DESIGN AUTOMATION IN MULTIPLE CRITERIA PROBLEMS USING KNOWLEDGE ENGINEERING AND FUZZY CONTROL

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ABSTRACT

This paper describes an automated design system for nuclear structural components subjected to complicated loading conditions.

As a basic strategy of designing structures considering various loading conditions, the "generate and test" strategy is adopted because of simplicity and broad applicability.

An object-oriented knowledge representation technique is adopted to store knowledge modules related to design problems, while a data-flow processing technique is utilized as an inference mechanism among the knowledge modules.

As efficient design modification mechanisms, the present system utilizes two approaches, (a) an empirical approach based on experts' empirical knowledge and the fuzzy control, and (b) a mathematical approach based on numerical sensitivity analyses.

Using this system, one can also obtain "design window" which designates satisfaction area for all design criteria in an designing space.

INTRODUCTION

In conventional design procedures of practical structures, which are mostly based on the "generate and test" strategy [1], a number of calculations and evaluations are carried out repeatedly to obtain the optimum shape of structure which can prevent all the failure modes such as melting, yielding and fracturing during a design life. Such iterative design processes require experts' empirical knowledge embedded over various engineering fields, and are very complicated and time-consuming tasks.

Due to a progress of computational mechanics techniques, the accuracy and the reliability of analyses of a uni-phenomenon such as structural deformation, heat conduction or fluid dynamics have been dramatically increasing. In some cases, an optimum shape of structure under a simple loading condition can be obtained automatically by means of mathematical techniques based on numerical sensitivity analyses [2,3]. However, such mathematical techniques have not been applied yet to design optimization of practical structures considering various complicated loading conditions.

To overcome the problem described above, the present authors have been developing an automatic design system for practical structures, such as the fusion first wall and vessel components of the FBR using some artificial intelligence techniques [4-11].

The following sections describes methodologies for design automation implemented in the present automated design system.

SYSTEM CONFIGURATION

The present system is essentially based on the "generate and test" strategy [1] supported by several artificial intelligence techniques.

An object-oriented knowledge representation technique [12] is adopted to store knowledge modules related to a design of structures subjected to various loadings. A data-flow processing technique [13] is utilized as an inference mechanism among the knowledge modules, that is, objects. These techniques realize high flexibility and extensibility of the present design. The functions of design modification are also included in some of objects.

To perform a large amount of symbolic inference processing and numerical calculations on a single CPU computer, a 32-bit engineering workstation (SUN SPARC station 1, SPARC IU [20 MHz] and SPARC FPU [20 MHz]) is employed here, which has the capacity of a speed of 12.5 MIPS and 1.2 MFLOPS, a main memory of 16 MB and a disc of 200 MB.

The main portion of the system including a knowledge base of objects and an inference engine is written by KCL (Kyoto Common LISP), and outer procedural programs such as finite element codes are written by either FORTRAN or C.

DESIGN MODEL AND DESIGN CRITERIA

As one of design examples, we take a two-dimensional model of the fusion first wall with a circular cooling channel as shown in Fig. 1. The wall is subjected to membrane tensile loading, F, which might be caused by electromagnetic loading and pressure from the breeder blanket, and to surface heat loading, Q on the plasma-side surface. An upper half portion of the wall is modeled with a finite element mesh. The employed design criteria are as follows.

(i) Temperature criterion : $T > T_o$ (1)

(ii) Stress criterion : $\sigma > \sigma_o$ (2)

where T is the maximum temperature, T_o an allowable value of temperature, σ the maximum equivalent stress and σ_o an allowable value of stress, respectively.

In this example, two design variables of the wall thickness (W) and the diameter of the cooling channel (R) are designed to satisfy the above design criteria under the given condition.

AUTOMATIC DESIGN MODIFICATION

In the generate and test strategy, design parameters have to be somehow modified in a permissible design space when the former design candidate does not satisfy any of design criteria. Such a design modification process is iterated until an optimum design is attained. This process usually takes much time as the number of design parameters increases and the design space is spread. As one of efficient techniques for design modification, much attention has been paid to mathematical approaches based on numerical ensitivity analyses. However, the application of such approaches has been limited to only simple problems such as shape optimization of simple structures subjected to mechanical loading.

Here we describe two approaches for design modification, i.e. empirical and mathematical approaches.

Mathematical Approach Based on Sensitivity Analysis

A number of optimization techniques by which an objective function is minimized with several constraints have been proposed so far. These include transformation techniques such as the Lagrange multiplier and the penalty function method, and direct techniques such as the gradient method [2,3].

Since it is suitable for shape optimization using the finite element method, we adopt the following shift synthesis technique [3]. The technique is based on the concept that design parameters are determined so that the objective design is sought as near an initial design as possible while the constraint conditions set for the attainment of the objective design are imposed in terms of the Lagrange multiplier method. The formulation is summarized as follows.

Let us consider a functional as :

$$\Pi_o = \sum_{i=1}^{n} \left(\frac{\Delta S_i}{S_i} \right) \tag{3}$$

where n, Si and ΔSi are the number of design variables to be designed, the value of i-th design variable and the magnitude of its modification, respectively.

The constraint considered here is generally written as follows :

$$f_j \left(S_i + \Delta S_i \right) = 0 \qquad \text{for } j = 1, m. \tag{4}$$

The problem of minimizing the functional of Eq. 3 with the constraint of Eq. 4 can be converted, by means of the Lagrange multiplier method, to that of minimizing the following new functional :

$$\Pi = \Pi_o + \sum_{j=1}^{m} \lambda_j f_j \left(S_i + \Delta S_i \right) \tag{5}$$

$$= \Pi_o + \sum_{j=1}^{m} \lambda_j \left[f_j (S_i) + \sum_{i=1}^{n} \frac{\partial f_j}{\partial S_i} \Delta S_i \right] \tag{6}$$

with respect to ΔSi and λi in the following :

$$\frac{\partial \Pi}{\partial \Delta S_i} = 2 \frac{\Delta S_i}{S_i} + \sum_{j=1}^{m} \lambda_j \frac{\partial f_j}{\partial S_i} = 0 \qquad \text{for } i = 1, n \tag{7}$$

$$\frac{\partial \Pi}{\partial \lambda_i} = f_j (S_i) + \sum_{i=1}^{n} \frac{\partial f_j}{\partial S_i} \Delta S_i = 0 \qquad \text{for } j = 1, m. \tag{8}$$

Thus, ΔSi (i=1,n) and λj (j=1,m) can be obtained by solving Eqs. 7 and 8. It should be also noted here that, since sensitivity coefficients included in Eqs. 7 and 8 are usually evaluated in the following numerical manner :

$$\frac{\partial f_j}{\partial S_i} = \frac{f_j \left(S_i + \Delta S_i \right) - f_j (S_i)}{\Delta S_i} \tag{9}$$

the present mathematical approach requires more finite element calculations for each design modification than the empirical approach described subsequently.

Empirical Approach Based on Experts' Knowledge

The most serious problem of the mathematical approaches may be the fact that the mathematical design modification is often trapped at one of locally optimum points in complicated design problems. Thus, the present authors have proposed the "generate and test" strategy combined with an empirical design modification technique [4-6]. As shown in Fig. 6, the "IF-THEN" type rule, which is so-called Production Rule, is utilized to describe the experts' empirical knowledge related to the design of the fusion first wall. In Fig. 6, ΔW and ΔR denote the unit steps for changing the magnitudes of the design parameters (W) and (R) at one design modification process.

For example, RULE 1 says that, if the maximum temperature exceeds the allowable value, the wall is thinned and the cooling channel is enlarged in order to increase its cooling capability. RULE 2 says that, if the maximum equivalent stress value exceeds the allowable value and a tensile stress component is dominant as well, the wall is thickened to decrease the effect of mechanical tensile loading. On the other hand, RULE 3 says that, if the maximum equivalent stress value exceeds theallowable value and a compressive stress component is dominant, the cooling capability of the wall should be increased. These "IF-THEN" type rules, which have been derived based on experts' qualitative inference, instruct how to modify the former design, considering the reason why the former design candidate violates either or both of the design criteria.

Empirical Approach with Fuzzy Control

(1) Fuzzy control rules and membership functions

The "IF-THEN" type rules given in Fig. 2 are suitable for the estimation of the direction of design modification, but it may take many iterations to obtain convergence in the case that the value of $\sigma / \sigma o$ is nearly equal to 1.0. The main reason for such less ability of the empirical approach in quantitative estimation may be that the magnitudes of the unit steps are always fixed to be small constants during the design modification process. To solve this problem, one can employ the fuzzy control technique [14] as follows [7-10].

The fuzzy rules employed here can be generalized as :

$$\text{RULE}^{i} : \text{IF } p \text{ is } A^{i} \text{ and } \Delta p \text{ is } B^{i}, \text{ THEN } \Delta W \text{ and } \Delta R \text{ are } C^{i} \qquad (10)$$

where RULE ^{i} is the i-th fuzzy rule, A^{i}, B^{i} and C^{i} the i-th fuzzy variables, p the value of $\sigma / \sigma o$, and Δp the difference of the current and the next values of p, i.e. $| p(n+1) - p(n) |$ (n : the iteration number of design modification), respectively. The labels of the fuzzy variables are defined as follows.

As for A^{i},

LARGE -> P is much larger than 1.0.
MEDIUM -> P is larger than 1.0.
SMALL -> P is a little larger than 1.0.

As for B^{i} and C^{i},

LARGE -> Δp, ΔW, ΔR are positive and large.
MEDIUM -> Δp, ΔW, ΔR are positive and Medium.
SMALL -> Δp, ΔW, ΔR are positive and Small.

As shown in Fig. 3, trapezoid type membership functions are utilized as those of labels of A^i and B^i, and constant functions are used for C^i from the viewpoint of efficiency and simplicity. As a fuzzy reasoning method, adopted is the "Min-Max-Gravity" [14].

(2) Tuning process of fuzzy control rules and membership functions

It is not a general case that design engineers can determine both fuzzy control rules and membership functions precisely. Therefore, the fuzzy control rules and membership functions need certain tuning processes before utilization. Here they are first tuned up through trials and errors under the condition that F and Q are 303.8 N and 0.1 MW/m^2, respectively. The tuned membership functions of labels of A^i and B^i are shown in Fig. 7 and those of C^i are tabulated in Table 1. The tuned fuzzy rules are tabulated in Table 2. Figure 4 shows the distribution of ΔW plotted against p and Δp as the summary of the tuned fuzzy rules and membership functions. The figure clearly demonstrates that complex nonlinear functions for the control of the present design modification can be expressed only by using such simple fuzzy rules and membership functions.

DESIGN WINDOW

In conventional designs, a designing proces is finished when one satisfactory design is obtained. In practical situations, "design window" which schematically indicate satisfactory area in a permissible design space may give us much more meaningful information than one satisfactory design. It is very useful for designers to make final decision, considering some other design criteria such as economics and manufacturability and so on. One of important outputs of the present automated design system is the "design window".

One approach of obtaining the design window is as follows. At first, the system finds one satisfactory result, and then it starts searching the edge of the design window. This algorithm is schematically illustrated in Fig. 5.

Another approach is to calculate satisfactory results one by one, starting from various different initial design values. The latter approach is less efficient than the former one in the case of two design variables as shown in Fig. 5, but the latter one is much simpler and may be applicable to even the cases of more than two design variables.

RESULTS AND DISCUSSIONS

Design Based on Expert's Knowledge

Figure 6 shows the convergence features of the design variables W and R under the condition of F = 303.8 N and Q = 0.1 MW/m^2, starting from three different initial values. Here bracketed numbers indicate the total number of design modifications. One design modification involves a mesh generation, a thermal conduction analysis and an elastic thermal stress analysis. The rules of the expert's knowledge shown in Fig. 2 are utilized in these particular problems. It can be seen in the figure that convergence processes are very complicated in coupled problems such as the fusion first wall design. In Fig. 6, when the initial value of W is larger, W decreases and R increases monotonously to increase the cooling capability of the wall. When the initial value of W is medium and that of R is smaller, R increases, accompanying small oscillation of W. This oscillatory feature may be attributed to the competition between RULEs 2 and 3. When the initial value of W is smaller, only W increases to decrease tensile stress effects, and then R increases to improve cooling capability.

Comparison Between Empirical and Mathematical Approaches

Figure 7 shows the convergence features of design variables W and R, starting from the initial values of Wo = 0.012 m and Ro = 0.003 m. The open square marks and the solid line denote the results of the empirical approach without the fuzzy control, while the solid square marks and the broken line do those of the mathematical approach. The bracketed numbers also indicate the total number of sets of finite element calculations during a whole designing process, each set of which involves a mesh generation, a thermal conduction analysis and an elastic thermal stress analysis. For example, in the empirical approach, each design modification requires a set of finite element calculations. On the other hand, each design modification in the mathematical approach with two design variables requires three sets of finite element calculations since sensitivity coefficients usually have to be evaluated in a finite difference manner as described in Eq. 9. In these examples, a set of finite element calculations requires about 250 seconds, and the total CPU time for the whole finite element calculations takes about 95 percents in the whole designing time. Considering those situations, it can be seen from the figure that, in this particular case, the empirical approach is more efficient than the mathematical one.

Figure 8 shows the similar comparison between both approaches, starting from the initial values of Wo = 0.008 m and Ro = 0.0025 m. In Fig. 8, the mathematical approach is more efficient because the empirical approach yields an oscillatory result.

From those examples, the characteristics of both approaches can be summarized as follows :

(a) The empirical approach predicts the appropriate direction for design modification from a global viewpoint. However, the magnitude of variable change in each design modification is almost fixed, so that the approach requires more design modifications. This is the reason why the fuzzy control is employed in the empirical approach as described later.

(b) In the mathematical approach, intermediate designs move around in the permissible design space, because the direction for design modification is determined based on a sensitivity analysis of a local region. In other words, it is expected that, if a problem is so complicated that a number of local minimum points exist in a design space, there is a high possibility such that an intermediate design would be trapped in a local minimum point. However, if starting from an appropriate initial design, the convergence would be very fast in the mathematical approach because both the direction and the magnitude of design modification are theoretically determined.

Design Based on Both Expert's Knowledge and Fuzzy Control

Figure 9 shows the similar convergence features of the design variables W and R when the values of ΔW and ΔR are dynamically controlled using the tuned fuzzy rules and membership functions. The comparison between both Figs. 6 and 9 clearly shows that the fuzzy control technique is very effective to improve the capability of the empirical approach in quantitative design modification, that is, to reduce the number of design modifications.

Design Window

Figures 10(a) and 10(b) show final designs, under slightly different loading conditions, obtained starting from various initial designs. The areas involving such final results roughly indicate the "Design Window" in which all the design criteria are satisfied.
Comparing these design windows, one may recognize degrees of feasibility of design.

CONCLUDING REMARKS

Various methodologies for design automation of nuclear structural components subjected to complicated loading conditions are described here. The most important issue of the present system is the best combination of knowledge engineering and the fuzzy control.

This system is now applying to a design of the fusion first wall of the ITER [10], and that of vessel components of a pool type FBR [11].

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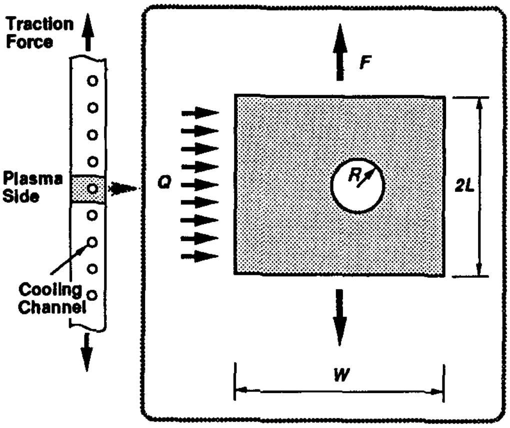


Q : Heat Flux (fixed through design process)
F : Traction Force (fixed through design process)

Fig.1 Two-Dimensional Model of the Fusion First Wall

Rule1

IF Maximum Temperature T > Melting Point T_m
Then $W \rightarrow W - \Delta W(T/T_m)$
$R \rightarrow R + \Delta R(T/T_m)$

Rule 2

IF Maximum $\bar{\sigma}$ > Yield Stress σ_{ys} and Tensile Stress is dominant
Then $W \rightarrow W + \Delta W(\bar{\sigma}/\sigma_{ys})$

Rule3

IF Maximum $\bar{\sigma}$ > Yield Stress σ_{ys} and Compressive Stress is dominant
Then $W \rightarrow W - \Delta W(\bar{\sigma}/\sigma_{ys})$
$R \rightarrow R + \Delta R(\bar{\sigma}/\sigma_{ys})$

ΔW, ΔR (> 0) : unit steps for design modification

Fig.2 Examples of Expert's Knowledge on Design Modification

Table 1 Constant Membership Functions of Labels of C^i

Label / Unit Steps	Small	Medium	Large
ΔW	0.4	0.6	1.2
ΔR	0.08	0.14	0.20

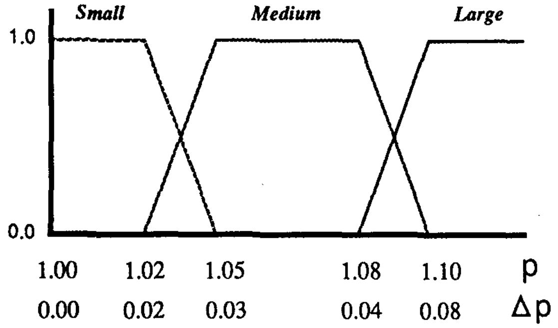


Fig.3 Membership Functions of Labels of $A^i(p)$ and $B^i(\Delta p)$

Table 2 Tuned Fuzzy Rules

Δp \ p	Small	Medium	Large
Small	Medium	Large	Large
Medium	Small	Medium	Large
Large	Small	Small	Medium

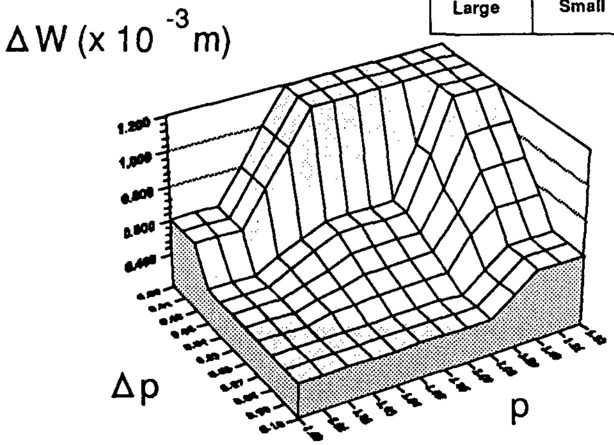


Fig.4 Distribution of ΔW Derived from Tuned Fuzzy Controller

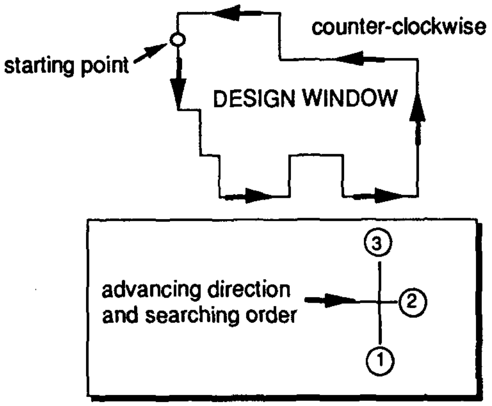


Fig. 5 Searching Algorithm of Design Window

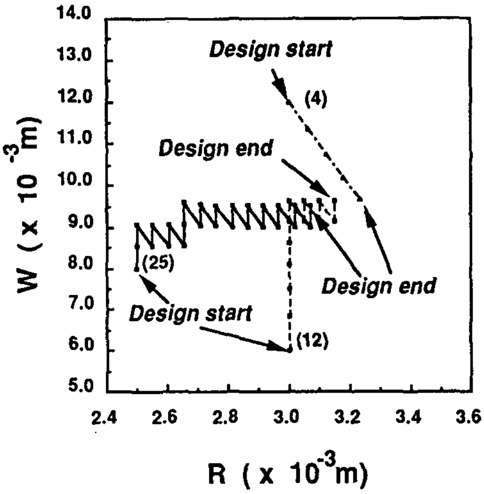
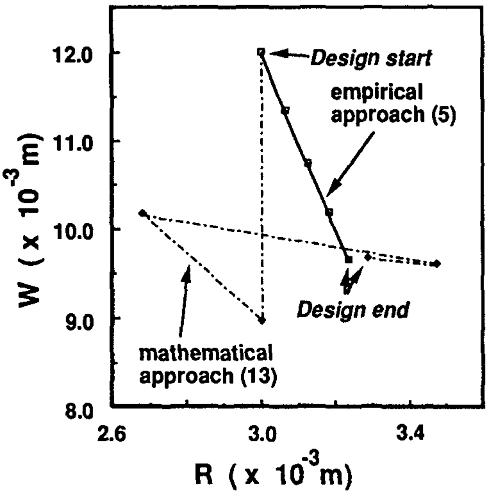
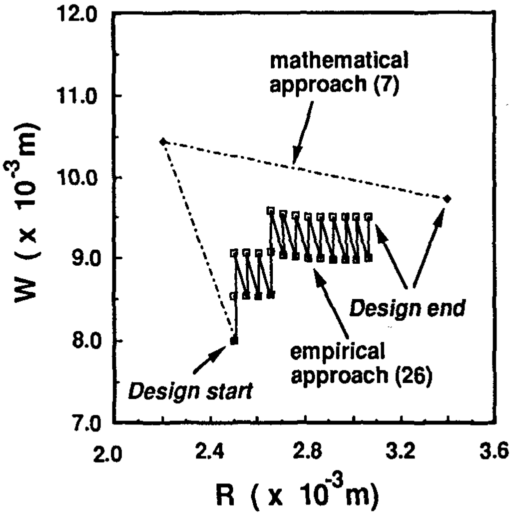


Fig.6 Convergence Features of Design Modification Process Based on Expert's Knowledge without Fuzzy Control



Traction Force F : 303.8N
Heat Flux Q : 0.1MW / m ^{2}

Fig. 7 Comparison of Convergence Features Between Empirical and Mathematical Approaches
(Wo = 0.012 m, Ro = 0.003 m)



Traction Force F : 303.8N
Heat Flux Q : 0.1MW / m ^{2}

Fig.8 Comparison of Convergence Processes Between Empirical and Mathematical Approaches
(Wo = 0.008 m, Ro = 0.0025 m)

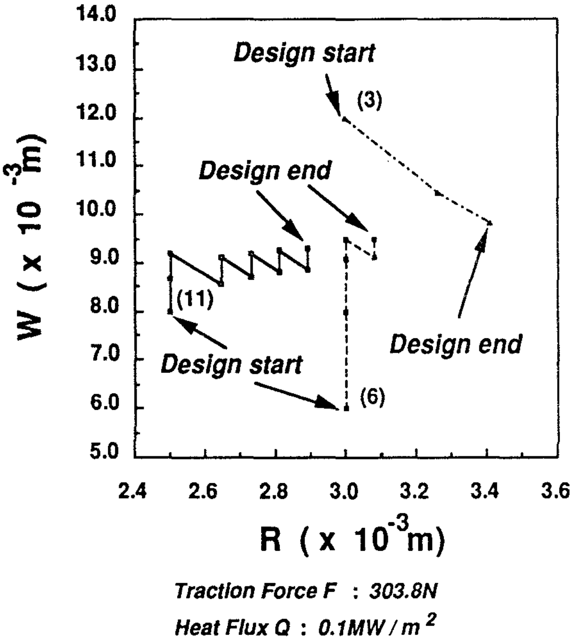


Fig. 9 Comvergence Processes Based on Empirical Approach with Fuzzy Control

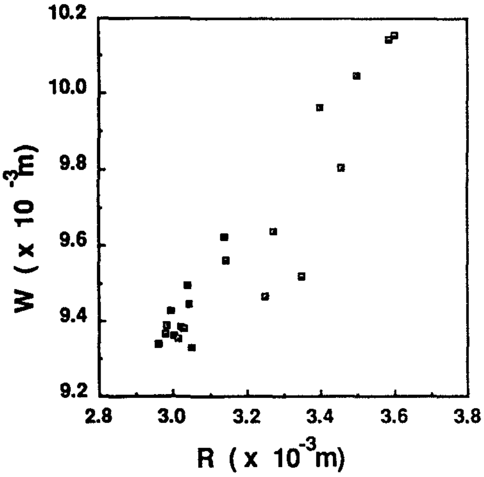


Fig. 10(a) Final Designs for F=303.8N and Q=0.1MW/m^2

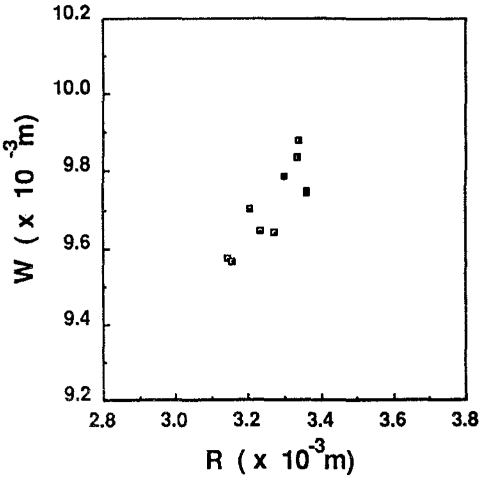


Fig. 10(b) Final Designs for F=313.6N and Q=0.1MW/m^2