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PRELIMINARY ANALYSIS OF A TARGET FACTORY FOR LASER FUSION

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ABSTRACT

An analysis of a target factory leading to the determination of production expressions has provided for the basis of a parametric study. Parameters involving the input and output rate of a process system, processing yield factors, and multiple processing steps and production lines have been used to develop an understanding of their dependence on the rate of target injection for laser fusion. Preliminary results have indicated that a parametric study of this type will be important in the selection of processing methods to be used in the final production scheme of a target factory.

INTRODUCTION

The fabrication of laser fusion targets involves the processing of metal, ceramic, and organic materials that must meet target design specifications. The processing systems that will be responsible for meeting these specifications must also meet target production requirements for laser fusion. As a preliminary examination of what will be required of processing systems for target production, a target factory concept has been analyzed in terms of the rate of target injection into the fusion chamber.

To do the analysis a production scheme was conjectured to represent the operation of a target factory. Production expressions based on the proposed target factory were derived and used to initiate a parametric study. The derived expressions reflect generalized production systems having multiple processing steps. The expressions also relate both input/output rates and processing yield factors to the target injection rate necessary for continuous laser fusion.

TARGET FACTORY SYSTEMS

The production of laser fusion targets may be viewed as consisting of three main processing systems. A basic target factory block diagram as shown in Figure 1 indicates the three parts: the shell development and DT fill system, the coating process system, and the cryogenic injection fusion chamber system.

A. Shell Development and DT Fill System

The shell development and DT fill (SD&DT) system is shown in Figure 2 as a general process system composed of multiple production lines. A number of shell processing steps are indicated to represent the initial shell formation and the final DT fill steps along with other possible steps i.e., wash, sort, and selection. The symbols shown in the diagram are defined as:

v = number of production lines in the SD & DT system.

n = number of shell process steps in a SD & DT production line.

f = yield factor for a shell process step.

r_G = input rate of shell forming drops entering a SD & DT production line.

t_g = time of operation of a droplet generator.

G = number of items entering a SD & DT production line after time t_g.

r_F = output rate of a SD & DT production line.

t_F = time interval for the slowest process step in a SD & DT production line.

F = number of items leaving a SD & DT production line.

The output rate r_F of a single production line (v = 1) is related to its input rate r_G by the following expressions

$$\text{input rate; } r_G = \frac{G}{t_g} \qquad (1a)$$

$$\text{output rate; } r_F = \frac{F}{t_F} \qquad (1b)$$

$$\text{yield; } F = \left[\prod_{i=1}^{u} f_i \right] G \qquad (1c)$$

$$r_F = \frac{\left[\prod_{i=1}^{u} f_i \right] t_g \quad r_G}{t_F} \qquad (2)$$

B. Coating Process System

A general production diagram for the coating process (CP) system is shown in Figure 3. A number of processing steps are listed to represent multiple material deposition and characterization. The symbols displayed are defined as:

m = number of production lines in the CP system.

n = number of process steps in a CP production line.

y = yield factor for a coating process step.

r_A = input rate of DT filled shells in a CP production line.

t_L = time interval for the slowest process step in a CP production line.

A = number of items entering a CP production line.

r_B = output rate of a CP production line.

B = number of items leaving a CP production line.

From the following expressions

$$\text{input rate; } r_A = \frac{A}{t_L} \tag{3a}$$

$$\text{output rate; } r_B = \frac{B}{t_L} \tag{3b}$$

$$\text{yield; } B = \left[\prod_{i=1}^{n} y_i\right] A \tag{3c}$$

the input and output rate of a single CP production line (m=1) can be related by the substitution of (3a) and (3c) into (3b). Hence,

$$r_B = \left[\prod_{i=1}^{n} y_i\right] r_A \tag{4}$$

C. Cryogenic Injection Fusion Chamber System

The cryogenic injection fusion chamber (CIFC) system is represented in Figure 4. Multiple processing steps are assumed for preparation of the target. These steps may include a gradual cooling procedure, DT layering by laser heating, and possibly inspection of the targets before injection into the chamber. The symbols shown in Figure 4 are defined as:

p = number of production lines in the CIFC system.

s = number of cryogenic process steps in a CIFC production line.

q = yield factor for a cryogenic process step.

r_C = input rate of coated targets into a CIFC production line.

t_C = time interval for the slowest processing step in a CIFC production line.

C = number of items entering a CIFC production line.

r_I = output rate of a CIFC production line.

I = number of items leaving a CIFC production line.

R = rate of target injection into the fusion chamber.

The relationship of r_I to r_C is determined from the following expressions:

$$\text{input rate; } r_C = \frac{C}{t_C} \tag{5a}$$

$$\text{output rate; } r_I = \frac{I}{t_C} \tag{5b}$$

$$\text{yield; } I = \left[\prod_{i=1}^{s} q_i \right] C \tag{5c}$$

and by substitution,

$$r_I = \left[\prod_{i=1}^{s} q_i \right] r_C \tag{6}$$

RATE OF TARGET PRODUCTION

The three target process systems are shown together in Figure 5. The rate R of target injection into the fusion chamber is related to the output rate of the cryogenic process system as

$$R = p \, r_I \tag{7}$$

The input rate r_C of a CP production line can be written in terms of R by substitution of (6) into (7),

$$r_C = \frac{R}{p \left[\prod_{i=1}^{s} q_i \right]} \tag{8}$$

However, the input rate r_C is also related to the output rate r_B of the CP system,

$$r_C \quad p = m \, r_B \tag{9}$$

From (8) and (9), an expression for r_B becomes

$$r_B = \frac{R}{m \left[\prod_{i=1}^{s} q_i \right]} \tag{10}$$

By equating (10) and (4), an equation for r_A in terms of R results:

$$r_A = \frac{R}{m \left[\prod_{i=1}^{s} q_i \right] \left[\prod_{i=1}^{n} y_i \right]} \qquad (11)$$

In a similar manner, the input rate r_A of a CP system can be related to the output rate r_F for a SD & DT system,

$$v r_F = m\, r_A \qquad (12)$$

Substitution of (11) into (12), the output rate of a SD & DT production line is

$$r_F = \frac{R}{v \left[\prod_{i=1}^{s} q_i \right] \left[\prod_{i=1}^{n} y_i \right]} \qquad (13)$$

From equations (2) and (13), the input rate r_G of a SD & DT production line can now be expressed in terms of R. Solving for R, the following equation results.

$$R = \left[\prod_{i=1}^{s} q_i \right] \left[\prod_{i=1}^{n} y_i \right] \left[\prod_{i=1}^{u} f_i \right] v\, r_G \left(\frac{t_g}{t_F} \right) \qquad (14)$$

Likewise, the rate of target injection into the fusion chamber may be written as a function of the input and output rates for each of the process systems:

$$R = \left[\prod_{i=1}^{s} q_i \right] \left[\prod_{i=1}^{n} y_i \right] \left[\prod_{i=1}^{u} f_i \right] p \left(\frac{t_g}{t_F} \right) \left(\frac{r_G \; r_C \; r_A}{r_B \; r_F} \right) \tag{15}$$

Using the above expressions, a parametric study can be performed to examine the dependence of the various parameters on the rate of production.

INPUT RATE AND CAPACITY

The input rate of a production system is dependent on its processing efficiency and the required output rate for target production. If the values of these factors tend to force a high input rate, an additional factor develops based on the processing capacity of the system. This can be examined, in particular, utilizing the coating process system.

The expression for the input rate to the CP system is given by equation (11):

$$r_A = \frac{R}{m \left[\prod_{i=1}^{s} q_i \right] \left[\prod_{i=1}^{n} y_i \right]}$$

The rate of input of items into the CP system is shown in Figure (6) as a function of the fusion chamber injection rate for several processing yield factors. For a single production line (m=1) and with processing steps s=n=5 operating at 90% efficiency, the rate r_A is shown to be approximately 3 times the injection rate at $R = 10\ sec^{-1}$. However, at this injection rate with a 70% operating efficiency, r_A increases to a value approximately 35 times R. The required input rate may therefore be significant depending on the yield factors and the rate of production.

As an estimate of the number of items that would need to be processed for this range of input rate, the time interval t_L for the slowest processing step may be set at 8.64×10^4 sec (24 hr.). From equation (3a), the value of A would range from 10^6 to 10^8 items. The capacity of the processing steps must therfore be able to handle a large quantity of items to meet the specified production rate. Consequently, a factor that may have to be considered in the selection of a coating process technique for the target factory is the ability of the coating technique to operate at a capacity to meet high input rate production.

PRODUCTION LINES

The overall input and output rate for each target process system has been generalized in terms of multiple production lines. By considering the input rate for each system, an expression for the production lines v, m, and p can be written using (14), (11), and (9), respectively:

$$v = \frac{R}{r_G \left[\prod_{i=1}^{u} f_i\right]\left[\prod_{i=1}^{n} y_i\right]\left[\prod_{i=1}^{s} q_i\right]}\left(\frac{t_F}{t_g}\right) \qquad (16a)$$

$$m = \frac{R}{r_A \left[\prod_{i=1}^{n} y_i\right]\left[\prod_{i=1}^{s} q_i\right]} \qquad (16b)$$

$$p = \frac{R}{r_C \left[\prod_{i=1}^{s} q_i\right]} \qquad (16c)$$

Figures (7), (8), and (9) show how the number of processing lines are affected with a change in production yield. With the assume parameters indicated in each Figure, it is shown that v, m, and p increase significantly as the production yield factor decreases. This is indicated in Table 1 where the number of production lines needed to operate a target factory are given for different production yields.

Table 1. Number of production lines needed in each system for a target factory operating at various production efficiencies.

Production Line		Production Yield	
		90%	70%
SD &DT	v	1	11
CP	m	3	36
CIFC	p	2	6

$R = 10\ \text{sec}^{-1}$; $r_A = r_C = 10\ \text{sec}^{-1}$

$r_G = 200\ \text{sec}^{-1}$; $u = n = s = 5$ steps

For a target factory operating at a production efficiency of 90% at an injection rate of R=10 sec^{-1}, the number of processing lines required are v=1 for the SD & DT system, m=4 for the CP system, and p=2 for the CIFC system. However, at a production yield of 70%, the number of processing lines needed, especially in the case of the CP system, could be too large to be practical. Consequently, since the cost of a target factory will be proportional to the number of processing lines needed to meet the target production rate for laser fusion, production efficiency must remain high for each processing system. This also will be a factor to consider in determining what processing techniques may be used in a target factory production scheme.

SUMMARY

Target fabrication and target production are areas that must blend together in the concept of a target factory. An understanding and development of these areas to meet both target design and target production criteria have been initiated by the derivation of production expressions to perform a parametric study. Preliminary results have indicated that a parametric study of this type will be important in deciding what factors will have a major influence on the operation and cost of a target factory for laser fusion.

FIGURE CAPTIONS

1. A basic target factory block diagram consisting of three main processing systems.

2. The shell development and DT fill (SD&DT) system.

3. A general production diagram of the coating process (CP) system.

4. The cryogenic injection fusion chamber (CIFC) system.

5. A general production diagram of the three processing systems representing the basic target factory.

6. The rate of input of items into the coating process system as a function of the fusion chamber target injection rate.

7. The dependence of the number of production lines of the shell development and DT fill system on the target injection rate and production yield factor.

8. The number of production lines needed for the coating process system as a function of the production yield factor and rate of target injection.

9. The number of production lines required for the cryogenic injection fusion chamber system as a function of the target injection rate and production yield factor.

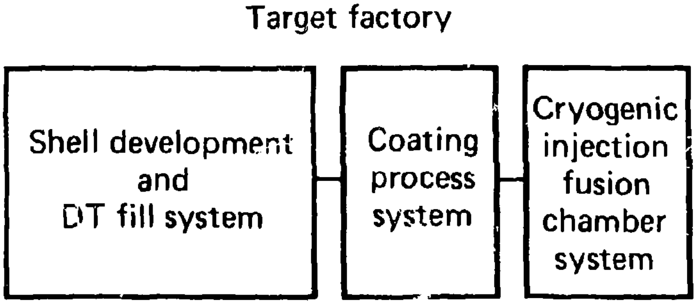

Target factory
Shell development and DT fill system
Coating process system
Cryogenic injection fusion chamber system

FIGURE 1

Shell development and DT fill system

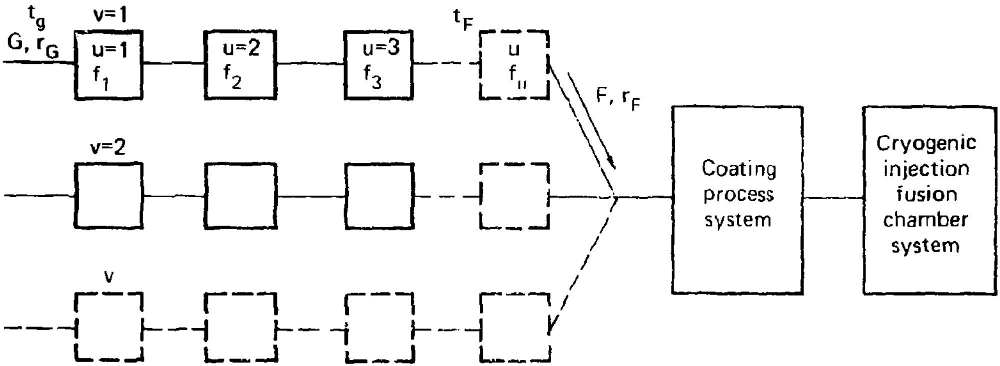


FIGURE 2

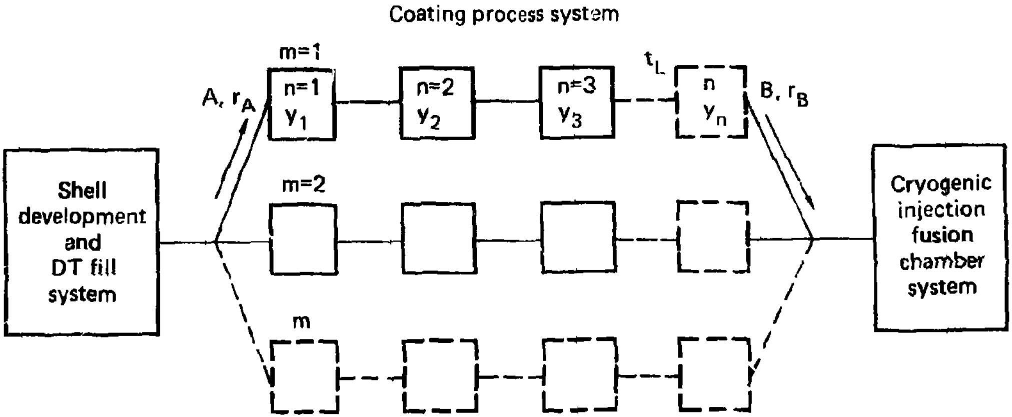

Coating process system
m=1
A, r_A
n=1
y_1
n=2
y_2
n=3
y_3
t_L
n
y_n
B, r_B
Shell development and DT fill system
m=2
m
Cryogenic injection fusion chamber system

FIGURE 3

Cryogenic injection fusion chamber system

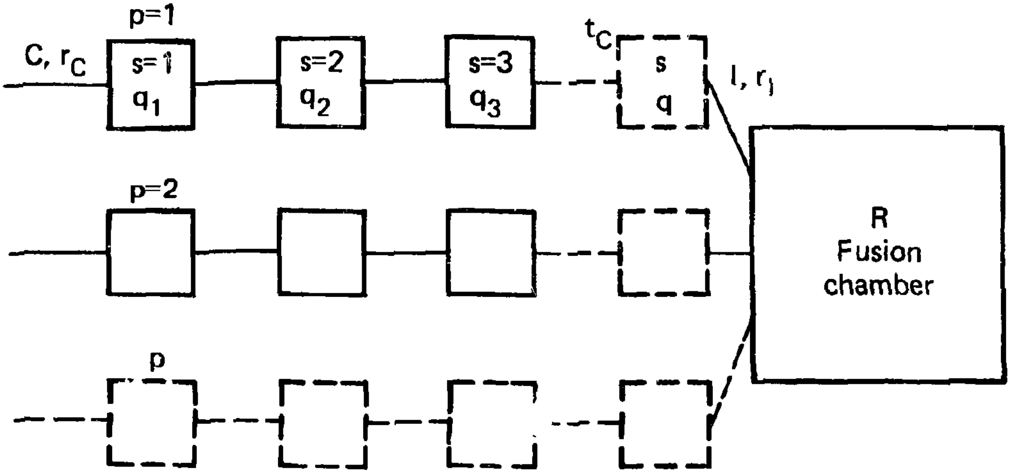
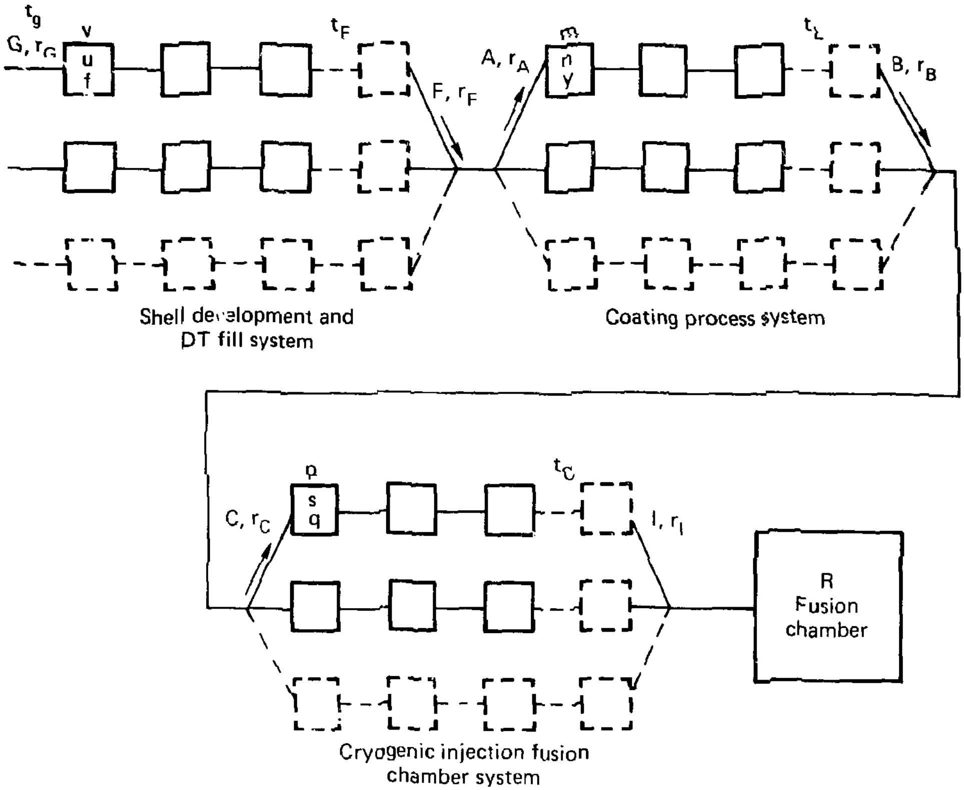
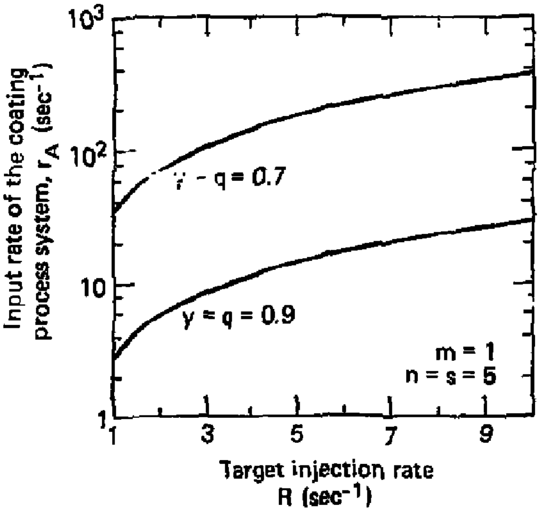


FIGURE 4



t_g
G, r_G
v
u
f
t_F
F, r_F
A, r_A
m
n
y
t_L
B, r_B
Shell development and DT fill system
Coating process system
p
s
q
t_C
C, r_C
I, r_I
R
Fusion chamber
Cryogenic injection fusion chamber system

FIGURE 5



10^3
10^2
10
1
1
3
5
7
9
Input rate of the coating process system, r_A (sec^{-1})
Target injection rate R (sec^{-1})
$\gamma = q = 0.7$
$\gamma = q = 0.9$
m = 1
n = s = 5

FIGURE 6

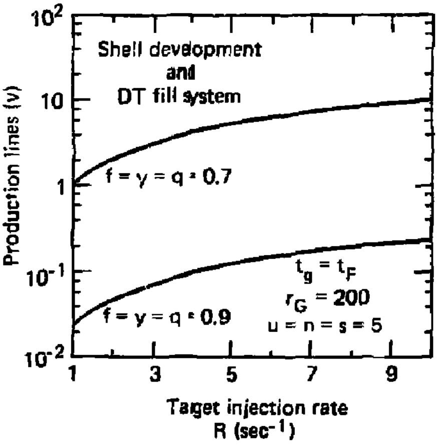

Shell development
and
DT fill system
f = y = q = 0.7
f = y = q = 0.9
$t_g = t_F$
$r_G = 200$
u = n = s = 5
Production lines (v)
10^2
10
1
10^{-1}
10^{-2}
1
3
5
7
9
Target injection rate
R (sec^{-1})

FIGURE 7

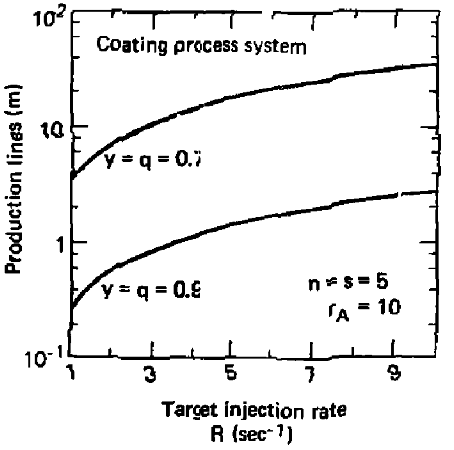
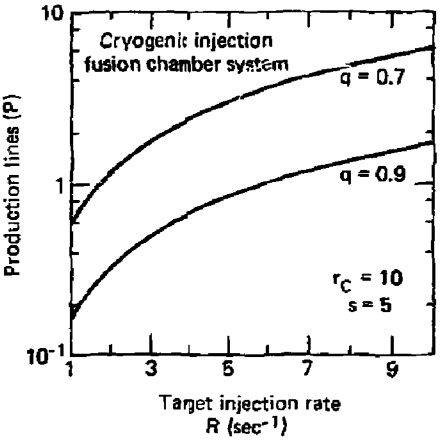

Coating process system
Production lines (m)
10^2
10
1
10^{-1}
$y = q = 0.7$
$y = q = 0.9$
$n = s = 5$
$r_A = 10$
1
3
5
7
9
Target injection rate
R (sec^{-1})

FIGURE 8



Cryogenic injection fusion chamber system
q = 0.7
q = 0.9
$r_c = 10$
s = 5
Production lines (P)
10
1
10^{-1}
1
3
5
7
9
Target injection rate
R (sec^{-1})

FIGURE 9

APPENDIX

COMPARISON OF BATCH AND LINE PROCESSING FOR TARGET PRODUCTION

A comparison of batch processing to that of individual line processing has been examined in terms of the rate of production of laser fusion targets. The comparison is made with reference to the coating process system of a target factory.

Batch Processing

The batch processing method involves loading a processing step with a number of items at one time. For a single step processing system, the batch processing rate is defined as

$$r_B = \frac{yA}{t_L} \qquad (1)$$

where A = the number of items entering the process step
y = the production yield factor, and
t_L = the time interval for processing.

For a coating process, the time interval t_L is determined by the thickness th of the deposited layer and the rate r_D of deposition.

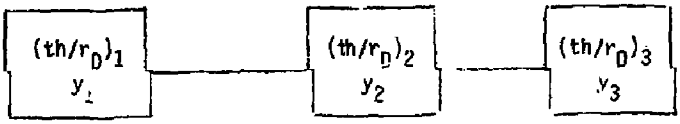
$$t_L = \frac{th}{r_D} \qquad (2)$$

Thus, the output rate or batch processing rate for a single step process becomes

$$r_B = \frac{yA}{(th/r_D)} \qquad (3)$$

In the case of a multiple coating process, each coating step would have a characteristic time interval represented by $(th/r_D)_i$ and a production yield factor y_i:

Batch Coating Process

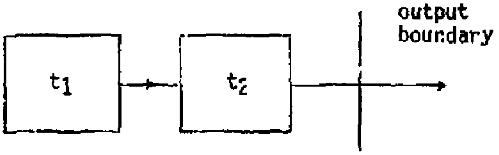


The total time to overcome the "pipe-line effect" is the sum of the characteristic time intervals

$$t_T = \sum_{i=1}^{n} \left(\frac{th}{r_D}\right)_i \qquad (4)$$

However, once the pipe-line effect is complete the characteristic time interval that controls the batch processing rate is the slowest th/r_D deposition step. This can be demonstrated by a simple example:

Consider a two step coating process where one step takes a time interval of t_1 and the other an interval t_2. Let the t_1 step be the initial coating process and the t_2 step the last and let t_1 t_2. An item entering the first step stays



there for t_1, then moves on to the next. After a time t_2 in the second coating step it leaves and crosses the output boundary. The total time the item was in the system was $t_1 + t_2$ and this is referred to as the time to fill the pipeline to produce an initial output for the system.

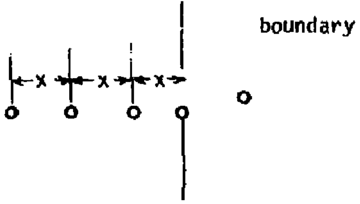
In the case of a second item in the system, it can enter the first coating step after t_1. Although the last coating step is vacant when the first item leaves, the second item must remain $t_1 - t_2$ longer in the first coating step. As a result, there exist a wait period of $t_1 - t_2$ before the second coating step can be filled with an item. However, after this period the second item enters the next coating step and remains there for t_2. The total time that has lapsed since the first item crossed the output boundary and the time the second item crosses is $(t_1-t_2) + t_2 = t_1$. The characteristic time interval controlling the output rate t_L is therefore t_1 or the slowest deposition step. For the case where $t_2 > t_1$ the analysis leads to the same conclusion.

The rate for the batch coating process is determined from (1) using t_L for the slowest deposition step and the number of acceptable items that cross the output boundary. For a multiple coating process, the batch coating rate becomes

$$r_B = \frac{\left(\prod_{i=1}^{n} y_i\right) A}{t_L} \tag{5}$$

Line Processing

Line processing is a method where an item is processed individually. If it is assumed that the item is continuously in motion during processing, the rate of output can be determined from the following example:



Line Processing Unit

A number of items are traveling in a line processing system at a velocity v and are separated from each other by a distance x. The distance x has a value defined as $x > d$ where d is the item diameter. The line processing rate r_L is the rate that the items cross the output boundary and is expressed as

$$r_L = \frac{v}{x} \qquad (6)$$

For a coating process step, the velocity at which the items must travel is based on the time t_L required for deposition and the length L of the coating unit. Thus,

$$v = \frac{L}{t_L} \qquad (7)$$

where t_L is given by equation 2:

$$t_L = \frac{th}{r_D} \qquad (8)$$

Substitution of (7) into (6) gives an expression for the rate of a process line as,

$$r_L = \frac{L}{x\, t_L} , \qquad (9)$$

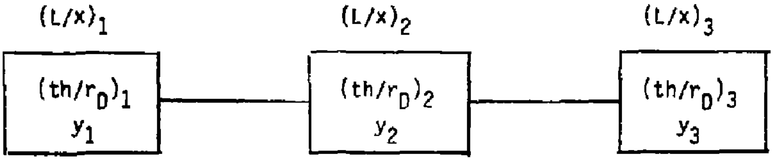
or from (8) as $r_L = \left(\frac{L}{x}\right)\left(\frac{r_D}{th}\right)$ (10)

The term L/x represents the number of items in the coating system. If a production yield factor is included in the process, equation (10) becomes

$$r_L = y\left(\frac{L}{x}\right)\left(\frac{r_D}{th}\right) \tag{11}$$

In the case of a coating system having multiple line processing units, the output rate r_L can be determined by the following example:

Line Processing Coating System



Assume a multiple coating system having three line processing units each with a production yield factor y. The characteristic time interval of coating for each unit is $(th/r_D)_i$ and number of items in each unit during the production mode is $(L/x)_i$. Consequently, the number of items in the first line processing unit is $(L/x)_1$ while the number of items leaving the unit and entering the second unit is expressed as y_1 $(L/x)_1$. Therefore

$$(L/x)_2 = y_1(L/x)_1 \tag{12}$$

and likewise, $(L/x)_3 = y_2\,(L/x)_2$ (13)

where y_3 $(L/x)_3$ would represent the number of items leaving the third unit.

Equating (12) and (13), the quantity of items leaving the multiple coating system becomes

$$y_3(L/x)_3 = y_3y_2(L/x)_2 = y_3y_2y_1(L/x)_1 = \left(\prod_{i=1}^{n} y_i\right)(L/x)_1 \quad (14)$$

By dividing (14) by the slowest characteristic time interval t_L the output rate r_L becomes

$$r_L = \frac{\left(\prod_{i=1}^{n} y_i\right)(L/x)_1}{t_L} \quad (15)$$

In comparing the output rate (5) and (15) for the two methods of processing, the difference is in the expression for the number of items being processed. In the batch processing method the number of items acceptable for a production output is

$$\left(\prod_{i=1}^{n} y_i\right) A \quad (16)$$

Where in the case of line processing the number is represented by

$$\left(\prod_{i=1}^{n} y_i\right)(L/x)_1 \quad (17)$$

The main difference in (17) is that the number of items is expressed in terms of the length of a coating unit needed for deposition of an item moving at a constant velocity. However, it may be that in comparing the two methods, the significant difference is in the yield factor term. The yield factor term could be considerably different in one case than in the other due to the production scheme for coating. Consequently, for a particular coating scheme, one or the other processing methods may be more efficient to provide the production yield needed for a target factory.