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A STUDY OF DESIGN TRADE - OFFS USING A COMPUTER MODEL

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ABSTRACT: The paper is an extension of previous work undertaken by the author. It studies the interaction between the efficiency of the structural design and the cost of the structure used; and shows that future effort is best directed at producing a low cost structure of medium efficiency, but with the ability to withstand normal service wear. The paper then goes on to study the trade-off between aerodynamic drag and structure weight in selecting a length to diameter ratio for the hull, and to evaluate the implications of power plan type and fuel cost on the economics of the airship. As a final study the choice of lifting gas is considered.

Introduction

The development of technological research into vehicles such as large airships is in itself a complex problem. While working on "new" vehicles of this type, the design engineer is unable to fall back upon the benifits of past development and operational experience. This means that those responsible for directing the research effort have a problem in separating those areas of airship technology requiring extensive effort from those that can be considered of little or no importance.

In order to surmount this problem a cost model was developed at Cranfield, which allowed us to study the impact of varying key design parameters. It permitted sensitivity analysis to be undertaken in order to produce a simple ranking of problem areas.

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The results produced from the initial model were published in a previous paper (ref 1), a summary of which is given in table 1.

		% change in operating cost	
Parameter	Initial Assumption	-50%	+50%
Altitude	3,000 ft	-4%	+4%
L/D	6.	-22%	+22%
s.f.c	.47 lb/HP/hour	-4%	+7%
s.w	.5 lb/HP	-1%	+0%
min t_e	.06 inches	-47%	+70%
F	1.27	+108%	
Transmission efficiency	.85	-10%	+12%
Max Speed/ Cruise Speed	1.1	-5%*	+27%
Utilisation	5,000 hrs	+55%	-14%
Interest on Capital	10%	-15%	+17%
Vehicle life	10 years	+46%	-14%
Structure cost	£20,000/ton	-40%	+42%
Gas cost	£30/1000 ft^3	-4%	+3%
Power plant cost	£20/HP	$-\frac{1}{2}$%	$+\frac{1}{2}$%
Fuel cost	£20/ton	-3%	+5%
Crew wages	£140,000	-4%	+4%
Maintenance	4% first cost	-9%	+9%
Insurance	1% first cost	-3%	+2%

* Ratio taken as 1

TABLE 1

A SUMMARY OF THE SENSITIVITY ANALYSIS PRODUCED IN REF 1

Structure of the Model

The earlier model has now been improved in those areas shown to be critical in the previous study in order to provide greater clarity, with the hope that it will show where future research would be best directed. It must be stressed at this point that, although the philosophy of the model is based upon a conventional design process, the results produced here are intended to illustrate critical areas and Key variables rather than suggest an ideal design.

A simplified diagram of the model is shown in figure 1. The model is structured to allow all the individual variables to be varied independently or jointly, to cater for "trade-offs" to be studied. The input to the model, once it has been set-up, is the route capacity in tons/year, range in miles and the flight altitude in feet. The speed is then determined for the lowest operating cost within the constraints applied.

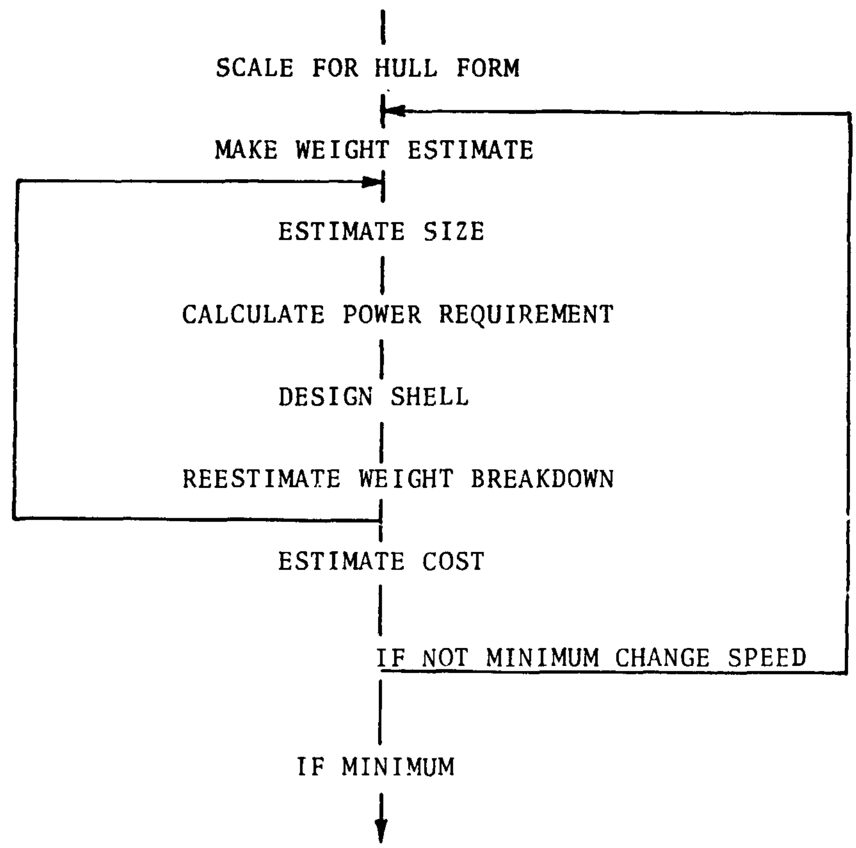

FIGURE 1 - MODEL STRUCTURE

Decision Criterion

The criterion chosen for the evaluation was that of minimum fare level for a set rate of return. This was chosen on the grounds that a freight system is purely commercial, social inputs being small, and the ultimate decision would therefore be on commercial possibilities.

Method of Analysis Used

As all parts of the system are as yet undefined, it was necessary to consider it in a mathematical form, representing each component as an input to the operating cost. The form of the mathematical model so produced was then optimised for minimum operating cost as follows:

A technology assessment techniqu· based upon Net Present Value

The net present value (NPV) of any project is given by

$$NPV = \sum_{\ell=1}^{\ell=n} \left[C_{f_\ell} \times (1 + r)^{-\ell} \right] - C_o$$

where

ℓ is a year in the projects life
n is the life of the project
C_f is the net cash flow
C_o is the first cost
r is the interest on capital

If the cash flow is assumed smooth (ie there are no discrete payments all are smoothed throughout the project's life then the equation can be simplified to give

$$NPV = C_f \left[\frac{1 - (1 + r)}{r} \right]^{-n} - C_o$$

Putting $C_f = C_r - C_c$

and $C_r = T \times F$

where

C_r is the cash revenue/year
C_c is the cash cost/year
T is the system capacity/year
and F is the charge per unit capacity/trip

gives

$$NPV = (T \times F - C_c) \left[\frac{1 - (1 + r)}{r} \right]^{-n} - C_o$$

as an optimum it can be taken that NPV = 0, allowing the relationship

$$F = \frac{1}{T}\left[\frac{C_o}{\left[\frac{1-(1+r)^{-n}}{r}\right]} + C_c\right]$$

This now provides a simple relationship between the cost of a system in terms of its total first cost (C_o), its operating cost (C_c) and its fare level (F). (This is easily modified for systems that have components with different book lives, but for simplicity in this example, they have all been assumed constant).

Evaluation of C_o and C_c

a) Considering the vehicle only;

The major first cost (C_o) components are

1) Structure Cost
2) Lifting Gas Cost
3) Power Plant Cost

and the major annual cash costs (C_c) were assumed to be

4) Fuel
5) Crew Pay
6) Repairs
7) Insurance

Table 1 shows how these may be described in terms of vehicle parameters

	Function Of	Major Parameters
Structure Cost	Weight of structure	W, u
Lift Gas Cost	airship volume	V
Power Plant Cost	installed power	S, u
Fuel Cost	fuel used	S, u
Crew Pay	assumed constant	
Repairs }	assumed to be a	} C_o
Insurance }	percentage of first cost	

where W = size of airship
u = speed of airship
V = volume of airship = f(W)
S = surface area of airship = f(W)

Hence all components of the vehicle are some function, in this simple case, of vehicle size and speed.

Analysis of Vehicle only

Using this theory and inserting the necessary engineering relationships, it was possible to derive an iterative technique (fig 1) that gave a solution for the optimum design where

$$\frac{dF}{du} = 0$$

The Datum Situation

It is impossible in a paper like this to cover the full range of options available. For this reason a single specification has to be chosen to act as the datum situation and, unless otherwise stated, the assumptions should be taken as given in table 2.

The following is a list of the basic assumptions used in the assessment, together with the justification for these assumptions.

Assumption	Value
Tons/year	150,000
Range	1000 miles
Life	10 years
Operational altitude	5,000 ft
Length/diameter ratio	6.
Specific fuel consumption	.47 lb/hp/hr
Specific weight of power plant	.5 lb/hp
Minimum practical value of t_e	.06"
Reserve fuel	33%
Power plant cost	£20/HP
Fuel cost	£100/ton
Crew wages	£140,000
Maintenance cost	4% first cost
Insurance cost	1% first cost
Interest on capital	20%

TABLE 2 ASSUMPTIONS USED IN STUDY

STRUCTURE

As a first step in the study a totally unconstrained analysis was undertaken. Structures of various efficiencies and ranges of costs were studied, the results of which are shown in figure 2. The structural efficiency is reflected by the equivalent shell thickness

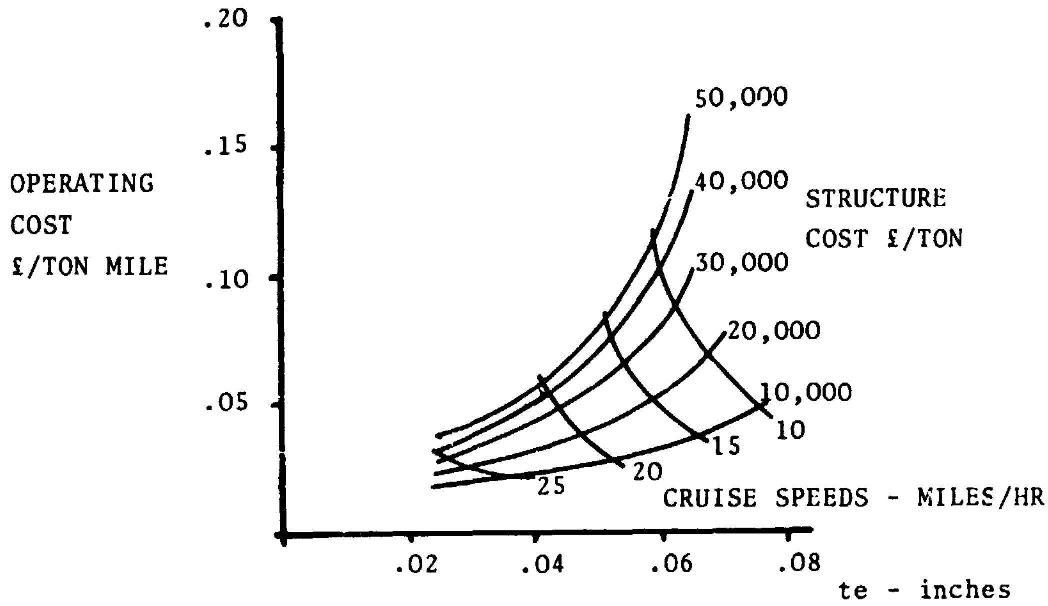

FIGURE 2 UNCONSTRAINED SOLUTION

which is given by

$$te = \frac{\text{Total Structure Weight} \times 12}{\text{Density of Duraluminium} \times \text{Surface Area}}$$

te is in inches and other units in pounds and feet

From figure 2 it can be seen that in the unconstrained situation the results produced are trivial. The low equivalent thickness would not have any resistance to hail impact or bird strikes of the lowest magnitude. Those shells that do have higher equivalent thicknesses are discounted by the low optimum cruise speeds associated with them, which are incapable of providing an acceptable level of aerodynamic stability.

The study was repeated with the solutions constrained to a minimum speed of 50 miles/hour and a minimum equivalent shell thickness of .06 inches. This resulted in a set of solutions all of which lie along one of the applied constraints. The results of this study are shown in figure 3.

Analysis of figure 3 shows a number of designs all above the .06 inch constraint, but with speeds of 50 miles/hour. When these solutions were studied in greater depth the structural efficiencies which related to the designs were found to be so low as to make them trivial solutions to the problem. This implies therefore that all the useful solutions lie on the minimum equivalent thickness constraint had optimum speeds increasing from 50 miles/hour to 70 miles/hour. The speed increased linearly as the structure was used more efficiently from 50 miles/hour to some constant value, dependent upon the structure cost assumed, the higher the structure cost the higher the

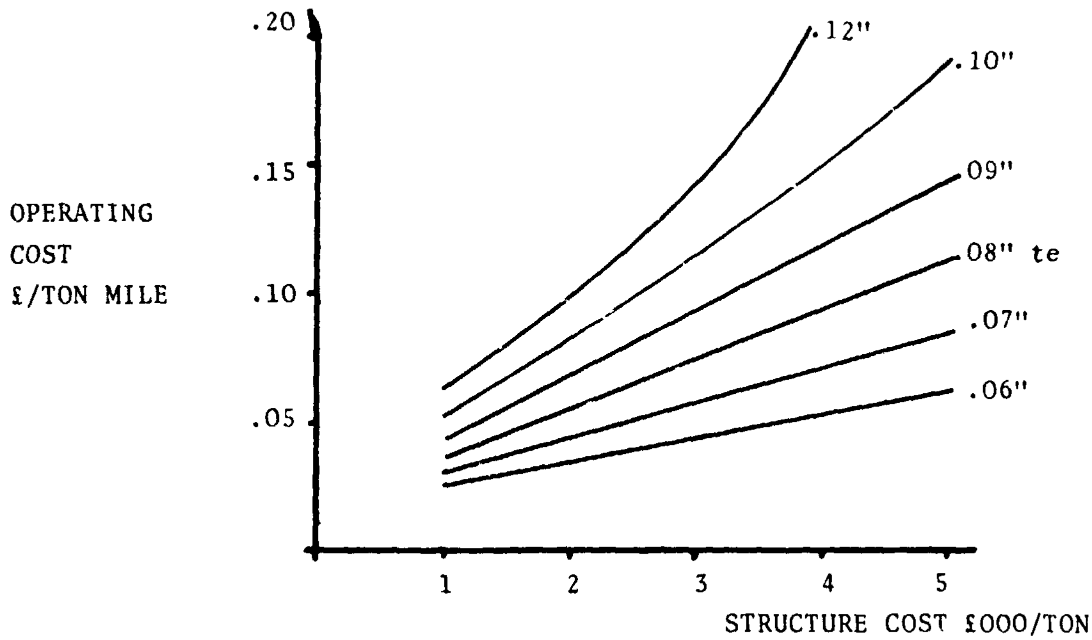

FIGURE 3 CONSTRAINED SOLUTION

the steady state value of the optimum speed. The reason for this is that for cost effectivness the more expensive structures have to be used more efficiently. Hence, to off set the increased cost of the structure the design becomes smaller and faster, as structure cost increases. Figure 4 shows the value of these steady state results for optimum cruise speed.

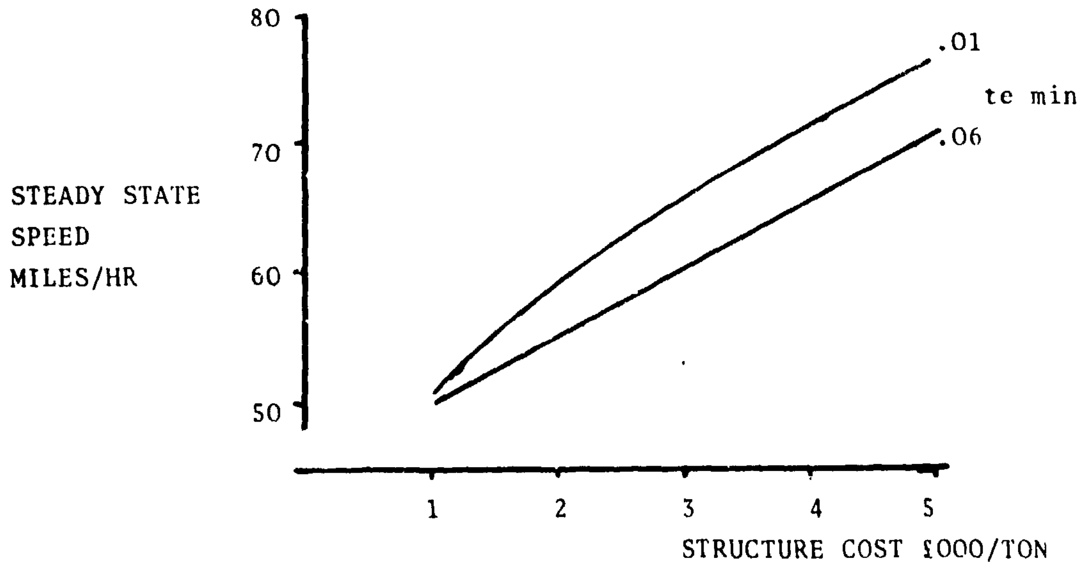

FIGURE 4 STEADY STATE SPEEDS

The Minimum Equivalent Thickness Constraint

From the results already produced, it becomes apparent that the equivalent thickness constraint is a key area. The production of a light weight design which is also resilient enough to withstand rigorous service conditions is difficult. Experience in structures of this type is completely lacking and the possibility of achieving a minimum value of .06" is unknown. A value of .1" has also been considered, therefore, and the results are included in figures 3 and 4.

Implications of the Structure Study

This study illustrates the unique problems of designing airship structures. It shows quite clearly that high efficiency structures have no major role to play in the shell design of conventional airships, and the need is for practical structures, the major constraint being the ability of the structure to withstand general in-service knocks. The future lies, therefore, in producing low cost structures of medium efficiency, weight being a second order problem.

This lies in contradiction to present aircraft design philosophy, where weight saving is a major criterion, and the use of materials such as titanium and carbon fibre reinforced structures is commonplace. In designing an airship shell there is a need for low density structures, not to reduce weight but to allow greater thicknesses to be used in order to increase resilience to damage. At the same time, however, costs should be low whilst strength is a problem of the second order. Structures that provide possible solutions to this requirement are glass fibre structures or foam supported structures. Thought must also be directed towards varying the design of the conventional rigid airship in order to introduce some of the requirements already outlined.

The same problems are also relevant to the production of the hull. The structure should be robust enough to allow simple handling during construction, since any special requirements will only increase production costs. This could lead to a situation where even the simplest of structures could be highly expensive due to high handling cost.

In conclusion to this section, it would seem that, with the relativly small variation in operating cost for changes in equivalent thickness at the low structure costs, as shown in figure 3, a weight penalty could be accepted provided the use of heavier structures assist in reducing production costs. With this in mind, it is recommended that future research should be directed at producing a structure with a low equivalent thickness but with the major constraints of being able to be easily and cheaply produced and to undergo normal handling in service and during production.

LENGTH/DIAMETER RATIO

Closely related to the previous problem is the choice of length/diameter ratio of the hull. The selection of the optimum value requires a trade-off between the structure weight and the skin friction drag.

Drag

In order to relate the drag to the length/diameter ratio the following drag relationship was used:

$$\text{Drag} = q\, S_D\, C_D$$

where q is the dynamic pressure

S_D is the wetted drag area

and $C_D = \frac{.03}{R_E^{1/7}} \left[1 + \frac{1.5}{\left(\frac{l}{d}\right)^{3/2}} + \frac{7}{\left(\frac{l}{d}\right)^{3}} \right]$

(Source - Ref 2)

The results of this study are shown in figure 5.

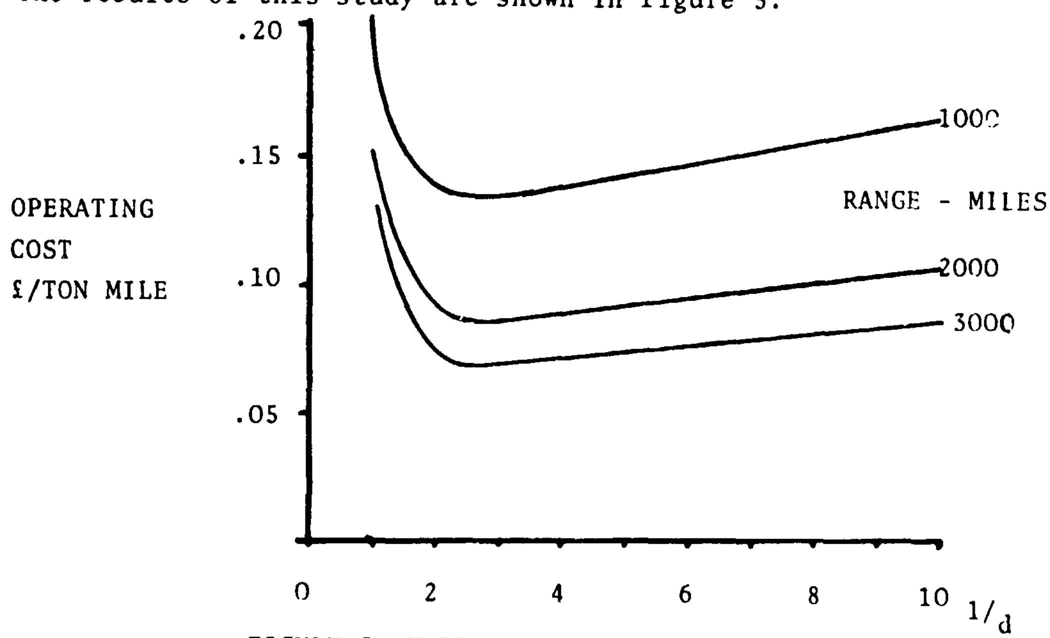

FIGURE 5 VARIATION OF LENGTH/DIAMETER

From this it can be seen that the optimum ratio of length to diameter is 2.5, and that this value is independent of range. This optimal value is based on a trade-off of fuel cost and structure cost and gives no consideration to stability. In selecting the final value it will be necessary to consider the requirements of directional stability, which is likely to increase the value.

FUEL AND POWER PLANT

Although it was shown previously (Ref 1) that the choice of power plant and the cost of the fuel were not critical areas in terms of airship economics, it was decided that, with the rapid increase in fuel prices that has occured, the problem should be reassessed.

Fuel Cost

In order to study the effects of fuel cost on cost effectiveness, two designs were undertaken to fulfill the same requirements. Each design had a different fuel cost; the first £20/TON, a typical value for two years ago, and the second £100/TON, a value representative of present high fuel costs. The major characteristics of the designs are given in table 3.

FUEL COST	£20/TON	£100/TON
OPTIMUM MAX LIFT	1170 TONS	1490 TONS
OPTIMUM CRUISE SPEED	77 MILES/HR	51 MILES/HR
OPERATING COST	£.026/TON MILE	£.03/TON MILE

TABLE 3 EFFECT OF FUEL COST

The results illustrate how rapid changes in costs can modify past results. Fuel cost has increased from a minor variable to a major variable, and has caused a marked decrease in the optimum speed.

Power Plant Choice

The importance of the fuel cost is also reflected in a study of power plant characteristics. The importance of specific fuel consumption is clearly seen from figure 6, the specific weight of the power plant having very little importance by comparison, (values of specific weight from .5 to 5 fall on the same curve).

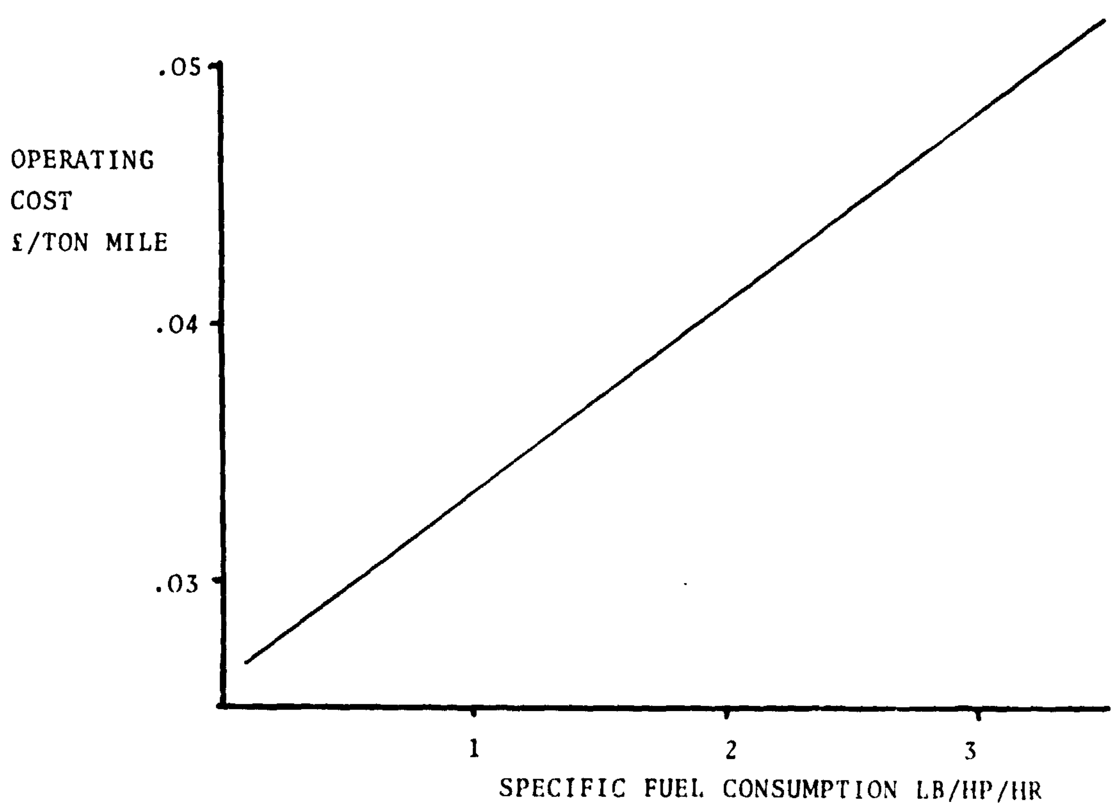

FIGURE 6 EFFECT OF POWER PLANT

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1. Coughlin S., An Appraisal of the Rigid Airship in the UK Freight Market, Cranfield CTS Report 3, Cranfield Institute of Technology, England. (March 1973).