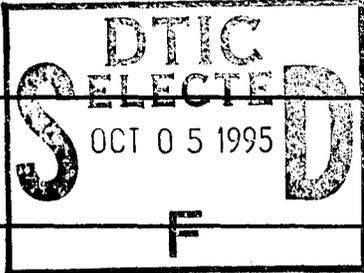


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*Final Technical Report to AFOSR for Project*

## Developing Model-Based Control Strategies for Hot Isostatic Pressing

Sponsor of Project: Air Force Office of Scientific Research

Grant or Contract Number: F49620-93-1-0190

Period of Performance: March 1, 1993 --- August 30, 1994

Principal Investigator: Dr. Weiping Li  
Department of Mechanical Engineering,  
Wayne State University, Detroit, Michigan

Date of Report Preparation: August 31, 1994

AFOSR program manager: Dr. Marc Q. Jacobs

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## Part A. Executive Summary

The objective of the project is to study the model-based feedback control of hot isostatic pressing process for the purposes of improving product quality and maintaining product consistency. A control strategy in the form of feedforward and feedback is developed based on the dynamic model of the HIPping process. The process model is a modified version of the Ashby model, incorporating the effects of yielding, creep, diffusion and container deformation. Nominal profiles of process inputs such as temperature and pressure are determined based on understandings of and experiences on the process, so that product quality will be optimal under the nominal conditions. These profiles are then used to generate the nominal profiles of the powder density. In real time control, the nominal density profile is followed by in-situ measurement of powder density and on-line adjustment of processing conditions. The adjustment is based on the combined use of input feedforward (using nominal profiles of process inputs) and density feedback. It was found that density feedback based on PI control (proportional plus integral) has better performance than proportional control alone. The sensitivities of densification response to various inputs and various process parameters are studied using theoretical analysis and computer simulation. The densification process is more sensitive to pressure adjustment at initial stage of HIPping, while more sensitive to temperature adjustment at later stages. Without feedback control, the process was found to deviate significantly in the presence of process disturbances and batch-to-batch parameter variations (in parameters such as initial packing density, material yielding strength and creep exponent). However, with the proposed close-loop control, the densification process becomes quite robust to process disturbance and parameter variations. It is demonstrated in computer simulations that the resulting densification will be consistently close to the optimal densification profile, unlike the case of open-loop HIPping control. Some tests were also carried out on the finite element 3-D model of the process.

The project was planned to last for three years, but it was discontinued after less than two years because the PI had to leave the university for personal reasons. The following publications resulted from the research effort:

W. Li and Q. Tang, "Control Design for a Highly Nonlinear System", Proc. of the Symposium on Mechatronics, Dec., 1993, Edited by Tsao, Hu, Olagac, Liang, and Weins.

W. Li and M. Rahani, "A Closed-loop Control Strategy for Controlling Powder Densification", submitted for publication in the International Journal of Control, Oct., 1994.

The following personnel participated in the research:

Dr. Weiping Li, Principal Investigator, Assistant Professor of Mechanical Engineering, Wayne State University;

Mr. M. Rahani, M.S. Candidate, Department of Electrical and Computer Engineering, Wayne State University;

Mr. Q. Tang, Ph.D. Candidate, Department of Mechanical Engineering, Wayne State University;

## Part B. Details of the Technical Report

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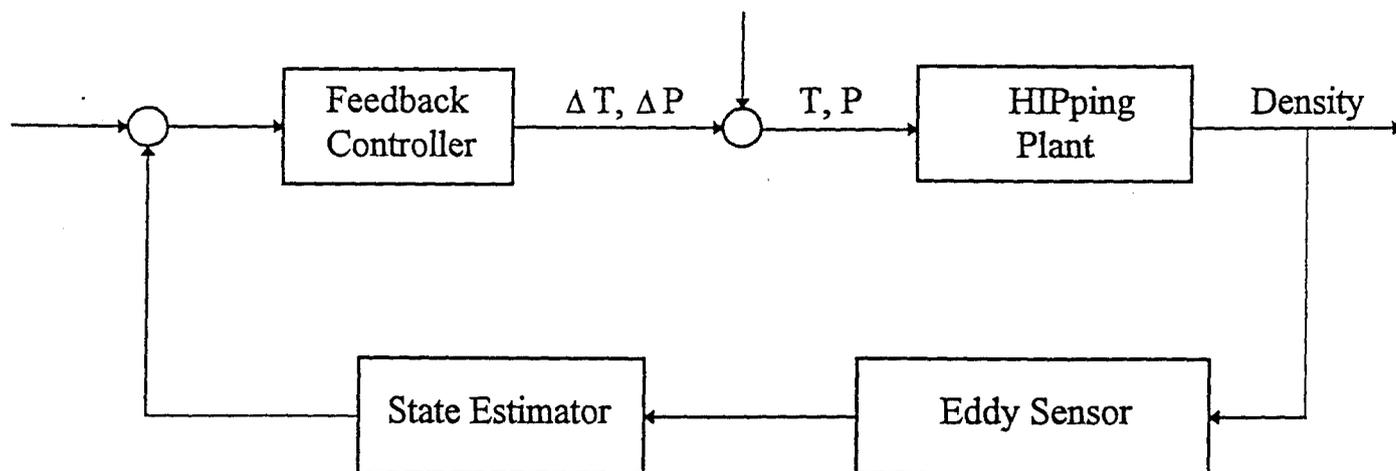
### **1. Introduction**

An important problem during Hot Isostatic Pressing(HIP) process is the deviation of the product characteristics from the desired goals due to changes or variations in parameters of the powder, the container, or the process cycle. This deviation is unavoidable when the HIPping process is carried out using a fixed process schedule which is conventionally applied in industries. A response characteristics of a HIPping process is generally concerned through following factors: final density, final grain size, shape change, interparticle bonding, the maximum vessel temperature and pressure, the maximum rate of vessel temperature and pressure, and the time period of process cycle. In order to obtain a satisfactory HIPping product specification, an optimal response of HIPping process is usually proposed through synthetically and optimally considering all the factors listed above. So long as the optimal response is set, a nominal HIPping process schedule which describes the input variable profiles of time variant temperature and

pressure should be consequently determined. Based on the knowledge of the HIP model, it is believed that this schedule will give satisfactory results of the HIPping response. However, the practical condition of the HIPping process is not so fixed and invariable as it is described in HIP model. The nominal schedule is actually not capable of leading to an optimal response when the uncertainties and disturbances exist.

It is possible that the workpiece and the HIPping process undergo predictable changes and unpredictable variations when these disturbances are quite small. Predictable changes might include modifications to the apparatus or procedure which allowed more efficient use of equipment (installation of a larger compressor, pre-heating of the workpiece before installation in HIP, etc.) or changes in the powder characteristics (different particle size distribution from a new vendor, etc.). Unpredictable variations might include shortcomings of the equipment (deterioration of compressor operation, etc.) or irregularities in sample material or preparation (different impurity levels, etc.). If these variations are large enough, the product may deviate unacceptably from its specifications.

A reasonable measure to eliminate the deviation of optimal HIPping response caused by the uncertainties and disturbances is to introduce a suitable closed loop control. The objective of the control scheme is to cope with those variations by developing a closed loop control system which can adjust the process schedule automatically to keep the product within specifications. This means that sensors for detecting density and grain size of the workpiece must be developed to give the controller on-line feedback signals, and a feedback control law, which is based on the process model and used for modifying the nominal HIP schedule, should be constructed to drive the HIPping process into the optimal response whenever there exist uncertainties or disturbances during the process. A typical such designed control system is shown in Fig. 1.



## Figure 1

There are four major blocks in the closed-loop system. The HIP plant is a real physical process which receives the furnace temperature and pressure as input and provide density and grain size as output. The eddy current sensor is used to detect the output of HIP plant and gives the signals in the form of its impedance variations. The impedance values are then processed in an algorithm called state estimator to obtain an estimate of the densification status. The estimated values are compared with the optimal response that is the output of HIP model to detect the deviation of the densification process. Then, based on the deviation, the feedback controller calculates to the adjusted increments of temperature and pressure and add them into the nominal schedule to give a corrected schedule which is finally applied to the HIP plant.

A brief comparison between the response of HIP process under fixed schedule with disturbances and its closed loop control approaches is shown in figure 2 and figure 3. The effect of eliminating the disturbances in HIP process using closed loop control is obviously observed.

## HIPping Densification Model

### I. Ashby Model and Active Mechanisms Concerned

There are several approaches can be used to describe the behavior of a body of powder subjected to high temperature and pressure. These include empirical constitutive equations describing the bulk response of particulate or porous materials to localized stresses around regions of interparticle contact. Macroscopic constitutive equations can be derived from mechanical tests of materials subjected to different stress states at different densities and temperatures: a series of tests sufficient to describe the conditions experienced during HIP densification would be an unreliable guide to behavior of the material under conditions outside the range of variables used in the test. A microstructure-based model, on the other hand, should describe material behavior under a wide range of conditions, but it may require input of many physical parameters, not of all which are likely to be known well for any alloy of practical importance. Once the microstructure-based model has been developed and refined, however, it should be applicable over a wide range of conditions. Such a model, describing the densification of spherical powders subjected to hydrostatic pressure, has been developed by Ashby and collaborators [ ] [ ], and is widely used in HIP research and development.

The Ashby model for HIP densification of powders considers the deformation of spherical powder particles under the influence of an applied pressure. The geometry of interparticle contacts changes as the powder densifies. Initially (called "stage 1"), the geometry is described as an array of spherical powder particles which contact one another at "necks" which grow in area as the material densifies. Toward the end of densification (called "stage 2"), the material is described as a solid containing spherical pores. For each of these geometry, the densification due to several different deformation mechanisms is calculated. Densification due to plastic deformation of powder particles occurs immediately when the yield stress is exceeded at some point within the powder particles. Subsequent densification due to several other deformation mechanisms such as power law creep and boundary diffusion is time-dependent and occurs at rates which can be summed to give a total densification rate.

The equations describing densification rate under the different mechanisms mentioned above has been well worked out by several researchers. These equations, based on the Ashby model, are simplified and reformulated to suit representation of how a material would respond to a complex cycle in which the temperature and pressure vary with time, i.e., the densification rate in the form of a time-function has been achieved. This makes it possible to conduct the analysis, simulation and designing of a control system of HIP process.

Following equations (eq. 1 to eq. 8) describe the whole densification process. For each of the time-dependent densification mechanisms, the calculated densification rate  $\dot{\Delta}$  for stage 1 or stage 2 can be expressed as  $\dot{\Delta}_{n,i} = F_{n,i} + G_{n,i}$ , where  $F_{n,i}$  is a function of the physical parameters of the material,  $G_{n,i}$  is a function of the geometry of the powder material as described by the initial density  $\dot{\Delta}$  and the instantaneous density  $\Delta$ , and  $i$  is 1 or 2 (for stage 1 or stage 2). This is strictly true only if there is no residual gas pressure in the interparticle spaces, and in this case  $F_{n,1} = F_{n,2} = F_n$ . The only exception is that for the power law creep mechanism, the function  $G_n$  also depends on the power law creep exponent "n". At intermediate densities, the geometry is intermediate between that described as "stage 1" and that described as "stage 2", and the densification rate is described as  $\dot{\Delta}_n = \dot{\Delta}_{n,1} * S_1 + \dot{\Delta}_{n,2} * S_2 = F_n * \{G_{n,1} * S_1 + G_{n,2} * S_2\}$ , where  $S_1$  and  $S_2$  are smoothing functions which cause the relative contributions from stage 1 and stage 2 mechanisms to change as the sample density increases.

Equation 1 -- 8

## II. Simulation

The conducted simulation is based on Ashby model which is described in equation (1) through equation (8). Figure 4 and figure 5 shows the plots of densification rate vs. relative density and relative density vs. time respectively. The powder material adopted here is  $\gamma$ -titanium aluminide powder of type Ti-50.3at%Al-1.8at%Nb REP. Table 1 listed its physical parameters and environment conditions during HIP process. The nominal HIP schedule is illustrated in figure 6.

Figure 4 is a semi-logarithmic plot where various kinds of mechanisms that contribute to densification are illustrated. If only a single mechanism were operating, the shape of the semi-logarithmic plot of densification rate (as a function of density) should reveal what that mechanism was. In most cases there will be contributions from more than one mechanism and the shape of the densification rate curve will be obtained as the sum of the curves in figure 4.

The relative density shown in Figure 5 is actually an integration of summed densification rates in figure 4 with respect to time, which is related with the HIPping schedule shown in figure 6. Different schedule can result in different density process. Figure 7 illustrates the comparison of these results. We will find that the relative density can never reach the full density if the temperature and/or pressure in the schedule are not large or last long enough to ensure the necessary consolidation. This circumstance means the failure of HIPping process. It can also appear if the parameters of powder material varies too much. The closed loop control will then need to be installed into the system so that it can push the response toward the expected process curve.

## III. Model Sensitivity Analysis

Model sensitivity analysis is to further investigate in details of how the HIPping process would respond and what the extent it can reach under either the input of temperature and pressure, or the parameter changes. Two cases were studied and presented as follows.

### 1. Sensitivity to the input

Figure 8 shows the different densification response when the vessel pressure is fixed while the vessel temperature changes. The fixed pressure is chosen as a nominal value of 182MPa. The temperature varies from 293K to 1323K. Figure 9 shows the different densification response when the vessel temperature is fixed while the vessel pressure

changes. The fixed temperature is chosen as a nominal value of 1223K. The pressure varies from 10 MPa to 182 MPa. Figure 10 shows the densification response when both the vessel temperature and pressure changes.

From the comparison of the densification responses illustrated above, we will see following phenomena about the model sensitivity to input.

- a) The densification response is quite sensitive to either the temperature or the pressure. Higher temperature and pressure will accelerate the densification response into its final status. (note: the densification response should not be designed to be too fast for the sake of considering other characteristics such as grain size response).
- b) Too much lower temperature and pressure will cause HIPping process failure, that is, the final density can not reach to full.
- c) Compensation for slower densification response through adjusting temperature and/or pressure is feasible before the density have reached to the final status.

## 2. Sensitivity to parameter change

Four parameters were taken into account in our simulation. These are particle radius, grain size in particle, power law creep exponent and initial density. Figure 11 through figure 14 shows the four cases of the densification response. Each case contains a varied parameter while other parameters are fixed. The input of all the cases is the fixed nominal schedule shown in figure 6.

The densification response of HIP process is also very sensitive to its parameter variations. The phenomena are obviously observed from the results of the simulation. Grain size in particle, radius of particle and  $n$  affect the densification speed positively. The larger the values of this parameters are the faster the densification would respond. Contrarily, initial density and  $\rho_0$  affect the densification speed inversely. The increase of these parameters will decelerate the densification response. If only one of the parameters deviates from its nominal value too much, the final relative density could not reach to full, and the densification of the HIP process would be failure.

## HIPping Densification Sensing

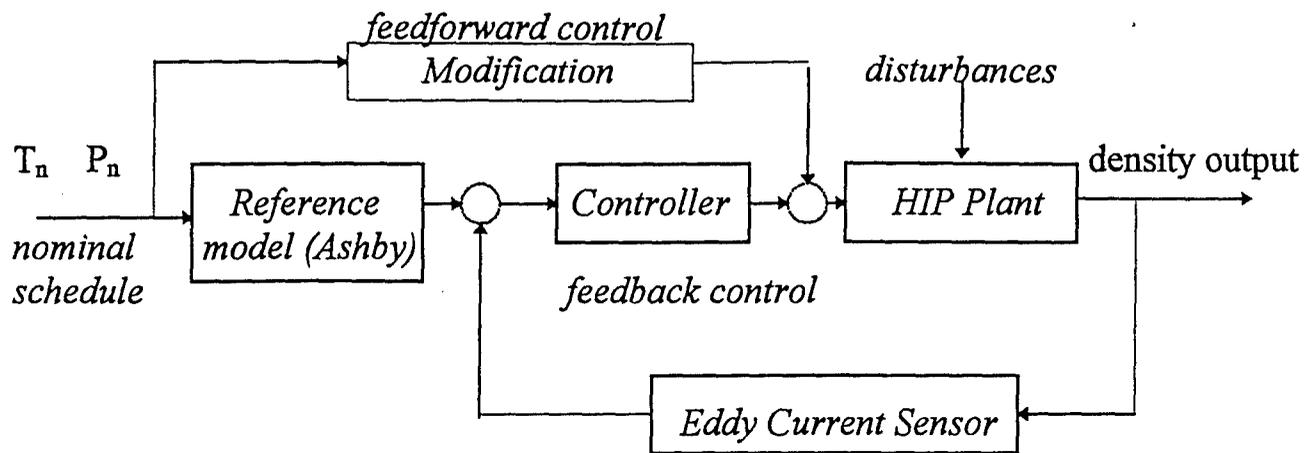
The real time measurements of workpiece sample dimensions during a HIP run have been accomplished by a variety of methods. Klimker et al. [6] measured the transit time through a sample of ultrasonic signals transmitted from outside the pressure vessel, and deduced from this the shrinkage of sample length. Buchkremer et al. [7] measured the change in length of HIP samples by means of a dilatometer which mechanically linked the sample to an electronic sensor in the cool part of the pressure vessel. Kahn et al. [8] have developed eddy current sensing to measure the cross-sectional area of cylindrical samples. For any of these techniques to yield accurate data, one must account for the effects of thermal expansion of the sample and of the sensor.

The eddy current sensor, which is shown schematically in figure 15, consists of a large primary coil and a smaller secondary coil surrounding a sample of powder enclosed in a cylindrical can. The primary coil generates an electromagnetic field which penetrates into the sample to a depth which is function of frequency. As the frequency increase, the flux is confined to a progressively thinner skin depth in the can. By analysis of the impedance of frequency, one can extrapolate to determine the impedance at infinite frequency, where the flux would be entirely excluded from the sample. By comparing the impedance at infinite frequency of the sensor containing the sample to that of the empty sensor, one can then determine the factor of the secondary coil and thus the sample cross-sectional area.

To make a reliable extrapolation of the impedance data to obtain the impedance at infinite frequency, the frequency must be high enough so that the electromagnetic flux is confined to the can wall. The required frequency is inversely proportional to the electrical conductivity of the can material and thus it is not only higher for can materials such as titanium or stainless steel than for materials such as copper or aluminum, but for a given material it becomes higher as the temperature increases. However, as the frequency increases the impedance data can be distorted by resonance of the sensor coils, parasitic circuit elements (small stray capacitance, etc.) and transmission line effects. Careful study of the impedance data is thus necessary to be certain that such effects are not influencing the dimensional measurements.

### **Closed Loop Control During HIP**

The idea of closed loop control for HIP process is actually a combination of feedback and feedforward control strategy. Figure 16 shows the block diagram of the closed loop system.



THE BLOCK DIAGRAM OF CLOSED LOOP HIP SYSTEM

Figure 16

The nominal schedule in the system consists of two active variables: the vessel temperature  $T_n$  and the vessel pressure  $P_n$ . A typical nominal schedule is such designed, based on HIP model, that under this input the response of HIP process will be optimal. This case happened only when the HIP Plant is not disturbed by any uncertainties or system variations. Consequently, the expected output density, which varies with time and finally reaches to full, is also uniquely determined for a given sort of powder. This expected output density is in fact based on the meaning of optimal densification response and is obtained through the reference model appeared in the closed loop system.

The feedback controller then detects the error between the expected response and the real output of practical HIP plant subjected to various kinds of disturbances or uncertainties. The controller algorithm should be designed convergent and efficient in coping with this error, and turns out the modified and/or corrected vessel temperature and pressure within the range of maximum value of them and their rates allowed. In order to diminish the overshoot of the densification response and obtain a better relative stability of the entire closed loop system, a feedforward control scheme is necessary. This means that all the predictable changes of HIP plant parameters can be processed in pre-planned nominal schedule and the modified schedule can be applied on the plant directly through the feedforward route. Obviously, the density error will be greatly reduced because it is yielded only by unpredictable variations in system, and so, the load of controller is abated. This will make us practicable to linearize HIP system since the error signals are relatively small, and the design of controller can be conducted in

terms of linear theory which has been developed perfectly and successfully in engineering.

The simplest zero-error steady state response controller in linear system is the well-known proportional-integration (PI) controller. We will see that the unpredictable variations in HIP plant could be effectively eliminated through PI feedback control. However, it should be noticed that, when introducing a PI control, the proportion gain and the integrating constant of the controller must be carefully chosen to prevent the system response from another overshoot. The overshoot is prohibited in HIPping process because of the unreversible nature of the HIP cycle. So, a non-overshoot response control system is one of the fundamental requirement for HIP process. The controller should be then designed to make the entire system respond under the state of over damped condition. This could cause an extra burden to the controller and even make it failure in responding the variations of HIP plant, if the robustness of controller is not enough to cover the system uncertainties or on the other hand, if the controller is robust enough but its response has delayed too much to trace the error. The problem may aggravate when the controlled variable is expanded to be not only density but also some other HIP product characteristics such as grain size, interparticle bonding, etc. To solve this problem, a suitable nonlinearity analysis is needed and the modern control technology such as adaptive control, fuzzy logical, etc. may be introduced into the feedback controller design. These issues are beyond the scope of this paper and will be discussed in our later publications.

The feedback controller, having coped with the unpredictable variations, provides a corrected schedule, i.e. the incremented vessel temperature  $\Delta T$  and pressure  $\Delta P$ , which is added into the modified schedule from the feedforward route. Finally, the temperature  $T$  and pressure  $P$  applied onto the HIP plant will be composed of three parts, the nominal  $T_n, P_n$ , the modified  $T_m, P_m$ , and the corrected  $\Delta T, \Delta P$ , which can be given as follows:

$$T = T_n + T_m + \Delta T$$

$$P = P_n + P_m + \Delta P$$

### **HIP Densification under Closed Loop Control**

The ultimate goal of closed loop controlled HIP process is to eliminate the deviations of product characteristics caused by process disturbances or uncertainties. The mainly concerned product characteristics are the relative density, the grain size, the interparticle bonding, etc. The effects of the control depend largely on the accuracy of sensors

through which the above product characteristics could be measured on-line. At present, the only available sensor which can satisfy the accuracy requirement of application is the dimensional sensor. The closed loop control are then naturally and firstly applied to the densification process. It is supposed that the sensor (usually in-situ eddy current sensor) responds fast and accurate enough, and the feature of its secondary signal processing (called state estimator) is well mannered and could be treated as a time invariant process. Thus, the behavior of HIP densification under closed loop control should be determined only by the controller adopted.

A further investigation into the closed loop densification was conducted through simulating the entire system. The physical parameters of the powder is the same as those adopted in the model simulation (see Table 1). System disturbances of HIP plant should be artificially introduced. These can simply be obtained through making the standard parameters change in certain range. For example, if the standard system has a powder average radius of 0.07 mm, the disturbed system could be set to have a powder average radius of 0.07 mm plus or minus  $0.07 \cdot x\%$ . The  $x\%$  is the percentage reflecting the extent of variation, which was chosen as 20% in our simulation.

Three cases of closed loop system response were investigated. Case 1 deals with the feedback variable of only vessel temperature. Case 2 deals with the feedback variable of only vessel pressure. Case 3 deals with the feedback variables of both temperature and pressure. The nominal schedule is given the same as it is adopted in model sensitivity analysis shown in figure 6. All the results of these three cases are compared to the response of their correspond open loop systems in which the input is only a fixed nominal schedule.

The result of each case contains four different curve plots. Plot 1 shows the densification response of open loop system and the expected optimal response. Plot 2 shows the densification response of closed loop system and the expected optimal response. Plot 3 shows the errors between the densification responses, of both open loop and closed loop system, and the expected optimal response. Plot 4 shows the adjusted schedule that is applied on the closed loop system. All these results are illustrated in figure 17 through figure 22 respectively.

We can obviously find from these figures that the closed loop system can successfully diminish the deviations of densification response. From the error response plots for all the three cases, the maximum errors of closed loop systems are obviously less than those of open loop systems. Particularly, the final errors of closed loop systems are tend to be

zero(see plots 3). In stead, an open loop system can never possess such kind of important characteristics.

Temperature feedback is more efficient than pressure feedback in eliminating the deviation of densification response. A small adjustment percentage of temperature can largely compensate for the deviations(see plots 4). However, the same compensation will cost the pressure a bigger adjustment percentage, and even makes the pressure exceed its maximum limit value. Using the combination of temperature and pressure for feedback seems possess the best efficient in eliminating the deviation of densification response. But this will be more costly and make the practical closed loop system more complicated.

### Conclusion

The concept of closed loop control for powder densification during Hot Isostatic Pressing has been established now. The concrete closed loop control scheme which is the combination of feedback and feedforward strategy has been proposed and constructed theoretically. Ashby model for describing the HIP process characteristics is the basis of the closed loop control idea. It supports the algorithm of reference model needed in the closed loop controller.

The simulation conducted in the literature shows the successful effect of the closed loop control in eliminating the deviation of powder densification response when the disturbances and/or uncertainties exists during HIPping process. In terms of the critical idea of closed loop control, the above result can also be expanded to solve the problem of shape distortion occurred frequently in HIPping products.

The variables that can be used for control now are only the vessel temperature and the vessel pressure. According to the nature of HIP process described by Ashby model, the sensitivity of densification response to the temperature is much stronger than that to the pressure. This phenomenon has also been proved in the simulation of closed loop system. So, a potential application of closed loop control for HIPping densification in industries may be the temperature feedbacked system because it is either efficient or economic, and it is easier to be implemented.

The technology of sensing HIPping product characteristics takes a very important role in closed loop control system. The power of the closed loop control will be enhanced as additional sensors become operational and available.

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powders subjected to hydrostatic pressure, has been developed by Ashby and collaborators [ ] [ ], and is widely used in HIP research and development.

The Ashby model for HIP densification of powders considers the deformation of spherical powder particles under the influence of an applied pressure. The geometry of interparticle contacts changes as the powder densifies. Initially (called "stage 1"), the geometry is described as an array of spherical powder particles which contact one another at "necks" which grow in area as the material densifies. Toward the end of densification (called "stage 2"), the material is described as a solid containing spherical pores. For each of these geometries, the densification due to several different deformation mechanisms is calculated. Densification due to plastic deformation of powder particles occurs immediately when the yield stress is exceeded at some point within the powder particles. Subsequent densification due to several other deformation mechanisms such as power law creep and boundary diffusion is time-dependent and occurs at rates which can be summed to give a total densification rate.

### **POWDER DENSIFICATION MODEL**

#### *1. Volume Diffusion, Surface Tension Driven (VDSTD)*

$$\dot{\Delta}_1 = D_v \gamma \frac{\Omega}{R^3 kT} \cdot \{72 C \Delta_0 S_1 + 36 S_2\} \quad \text{----- (1)}$$

#### *2. Boundary Diffusion, surface Tension Driven (BDSTD)*

$$\dot{\Delta}_2 = D_b \delta \gamma \frac{\Omega}{R^4 kT} \left\{ 18 C \frac{\Delta}{\Delta - \Delta_0} S_1 + 18 \left[ \frac{6}{1 - \Delta} \right]^{\frac{1}{3}} S_2 \right\} \quad \text{----- (2)}$$

#### *3. Volume Diffusion, Pressure Driven (VDPD)*

$$\dot{\Delta}_3 = \frac{D_v P \Omega}{R^2 kT} \left\{ 43 C (1 - \Delta_0) S_1 + 270 (1 - \Delta)^{\frac{1}{2}} \left[ \frac{1 - \Delta}{6} \right]^{\frac{1}{3}} S_2 \right\} \quad \text{----- (3)}$$

#### *4. Boundary Diffusion, Pressure Driven (BDPD)*

$$\dot{\Delta}_4 = \frac{\delta D_b P \Omega}{R^3 kT} \left\{ 43 C^2 S_1 + 270 (1 - \Delta)^{\frac{1}{2}} S_2 \right\} \quad \text{----- (4)}$$

5. Power Law Creep (PLCP)

$$\dot{\Delta}_s = D_{crp} \left( \frac{P}{S_{ref}} \right)^n \cdot \left\{ \frac{3.1\Delta}{C^{\frac{1}{2}}} \left[ \frac{C}{3\Delta^2} \right]^n S_1 + 1.5\Delta \left[ \frac{1.5}{n(1-(1-\Delta)^{\frac{1}{n}})} \right]^n S_2 \right\} \quad \text{----- (5)}$$

6. Nabarro-Herring Creep (NHCRP)

$$\dot{\Delta}_s = \left[ \frac{D_v}{G^2} + \frac{\pi\delta D_b}{G^3} \left[ \frac{P\Omega}{kT} \right] \right] \left\{ 14.4 \frac{C^{\frac{1}{2}}}{\Delta} S_1 + 32(1-\Delta) S_2 \right\} \quad \text{----- (6)}$$

7. Where:

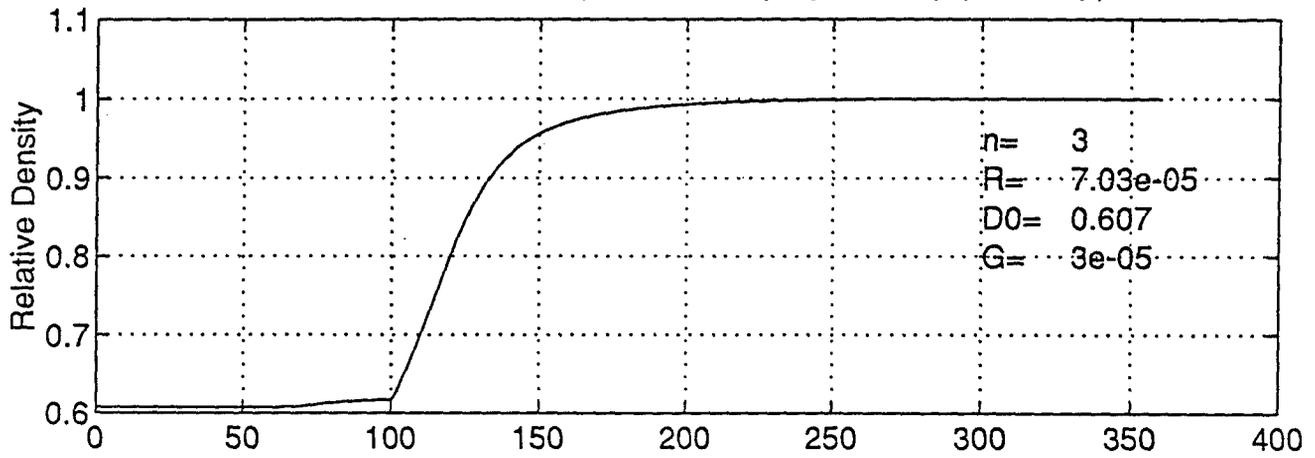
$$C = \frac{1 - \Delta_0}{\Delta - \Delta_0}$$

$$S_1 = 1 - e^{-\left(\frac{1-\Delta}{0.1}\right)^2}$$

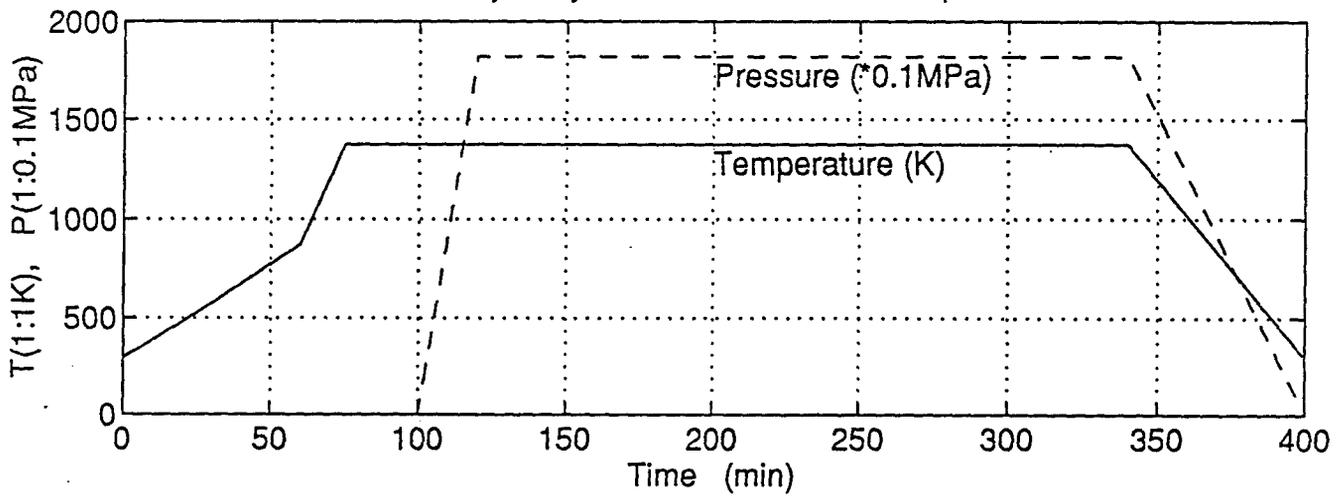
$$S_2 = 1 - S_1$$

- G ----- Grain size in particle
- $\Delta$  ----- Density
- $\Delta_0$  ----- Initial density
- $D_v$  ----- Volume diffusion coefficient
- $\gamma$  ----- Surface energy
- $\Omega$  ----- Atomic volume
- R ----- Particle radius
- k ----- Boltzman constant
- T ----- Temperature
- $D_b$  ----- Boundary diffusion coefficient
- $\delta$  ----- Boundary thickness
- P ----- Pressure
- $D_{crp}$  ----- Power law creep diffusion paramwter
- $S_{ref}$  ----- Reference stress for power law creep
- n ----- power law creep exponent

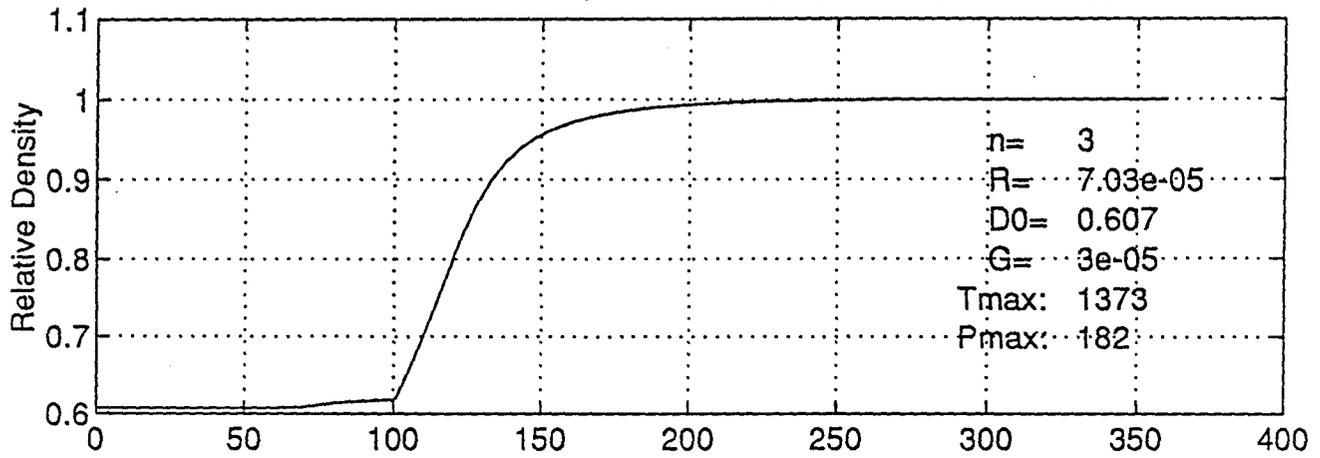
The Densification Response of HIPping Modle (Open Loop)



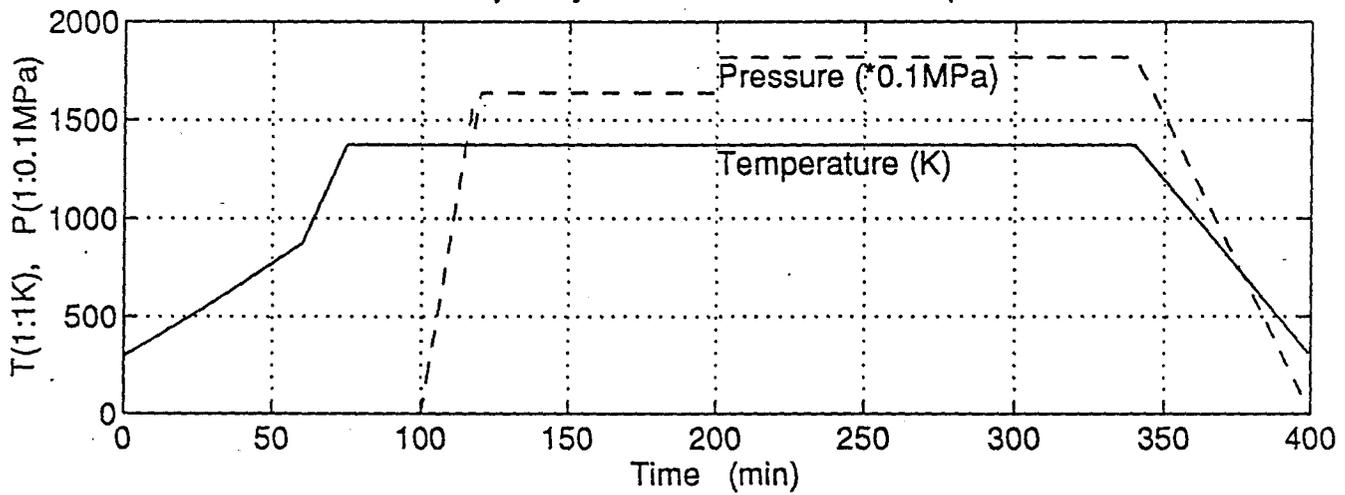
The Trajectory of the Pressure and Temperature



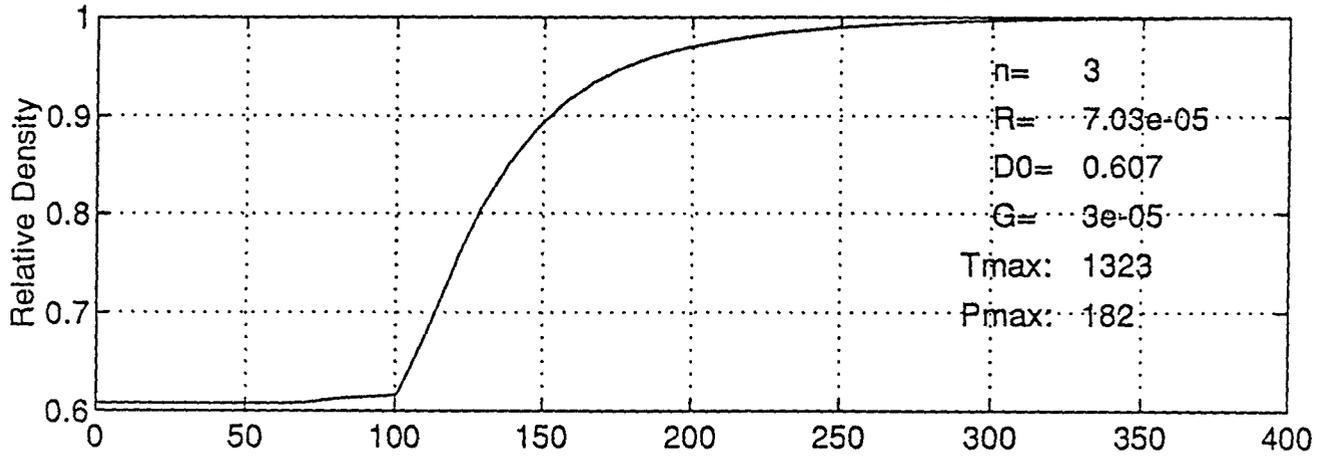
The Densification Response of HIPping Modle (Open Loop)



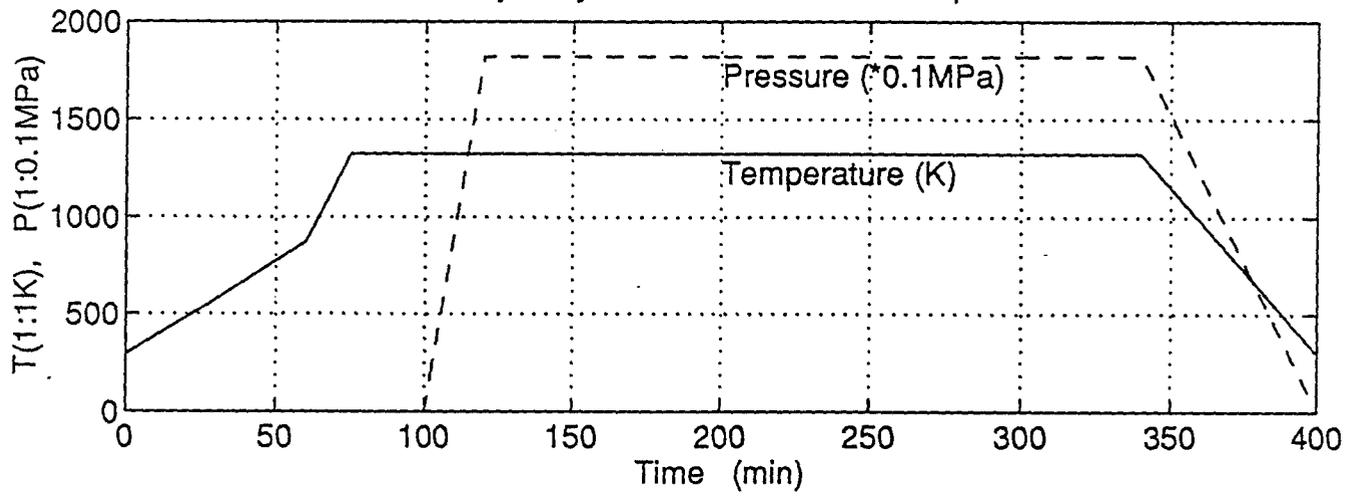
The Trajectory of the Pressure and Temperature



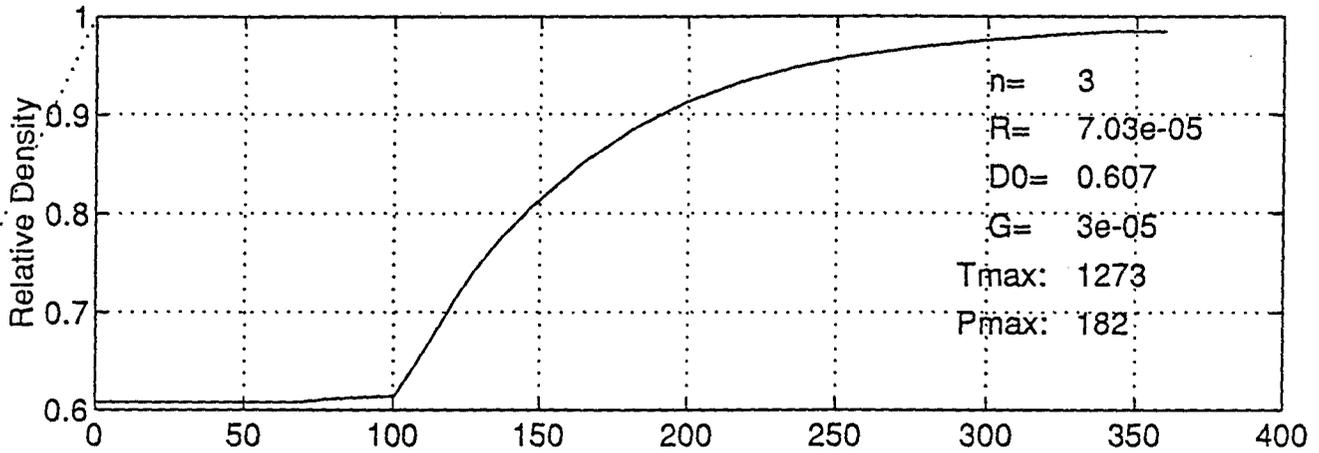
The Densification Response of HIPping Modle (Open Loop)



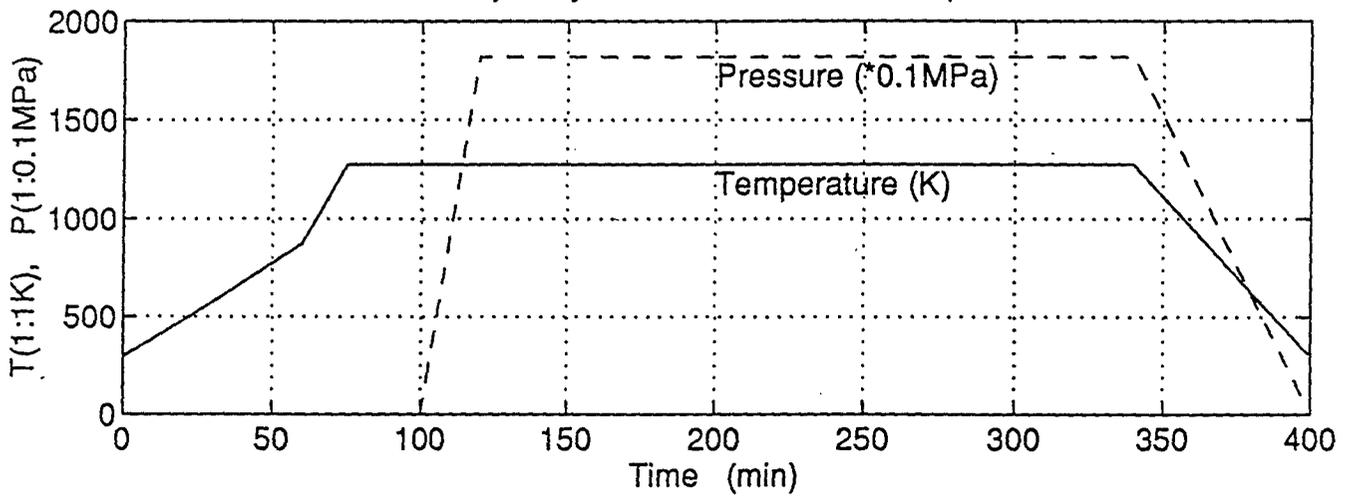
The Trajectory of the Pressure and Temperature



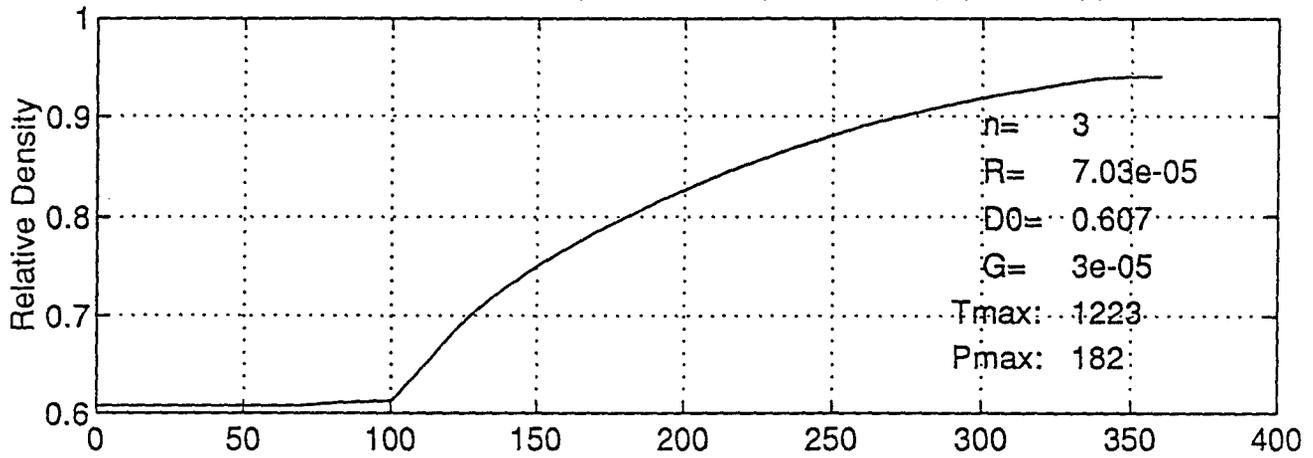
The Densification Response of HIPping Modle (Open Loop)



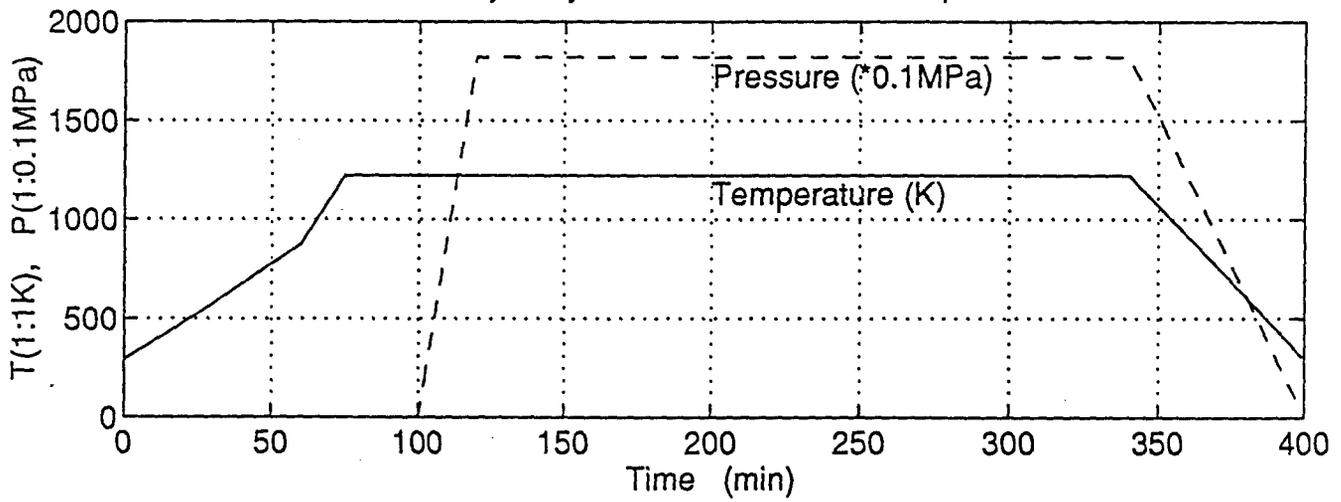
The Trajectory of the Pressure and Temperature



The Densification Response of HIPping Modle (Open Loop)

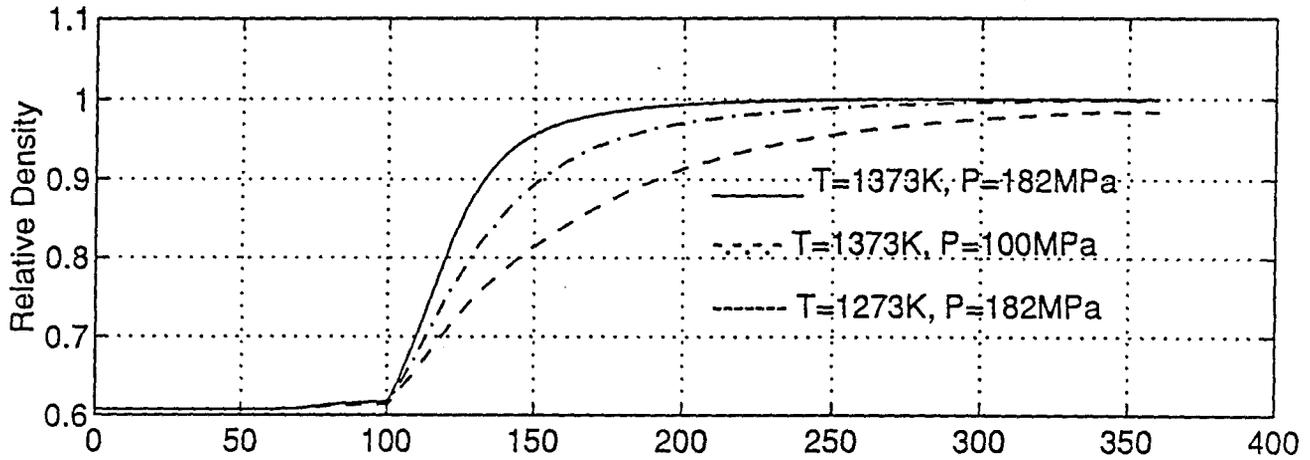


The Trajectory of the Pressure and Temperature

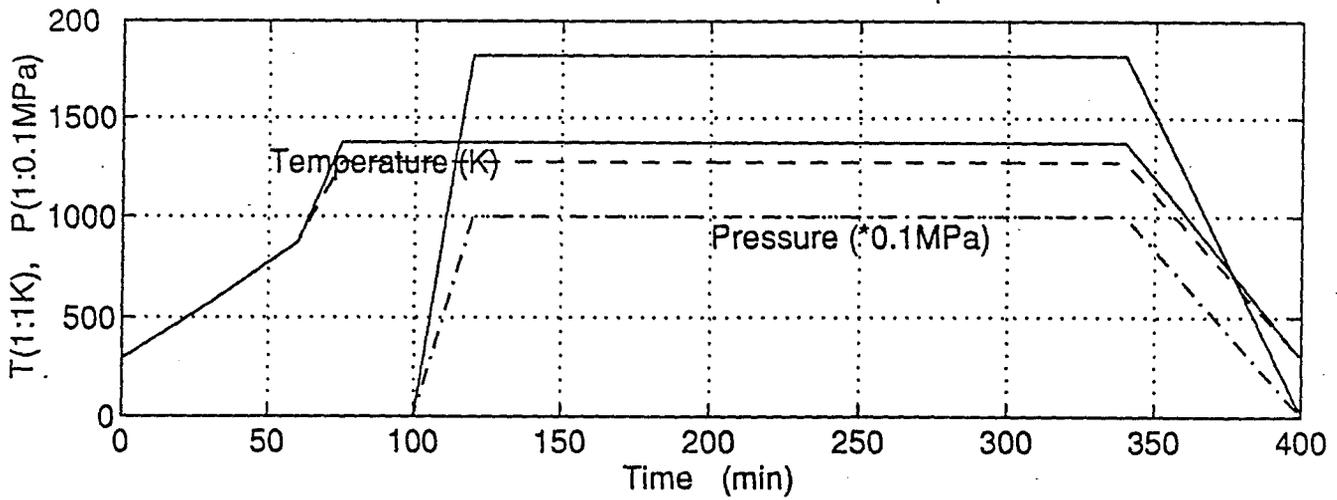


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The Densification Sensitivities to the Processing Input

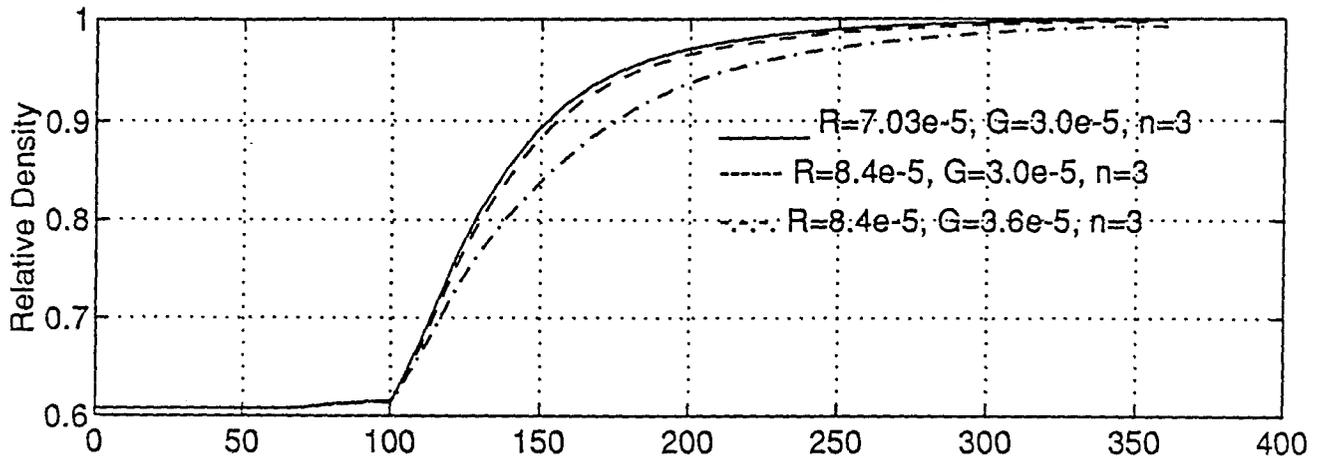


The Schedule of the Pressure and Temperature

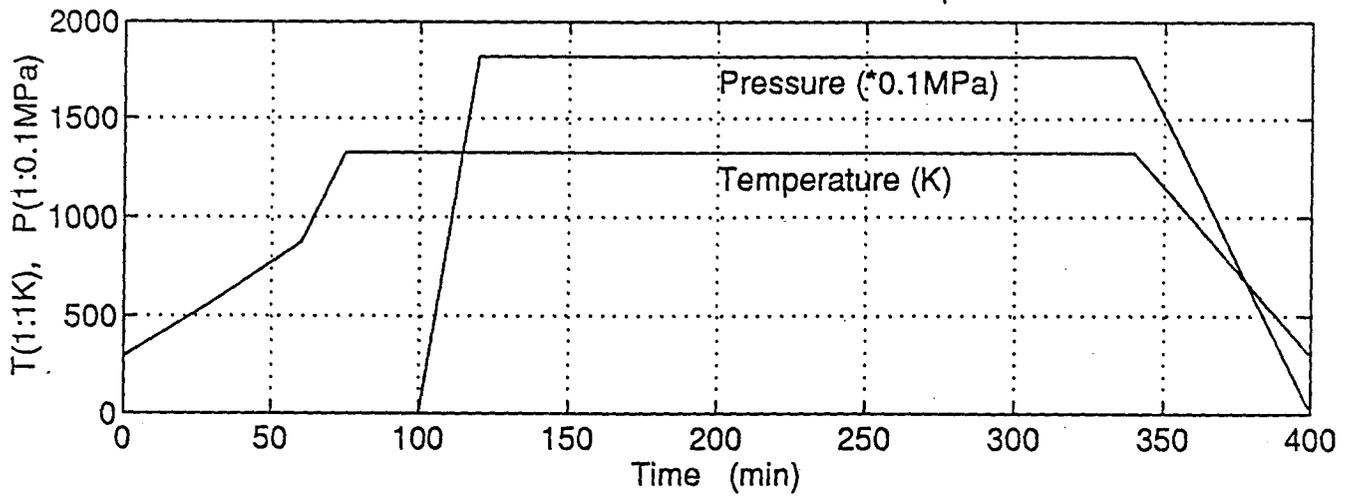


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The Densification Sensitivities to the Processing Parameters

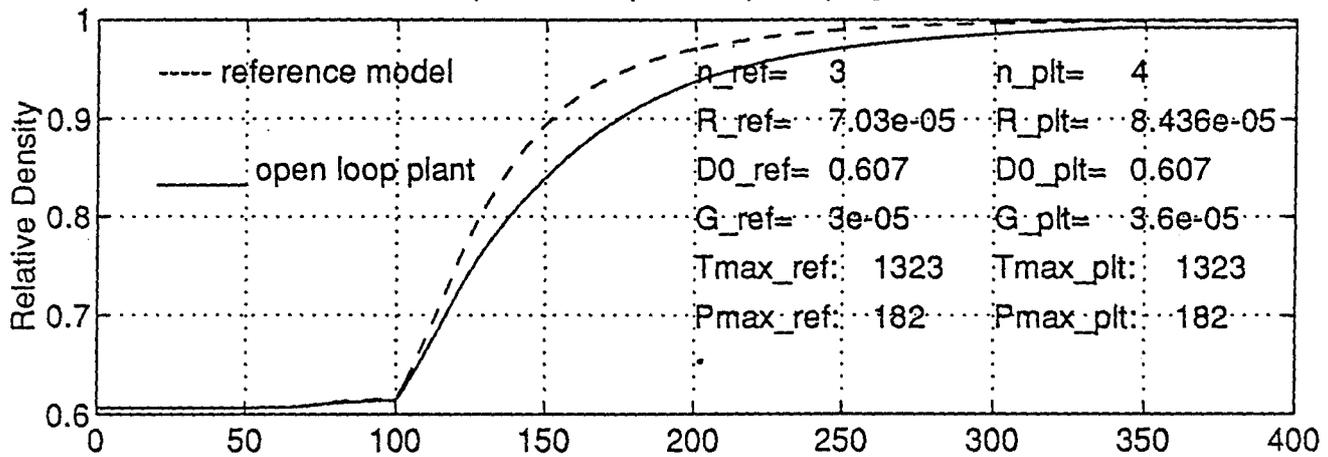


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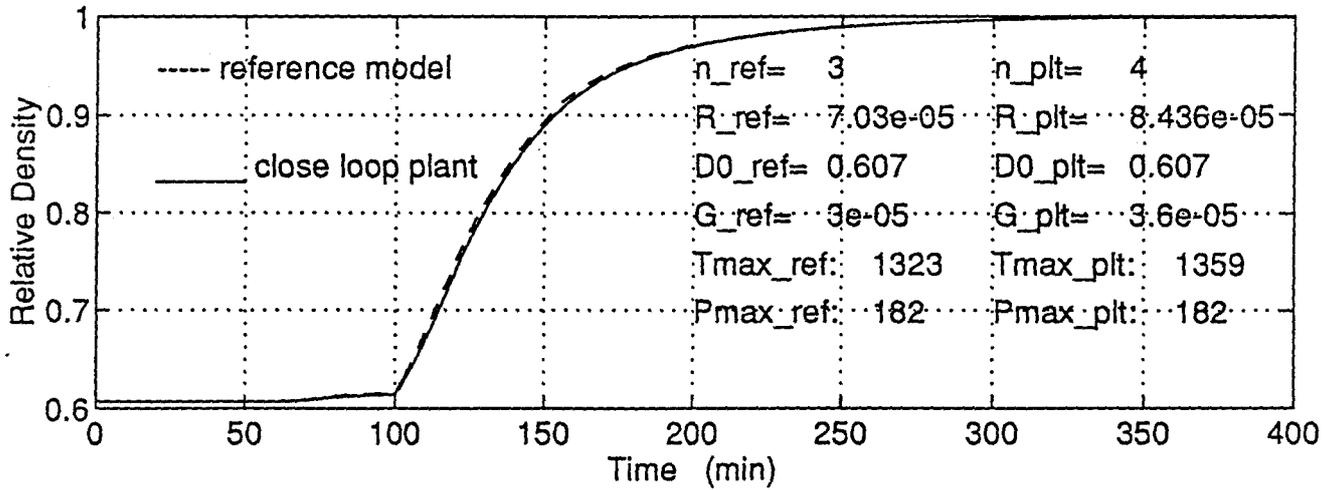


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The Densification Response of Open Loop HIPping Plant and Its Ref. Model

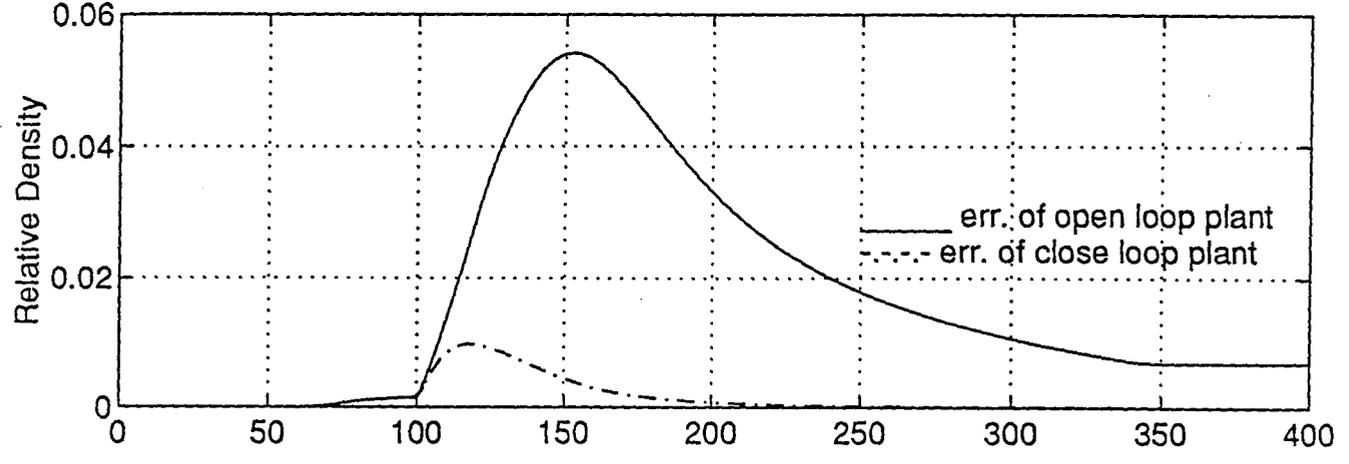


The Densification Response of Close Loop HIPping Plant and Its Ref. Model

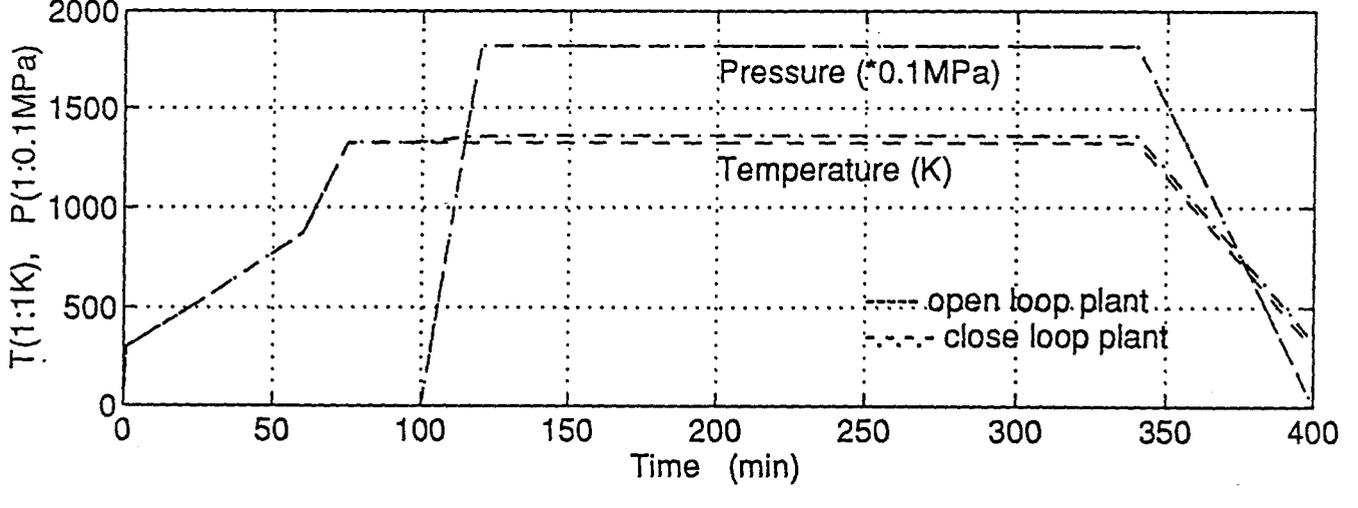


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The Error Response of Open Loop and Close Loop HIPping Plants vs a Ref. Model

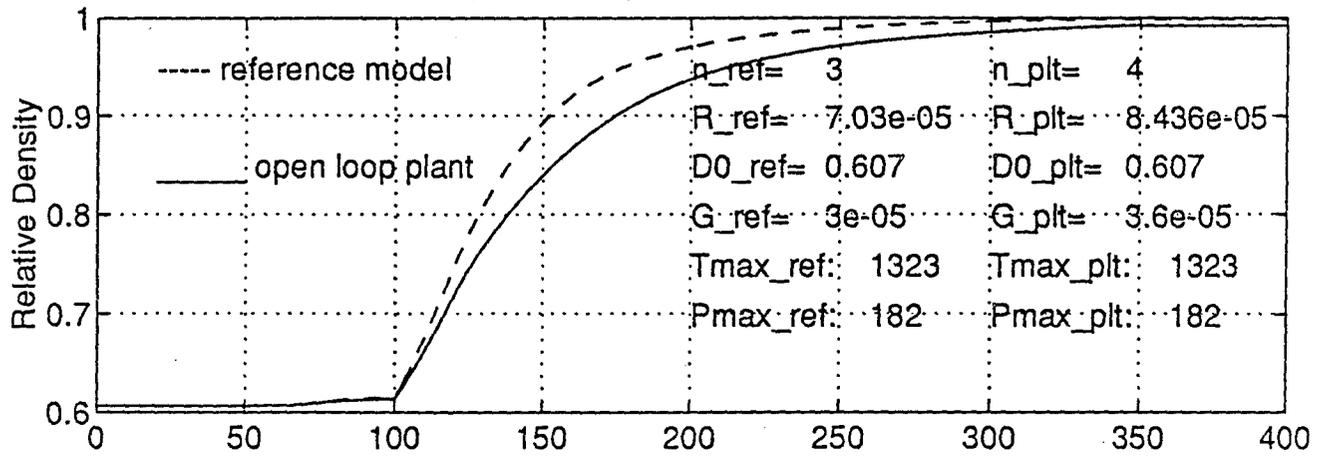


The Pressure and Temperature Trajectories of Open Loop and Close Loop Plants

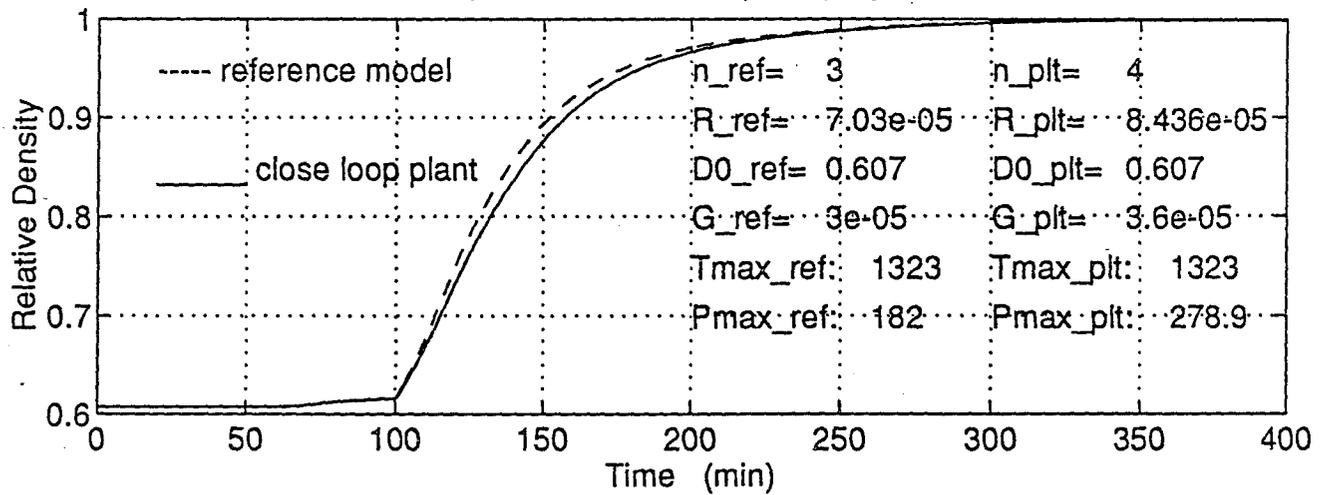


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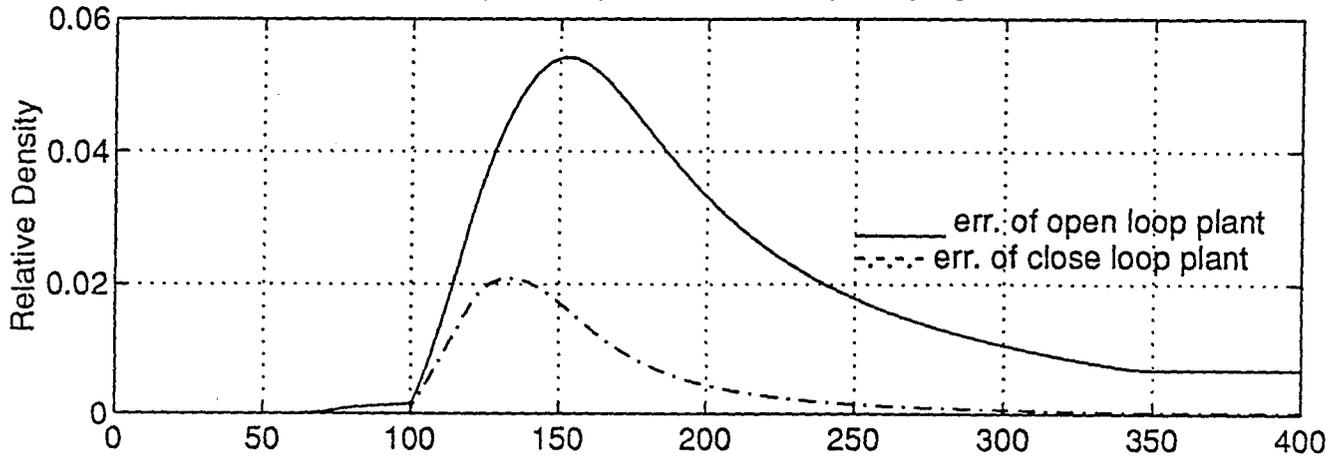
The Densification Response of Open Loop HIPping Plant and Its Ref. Model



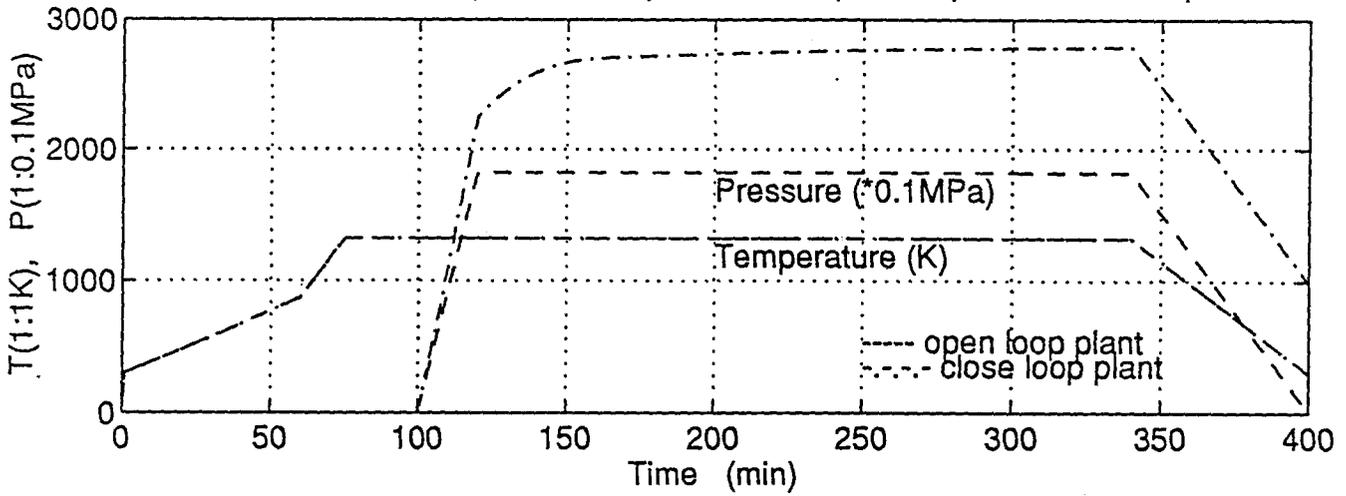
The Densification Response of Close Loop HIPping Plant and Its Ref. Model



The Error Response of Open Loop and Close Loop HIPping Plants vs a Ref. Model

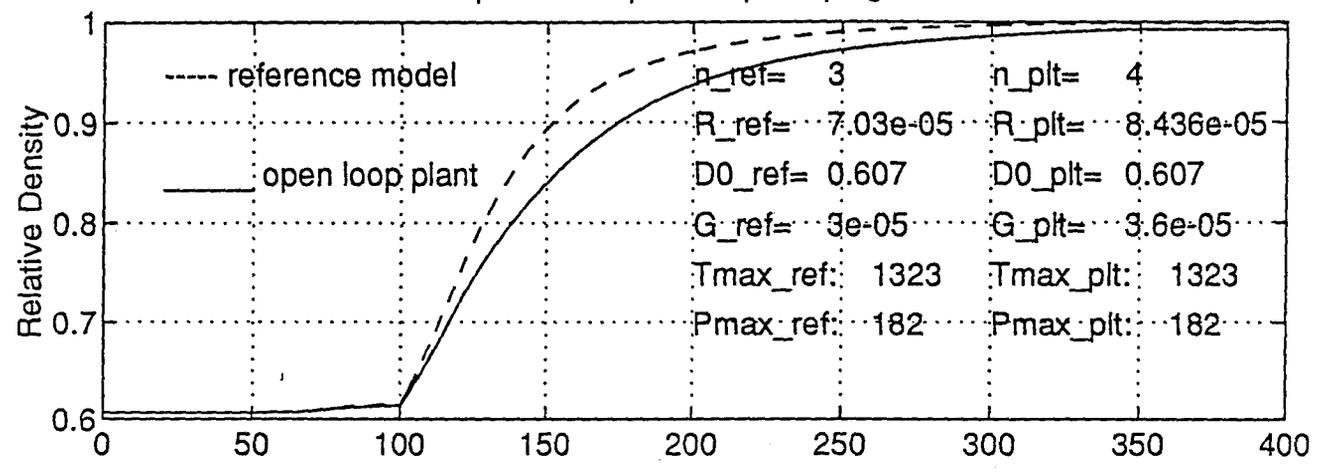


The Pressure and Temperature Trajectories of Open Loop and Close Loop Plants

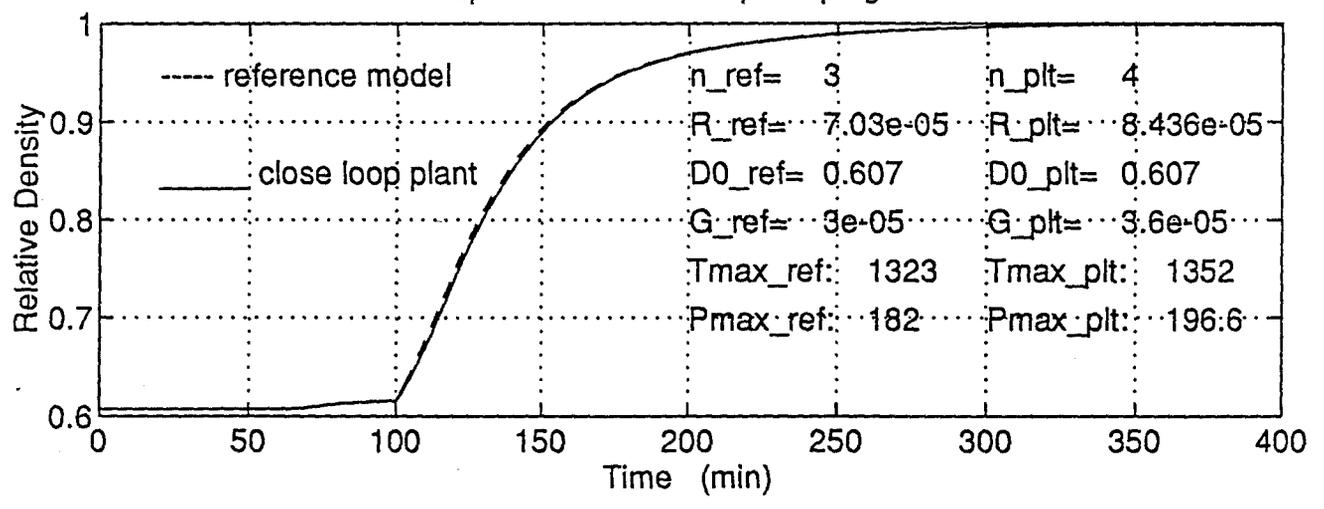


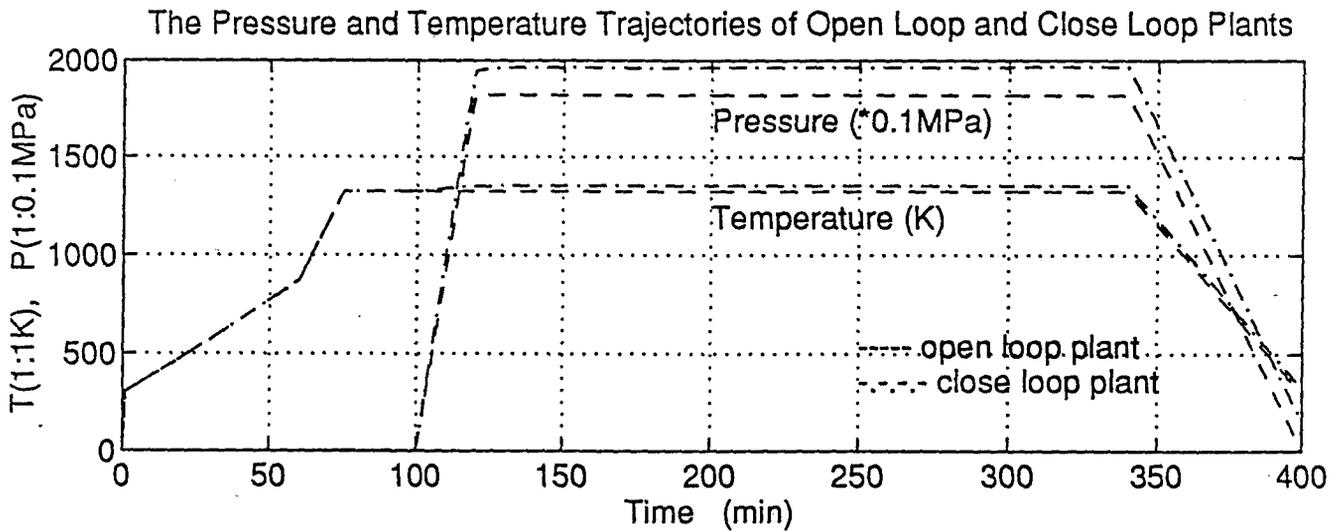
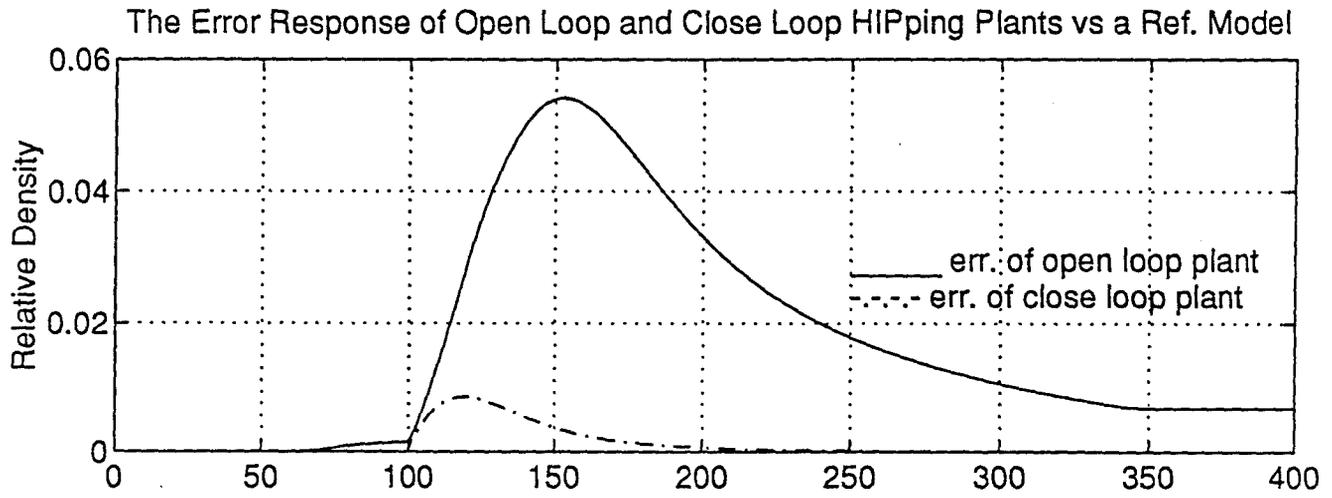
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The Densification Response of Open Loop HIPping Plant and Its Ref. Model

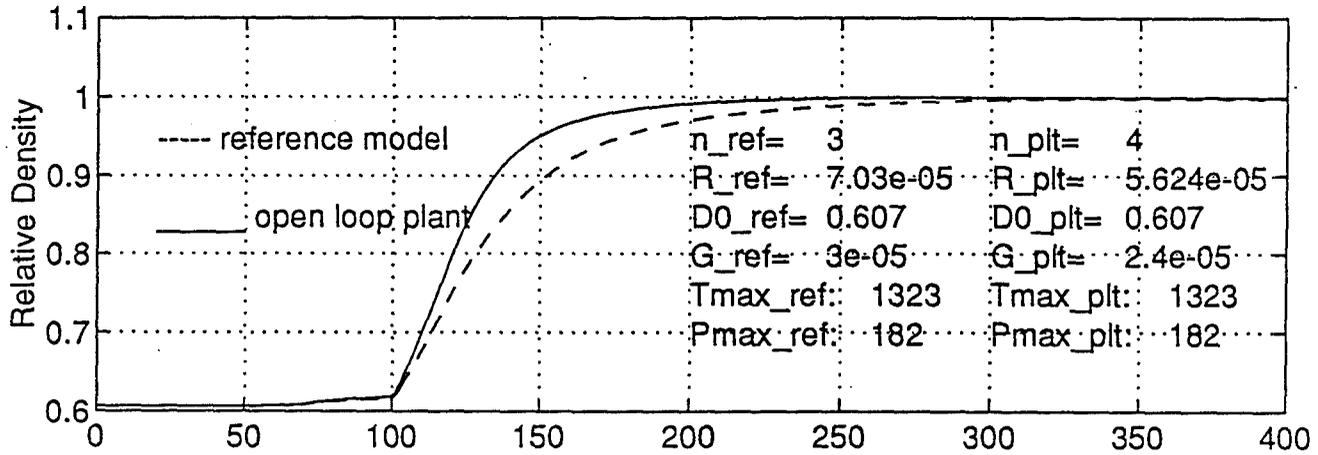


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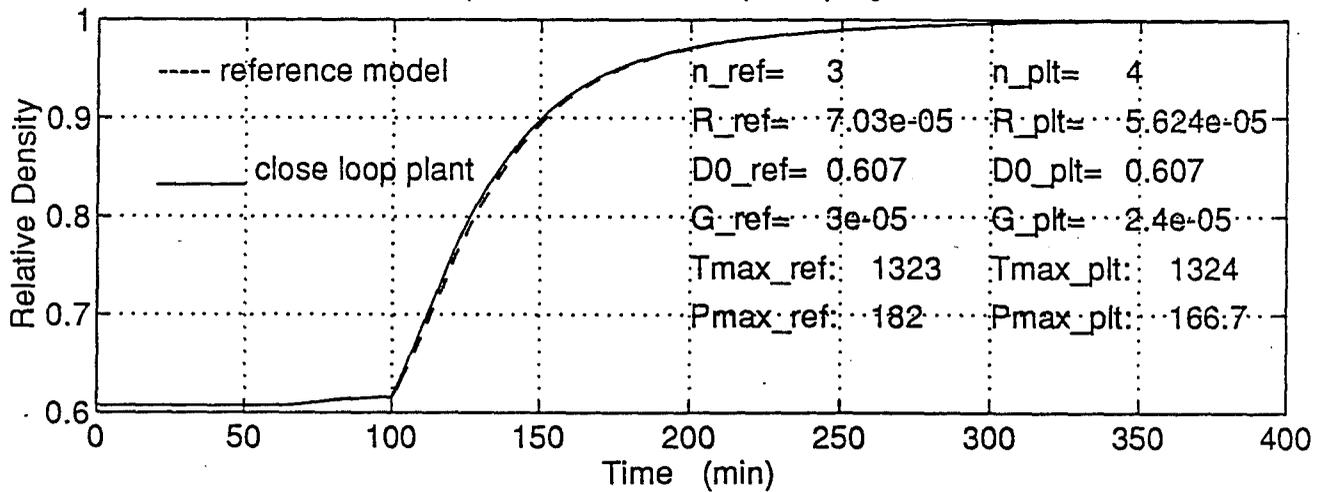




The Densification Response of Open Loop HIPping Plant and Its Ref. Model

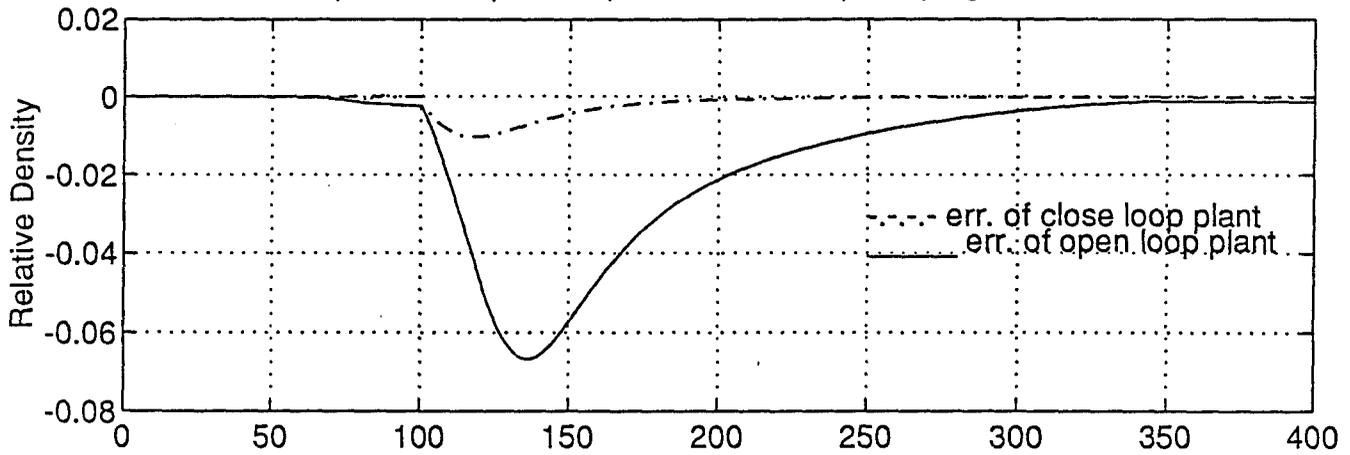


The Densification Response of Close Loop HIPping Plant and Its Ref. Model

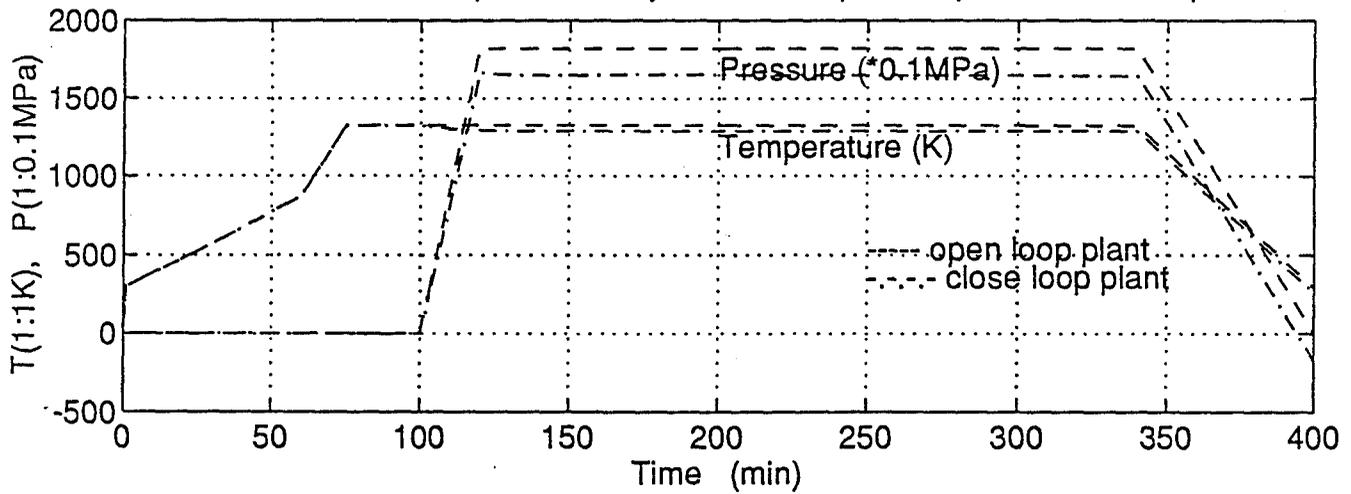


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The Error Response of Open Loop and Close Loop HIPping Plants vs a Ref. Model

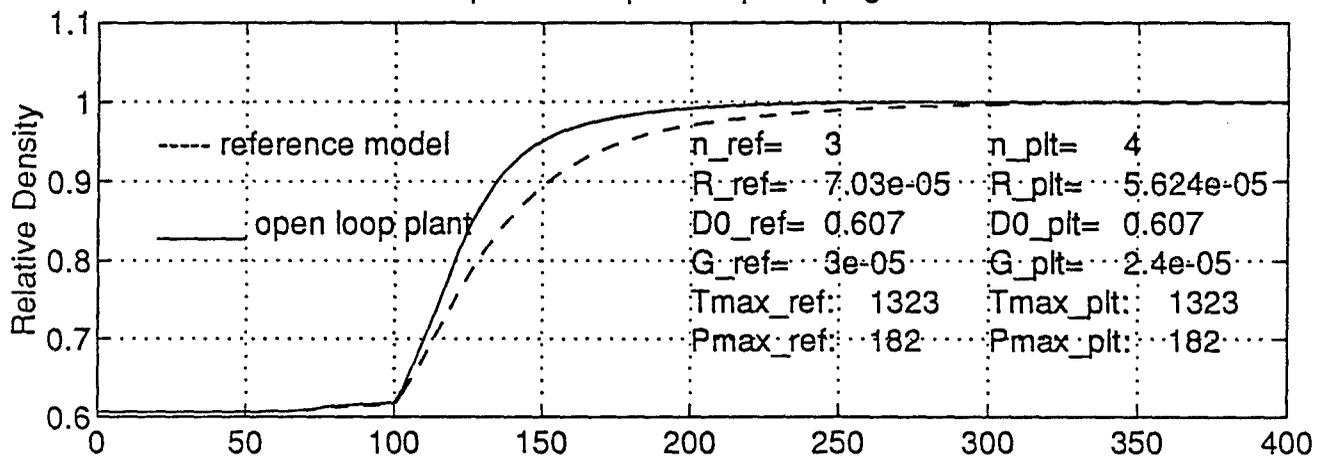


The Pressure and Temperature Trajectories of Open Loop and Close Loop Plants

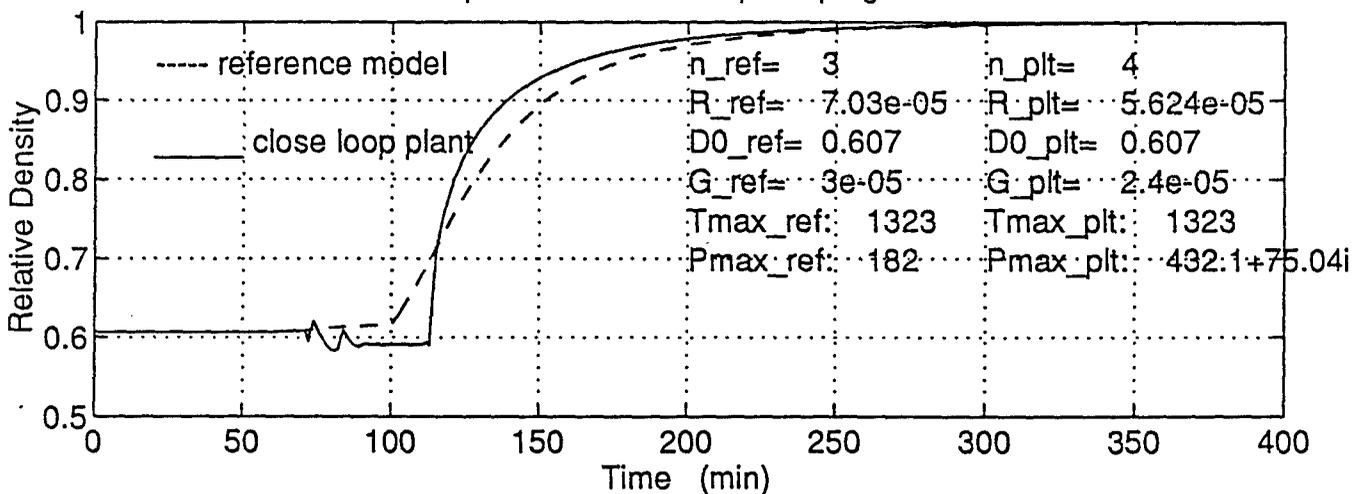


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The Densification Response of Open Loop HIPping Plant and Its Ref. Model

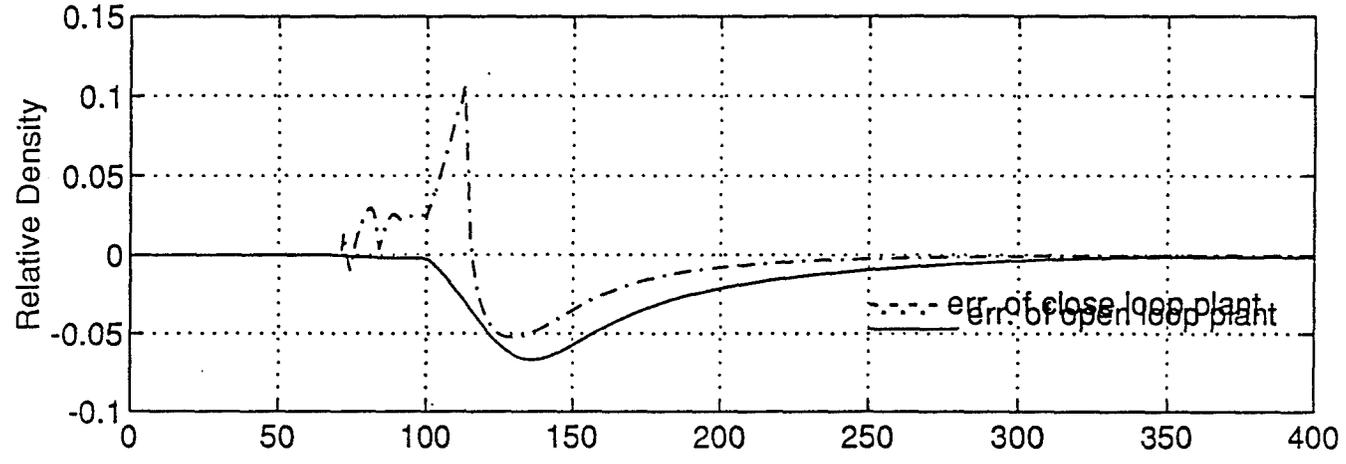


The Densification Response of Close Loop HIPping Plant and Its Ref. Model

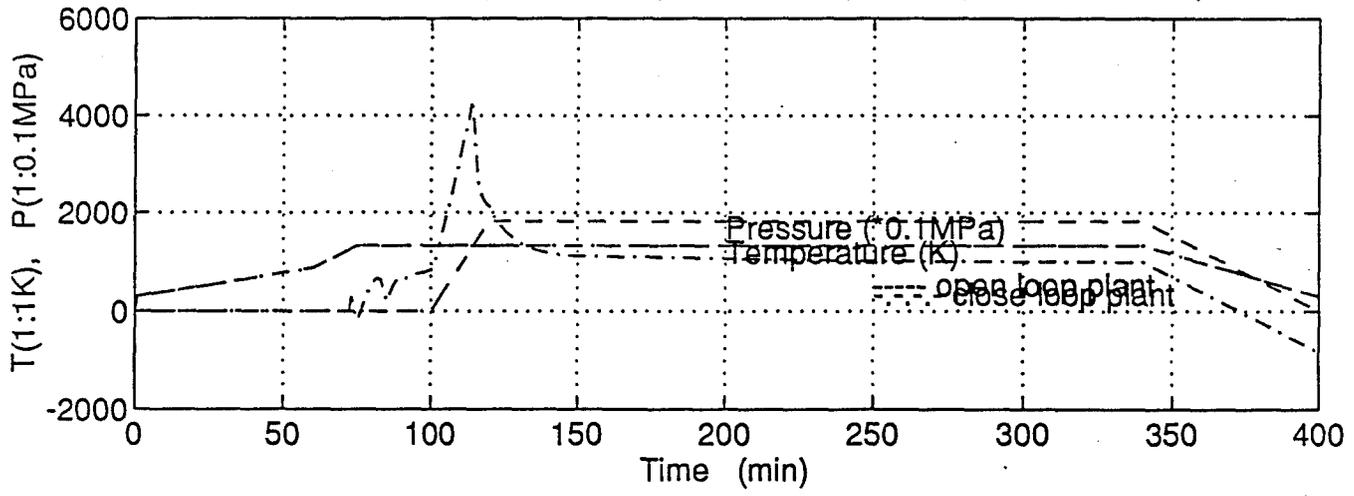


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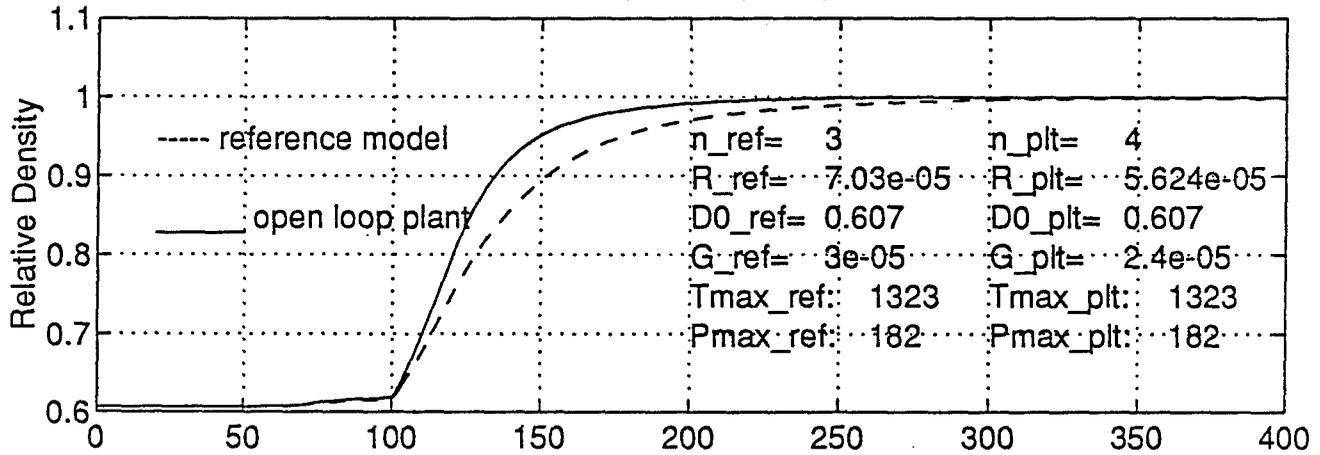
The Error Response of Open Loop and Close Loop HIPping Plants vs a Ref. Model



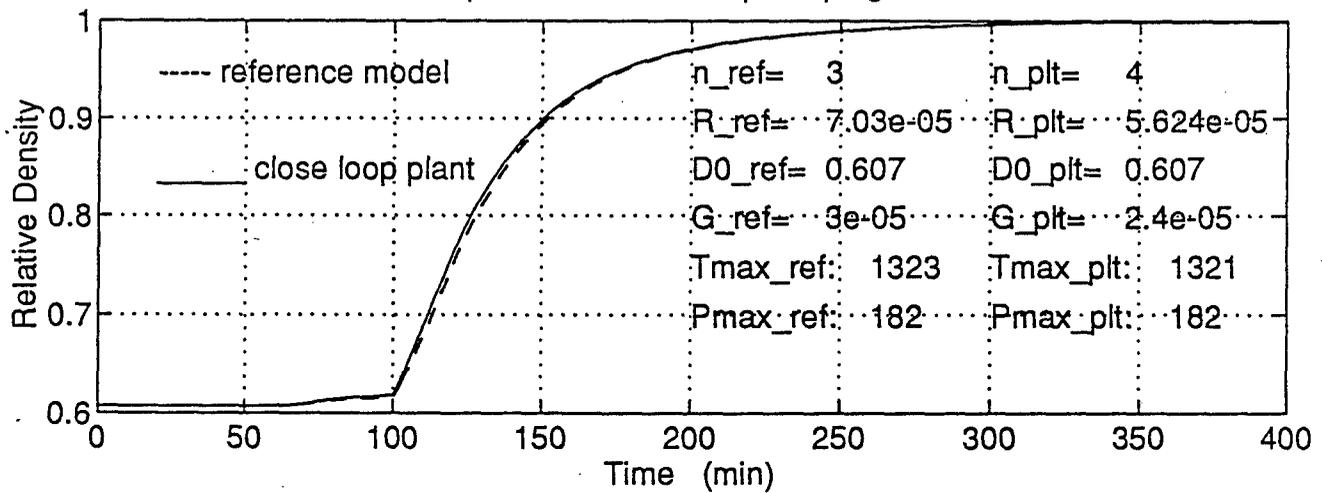
The Pressure and Temperature Trajectories of Open Loop and Close Loop Plants



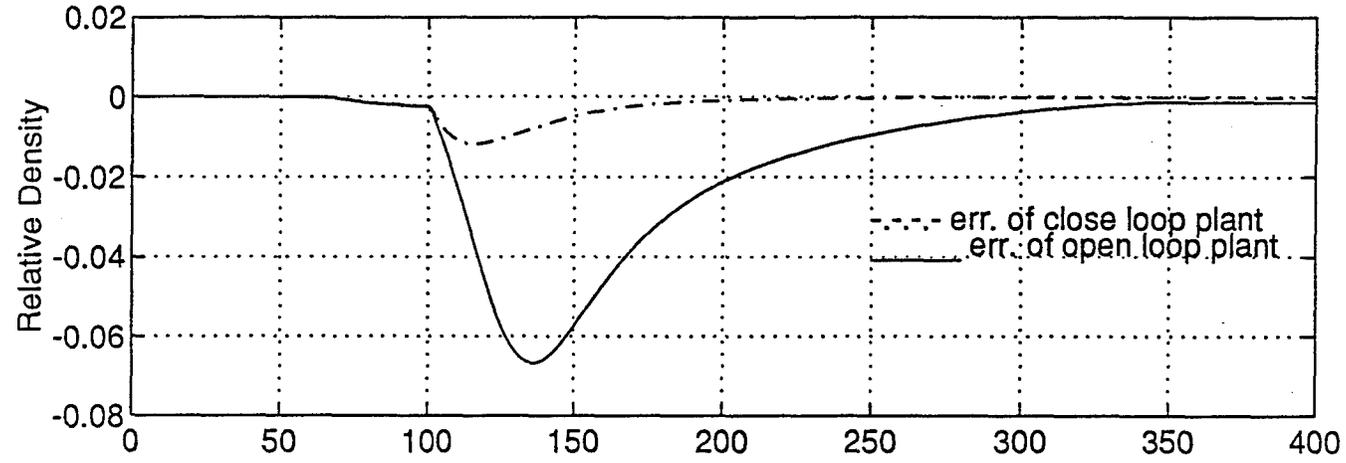
The Densification Response of Open Loop HIPping Plant and Its Ref. Model



The Densification Response of Close Loop HIPping Plant and Its Ref. Model



The Error Response of Open Loop and Close Loop HIPping Plants vs a Ref. Model



The Pressure and Temperature Trajectories of Open Loop and Close Loop Plants

