
211	.796	.010	.139	1.074	1.062	1.052	.810	.820	1.059	.813	.187
212	.859	.010	±.004	1.137	1.125	1.115	.873	.883	1.122	.876	
213	.921	.010		1.199	1.187	1.177	.935	.945	1.184	.938	
214	.984	.010		1.262	1.250	1.240	.998	1.008	1.247	1.001	
215	1.046	.010		1.324	1.312	1.302	1.060	1.070	1.309	1.063	
216	1.109	.012		1.387	1.375	1.365	1.123	1.133	1.372	1.126	
217	1.171	.012		1.449	1.437	1.427	1.185	1.195	1.434	1.188	
218	1.234	.012		1.512	1.500	1.490	1.248	1.258	1.497	1.251	
219	1.296	.012		1.574	1.562	1.552	1.310	1.320	1.559	1.313	
220	1.359	.012		1.637	1.625	1.615	1.373	1.383	1.622	1.376	

†This groove width does not permit the use of Parbak rings. For pressures above 1500 psi, consult design chart A6-5 for groove widths where Parbak rings must be used.
*These designs require considerable installation stretch. If assembly breakage is incurred, use a compound having higher elongation or use a two-piece piston.

Standard Specifications

SCHEDULE 40, 80 120 PVC PIPE

Scope: Th[redacted]ification covers requirements for Schedule 40, 80, and 120 PVC pressure pipe as described in ASTM D-1785.

Material: PVC used is of Type I, Grade 1 compound as stated in ASTM D-1784.

Dimensions: Dimensions and tolerances shall be as shown in the following tables when measured according to Method D-2122. Tolerances for out-of-roundness shall apply only to pipe prior to shipment.

Marking: Indicates manufacturer's name, material designation code, nominal pipe size, Schedule size with pressure rating in PSI for water at 73°F, ASTM designation number D-1785, NSF seal for potable water, and manufacturing date code.

Outside Diameters and Tolerances

Nominal Pipe Size	Outside Diameter	Tolerances			
		Average	For Maximum and Minimum Diameter (Out-of-Roundness)		
			Schedule 40	Schedule 80	Schedule 120
⅛	0.405	±0.004	±0.008	±0.008	±0.008
¼	0.540	±0.004	±0.008	±0.008	±0.008
⅜	0.675	±0.004	±0.008	±0.008	±0.008
½	0.840	±0.004	±0.008	±0.008	±0.008
¾	1.050	±0.004	±0.010	±0.010	±0.010
1	1.315	±0.005	±0.010	±0.010	±0.010
1¼	1.660	±0.005	±0.012	±0.012	±0.012
1½	1.900	±0.006	±0.012	±0.012	±0.012
2	2.375	±0.006	±0.012	±0.012	±0.012
2½	2.875	±0.007	±0.015	±0.015	±0.015
3	3.500	±0.008	±0.015	±0.015	±0.015
3½	4.000	±0.008	±0.050	±0.015	±0.015
4	4.500	±0.009	±0.050	±0.015	±0.015
5	5.563	±0.010	±0.050	±0.030	±0.030
6	6.625	±0.011	±0.050	±0.035	±0.035
8	8.625	±0.015	±0.075	±0.075	±0.045
10	10.750	±0.015	±0.075	±0.075	±0.050
12	12.750	±0.015	±0.075	±0.075	±0.060

Wall Thicknesses and Tolerances

Nominal Pipe Size	Wall Thickness					
	Schedule 40		Schedule 80		Schedule 120	
	Minimum	Tolerance	Minimum	Tolerance	Minimum	Tolerance
⅛	0.068	+0.020	0.095	+0.020	—	—
¼	0.088	+0.020	0.119	+0.020	—	—
⅜	0.091	+0.020	0.126	+0.020	—	—
½	0.109	+0.020	0.147	+0.020	0.170	+0.020
¾	0.113	+0.020	0.154	+0.020	0.170	+0.020
1	0.133	+0.020	0.179	+0.021	0.200	+0.024
1¼	0.140	+0.020	0.191	+0.023	0.215	+0.026
1½	0.145	+0.020	0.200	+0.024	0.225	+0.027
2	0.154	+0.020	0.218	+0.026	0.250	+0.030
2½	0.203	+0.024	0.276	+0.033	0.300	+0.036
3	0.216	+0.026	0.300	+0.036	0.350	+0.042
3½	0.226	+0.027	0.318	+0.038	0.350	+0.042
4	0.237	+0.028	0.337	+0.040	0.437	+0.052
5	0.258	+0.031	0.375	+0.045	0.500	+0.060
6	0.280	+0.034	0.432	+0.052	0.562	+0.067
8	0.322	+0.039	0.500	+0.060	0.718	+0.086
10	0.365	+0.044	0.593	+0.071	0.843	+0.101
12	0.406	+0.049	0.687	+0.082	1.000	+0.120

No[redacted]he minimum is the lowest wall thickness of the pipe at any cross section. The maximum permitted wall thickness, at any cross section, is the minimum wall thickness plus the stated tolerance. All tolerances are on the plus side of the minimum requirement. These dimensions conform to nominal IPS dimensions, with the exception that Schedule 120 wall thickness for pipe sizes ½ to 3½ in., inclusive, are special PVC plastic pipe size.

igus norm-program information

igus® Energy Chains Plastic

igus® Series 05 "igus® micro"

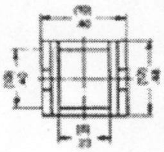
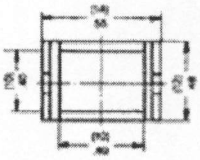
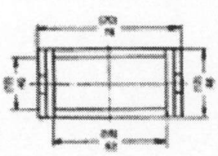
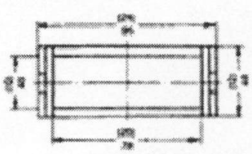
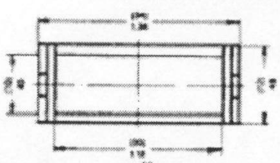
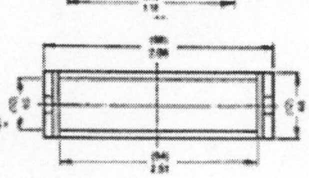
igus® inc
P.O. Box 14349
E. Providence, RI 02914
Phone: (800) 521-2747 / (401) 438-2200
Fax (401) 438-7270

Series 05 – "igus® micro" ("only for the little ones")

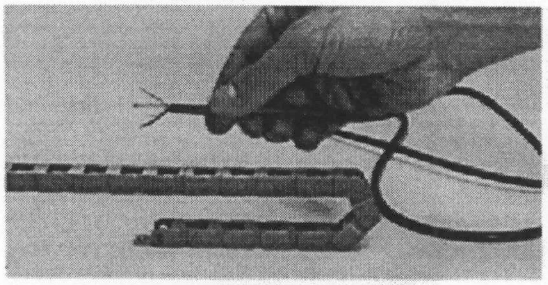
"igus® micro" Series 05 is the ideal Energy Chain where space is a at a premium. It protects even the smallest cables and hoses from damage, even driving high-speed movements.

The minimum curve height of an S05 carrier is only 1.97" (50mm). Up to .36" (9 mm) in diameter may be used with the carrier, such as control cables, pneumatic hoses and fluid hoses.

Parts in stock

Part No.	Dimension	(mm) in.
05-1-		(018), (028), (038) 0.71, 1.1, 1.5
05-2-		(018), (028), (038) 0.71, 1.1, 1.5
05-3-		(018), (028), (038) 0.71, 1.1, 1.5
05-4-		(018), (028), (038) 0.71, 1.1, 1.5
05-5-		(018), (028), (038) 0.71, 1.1, 1.5
05-64-		(018), (028), (038) 0.71, 1.1, 1.5

Applications: Measuring apparatus, medical devices, electronic equipment, assembly robots and miniature power supplies to all machines.



S05 has Minimal Height Requirements.

Colors

igus® Series 05 is available in eight colors. The choice of color can be made for aesthetic reasons. Colored E-Chains can also be used for encoding the conduits (e.g. "red" for electrical cables, "blue" for pneumatic hoses) or else as warning signals.

How-to-Order

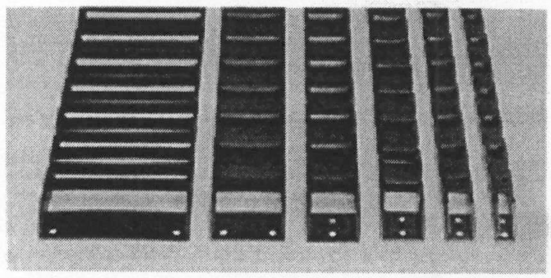
(1) Add desired bending radius in **millimeters** to Part No., eg. "05-1-028."

(2) For 10 feet igus® E-Chain 05-2 radius 28mm, plus mounting brackets, color black: "10 ft. 05-2-028-0 with 502-12".

Order Toll Free 1-800-521-2747 Over 500 sizes in stock

Available colors:

0 Black	1 White
2 Orange	6 Red
3 Grey	7 Green
4 Yellow	8 Blue
	9 Black-Yellow



New plastic one-piece mounting brackets for Series 05.

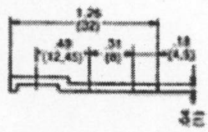
Mounting Brackets

Mounting brackets are made of stainless steel. Each set consists of two brackets, one for each of the E-Chain. The mounting brackets are hooked onto the E-Chain crossbar and bolted to the machine. For E-Chain types 05-5 and 05-64, two sets of 502-12 brackets are required.

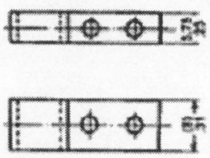
Part No.

501-12	Complete Set for S05-1-
502-12	Complete Set for S05-2-
503-12	Complete Set for S05-3-
504-12	Complete Set for S05-4-

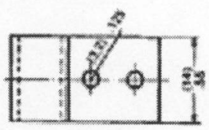
501-12



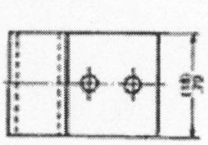
502-12

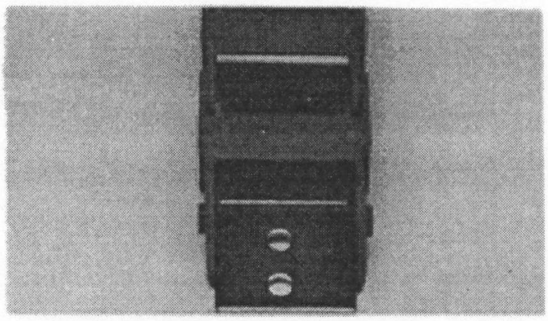


503-12



504-12

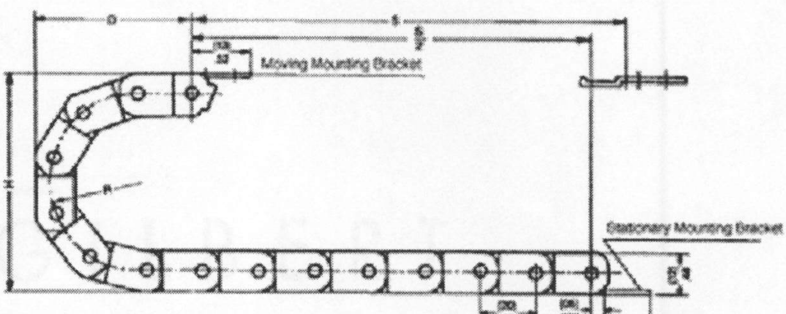




Mounting brackets, installed

Material: igumid G (Refer to page 0.32)

Design Data



E-Chain Length = S/2 + K (Center mount)

Pitch: (20)/.78

Links per foot: 15.38

Total Travel: S

R	(18) .710	(28) 1.10	(38) 1.50
*H	(50) 1.97	(70) 2.75	(90) 3.54
D	(40) 1.57	(50) 1.97	(60) 2.36
K	(100) 3.94	(140) 5.51	(160) 6.30

*The required operating space is HF = H + .50"

Please contact igus® for more confined spaces.

R = Minimum bend radius
H = Mounting height
D = Curve radius depth
K = Curve radius length

The values shown here are theoretical values which must be confirmed in a real-life test. Because of the multitude of different applications we always recommend a test in critical cases.

igus® Series		05-1	05-2	05-3	05-4	05-5	05-64
Weight per foot	lbs./ft.	.040	.044	.047	.051	.061	.088
Temperature Range Speed of Travel, max.	°F ft./min.	-40/+266 600					

Vita

William Scott Klein was born on October 9th, 1946 in Jefferson City, Tennessee. He grew up on the family farm until all moved to West Palm Beach, Florida in 1956. There he attended the remainder of elementary and a portion of junior high school. Moving with the family to Fort Pierce, Florida, Mr. Klein completed junior and high schools and was inducted into the U.S. Air Force in April of 1966. He served a four-year tour of duty in Fort Worth, Texas, where he received training in Surveying, Inspection and Architectural Drafting. He returned to Fort Pierce and enrolled in Indian River Community College in September of 1970. Mr. Klein graduated with an Associate of Arts degree and spent a short time at the University of Florida in Gainesville, Florida before transferring to Carson-Newman College in Jefferson City, Tennessee, where he graduated *Cum Laude* with a Bachelor of Science in Chemistry degree in May of 1974. Mr. Klein also received "The Outstanding Student in Chemistry" award for his class and held membership in the Science Honor Society. Mr. Klein has been employed as a Chemist, Purchasing Manager, Salesman of real estate, automobiles and periodicals, Automobile Mechanic, Author and has pursued various entrepreneurial interests. In August of 1989 he entered the University of Tennessee at Knoxville, Tennessee to pursue a second degree in Mechanical Engineering. Mr. Klein received several scholarships as an undergraduate for academic excellence in engineering and was granted the Bachelor of Science in Mechanical Engineering degree in May of 1995, when he entered graduate school at the University of Tennessee. The Master of Science degree with a major in Mechanical Engineering was granted to him in May of 1997.