Machine Issues Associated with Solid Freeform Fabrication

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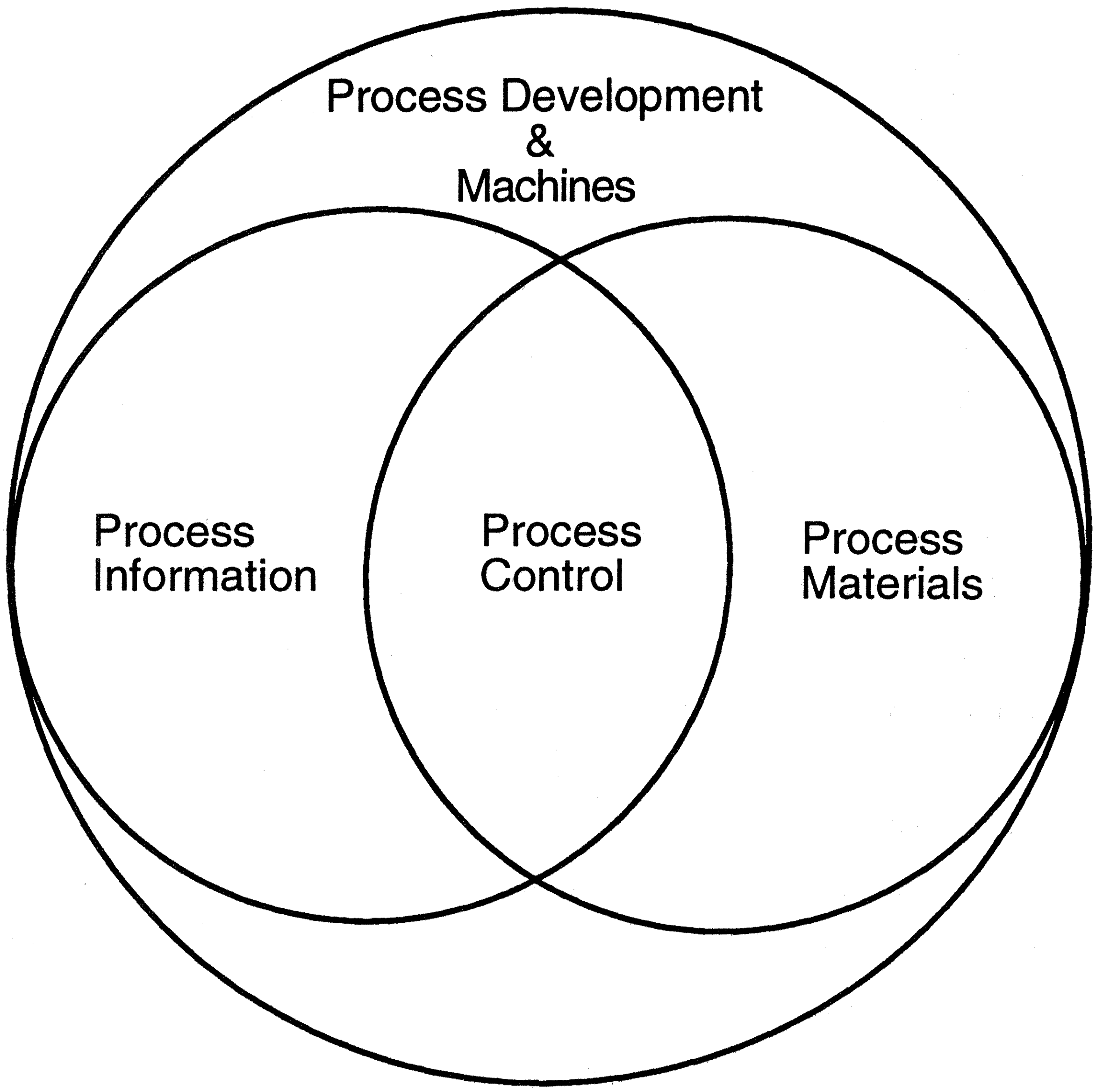
Before we begin a discussion of machine issues it is important that we categorize exactly what we mean. There are differences between the design of a research piece of equipment as compared to a commercial piece of equipment. A research piece of equipment has to have the flexibility to demonstrate a success pattern. A commercial piece of equipment, on the other hand, assumes that you have a stable platform and you are now trying to assess how broad a success path you have (Figure 1). In fact, you are trying to make that path as broad as possible so that the machine will not fail and will always work the same way. This particular talk, and my expertise, is much more along the lines of design of a research piece of equipment. What I will be talking about today are machine issues associated with developing a success path in Solid Freeform Fabrication. The machines we will be talking about have to have the flexibility to operate in a wide variety of ways with a wide variety of experiments.

Given that we are going to talk about machines, we should also discuss what we mean by machines. If we look at the next figure we see that, if we are trying to make a part by Solid Freeform Fabrication which we have defined to be the ability to go directly from the computer rendition of an object directly to the part itself, requires several components. It requires process information which stores the information of the object itself, it requires materials, and it requires process control. All of this sum total is the machine. The point I am trying to make is that it doesn't make sense to talk about a machine without a process (Figure 2). In fact, a machine is nothing more than an embodiment of a process. I am going to be talking about the Selective Laser Sintering process but in such a way to emphasize the general concepts associated with designing and implementing research machines to demonstrate freeform fabrication.

Machines

Research	Commercial
• Flexibility	• Stability
• Success Path	• Width of Path

Figure 1



Machines without Process?

Figure 2

In the next figure (Figure 3), we see how we organize our research in Selective Laser Sintering. At the top of this diagram you will see fundamental process understanding. Our process by its very nature is a thermodynamic process. Here we find basic models by which we understand and describe our process. Underneath this we have information processing which includes geometric representation, materials and related microstructures, process control, process development and machines, and finally, parts and applications. I would like to talk about each one of these separately.

At the top of our research hierarchy we included fundamental process understanding. This area contains our thermodynamic models, both written and conceptual that we use to help design our equipment. A particular point I want to make here is that the thermodymics involved, at least in Selective Laser Sintering, includes both macroscopic and microscopic phenomena (Figure 4). What is crucial to Selective Laser Sintering is control not only at the small scale with a laser but also control of the large scale thermodynamics and heat transfer with heaters, either radiant or conduction. If this is not done properly the parts you make can have large amounts of curl or growth. Although I do not want to discuss the details, I do want to make the point that any given process, not just Selective Laser Sintering, will be involved in certain fundamental processes. It is important that we understand what those processes are in order to most effectively optimize the equipment that we design.

Information processing (Figure 5) is one of the processes required for Selective Laser Sintering. We must have a geometric representation of the part. Associated with that we must have a process interface which allows various representations. For example, you have a CAD representation which must effectively talk with the machine slice level. There are other instances where we may not even have a CAD representation. Image data, for example, in scanning where you have data to perform reverse engineering or automatic copying of a part. To achieve this requires a good

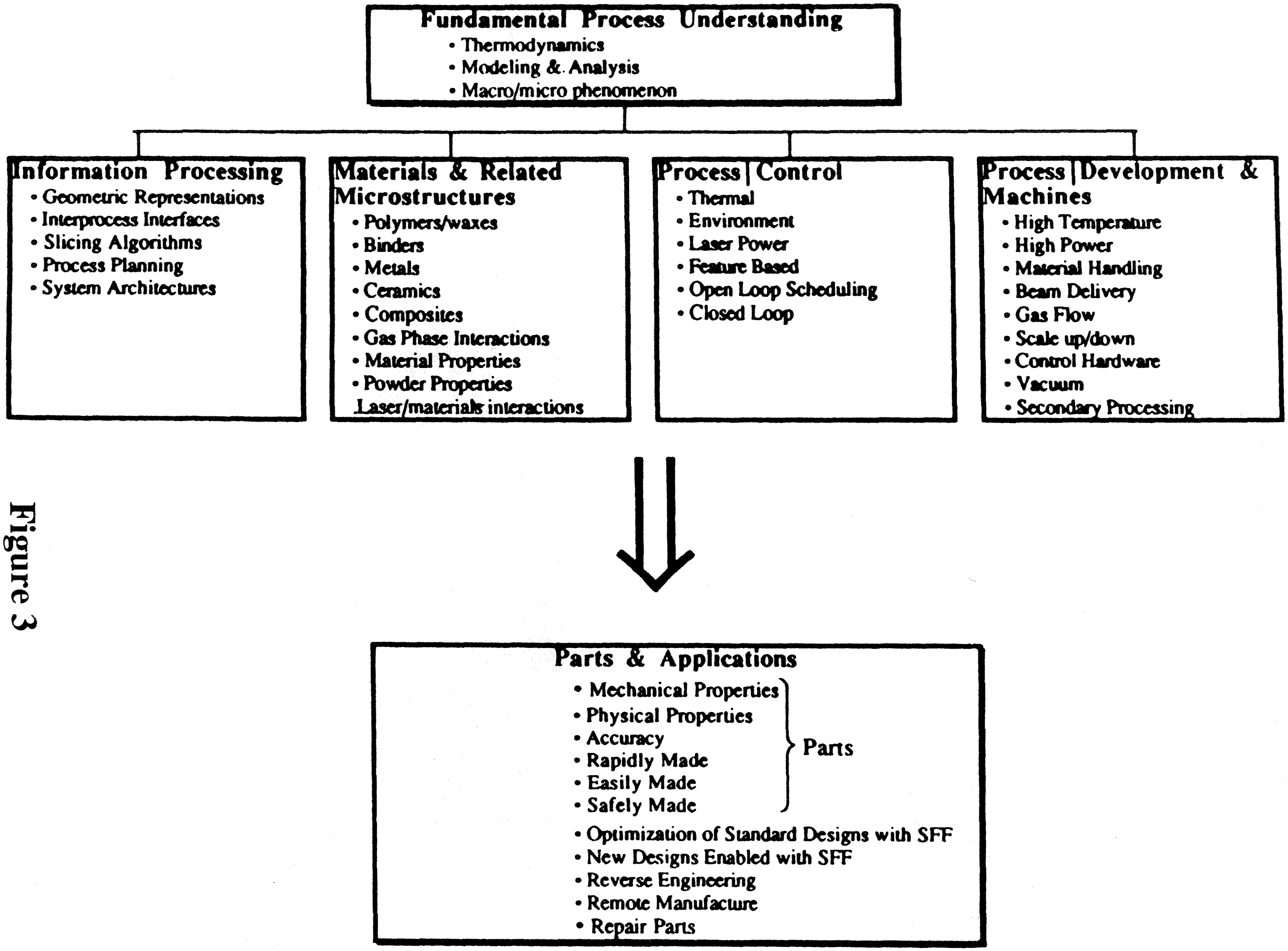


Figure 1: Structure of Overall Solid Freeform Fabrication Research

Figure 3

Fundamental Process Understanding

- Thermodynamics
- Modeling & Analysis
- Macro/micro phenomenon

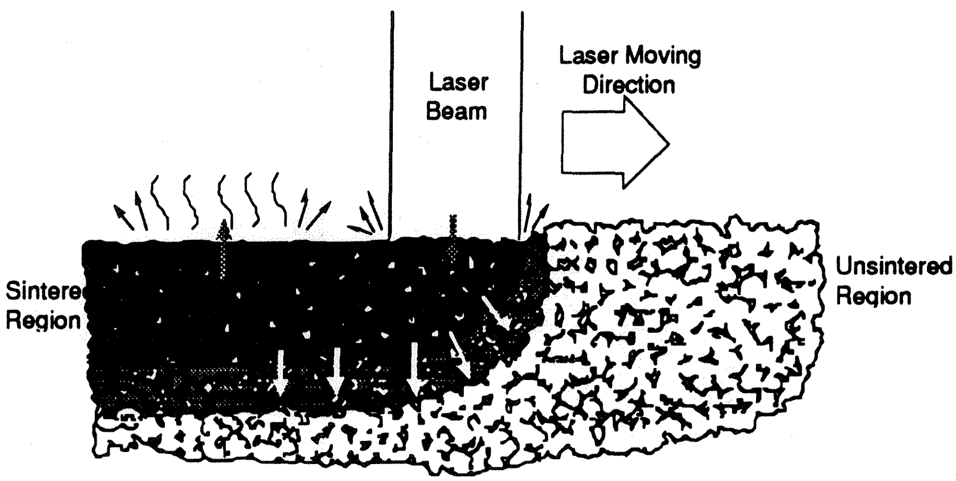


Figure 4

Information Processing

- Geometric Representations
- Interprocess Interfaces
- Slicing Algorithms
- System Architecture
- Artificial Intelligence

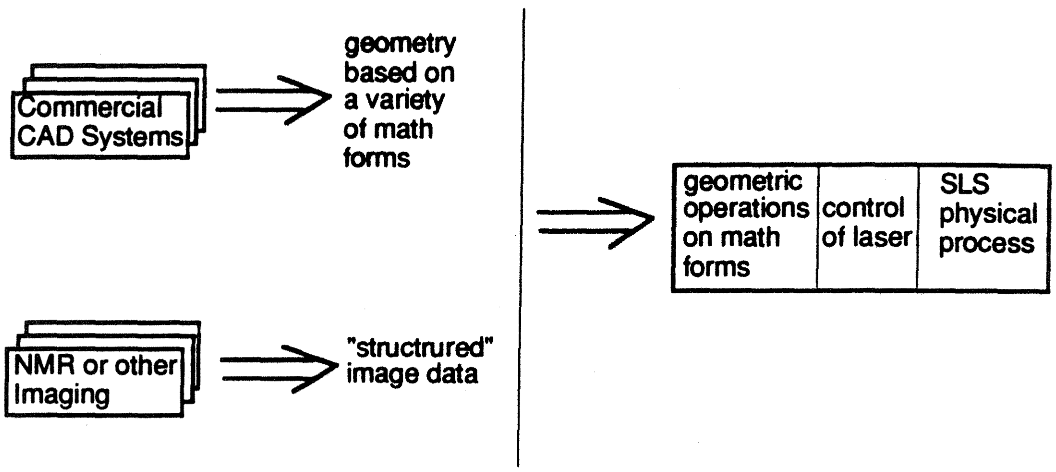


Figure 5

Process Control

- Thermal
- Environment
- Laser Power
- Open Loop Scheduling
- Closed Loop
- Artificial Intelligence
- Neural Nets

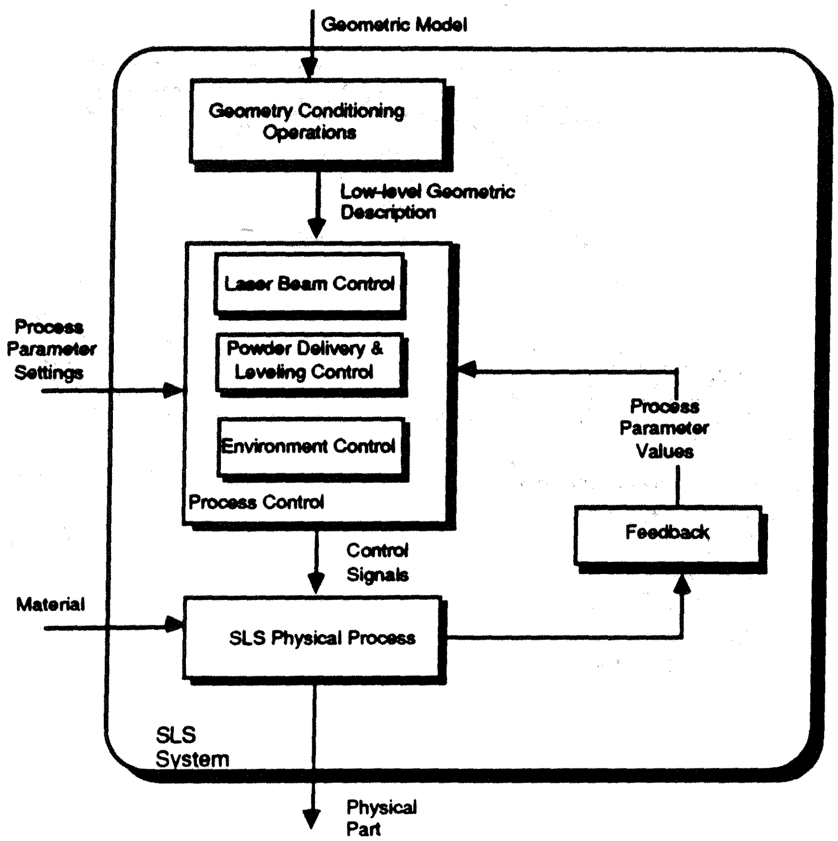


Figure 7

Process Development

- High Temperature
- High Power
- Material Handling
- Beam Delivery
- Scale Up/Down
- Hardware
- Secondary Processing
- Material Processes

Figure 8

temperature materials, higher power up to kilowatt laser system, different material handling systems, how to handle the beams, and particularly, how to scale up or scale down-both down to the micro and up to very large machines. Given a part we also have to talk about secondary processing in order to best finish this part. We are also concerned with material processes associated with actually making selective sintering specific materials.

Our goal is parts and applications (Figure 9). It is not good enough to say a part just has to be accurate or it just has to be strong. There are a lot of different functions and concerns in a part. For example, if I want a conducting part, the part has to have the right electrical properties. We are also concerned with mechanical and physical properties. In addition, these parts have to be accurate, rapidly and easily made.

What are the applications? One is to optimize standard designs and processes with freeform fabrication. Now that is useful, but what is even more exciting is enablement of new designs and processes. Things that can never be made by any other process can be made with Solid Freeform Fabrication processes. As this technology gets introduced into the market place, we will see more and more designs enabled. Other applications are reverse engineering where items are scanned and then refabricated, remote manufacturing where machines are distributed throughout the world and the information to make parts on those machines is telecommunicated to those locations. Even more exciting, is that once you develop structurally sound parts, inventory can be reduced with machines that make parts on demand.

As a particular example of our research approach consider the design of a high temperature workstation that we are in the process of implementing. Figure10 is an analysis of our starting point for this workstation design. Basically the state-of-the-art at that point was Selective Laser Sintering for low temperature parts, basically low melting point materials like polymers. We wanted to extend the state-of-the-art to handle high temperature materials with an ultimate goal of being able to sinter fully dense structural

Parts & Applications

- Mechanical Properties
- Physical Properties
- Accuracy
- Rapidly Made
- Easily Made

} Parts

- Optimization of Standard Designs & Processes with SLS
- New Designs & Processes Enabled with SLS
- Reverse Engineering
- Remote Manufacture
- Repair Parts

Figure 9

PROJECT BACKGROUND

- **THE STATE OF THE ART**

  THE SELECTIVE LASER SINTERING PROCESS IS USED TO BUILD PREFORMS AND PROTOTYPE PARTS FROM LOW MELTING POINT MATERIALS

- **EXTENDING THE STATE OF THE ART**

  THE SELECTIVE LASER SINTERING PROCESS WILL BE USED TO DIRECTLY SINTER PARTS FROM HIGH-TEMPERATURE MATERIALS

- **ULTIMATE GOAL**

  THE SELECTIVE LASER SINTERING PROCESS WILL BE USED TO DIRECTLY SINTER FULLY-DENSE STRUCTURAL PARTS

Figure 10

parts in metals and ceramics. We subdivided this into three phases (Figure 11): the first phase being a direct sintering of high temperature materials with just a high laser power sintering. We did not expect full success at this point because we knew from our understanding of the process that you have to elevate the powder temperature to alleviate thermalstresses. Phase two of our process, which we are in the middle of implementing, involves combining a high power laser system with high temperature powder preheating capability for much improved part quality. Phase three of the process will be to get much better control and implementation of our atmosphere, basically to vacuum standards.

Here is a sample of some of the questions we asked ourselves in this design procedure (Figure 12). We looked at the window seal tolerances, maximum obtainable temperatures for representative powders, what kind of temperature distribution you can get, temperature dynamics, what kind of control systems and the effect of chamber walls in designing a higher temperature system. In addition we looked at the effect of powder bed heights, convection effects, temperature measurement calibration, and heater efficiency. For each of these categories we proposed solutions and designs to optimize between the various questions. Out of these discussions in design came a basic configuration which consisted of dual heaters, a laser window, a small powder bed, actually the smallest system we have built to date (Figure 13). We did not want to concern ourselves with building large high temperature systems with uniform temperature distribution. Just recently our first implementation of this design has come into operation. We have achieved powder bed temperatures of 950°C. We have had some problems as well. We were able to melt one of our zinc selenide windows which has now been replaced with a salt window. As testing proceeds we will continue to design and redesign. We have discovered that at full power the chamber becomes too hot and we are going to have to worry about how to take some of the heat away (Figure 14).

In summary, I would like to state that it is our view that machines cannot be designed without a good understanding of the process and that understanding of the process has to come from fundamental process understanding which then can be reticulated into information processing, control and process development, out of which will flow all the applications and parts that we would all like to see coming out of Solid Freeform Fabrication.

DESIGN STRATEGY

- **PHASE I– HIGH LASER-POWER SINTERING**

  DIRECT SINTERING OF HIGH-TEMPERATURE MATERIALS

- **PHASE II – HIGH TEMPERATURE SINTERING**

  CONTROLLED HIGH-TEMPERATURE POWDER PRE-HEATING CAPABILITY FOR IMPROVED PART QUALITY

- **PHASE III – VACUUM SINTERING**

  MEDIUM TO HIGH VACUUM WORKING CHAMBER FOR CREATING HIGH-DENSITY SINTERED PARTS

Figure 11

OBJECTIVES

Window Seal Tolerance
- Will the heater window O-ring seals stay at a safe operating temperature?

Maximum Obtainable Temperature (MOT)
- What is the MOT at steady state for some representative powders?

Temperature Distribution
- How does the heat flux distribution compare with the model predictions?
- How does heat flux distribution relate to temperature distribution for powders having different thermal properties?
- How is temperature distribution effected by various parameters?

Temperature Dynamics
- How quickly can we reach steady state operating conditions?
- How does the system respond to a change in heater power?

Temperature Control System Performance
- How precisely can the powderbed temperature be controlled using the IR sensor and PID controller?

Effect of chamber wall reflectivity
- How will chamber wall reflectivity affect thermal performance?

Figure 12

Figure 13

Effect of Powderbed Height
- Is thermal performance an important criteria for selecting powderbed height?

Convection Effects
- How will forced convection affect the thermal performance of the powderbed?

Temperature Measurement Calibration
- The IR sensor must be calibrated to account for attenuation.

Heater Efficiency
- How much of the heater power reaches the powderbed?
- How much reaches the thermal absorbers?

Figure 14

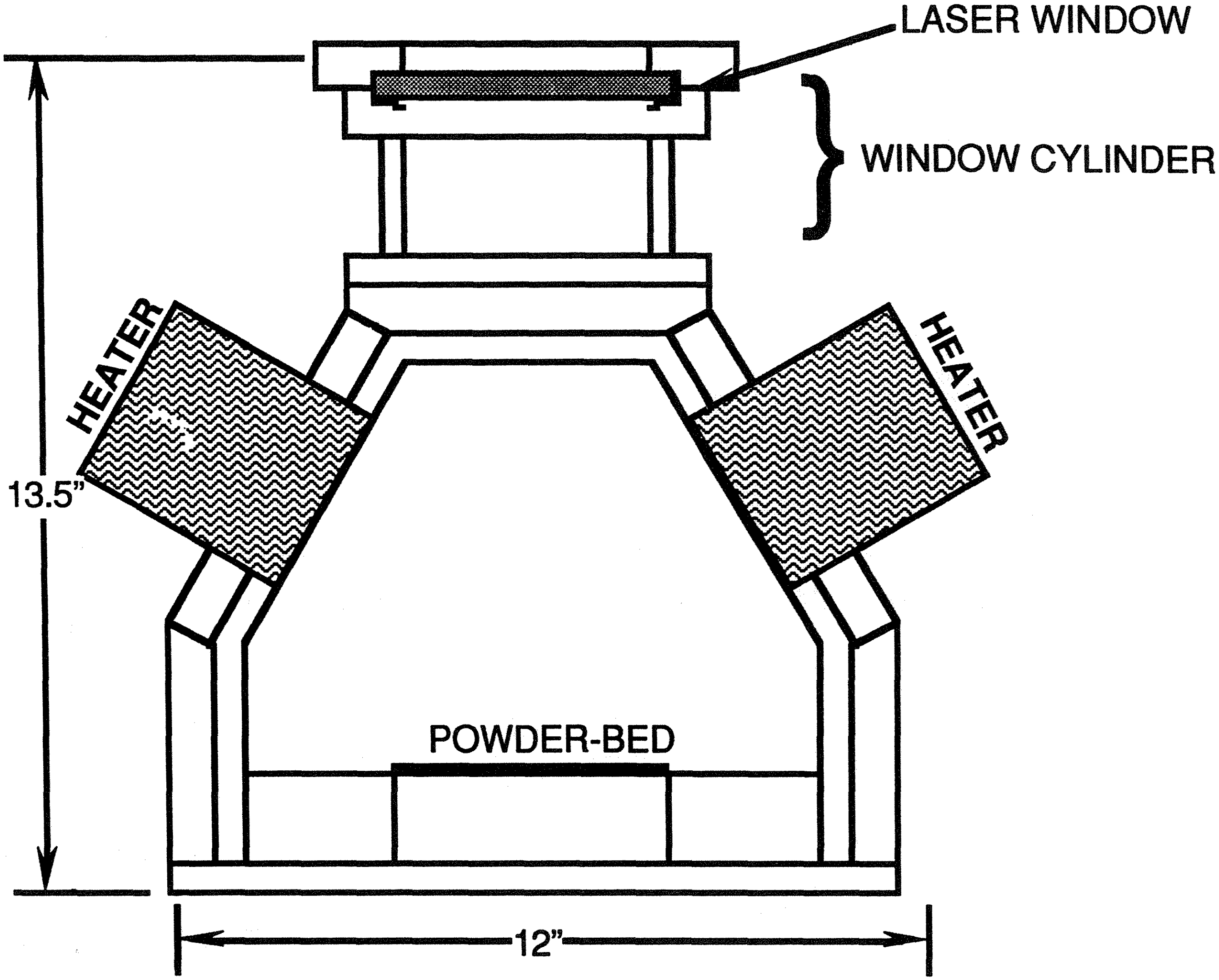


Figure 3: Chamber Configuration

PROJECT STATUS AND FUTURE DEVELOPMENT

- Powder bed temperatures of up to 950°C have been obtained in the high temperature Process Chamber.

- The coating on the zinc selenide laser window was damaged during initial testing. A sodium chloride window is now being tested.

- At full power, the chamber becomes too hot, which may result in damage to the seals. Radiation absorbers were designed to remove excess energy from the chamber.The absorbers will be tested soon.

Figure 15

Figure 16