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# RATIONAL METHODS FOR ENGINE RATING

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## INTRODUCTION

The purpose of rating an engine is to give a prospective user a complete picture of the capabilities of the engine in relation to the system in which it is expected to operate. To describe the interaction of the engine and the system, a set of standard measurable qualities peculiar to each engine and of pertenance to the rest of the system is required. These qualities, presently in use as standards, are well known and are stated in different manners by various manufacturers and users, but fall eventually into relationships between power, engine speed (RPM), fuel consumption, displacement, and cylinder pressure. These qualities, when used with principles of engineering, are sufficient to insure that the system in which the engine is to operate is mechanically sound. There is, however, another consideration that an engineer should make when studying the application of a power system. This is a judgement of how long and how effectively the system will operate before expensive repairs or replacements become necessary. This brings to mind the problem of engine life and how it varies with the individual application. It seems only reasonable that some sort of data should be furnished by the manufacturer in addition to the other rating information, which will facilitate the engineer's selection of a proper engine to perform a given task.

There are myriads of possibilities to choose from when one tries to pick a criterion for judging engine life. Many sources say that crankshaft bearing life is the controlling factor; others claim that wrist pin bearings will eventually determine the life; while still others believe in cylinder component distress as the limiting variable.

To a large extent, each point of view is correct, depending upon the peculiarities of the particular engine in question. However, in the end most involved parties will agree that if the individual components of the engine are properly designed and installed, the part which will experience the earliest natural failure (due to wear) is the cylinder kit. This seems reasonable from the standpoint that the highest temperatures and pressures and the least amount of lubricating oil are concentrated in this single area. In addition, whenever a piece does fail in the region of the piston cylinder, the reapir necessitated is usually extensive and expensive.

For the purpose of this study, failure or extreme wear of the cylinder components to the point where they must be replaced will serve as the basis for one engine life. The procedures developed in subsequent pages are not peculiar to this basis, however, but may be applied to any terminal wear or failure criterion which the user wishes to select.

Having decided the matter of how to designate one engine life, the problem of determining an acceptable length for that life naturally arises. The first point to make clear when talking about engine life is that there are an infinite number of possible lengths of life which any engine can experience, barring abnormal failures. Wear in an engine, as in any other machine, is a function of the number of cycles it is expected to endure and the load which it experiences during each of these cycles, assuming, of course, that maintenance is properly performed at all times. Obviously, then, if the loading per cycle is decreased, the number of possible operating cycles should increase, thus yielding a longer life span. On the other hand, if the load per cycle is increased, the number of possible operating cycles should decrease proportionally, thereby shortening the total life of the engine. In the mind's eye, one can stretch this idea to the point at which an engine should exist that will carry an infinite load but will last less than one cycle; or, conversely, will carry no load and last forever. There is little doubt of the facetiousness of these extreme cases, but they do serve the purpose of domonstrating the existence of a range of engine operating conditions rather than the usual one, two, or three points of operation specified in most manufacturers published ratings.*

Herein lies the principal shortcoming of the existing rating system. Instead of selling an engine which costs one price but can furnish its user with a continuum of possible operating characteristics ranging from a great deal of power for a short period of time to a very small amount of power for an extended period of time, the manufacturer truncates his market by vending an engine which he states will perform at a given power output or two (or less) for a minimum specified (though not usually publically specified) period of time. Since the real nature of the engine is more flexible than this, there should be a method for exploiting this versitility in a manner which will be beneficial to both the manufacturer and the user.

In order to find such a method one must have a basis for judgement. There are several measures of merit which might be called upon to provide a basis for determining the optimum power output and length fo engine life for a given application. For instance, in a military setting the controlling factor could be the average life of the powered system in combat. In an emergency back up system the most important factor might be dependability over extended periods of time. The most common measure

* as upper limits

of merit, however, is economic feasibility. The problem of being faced with the choice of either a system which will increase income by operating at a high power output level, but which will also cost more to maintain by virtue of the fact that it will have to be rebuilt more often, or of a system which will run for long periods of time without incurring failure or downtime, but which will also reduce income for the same initial investment, is a complex one indeed. This problem is not a new one and has been investigated and welldefined in other areas where appropriate data is available. The remainder of this paper will be devoted to:

1. defining what type of information is necessary to provide a basis for determining the proper life-power output ratio to optimize the profit of the power system by using existing theory
2. presenting data obtained from engine manufacturers and users which is pertinent to making such a determination.

## PART I ENGINE RATINGS AND ECONOMICS

It is proposed that, given a ship operating in a reasonably well-defined economic climate and given a power plant which can be operated at a wide variety of power outputs to be used for that ship's propulsion, the output rating of that power plant should be determinable by an economic study involving six basic factors:

1. Engine operating costs as a function of power output.
2. Engine maintenance costs as a function of power output.
3. Initial engine costs as a function of power output.
4. Engine life (time between major overhauls) as a function of power output.
5. Earning power of ship as a function of engine power output.
6. Less well-defined measures of merit (predictability of failure, safety, parts unity, etc.).

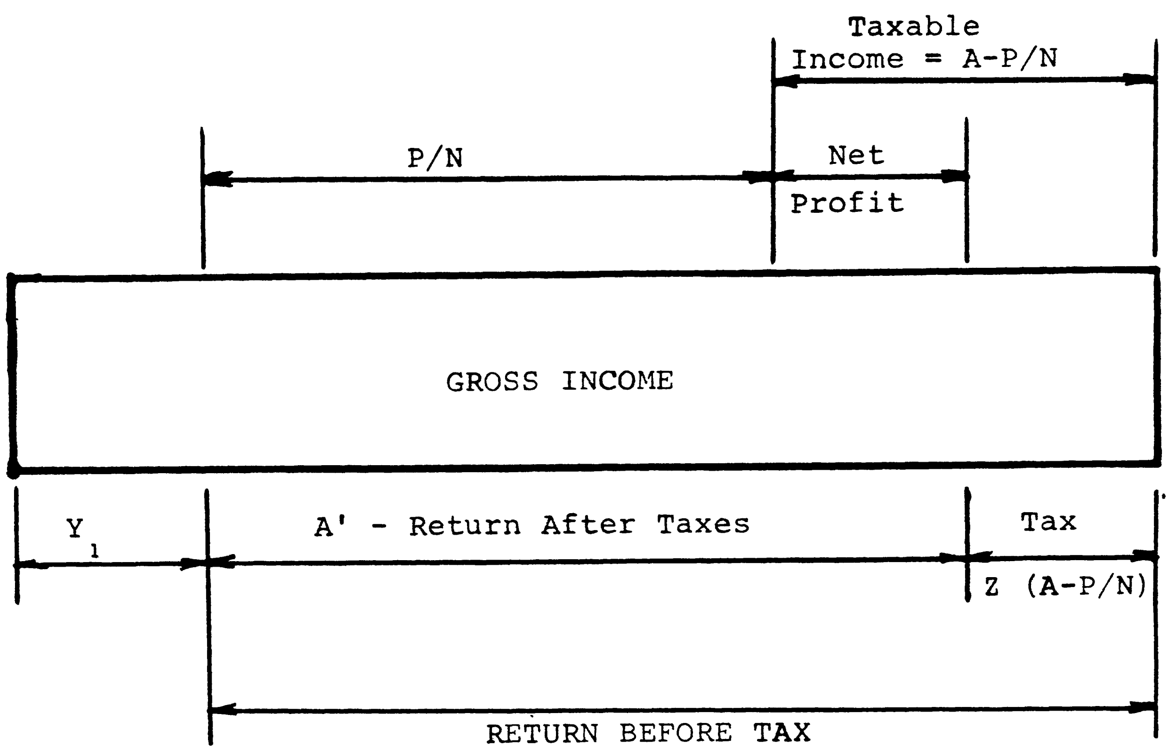
Once the above factors are known, a dererministic economic study becomes a distinct possibility. The factors may be combined to give an infinite set of economic operational characteristics for any given ship in any given economic climate. From the set of operational characteristics, a curve of characteristics may be plotted to indicate an operation point which optimizes return on investment.

To demonstrate this argument a little more clearly, suppose that in addition to the things which are usually known about the economics of the marine system (cost of building the ship, ship maintenance, ship operating costs, labor expenses, etc.), the above six factors are known. A cash flow diagram (Reference 1) for a years operation should be easy to construct might be similar to that shown in Figure 1. The three basic inputs of Figure 1 are directly affected by the first three engine output characteristics in the following way:

1. P, the capital investment, is affected by the initial cost of the engine #1 (usually about 20% of the total cost of the ship.).
2. N, the depreciation life of the marine system, will be affected by the life of the power system.
3. Y, the operating costs of the marine system, will be affected by the operating and maintenance costs of the power system.
4. Gross income is affected by factor #5.

Keeping in mind all of the time that each of the three characteristics mentioned is directly related to the way the engine is rated, it becomes quite clear that the annual cash flow is, in turn, closely affected by engine output ratings. It should be noticed that the fourth factor (engine life vs. output rating) does not enter, in its entirety, into the annual cashflow diagram unlses rebuild happens to occur every year. Since this is not the usual case and since the economic life of the ship is far greater than one year long, it is necessary to extend an economic study to cover the entire depreciable life of the system. Each year of the study would be representable by a figure similar to Figure 1. Each of these, in turn, would be reducible to two indicators such as "after tax income" or "annual cost." These latter figures may be then combined to yield an over-all economic picture such as that in Figure 2. With Figure 2 it becomes possible to make full use of the fourth relationship of engine rating. In the general diagram the engine rebuild period is every three years. By changing the engine's output rating this cost might occur as often

BAR CHART REPRESENTATION
OF A TYPICAL YEAR'S INCOME AND EXPENDITURES




where:

$Y_1$ is affected by factors #1, #2, and possibly by #4

P is affected by factor #3

N is the economic life of the ship system

Gross Income is affected by #5

Figure I

(Reference 1)

CASH FLOW DIAGRAM FOR A SHIP OPERATING WITH A THREE YEAR ENGINE OVERHAUL.
ALL OTHER INCOME & EXPENSES DISTRIBUTED UNIFORMLY

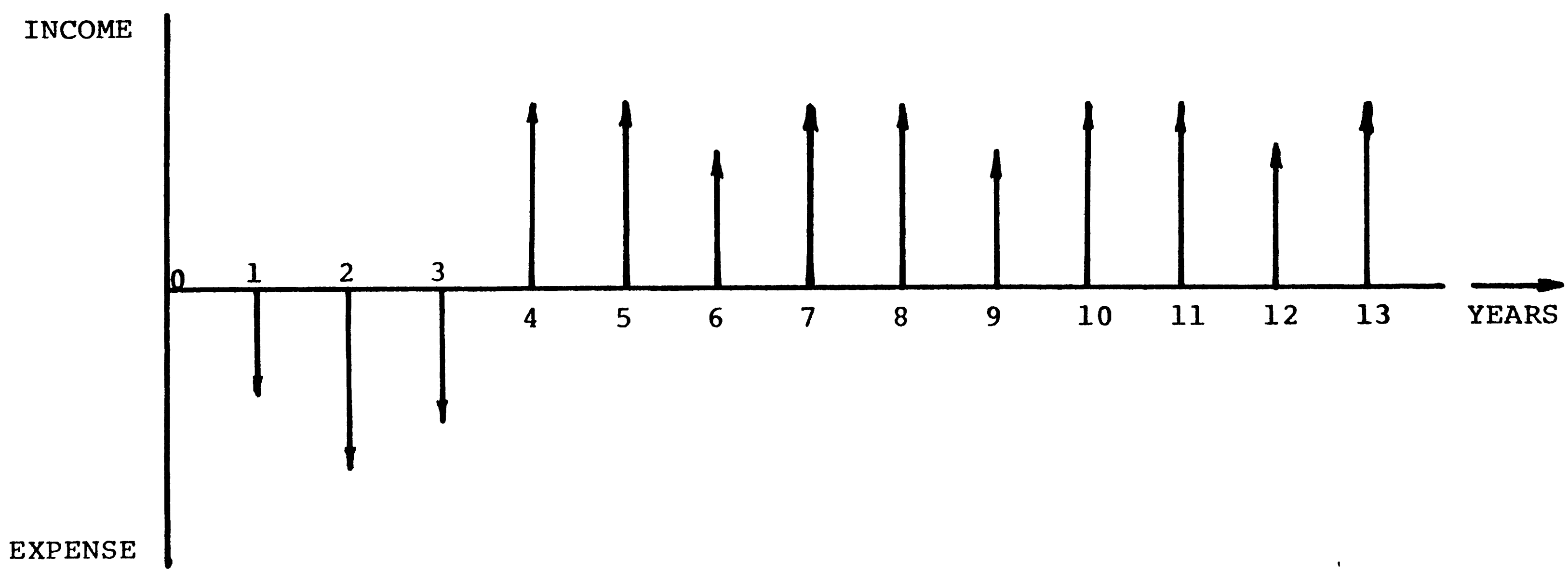



Figure 2
(Reference 1)

as every year or as seldom as every 6 or 7 years. At first glance it looks as if the only logical course of action is to make the frequency of rebuild as long as possible since this would decrease the total number of rebuilds and the total amount of downtime during the lifetime of the ship. However, it must be remembered that each time the rebuild interval is increased the annual income is decreased by reason of the ship's speed being decreased due to a necessary reduction in output power (factors #4 and #5). It also should be remembered that the initial cost of the engine and the economic life of the machinery can have an effect on the structure of the cash flow diagram as shown in Figure 1.

After Figure 2 has been described for several possible engine ratings and operating conditions, any one of several methods of economic reduction may be used to compare the various possible conditions (DCF, NPV, delta DCF, RFR, cost of service (Reference 1)) and once these have been employed their respective results may be plotted to give the investigator a method for determining the optimum engine rating to be used in his marine systems operation.

## PART II ENGINE RATINGS AND COSTS

With the theories stated in Part I as the premise, an investigation was initiated to determine the six relationships stated as being necessary to perform a meaningful economic analysis of engine rating. Because of the size of the endeavor and the complexity of the subject, the results of the investigation were necessarily limited. Therefore, while the data obtained and here presented is felt to be reliable and valid, it should be reviewed with the thought in mind that it is preliminary to more extensive research and is somewhat shallow in its coverage of the field describable as Diesel Engines.

A total of ten businesses were contacted to provide three types of information:

A. Credibility of the theories involved.

B. Present methods being imployed to determine what engine rating and ship speed should be utilized in a given operation.

C. The six engine output rating relationships.

A list to firms visited in the course of gathering data, including contributors and non-contributors, is as follows:

Detroit Diesel

Electromotive Diesel

Fairbanks Morse

Caterpillar

Cummins

Valley Lines

Ohio River Company

Ashland Oil

Grafton Boat Works

St. Louis Ship

A synopsis of the results is as follows:

A. Credibility

Of the ten firms and eighteen individuals interviewed, only two felt that there was definitely no need or use for additional engine rating information. However, only two individuals were actively attempting to alter the existing system or searching for a better one. The remainder felt that while there probably was a better method for doing things, the present one was doing an adequate job and would be too expensive to augment.

B. Present Methods of Determining Ship Speed and Engine Rating

Ship Speed: Some disagreement seemed to exist among builders and owners as to who specifies ship speed (and thereby governs one of its economic characteristics), the owner-operator or the builder-designer. The builders were of the unanimous opinion that it was the owners who made such a specification, while the owners were of the opinion that it was on the builder-designers recommendation that he made a speed selection. Both, however, were in complete agreement about the fact that there was an undesirably high amount of guesswork involved in specifying ship speed.

Engine Power Rating: The methods employed by engine manufacturers for setting an upper limit on power output and the reasons lying behind selecting the method were consistent over the group interviewed. The principle method employed in each case was the use of intrinsic judgement on the part of the staff level engineering personnel. This judgement was motivated by the idea of protecting the outflow of cash due to waranty claims. It was felt by those involved in power rating that the figures listed as maximums for power output reflected an engine life which was considered by the user to be good enough to require no waranty by the manufacturer at the time of overhaul. Any life that fell short of this, of course, would have to be covered by reimbursement. When asked how they knew that this maximum figure was a true representation of an acceptible life on the part of the owner-operator, it was stated that over past years of operation the life given by this maximum figure was the point at which the owner-operator ceased to request rebuild aid from teh manufacturer due to premature failure. In short, this life was what the market would bear and not necessarily the optimum life for the particular application. It was also noted that none of the engine manufacturers interviewed had stated in their waranty what length of life could be expected from the maximum rating. When questioned as to how they accepted or denied repair requests, it was stated that this also was a judgement to be made at the staff level, usually governed by the past or future business relationship with the individual customer.

C. The Six Engine Output Rating Relationships

1. Operating Costs at Various Output Ratings

There are two basic factors affecting this relationship; fuel consumption and lube oil consumption. Of those interviewed, it was generally agreed that the oil consumption over the reasonable range of engine ratings to be considered would rise linearly with engine output. Published data on oil consumption is available at request from most engine manufacturers. From published data reviewed, it was noted that the oil consumption is directly relatable to engine RPM for a given cylinder displacement, regardless of power output rating, by the formula:

% rise in oil consumption = % rise in RPM.

2. Maintenance Costs vs. Output Ratings

No hard and fast publishable data was available from any of the sources contacted, but the general feeling among both the engine manufacturers and the field maintenance personnel was that the maintenance costs would rise linearly at a 1 to 1 ratio with the engine's output ratings. Major considerations for making such a judgement were:

1. Increased failure of minor associated parts.
2. More frequent changing of oil, fuel, and air filters.
3. More constant necessary personal attention to minor repairs (tightening loose bolts, etc.) because of engine sensitivity to minor failures.
4. More constant personal attention to watching for and predicting major failures, since major failures would tend to be more costly as the engine ratings increased.
5. Earlier breakdown of lubricating oil.

When questioned about the fifth factor, manufacturers felt that the premature breakdown of lubricating oil would accur but would not fall outside their normally specified period of oil renewal for a reasonable range of output ratings.

3. Initial Costs vs. Engine Output Ratings

It was the original intention, when the study began, to leave this realm of interest for further investigation since accessability to pricing data is reasonably good. However, some rough figures have been obtained for estimating purposes. The data represents a cross-section of engine manufacturers and is divided into three basic

| ENGINE SIZE | COST PER HORSEPOWER FOR FAN TO FLYWHEEL MODELS | COST OF ACCESSORIES TO CONVERT TO MARINE CONFIGURATION |
|---|---|---|
| Small (less than 500 HP) | 16-19 $/HP | 4-13 $/HP |
| Medium (greater than 500 HP but less than 1500 HP) | 21-27 $/HP | Estimated at 15 $/HP (usually a bid price) |
| Large (greater than 1500 HP but less than 4000 HP) | 50-60 $/HP | Not available (done by bid) |

categories. The first two categories represent figures applicable to small and medium displacement engines and each contains two sets of data; first, a $/HP figure for the standard bare engine; second, a $/HP figure for adapting the bare engine to marine use (heat exchangers, raw water system, etc.). The third category lists approximate $/HP figures for large displacement engines. It should be mentioned at this point that no hard and fast pricing data was available for the large displacement engines, as it was for the small and medium categories, since most sales work in this area is done by bid only. The figures given represent ballpark estimates made by several sales personnel interviewed.

4, Output Rating vs. Engine Life

Some disagreement exists throughout the industry as to the best and most meaningful characteristics to be used when describing the duress which an engine is experiencing. The indicators most frequently recognized as being the most significant were BMEP, HP per CU. IN. DISPL., Fuel Consumption, and Firing Pressure. For the purpose of this paper, fuel consumption in gallons per hour per cubicinch displacement was chosen for usage because of its universal availability. The curve represented in Figure 4 was contributed by one information source. The individual data points were contributed by three additional sources from service records and personal experience. In addition to these four information sources, six more companies in the marine field were visited in search of corroborative data. These companies either did not have the requested information or refused to part with it on the grounds that it was a trade secret. The credibility of the relationship depicted in Figure 4, however, is not necessarily reduced by the limited data sources. The curve was formed by a review of actual field data which was obtained over several years of service operation of engines with approximately 100 cubic inches displacement per cylinder. Points A and E were results of field service data accumulated by an owner-operator for engine displacements of approximately 300 cubic inches per cylinder (point E) and 700 cubic inches displacement per cylinder (point A).

Point B is a personal judgement of the current field conditions, by a staff level engineer of a major engine manufacturer, for engines having a cylinder displacement of about 1,000 cubic inches.

Points C and D are the net results of field data accumulated over several years of operation of engines having the same cylinder displacement (approximately 1,000 cubic inches) but having different fuel rates and power outputs. Engines C were non-turbocharged and Engines D were turbocharged.

5. Economic Climate of Ship Operation

As stated earlier, this phase of the economic study was considered by those in a position to reveal it to be a matter of trade secret. This is academic for those actively participating in the industrial theater, since each business would have this information available to it. However, for present purposes the lack of this information prevents any sort of meaningful sample calculation from being made.

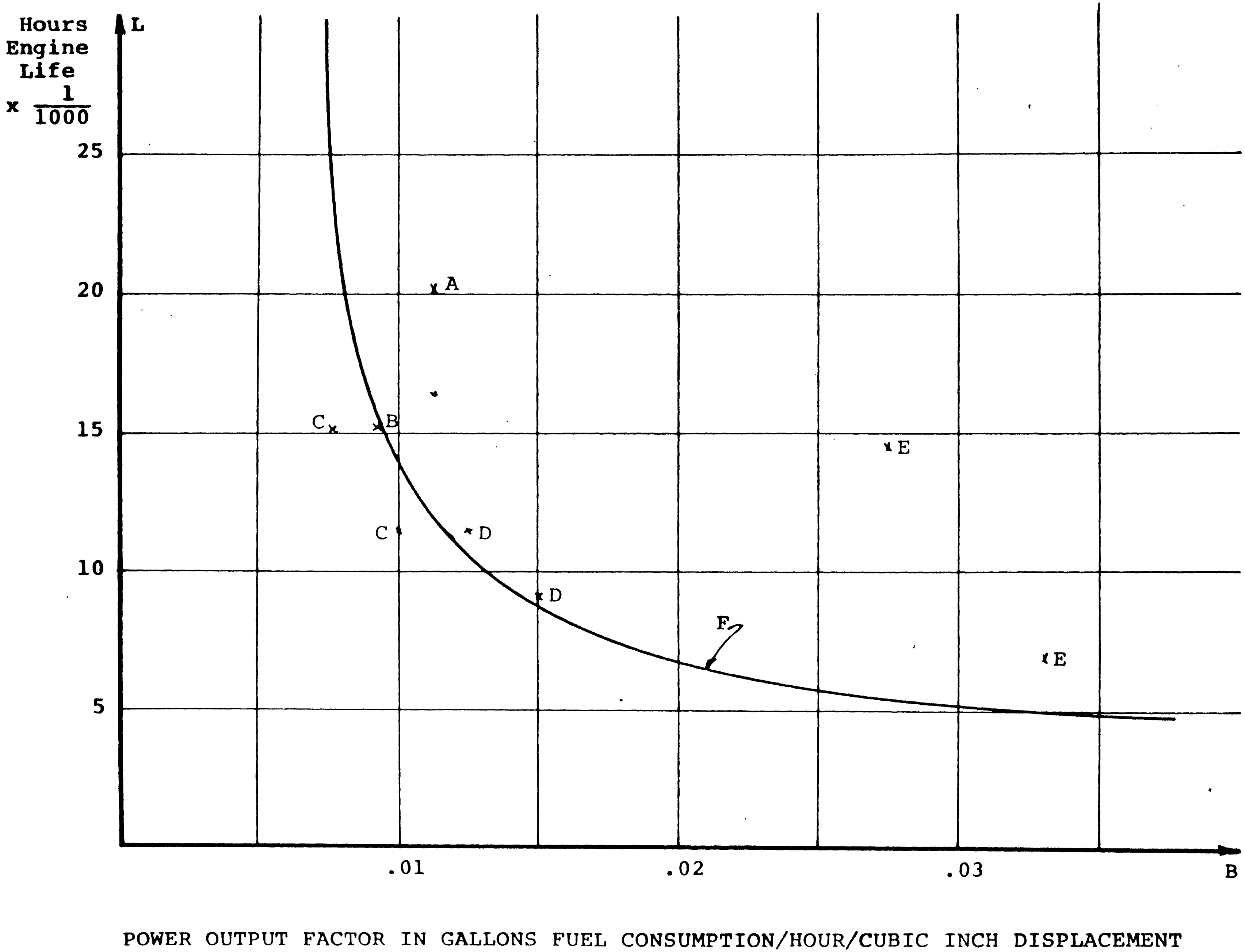

Hours
Engine
Life
x 1/1000
L
25
20
15
10
5
A
B
C
C
D
D
E
E
F
.01
.02
.03
B
POWER OUTPUT FACTOR IN GALLONS FUEL CONSUMPTION/HOUR/CUBIC INCH DISPLACEMENT

Figure 4

# REFERENCE LIST

[1] Benford, Harry, Measures of Merit for Ship Design, University of Michigan, February 1968.