# Design and Manufacture of an Icosahedral Virus Model for Educational Use

by

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Submitted to the Department of Mechanical Engineering
in Partial Fulfillment of the
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## ABSTRACT

A model of an icosahedral virus was designed and manufactured. Much consideration was given to the design of different aspects of the part, though there were many uncertainties about some parameters that disallowed precise prediction of part outcomes. The part was designed in SolidWorks and Mastercam, and converted to a tool path that allowed machining of the mold on the CNC milling machine. This mold was then taken to the injection molding machine where multiples of the part could be produced. The mold had to be redesigned several times to incorporate solutions to problems that arose along the way due to the uncertainties inherent from the beginning. New parts were produced upon each revision and tested. Finally, both the core and cavity molds were redesigned and rebuilt. These new molds produced parts that fit together properly and provided an accurate model of the icosahedral virus. A majority of the knowledge obtained from this project arose from the uncertainties and their corresponding problems and solutions. Making mistakes allowed the potential for creativity with designing a solution. The two objectives of the project were achieved; a three-dimensional virus model for educational use in the biology classroom was built and knowledge about the design and manufacturing process was obtained and documented.

Thesis Supervisor: David Gossard
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# Chapter 1

## INTRODUCTION

### 1.1 Motivation

The structure and complexity of each individual subunit of a virus, as well as the ingenuity that is inherent in the symmetry of the entire assembly is difficult to visualize and understand on a two-dimensional representation. Much of the ability to understand each individual component that contributes to the overall model is lost when looking at a picture of the virus on paper. In order to facilitate a better understanding of the repetition and symmetry that is fundamental to the structure of viruses, it would be helpful to have a three-dimensional representation of the virus that shows its individual components and the symmetry and repetition associated with them.

There are some three-dimensional representations of a virus available, but many of these are made out of paper, so that they are not robust enough to withstand several classrooms of instructional use. Also, being made out of paper, they have limitations on their assembly and disassembly, so that individual components are difficult to extract and show on their own. It allows some representation of the symmetry and repetition of the virus, but has its limitations as well.

Another goal of this project of designing and manufacturing an icosahedral virus model is to further develop an understanding of the design and manufacturing process in mechanical engineering by applying it to an outside field. The parts, models, and the documentation of their progress are intended to serve as educational tools in the future. The models will assist primarily in the field of biology where virus research is most conducted. The documentation of the progress of the design and manufacturing steps, especially with injection molding, will assist in mechanical engineering, particularly those students requiring the design and manufacture of similar molds and parts in the *2.008 – Design and Manufacture II* class.

## 1.2 Scope and Organization

This project will discuss the design possibilities, requirements, and decisions, as well as the manufacturing limitations and allowances available with the associated machines. The background on viruses, their structure, and icosahedral structure will be discussed shortly. The design process will be then analyzed in detail to allow a full understanding of the reasons behind each design decision. These decisions had some uncertainties that allowed for a learning based on making mistakes. The actual production of the SolidWorks and Mastercam models will not be discussed, since they are not vital to the production of this part specifically, though their applications will be noted. Finally, the machining of the mold and the manufacturing of the part will be discussed in great detail, pointing out all of the problems along the way, the desired solution, and the design that ultimately developed the full model.

# Chapter 2

## BACKGROUNDS

## 2.1 Background on Viruses

Viruses are parasites that require a host cell in order to survive and replicate. While they cannot reproduce on their own, they are still responsible for thousands of deaths each year[1]. They deliver the genomic material into the host cell and produce new particles, which undergo self-assembly. Viruses tend to be on the order of 17 – 3000 nm in diameter and have the basic shape of being either rod-like or "spherical." Since the viruses are so small, they have very limited volume on the interior to store their genomic material. Since there is limited volume, it is convenient that the exterior of the virus is composed of many identical subunits, which are symmetrically organized[2].

Virus structure was originally approximated to be spherical. In 1956, though, Crick and Watson proposed many principles of virus structure, including a conclusion that the symmetry is based on either an icosahedral or dodecahedral configuration[3]. Soon later, x-ray crystallographers Donald Casper and Aaron Klug confirmed that viruses had icosahedral symmetry. This was done by negative staining and electron microscopy. The icosahedral symmetry allows the virus to be more stable[2].

## 2.2 Icosahedral Structure

### *2.2.1 Basic Structure*

The basic structure of an icosahedron consists of twenty identical faces, where each face is an equilateral triangle. Each of the twenty faces has three fold axes, each of the thirty edges has two fold axes, and each of the twelve vertices has five fold axes. An icosahedron is then said to have 5-3-2 symmetry[4]. Were each equilateral triangle face divided into three identical subunits, sixty total identical subunits could be assembled to form an icosahedral structure. This is the composition of a virus.

The dimensions of an icosahedron are fairly straightforward. The distance from the midpoint of an edge to the center of the structure is phi, the golden ratio. The vertices are then given by (0, ±1, ±phi), (±phi, 0, ±1), and (±1, ±phi, 0)[4]. If the icosahedron were flatted to two-dimensions, there would be four rows of five equilateral triangles. A two-dimensional representation of the flattened icosahedron is shown in Figure 1.

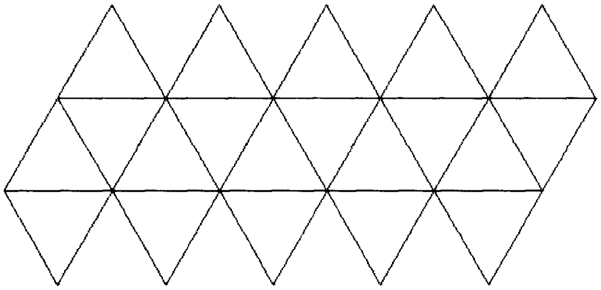

**Figure 1:** Three-dimensional icosahedron flattened to two-dimensions

If this figure were cut out around the outside lines and folded to form creases at all of the lines, it would form a three-dimensional icosahedron. Making one of these three-dimensional forms is helpful to understanding the structure of the virus.

### *2.2.2 T Numbers*

In 1962, Casper and Klug proposed the "quasi-equivalence" theory. This is the theory that not all of the protein subunits are identical[2]. This only is the case when there is a multiple of sixty subunits. If $N$ is the number of subunits, then

$$N = 60T \tag{1}$$

and $T$ is further defined as

$$T = h^2 + hk + k^2 \tag{2}$$

where

$$h,k = 1, 2, 3, \ldots \tag{3}$$

The multiples of sixty that are then available to form a virus in the icosahedral structure are then

$$T = 1, 3, 4, 7, 13, \ldots \tag{4}$$

Each equilateral triangle would contain $T$ different types of subunits and would have three of each of these subunits per triangle. The $h$ and $k$ values correspond to the coordinates of one of the vertices with the original position being another vertex[5]. The triangle is then completed to be equilateral. A picture representation of this concept is shown in Figure 2.

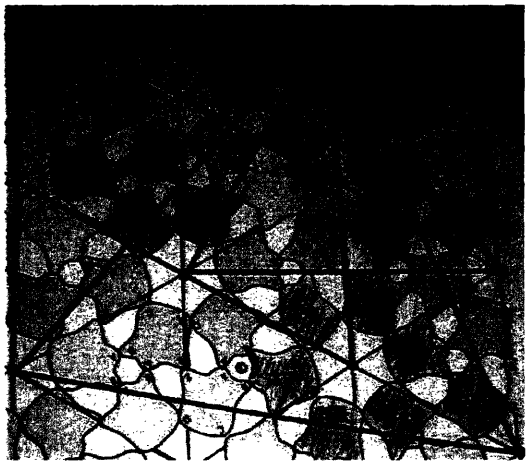

**Figure 2:** Picture representation of meaning of $h$, $k$, and $T$ values

The shaded region within each $T$ value are each different from one another due to the manner they interact with the boundary of the triangle. All of the triangles start from the same original point and move diagonal down and left one line segment for each increment of $h$ and move straight down one line segment for each increment of $k$.

### *2.2.3 Relation to Dodecahedron*

The icosahedron and dodecahedron are considered to be dual polyhedrons of one another. This means that they have a similarity that is inherent with their symmetry. While they both have the same number of edges, the number of vertices and faces are exactly opposite one another[4]. This comparison can be seen in Table 1.

**Table 1:** Comparison of vertices, edges, and faces between an icosahedron and dodecahedron

| | Icosahedron | Dodecahedron |
|---|---|---|
| Vertices | 12 | 20 |
| Edges | 30 | 30 |
| Faces | 20 | 12 |

While the virus structure utilizes three identical subunits per face, the dodecahedron could similarly have five identical subunits per face to achieve the same total number of subunits. In fact, the same basic subunit shape could be modified by slightly altering angles to alternate between the two geometric shapes.

The midpoints of the face of an icosahedron connect to form the dodecahedron, and likewise the midpoints of the face of a dodecahedron connect to form the icosahedron[4]. This can be seen in Figure 3 where the dodecahedron is outlined in black with the vertices in blue, and the icosahedron's vertices are the center points of the faces of the dodecahedron.

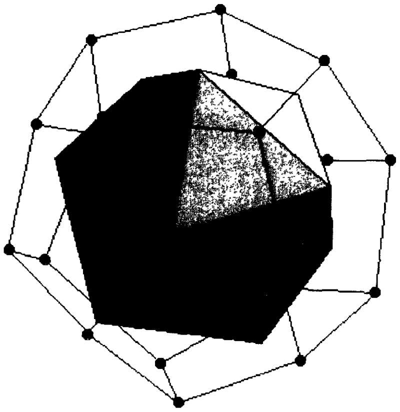

**Figure 3:** Picture showing the formation of the icosahedron by connecting the center points of the faces of a dodecahedron

This further shows the dual nature of these two shapes. While the virus structure has been determined to be icosahedral, there are potential hybrids of an icosahedron and dodecahedron that would allow a more spherical configuration of subunits. An example of this can be seen in Figure 4.

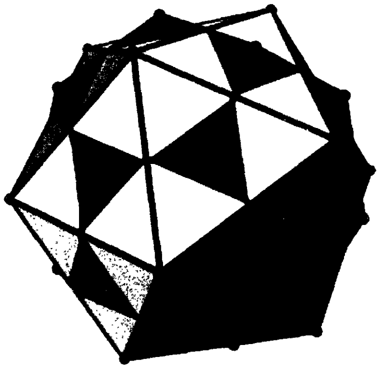

**Figure 4:** Icosahedron and dodecahedron hybrid shape

The icosahedron has the green wire frame and yellow faces while the dodecahedron has the blue wire frame and light blue faces. This hybrid is more spherical and may contain some answers to questions raised about the maturation transition process.

### *2.2.4 Maturation Transition*

A virus undergoes a transition from a more spherical assembly of the subunits to the stable icosahedral configuration that is to be modeled in this project. When the structure is more spherical, it has some minor holes in the faces, and upon reconfiguring the positions of the subunits, the holes in the face close and the entire shape becomes an icosahedron. This final assembly is much more stable and increases in radius by approximately 15%, despite the closure of the holes in the face.[2]

## 2.3 Injection Molding

The injection molding machine itself is important to understand so that it can be setup properly. The plastic granules enter through a large funnel and are forced through the barrel by a rotating screw that increases in diameter along its length. This is run by means of a screw motor drive. The barrel gets increasingly hotter as it approaches the nozzle, which is where the molten plastic exits the barrel and enters the mold cavity. The molds are held together for injection, packing, and cooling, and then opened, whereupon optional ejector pins assist in ejecting the part from the cavity of the mold[3]. A diagram of these components of the apparatus can be seen in Figure 5.

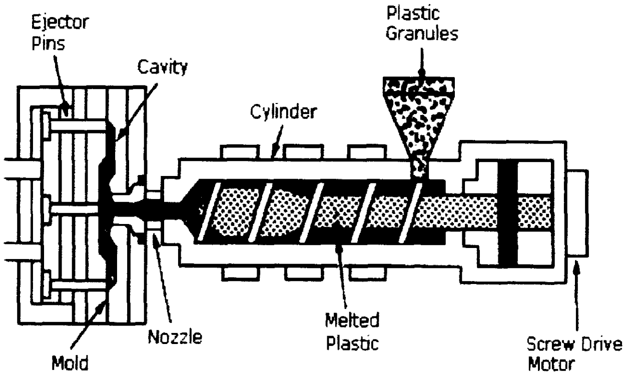

**Figure 5:** Diagram of injection molding apparatus

There must also be an understanding of the insertion of the molds and ejector pins, as well as an understanding of the machine parameters. A photograph of the exact injection molding machine to be used for this project can be seen in Figure 6.

**Figure 6:** Photo of injection molding machine in LMP machine shop

The sliding glass door on the far left of this picture is the door to the molds. There are holders set up to hold the molds correctly relative to one another, and also allow proper alignment of ejector pins. Ejector pins must be measured based on the size of the mold and inserted through the back of the mold holder. When the ejector pins are initiated, a spring allows them to thrust forward and force the part off of the core mold. The other sliding glass door contains the funnel for plastic, cylinder, screw, and nozzle, all featured in Figure 5. Finally, on the far right of the picture is the screen and keyboard that allows values to be input for specific parameters.

The plastic to be injected is polypropylene. It comes in a granulated form and is subject to heating through the nozzle and friction from the screw. A picture of some polypropylene granules can be seen in Figure 7.

**Figure 7:** Picture of granules of polypropylene

The plastic granules used are primarily clear, and if color is to be added, a small amount of colored granules are added to a tin of the clear granules.

The steps of injection molding are as follows: (1) close mold, (2) fill, pack and hold, (3) cool, (4) open and remove part[6]. Filling the mold is when the majority of the material is injected into the mold. Packing and holding involves adding pressure and more material to the material already existing in the mold, to minimize the negative effects of cooling and shrinkage on the outcome of the part. The longest portion of the cycle is the time allowed for the part to cool while the molds are still being held together. Finally, the mold is opened and the part is removed, either by coming off on its own or by the use of ejector pins. A typical injection cycle and the times for each portion of the process are shown in Table 2.

**Table 2:** Steps of the injection molding process and the cycle time of each

| Process | Cycle Time |
|---|---|
| Close Mold | 1-2 sec |
| Fill Mold | 2-5 sec |
| Pack and Hold | 8-10 sec |
| Part Cool | 10-20 sec |
| Open Mold | 1 sec |
| Part Ejection | 1 sec |

These numbers reflect the sizes of parts attainable by the injection molding machine available at MIT[6]. While these numbers are important to consider during the design portion of the process, they are most relevant during the manufacturing of the part.

# Chapter 3

## DESIGN CONSIDERATIONS

I decided to make my model be the most simple virus structure, that of the T = 1 where there are sixty identical subunits. Since each of the subunits is identical, only one part and its corresponding mold needs to be designed. The potential for problems is then also limited to the flaws of only one part. If this first model proceeded flawlessly, the plan was to create other models with more complicated geometry, such as the T = 3 or T = 4 configurations. Given the problems that arose throughout the process, though, I was never able to move on to these other models.

### 3.1 Machining Limitations

Most of the machining of the molds was done by using the computer navigated control (CNC) milling machine in LMP machine shop, and running it off of tool paths developed in Master cam software. The tools available for use on this machine and each their capabilities propose limitations on the potential for draft angles, depths, and thicknesses that can be machined into the mold.

Some work was also done on the lathe and press fit, but these modifications were only done to correct problems associated with former drafts of the mold. The lathe was used to machine a plug of a specific diameter that could then be press fit into a hole that machined into the mold on the CNC milling machine to remove material associated with the problem. These modifications were subject primarily to the limitations involved with injection molding, which will be discussed in the next subchapter.

### *3.1.1 Draft Angles*

The draft angles of the walls of the mold are limited by the machining capabilities. The tools available for the CNC milling machine primarily provide no draft angle (bottom and side of cavity being at 90 degrees to one another). There are also tools that allow 5, 10, and 15 degree draft angles, which also have limitations based on the width of their tips and the length of the angled portion of the tool. For this project, a 21 degree draft angle was needed, which was not available by traditional methods. This required the additional tooling or machining methods.

The 21 degree draft angle could be accomplished in a variety of ways. The options explored were to purchase a special draft tool, to obtain a vise that could hold the mold at a specific angle to the head of the machine, or to tilt the head of the machine to obtain the angle. The original decision was to purchase a draft tool, but given the amount of time that would be lost in waiting for the tool to arrive, other options were explored and found to be advantageous. Edgerton student shop allowed me to tilt the head of one of their milling machines, whereupon I was able to obtain exactly the 21 degree draft angle needed in a limited amount of time.

### *3.1.2 Depths*

The tools to be used for this project are the smallest of the flat end mills available for the CNC milling machines. These are the 1/16", 1/8", and 1/4" flat end mills. These tools may not exceed a depth of three times the width their width. This means that the 1/16" end mill cannot exceed a depth of 3/16", the 1/8" tool cannot exceed 3/8", and the 1/4" cannot exceed 3/4". This posed distinct limitations on the portions of the wall that were to be milled using the 1/16" end mill. This posed many original depth limitations on the walls, which were later redesigned with a thickness that would allow a larger tool that could attain a greater depth into the cavity.

### *3.1.3 Thickness*

As discussed above, the smallest of the end mills were used most for this project. Since the smallest of the end mills is 1/16", this is the absolute smallest thickness attainable. This was originally the thickness of some of the walls of the part, though these thicknesses were later changed to be able to attain greater depths, due to the depth limitations described above. For the purposes of this project, machining capabilities did not force a maximum thickness of the walls.

## 3.2 Injection Molding Limitations

The portions of the injection molding that pose limitations on the design are primarily the dimensions of the mold blanks and the characteristics of the flow of polypropylene, the plastic to be used in injection molding the parts. Material flow limits thickness, shrinkage, and runner placement, while the dimensions of the mold blanks limit the size and shape of the part.

### *3.2.1 Thickness*

There are many factors to consider when deciding the thickness of a part to be injection molded. The main concerns involved in this project were (1) weight, (2) robustness, (3) injection flow, (4) shrinkage, and (5) changes in thickness.

Weight and robustness are issues for several reasons. If a subunit is thick, it will be very strong and robust. It would also be heavy, though, so that when the entire model is assembled, it will have difficulty staying together because of the forces associated with the weight. On the other hand, if the part is too thin, the model will be light, but will not be very robust. Since polypropylene is not very heavy to begin with, parts are generally not heavy enough to pose problems associated with weight, so that large thickness is not an issue under this consideration.

The injection flow must also be considered. The material has difficulty flowing into a section that is very long and thin. The general rule is not to exceed a length to thickness ratio of six[6]. If this is exceeded, a small hole should be drilled all the way through the mold so that air can escape so as to avoid burning when the material is forced to travel into the cavity.

Finally, shrinkage and changes in thickness must be considered. It is generally recommended to utilize uniform wall thickness, so as to have close to uniform shrinkage. Uniform thickness allows proper material flow into the mold and minimizes warpage.

For all of these reasons, plus the recommendation of the shop assistants of LMP shop, a constant thickness of 1/8" was decided upon. This would allow machining with the 1/8" milling tool that could travel more quickly than the 1/16" tool. It would also allow robustness of the part and acceptable material flow.

### *3.2.2 Size*

The injection molding machine has the capacity to hold a mold with maximum cross-sectional area of 4" by 4.25". This also includes the necessary corner holes for alignment on the milling machine and on the injection molding machine, as well as the sprue hole. Some room must also be left between the sprue hole and the part so that a runner may be added. All of these requirements leave enough room for a part that is 3" wide and 3" long to fit comfortably. This influenced the decision to have the maximum length of one side of the subunit to be 2.5", so that if any modifications need to be made, there would still be room on the mold without having to entirely start over with the manufacturing process.

Another limitation of the injection molding machine is the stroke size, which is the volume of material that can be injected into the part. The maximum part volume that this machine can inject is a 2.7 cubic inches. This part falls well under this limit, and so is not a limiting factor in the design process.

### *3.2.3 Shape of Subunit*

The shape of the part was limited by the symmetry that is necessary in order to compose an icosahedron. Three of the exact same subunit must assemble into a perfect equilateral triangle, and twenty of these triangles must fit together to form an icosahedron. Three shapes were taken into consideration and compared. These shapes are shown in Figure 8.

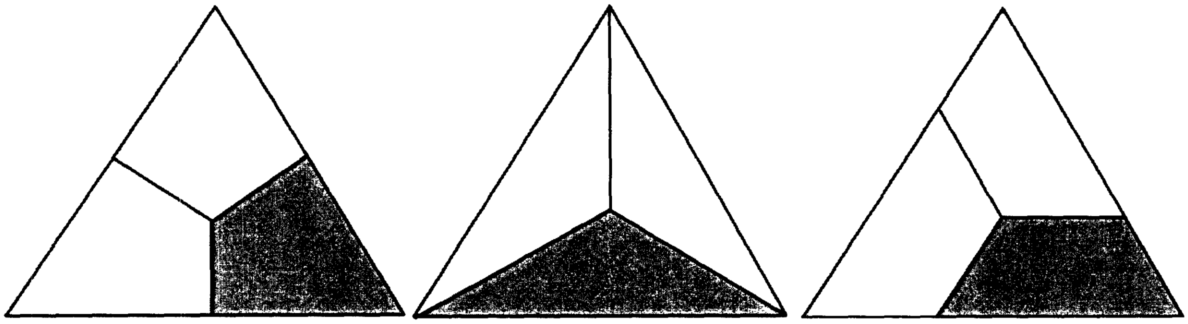

**Figure 8:** Shapes 1 (left), 2 (middle), and 3 (right) under consideration for model subunit shape

All three of these shapes have some form of symmetry and can be designed to snap fit together into an equilateral triangle in the configurations shown. Many other requirements were considered when deciding between these three options.

The first of these requirements was the ability to machine it on the milling machine. Given the limitations of the tools, thin parts (under 1/16") and sharp corners are difficult. Shape 2 is very thin on the sides and has very sharp corners that would be difficult to obtain with the tooling available. The smallest angle on this part is 30 degrees, while Shapes 1 and 3 have a minimum angle of 60 degrees, which makes them more ideal for machining purposes.

The next consideration was related to the constraints imposed by injection molding. The length of Shape 2 makes the flow of the material more difficult, though not entirely unobtainable. Shape 3 does not have a place that the runner could be placed where it would not interfere with a crucial face and yet would still allow symmetry of flow.

The assembly of the three shapes is similar. While Shapes 1 and 2 interact with four and three other parts respectively, Shape 3 interacts with five. This makes it slightly more difficult to design and assemble since there are more snap fit interactions to consider.

The size of the part is of crucial consideration as well. There is a limitation based on the size of the molds available. This means that if the size of the overall model is to be maximized, the longest side length of the part should be minimized. Shapes 1 and 3 have similar dimensions, while the long and skinny nature of the subunit in Shape 2 puts it at a distinct disadvantage.

Finally, the stability of the part based on the number of other parts it interacts with was analyzed. This is the only requirement that puts any of the shapes at an advantage over Shape 1. Shape 2 is at an obvious disadvantage, interacting with only three other parts. While Shape 1 interacts with four other parts, Shape 3 interacts with five. This was considered a disadvantage when analyzing assembly capabilities, but is an advantage in stability since there is more interaction between parts.

A summary of these findings are shown in Table 3, where Shape 1 was held as the control design at a constant value of 0, and Shapes 2 and 3 were given positive or negative numbers depending on how they compared to Shape 1.

**Table 3:** Pugh chart comparing the three options of shape for the model subunit

| Requirements | Shape 1 | Shape 2 | Shape 3 |
|---|---|---|---|
| Milling Capability | 0 | -1 | 0 |
| Injection Molding | 0 | -1 | -1 |
| Assembly | 0 | 0 | -1 |
| Size | 0 | -1 | 0 |
| Stability | 0 | -1 | 1 |
| **Total** | **0** | **-4** | **-1** |

While Shape 1 obtained a total score of 0, shapes 2 and 3 each scored negative total points, meaning Shape 1 was ultimately decided upon.

### *3.2.4 Shrinkage*

The usual shrinkage rate of polypropylene that has been injected into an aluminum mold is 1-3%[6]. An analysis in *2.008 – Design and Manufacture II* showed the shrinkage rate of a part with similar cross-sectional area and volume to the part in this project to be approximately 2%. This shrinkage rate would have been very important if there were to be more than one type of part, since different parts would shrink differently. Since there is only one part in this model, all of the parts can be assumed to shrink at the same rate, so that the shrinkage effect can be ignored when designing.

### *3.2.5 Parting Line*

There are many options for the parting lines of most molds. The potential for flashing and the ability to extract the part after injection are of primary consideration when making this decision[6]. For this project, there was only one possible decision for a parting line, since the draft angle would not allow the part to be extracted at any other parting line. The core mold would have the half of the part that contained the draft angle, while the cavity mold would have the half of the part that is rounded for ease of assembly and aesthetic value. The part could have been redesigned to allow different options for a parting line, but the one available with the initial design was satisfactory and required no further modification.

### *3.2.6 Runner Placement*

The delivery of the material to the mold is done through three parts. The material is initially injected into the sprue, which is the channel from the injection nozzle to the interior of the molds. The sprue is connected to the runner, which is the thin channel that guides the molten plastic into the mold. This is a thin channel so that it is easily cut off after the part is removed from the mold. Finally, the gate is the molten plastic's entrance into the cavity of the mold[6]. The sprue hole is already set in the mold blanks available in the LMP shop, so the only variables are the placement of the part within the mold and therefore the placement of the runner.

The main consideration when deciding on the placement of the runner is the flow of the material into the mold, and how it will affect the outcome of the part. Too large of a runner results in a longer cooling time, too small of a runner can cause short shot, sink marks, or poor quality, and too long of a runner causes problems with pressure drops and cooling. The distance that the material must travel within the mold should therefore be minimized. The runner should be on a side or corner of the mold whose tolerances are not crucial to the outcome of the part. The runner must be cut off of the part, which is not a very exact process, and inconsistencies of this process are minimized if the runner is attached to an area which is not crucial. The runner should also be placed somewhere on the part that has some degree of symmetry, so that the material can flow into the part more easily.

## 3.3 Dimensioning

### *3.3.1 Size*

I wanted to maximize the diameter of the ball within the size limitations of injection molding. As discussed above, the side length of the part was decided to be 2.5", so that the part could fit comfortably into the allowable space on the mold with extra room in case of potential later modifications.

Since the decision had already been determined for a shape of the subunit, I could use the dimension of 2.5" to be one half of the length of one entire side of an equilateral triangle face of the icosahedron. The relation between the entire side length of one of these triangles and the volume of the icosahedron is:

$$V = \frac{5}{12}(3+\sqrt{5})a^3 \tag{5}$$

where $V$ is the volume and $a$ is the side length. This must then be related to the radius of the entire model. For this, I approximated the icosahedron as a sphere so that the volume equals:

$$V = \frac{4}{3}\pi * r^3 \tag{6}$$

where $r$ is the radius of the model. I then equated these two formulas for volume to find a relationship between the radius of the model and the length of the edge of the equilateral triangle face. This gave the following relation:

$$r = 0.8045 * a \tag{7}$$

Different values for the radius or edge length could now be plugged into this equation to find an ideal size for the subunit edge length, and therefore diameter of the model.

While I originally thought that a twelve inch diameter would make a good size for a model, this corresponded to an edge length, $a$, of 7.14inches. Even though this edge length is the edge of the entire equilateral triangle face, one half would still result in an edge length of 3.57inches, which is far too large. The edge length of one subunit was decided to be 2.5 inches, so that the edge of an equilateral triangle should be 5 inches. This corresponds to an entire diameter of about 8 inches, which maximizes the diameter of the model while still staying within the previously established edge length limit.

### *3.3.2 Face to face angles*

The face to face angle of an icosahedron must be determined in order to be able to design the subunit to fit properly. This can be done using Figure 9 and known geometric relations.

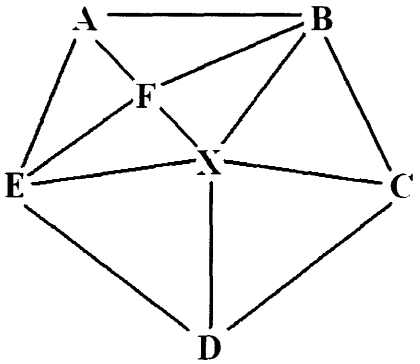

**Figure 9:** Drawing of the portion of the icosahedron used to find face to face angles

The goal is to find the angle of EFB where ABX and AEX are two equilateral triangle faces of the icosahedron and F lies along the edge AX. The edge length of the original equilateral triangles of the drawing are defined as being 1. Since BF and FE are altitudes of their corresponding equilateral triangle faces, they have a length of $\sqrt{3}/2$. BE can be found with trigonometry to be $2*\sin(54^{o})$ or approximately 1.618. This makes the angle at F equal to approximately $138.2^{o}$. The angle between either FE or FB and the center point of the icosahedron is half of this, or $69.1^{o}$[7]. This will be the draft angle of the two parts so that they will fit together to form the icosahedron.

### *3.3.3 Contour of Surface*

The original parts were designed to have a flat surface, so that problems associated with the basic design could be determined more easily. Once the part was near completion for assembly, though, contours could be added to the surface. The intention of these contours is to make the model look more like a virus. After examining many photographs of viruses, one specific virus was chosen for its aesthetic value and ease of incorporating into the subunit without much difficulty. The virus chosen was the human poliovirus, shown in Figure 10.

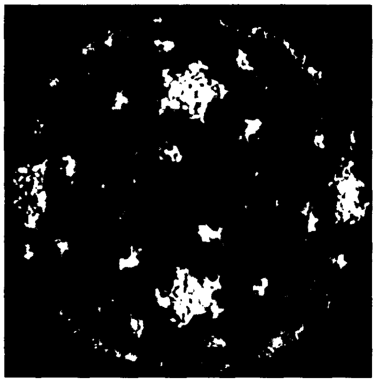

**Figure 10:** Actual picture of human poliovirus

The five-fold symmetry and three-fold symmetry shown in this photograph was able to be incorporated into each subunit, since there are already distinct vertices corresponding to these symmetries. In order to make the assembly look slightly more spherical, the cavity necessary in the mold exceeds the depth limits of the 1/16" and 1/8" end mills. This means that the 1/4" end mill is required. A maximum thickness of this width is also necessary, since making the thickness of any portion of the part greater would cause problems with dishing, shrinkage, and warping. This meant having the large protruding portions shown in Figure 9 be only lines in the same basic shape, so that shrinkage would not cause problems

A rough sketch in the CAD software SolidWorks of the intended surface contours of the individual subunit can be seen in Figure 11.

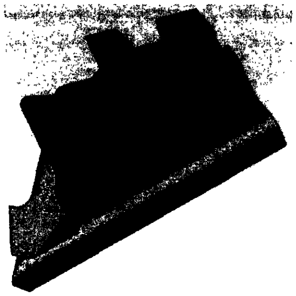

**Figure 11:** SolidWorks drawing of basic idea for surface contours applied to one subunit

The top of this drawing corresponds to the three-fold symmetry in the photo of the poliovirus, while the smaller projection on the bottom of the part corresponds to the five-fold symmetry that looks star-like in the poliovirus photo. A SolidWorks drawing of the entire assembly of sixty subunits can be seen in Figure 12.

**Figure 12:** SolidWorks drawing of basic idea for surface features applied to entire assembly

The symmetry of the single subunit allows it to line up properly with adjacent subunits to form the repetition necessary to the virus structure. The symmetry in this CAD drawing very obviously mimics that of the human polio virus photo shown in Figure 10.

While not represented in this SolidWorks photo, the actual Master cam generated tool path has minor differences. The projections are at a constant thickness of 1/4" for the reasons stated above. The tool path also makes spherical projections out of these protrusions so that the part looks even more like the human polio virus.

## 3.4 Assembly

### *3.4.1 Type of Assembly*

The assembly was the most difficult part of the design process. The model should be stable enough to stay together on its own and withstand some small forces, but should also be able to be disassembled if the need should arise. The decision came down to three different basic methods of assembly.

The first method was using a snap fit. While this would require some tight tolerances in order to be able to have the proper interference, it would have distinct advantages as well. It would require no extra parts, would be able to be disassembled, and would not require much extra time with assembly.

Another idea was to use an adhesive to connect the subunits. This would require extra time during assembly for holding and drying, and would require the extra component of the adhesive itself. While it would not require very tight tolerances of the part, it would not be able to be disassembled.

Finally, the third option was to have some kind of mechanical assembly, such as nuts and bolts. This would require a lot of extra parts and extra time for assembly. It would also be difficult to disassemble, which would also be time consuming.

The only advantage that the adhesive or mechanical fasteners have over the snap fit assembly is the requirement of tight tolerances. Given the machines available at LMP machine shop, though, the tolerances are not a distinct problem. One problem that all three types of assemblies have difficulty solving is that of the last few pieces being able to be assembled into the model. This is a problem that will have to be dealt with as it arises.

A summary of the comparison between the three types of assemblies can be seen in Table 4.

**Table 4:** Pugh Chart comparing the three explored options for assembly

| Requirements | Snap Fit | Adhesive | Mechanical |
|---|---|---|---|
| Extra Parts | 0 | -1 | -2 |
| Tolerances | 0 | 1 | 1 |
| Disassembly | 0 | -2 | -1 |
| Extra Time | 0 | -1 | -1 |
| Last Pieces | 0 | 0 | 0 |
| **Total** | **0** | **-2** | **-3** |

The snap fit assembly was held constant at zero while the other two assembly types were compared. A positive number indicates an advantage over the control, while a negative number indicates a disadvantage. If there is a very large advantage or disadvantage, there is a proportionately larger positive or negative number respectively. The option to be chosen should be the one totaling the greatest value in the bottom row. This means that the snap fit assembly is chosen as the method for assembly.

### *3.4.2 Type of Snap Fit*

Though the snap fit was decided upon for a type of assembly, there are many possible options within the realm of snap fits. Machining and injection molding pose limitations that made this decision straightforward.

~~Chapter 1~~The first option explored was a pin-hole joint. This would be very secure and would allow only one degree of freedom, that of the direction that the protrusion and cavity were in. Unfortunately, machining this mold and extracting the part from the mold are outside the realm of possibility with a traditional two-part mold. A drawing of the pin-hole fit can be seen in Figure 13.

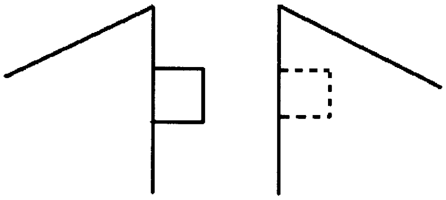

**Figure 13:** Side view dawing of pin-hole joint as a possibility for snap fit assembly

The next option considered was slots and tabs. This has a much easier mold than the pin-hole joint and can be accomplished with a traditional two part mold. One problem with a regular slot-tab snap fit is that with 90 degree angles, the parts can move relative to one another in more than one direction. Ideally, the parts would only be able to move relative to one another in the one direction that they are connected by. A possible remedy for this problem is to change the angle at which the parts interact with one another to assure the part will line up properly. A drawing of this type of assembly can be seen in Figure 14.

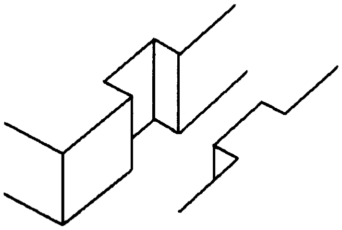

**Figure 14:** Orthogonal view drawing of slot-tab joint as a possibility for snap fit assembly

The final option considered is a modification of the normal slot-tab joint. It is where the slot has a lip that disallows the parts to slide vertically both up and down relative to one another. This solves the problem discussed above of the number of degrees of freedom. It develops another problem though. The mold becomes difficult and even impossible at draft angles other than 90 degrees. Since the face to face angle has already been determined to be different than 90 degrees, this option must be rejected. A drawing of this option can be seen in Figure 15.

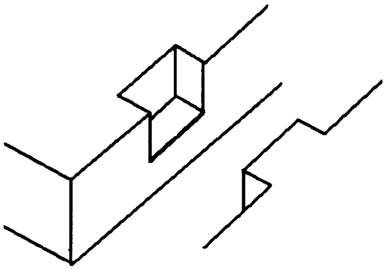

**Figure 15:** Orthogonal view drawing of tab-slot w/ lip joint as a possibility for snap fit assembly

Due to the descriptions of each of the options above, and the impossibilities associated with the pin-hole fit and the modified slot-tab fit with added lip, the regular slot-tab fit was chosen.

# Chapter 4

## INITIAL DESIGN

### 4.1 CAD Solid Modeling

The primary CAD software used for solid modeling during the design portion of the project was SolidWorks. The secondary software used was Master cam for its ability to convert the drawing into a tool path to be used on the CNC milling machine. The initial design was very simple, incorporating the tab and slot snap fit onto the flat interface and angled interface. A SolidWorks drawing of this first subunit can be seen in Figure 16.

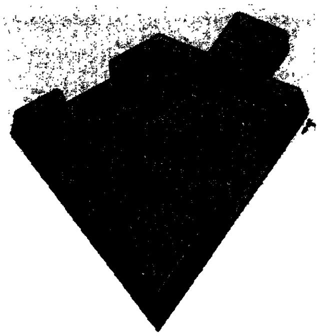

**Figure 16:** SolidWorks drawing of individual subunit as viewed from the bottom

This individual subunit could then be inserted three into an assembly drawing and mated to develop one of the equilateral triangle faces of the entire icosahedron model. This utilized only the flat surface snap fit and produced the SolidWorks model shown in Figure 17.

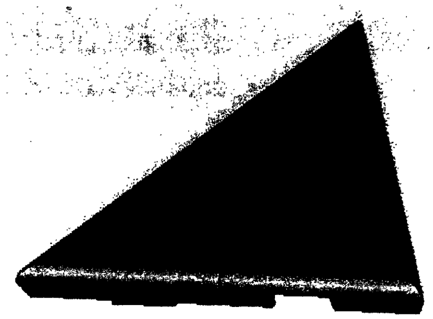

**Figure 17:** SolidWorks drawing of three subunits as viewed from the top, combined to form a flat equilateral triangle

This model was further developed by opening a new assembly file and inserting twenty of the equilateral triangles to develop the entire model. This full model looks very similar to the figures shown in the background on icosahedrons, and can be seen in Figure 18.

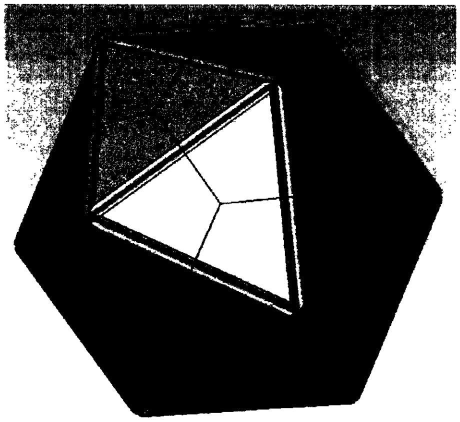

**Figure 18:** SolidWorks drawing of entire assembly of sixty subunits

The basic subunit was then redrawn into Master cam so that the tool paths could be developed for machining. The original Master cam drawings of both the top portion corresponding to the cavity mold and the bottom portion corresponding to the core mold can be seen in Figures 19 and 20 respectively.

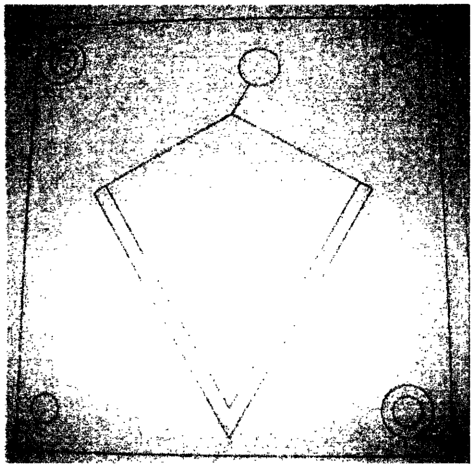

**Figure 19:** Mastercam drawing of cavity mold corresponding to top half of part

The circles on the corners of the drawing correspond to screw holes that assist in holding the part during both machining and injection molding. The hole that is offset from the top middle of this part is the sprue hole. All of these holes are already incorporated into the mold blanks. The line running from the part to the sprue hole is the runner, and is the shortest distance from the part to the sprue hole while still reaching the part at a point that has some degree of symmetry.

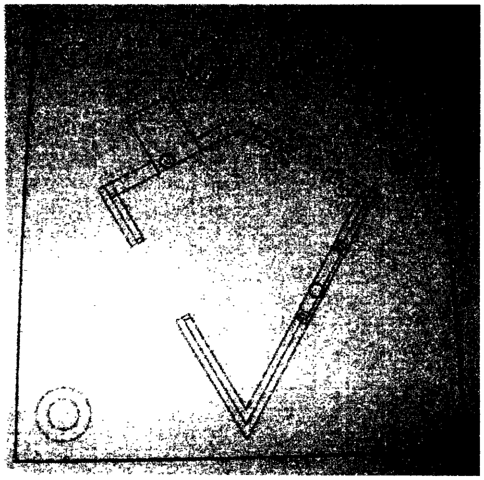

**Figure 20:** Mastercam drawing of core mold corresponding to bottom half of part

The circles on the corners and in the middle top of the mold correspond to the same holes on the cavity mold. The small holes that lie along the part itself are the ejector pin holes. Extra lines that lie along the part assist in making tool paths that go the proper distance along the part.

## 4.2 Machining

The Master cam file corresponding to the cavity mold allowed the production of a tool path utilizing the 1/4" flat end mill, 1/4" round end mill, and the 1/8" flat end mill to produce the mold shown in Figure 21.

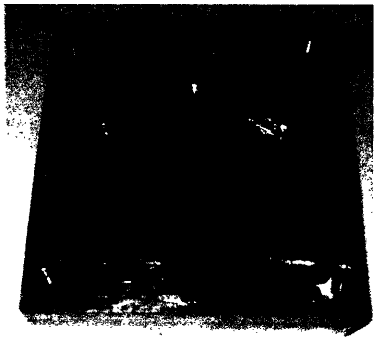

**Figure 21:** Cavity side of mold featuring top of part to be injection molded

The core was similarly produced using mostly smaller flat end mills, and tilting the head of the machine at one point to obtain the proper 21 degree draft angle. This mold can be seen in a modified version from the original in Figure 22.

**Figure 22:** Modified core side of mold featuring bottom of part to be injection molded

As already stated, this mold has been modified from its original design. It incorporates some changes that will be discussed in the next chapter.

# Chapter 5

## PROBLEMS AND SOLUTIONS

The part was initially injection molded with the features described above. This part had several problems that were remedied. Some of these problems were associated with injection molding, and could be fixed with a minor change of features or altering parameters on the injection molding machine. Other problems, primarily associated with the snap fit, required the mold to be redesigned. Each version of the part came across other problems that were sequentially solved. This chapter will discuss each of those problems and the solutions found to each.

## 5.1 Injection Molding

### *5.1.1 Shortshot*

The cause of shortshot is generally that the volume or injection pressure is not sufficient to fill the mold properly. There are several remedies to this problem based on which of these causes is the case. If the problem is that not enough volume of material is injected, the stroke size can just be increased to provide more volume. If the injection pressure is too small, it can be increased, an air vent can be installed to allow air pressure to escape, or the shape of the mold or the gate position can be changed so that the injection pressure is not decreased so drastically at the gate[6].

The problem faced at the onset of injection molding was drastically underestimating the volume to be injected into the mold. This resulted in a shortshot of the part. An example of parts that were shortshot can be seen in Figure 23.

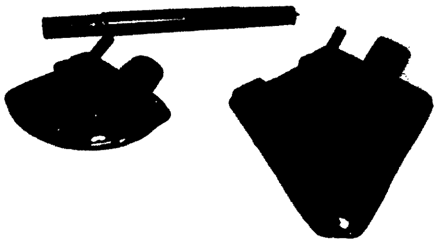

**Figure 23:** Initial shortshot injection molded parts

The volume of the part on the left was drastically underestimated, making only a small portion of the entire part. It is an excellent representation of the flow of the material into the mold, though. The semicircular shape at the base of the part shows the material flow. The part on the right was much closer, but still slightly shortshot, as can be seen most easily at the very base of the part and at the tab on the upper right portion of the part. Other portions of the part that should be at sharp angles became rounded edges since not enough material was inserted to create the pressure to force material into these sharp corners.

The stroke size was changed to be even larger and a new part was created. This solved the problem of the shortshot, but resulted in new problems. This part can be seen in Figure 24.

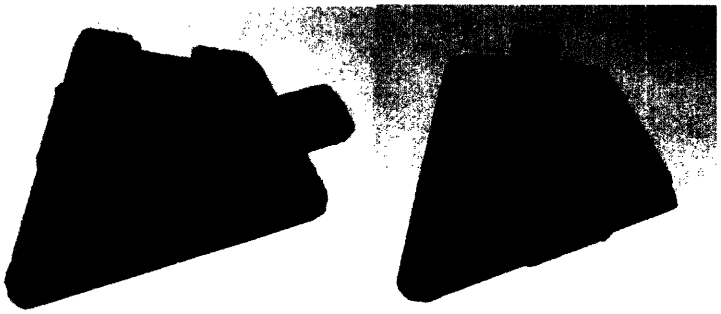

**Figure 24:** Whole part from original part mold; bottom view (left) and top view (right)

Once enough material was injected into the mold for there to be no shortshot or flashing, a new problem arose. At the bottom of the part, the portion of the part furthest from the runner, some burning started to occur. This is what caused the black coloring on the bottom of the left picture of Figure 24. This problem also had a simple remedy, which will be discussed in section *5.1.4*.

### *5.1.2 Flash*

There are many causes of flashing. It is usually the opposite cause of shortshot. It results when there is too much injection pressure, too little clamping force, a poor quality of mold that does not allow a proper parting line, or a polymer that is at too low viscosity. The quality of mold is increased when there is uniform thickness of the part and when the surface quality of the parting lines is increased. Injection pressure could be changed to be lower, allowing the mold to fill properly[6].

There was only ever one issue with flash throughout the project. This occurred after the surface of the mold had been refinished when some plugs had been installed. The recently finished portion was just a hair's width deeper into the mold than the rest of the surface. This poor surface finish caused the flash that can be seen in Figure 25.

**Figure 25:** Photo of injection molded part that contained flash

This problem was corrected for by refinishing the entire surface of the mold instead of just the portion near the plugs.

### *5.1.3 Warpage*

There are varied causes of warpage as well. It can be due to uneven shrinkage, differences in thickness, injection pressure being too low, or insufficient packing. Another possibility is that the part does not properly come off of the mold because of the shrinkage that occurs during cooling. The solution to most of these problems is to allow a longer cool time, reexamine thickness differences, or increase packing pressure. The problem of the part not coming off of the mold may be anticipated in advance and ejector pins added. In some cases, this is not a possibility since the available places for pin holes do not align properly with the part. Other options include the use of a release agent on the mold so that the part comes off more easily or increasing the draft angle so that shrinkage does not affect the part's ability to come off of the mold.

In this project, the part often had the problem of staying on the mold. Ejector pins were added in three locations, but these were the only places that they could be incorporated. When there were still issues with the part coming off of the mold, draft angles were added on the interior of the core mold. While this helped some, there were still occasional issues, which forced the use of lubricant. Some portions of the core side of the mold were plugged so that material was less prone to get stuck onto the mold. Finally, the core mold was entirely redesigned so that more ejector pins could be added and so that there were fewer protrusions into the mold.

### *5.1.4 Burning*

Burning occurs when the cavity into which the polypropylene must flow allows no air escape, so that the material burns and turns black. This rarely occurs near the parting line, since air can escape freely through this small gap. At locations in the mold that are very narrow and deep, though, the increase in pressure causes the plastic to burn. The solution to this problem is usually to design so that there are no deep cavities. In the case that they are necessary, small holes can be drilled to the other side of the mold that are intended to let air escape, but not to let material escape. A photograph of a burned part can be seen in Figure 26.

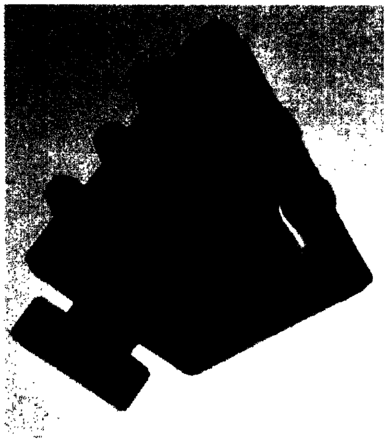

**Figure 26:** Photo of part with burning at ends of long narrow cavities

Though tiny holes were drilled immediately, burning still took place. This is because the material was escaping the hole instead of just air. This material stayed in the hole and would not allow air to escape. The solution to this problem is a method called peening. On the back side of the mold, a short metal rod with a tip slightly larger than the air hole is placed over each hole and hammered. This makes the metal around the hole close over the hole slightly so that there is less room for the material to escape through, but still enough room for air to escape through. A picture of the back of the mold after it has been peened can be seen in Figure 27.

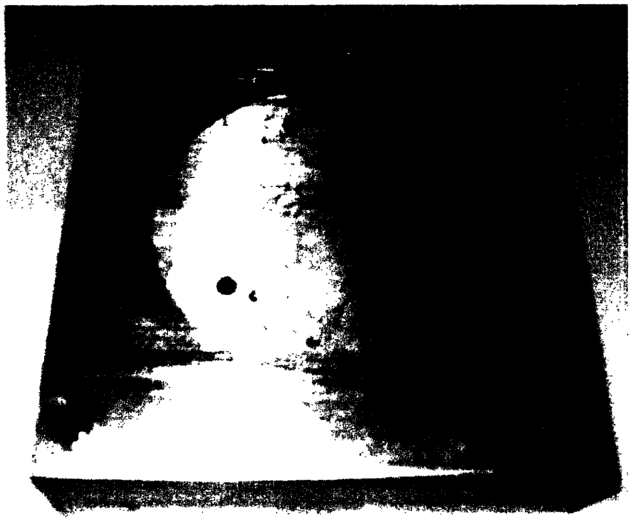

**Figure 27:** Picture of back of mold with small air holes peened

This corrected the problem and allowed the air to escape, while forcing the material to remain within the interior of the mold. The tips of the extensions were no longer black, but contained a small extension the same size and length as the air hole. This can be seen in Figure 28.

**Figure 28:** Picture of extensions after peening

All of the problems associated with injection molding were easily remedied, leaving the problems with the snap fit to be the primary focus of much of the time spent on this project.

## 5.2 Snap Fit

### *5.2.1 Wall Extension*

The part was originally injection molded to produce the part shown in Figure 29.

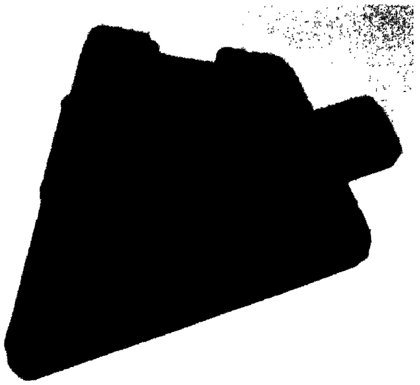

**Figure 29:** Original injection molded part

This part had difficulties with all of the snap fits. The flat wall snap fit did not have a large enough thickness on the tab to obtain a good fit, while the angled wall snap fit had the tendency to push off from the other parts due to the size of the walls. The thickness of the tab on the flat wall was increased, and the walls on the angled portion were lengthened. The walls on the side corresponding to the slot were increased perpendicular to the interior face of the part, and the height of the tab from this same interior face was increased. Limitations on the 1/16" end mill required that the depth be only 3/16". The resulting part from these changes can be seen in Figure 30.

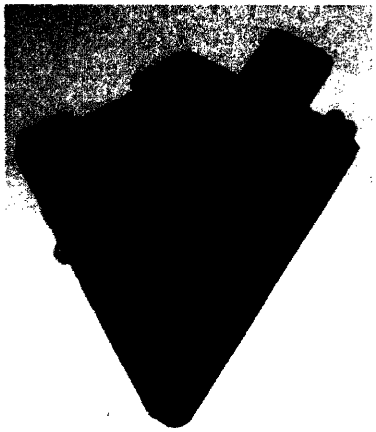

**Figure 30:** Part changed to have wall extensions

This made the snap fit on the flat portion of the wall work, while the angled portion still did not have enough interference to work beyond the connection of just a few parts. This led to more changes.

### *5.2.2 Increased Contact Surface*

The angled wall snap fit had formerly been the product of only one point of contact on each side of the tab. This was because the circular end mill could only produce a point of tangency with the dimensions originally laid out. In order to increase the contact surface, the part was altered to make an "L" shape where the tab was to interfere with the slot. Also, in order to increase the stiffness of the slot to disallow warpage when the parts were connected, a small rib was placed between the two edges on the surface of the interior of the part. These modifications can be seen in Figure 31.

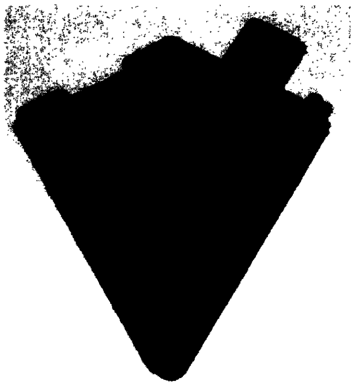

**Figure 31:** Part changed to have increased surface contact of snap fit on angled wall

This fit still had the tendency to repel other parts being attached to it, though, due to the limitations of the height of the walls from the depth requirements of the tools being used.

### *5.2.3 Further Extension*

Extending the walls of the interacting portions of the slots and tabs were then attempted. This would allow greater interference between the parts that would allow the snap fit to hold more solidly. This modification can be seen in Figure 32.

**Figure 32:** Part changed to extend the interfering portions of the angled snap fit

While this changed helped, there was still not enough contact to ensure a proper fit throughout the entire assembly.

### *5.2.4 Addition of contact points*

While the contact points already available were useful, the addition of more points of contact would allow greater interference and a better fit. Extra protrusions were added so that there would be alternating protrusions interacting with one another on the angled wall fit. This change can be seen in Figure 33.

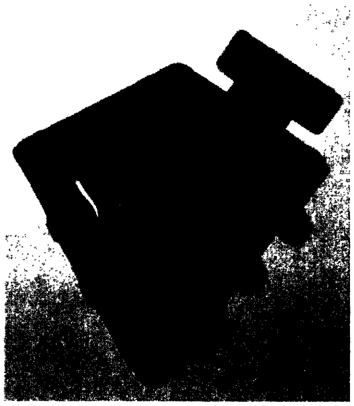

**Figure 33:** Part changed to allow more points of contact

This change added great stability to the interference fit. About twenty parts could be assembled toward the model before they would fall apart.

### *5.2.5 Locking Fit on Flat Tab*

While the snap fit on the flat wall of the part was working properly, it needed to be strengthened so that it would stay together solidly when assembled. While the tab width stayed the same at the portion that would be interfering with the slot, it was widened past this point, so that it would restrain the degree of freedom that would allow it to move horizontally relative to another part. This modification can be seen in Figure 34.

**Figure 34:** Part changed to have locking fit on flat tab

This change made the snap fit extremely solid. When three parts were combined to form an equilateral triangle, their strength was actually greater than the strength of one individual part, as is the case with the assembly of subunits in an actual virus. The assembly of three parts could be shaken or hit and would remain intact. The assembly of an equilateral triangle out of three parts with the locking fit on the flat tab can be seen in Figure 35.

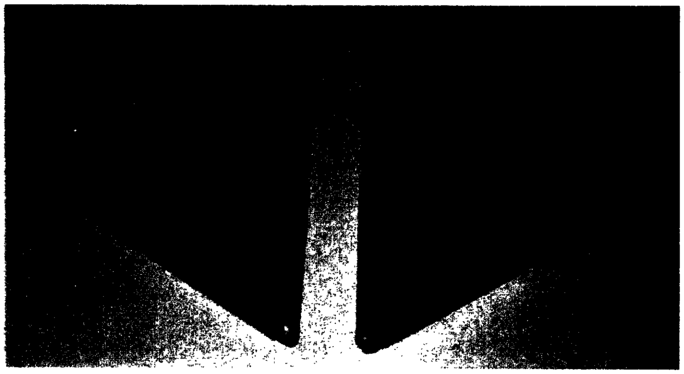

**Figure 35:** Assembly of three parts to form equilateral triangle; bottom view (left), top view (right)

This alteration made the assembly of three parts extremely solid. This motivated the idea to integrate a locking snap fit into the angled wall snap fit.

### *5.2.6 Attempt at Locking Fit on Angled Tab*

The same idea that allowed great stability on the flat tabs was incorporated into the angled tabs. The correct lengths of tabs and slots were calculated so that the tabs could reach through the top surface of the adjoining part and lock around it. Simultaneously, the top part was changed to incorporate the features discussed previously. These modifications can be seen in Figure 36.

**Figure 36:** Part changed to include locking fit on angled tab and surface features

This stabilized the angled fit greatly. Two parts joining at this angled face can be seen in Figure 37.

**Figure 37:** Two parts assembled with locking fit at angled face

Unfortunately, this part developed a new problem. When the surface features were added, they disrupted the fit that was associated with the flat face of the part. When this part was changed to allow the fit to work as before, the core portion of the mold was no longer working as before. The ejector pins and mold release lubricant were no longer allowing the part to come off of the mold, so that they were warped beyond the ability of use. This required the core mold to be entirely redesigned and rebuilt.

### 5.2.7 *Final Model*

The core mold was redesigned so that the locking tab was the only snap fit associated with the angled portion of the wall. The wall extensions were removed, as well as the original slot and tab. Since the mold was being entirely redesigned and rebuilt, the problem associated with the draft angle of this face was still prominent. The solution to this was to have the wall on one side of the mold be perpendicular to the interior of the part, and have the wall on the other side assume the entire angle, being 42 degrees instead of two sides of 21 degrees. This draft was accomplished by making incremental steps with the milling machine whose edges would correspond to the correct angle. The locking tab on the flat wall had to be altered to accommodate this change in the core mold. The core mold associated with all of these changes can be seen in Figure 38.

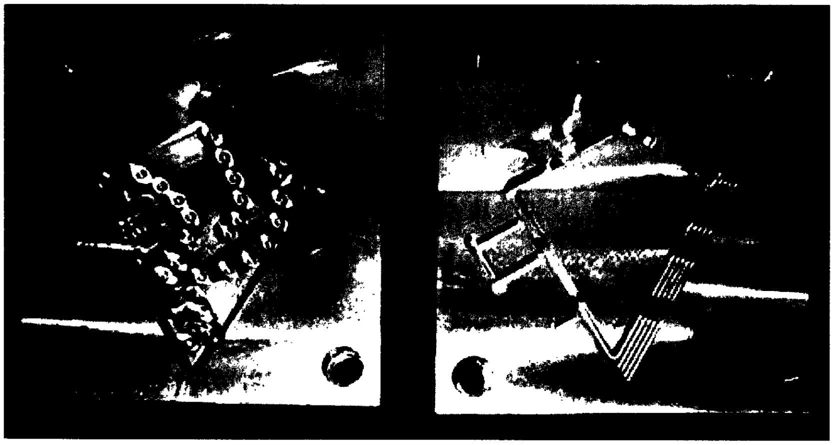

**Figure 38:** Cavity mold (left) including cavities corresponding to surface features and core mold (right) incorporating only locking tabs and having draft angle on only one side

The final part produced by these changes can be seen in Figure 39.

**Figure 39:** Parts from redesigned and rebuilt molds to incorporate only locking fit tabs

Sixty of these identical subunits can be assembled to form the entire icosahedral virus model. This model, shown in Figure 40, can be compared to the photograph of the actual human polio virus and to the SolidWorks model of the design, shown in Figures 41 and 42 respectively.

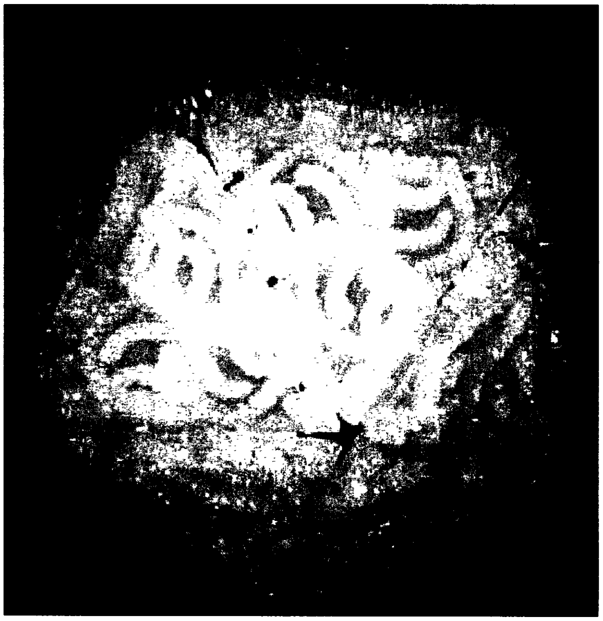

**Figure 40:** Sixty parts assembled to form icosahedral virus model

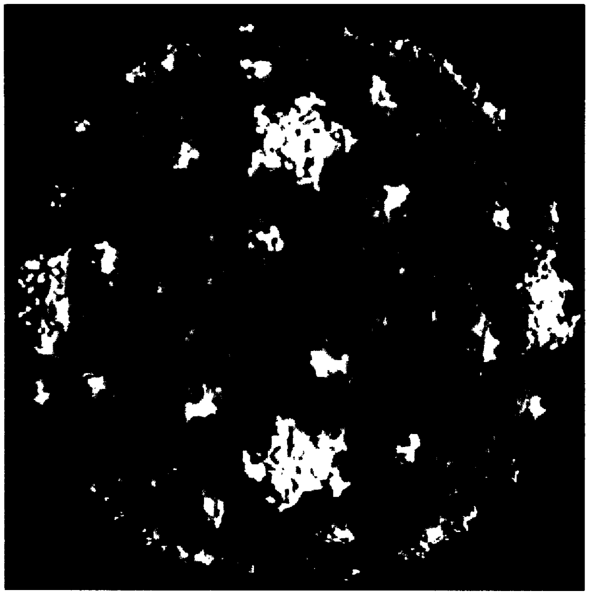

**Figure 41:** Photo of human polio virus

**Figure 42:** SolidWorks drawing of entire assembly including surface features design

The final design accomplished the goal of creating a three-dimensional icosahedral virus structure with the requirements specific to this project.

# Chapter 6

## CONCLUSIONS AND RECOMMENDATIONS

In conclusion, a model of an icosahedral virus was designed and manufactured. The part was designed in SolidWorks and in Master cam, and converted to a tool path that allowed machining of the mold on the CNC milling machine. This mold was then taken to the injection molding machine where multiples of the part could be produced quickly. The mold had to be redesigned several times to incorporate solutions to problems that arose at various points along the way. Corresponding parts were produced upon each revision and tested. Finally, the most recent revision of the molds produced a part that succeeded in all of the requirements of the design and provided a very robust assembly. Sixty of these parts were made and assembled into the icosahedral virus model.

Much consideration was given to different aspects of the design process. Limitations inherent with the machining technology and available injection molding machine contributed to the decisions of design parameters. Ultimately, the part was designed to have a symmetric shape, large size given the size constraints of the available machines, and a tab-into-slot snap fit assembly. The uncertainty associated with the snap fit created most of the problems along the way, so that more options should have been developed early on, making the final solution attainable more quickly.

The changes in design and process capabilities that arose along the way caused many redesigns that disallowed a final product to be produced. Many parts were produced that allowed several lessons on designing and the machining and injection molding processes. This project was one that allowed learning through making of mistakes. Many uncertainties were inherent with the project from the beginning, which made the learning process unique.

Ultimately, this project reached both of its goals. It produced a three-dimensional icosahedral virus model for educational use, while also providing knowledge on the design and manufacturing processes associated with the machining and injection molding of the project, which will prove useful to any mechanical engineering students that aim to develop similar models.

# ACKNOWLEDGEMENTS

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