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A PARAMETRIC STUDY OF A TARGET FACTORY FOR LASER FUSION

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A PARAMETRIC STUDY OF A TARGET FACTORY FOR LASER FUSION*

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ABSTRACT

An analysis of a target factory leading to the derivation of production rate equations has provided the basis for a parametric study. Rate equations describing the production of laser fusion targets have been developed for the purpose of identifying key parameters, attractive production techniques and cost scaling relationships for a commercial target factory.

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INTRODUCTION

The analysis of a target factory presented here is based on a production scheme conjectured to represent the operation of a target production facility. A basic block diagram representing a target factory is shown in Figure 1 consisting of three main processing systems: the shell development and DT fill system, the coating process system, and the cryogenic system. The rate equations were derived by representing each system as a generalized facility with multiple processing steps and production lines. By interfacing the production flow of the systems, a general expression was determined for the production rate of a target factory. Parameters involving the input and output rate of a process system, the efficiency of each step, and the number of process steps and production lines have been used to develop an understanding of their dependence on the rate of target injection for laser fusion.

The rate equations for the target factory have also been used to develop scaling laws for the cost of the facility as a function of the production rate and the fusion energy yield per target. The time required for the key process steps are first related to the size (yield) of the target. For a given production technique the number of parallel process lines required to meet a specified production rate is determined and the cost of the target factory is then taken to be proportional to the number of process lines.

Target fabrication and target production are areas that must blend together in the concept of a target factory. Parametric studies of this type help identify factors that have a major influence on the operation and cost of a target factory and thus can be useful in guiding our development of production techniques for laser fusion targets.

TARGET FACTORY SYSTEMS

The production of laser fusion targets may be viewed as consisting of three main processing systems: the shell development and DT fill system, the coating process system, and the cryogenic system.

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.

u = 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

$$\text{input rate; } r_G = \frac{G}{t_g} \tag{1a}$$

$$\text{output rate; } r_F = \frac{F}{t_F} \tag{1b}$$

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

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

COSTING 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,

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

CRYOGENIC SYSTEM

The cryogenic (CRY) 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 CRY system.

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

q = yield factor for a cryogenic process step.

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

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

C = number of items entering a CRY production line.

r_I = output rate of a CRY production line.

I = number of items leaving a CRY 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 CRY 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

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

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.

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

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 36 times R. The required input rate may therefore be significant depending on the yield factors and the rate of production.

From equation (3a), the number of items A that must be processed to meet the desired production rate is proportional to t_L the time interval for the slowest processing step. For example, if t_L is 1 sec, A would range from 30-360 items for the case of R=10 sec^{-1}. However, if the process takes one day, A would be in the range of 10^6 to 10^8 items. The capacity of the processing steps therfore may be required to handle a large quantity of items to meet the specified production rate. Consequently, a factor that must 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 high enough to meet the rate of 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 (8), respectively:

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

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

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

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.

COST SCALING

Scaling laws based on the previous equations have been developed to estimate the cost of the target factory as a function of the production rate, R, and the fusion-energy yield, Y, of the targets. The cost of each of the three process systems is assumed to be proportional to the required number of parallel process lines, (v, m and p) times the cost per line. The total cost of the target factory is the sum of the costs of the three subsystems. That is:

$$CC = vD_1 + mD_2 + pD_3 \quad (17)$$

where CC = total capital cost of the target factory

D_1, D_2, D_3 = cost per line of the respective process systems

The number of process lines v, m and p given in equations (16a), (16b) and (16c) can be rewritten in terms of the time intervals for the slowest process step (t_F, t_L and t_C) and the number of targets (G, A and C) entering the production lines of each of the target process systems by substitution of (1a), (3a) and (5a) respectively:

$$v = \frac{Rt_F}{G\left[\prod_{i=1}^{u} f_i\right]\left[\prod_{i=1}^{n} y_i\right]\left[\prod_{i=1}^{s} q_i\right]} \tag{18a}$$

$$m = \frac{Rt_L}{A\left[\prod_{i=1}^{n} y_i\right]\left[\prod_{i=1}^{s} q_i\right]} \tag{18b}$$

$$p = \frac{Rt_C}{C\left[\prod_{i=1}^{s} q_i\right]} \tag{18c}$$

Recall that G is the number of shells entering a SD & DT production line after operating a drop generator for a time t_g at a rate r_G. If the drop generator operates continuously (i.e., $t_g = t_F$) then r_G must be set such that the number of shells in the batch entering the slowest step does not exceed the capacity of that component. G is, therefore, proportional to the capacity of the slowest step in a SD & DT process line. Also, since A is the number of targets entering a CP production line in a time t_L, A is proportional to the capacity of the slowest step in the CP production line. Likewise, C is proportional to the capacity of the slowest step in the CRY production line.

In order to relate the target factory cost to the target yield, the process times (t_F, t_L and t_C), component capacities (G, A and C) and production yield factors (f_i, y_i and q_i) in equations (18a-c) must be related to the target yield. One approach is to relate these factors to the physical size of the target.

While the characteristics of the target factory will depend on the type of target, we consider the scaling of a factory that produces a single type (i.e., a given number of layers of a given composition) with dimensions that are related to the expected target yield, Y. Specifically, the fuel shell volume is taken to be proportional to the target yield, and coating-layer thicknesses scale directly with the shell radius so that all relative proportions remain constant. Therefore,

$$a^3 \propto Y \quad \text{and} \quad a_i \propto a$$

where a_n = thickness of the nth layer (cm)

a = fuel shell radius (cm)

Y = pellet yield (MJ)

It has already been noted that the number of process lines is strongly dependent on the production yield factors. For example, if $f_i = y_i = q_i = w$ and $u = n = s = 5$ steps each, then

$$V \propto w^{-15}$$

In this case, if w is decreased from 0.9 to 0.7 the number of lines increases by over a factor of 40. This demonstrates the importance of achieving production efficiencies that are as high as possible for each process step. At this point, any values selected for the production yield factors for a target factory are at best arbitrary. We assume, however, that these production yield factors are independent of target size and also independent of component capacities G, A and C. Therefore, whatever the selected values, they appear as constants in the cost scaling equation.

Another simplifying assumption is that the targets are physically separated during the slowest step of each process system such that the process volume allowed per target is independent of the target size. Therefore, the capacities G, A and C are also independent of target yield.

It is assumed that the time intervals for the slowest process steps are only a function of target yield and given by

$$t_F \propto Y^{\varepsilon_1} \qquad (19a)$$

$$t_L \propto Y^{\varepsilon_2} \tag{19b}$$

$$t_C \propto Y^{\varepsilon_3} \tag{19c}$$

where ε_1, ε_2, and ε_3 are scaling exponents determined by the particular production process.

Therefore, from (18) and (19) the number of process lines for the different subsystems can be expressed as:

$$v \propto \frac{RY}{G}^{\varepsilon_1} \tag{20a}$$

$$m \propto \frac{RY}{A}^{\varepsilon_2} \tag{20b}$$

$$p \propto \frac{RY}{C}^{\varepsilon_3} \tag{20c}$$

The cost per process line is taken to be a function of the component capacities G, A and C. Assuming economies of scale exist for the components that make up the process lines, the cost per line can be expressed as

$$D_1 \propto G^{\eta_1} \tag{21a}$$

$$D_2 \propto A^{\eta_2} \tag{21b}$$

$$D_3 \propto C^{\eta_3} \tag{21c}$$

where η_1, η_2, η_3 = scaling exponents less than 1.0

A general expression for the capital cost of the target factory can then be written as:

$$\begin{aligned} CC = CC_0 \, [\, & \delta_1 \, (G/G_0)^{\eta_1} \, (G_0/G) \, (R/R_0) \, (Y/Y_0)^{\varepsilon_1} \\ & + \delta_2 \, (A/A_0)^{\eta_2} \, (A_0/A) \, (R/R_0) \, (Y/Y_0)^{\varepsilon_2} \\ & + \delta_3 \, (C/C_0)^{\eta_3} \, (C_0/C) \, (R/R_0) \, (Y/Y_0)^{\varepsilon_3} \,] \end{aligned} \tag{22}$$

where δ_1, δ_2, and δ_3 are the fractions of the total capital cost CC_0 that the three major subsystems comprise at the reference production rate R_0, target yield Y_0, and component capacities G_0, A_0 and C_0.

That is

$$\delta_1 = v_0 \, D_{01}/CC_0 \tag{23a}$$

$$\delta_2 = m_0 \, D_{02}/CC_0 \tag{23b}$$

$$\delta_3 = p_0 \, D_{03}/CC_0 \tag{23c}$$

The size and cost of the building that contains target production equipment will be dependent on the number of process production lines and the size of the components. It may be dominated by area requirements for a single process or it may be some weighted function of the three process systems. If the building cost is directly proportional to the number of process lines it can be explicitly accounted for in the values of δ. Alternatively, an additional term could be added to equation (22) to account for the cost of the building.

As an example of the scaling for a particular target assume that:

1) t_F is for the DT fill step and is proportional to the total fuel mass

$$t_F \propto a^3 \propto Y$$

$$\varepsilon_1 = 1$$

2) t_L is for a coating step and proportional to the thickness of the deposited layer

$$t_L \propto a \propto Y^{1/3}$$

$$\varepsilon_2 = 1/3$$

3) t_C is for a cooling step and the heat flux (W/cm^2) from the surface of the target is constant.

$$t_L \propto a \propto Y^{1/3}$$

$$\varepsilon_3 = 1/3$$

This follows since the energy removal rate is proportional to the target surface area while the total energy that must be removed is proportional to the target volume.

We also assume that each of the process systems comprises 1/3 of the total cost at the reference parameters and that all capacities have economies of scale exponents of 0.6 which is a typical rule of thumb.[1]

$$\delta_1 = \delta_2 = \delta_3 = 1/3$$

$$\eta_1 = \eta_2 = \eta_3 = 0.6$$

Using these parameters we examine equation (22) for several cases of interest.

Case 1a Fixed Component Capacities and Fixed Target Yield.

$$(G/G_0) = (A/A_0) = (C/C_0) = (Y/Y_0) = 1$$

$$CC = CC_0\ (R/R_0) \tag{24}$$

In this case the only way to increase the production rate is to increase the number of process lines. Since target yield is fixed the fusion power increases linearly with production rate. An example would be a factory fueling multiple similar reactors with the same type of target.

Case 1b   Fixed Component Capacities and Fixed Fusion Power

$$(G/G_0) = (A/A_0) = (C/C_0) = 1$$

$$RY = R_0Y_0$$

$$CC = CC_0 \left[1/3 + 2/3\ (R/R_0)^{0.667} \right] \tag{25}$$

In this case the number of process lines depends on the production rate and target yield which are coupled. This expression allows one to compare target factory costs for power plants of a given size (i.e., power).

Case 2a   Fixed Number of Process Lines and Fixed Target Yield

$$(v/v_0) = (m/m_0) = (p/p_0) = (Y/Y_0) = 1$$

$$CC = CC_0\ (R/R_0)^{0.6} \tag{26}$$

Here the production rate is increased by increasing the capacity of the components hence benefitting from the economies of scale.

Case 2b Fixed Number of Process Lines and Fixed Fusion Power

$$(v/v_0) = (m/m_0) = (p/p_0) = 1$$

$$RY = R_0Y_0$$

$$CC = CC_0 \; [1/3 + 2/3 \; (R/R_0)^{0.4}] \qquad (27)$$

The scaling here is more favorable than case 1b again reflecting the benefit of increasing component sizes rather than duplicating process lines.

The relative target factory cost (CC/CC_0) as a function of the relative production rate (R/R_0) is shown in Figure 10 for these four cases. The relative cost per target is shown in Figure 11 for case 2b. This is only the capital cost contribution to the target cost; it does not include material or operations and maintenance costs. The fixed capital charge per year divided by the number of target produced per year gives the cost per target. The cost per target is therefore proportional to the target factory capital cost divided by the production rate.

Equations (24) through (27) are examples of target factory scaling relationships based on the particular assumptions made here. As production techniques are developed and the relationship between target quality and performance and between target quality and production efficiency or cost become known, better relationships can be developed and tradeoffs can be made within the framework of the overall system. For example, if improved quality control increases gain of a particular target 10%, but also lowers the production yield and increases the cost, then depending on the relative costs of the target factory, reactor and driver, the cost of electricity might actually increase. This is the level of understanding we eventually hope to achieve.

SUMMARY

The concept of a target factory capable of supplying > 10^7 targets per year for an ICF power plant will evolve from the marriage of techniques used in the fabrication of targets with processes suitable for automated mass production. To help us understand how target design and target production requirements interface, production expressions for a generalized system have been derived. We find that the key parameters in determining size of the factory in terms of the number of parallel processing lines required to meet the target requirements of the power plant are:

1) the target injection rate,
2) the time required for the slowest process step,
3) the capacity of the process unit, and
4) the production yield factors for each step.

A relationship has been developed to estimate how the cost of the target factory scales with production rate and fusion energy yield. It is by necessity simplistic and only illustrative in that we are unable at this time to relate the process yield factors and capacities to the characteristics of the target.

The intent of this work is to provide a basis for continued studies. Parametric studies of this type can help identify factors that have a major influence on the operation and cost of a target factory, and consequently, will be useful in guiding our development of production techniques for laser fusion targets.

ACKNOWLEDGEMENTS

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1) F. T. Moore, "Economies of Scale: Some Statistical Evidence," Quarterly Journal of Economics, 1959.

FIGURE CAPTIONS

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

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

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

Fig. 4. The cryogenic (CRY) system.

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

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

Fig. 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.

Fig. 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.

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

Fig. 10. Relative target factory cost versus relative production rate for various assumptions.

Fig. 11. Relative target cost versus production rate for fixed number of process lines and fixed fusion power.

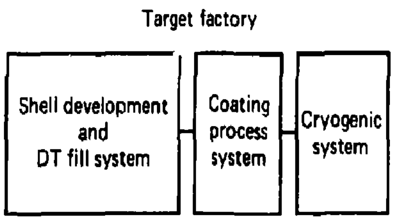
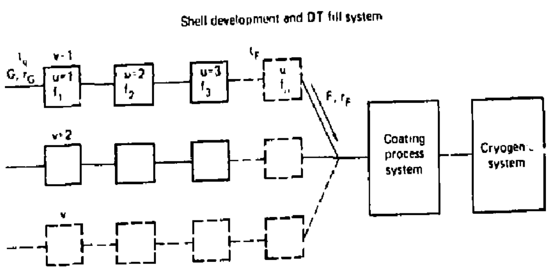

Target factory
Shell development
and
DT fill system
Coating
process
system
Cryogenic
system

FIGURE 1



Shell development and DT fill system
G, r_G
v=1
u=1
f_1
u=2
f_2
u=3
f_3
F, r_F
v=2
v
Coating process system
Cryogenic system

FIGURE 2

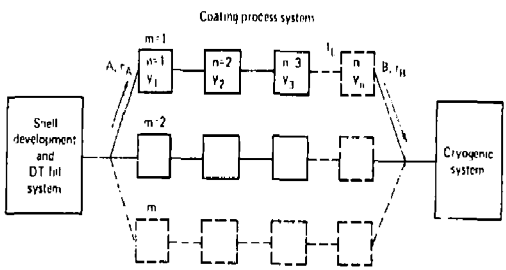

Coating process system
m=1
A, r_A
n=1
y_1
n=2
y_2
n=3
y_3
t_L
n
y_n
B, r_B
m=2
m
Shell development and DT fill system
Cryogenic system

FIGURE 3

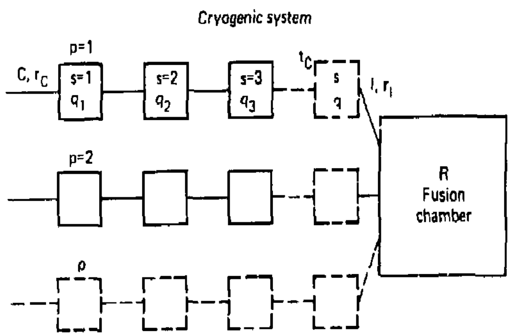
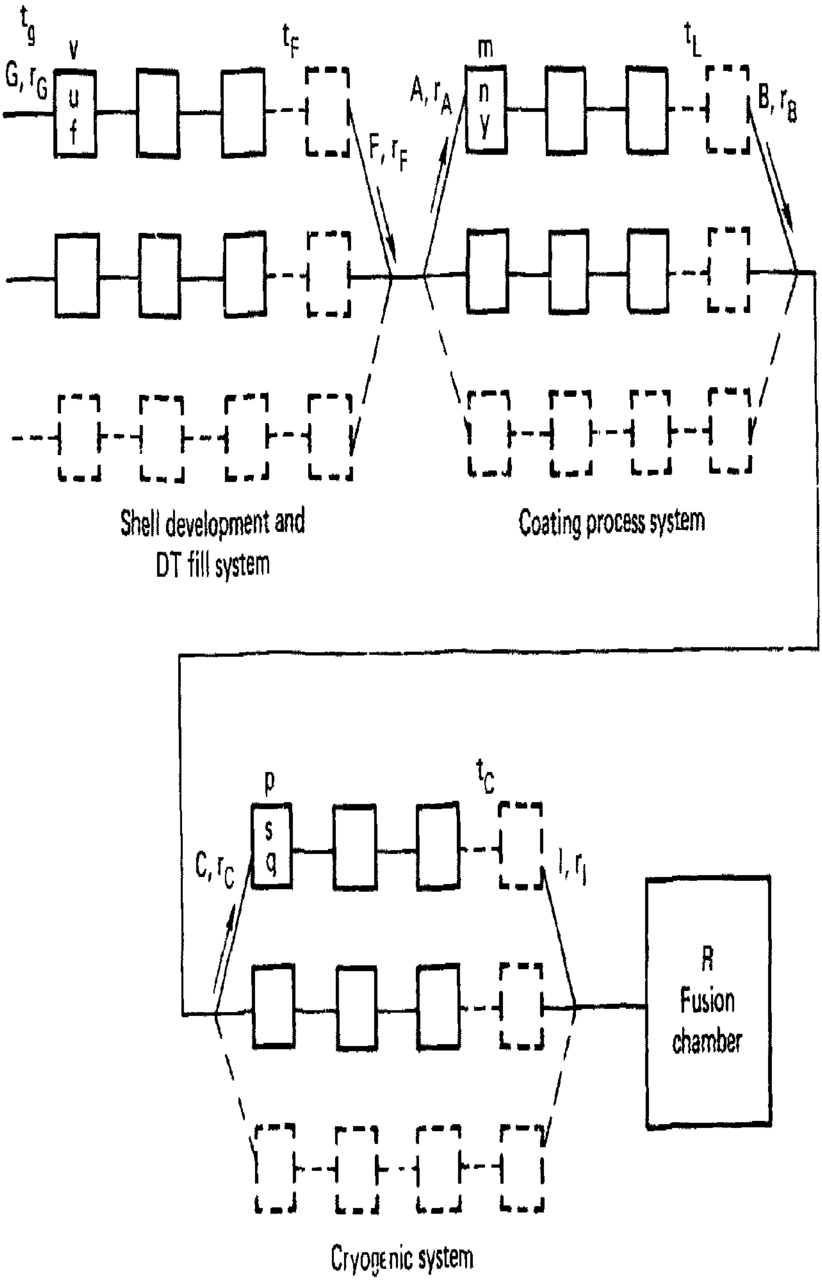
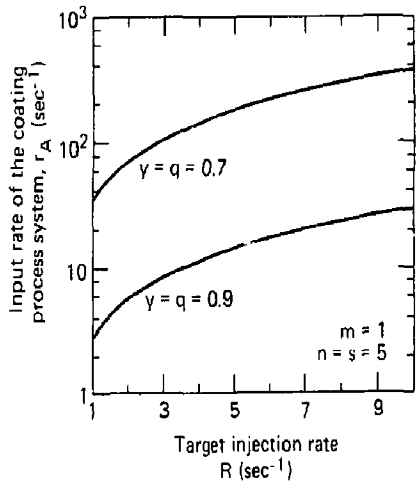

Cryogenic system
p=1
C, r_C
s=1
q_1
s=2
q_2
s=3
q_3
t_C
s
q
I, r_I
p=2
p
R
Fusion
chamber

FIGURE 4



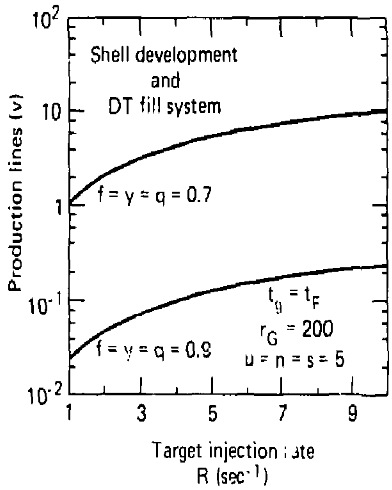
t_g
v
G, r_G
u
f
t_F
F, r_F
m
A, r_A
n
y
t_L
B, r_B
Shell development and
DT fill system
Coating process system
p
s
q
C, r_C
t_C
I, r_I
R
Fusion
chamber
Cryogenic system

FIGURE 5



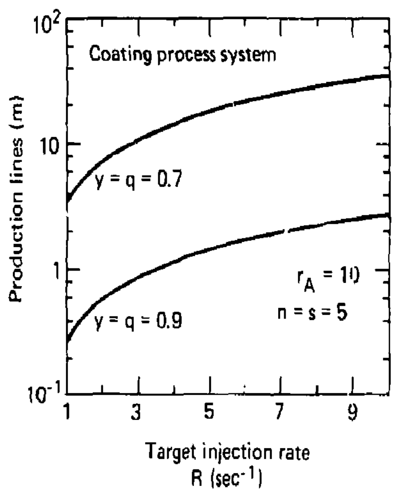
Input rate of the coating process system, r_A (sec^{-1})
10^3
10^2
10
1
$\gamma = q = 0.7$
$\gamma = q = 0.9$
m = 1
n = s = 5
1
3
5
7
9
Target injection rate R (sec^{-1})

FIGURE 6



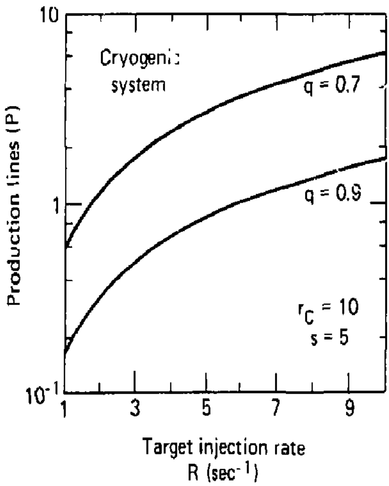
Shell development
and
DT fill system
Production lines (v)
f = y = q = 0.7
f = y = q = 0.9
$t_g = t_F$
$r_G = 200$
u = n = s = 5
Target injection rate
R (sec⁻¹)

FIGURE 7



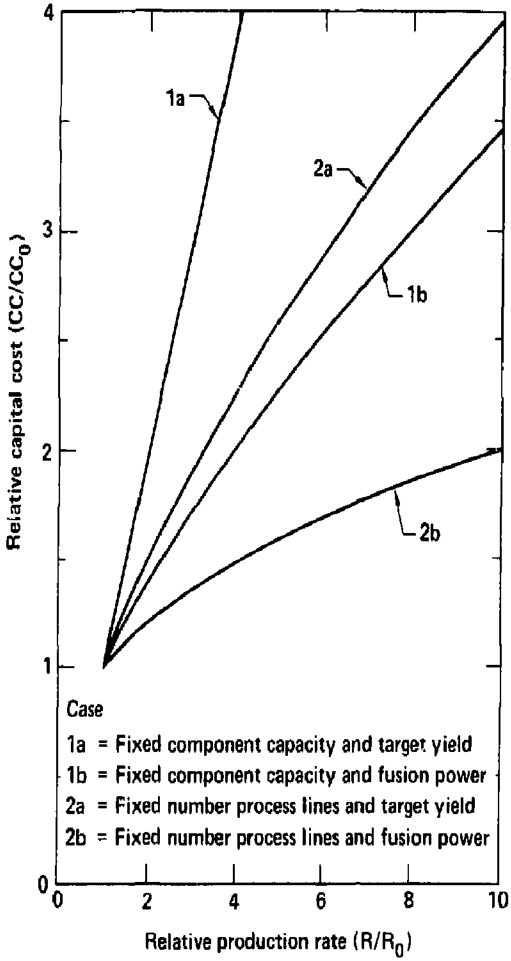
Coating process system
y = q = 0.7
y = q = 0.9
r_A = 10
n = s = 5
Production lines (m)
Target injection rate
R (sec^{-1})

FIGURE 8



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

FIGURE 9



Relative capital cost (CC/CC0)
4
3
2
1
0
1a
2a
1b
2b
Case
1a = Fixed component capacity and target yield
1b = Fixed component capacity and fusion power
2a = Fixed number process lines and target yield
2b = Fixed number process lines and fusion power
0
2
4
6
8
10
Relative production rate (R/R0)

FIGURE 10

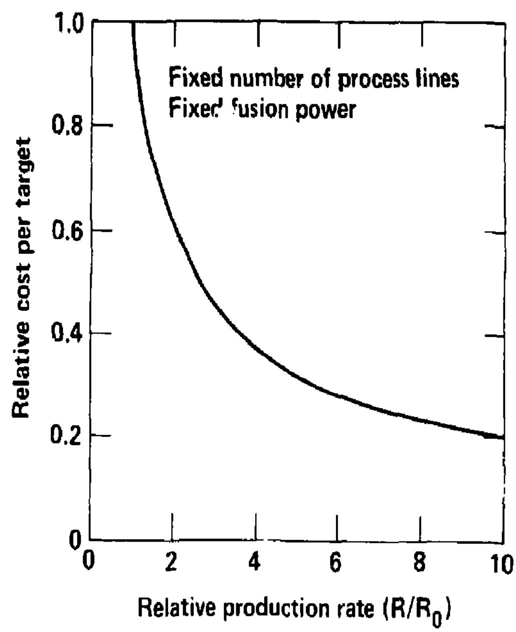

Fixed number of process lines
Fixed fusion power
Relative cost per target
Relative production rate (R/R0)
1.0
0.8
0.6
0.4
0.2
0
0
2
4
6
8
10

FIGURE 11