Problem Solving Processes in the Development of Three Dimensional Printing

by

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Abstract: Understanding the problem solving processes that occur during the development and transfer of new technologies can help companies improve their transfer methodologies. This work uses observations made during the transfer of three dimensional printing into a manufacturing operation from a development environment to understand the factors that influence the rate and quality of solutions to problems.

The technical issues associated with using slip casting to improve the surface finish of ceramic molds produced by 3-D printing were also examined as part of this work. The results were used to define the limitations of the current process and identify directions for future work with the 3-D printing equipment, process and slip casting.

A combination of inductive and deductive logic was used to define a framework that can be used to examine other technologies that are being considered for transfer from one site to another. The main insights from this work can be summarized as follows:

- Slip casting can provide an improvement in surface finish.
- The type and degree of human interaction are key factors in problem solving.
- The maturity of a technology may often determine if it is ready to be transferred
- Capturing the hidden knowledge in the minds of people is an important aspect of a successful transfer process.

Ultimately the effectiveness of any transfer process will depend on how the different pieces discussed in this thesis are put together for the specific transfer application.

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Chapter 1: Introduction

1.1. Licensing new technologies and technology transfer

Developing a competitive edge in the marketplace these days takes different forms. Companies fund university research primarily so that the product of the research work may give them a competitive advantage in the market. Their motivation goes beyond fundamental research to applied research where new methods or technologies developed are applied to producing products or processes for which they have a commercial application. Licensing and purchasing of new technologies from universities and other sources offers companies one way of differentiating themselves and staying ahead of their competition.

Frequently the technology that is being licensed is still under development and it offers the receiving company an opportunity to be involved in the development work, and hence gain an advantage in developing applications based on the technology. The developers on the other hand get an opportunity to see the applications of the technology developed and customized, which gives them insights into the issues faced with the commercialization of the technology.

Making effective use of this opportunity involves transferring specific knowledge about the process and the equipment that uses the process, from the developing site to the company in an efficient and cost effective manner. It requires commitment on the part of all parties involved to provide human resources and funding. It also requires understanding the maturity of the technology being transferred, the capabilities of the receiving site, and the abilities of the individuals involved in the transfer process. Introducing new technologies is a learning process with trials and tribulations, and <u>not</u> a turn-key operation.

1.2. Motivation and research objectives

The work done herein was performed while the author was resident at Johnson & Johnson and part of the team responsible for the introduction of the 3-D printing technology into Johnson & Johnson. Johnson & Johnson is a partner in the Leaders for Manufacturing program that sponsored the author's work, and a member of the Consortium on Three Dimensional Printing at MIT. The consortium is exploring the use of 3-D printing not only for investment casting, but for metal tooling and specific medical applications, all of which are areas of importance to Johnson & Johnson. Hence, Johnson & Johnson was not only interested in understanding the technology and its limitations, but how to develop, and rapidly assimilate future applications based on this technology into various Johnson & Johnson companies.

This study focused on the process of jointly developing the 3-Dimensional Printing technology among MIT, Johnson & Johnson and Zygote Inc., for its application in investment casting. While Johnson & Johnson was quite familiar with investment casting in its current form, what 3-D printing aimed to do was eliminate the need for the elaborate wax modeling and ceramic slurry dipping processes, thereby allowing a product developer to go from computer generated model to metal casting in a single step. Needless to say, the potential benefits were enormous. However, the simplification required a quantum change upwards in the level of sophistication of the users and equipment.

Johnson & Johnson was licensed by MIT to use 3D printing for investment casting, while Zygote was licensed to design and fabricate the equipment to be used for the process. The equipment used at Johnson & Johnson was an alpha prototype produced by Zygote Inc.. Johnson & Johnson along with two other sites, were testing out the new equipment even as they developed the process. Their intent was to provide feedback to Zygote on the performance of the machine and other aspects of its capabilities so that Zygote might improve future generations of machines to better meet Johnson & Johnson's needs. At the start of the internship assignment, the process on the alpha equipment produced castings that did not meet the surface finish requirements for Johnson & Johnson applications. Further, the reliability of the equipment was far below Johnson & Johnson's initial expectations.

Consequently, this work revolved around resolving equipment reliability issues and determining the feasibility of using slip casting to improve the surface finish of the final castings. A key component of addressing the reliability issues involved understanding the problem solving process which determined the rate and quality of solutions to problems with the equipment. The questions that we were trying to answer were:

i. What factors influence the surface finish of the metal parts when the mold is subjected to slip casting ?
ii. What factors affect the problem solving processes, which in turn affect the technology transfer process? How might Johnson & Johnson influence the problem solving process in the future ?
iii. Are there specific characteristics of the process and organization that influence the rate and effectiveness of the transfer process?

1.3. Project deliverables and content

The work presented in this document focuses on (i) the technical issues surrounding the slip casting process and (ii) the problems with the equipment used to make the investment casting shells. The problems faced with the equipment were the basis for studying the problem solving process, technological and organizational maturity issues.

This work is divided into chapters to facilitate focusing on specific aspects of the internship.

Chapter 2: This chapter defines the need for rapid prototyping in the investment casting industry. It also covers the specific customer needs that have to be met by the current 3-D printing technology. The needs surrounding the equipment that have to be addressed for the technology to be accepted as a tool within Johnson & Johnson are also described.

Chapter 3: This chapter deals with the technical issues around the slip casting process. The experimental work is described along with the data and results obtained from the experiments. The problems with the existing equipment and how they influence the slip casting process are covered. Lastly, the areas that need further investigation, trade-offs involved in using slip casting are pointed out, and recommendations are made on how to address some of the immediate problems that affect the slip casting process.

Chapter 4: This chapter examines the problem solving process associated with resolving the many problems faced by the team in improving the performance of the equipment. The problems are classified based on their degree of difficulty, quality and speed of resolution. The interaction patterns in the course of solving the problems are examined in detail. The effect of the frequency and type of interactions between the Johnson & Johnson team and the developers is then examined in the light of the classifications to determine if there are relationships that exist between them.

Chapter 5: In this chapter the larger issues involving the organization and technology which influence the rate of introduction and its acceptance are examined. Comparisons between the introduction of stereo lithography and 3-D printing are made to illustrate how the state of the technology when it is introduced affects not only the time it takes to introduce it, but the organization's perception of its capabilities. The role that expectations, structure and capabilities of the team members played in determining the rate of introduction are discussed.

Chapter 6: In the final chapter the observations and conclusions from chapters 3,4 and 5 that address the specific research questions are drawn together. It would be presumptuous to try to provide a definitive stepwise procedure for technology transfer, because I do not believe that only one exists. However, a framework with which to examine not only new technologies, but the organizational aspects that influence the process of transfer is provided. Pitfalls and potential effects that can be expected when one or more factors are ignored or dismissed as unimportant are pointed out where appropriate.

Chapter 2: Rapid Prototyping of Investment Castings

2.1. Rapid prototyping in investment casting

Traditionally investment casting has been a time consuming process. First, wax patterns of the desired shape are made. These are assembled into a 'tree' that may contain many molds. The 'tree' is then dipped in a ceramic slurry which coats the wax pattern and ultimately forms the actual ceramic mold. Ceramic layers immediately adjacent to the wax are made from slurries that contain fine particles and consequently give the final casting a smooth finish. Between dips the ceramic coating is allowed to dry naturally to prevent it from cracking. The dipping and drying process is repeated many times to form a thick shell around the wax. The slurries used for the outer coatings contain coarser particles of sand. Once the final thickness of mold is achieved, the mold is allowed to dry and harden before the wax is melted out. The mold is then fired at temperatures close to the melting point of the metal being cast before the casting metal is poured into the shell. The process of creating a mold from a wax can take from hours to days depending on the types of slurries used, the size of the casting being made and the processing conditions.

The product development process within Johnson & Johnson was an iterative one where concepts were generated within product teams and refined over time. However, beyond a certain point in the development process it was not possible to develop the product without a prototype that the team could hold and test for functionality. The look, feel and fit of the product was critical in determining if it could and should be produced. Since the prototypes were used to develop the product itself, as well as jigs and fixtures for the manufacturing operations, they had to replicate the final product as closely as possible. Dimensional tolerances and surface finish of the prototype were used to determine the type and amount of post processing that would be required. The post processing requirements influenced plant capacity, throughput and cost of the parts. The dimensions and shape of the prototype determined if new tools and software programs for computer numerically controlled machines would be required. The prototypes themselves were used to obtain customer feedback on the actual part to determine to what extent it satisfied the customer's needs. Since the bulk of the customers were not intimately familiar with the technical aspects of the production process, the prototype had to closely resemble existing products cosmetically.

The conventional process for generating these prototypes involved: (i) creating drawings of the parts, (ii) submitting a tooling request for the part (iii) making a wax representation of the part, which required a skilled craftsman, (iv) dipping the waxes to create the ceramic shells for pouring metal, (v) and actually producing the metal part. The process was not only time consuming but expensive, and all it yielded was a single prototype. Subsequent iterations involved the entire process over again. Hence, the ability to rapidly produce functional metal prototypes that allowed the designer to get feedback on the form, fit and functionality of the design was particularly valuable. It also allowed other groups such as packaging and marketing to develop appropriate methods and strategies to handle the new product.

2.2. Current techniques for prototyping cast parts

Stereo-lithography (SLA) allows the designers to produce resin based prototypes of designs in significantly shorter times. Stereo-lithography uses the computer aided design (CAD) drawing created by product developers to make a resin based replica of the drawing [Deitz, 1990, Miller, 1991]. The primary drawback of prototypes made out of resin are its physical weakness, which prevents its use in functional tests. While it is a significant improvement over conceptual sketches on paper and reduces the time required to produce conceptual prototypes by a factor of two or three, it fails to meet the need for fully functional parts. Recent modifications to the SLA process allows designers to produce models that can be used in place of waxes. While this reduces the wax modeling time, it still requires the time consuming slurry dipping process. Further, parts with internal cavities in the castings still cannot be produced using this process.

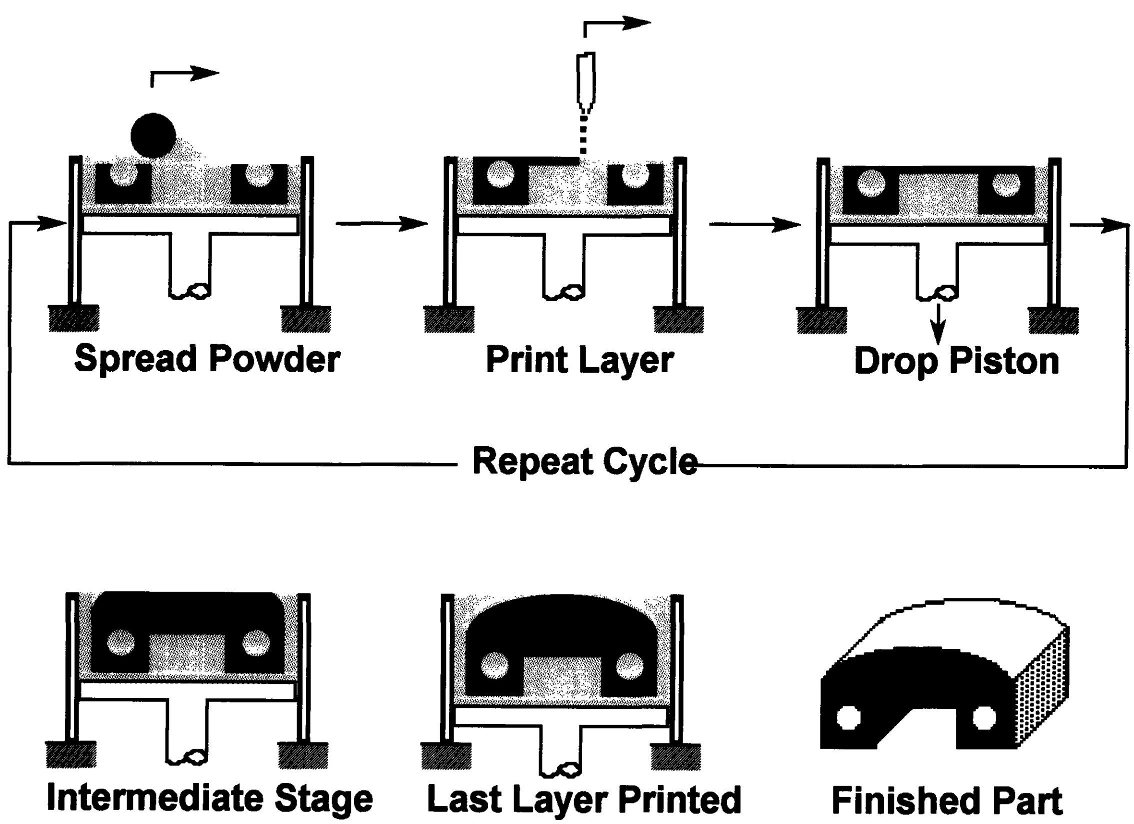
Other technologies such as direct sintering of waxes and laser sintering are under development, these techniques allow the user to rapidly create the wax model required to make the mold. These techniques still do not allow the product designer to create internal cavities in the casting. The nature of the wax and slurry dipping process inherently prevents the foundry from producing molds that have internal cores.

2.3. Three dimensional printing overview

The three dimensional printing process allows the product designer the ability to produce a limited number of working prototypes within a matter of days rather than weeks. The designer can create a solid model on a computer aided design (CAD) station using any number of software packages. The CAD file is then used to drive the 3-D printing machine which builds the ceramic mold. The machine parameters are determined by the CAD drawing and the settings on the machine. Metal is then poured into the ceramic mold to produce the desired part. The process eliminates the capital intensive slurry dipping process equipment, allows the designer to create molds with ceramic cores and dramatically shortens the time to create a functional prototype.

In the 3-D printing process (figure 1), a thin layer of powder, which is a mixture of a ceramic and an anhydrous acid, is spread on top of a piston. A moving jet that traverses the bed, places microscopic drops of a liquid binder that reacts with the acid to bind the ceramic powder together. The placement of the drops is determined by the machine software and the CAD file of the mold being built. After the first layer is 'drawn', the piston drops a fraction of an inch and a second layer of powder is spread on top of the first one. The 'drawing' process is repeated again. In this fashion the entire solid object model is built up of layers in the bed. When the part is complete it is removed and fired to burn off the remaining acid component and to fuse the ceramic. The unbound powder is then removed by vacuuming and microwave boiling. The ceramic shell is then used to cast the metal part.

Figure 1: 3-Dimensional printing process sequence



Structurally the mold is composed of layers of powder that are held together by fused binder. As a result the part is quite porous and has a visible layered structure. Consequently, the metal castings made directly from the mold produced in the steps described above have a very rough surface and the position of the layers is easily observed in the final part. This means that the castings require significant machining after casting to make the surface smooth. On the other hand, the parts produced from the wax process are almost perfectly smooth and require almost no machining of the surfaces.

2.4. Customer needs in investment casting

At Johnson & Johnson the parts produced from investment casting had to have specific characteristics. To be a substitute to the wax process, 3-D printing had to demonstrate equivalent or better performance in the following areas:

1. Surface finish
2. Dimensional accuracy
3. Feature definition
4. Cost

While all of the above areas were required for a useful process, surface finish was the most easily perceived and compared by an individual casually handling a part. Hence, it had the greatest impact on peoples' perception of the capabilities of the 3-D printing technology. Since the most obvious weakness in the molds produced was their surface finish, the research efforts were focused on developing a process that would allow Johnson & Johnson to create parts with a surface finish as close as possible to those produced using the wax process. The intent was to examine dimensional accuracy and feature definition once the capability to repeatably produce parts with a surface finish better than 100 μ inches had been developed.

The 3-D printing process itself was relatively slow. The build times for a typical product ran from a few hours to a few days. This was still faster than the conventional method of getting a metal prototype, which under normal circumstances took 4-18 weeks to produce. The development of the 3-D printing process was being done within the research group at Johnson & Johnson Professional. The members of the team were responsible for other processes and design activities in addition to 3-D printing. Hence, a key requirement was that the machine be capable of running unsupervised. Further, given the nature of the process, once a build had been started, it could not be aborted and restarted without affecting the quality of the finished part significantly. This meant the machine and its components had to be very reliable in order to build parts for process development.

Chapter 3: Experimental Work and Results

3.1. Slip casting as a means to a better surface finish

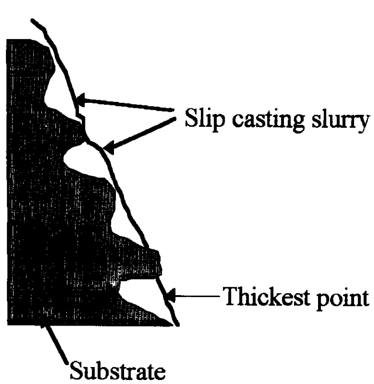
Given the porous nature of the parts produced by 3-D printing, slip casting was explored as a technique to produce a smooth surface on the ceramic shell. The feasibility of the technique was demonstrated at MIT (Sachs et. al. 1992) on flat surfaces. The focus of the research work was to determine if it could be used with the shells produced by the 3-D printing machine to produce castings with smooth surfaces.

The slip casting process is primarily a function of the following variables:

1. Porosity of the substrate
2. Solid content of the slurry
3. Slip casting time
4. Viscosity of the slurry
5. Particle size

The slip casting process involves making a slurry composed of microscopic particles of ceramic suspended in a liquid medium. The slurry is then poured into the porous ceramic mold and allowed to sit for a predetermined amount of time. Capillary action draws the liquid medium into the mold causing a fine layer of ceramic to be deposited on the wetted surface of the mold thereby making it smooth (figure 2).

Figure 2: Sketch of slip casting over a ceramic substrate



The remaining slurry is then poured out of the mold and the 'wet' part is dried and fired to fuse the ceramic coating.

3.1. Dynamics of the slip casting process

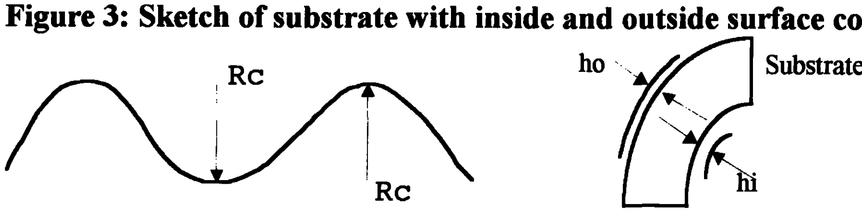
The slip casting process is fundamentally used to create a non-conformal coating on the substrate. This is key because it is the formation of this non-conformal coating that causes the smoothening of the ceramic substrate. The differential equation (Dodds, 1985) that describes the cast layer thickness, *h*, as it varies with time, *t*, is:

$$\frac{dh}{dt} = \frac{d^2 \varepsilon^3 \Delta P \ 2\gamma}{36K\mu(y-1)(1-\varepsilon)^2}$$

where *d* is the particle size in the slip, ε is the void fraction of the cast layer, μ is the viscosity of pure water, *y* is a function of the solids content of the slip, γ is the surface tension of water, K is a constant and ΔP is the capillary pressure drop.

Consider an uncoated substrate shown in the figure 3. The initial roughness of the uncoated surface is defined by R_c, which also represents the maximum 'peak' or 'valley' on the surface which has to be covered by the slip cast coating.

Figure 3: Sketch of substrate with inside and outside surface coating



The relationship between the coating thickness and its effect on the roughness is given by,

$$\frac{dh}{dt} = \frac{d^2 \varepsilon^3 \Delta P \ 2\gamma \ Rc}{36K\mu(y-1)(1-\varepsilon)^2 \ h(Rc \pm h)} \tag{1}$$

For outside surfaces the relationship in (1) can be expressed as

$$\frac{dh}{dt} \propto \frac{Rc}{(Rc + ho)} \tag{1a}$$

where h_o is the thickness of the coating formed on the outer surface.

For inside surfaces the relationship in (1) can be expressed as,

$$\frac{dh}{dt} \propto \frac{Rc}{(Rc - hi)} \qquad (1b)$$

where h_i is the coating thickness formed on the inside surface. What this suggests is that the coating thickness on inside surfaces is thicker than that on outside surfaces. It is this non-conformal coating phenomena that causes the surface to become smooth. The coating thickness is thinner over 'peaks' on surface, and thicker in 'valleys' on the surface.

For the current application the desired result was a ceramic shell with a very thin coating of a ceramic material, like alumina, on all surfaces that the molten metal would be in contact with. If the coating was smooth the metal casting produced using the shell would have a smooth surface. Hence, the critical measures of process capability were (i) the uniformity of the coating thickness over the surfaces and (ii) the repeatability with which the coating could be produced.

3.2. Experimental methodology

Since ultimately the benefit of the research activity to Johnson & Johnson lay in being able to produce good metal castings, rather than attempting to perform a comprehensive fundamental analysis of the process, emphasis was placed on quickly developing a process that would result in acceptable metal castings. A formalized approach was taken to characterize the slip casting process for the porous shells produced by 3-D printing . In order to maintain management enthusiasm about the technology, and continued support for the development effort, the purely academic nature of research was balanced against the practical aspect of producing acceptable metal parts. This meant the process would have to be refined as the performance of the equipment improved. Hence the focus of the research work was to,

1. Identify a process that could be used to produce acceptable coatings.
2. Develop a process that was repeatable.
3. Identify key characteristics and trade-offs.
4. Identify key issues to keep in mind as further development was done.

The sequence of activities that led to the results presented here were:

- Experimental design.
- Test structure design.
- Experiments.
- Data analysis.

3.2.1. Experimental design

To limit the scope of the research work to that which could be performed in the time available, the first step was designing the experiments needed to achieve the objectives. It was obvious that determining the current characteristics of the parts being produced was critical. The porosity and the microstructure of the substrate (the ceramic parts) had to be determined since they had a profound effect on the formation of the slip cast coating. Screening experiments were run to identify suitable slurries for the slip casting process. Once the slurries were identified, tests were run to determine the coating thickness produced as a function of the slip casting time.

There were three reasons for keeping the experimental design simple:

1. The entire process from building test parts to obtaining results took weeks. Hence, to complete all the experiments in the available time, they had to be simple.
2. The experiments had to be repeatable by others and not inordinately complex or costly.

3. The focus was on determining a process window and not the optimum operating point.

Ultimately the following tests were performed

- Porosity and surface structure tests
- Slurry concentration tests
- Slip casting time tests

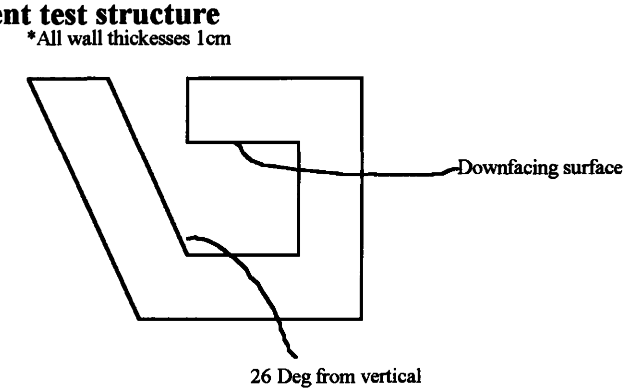
3.2.2. Test structure design

Close examination of the shells produced by the process revealed that there were distinct problems associated with horizontal, vertical and inclined surfaces. The orientation of the surfaces with respect to the powder layers, the direction of the printing, and whether the surface was supported by layers underneath it that had been printed on (downfacing surfaces), played a major role in the smoothness of the surface. Further, the software algorithm used to compute the placement of the binder drops determined the accuracy and surface finish of the parts. Any errors in drop placement and the resultant surface roughness were exaggerated on inclined surfaces since errors in two axes were compounded along inclined surfaces. Hence the test part had to facilitate examining each of these problems independently. An inclined surface with a 26° angle was designed in the test part since theoretically it would require an additional printed line on every other layer. The additional line made examining the inclined surface and detecting any printing errors easy.

Other factors that were considered in designing a test part were the volume of ceramic material in the part, and the time it took to build a part. The volume of the ceramic substrate was critical since it determined the capillary volume required for the slip casting and the cost of the part. If the volume were too small it would be impossible to form thick layers of coating. If it were too large it would be expensive to produce. Lastly, since reliability of the machine was very poor and the factory only operated for 8 hours a day, the part had to be small enough to be built within an 8 hour shift.

The test structure is shown in figure 4. The intent of creating a cup shaped object was to meet all the requirements defined above, facilitate holding the slip casting slurry and replicate the process of coating the inside of a ceramic mold.

Figure 4: Experiment test structure



3.2.3. Experiments

Porosity The porosity of the test part was determined by simple volumetric analysis. The dry volume of the part was determined directly by calculation. The part was designed to facilitate this. It could also be determined directly from the CAD system. The part was then placed in a polystyrene weighing dish (weighed previously) and its dry weight determined using a calibrated Mettler balance. While still on the balance cold distilled water was added drop by drop into the part till it was completely saturated. The excess water was then poured out carefully. This process was repeated for five samples. The parts were then dried at 180°F for 16 hours, cooled, and re-weighed on the same balance to determine the weight of the parts after the experiment. The volume of water required to saturate the part was used to determine the porosity of the parts. The experimental data is provided in table 1.

$$Porosity = \frac{Volume\ of\ water}{Volume\ of\ substrate}$$

Table 1: Porosity of substrate

Sample	*Dry Weight* (gms)	*Sat. Weight* (gms)	*Redry wt.* (gms)	*Vol. of water* (ml)	**Porosity**
1	65.56	82.63	65.56	17.07	0.490
2	65.68	83.32	65.66	16.64	0.477
3	65.06	81.75	65.28	16.70	0.479
4	65.48	82.10	65.49	16.62	0.477
5	65.67	82.43	65.83	16.76	0.481

Volume of ceramic part 34.85 ml.

The dry volume of the part used in the calculations was determined directly from the CAD drawing of the part.

Slip Casting The slip casting experiments were performed for a range of slip casting times using two slurry concentrations. The slurries were prepared at MIT using a 1μm nominal particle size commercial grade alumina (Reynolds RC-172 DBM). The process for preparing the slurry is described in the appendix. In all cases, the slurry was mixed in a ball mill for a minimum of 12 hours prior to use. The mixing ensured that the slurry was free of all agglomerates and the solid particles were thoroughly dispersed. The pH of the slurry was maintained between 3.0-3.5 by adding 1N nitric acid to the mixture prior to ball milling. The low pH ensured charge separation of the alumina particles and hence less aggregation [Napper, 1983, Reed, 1989].

Prior to slip casting, the parts were pretreated with colloidal silica to fill in any large voids in the parts, and create an internal void structure that was uniform. The parts were soaked in colloidal silica (Nyacol 830) for 30 minutes until they were saturated. They were then dried in an oven at 180°F for 16 hours and allowed to cool down to room temperature before use.

The prepared slurry was poured into the part as rapidly as possible, and the part allowed to stand for the test period. During the casting process, more slurry was added slowly to make up for the lost volume. At the end of the test time, the slurry was poured out of the part carefully, but quickly, to prevent the coated surface from being disturbed. The coated parts were then dried in air for 24-48 hours or in an oven at 180°F for 16-20 hours. The parts were then fired (see appendix for drying/firing recipe) to fuse the silica and alumina coating and burn off any organic binder present in the coating.

The initial experiments were based on tests run at the Ceramics Processing Research Laboratory at MIT using slurries that had 10% and 20% by volume of solids. The coatings showed cracking due to shrinkage and differential stresses in them. The cracking was minimized by the addition of an organic binder, polyvinyl alcohol, to the slurry for subsequent experiments.

3.2.4. Coating thickness measurements

Cross sections of the parts were prepared for examination under a scanning electron microscope (SEM). The parts were cross sectioned and encapsulated in clear epoxy. They were then lapped in stages (9µm-6µm-3µm-1µm) using a polishing wheel down to the ceramic surface and finally gold coated. SEM photographs were taken of the coated surfaces and the ceramic substrate. The photographs included a calibration bar which allowed measurement of the coating thickness directly from the photographs (figure 10) using a digital caliper.

There are different methods available to determine the coating thickness and the size of the defects present on the ceramic substrate. However, the method used here was selected for its simplicity, ease of training and repeatability. Figure 10 is an example of the SEM photographs that were taken for the thickness measurements. Multiple photographs were taken across the length of the surface of interest, covering a total length of not less than 1 cm. The coating thickness was measured on these photographs at five points along the surface covering a 1 cm length. For the purposes of these experiments the thickness was measured at points where the coating appeared to be thickest. The thickness was defined as the height from the top surface of the substrate to the top surface of the coating (i.e. from the base of a 'valley' to the top of the coating) as illustrated in figure 2. The arithmetic average of five readings taken across the length of the surface was used in all the calculations.

3.3. Results

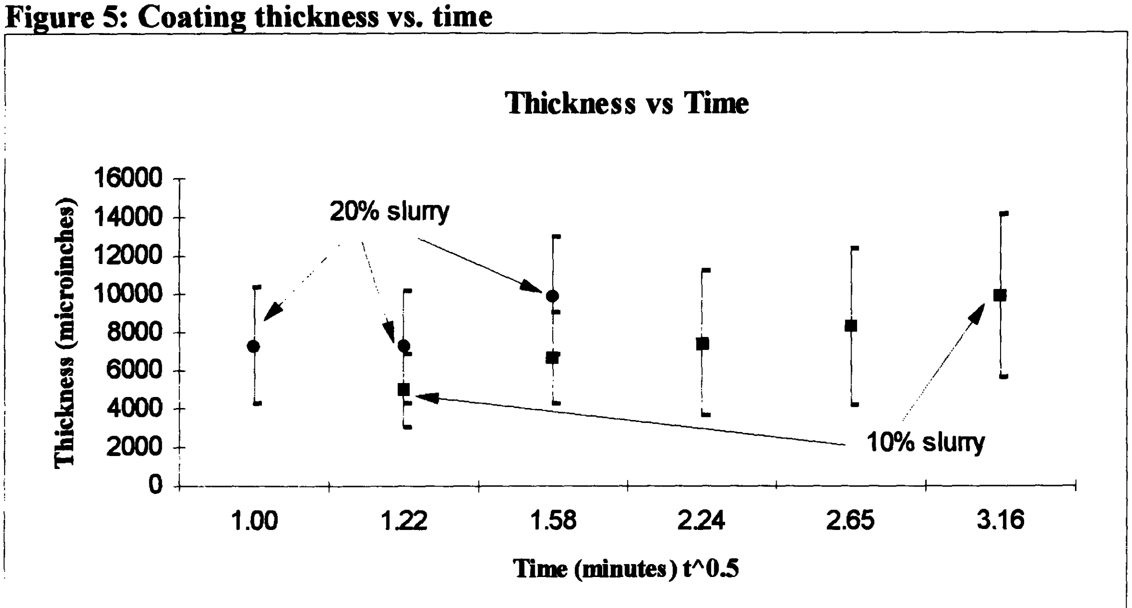
The most obvious result observed from the SEM photographs was the formation of non-conformal coatings on the surface of the substrate. This supported the theoretical predictions that non-conformal coatings would be formed on the surface. This is highlighted in Figure 10 where a defect present on the surface of the substrate is essentially uncoated while the surrounding 'inside' surfaces are coated with the slip cast film. It is important to note that the microstructures of the substrate play a key role in the formation of the non-conformal coatings. At locations where there were defects in the underlying microstructure the coatings were not formed as expected. This is described in greater detail later in this document.

3.3.1. Coating thicknesses

Figure 5 shows the variation in coating thickness as a function of slip casting time for two different types of slurries. The data shows almost a linear relationship between the thickness (h) and square root of time (t^0.5), this is consistent with equation (1). When the data is plotted on a log-log scale of thickness vs. time the slope of the line is ~0.5 as expected from theory. By fitting an equation of the form $h \propto t^a$ to the actual data it is possible to determine the value of 'a' and compare it to the theoretical value of 0.5. The error bars in figure 5 represent the three standard deviation limits for the measured data. The standard deviation in the data ranged from 600-1400μinches, significantly greater than the initial roughness of the substrate. However, it is reasonable to assume that the underlying roughness contributed to the spread in the measured data.

The shells produced from the 3-D printing machine had layers that were designed to be 176μm thick. Hence, the coatings were expected to cover steps at least 176μm high. Given the inherent variability in the layer thickness we believed it was necessary to look

Figure 5: Coating thickness vs. time



at a range of thickness which would allow better understanding of the process. Looking at the thickness data it is clear that for very thin and very thick coatings, there is greater spread in the data. This can be explained in two ways.

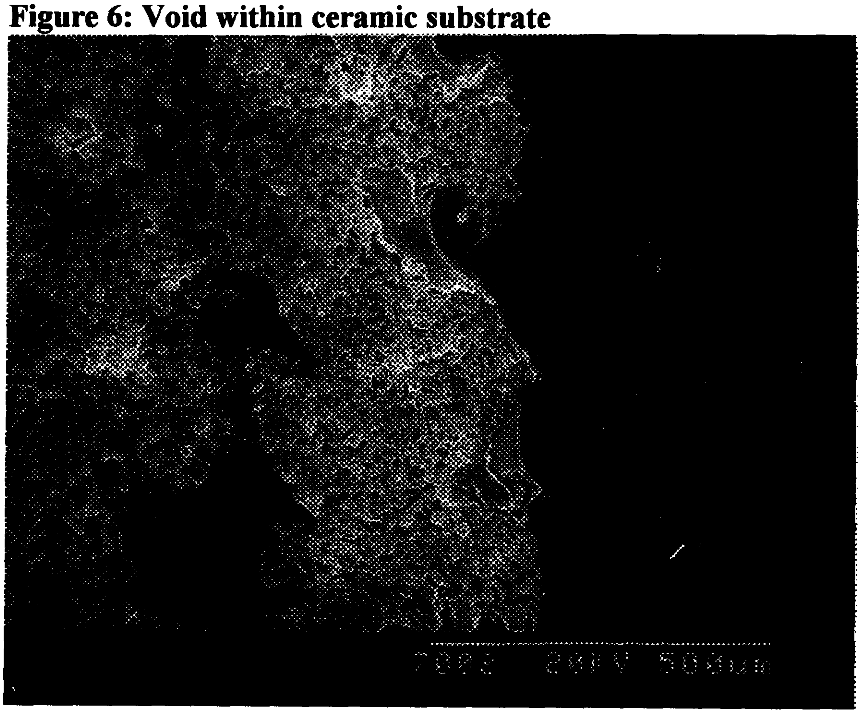
3.3.1.1. Changes in porosity due to the coating

When the slurry is first poured into the ceramic substrate, the larger voids within the substrate are filled first with the slurry. As a result the actual pore size and hence the porosity of the substrate, gradually changes. The capillary action which is the driving force behind the formation of the coating drops off rapidly causing the coating thickness to be thinner than predicted by equation (1).

3.3.1.2. Inherent variations in substrate porosity

The substrates produced from the machine inherently had non-uniform porosity. This can be observed in figure 6 which is a SEM photograph of a cross section of the substrate. The dark region in the lower left side is the void. There were large voids within the substrate which caused localized variations in porosity. For very short slip casting times the slurry would only fill the voids rather than

Figure 6: Void within ceramic substrate



forming a coating on the surface. Thus, until the void was sufficiently filled with slurry very little coating was formed on the primary surface of the part.

3.3.2. Feature definition

The definition of features on the surface of the part is modulated directly by the thickness of the coating formed on the surface of the part. Since the primary purpose of forming a coating is to obliterate the 'steps' created by the 3-D printing process, any other features that are the same size as the coating thickness are also covered up by the coating. Thus, there is a direct relationship between the smallest feature that can be defined on the part and the coating thickness. As the coating gets thicker, the size of the ***smallest*** feature that can be produced on the metal castings increases. This is because the coating causes 'blurring' of sharp corners and projections resulting in a smoother surface and indiscriminately covers up any small features that may be present.

As mentioned earlier, driving force causing the formation of the coating is the capillary action due to the porosity of the substrate. In 'valleys', the coating rate is faster because the porous volume per unit surface area exposed to the slurry is greater. On projections, the porous volume per unit surface area is smaller resulting in a lower coating rate. It is this differential rate that allows the smoothening of the surface.

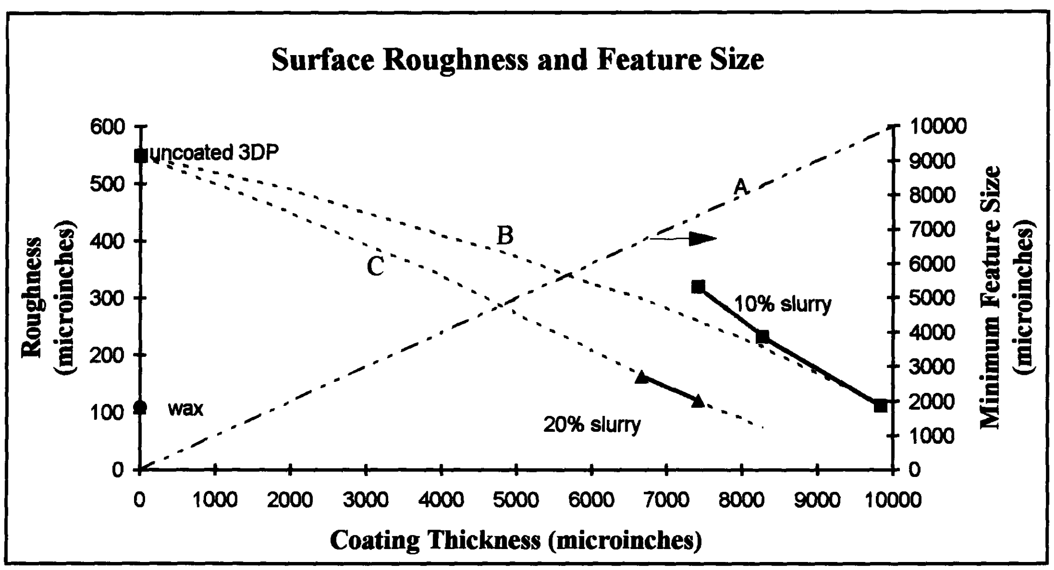
Figure 7 shows the relationship between the coating thickness and the feature size (Y2 axis on the right). As the coating thickness increases so does the minimum feature size that can be defined on the finished part. Features on the substrate that are smaller than the coating thickness are completely covered up by the slip cast coating. Hence, it is desirable to obtain as thin a coating as possible if fine features are to be defined.

3.3.3. Surface roughness

The surface roughness of the final metal casting was the critical feature, and the driving force behind this work. Ultimately, it is the final test that determines the success or failure of the slip casting process in modifying the surface of the ceramic shell that is used to produce the metal casting. The instrument used to measure the surface roughness of the casting is a profilometer with a diamond or ruby stylus.

Figure 7 shows the relationship between the coating thickness and the roughness as measured on the metal casting produced. It is important to note that the coating thickness data was obtained by cross sectioning a ceramic test mold that had been treated with slip casting. The metal casting which was used for the surface roughness test was produced using a ceramic mold that had been treated with the slip casting slurry in exactly the same fashion as the test part used for the coating thickness experiment. Since both parts had been treated by the same researcher, using the same slurry, at the same time, it is reasonable that the slip cast coating thickness was similar in the two molds.

Figure 7: Surface roughness and feature size



Line A on figure 7 is the feature size line, and represents the relationship between coating thickness and feature size. The experimental data and the family of curves (dashed lines, B, C) drawn by extrapolating the experimental data are the roughness curves and show the trend in roughness vs. coating thickness that we would expect to see for the different slurries. As the initial roughness of the ceramic mold improves the starting point for these curves drops thereby allowing a smoother surface to be obtained with a thinner coating. These dashed lines *do not* represent actual experimental data. By reading across from the desired roughness to the roughness curve, it is possible to determine the coating thickness required to get the desired roughness. The feature size curve then indicates the minimum feature size that can be obtained for a particular slip cast coating thickness.

For example, if the desired roughness of the part was 100 microinches and we wanted to use a 20% slurry. We would read across from the Y axis from the 100 microinch point to the 20% curve (curve C), and then read the corresponding value on the X axis. The required coating thickness would be approximately 7250 microinches. Then, reading up from the X axis to the feature size curve (curve A) and across to the Y2 axis we would see that the minimum feature size that could be obtained would be 7250 microinches.

There are two points on the Y axis which show the roughness of a casting made using an uncoated mold made with the 3-D printing process, and one made from a wax master. There is a substantial difference in the roughness. As expected the roughness of the metal casting was improved substantially by adding a slip cast coating to the ceramic shell prior to metal casting. These are the experiment data points on the graph. However, there is a trade-off between having a smooth surface and being able to create fine structures in the casting. It is this trade-off that poses a serious limitation to the applicability of the slip casting process to the current investment casting application.

3.3.4. Substrate and coating defects

The substrate and the defects present in and on the substrate have a profound effect on the quality of the slip cast coating. A closer examination of the substrate revealed the following features:

1. Porosity of the substrate was very non uniform.
2. Drop placement accuracy of the machine was poor.
3. Spacing between the lines (related to drop placement) varied considerably.

Optical examination and SEM photographs also showed that the porosity of the part was very non-uniform. There were large gaps in the structure between layers and between lines. This caused non-uniform coating because the liquid was drawn into these cavities while the coating formed in surrounding areas, ultimately resulting in an undulating surface.

Figure 8: Undulating surface after coating

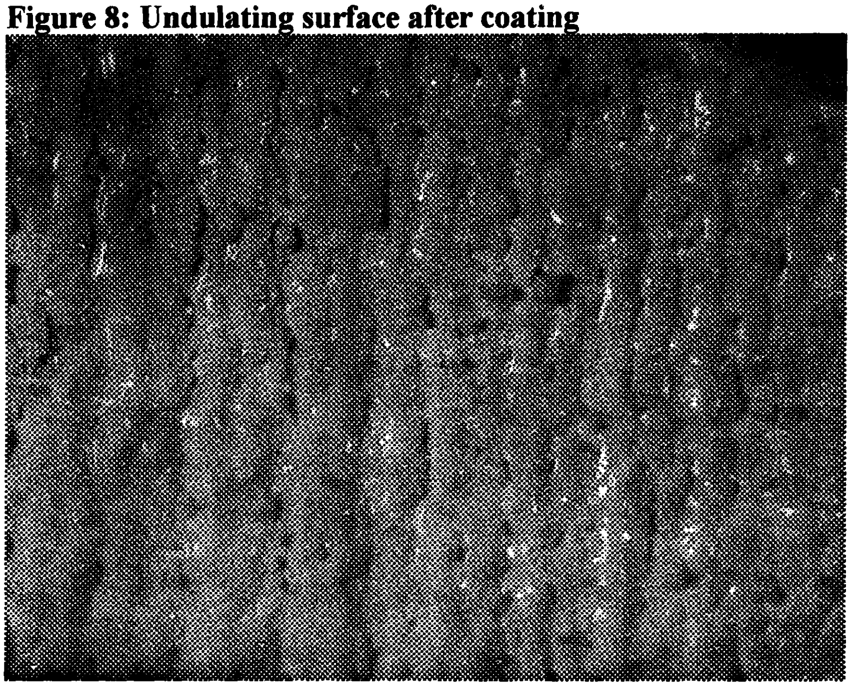
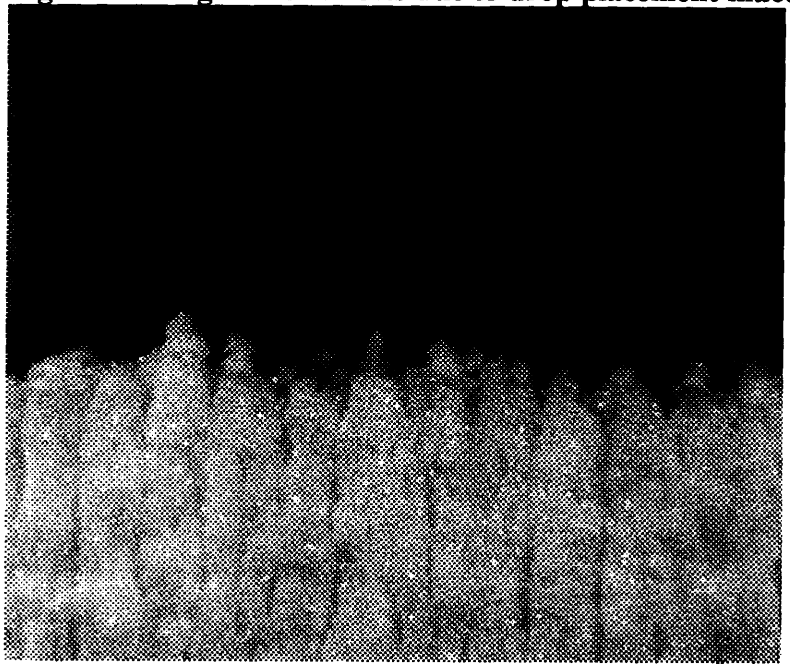
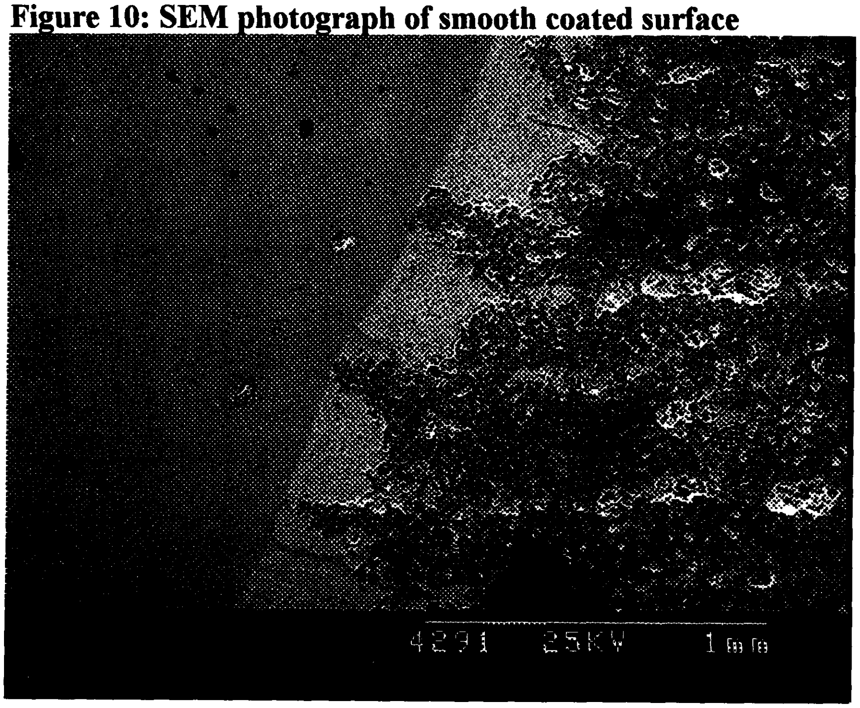


Figure 9: 'Finger like' defects due to drop placement inaccuracy



While the colloidal silica treatment filled in some of these cavities with silica deposits, other cavities were too large to be completely filled in. Consequently, the effectiveness of the colloidal treatment was sub-optimal.

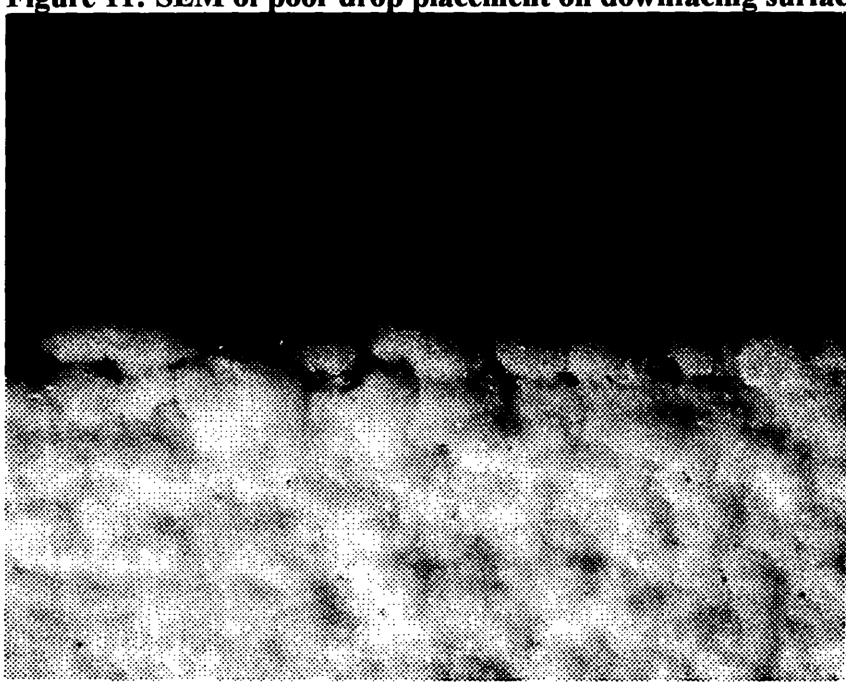
Figure 10: SEM photograph of smooth coated surface



Optical examination of the uncoated ceramic mold revealed that drop placement accuracy of the machine was very poor. Viewing the surface normal to the direction of the fast axis, extra drops of binder were observed at the end of the lines. The presence of these drops was very random and resulted in 'projections' that had to be covered by the coating (figures 9, 10). This required a thick coating, thereby limiting the minimum feature size.

Looking at the surface parallel to the fast axis, lateral shifts in line placement were observed. This was magnified along the inclined surfaces (figure 10). It appeared that the algorithm that determined the number of lines to be drawn at a given layer was inaccurate. While there should have been an additional line on alternate layers, the cross-sectional view showed missing lines and extra lines at random. Further, looking at the top surface of the part, it was possible to see waviness in the printed lines either due to line pairing or other problems. The large gaps between the lines resulted in unbound powder and high porosity, exacerbating the surface roughness problem.

Figure 11: SEM of poor drop placement on downfacing surface

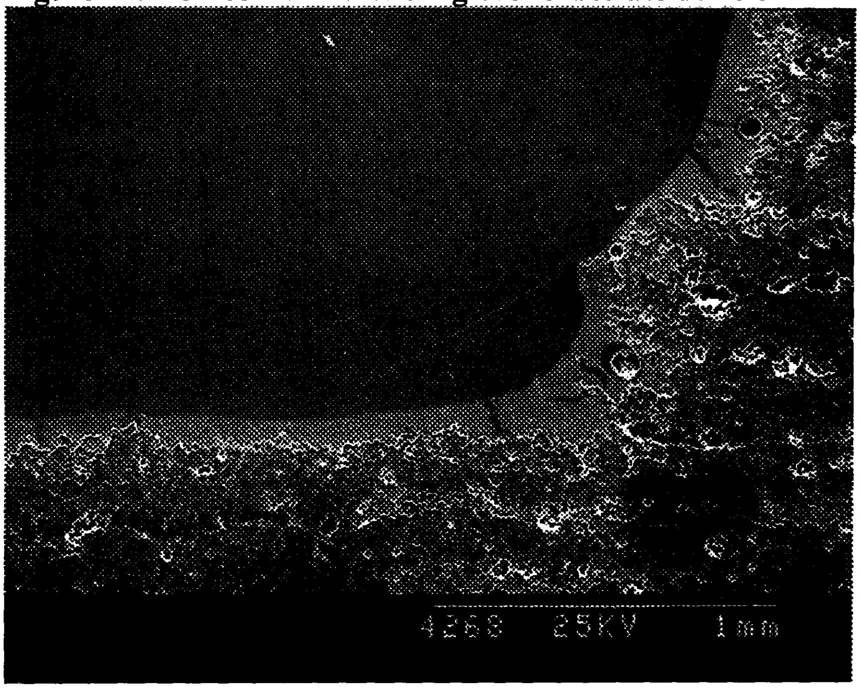


On 'downfacing' surfaces (figure 11), the inaccuracy in the drop placement was magnified to the point where adjacent lines did not touch each other leaving very large gaps between binder lines causing them to break off easily. Consequently, within a mold cavity the roughest surfaces were the 'downfacing' surfaces. The slip casting process was ineffective in making them smooth.

As mentioned earlier, the slip cast film was sensitive to cracking (figure 12) when either the coating thickness increased or the drying rate increased. The addition of an organic binder reduced the crack formation but increased the sensitivity to bubble formation within the slurry by increasing the surface tension of the slurry. The bubbles were created due to turbulence when the slurry was first poured into the ceramic shell, or when it was drained out. The slightest shaking of the shell to assist in removal of the slurry caused bubbles that were not easily broken due to the presence of the polymer. These bubbles prevented a smooth coating from forming on the surface of the substrate. As a result 'rings' of ceramic were left behind on the surface when the bubbles ultimately burst, causing an irregular and rough surface. These bubble rings were evident on the castings produced as indentations on the surface.

The addition of an organic alcohol, to reduce the surface tension of the slurry had a dramatic effect on bubble formation in the tests performed. As expected, there was a sharp drop in the surface tension of the slurry and fewer bubbles. However, the drop in surface tension of the slurry resulted in much thinner coatings for the same sit time. Consequently, longer sit times were required to produce coatings to cover up the 'defects' observed on the surface of the substrate.

Figure 12: Non-conformal coating over substrate defects



Ultimately, when the metal castings were produced using shells that had a coating with an organic binder and shells that had a coating without an organic binder, little difference was observed visually in the quality of the castings. There were no microscopic cracks that could be seen on the surface of the metal casting indicating that; (a) there were no cracks present or, (b) the crack width was small enough that the surface tension of the molten metal prevented it from filling the cracks. Some of the castings with the binder showed evidence of surface defects as a result of the bubbles mentioned earlier.

3.4. Trade-offs

The slip casting process can be used to create smooth surfaces on the ceramic substrate, however, the effectiveness of the technique is severely constrained by the quality of the substrate. The process can create surfaces that completely eliminate the defects present on the surface of the substrate, but the trade-off is poor feature definition. Ideally, a very thin coating should be used to produce the smooth surface while retaining the smaller features. As discussed earlier, as the coating thickness increases so does the minimum feature size that can be defined. Further, there are corresponding losses in the minimum radii that can be produced on the surface features.

The best means of obtaining uniformly thin coatings is to have a substrate that is uniformly porous, and whose porosity can be accurately controlled. In the case of Johnson & Johnson this meant much better equipment performance with respect to drop placement accuracy and layer thickness accuracy. Both of these are critical factors in creating a ceramic substrate from 3-D printing that has controllable and uniform porosity. One means of reducing the local variation in porosity is to treat the parts with colloidal silica. In the experiments conducted by the researcher the parts were treated once with colloidal silica. It is conceivable that repeated treatments would reduce the porosity sufficiently to produce better slip cast surfaces.

It is important to remember that the slip casting process is not designed to correct defects in the substrate like the large voids (Figure 6) and large projections (Figure 12). Those have to be addressed via equipment improvements. Slip casting can be used as a finishing process to improve the surface finish.

Chapter 4: The Problem Solving Process

4.1. Types of problems studied

The problems studied are limited to the technical problems associated with the 3-D printing equipment and the slip casting process used to improve the surface finish of the ceramic shells produced by the machine. Organizational problems are discussed as they relate to the solution of the technical problems with the equipment and process. In the course of the study eleven unique problems were identified and tracked by the author. By the end of the study period new problems had been identified and work on resolving them had just started. The problems were collectively owned by a team at Johnson & Johnson, and resolved, in most cases, with the assistance of Zygote Inc., the manufacturer of the 3-D printing machine.

Given the author's role as a team member at Johnson & Johnson and as a primary developer of the slip casting process it was hoped that tracking the progress of the problems until they were solved would give insight into the factors that influenced the rate and quality of solution to problems.

4.2. Data collection

The data collection was done at the Johnson & Johnson site to ensure accuracy and facilitate consistent interpretation of symptoms relating to the problems. As with most other problems with equipment, the symptoms observed by Johnson & Johnson and Zygote were frequently indicative of more than one problem. Familiarity with the equipment and a good understanding of its behavior and performance characteristics were required in order to decouple problems from each other and attribute specific symptoms with specific problems. The researcher's role as a development team member at Johnson & Johnson allowed close association with the equipment.

There were two major problems faced in data collection. The first was completeness of the data, the second, accuracy of the data. The problems with the equipment occurred at random times. Hence, the individuals working with the equipment had to be conscientious about recording the events leading to a problem. Detailed and accurate records of the symptoms and the problem itself were key to solving recurring problems. Unfortunately, given the nature of the process, the problems with the equipment tended to have catastrophic effects on the parts being built. More often than not, when a problem occurred, the immediate focus was on trying to minimize the damage to the parts being built rather than objective observation of the symptoms, and the problem. Hence, details related to the problems frequently were sketchy or entirely missing. Data entry in the equipment log book improved over time as the team members realized that the data was going to be used for analysis. Entries in the log book that were unclear were supplemented by immediate follow-up by the researcher every time a problem occurred to collect the details of the problems.

The problem with accuracy was linked to the lack of complete records. When the team members were questioned about the symptoms exhibited by a problem, or the frequency of the problems, their responses were largely from memory and often inaccurate. When multiple problems occurred in a short space of time there was confusion about the order of problems and the symptoms associated with each one of them. Follow-up discussions with all the people involved with the problem solution were used to clarify the sequence of events, the symptoms, and the order in which they were observed. The symptoms were then categorized within the researcher's records to permit subsequent analysis. Hence, the researcher relied heavily on his own records of the problems.

4.2.1. Means of data collection

Several methods were used to collect the data. Equipment log books, personal records and direct interviews were primarily used to collect the details about the problems and solutions.

4.2.1.1 Equipment and personal log books

The bulk of the data collection was done via direct record keeping in an equipment log book. Details about the problems were recorded soon after they occurred. The problems were recorded in chronological order and entries were usually a description of the problem as it occurred and any actions that were taken to correct it. Entries in the log book were made by all the members of the team and field service personnel from Zygote Inc.

In addition to the log book the researcher maintained a personal daily log of the events relating to the machine. The researcher's log contained not only the details of the problems observed, but a description of the symptoms, actions taken and discussions with Zygote personnel about the problems observed. If the researcher was not physically present at the time the problem occurred, the details were obtained by interviewing the people who witnessed the problem occurring.

Due to the distance between the Johnson & Johnson site and Zygote a number of problems were addressed over the phone. Records of phone calls and the conversations between the Johnson & Johnson site and Zygote were used to establish the frequency of communication between Johnson & Johnson and Zygote.

4.2.1.2 Interviews

In addition to the data collected via the log books, the researcher conducted personal interviews with members of the team and with people indirectly associated with the development effort. These interviews were used to understand organizational aspects of the problems and clarify personal assumptions and beliefs held by the individuals. Understanding the shared assumptions which formed the culture of the organization [Schein, 1992] was an important part of understanding the reasons behind the behavior observed during the course of the study.

Interview questions were open ended to allow the respondent to discuss freely his/her thoughts about the subject. In all cases the questions were used to elicit more information about topics that the respondent had brought up of her/his own accord. This facilitated the dialog between the researcher and the respondent.

4.3. Problem classification

The problems with the equipment faced by the team were classified based on the degree of difficulty, quality and speed of solutions to the problems.

4.3.1. Problem difficulty

The term 'difficulty' is used to describe not only the difficulty associated with identifying the source of the problem, but also in developing a solution to it. In some instances the problem was easily identified, but developing and/or implementing a solution was very difficult. In other cases the myriad of symptoms or the same symptom for a number of different problems made identifying the root cause of the problem difficult. A three point rating scale was used to classify the problems. The most difficult problems were rated

'High'. These were problems where detecting the root cause and developing solutions were difficult. Problems rated 'Medium' were those that were either difficult to detect or difficult to solve but not both. Problems rated 'Low' were relatively easy to identify and resolve. The process of rating the difficulty of the problem was performed prior to analyzing the log books and other records.

4.3.2. Solution quality and solution speed

It is commonly believed that there is a trade-off between quality and speed of solution to problems. The reason for this is the tendency to make 'quick-fixes' to problems, rather than addressing the root cause of the problems. The mean time between failures (MTBF) is commonly used to determine the quality of a solution. The speed of solution is often measured as the mean time to repair (MTTR). Ideally, within a manufacturing environment a small MTTR and a large MTBF is desirable. In this instance, since the research was conducted over a relatively short period, few problems showed multiple failures. Hence, the time to arrive at a solution (solution speed) was used for the analysis.

The quality of repair (solution quality) was judged by a subjective rating assigned by the researcher which considered both the probability that the problem would reoccur within a short period and whether the solution truly addressed the root cause of the problem. A 'Good' rating was assigned to a solution that not only addressed the root cause but was also unlikely to reoccur quickly. A 'Medium' rating was assigned to solutions that alleviated the problem for an extended period but would reoccur. A 'Low' rating was assigned to solutions that were essentially temporary or 'quick' fixes.

4.4. Data analysis

The analysis performed focuses on:

(i) The relationship between the solution quality and difficulty of the problem

(ii) The relationship between the solution speed and the difficulty of the problem

The analysis is used to describe the evolution in the problem solving processes of groups

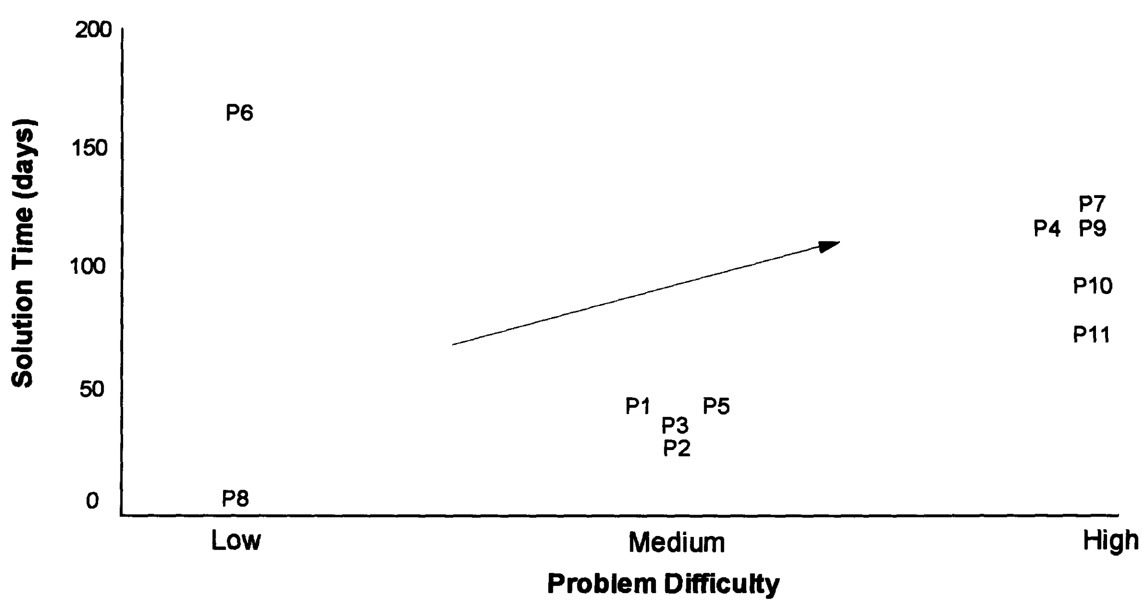
Table 2: Problems, difficulty, solution speed and solution quality

Problem Description	Difficulty	Solution Speed	Solution Quality
Poor powder dispersal due to wrong proportion of citric acid (P1).	Medium	45 days	Medium
Poor powder dispersal due to malfunctioning solenoid springs (P2).	Medium	30 days	Good
Poor powder dispersal due to wrong PDA screen (P3).	Medium	37 days	Good
Poor powder dispersal due to vibe board malfunction (P4).	High	120 days	Low
SPIT box failure (P5).	Medium	44 days	Good
Deflection door wire breakage (P6).	Low	168 days	Medium
Main harness failure (P7).	High	130 days	Medium
Vacuum pump failure (P8).	Low	5 days	Good
Linear bearing failure (P9).	High	120 days	Low
Rough printing of parts P10).	High	95 days	Low
Poor part accuracy (P11).	High	75 days	Low

such as the one at Johnson & Johnson. The resulting change in the state of the project, as measured by the type and nature of the problems faced by the group, is a function of the competencies within the group, the type and nature of the problem, and endogenous factors pertaining to the organizational structure. Factors such as the team's relationship with Zygote, and Zygote's responsiveness are considered in the overall effectiveness of the communication process. Table 2 lists the problems identified, their ratings for difficulty, solution speed and solution quality. Subsequently, the problems are referred to by their codes P1,P2..etc.

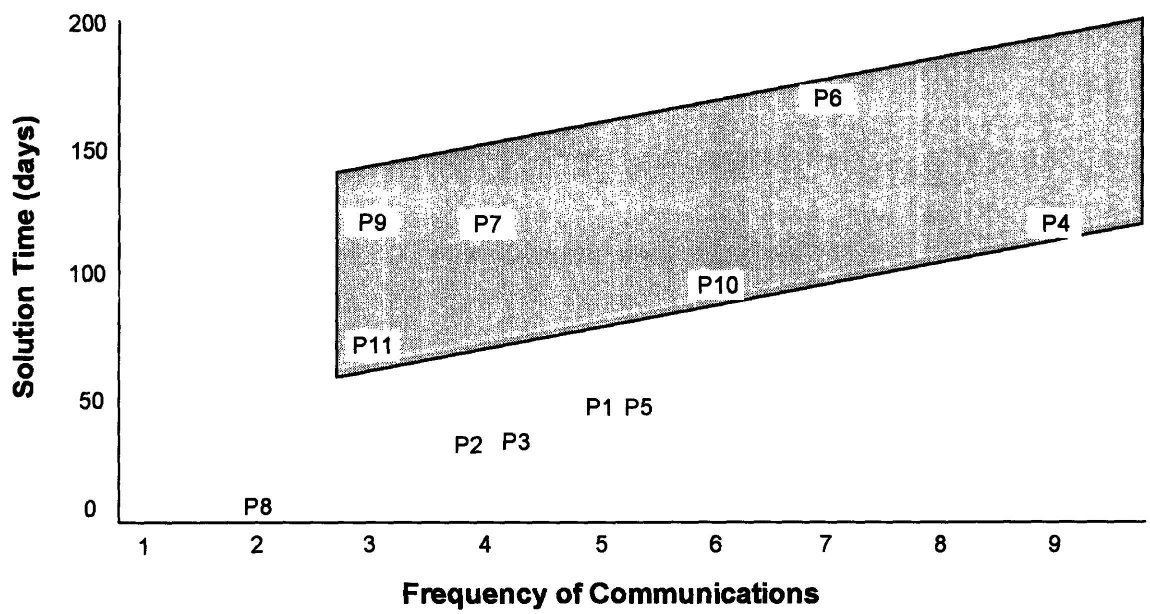
Figure 13 shows a plot of the solution speed plotted against the problem difficulty rating for the problems listed above. It is easy to observe an obvious trend in the data (as indicated by the arrow). As the problem difficulty increases the time to arrive at a solution to the problem increases.

Figure 13: Solution time as a function of problem difficulty



While this in itself is not an unique observation, it is important to note that the process of rating the difficulty of the problem was performed prior to analyzing the log books and other records to determine the time it took to solve the problem. Hence, the difficulty rating process was not biased by the solution speed data. The difficult problems were perceived by the team as being very complex and the symptoms of the problem often misleading. Problem P6 was a relatively simple problem yet took the longest time to solve.

Figure 14: Solution time as a function of frequency of communications



Examining figure 14 which illustrates the relationship between the solution time and the frequency of the communication between Johnson & Johnson and Zygote, the data appears to be scattered rather haphazardly. Closer examination of the actual problems themselves reveal more than the graph. In each case where the time to arrive at the solution was greater than 50 days, the problem was inherently caused by a fundamental flaw in the design of the system, or the sub-component. However, a casual observation of the problems within the shaded region or the problems outside the shaded region also indicates that for problems of similar difficulty rating the solution time is increased as the frequency of communication increases, which is not what one might expect.

Figure 15 shows the relationship between the rated quality of the solution to each of the problems and the difficulty of the problems. As one might expect the simpler problems were resolved with solutions that were rated medium or high. The most difficult problems also had the weakest solutions.

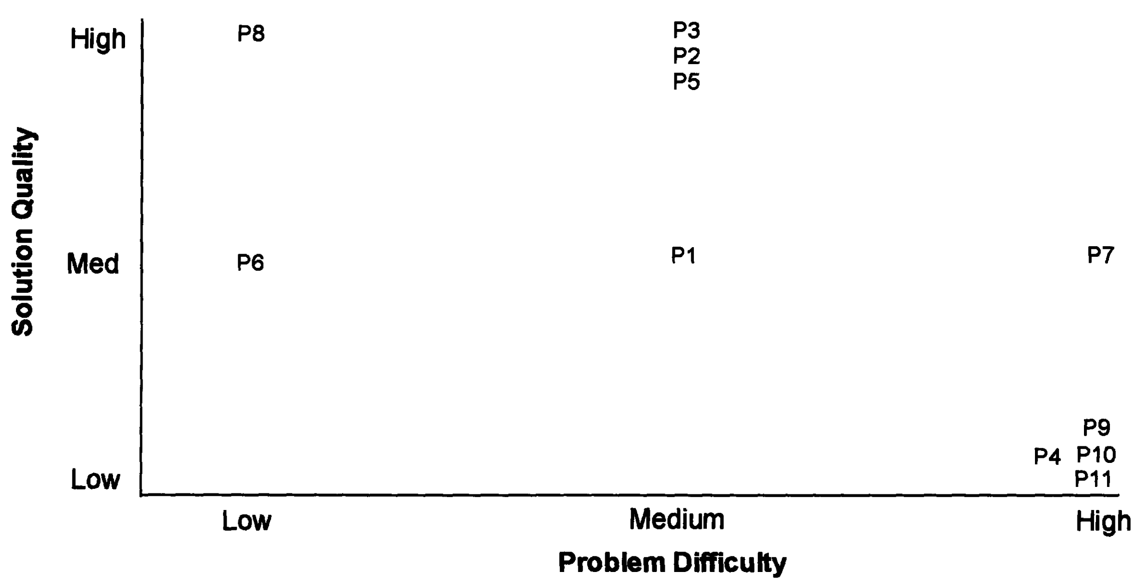
There are multiple reasons for this.

(a) The emphasis within Zygote was on preventing the same mistakes on the next machine, rather than fixing them on the machine at Johnson & Johnson.

(b) The resources allocated within Zygote to resolving the problem were limited.

(c) Johnson & Johnson internally lacked the technical capabilities to address all but the simplest of problems with the machine.

Figure 15: Solution quality as a function of problem difficulty



In most cases the simpler problems were related to the failure of a part, or errors in the installation of a component. Most of these problems did not reoccur, and when they did, they could be easily fixed by trained members of the Johnson & Johnson team. Consequently, root cause solutions were implemented for the majority of the easier problems.

The difficult problems were usually temporarily fixed by Zygote and/or Johnson & Johnson personnel and frequently were the source of subsequent failures. Little emphasis seemed to be placed on basic analysis of the failures and failure modes. In some cases, the design flaws were uncovered by Zygote and in others by Johnson & Johnson. The solutions to each of the problems were developed in parallel with apparently little emphasis on prioritization. There appeared to be the lack of a focused prioritized approach to the problems which led to frequent changes in direction. In order to demonstrate their responsiveness to their customer's problems Zygote tried to respond to the 'crisis of the week' which was highlighted in the weekly faxes that were sent. Resources were diverted to addressing the immediate problems and consequently, developing permanent solutions took much longer than expected.

The lack of mechanical and electronics expertise at Johnson & Johnson, made them completely dependent on Zygote to implement simple solutions which did not facilitate quick solutions either. At the same time the team members' technical background allowed them to suggest solutions. However, there seemed to be some reluctance on Zygote's part to accept suggestions from Johnson & Johnson in the development of solutions, this further slowed the process down. The data provided by the researcher in his effort to speed up the solutions only served as a reference point used by Zygote in their development of future generations of the machine.

4.5. The communication process

An essential part of any problem solving process is communication between the 'users' who are experiencing the problems and the 'developers' who may have the expertise to resolve the problem. For the purposes of this research work the 'users' are defined as the team at Johnson & Johnson, even though the developers at Zygote were also using a machine similar to the one at Johnson & Johnson. The developers of the technology were Zygote, and the research group at MIT. The engineers at Zygote designed and manufactured the equipment used by Johnson & Johnson. The concept of 3-D printing was invented at MIT and the bulk of the technical development surrounding the process was made there.

The relationship between Johnson & Johnson, MIT and Zygote, described in Chapter 1, partly determined the nature of the communication process. Communication between Zygote and Johnson & Johnson primarily revolved around the performance of the equipment, and secondarily the strategic direction of the development program. The communication between MIT and Johnson & Johnson was limited to strategic direction, and guidance in process development. On occasion it also involved support in solving technical problems that did not require hands-on work on the equipment.

4.5.1. Effect of onsite work

The co-location of the developers and the users at each others site was a factor that affected the solution speed. This has been discussed in other situations in the context of adaptive learning (Tyre and von Hippel, 1993, Suchman, 1987). It is particularly relevant in the transfer of process technologies where the participants are in a learning mode. In the present case Zygote was located in Oregon while Johnson & Johnson was located in Massachusetts. Even though there was a field service engineer who served the eastern region, many of the problems faced by Johnson & Johnson required technical expertise that was available only in the Oregon office. This had an impact on the service level and on the shared learning process between Johnson & Johnson and Zygote.

The team at Johnson & Johnson was in contact with Zygote primarily to communicate the problems they were facing with the equipment. The time difference between the two sites meant the effective working day (when the developers in Oregon had to be contacted) was only 5 hours long. This frequently led to multiple phone calls and messages being left for people on both sides since they were unable to reach each other. When the team members were able to reach developers at Zygote, a lot of time was spent trying to explain problems verbally. Many of these problems related to specific components or specific parts of the machine, and an intimate, almost 'photographic', memory of the parts and components was required to communicate the exact nature of the problem and/or failure. Delays resulted when either the description of the problem or the interpretation of the verbal description was incorrect. On occasion, wrong components were shipped out, or troubleshooting directions communicated verbally failed to solve the problem. Each time the communications broke down, Johnson & Johnson's confidence in Zygote's ability to solve their problems in a timely manner was eroded.

Every couple of months the teams from Zygote and Johnson & Johnson would meet face to face at each others site to discuss the status of the equipment. At these meetings the progress made by Zygote in resolving the major problems identified by Johnson & Johnson was discussed along with future enhancements. The meetings also gave the attendees a chance to observe first hand, the performance of each other's machine. These 'tour of the facility' sessions proved invaluable in identifying differences between the machines at the two sites. 30% of the problems observed at Johnson & Johnson were also observed at the Zygote site, however, this was not discovered until the Johnson & Johnson team members had an opportunity to observe the Zygote machine personally. The problems had been verbally described many times before the site visit, but when the visiting team members said "Yes, we have the same problem" at the Zygote site, it gave the problem greater credibility.

Members of both organizations were able to describe problems, such as subtle noises with the machine, that could not be described without both the users and the developers being simultaneously in the presence of the machine. The physical clues associated with specific problems could only be communicated when the members of both teams were co-located at either of the sites with the equipment (Tyre and von Hippel, 1993). The combination of physical examination of the machine, the ability to rapidly exchange questions, ideas and obtain instantaneous feedback proved invaluable in establishing the true symptoms of the problem and better classification. An example of this was the distinction between a 'stop' and a 'stall' of the slow axis of the machine. All errors relating to the stopping of the slow axis were considered stalls at Johnson & Johnson, while at Zygote only slow axis stops that were accompanied by a noise were considered 'stalls'. Until the face to face meeting, the Johnson and Johnson team used the words interchangeably. However, at Zygote the terms were manifestations of two different problems. This revealed a critical side to the transfer process, namely, the communication of hidden information.

The hidden information referred to here is the relational knowledge pertaining to a particular problem that is in the mind of the developer or user which is brought to the surface only when presented with a specific 'clue' or piece of information which triggers the response. In some cases the responses were different for the users and the developers based on the other circumstances surrounding the event. Computer 'lock-ups' were invariably re-booted at Johnson & Johnson while at Zygote there were specific recovery steps based on the sequence of events that led to the 'lock-up'. This type of information is rarely, if ever, documented in manuals and operating procedures because it is very specific to a set of circumstances surrounding a problem that occurs infrequently. The fact that the user and developer were both present at the same place allowed them to discuss the solutions that they had developed. The closer the developers are to the user site the higher the probability of such discussions (Allen, 1984) and the higher the number of encounters, the greater the degree of communication of hidden information.

Nonetheless, the increased communication did not necessarily always result in faster problem resolution, just better consistency in problem definition between the two groups. The reason for this was related to the lack of prioritization. Since the data on the frequency and severity of each type of problem were scant at best, efforts were shifted back and forth on addressing the different problems. Another reason for this was that the face to face meetings only lasted a couple of days and the problem solving process continued to be conducted primarily over long distances.

The onsite presence of the developers at the user's site benefits both parties. Enhanced communication is the primary but not the only benefit of the co-location of the users and developers. Communication does play a key role in establishing a better working relationship which improves problem solving. In this instance greater opportunity for the two teams to be onsite together may have enabled the following.

i. Rapid and clear communication of the problems faced by Johnson & Johnson to Zygote.
ii. Smaller delays in solving the problems in some cases.
iii. Joint development of solutions to problems.
iv. Enhanced working relationship between Johnson & Johnson and Zygote.
v. Better communication of expectations.

4.5.2. Effect of communication medium

The machine was equipped with an electronic bulletin board and mail system that could be used to communicate with the designers at Zygote. Nevertheless, the bulletin board failed miserably in serving its sole purpose - open and clear communication between Zygote and Johnson & Johnson. The intent of the bulletin board was to create an electronic forum where problems, ideas and solutions could be freely discussed and the best practices identified. The electronic mail was to provide direct access to any of the people at Zygote to get answers to specific questions.

Unfortunately, neither the bulletin board nor the mail could be accessed when the machine was running. The network at Johnson & Johnson was based on the Apple Macintosh™ while the one provided by Zygote was based on IBM compatible personal computers. As a result, none of the team members at Johnson & Johnson had access to the bulletin board from their offices, and could only use the PC on the machine when it was not running. The inconvenience of using the computer on the machine in laboratory <u>*only*</u> when it was <u>*not*</u> running, meant it was rarely used. Most of the team members at Johnson & Johnson barely knew <u>*how*</u> to use it.

The bulk of the problem solving was done over the telephone and via facsimiles sent weekly. Initially, the faxes described the problems in great detail but shortly thereafter they only carried a brief description of the events of the past week. Most of the specifics about the problems were communicated via long telephone conversations, and frequently the same problem would be described multiple times to different people at Zygote. The developers at Zygote usually verbally communicated solutions related to mechanical or electrical problems with the machine to the field service engineer who then made the appropriate repairs or adjustments to the machine. When the problem required less mechanical work or was related to technique, it was directly communicated to the individuals at Johnson & Johnson. Unfortunately, most solutions that were subjective or related to technique were not easily described via the phone or fax.

Further, the quality of the communication almost directly translated into the quality of the solution. The quality of communication was measured by the number of errors made in communicating the information required to solve a given problem. Simple problems usually required a single phone call to clarify what needed to be done to resolve the problem. In some instances such as the rough printing, vibe board malfunction and deflection door wire breakage, repeated phone calls were required. Multiple shipments of parts were made because either wrong parts were shipped or the parts shipped were broken and/or malfunctioned. The errors led to increased frustration and low confidence in the solutions as they were implemented.

As one might expect, face to face onsite communication was most effective in communicating the problems and the solutions. There was evidence of this in the resolution of the door wire breakage and the PDA screen problem. In the case of the breaking wire, the door had been re-soldered temporarily multiple times, only to fail again. The suggestion to reroute the wire and replace with a heavier gauge wire was ignored until a field service engineer from the Oregon site visited the Johnson & Johnson facility and personally observed the failure mechanism. Shortly thereafter, a replacement door was received with the wires replaced with a heavier gauge and re-routed. Similarly, until the engineers and team members physically examined the screens at Zygote and at Johnson & Johnson, and agreed that they were different, they were not replaced. There are multiple reasons for the effectiveness of face to face onsite communication.

i. Speed of communication.
ii. Clarification of problems.
iii. Ability to teach techniques and subjective decision making.

iv. Ability to arrive at common set of problems and solution techniques.

v. Credibility or seeing is believing.

As we see in the problem with the breaking wire, the very nature of some of the problems required the physical presence of the team members and developers in the same location to experience the problem and develop the solution together. In the case of the PDA screen, the problem had been explained over the phone a few times by the users before the screen was inspected by the developers. When the developers inspected the screen they concurred that the screen was in fact the source of the problem. This visual confirmation of the problem by the developers at the user's site enhanced the credibility of the users and the level of trust between the individuals. A combination of both these factors along with some of the others listed above has a major impact on the problem solving process.

4.6. Problem solving hypotheses

Based on this study some hypotheses can be developed around problem solving processes.

Problems with long solution times are fundamentally of a different nature than others, and not necessarily influenced by the level of communication

There is evidence in this study to substantiate this hypothesis. Figure 13 represents the type of analysis that is usually performed in attempting to determine the reason for long solution times. The fact that difficult problems take longer to solve is intuitive and frequently substantiated with the kind of empirical data as shown here. Further, when we look at figure 14 we observe that greater communication did not necessarily reduce the time to arrive at a solution for all problems. Some problems may be inherently more complex than others and in those instances it is to be expected that greater communication will be required to understand the problem and develop a solution. The problem involving the SPIT box was an example of such a complex problem. The symptoms were intermittent and the problem often irreproducible. It took a fortuitous coincidence of events and tests to identify the source of the problem. Developing the solution was simple once the problem had been identified.

Closer examination of the type of problems that took longer to solve revealed that they were frequently caused by design flaws. The fundamental nature of these problems and the magnitude of the changes required to develop root cause solutions made the solution times significantly longer than those for problems of comparable difficulty. Problems with short solution times were usually caused by component failures or human errors. It is important to note that the difficulty rating was given by the researcher and not Zygote.

Quality of solution is moderated by the long term impact of the problem and the ease of solution

In this instance the sense of urgency displayed by Zygote and their commitment to develop root cause solutions to the problems appeared to be a function of their perception of the impact that the problem would have on the future development. Problems of low and medium difficulty were due to component failures and design features that were not being changed in future generations of the equipment generally had higher quality solutions. Difficult problems, caused by fundamental design flaws, were by and large being completely designed out of the next generation equipment. Hence, there was little incentive to develop high quality solutions to those problems. For the most part the solutions were temporary fixes that allowed Johnson & Johnson to continue running the machine till the next failure occurred.

Zygote's failure to clearly communicate this tactical decision in supporting problem resolution had a detrimental effect on the working relationship between Zygote and Johnson & Johnson. However, in hindsight the decision probably was the most prudent one on Zygote's part given their limited resources.

Establishing trust and credibility can moderate the level of communication

The divergence in strategy and goals between Johnson & Johnson and Zygote had far reaching consequences in the development of their working relationship. The assumption at Johnson & Johnson was that Zygote would provide adequate resources to develop the existing equipment. However, at Zygote it seemed that the equipment at Johnson & Johnson was merely a stepping stone in the learning process. At the same time Johnson & Johnson compared the development of the technology at MIT to that at Zygote and the comparison always favored MIT. Consequently, the support from Zygote in addressing the problems with the equipment fell far short of Johnson & Johnson's expectations. This resulted in the need for frequent communication to resolve simple problems and the perception at Johnson & Johnson that Zygote was unresponsive to their needs.

The escalating spiral that this induced was lower trust, lower credibility and longer times to resolve problems. Communication and information sharing between the groups decreased over time as evidenced by the level of information contained in the facsimile transmissions. It is unclear whether the quality of solution decreased as a result of reduced communication or merely as a result of less trust in each other. Nevertheless, it was quite obvious that communication was reduced to an 'as needed' basis when problems occurred or solutions were developed, rather than a continuing process of shared learning.

Competency of the primary interface is critical to the working relationship between the developers and recipients of the technology

The primary interface between the development and receiving site occurs at the level of the team members and the service representatives. They are most frequently in contact with each other, they are also most familiar with their respective organizations. In a sense they provide the 'window' into each other's organization. Consequently, the competence of these individuals and their ability to send a consistent message within their own organization, and to the other organization is important.

During the transfer of 3-D printing to Johnson & Johnson, on more than one occasion the competency of the field service personnel came into question. Mistakes made while at Johnson & Johnson, the fact that they needed a lot of guidance from the developers at Zygote, or their inability to influence the development work being done in Oregon, all served to undermine their credibility with the team at Johnson & Johnson. As a result the level of communication with the primary interface decreased and the team members were more inclined to go directly to the developers in Oregon rather than through the field service personnel. This further reduced the effectiveness of the field service personnel because frequently they were not directly involved in the discussions and problem solving except as a labor resource.

Greater onsite communication can facilitate the problem solving process

As seen in the case of the wire breakage and in the PDA screen problems the presence of the developer and user at the same site in the presence of the machine can facilitate the problem solving process. There are multiple reasons for this as described earlier in this chapter. Aside from the obvious aspect of improving communication between the two groups of people because they are face to face, there are intangible benefits such as greater trust and credibility that accrue from the physical presence of the developer at the user's site and vice versa. They are able to relate better to each other's problems and constraints and can jointly arrive at mutually acceptable solutions.

Chapter 5: Practical Aspects of Technology Transfer

5.1. Maturity of the technology

The transfer of new technologies from research facilities or the introduction of new equipment into a manufacturing environment is a complex task. The effectiveness of the transfer is often measured by how quickly the technology and/or equipment is capable of delivering the benefits it is expected to. This chapter suggests that the extent to which the technology is developed, as defined by its maturity level is a factor that needs to be carefully understood in trying to assess how long it is going to take to transfer technology, and make it useful within the manufacturing environment. It is possible to broadly classify technologies into level of maturity based on the extent of their development, as defined by their capabilities, at the time of transfer.

Table 3 describes the maturity classifications and the types of issues that are encountered when a technology is transferred at each of these levels. Using this as a starting point, the characteristics of the transfer team and resources that need to be allocated can be determined. The expectations of the new technology and the timeframe within which improvements can be expected need to be defined keeping the level of development in perspective. The type and nature of the interactions between the developers and the users that is necessary for successful technology transfer will also depend on the level of maturity.

In the case of 3-D printing the equipment and the process was at level 4. The machine developed was the first prototype produced by Zygote and their objective in the development program was to identify flaws in the design and sub-systems. The feedback obtained from Johnson & Johnson on the performance of the machine and the analysis of

Table 3: Maturity levels of technology

Maturity Level	*Capabilities*	*Issues faced during transfer*
Level 1	Fully developed. Output acceptable in the current form. Capable of running in high volume	Few problems. Equipment mismatch, different methods, training. Output characteristics are not identical. Improvements to enhance capabilities.
Level 2	Fully developed. Output acceptable in current form. Capable of running in low volume.	All of the above problems associated with level 1 and those associated with high volume manufacturing. Stability of process, process simplification issues. Customization and fine tuning of process and characterization.
Level 3	Partially developed. Output occasionally acceptable. Continuing development of more complex and unreliable components. Basic design parameters and functionality have been established.	Frequent changes in machine/process parameters. Incapable of high volume manufacturing. Significant effort required to keep equipment/process running.
Level 4	Under development. Output in rudimentary form. Continuing development of major components and sub-systems. Basic design parameters and functionality still in a state of flux and definition.	Frequent changes in major systems and components. Capable of producing experimental parts occasionally. Significant development activity is still in progress

the problems encountered, was used in the development of the next generation of the same equipment. Significant changes in the functionality and capabilities of the equipment were expected as a result of the program. The researcher's prior experience with equipment development indicated that the problems encountered with the machine were not atypical of new machines. They were just not the kinds of problems that the team at Johnson & Johnson expected.

The 1990 introduction of stereo-lithography at Johnson & Johnson was used to understand the impact that technology maturity had on the transfer process. After the viability of the stereo-lithography technology had been demonstrated at Orthopaedics, other Johnson & Johnson facilities also introduced stereo-lithography into their manufacturing process

At the time of transfer to Johnson & Johnson the stereo-lithography process technology was at the level 2 stage. The product from the process was of acceptable quality, and the functionality of the equipment met Johnson & Johnson's needs. The developers had installed equipment at other locations and had established confidence in the technology and in the capabilities of their equipment. They were capable of providing technical support and guidance in the best use of their equipment. Since little fundamental development of the equipment was required, the emphasis at Johnson & Johnson was on training and fine tuning the equipment to meet their specific needs.

Once an understanding of the maturity level of the technology is achieved it is possible to better estimate the amount and type of resources required to move the technology and/or equipment from one level to the next. Consequently, the resource allocation decisions have to take the level of maturity into consideration.

5.2. Resource capabilities, allocation and availability

The allocation of resources, both human and financial, to technology transfer processes is an aspect that is often poorly understood prior to the start of the transfer process. The type of resources that are needed and the timing of these resources are critical to the rate of progress of the project. As indicated in the earlier table, by virtue of the fact that the technology is in a state of transition as it progress from one level to the next the resources that need to be allocated to it also change.

The most frequently used basis for determining resources is 'to do what worked well in the past'. While prior experience should not be discounted, in the event that the level of the technology is different at the time of transfer, just doing the same thing again frequently fails. Thus, in determining the type of resources needed the level of the technology's maturity becomes important. In the case of the 3-D printing process the equipment and the process were at level 4. The process was under development at MIT, and the equipment at Johnson & Johnson was the alpha prototype that had been built by Zygote. However, what this meant in terms of human resources and their capabilities was not well understood. The expectation at Johnson & Johnson was that the machine would be capable of running unattended and produce parts that would require minimal post processing. Instead the machine frequently broke down for a variety of reasons, the parts produced were of unacceptable quality and problems were encountered through the entire duration of the study.

5.2.1. Capabilities

The capabilities of the resources allocated to the transfer process has a dramatic effect on the efficiency of the transfer process. The members of the team at Johnson & Johnson were capable of running the machine and making minor adjustments to the machine. Even that required a level of skill that was acquired only with practice running the machine. Most of the team members had computer modeling skills and basic equipment operation skills but only the researcher had experience with equipment maintenance. Training the team members to be able to perform some of the maintenance and repair functions of the field service engineer was not a viable option since it would have taken months to achieve the level of skill required.

One of the team members spent weeks at the Zygote headquarters for training where routine maintenance and 'tricks' and techniques on maintaining the equipment were learned from the developers. The importance of the physical setting (Tyre, 1993), namely, the Zygote facility, was critical in developing the skills that could not be communicated except by example. The other members received an abbreviated version of the training, primarily to familiarize them with the various knobs, dials and adjustments on the machine. The bulk of the learning by the team was via hands-on operation of the machine and by trial and error.

Over 80% of the time when the 3-D printing machine broke down it required the technical expertise of the field service engineer to resolve the problem. In 60% of the cases where the field service personnel was involved, solving the problem required technical assistance that could only be obtained from the development site in Oregon. Consequently, there was significant communication between the Johnson & Johnson site and the development site in Oregon as might be expected for a transfer program at the level 4 stage. However, the lack of technical expertise within Johnson & Johnson proved to be a serious drawback. It made them completely dependent on the field service personnel and schedules dictated by Zygote. While the pre-arranged response time to problems with the machine was 24 hours, on occasion it took 48-72 hours for any response. Even after the initial response further assistance was needed from Oregon to resolve the problem. The fact that the field service engineer could not address most problems without some assistance from Oregon affected Zygote's credibility.

In the case of the stereo-lithography equipment, little technical expertise was required to maintain the equipment since its capabilities were at level 2. The machine operators needed to learn how to operate the machine and understand how it functioned in order to fine tune it to meet their specific needs. The experiences at other Johnson & Johnson sites where stereo-lithography was introduced were similar. In all cases there was a primary owner who had the skills necessary to develop the process. Technical assistance was readily available when they needed it since the field service engineer was available within 24 hours, and 90% of all problems with the equipment could be resolved by the field service engineer. Specialized training was not required to develop the process to the point where it met all the needs.

The capabilities of the technical interface between the development and receiving sites is important because as the primary contact they project the image of the two sites. The professionalism and competence as demonstrated by their ability to quickly resolve problems and effect changes and generate support from within their respective organizations can instill a sense of confidence, especially in the early stages of the program.

5.2.2. Allocation and availability

The resources required to the transfer a process are often misjudged, as revealed in schedule delays and unplanned training and requests for additional resources once the project has been started. Frequently, the timing and capabilities of the resources are more important than the sheer number. With 3-D printing it was important to run the machine as long as possible to try and 'shake out' the problems. To eliminate 'teething' problems with the components and understand the relationship between the symptoms and the problems, the machine had to run for extended periods. Running the machine for extended periods was rarely possible given the work schedules of the team members. All the team members worked a standard workday from 8:00 a.m. until 5:00 p.m. which automatically limited the length of a single test run, and their ability to understand the types of problems that typically arose during extended runs.

When the team needed technical assistance it was rarely available immediately. Over 80% of the time when the field service engineer had to be called in, it was at least 24 hours before he was available, sometimes longer. Consequently, problems were not resolved immediately and frequently misdiagnosed since the machine had cooled down, or the operators had forgotten the specific details of the symptoms. The availability of a technically skilled resource at short notice was sorely missed during the entire period of the study.

In contrast, during the development of the slip casting process which was done by the researcher with the assistance of technical resources at MIT, problems were quickly resolved. Technical assistance was only an hour away. The same situation was true during the development of the stereo-lithography process. Technical assistance was less than an hour away at the worst of times. The accessibility of competent technical resources was a major factor in the development process.

5.3. Expectations

The process of setting expectations is an important part of any project and particularly in the case of technology transfer. An important aspect of this process is clarifying the deliverables, milestones and definition of success criteria. Sometimes cultural barriers to technology transfer (Radosevich, 1993) exist because of different operating styles. However, even where such barriers actually do not exist the lack of a shared destiny can affect the transfer process as seen in the case of the 3-D printing transfer.

5.3.1. Goal congruency

With 3-D printing there was a mismatch between the Johnson & Johnson team, and Zygote in terms of the expectations that each of them had of the machine. The peculiar nature of Zygote's relationship with Johnson & Johnson, that of a equipment supplier and partner in development created tensions. The team at Johnson & Johnson sought a reliable machine that would produce parts that were immediately usable. They expected the machine to perform at a level slightly below that of the stereo-lithography equipment when it first arrived. Further, the team believed that Zygote as a supplier, was committed to developing the machine to meet the *specific* needs of Johnson & Johnson. Ultimately, Johnson & Johnson's goal was to produce parts from the machine that would enhance their product offerings.

Over the course of the study it seemed that Zygote believed that the purpose of the joint development was mutual and shared learning about the process and 3-D printing equipment, regardless of the specific applications of the technology. This was most obvious during the quarterly meetings where the teams presented a summary of their work and the problems experienced over the past few months. During the discussions a number of issues were usually raised by Johnson & Johnson that related to specific improvements that they wanted to see in the equipment. However, owners were rarely assigned to follow up the discussions with specific action plans and actions. This created the perception at Johnson & Johnson that Zygote was not responsive to their needs. The lack of goal congruency manifested itself repeatedly during the course of the study.

5.3.2. Team dynamics

At the project team level, expectations tend to influence the actions taken by the team members. The expectations that the team members have of the state of the technology, each individual's capabilities and of the ultimate outcome, are all subject to change based on the actual events. Over time there is a slow evolution of their expectations which modifies their behavior and affects the performance of the team as a whole.

During this study the discrepancy between the initial expectations that the team members had of the equipment and its actual performance had a profound effect on the behavior of the team. The researcher's impression was that the team members felt a sense of betrayal, followed by despair, apathy and powerlessness. Towards the latter stages of the research project as the performance of the equipment improved, there was greater enthusiasm within the team. This was reflected in the comments made by some team members "...the machine seems to be running better each week". A critical turning point in the attitudes of team members and the management was when the first metal castings were produced. The change in attitude was reflected in their eagerness to create new CAD designs that they could make on the machine and have cast. The fact that the first castings had physical dimensions and surface characteristics that resembled existing products boosted the team's morale. It was a sign that their goals and expectations of the technology were not unreachable.

Informal discussions with the team members revealed that they felt it was important to set expectations of each of the members involved in the transfer process, and define their roles and responsibilities. The researcher's impression based on the discussions was that the expectation placed on them played a role in defining their attitude towards the project and influenced their motivation. Goal congruency between the developers and users also appeared to influence the team members' attitudes and behavior.

5.4. Managing the transfer process

5.4.1. Management control systems

Developing the control systems to manage the transfer process is a critical part of the overall success of the transfer process. There are three important aspects to the control system.

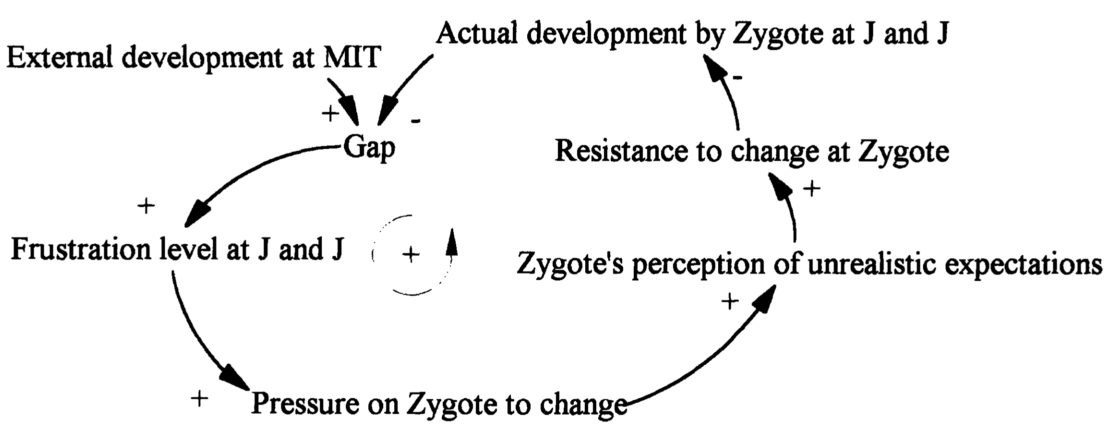
i. Measurable goals with explicit success criteria.
ii. Measurable intermediate milestones.
iii. Feedback mechanisms.

Transfer processes are evolutionary, especially those involving the transfer of technologies that have a maturity level of three or four. This is because even as the technology is being transferred it is changing. Hence, it is important to define at the start of the transfer whether the *current* state of the technology at the development site is what is expected at the receiving site once the transfer is completed. Often this is not the case, because the expectations of the receiving site rise as the process continues to be developed. What this leads to is continuos frustration because the receiving site perceives its technology as not being state-of-the-art even though they *just* finished transferring the technology. They are correct in their perception because the process and/or equipment has evolved over the period that the transfer took place. However, attempting to stay current with the technology at level four while it is being transferred is a prescription for disappointment because the state of the technology is a moving target.

The positive feedback loop that this creates is illustrated in figure 16. In the 3-D printing project the team at Johnson & Johnson kept abreast of the developments at MIT via the consortium meetings. The capabilities of the technology at MIT were mentally compared to the capabilities of the machine obtained from Zygote. The more progress MIT made the larger the difference became between what could be done at MIT and what could be done at Johnson & Johnson. This gap led to frustration within the Johnson & Johnson team because they perceived their machine to not be state-of-the-art. Consequently, they exerted pressure on Zygote to make modifications to try and match the capabilities at MIT.

Zygote seemed to perceive the pressure from Johnson & Johnson as unwarranted because they felt the expectations to change were unrealistic given their charter and focus. They seemed to feel they could not accommodate every request that Johnson & Johnson had for machine modifications. Conversely, the team at Johnson & Johnson felt that they were merely asking Zygote to replicate what had already been demonstrated at MIT. As a result there was resistance to change at Zygote which reduced the actual development of the Johnson & Johnson machine by Zygote because they perceived the Johnson & Johnson team's complaints as being irrelevant to the task at hand.

Figure 16: Causal loop diagram showing escalation of expectations



One way of short circuiting the constant game of catch-up while transferring partially developed technologies such as 3-D printing is to define key intermediate milestones at the start of the transfer process. These may be levels of performance, percentage of completion, acceptable fraction of scrap, cost of parts et cetera. When stereo-lithography was introduced, the primary objective was the ability to produce a specific test part that by virtue of its design was a measure of the machine's capabilities and accuracy. By defining an explicit measurable goal associated with milestones along the way, progress can be tracked and the team can be made more accountable for progress. It also eliminates the escalation process that was observed at Johnson & Johnson with respect to the development of the machine's capabilities.

Establishing feedback systems that are explicit and non judgmental is critical to enhance the communication between the development and receiving site. It allows all the participants in the transfer process to observe their progress relative to the stated objectives. This was observed when the problem with poor powder dispersal was being addressed. Rather than trying to determine if the 'right' fixes had been implemented, and if the quality of the workmanship of the field service engineer was good, data on the frequency with which the problem reoccurred was communicated via the weekly facsimile to Zygote. The data showing the frequency of failures made the quality of the solution self evident. As a result Zygote was more inclined to focus on resolving the issue since they felt their reputation was at stake. Feedback systems prevent changes in the overall direction of the project at mid-stream without buy-off from all the participants. Further, corrective action can be taken when the performance of the team or progress towards a milestone falls short of expectations.

The creation of a master schedule with sufficient detail to observe the interaction between the intermediate steps provides an overview of the entire transfer process. The effectiveness of such a tool is limited to the extent to which it is used. In the case of the 3-D printing transfer process, the master schedule was less of a working document and more a roadmap defining the general direction that Johnson & Johnson wanted to take with respect to 3-D printing. This resulted in frequent changes in short term direction while the overall road-map remained the same. This had the effect of demoralizing the team members because the short term focus appeared to change regularly.

The control system has to be goal seeking both in the short term and the long term. Every member of the team has to be clear about what the objectives of the transfer process are. These need to be defined in as specific terms as possible rather than generalities such as 'good' and 'acceptable' which leave room for interpretation. In the case of 3-D printing while the objective was to produce castings from the machine there were intermediate goals such as unattended operation of the machine that had not been defined.

5.4.2. Decision making processes

The decisions made during the process of transferring new technologies is sometimes determined more by perception of the decision makers than by reality. The effect of managerial style on decision making has been discussed before (Mosley et. al. 1991) but it assumes that the manager's perceptions are a true reflection of reality. Figure 17 below illustrates variation in individual perception of the capabilities of a new technology over time. The driving force behind the decisions is often the gap between actual capabilities and perceived capabilities.

The expected rate of increase in capabilities is shown by the straight upper line, while the straight line below it shows the actual rate of increase in capabilities. The curved line shows the change in peoples' perception of the technology's capabilities over time. During the initial stages of the transfer, managers perceive that the technology is capable of much more than it really is capable of. There is a lot of enthusiasm and hence support to continue the project. However, the large gap between reality and perception gives rise to disappointment. As time progresses and the gap persists it leads to disillusionment and a rapid drop in perceived capabilities.

Figure 17: Change in perceptions over time

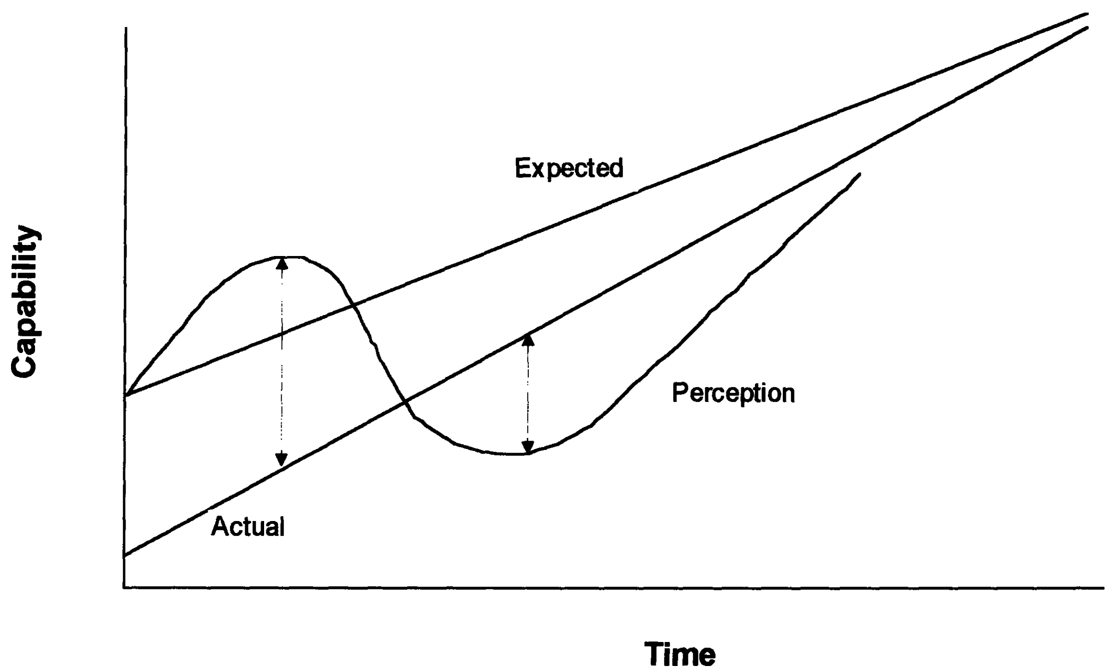


Table 4 which provides some comments from team members gives some sense of their perception of the machine's capability over time. The table also lists the actual capabilities of the machine over the course of the project. The comments and the capability data form the basis for the perception and actual capability curves respectively.

Table 4: Perception and true capabilities

Time period	*Perceived Capabilities*	*Actual Capabilities*
Initial phase. month 0 ↓ month 1	"... we should be able to run the machine overnight." (Test parts were not expected for more than 1 year). *Origin of figure 17.* "...expect functional custom test parts in one year" (Product parts expected in 2-3 years). "I expect we'll be producing production parts by December." *High point of figure 17.*	Average run time during a week was 2-4 hours Machine could not run 1 hour unassisted.
Second phase month 1 ↓ month 3	"I am not sure if we can run this unassisted." "If we focus on it maybe we can get it to run all day." "It requires too much operator assistance."	Average run time during a week was 4-6 hours. Basic test parts can be produced with operator assistance.
Third phase month 4 ↓ month 6	"We really should cancel this project, it is a waste of time and money." "The surface finish is completely unacceptable." "This is a science project not a manufacturing tool." *Low point of figure 17.*	Average run time during a week was 10-12 hours. Machine runs unassisted for 2-3 hours at a stretch. First cast parts are produced using molds produced on the machine
Fourth phase month 8 ↓ month 12	"The parts look okay, but still far from acceptable." "We can run during the day but we still cannot run it overnight which is a big limitation."	Average run time during a week was 15-20 hours. Machine ran for over 24 hours without failures.

The sharp drop in people's perception of the technology's capabilities, sometimes even below that of its actual capabilities, may cause problems during the transfer process. Successes are received with skepticism and support for the project is at its lowest point. Often there are discussions about canceling the project and reallocating resources. There is a positive gap between the real capabilities and the perceived capabilities. Continuing successes slowly but surely gives rise to increasing confidence in the technology.

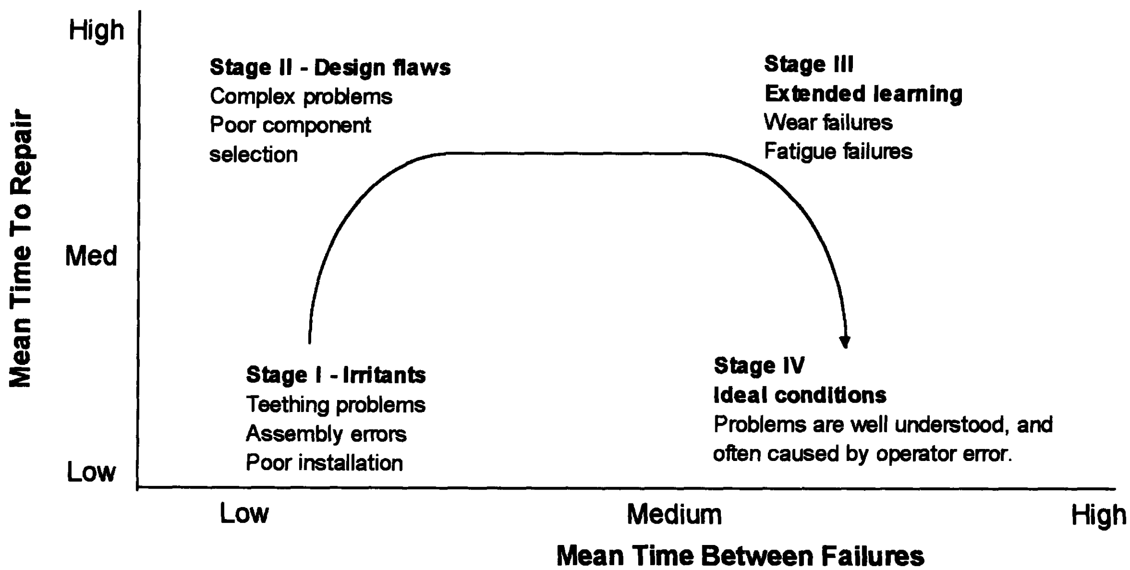
Based on the researcher's prior experience with transfer programs it seems that the team leader plays a crucial role as this dynamic evolves. The team leader needs to temper the optimism in the early stages of the project because often there is large gap between perception and reality. At this stage the leader's ability to create plans that keep the team focused on addressing the key limiters to progress can prevent the rise in optimism followed by the drop shown in figure 17. In the later stages of the project the team leader has to keep the team motivated and drive continued support for the program. The leader should not be misled by the assumptions made by others about the capabilities of the technology, rather strive to communicate as explicitly as possible the real challenges facing the team. The emphasis at this point should be on the real successes, the strides made by the team and the plans in place to address the outstanding issues.

Chapter 6: Conclusions and Recommendations

6.1 The transitional nature of technology transfer processes

Based on the facts and data collected during the course of the research work at Johnson & Johnson this last chapter covers the conclusions about the evolutionary nature of the transfer process and the problems encountered. The evolution that is sometimes observed (based on prior experience) is pictorially represented in figure 18 below.

Figure 18: Stages in problem evolution



Problems in the lower left quadrant (Stage I) are typical irritants. They are often related to simple failure of the components, errors that cause failures of systems or sub-systems. In general these do not persist as the equipment 'shakes out' or is put through a 'burn-in' phase. The nature of these problems dictates that they have low mean time between failures and the time to repair them is short. Cold solder joints and broken wires are typical examples of the types of failures observed. The equipment usually does not work at all, hence, pinpointing the source of the problem is relatively easy. These failures are usually encountered in the early stages of the transfer of a new technology. This is because they are often due to an oversight on the part of the designers or obvious problems that have to be fixed in order to continue to run the machine. The solution time tends to be short because diagnosis is relatively accurate and the solution often is the complete replacement of the part.

Problems in the upper left quadrant (Stage II) represent those that are design related. While they are present right from the start, they are rarely seen until the 'noise' from the 'teething' failures has decreased. In the case of 3-D printing there were a number of problems in this category that required design changes, many of which were to be made to the next generation of the equipment. An example of this type of problem was seen with the vibe board. The powder dispersal problems were first thought to be due to the citric acid concentration, subsequently, they were believed to be due to the solenoid springs and lastly, due to the PDA screen. During the period when the dispersal problems were being experienced the vibe board was also malfunctioning and was replaced a couple of times. However, it took 120 days before the vibe board was redesigned and even at that point the board needed further work.

Stage II problems take longer to fix and the failure rate is frequently higher than anticipated. This is because elaborate design changes are often required to fix these problems and there is resistance to making design changes. Teams are generally predisposed to assuming that they are more 'teething' problems than major design problems, and it takes a while before they are recognized as being design flaws in the system. The solutions are more complex since they involve the interaction between different design components and the changes are cascading, i.e. a change made to fix a certain design problem requires other changes to be made to the design.

Problems in the upper right quadrant (Stage III) generally represent failures related to wear and fatigue. Sometimes the failure may be caused by a malfunctioning component which results in a more serious problem such as the wear or fatigue failure of a more robust component. An example of this type of failure was a drive bearing failure observed on the 3-D printing machine where a screw thread was stripped causing the bearing to fail. The location of the bearing made it difficult to access and repair. These failures are relatively infrequent, however, when they do occur they are difficult to fix and result in significant downtime. This is because the failed components are often integral parts of the machine, spares/tools are not readily available, and special skills may be required to perform adequate repairs

The lower right quadrant (Stage IV) is the desired or ideal state of operation, where failures are infrequent and time to repair is usually small. The performance of the machine by this stage is relatively stable and few problems are experienced. Consequently, by this stage in the machine's life, the operators usually understand the causes for the problems encountered and have acquired the skill required to resolve them. Some of the failures may be accidentally induced by the operators when they fail to follow correct procedures. At this stage new advances in the equipment may be made by the operators. Sometimes these advances, which may be modifications, could cause failures that are easily corrected.

Equipment development programs often pass through all these stages sequentially during the transfer process, especially if the technology maturity is at level three or four. This evolution was certainly evident during the transfer of the 3-D printing technology. The researcher's prior work has shown that when the development and transfer process is improved the time spent in some of these stages can be reduced, thereby allowing a rapid move into stage III and IV.

6.1.1 Minimizing transition state problems

The researcher's prior work in the development of equipment suggests that Stage I problems can usually be minimized by 'shaking' out the technology or equipment before it gets to the receiving site. Even if it means shipping the equipment a couple of days late to do a final 'burn-in' on the equipment it is well worth the effort. The reason doing 'burn-in' testing at the development site is preferable to doing it at the user site is because the designers, spares, tools and experienced service personnel are all available. It is possible to quickly analyze if the failure is truly a 'teething' failure or indicative of a more serious problem.

Stage II problems which are more serious can either be obviously resolved by better design of the system and by using tools such as failure mode and effects analysis. 'Better design' is often viewed as a pie-in-the-sky, but often a combination of using failure analysis to refine the design can be used to reduce Stage II type problems. This was seen in the redesign of different sub-components on the MIT machine. By having competent technical resources (from the development site) at the receiving site, who are very familiar with the basic design of the system, and commitment from the developers to resolve the design flaws these issues can be addressed. The lack of strong commitment on the part of the developers can cause stagnation in Stage II and Stage III resulting in frustration and disillusionment with the technology.

In the development effort between Zygote and Johnson & Johnson a number of issues such as the vibe board, the harness failures and the rough printing of the parts fell victim to the stagnation described above. While all three problems had been identified, they were all difficult to solve and caused frustration. Zygote was committed to resolving the issues on the next generation of the equipment, while Johnson & Johnson wanted a solution on the equipment they currently had. Consequently, while some effort was made to alleviate the problems, most of the solutions appeared to be temporary fixes rather than fundamental root cause solutions. Machine downtime caused by these problems hampered the development of the technology and affected the working relationship between Johnson & Johnson and Zygote.

6.2 Problem solving summary

Sometimes when organizations think about technology transfer they view the technology as a complete, reasonably well defined package of processes, systems and technology. The transfer process then simply becomes moving what exists at one location to a different location. The truth is that often neither the processes, nor the systems, or the technology are well defined. What exists are loosely defined pieces of information around a technological concept. The 'glue' that holds the pieces together is undocumented information on solutions to problems in the minds of the developers. This information is frequently critical to be able to successfully start up the new technology at the receiving site and is discussed in more detail later in the chapter.

A more general view is that the entire transfer process is in a transitional state and there are major components that need to be considered. Some of these have been discussed as part of this research work. They are:

- Strategy and goal congruency
- Technology maturity assessment
- Resource capability and allocation
- Communication processes
- Management control systems

It appears from other transfer work done by the researcher that developing a coherent plan that addresses each of these elements separately and jointly may result in a transfer process where fewer problems are encountered during the transfer.

While many of the things stated here are not revolutionary ideas they are important because they form the basis for most large projects, especially technology transfer. Developing a transfer strategy that is consistent with the goals of the organization and is aligned with the developer's goals is paramount. The short term and long term goals need to be shared and a proposal that meets the needs of all the participants has to be developed. A mismatch between the goals of the participants can put an enormous strain on the relationship and slow down the entire transfer process.

While developing the proposal and defining the goals for the group the maturity level of the technology needs to be considered. An objective assessment of the extent of development and understanding the goals of the transfer process in relation to the current state of development is critical. Optimistic projections of future development or rate of improvement often are the root cause of disillusionment of the participants. Yet another critical aspect to this process is understanding the implication that the technical development has on the resource requirements. Recognizing that developing technologies will continue to evolve and that the degree of sophistication of the technology achieved at the development site will usually exceed that at the receiving site is important. By carefully defining measurable and quantifiable milestones and success criteria for the transfer it is possible to avoid the frustration born out of lack of clear direction. Breaking the feedback loop of escalating goals can sometimes be done by consciously defining what *will* and *will not* be achieved by the end of the transfer.

Once the proposal has been developed the operational aspects of the transfer process need to be defined. Part of this process is identifying the resources required, their timing and the source of these resources. It is most effective when the participants in the transfer process are prepared to share their expertise in certain areas. It is the researcher's view that rather than every member becoming equally skilled at all tasks, it makes more sense to have some level of specialization, to speed up the process and provide adequate depth to the different facets of the project. Some evidence that supports this view is seen in the organization of the development team. Within the development team different individuals had different strengths yet they all were familiar with the overall design of the 3-D printing machine which enabled them to rapidly develop and debug the prototype machine.

Finally, it is important to develop appropriate management control systems to maintain the checks and balances and to ensure that progress is maintained and to determine areas of weakness where additional support may be required.

6.2.1 Capturing the hidden knowledge and solving problems

To be able to successfully transfer the undocumented learning that has occurred over the course of the development a close relationship between the developing and receiving sites is required. Particularly because there are different maturity levels in technology, capturing the hidden knowledge acquired by working with the technology and/or equipment is a critical part of the technology package. Currently there are no good means of obtaining this hidden knowledge except by direct and frequent communication between the developers and the team receiving the technology. It is naive to assume that all knowledge can be transcribed onto paper given sufficient time and thought. It appears that during technology transfer, more relevant and necessary information is communicated in an hour of direct communication in the presence of the equipment, than in volumes of operating manuals.

The reason for this is the 'fuzziness' of the knowledge and relational information. Sounds, smells and visual signs are 'clues' to problems that may be revealed intermittently during the development of the technology. These clues are frequently forgotten when operating manuals are written. Even if recollected, they cannot be described as eloquently or accurately as would be possible if the developer and user were physically present by the equipment when the clue was seen or heard. This is the reason why training is often emphasized during technology transfer. Unfortunately, training is frequently assumed to mean learning how to adjust the dials and knobs, which is not the same thing.

What needs to be captured during the training is the information associated with the clues known to the developer but not recollected except when the clue is presented. The developer's ability to recall relevant information pertaining to a particular problem when presented with a clue or symptom is essentially a conditioned response to the clue. Hence, the physical presence of the user at that time the clue is presented to the developer can greatly facilitate the transfer of the information hidden until such time. This process of extracting the hidden information can be significantly enhanced by visits by the developers and receiving team members to each other's site. The visits also allow both groups to keep abreast of new developments and progress being made in solving the problems associated with the new technology. This was observed at every quarterly meeting of the Zygote and Johnson & Johnson teams. There were invariably revelations about problems that both sites were facing and solutions that each of them had developed.

Understanding the communication processes, both formal and informal, can be crucial to the transfer of the skills that are critical in the initial stages of the transfer. The ability to interact at the developer or user site can affect working relationship, the degree of trust, and credibility that exist between the participants (Lovett, 1992). All these factors can be all important to the success or failure of the project. They can determine whether the developing and receiving sites get deadlocked over issues, and the transfer process gets trapped in a transitional state for months, where it is neither completed nor canceled.

The frequent visits by the developers and receiving team members to each others site not only keeps them abreast of the development, the progress and problems associated with the transfer, but it allows the receiving site to participate in the development and provide useful feedback on what works and what does not work in the field. This was seen in the development of the next generation of the 3-D printing machine which was regularly discussed at quarterly face to face meetings. Many of the problems seen with the current generation of the machine were being corrected based on the feedback provided by Johnson & Johnson. This involvement in the development process builds the trust and relationship between the groups.

The speed and quality of the solutions developed to problems that arise during the course of the transfer is intimately linked to all of the factors described above and in the earlier chapters.

6.3 Technical directions in slip casting

The slip casting process as applied to improving the surface finish of castings produced from the 3-D printing machine molds certainly has room to grow. The work demonstrated the feasibility of using slip casting of alumina to smooth the surface of the ceramic mold. The experimental work was able to demonstrate that while it was possible to generate smooth surfaces, the repeatability of the process was unsatisfactory. The poor repeatability was primarily due to large variations in porosity of the substrate. This in turn was driven by poor drop placement accuracy of the machine, poor layer thickness uniformity, and poor line spacing repeatability. The combination of these errors compounded in three axes made the surface quite non-uniform and hence the slip cast layer rather uneven.

A critical dimension along which investment cast parts are measured is feature definition. Traditional wax processes allow fine features to be defined. The coating thickness in the slip casting process inherently limits the smallest features that can be defined. A tradeoff between smoothness and feature definition has to be made when using slip casting as the means of achieving smoother cast surfaces. For a given substrate surface as the coating thickness increases the surface becomes smooth but feature definition is lost. This can be minimized by improving the quality of the substrate produced by the 3-D printing machine which will then allow the use of thinner slip cast films.

The focus of future work has to remain on improving the properties of the underlying substrate produced directly by the 3-D printing machine in order to use slip casting as the means to better surface finish. The critical leverage points are (i) drop placement accuracy, (ii) layer thickness accuracy and (iii) porosity control. Without adequate control over the underlying substrate the slip casting process will be unable to produce the quality of surfaces that would be acceptable in investment casting.

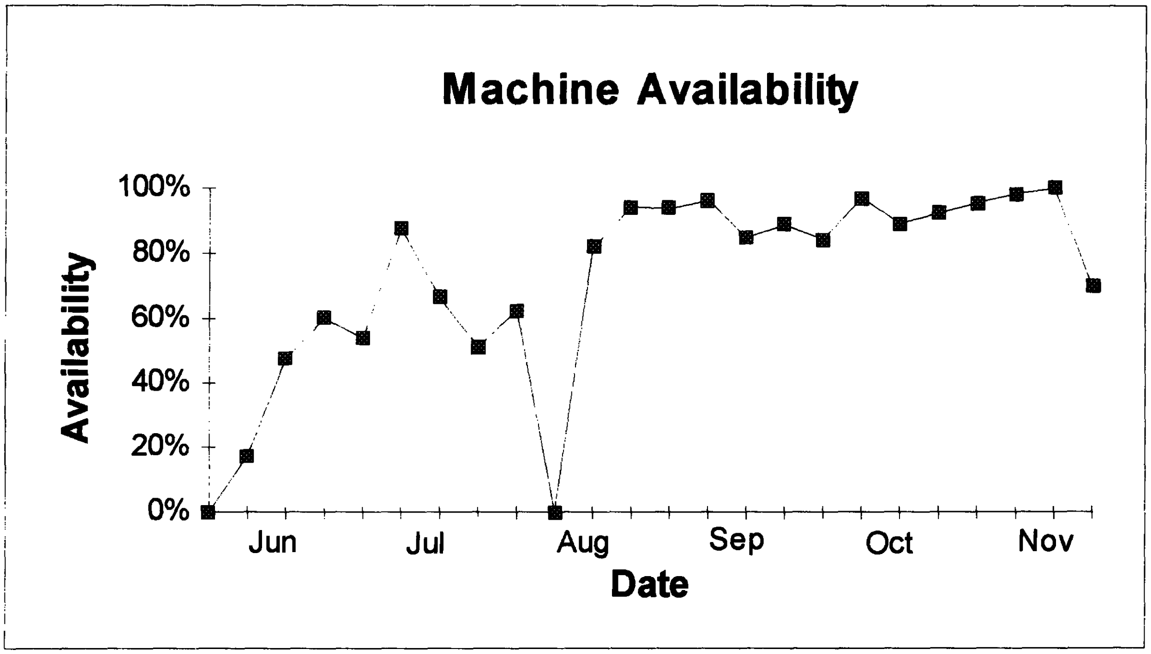
6.4 Closing remarks

Looking back at the transfer process it might appear that given the initial expectations that the team at Johnson & Johnson had for the new technology that the transfer process was fraught with problems. While there were a number of problems associated with the equipment and with the transfer process, many of which were discussed in this document, a remarkable amount of improvement was made in the performance of the 3-D printing machine. Hence, it is important to revisit the assumptions made at the start of the transfer in the light of the information presented and the ideas proposed.

The first assumption that was made initially at Johnson & Johnson was that the process and equipment were capable of running unassisted and with minimum development. This meant that the process and equipment were at level two. As the data clearly showed this was not the case in reality. The second assumption was that all the information needed to make the transfer could be communicated directly to the team members via the field service representative or via the face to face onsite meetings held quarterly. This indirectly meant that all relevant information around the technology and equipment was known, well understood and easily communicated.

If the technology had been evaluated under the criteria defined in chapter 5 the maturity of the 3-D printing process at the time of transfer should have been classified as a level three or four. The type and nature of the work involved in the transfer at level four is significantly different from a transfer at level two. There are differences in the amount of development, the rate of progress that can be expected and the degree of direct communication required to make the transfer. Keeping that in mind it would appear that in fact significant progress was made in the transfer process especially given the fact that the two sites were across the country. This can be seen in the figure 19 which shows the percentage of time in a 40 hour workweek that the machine was available to produce ceramic molds. The progress seen in the figure was made as a result of collaboration between the team members at Johnson & Johnson, the development engineers at Zygote

Figure 19: 3-D Printing machine performance over time



and MIT despite the numerous difficulties, difference in operating styles and differing objectives that had to be reconciled to make progress. Nevertheless, the process was a learning experience for all three organizations on the trials, tribulations and joys of technology transfer.

Ultimately, whether we think the transfer process was a success or failure depends on our assumptions and beliefs about the objectives and goals of the project. Besides the well-documented need for strategy, planning, schedules and resource allocation, the key lessons learned from this particular experience were:

- To improve the technology transfer process it is important to realize that often neither the processes, nor the systems, or the technology are well defined. What exists are loosely defined pieces of information around a technological concept. The 'glue' that holds the pieces together is undocumented information on solutions to problems in the minds of the developers. It is often the latter information that can spell the difference between success and failure of the transfer process.

- While post processing techniques such as slip casting can be used to modify the surface of the mold produced from 3-D printing, the onus of producing a good mold still lies with the 3-D printing process and equipment.
- Technologies exist at different levels of maturity. By careful analysis of the maturity level it may be possible to minimize the difficulties encountered during the transfer process and improve the decisions made around technology transfer.

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Appendix

A1: Preparation of slip casting slurry

The steps involved in preparing a batch of slurry for the slip casting process are given below. Caution should be used in adding the acid. If binder is to be added to the slurry mixture, the binder usually will have to be dissolved in hot water and caution should be used while dissolving the binder to prevent it from boiling over. The dissolved binders tend to coagulate rapidly hence care should be taken to ensure the solution does not cool down before it is added to the slurry mixture.

1. Determine the volume percent that you want to make (P= 0.1, 0.2 etc. for 10% 20%)
2. Use the equation X/(X+400) = P (this assumes volume of water to be 400 ml)
3. Solve to find the volume of alumina (X) that you need.
4. Density of commercial grade alumina 3.98 gm/cc (Reynolds RC-172 DBM)
5. Calculate the weight of alumina that you need using the density.
6. Take a dry clean poly bottle and fill 1/3 the bottle with alumina mixing beads
7. Add the volume of distilled water. Add nitric acid to get the pH between 2.8-3.0
8. Add the alumina powder a little at a time, close the bottle and shake to break up the alumina with the beads.
9. Check the pH after all the alumina has been added and mixed. It will be higher. Add more nitric acid if necessary to bring the pH back down to 3.0- 3.5
10. Place the closed bottle on the ball mill and mill for 24 hours to get the slurry thoroughly prepared and mixed.

<u>Note</u>: If binder is to be added to the mixture. Calculate weight of binder (poly vinyl alcohol) as a percent of the solid content. Calculate total volume of water required and use a portion of it to dissolve the binder. Binders should be dissolved in hot water and care should be taken to prevent the water from evaporating too quickly.

A2: Drying and firing recipe for slip cast parts

The recipe given below was used for all the tests that were performed on the slip cast parts.

Step	Setting
Ramp	5 F/min.
Set point	180 F
Hold	16 hours
Ramp*	5 F/min.
Set point*	750 F
Hold*	4 hours
Ramp	10 F/min.
Set point	2000 F
Hold	2 hours
Ramp	10 F/min.
Set point	70 F
Hold	1 hr

* Note these steps are required only if the slip slurry contains binder that needs to be fired. If no binder is mixed in the slurry, these steps can be eliminated.

A3: Experiment worksheet

Run number	*Slurry*	*Sit time (min.)*	*Binder*	*Casting*
1	10%	1.5	y	y
2	10%	2.5	y	y
3	10%	5	y	y
4	10%	7	y	y
5	10%	10	y	y
6	10%	1.5	n	n
7	10%	2.5	n	n
8	10%	5	n	y
9	10%	10	n	n
10	20%	1	y	y
11	20%	1.5	y	y
12	20%	2.5	y	y
13	20%	1	n	n
14	20%	1.5	n	n
15	20%	2.5	n	n