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HAS THE AVERCH-JOHNSON EFFECT BEEN EMPIRICALLY VERIFIED?

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SOCIAL SCIENCE WORKING PAPER 132

Revised October 1976

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I. INTRODUCTION

Recently three studies (1), (2), (3) have been published which claim to confirm the existence of the Averch-Johnson (4) effect in the electric power industry. Each of these papers uses a distinctly different methodology. This paper examines the general problem of what the nature of the A-J effect might be and what sort of data would be required in order to confirm its presence. The other studies are then critically examined on the basis of this discussion. A modification of the method used in one previous study is then used to test the A-J hypothesis, and no evidence of capital bias is found. The principal conclusion of this study is that if the A-J effect is significant in distorting input choices in the electric utility industry, very different sorts of data than those that have been used thus far are going to be required in order to verify its presence. Mechanical usage of gross input and output numbers, without understanding of the technological processes involved, leads only to erroneous conclusions.

II. ELECTRICITY AND THE A-J EFFECT

The Averch-Johnson model is a simple one, and before any tests of its empirical validity are possible it is necessary to reconcile the realities of the particular industry with the assumptions of the model. Courville (1) goes to some pains to do this, Spann (2) totally neglects the problem, and Petersen (3) relies on the econometric literature which has attempted to measure production and cost functions for the industry. This section will show that, apart from Courville who makes some reasonable points (but misses the crucial ones), these papers fail to relate the models they use to the particular features of the electric power industry. This is surprising since both Courville and Petersen cite Galatin (5) whose analysis of the technology of the industry is sound.

The single most important objection to these studies is that they neglect to take into account one of the basic assumptions which is made when production (or cost) functions are used to represent technological possibilities. This is the assumption that engineering suboptimizations have taken place so that the function gives the maximum output attainable with any given inputs. The use of annual energy as the output and either total plant cost or capacity as the measure of capital contradicts this assumption. This is because there are other active constraints that must be considered. Failure to take account of them invalidates any further optimization procedures using the production function, such as the derivation of the A-J hypothesis.

Regulatory commissions require that demand always be met. Since the time-varying demand generally cannot be met by changes in inventory, this requirement amounts to a constraint specifying the time-path of energy production. Thus, two plants may supply the same annual energy but, if they are faced with different time-paths of demand, they will generally choose different input combinations, even if they face the same prices. Fortunately, it is possible to identify the way in which the attributes of capital equipment contribute to energy production and satisfaction of the constraint. The use of either total cost or capacity as the measure of capital employed completely obscures this.

A useful way of viewing this problem is to consider production through time as a multiproduct operation. The first product is annual energy, the output of which is determined by price. The second product is the continuity of instantaneous power supply, the output of which is determined by regulatory decree. These two products have joint costs, but they are not pure joint products. While both are produced using the same capital inputs, the different attributes of the capital that each requires are distinguishable. To fashion a production function for annual energy output simply from the three factors of production without considering the constraints (which are not necessarily the same for each utility) that are operating on the other output is clearly wrong. Using a single measure of the capital involved, without a clear description of how it contributes to the output being considered, leads to erroneous results.

To illuminate this matter a brief description of the engineering processes will be given and the points at which choices are made that have an economic significance will be pointed out. The generation of electricity by the combustion of fossil fuels is a well-understood technology. The details of the technology will be avoided and the discussion limited to how usefully to describe the technological possibilities.

The equipment used can be characterized by two main attributes:

1. The maximum power output it will produce without risk of catastrophic failure (e.g., the point at which the short-run cost curve becomes vertical); i.e., the capacity.
2. The efficiency of its operation i.e., the ratio of energy output to energy input.

The capacity of the equipment is measured in kilowatts (kw) and, unfortunately does not have a completely unambiguous definition. The nameplate rating of the equipment, which is often used as the measure of capacity, is usually the a priori design specification of the equipment. The actual peak output is also often used as a capacity measure, but this is usually only sustainable for short periods. The peak output rating is almost always larger than the nameplate rating, and it is common practice for the capacity rating to be increased after a plant has been in service for some time. Conservatism in the original rating of design capacity is possibly a response to the penalties in contracts that are enforced when specifications are not achieved. The capacity of equipment is determined by, among other things; its size, the strength of materials used in its construction, and the quality of its cooling system.

The quality or efficiency of the capital equipment is expressible as the amount of fuel required to produce a particular time integral of power output. The input of fossil fuel can be measured in BTU/time (flow of energy) and, apart from minor differences such as moisture content, the heat energy made available in the boiler is independent of fuel type. The output is usually measured in kw's which are merely different units of energy flow more suited to electricity.—/ One gross measure of

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—/ 3412 BTU/hr = 1 kw.

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efficiency is the heat rate of the plant, which is the amount of fuel energy in BTU that is required to produce one kwh of electrical energy (a power flow of 1 kw for an hour). Steam stations range in annual average values of this parameter from 8,000 to 14,000.

The efficiency of equipment can be increased by several possible modifications to the thermal cycle. The maximum possible efficiency is theoretically limited by the maximum temperature and pressure which can be achieved, and the conditions of the heat sink. The temperature and pressure are limited by the quality of the metal boiler tubing used, and the heat sink usually by the temperature and quantity of cooling water available. The efficiency is not independent of output. Typical input-output curves are shown in figure II-1.[1] The method of constructing both the boiler and the turbines contributes to the nonlinearity of this relationship. In the United States, a multi-valve turbine is typical while Britain typically uses single-valve turbines. The difference is important, since the choice of turbine affects the cost minimizing operating procedures. The almost linear transformation curves of single valve turbines mean that, when run as part of a system, generating sets are fully loaded or not loaded at all. This is called merit-order loading, and requires a "strong" transmission system, usually a feature of geographically compact systems. The cost-minimizing operating conditions for American utilities that employ multi-valve turbines are then to partially load most sets by equating all marginal operating costs (adjusted for transmission losses).[2] This is a much more complex procedure and, unfortunately, introduces some extra difficulties for

STATION PERFORMANCE
AND OPERATION CHARACTERISTICS

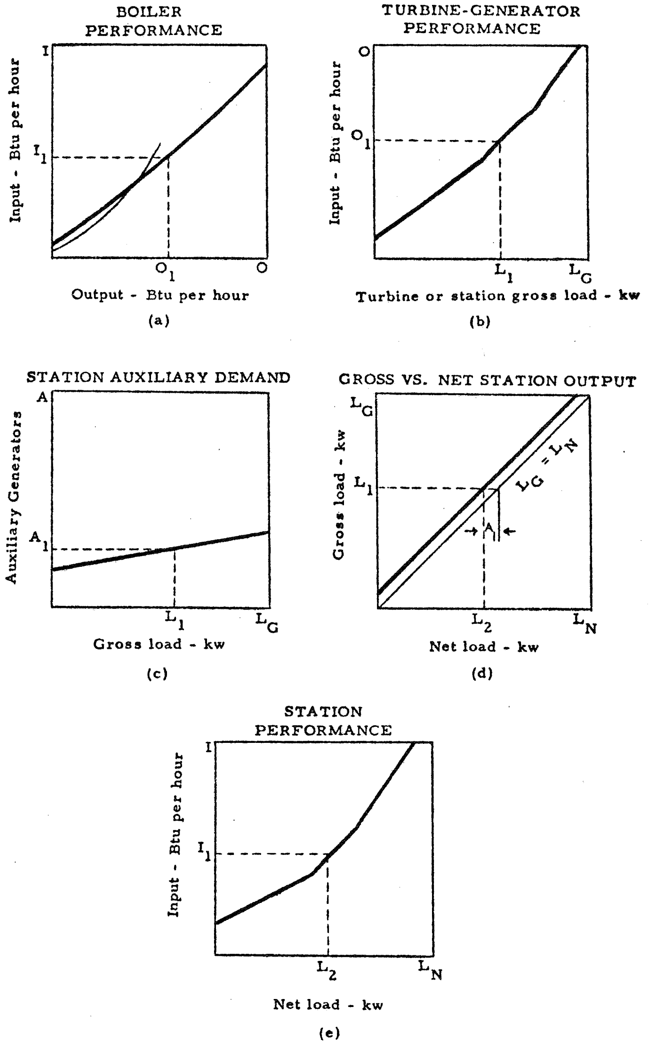

Figure II-1. Input-output curves of component station equipment and derivation of station input-output curve.

formulating production functions. Because of the curvature in the transformation curve, average heat rate will depend crucially on the time path of output. To illustrate,

$$\text{average heat rate} = \frac{\int_o^T f(t)dt}{\int_o^T g(t)\, dt}$$

where f and g are the instantaneous inputs and outputs, respectively. Hence, annual observations on energy input and output do not allow us to estimate the underlying transformation curve. The parameters of this curve are sufficient for most purposes to characterize a particular unit. This function is essentially what Nordin (7) was estimating and, as Galatin points out, he appears to be the only author of the econometric studies to appreciate fully the instantaneous nature of the output.

While we have just described a way in which the capital equipment can be fully characterized, for economic decisions the cost as a function of these characteristics is required.[3] If the data on the transformation curve were available (it is known to the operating engineers), a cost function could be estimated. A simplification of this approach is attempted later.

The preceding discussion suggests a fairly simple way of characterizing capital equipment by the capacity and efficiency of a unit. There are, however, additional decisions involved with the purchase of equipment that have a bearing on the A-J effect. First we will look at the choice of capacity and efficiency to see what form the A-J effect would take in these decisions. The other decisions on fuel type, location and whether the plant should have been replaced with purchased power are then examined. From this discussion it is clear that only very limited types of A-J effects can hope to be detected with the typical data used.

The choice of what capacity an electric generating unit should have is influenced by a number of factors. The dominant one being the regulatory requirement that demand be met at all times. Because a single price is charged through time and storage of electricity is prohibitively expensive, generated power varies significantly with time. The installed capacity clearly has to be at least equal to the maximum power demand. In fact, it has to be significantly greater than this in order that periodic maintenance can be undertaken as well as providing a reserve in case of equipment failure. There are a variety of ways that have evolved for economically handling this demand variation (with a fixed price and a regulatory stipulation that demand be met with high reliability). Those utilities lucky enough to have hydroelectric power available generally make use of the flexibility it allows to handle peaks. Some others, where geography is suitable, construct pumped storage facilities for peak service. In general, the trend has been towards installing low capital cost but high running cost gas turbine units specifically for peaks and interconnecting with another system whose peaks occur at other times. In small systems it is still common to use general purpose "cycling" steam plants which operate over a very large range of output.

A related problem is caused by the uncertainty in demand and the random nature of a particular unit's availability. The amount and composition of the reserve capacity required is a difficult engineering question. Rules such as fifteen percent of peak load, the sum of the two largest units in the system, etc., have all been used. With the advances in computer capability and the accumulation of data, more refined methods are now used. From an economic point of view they are still rather arbitrary as the objective is now to reduce the probability of having to shed load below some arbitrary amount. This probability level is not actually set by the regulators, but is discussed by them. An informal agreement apparently is reached which at least does not appear to cause much vocal consumer dissatisfaction. The capital inputs to maintain an adequate or excessive reliability of supply can at worst be viewed as gold plating. In general, they cause no substitution for fuel in the production of energy output; overcapacity is not a manifestation of the A-J effect.

The choice of efficiency is determined by the expected cost of fuel; when fuel is expensive, more efficient capital equipment is justified for a given energy output. If the unit is going to run at a high load factor (near capacity for much of the time), a higher efficiency is justified than in a plant which runs at a low load factor. As there are increasing returns in efficiency with unit size, the choice of efficiency is connected with the choice of unit size.—/ We must, therefore, conclude that before any predictions of the effect of regulation on unit size can be made, complete engineering information on the system must be examined.

Two main points emerge from this recitation of the technology of electricity production. First, as long as the capacity constraint is not active for a large proportion of the time, capacity does not influence the total energy produced. Second, the efficiency of the capital is the input, that can be substituted for fuel in the production of energy.

The empirical work has considered data at two levels, the plant and the firm. All three authors place much more confidence in the plant data than the firm data. At the plant level the points

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—/ Peck (8) has covered some of these problems, especially those of investment timing.

above concerning the contributions of capacity and efficiency are strictly true. It is only if excess efficiency is built into a plant (in relation to the energy output produced) that the A-J effect can be detected. The size of the units and the number of units in a plant must be considered as externally determined, as the decisions regarding these are based on considerably more information about the rest of the system, including the transmission network. They are of the same nature as questions such as whether the plant was built in the correct location, whether the correct fuel was chosen, or whether the plant was strictly necessary and should perhaps have been replaced by a transmission line for delivery of purchased power. There is possibility in all of these decisions for A-J effects, but to detect them requires knowledge of the particular alternatives available to the firm. For example a "mine-mouth" coal-burning plant could be evidence of the A-J effect since the coal-handling equipment and transmission lines expand the rate base and lower fuel costs. A mine-mouth plant could of course also be the least expensive way of delivering energy to a particular locality, so that it is impossible to generalize about such choices.

At the plant level, the appropriate cost-minimizing marginal condition that can be tested is whether the cost of improving efficiency equals the suitably discounted annual savings in fuel cost over the life of the plant. As data on instantaneous output and the transformation curve are not available, the best we can hope to measure is whether the annual average heat rate chosen was correct in relation to the price of fuel and capital for the actual output produced. There is a problem even with this approach, for after the plant is constructed it is obviously in the firm's interest to adopt the cost-minimizing operating procedure. This means that generating sets will be loaded so as to equalize the marginal generating costs (adjusted for transmission losses). If the newer units are of higher efficiency than the system average, the effect will be to load these more heavily and unload some older, less efficient plants. Thus, unless the overall system efficiency is too great we will not detect overcapitalization by observing the new plants, but instead should be examining the lightly loaded or retired old plants. Even this is hazardous as the planned life of equipment is dependent on expectations regarding technological change. Pessimism in this respect that is revealed only by retrospective analysis is not particularly strong evidence of the A-J effect. By examining new plants we are unlikely to observe overcapitalization unless it is of large magnitude and spread over the whole system. Detection at the firm level is even more difficult, considering the problem of determining what is the correct amount of reserve capacity and hence which old plants are correctly included.

Choice of fuel is a potential source of the A-J effect as coal requires greater investment in structures and equipment than either gas or oil. But to determine whether coal was chosen in order to get the extra equipment into the rate base, or because there was a shortage of gas not reflected in its price, requires that the availability and expected future costs of the alternative fuels be known. The choice between purchased power (usually requiring investment in transmission and switching facilities) or a new plant is dependent on the availability and cost of purchasable power.

All three empirical studies have used the FPC reports as their basic source of data. These plant data are limited to output, amount of fuel and its price, and the total cost of the plant. From this data the only meaningful test of overcapitalization is to

specifically test whether the efficiency of the plant is too great in relation to its output. An attempt to do this is reported in a later section.

III. CRITIQUE OF COURVILLE

Courville attempts to verify the existence of the A-J effect in a very direct manner. He estimates a Cobb-Douglas production function of annual energy produced, and then tests whether the ratio of the factor marginal productivities derived from this is different from the price ratio. He concludes that overcapitalization has been confirmed.

His data consists of observations on new steam electric plants in the period 1948-1966, which is split into four subgroupss according to vintage. The 1956-1959 group had to be discarded as it gave results which were drastically different from the other three periods. This was explained on the basis of the "electric conspiracy."

The major fault with this study is the totally inappropriate formulation of the technological possibilities. A Cobb-Douglas production function relating total plant cost and the fuel used to annual energy production is not relevant. It is surprising that Courville does not realize this, as he specifically gives the two reasons why it is inappropriate. On page 63 he notes that plants facing higher fuel costs will tend to be more efficient for a given capacity and in a footnote on the same page he notes that as peak loads must be met "overcapitalization can be inferred only if excess capacity is present at all points in time" (when using capacity as a capital measure). As these are the points which are being made here, it is indeed hard to understand why Courville failed to realize that, by using total cost as his measure of capital, he was confusing the choice of capacity with the choice of efficiency.

It was shown earlier that, to a reasonable approximation, the annual energy output of a plant is simply proportional to the energy input. Courville's results certainly bear this out as his estimated values of β (the coefficient of log F) are definitely not significantly different from unity. This certainly explains why such impressive values of R-squared were achieved, though when there are such strong a priori reasons to believe in linearity, these R-squared values are somewhat misleading. His procedure, therefore, actually tries to estimate the coefficient of proportionality in this linear process by a simple power of the total cost.[4] To illustrate this, the following equation was estimated using the 1960-1966 vintage plants.

$$\frac{1}{\text{heat rate}} = \frac{\text{annual output } (10^6 \text{ kwh})}{\text{fuel input (MBTU)}} = A \cdot [\text{total cost}]^{\alpha}$$

The results were

$$\hat{\log} A = -10.009$$

$$\alpha = 0.0889 \quad \Longrightarrow \quad t = 5.327$$

$$(0.0167) \qquad R^2 = 0.434$$

$$\text{D-F} = 37$$

This shows that as total cost increases, so does the efficiency with which the plant converts fuel to electrical energy. Two factors cause this: (1) for the same unit expenditure ($/kw of capacity) a larger plant will be more efficient; and (2) for a given size of plant a larger unit expenditure will purchase a thermodynamically more efficient plant. We have previously shown that at the plant level the first factor cannot be considered as a choice variable when considering the A-J effect, so we are thus interested in pinpointing the second factor. The previous result, like Courville's procedure, did not distinguish between these two factors. Indeed, by using a very simplistic approach the first effect can be shown to have contributed almost all the explanation to the total cost term.

This is done by estimating the following equation:

$$\frac{10^6}{\text{heat rate}} = A + \alpha \left[\frac{\text{total cost (\$1,000)}}{\text{capacity (MW)}}\right]$$

The following results were obtained.

$$\hat{\alpha} = -0.017 \quad \Longrightarrow \quad t = 0.39$$

$$(0.044) \qquad R^2 = 0.004$$

$$\hat{A} = 105.4 \qquad \text{D-F} = 37$$

The above indicates that unit costs explained none of the observed variation in heat rate. On this basis it appears that the coefficient of capital which Courville has estimated is totally determined by the size of the plant, and this can not be considered as a choice variable within the context that he is considering. It should be noted that in both the above estimations, plant rather than unit data are used, not because this is the correct level to look for these effects but to make the results more directly comparable to Courville's.

There are some other perturbing factors about this functional form when used with his measure of capital. Using Courville's description of his data set (i.e., new plants built during 1960-1966, under 800 Mw, capacity, and in first full year of operation) an attempt to reproduce his results was made (table III-1). They are designed as data set A^*. The coefficients differ significantly from those reported by Courville. They are also in the direction to make detection of the A-J effect less likely, and in fact when the t-test for overcapitalization was done with these coefficients, indecisive results were obtained. Clearly this was not the data set used by Courville.

TABLE III-1

Attempted Replication of Courville's Results

(1960-1966)

$$\log[\text{output}] = \log A + \alpha\log[\text{total cost}] + \beta\log[\text{fuel used}] + \delta\,\text{utilization} + b\,\text{capacity}$$

	$\log \hat{A}$	$\hat{\alpha}$	$\hat{\beta}$	$\hat{\delta}$	$\hat{b}$	R^2
Data Set A^*	-9.392	0.2146 (2.9708)	0.8623 (10.746)	0.003 (1.791)	0.00066 (0.247)	0.9856
A	-9.8709	0.0925 (2.158)	0.9718 (16.645)	0.002 (2.146)	0.0000 (0.0341)	0.9937
Courville	-1.2602	0.1036 (3.10)	0.9705 (17.36)	0.3361 (3.04)	0.00002 (0.96)	0.994

The values in parenthesis are t ratios in contrast to the rest of this paper where they are standard errors.

The same plants were then examined and the "best" year of operation before 1969 was selected. The criterion for "best" was the highest output for what appeared to be a typical plant factor and after as many capacity additions as possible (provided they seemed to be part of the original design). The coefficients for this data set are shown as data set A (which is listed in entirety in appendix B) and these appear to agree well with those obtained by Courville. This is certainly a rather perverse behavior of the data, as the second set would appear to be less likely to show overcapitalization, because output in general was greater and in many cases expenditure per unit of capacity was less. The feeling that this measure of capital has such serious flaws so as to make it totally unreliable was further reinforced when Courville's equation was reestimated using a sample of twenty-nine municipal, federal and Texas plants from the same period. The coefficient of capital was indistinguishable from zero.

While the above shows that Courville's estimated production function does not enable us to detect the A-J effect, his general approach is more promising than the two other methods. He gives many valid reasons why looking at a firm as a whole can lead to serious problems. He is also the only author to consider peak load effects, and within the context of his production function, his method of allowing for them seems reasonable.

He is in error on one point, however, when he postulates a MIN formulation as the appropriate joint production function for distribution, transmission and generation. He appears to be confused by the fact that the peak power which can be delivered is limited by the rating of the weakest link in the system. The annual energy is not subject to any such limitation, unless equipment is running at capacity for most of the year. The capacity of distribution systems is very seldom a limiting factor as overload merely produces degradation of performance (lower line voltage) with little risk of equipment failure. Transmission systems (AC) do have a point of maximum capacity which is determined by the reactive characteristics of the load and the line.^{5} When considering the delivery of energy, it is usually possible to use quite a simple model as the transmission losses are simply proportional to the square of the power level.—/

If the location of a plant is fixed and its costs of production determined, the choice of a transmission system can easily be stated in marginal terms. The value of the marginal energy lost as heat should be equal to the annual marginal expenditure on the transmission system.

There are possibilities (as outlined earlier) for A-J type interactions between transmission and generation showing up in fuel choice and location decisions. These are clearly not detectable unless the cost characteristics of all the alternatives facing the firm are known.

IV. CRITIQUE OF SPANN

Spann uses an indirect method in his attempts to confirm the A-J thesis in the electric power industry. He tests two related hypotheses:

1. The regulatory constraint is inactive given that the firm is is a profit maximizer (i.e., Lagrange multiplier = 0), or
2. If the constraint is active, the firms do not maximize profits.

To test these hypotheses, Spann assumes a trans-log production function for annual energy output and, from the normal Averch-Johnson first order conditions, derives two equations

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—/ See V. L. Smith (10) for discussion of this classical problem in engineering economics.

giving the factor shares of total revenue. By assuming that all firms face the same constant elasticity of demand he obtains a restriction on a coefficient in each equation. For the first hypothesis he jointly estimates these equations subject to this constraint. The estimated value of the Lagrange multiplier is significantly different from zero. From this he concludes that inefficient input choices have been made.

The first criticism is that evidence which shows that the constraint is active does not necessarily infer inefficiency. By considering taxation, Spann introduces a very good reason why the constraint may be active and efficient input combinations chosen. Very briefly, (for more detail, see McKay [11]) the effect of property taxation is to make capital appear more expensive and hence introduce a bias which favors the substitution of fuel for capital. Corporate income tax works in a similar manner as debt expenses are excluded from profit when computing taxes and it is the after tax rate of return that the regulators consider. Thus, if utilities face higher capital taxes than other business, taxation and rate of return regulation are offsetting effects.

Even assuming no problems with his theoretical model, Spann's results do not demonstrate a capital bias. Spann's plant data set was reconstructed and is listed in the appendix B. The two equations (for simplicity these have the labor terms neglected) are, using Spann's equation numbers:

$$\text{S (8)} \qquad \frac{rK}{PQ} = \lambda \frac{sK}{PQ} + b_1 + b_2 \log K + b_3 \log F$$

$$\text{S (10)} \qquad \frac{P_f F}{PQ} = b_4 + b_5 \log F + b_6 \log K$$

and these are subject to

$$b_3 = b_6 (1-\lambda).$$

To check Spann's results, these equations were reestimated separately using two different methods. The linear regression program produced superior printout with regard to errors and gave good agreement with the nonlinear program which was to be used for the joint estimation. The inverse of the standard error estimates were used to weight the observations when doing the joint estimation, as was done by Spann. The joint estimation was done with λ fixed at variety of values later to be considered as alternative hypotheses. To test the significance of the estimated value of λ, the following chi-square statistic was computed.

$$\chi_1^2 = -T \log \frac{\text{error sum of squares with } \lambda \text{ free}}{\text{error sum of squares with } \lambda = \lambda_o}$$

where λ_o is the alternative hypothesis. The results are displayed table IV-1 and figure IV-1.

Spann concluded from the fact the λ was significantly different from zero that there was overcapitalization. As has been shown (11), property and income taxation can produce a bias against capital inputs. The appropriate comparison is thus with the value of λ which implies the same input combinations chosen by an untaxed and unregulated cost minimizer. This value of λ_o is given by

$$\lambda_o = \frac{p - q + (q - ibc)/(1 - c)}{p - q + (q - ibc)/(1 - c) + (s - q)\,(1 - c)}$$

where

p - property tax rate
c - corporate income tax rate
i - interest cost of capital
b - fraction of debt capital to total
r - opportunity cost of equity capital
q - cost of capital = ib + r(1 - b)
s - allowed rate of return

TABLE IV-1

λ	SSE	$\left[\dfrac{\text{SSE } \lambda_{free}}{\text{SSE } \lambda = \lambda_o}\right]$	log [ ]	χ_1^2
0.5847	69.87	1.000	0.0000	0.00
0.000	99.35	0.703	-0.3524	26.70
0.050	94.30	0.741	-0.2997	22.08
0.100	90.14	0.775	-0.2549	18.85
0.300	76.93	0.908	-0.0965	7.14

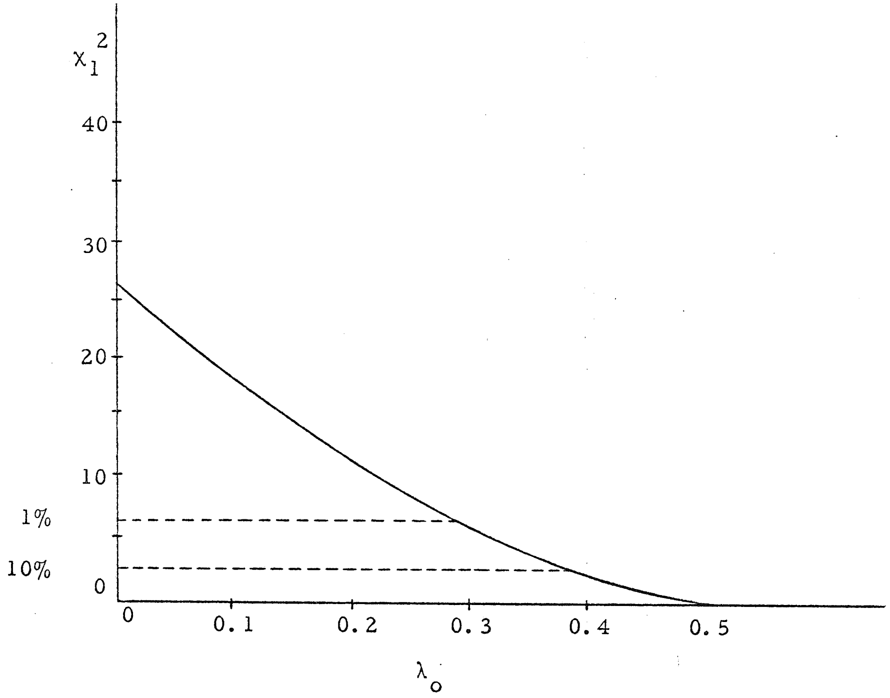

Figure IV-1

These values are displayed graphically as a function of allowed rate of return and the property tax rate (figure IV-2). The parameters used were

$q = 0.056$
$b = 0.52$ Spann
$c = 0.52$

and

$i = 0.043$ Moody's AAA bond yield 1963

These last two graphs show that even if the maximum rate of return occurring in Spann's data ($r = 0.0912$) is used and a property tax of zero is assumed, the hypothesis that there is no distortion is accepted at the 1% confidence level.

So far Spann's results have been considered under the assumption that his methodology is otherwise acceptable. This, unfortunately, is not the case. His method crucially depends on the trans-log production function being appropriate, and in particular the coefficients of the higher order terms being different from zero. The reasons why annual output can be expected to be linear with fuel inputs are discussed above. Small departures from linearity are caused by variation in output through the year, and not by interaction between some measure of capital and fuel used. The surprising feature that emerges is that when equation S (8) is estimated by itself, the coefficients b_2 and b_3 are not significantly different from zero.

$$\frac{rK}{PQ} = \underset{(0.1088)}{0.5992}\,\frac{sK}{PQ} + 0.0119$$

$$+ \underset{(0.0179)}{0.000293}\log K + \underset{(0.0197)}{0.006159}\log F$$

$$R = 0.7234$$

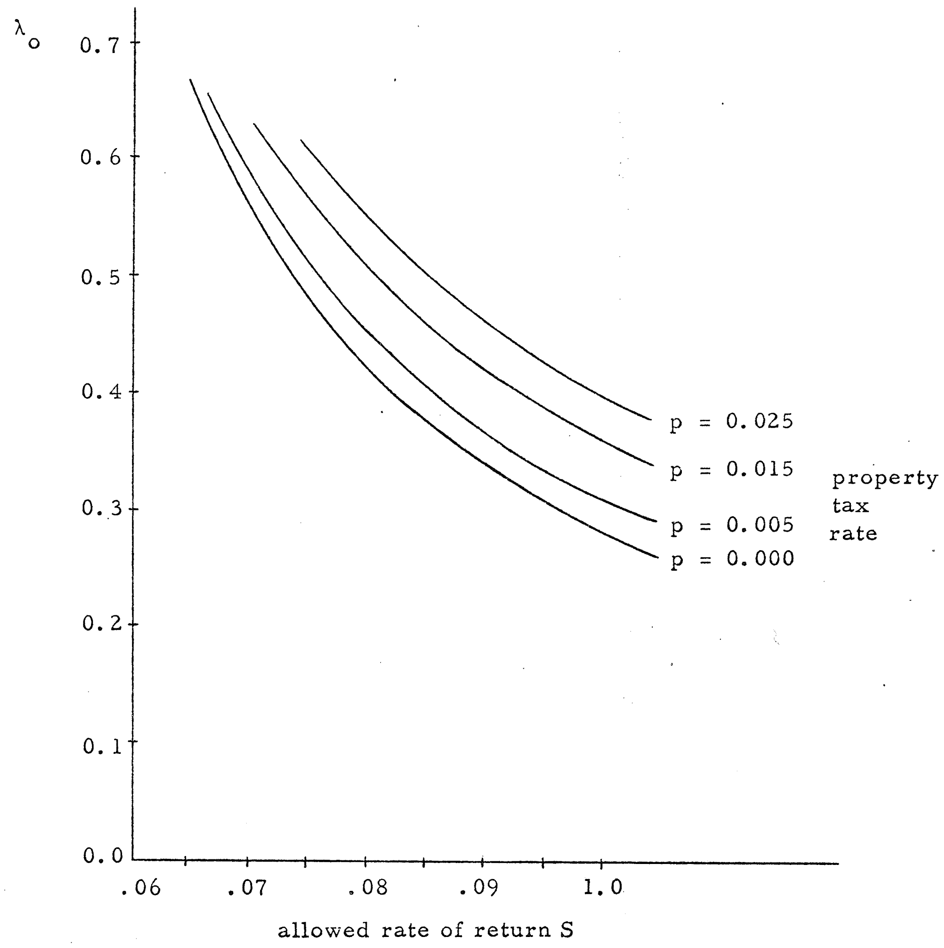

Figure IV-2

Spann does not discuss this result at all, though this is probably an editorial error as a nonexistent discussion is mentioned in footnote 14. From the a priori notion of linearity, (i.e., high order terms in the translog function vanish), estimation of equation (8) merely regresses allowed rate of return on a constant. Interpretation of the estimate of λ is certainly hazardous, as it appears to be merely the average ratio of the cost of capital to the allowed rate of return. By coupling the two equations and jointly estimating them, some of the coefficients are made significant, but it does seem a bold move to attribute Lagrangian properties to the estimated λ.

Reestimation of the equations jointly produced rather widely differing numerical estimates compared to those obtained by Spann, probably largely because of the omission of the labor terms and the rather flat minimum of the error-squared surface.

$$\frac{rK}{PQ} = \overbrace{0.5847}^{\lambda} \frac{sK}{PQ} + 0.2819 + 0.0192 \log K - 0.0215 \log F$$

$$\frac{P_f F}{PQ} = \qquad - 0.1130 + 0.0632 \log F - 0.0518 \log K$$

The signs are consistent with those obtained by Spann. No error estimates are included due to the nonlinear program used.

One difficulty with Spann's approach is that it gives absolutely no consideration to peak load effects. These effects are not the same for each plant. Furthermore, the assumption of constant elasticity of demand is also open to criticism, as different utilities certainly face different demand curves (due to, for example, regional climatic differences). The major error, though, is that the production process is incorrectly represented by the function chosen. Since this function is necessary in order for the method to be successful, the meaning of the results is dubious.

V. CRITIQUE OF PETERSEN

Petersen attempts to detect the A-J effect by using the comparative static results that show a rise in unit production costs and a rise in the share of costs going to capital as regulation tightens. He uses three measures to quantify tightness of regulation. The first is a dummy variable to distinguish states that evaluate the rate base on an original cost basis from those that use a replacement cost or fair value. The second measure is a dummy variable to distinguish between those states with statewide regulatory commissions and those without; the contention being that original cost and statewide regulation are "tighter" forms of regulation. His third measure is an adjusted return to equity capital which leads, after some assumptions, to a continuous variable measuring regulatory tightness. By starting with a generalized cost function he attempts to explain unit costs and capital's share of costs. He includes his measures of regulatory tightness as additive shifts in the cost estimations.

Petersen's results lead him to conclude that regulation induces higher costs and thus that the Averch-Johnson thesis has been confirmed. Specifically, his results are that while the coefficient of his fair-value dummy is of the predicted sign, it is not significantly different from zero in either the unit cost or share of cost estimation. His variable distinguishing statewide regulation has the expected sign and is significantly different from zero in both equations. The continuous measure of regulatory tightness is also of the correct sign and significant. Unfortunately, Petersen failed to examine any other explanations for these observed results. A particularly simple explanation does exist which has absolutely nothing to do with the Averch-Johnson effect. There are differences in the fuels used which happen to vary systematically with the statewide regulation and return to equity variables.

Petersen's data set was reconstructed from the FPC reports and is listed in the appendix. While a more precise measure of this effect would be to weight each plant by output or capacity, a simple counting test suffices to show the correlations between fuel use and Petersen's measures of regulatory tightness.

TABLE V-1

Fuel Used

	Number of Plants						
	C	O	G	CG	CO	OG	COG
Statewide Reg.	15	3	4	7	3	12	2
Texas	0	0	7	0	0	0	0
Iowa	0	0	0	1	0	0	0
Minnesota	1	0	0	0	0	0	0

C - coal O - oil G - gas

Plants using only gas have significantly lower capital costs as well as production costs, compared with those plants which can use coal.[6] Because the Texas plants dominate the unregulated part of the sample, both in number and capacity (table V-1), it is not at all surprising that the costs were less, and the share of costs going to capital less, than in the regulated states, which contained a majority of coal-burning plants. The other, though less important effect, is that completely outdoor construction is more prevalent in Texas than the nation as a whole due to climatic differences. The failure to control for these systematic technological differences means that it is incorrect to attribute cost differences to regulation. When using the return to equity measure, Petersen uses the same sample (excluding some for lack of data) which means that, if Texas firms do enjoy a higher rate of return (which they appear to do), the results of this measure are also thrown into doubt by the fuel differences.

The unanimous choice of gas by the Texas utilities compared with the choice of other fuels by regulated utilities could itself be taken as an indication of an A-J distortion. If so, regulated states with ample gas supplies might be observed to choose plants that burn other fuels. But this is not born out by examination of choices in Louisiana, a state with regulation and readily available natural gas, which also shows an overwhelming preference for gas-fired plants.

The above discussions would seem to be strong enough reasons for considering the Petersen case far from convincing, but there are other points which would need consideration if this approach were to be reattempted. The question of load factor has not been considered, and while it is unlikely that it systematically varies with regulatory activity, this would need to be confirmed, as firms with poorer load factors do have both higher unit costs and a greater share of costs going to capital. The other possible effect which could show up as higher costs and share of costs is if regulatory institutions set higher reliability standards. This is not an A-J type of capital-fuel substitution, but would be indistinguishable from conventional A-J distortions using this method.

Petersen's choice of a sample is, in many ways, arbitrary. He includes a plant if it expands its capacity at least 50%, claiming that this is a marginal decision and thus suitable for the theory. This is generally not true, as most of the expansion included in his sample was simply part of the original construction schedule as another identical unit was brought on line. Totally new plants are more nearly marginal decisions by the firms. Petersen also errs in believing multiple observations on the same plant constitute independent observations. While the desire to accumulate a large number of observations is understandable, the practice of using three annual observations on each plant leaves much to be desired. If the plants are operating under normal conditions the yearly observations will be almost identical, and if not (either due to breakdown or scheduled maintenance) the observation is spurious with regard to the A-J effect.

VI. A REVISION OF COURVILLE'S METHOD

Because of its directness and lack of restrictive assumptions, a test of the equality of the ratios of marginal productivities and of prices, as attempted by Courville, is attractive.[7] To do this in light of the points made previously about characterization of the technological possibilities, a new formulation of the profit maximizing model is needed. As outlined earlier, when constructing a new plant, the choice variable, as far as the A-J hypothesis is concerned, is the efficiency with which that plant converts fuel to electrical energy. The decisions concerning the location, capacity, number of units and fuel are constrained by exogenous technical and economic factors. These may be subject to A-J effects, but much more information on the alternatives available is required before this can be determined. The efficiency of a plant is not a unique quantity, but depends on the level and the time distribution of output. Because instantaneous output data is not available, this efficiency can not be captured more finely than by the simple annual heat rate. This section presents a reformulation of the classic A-J model with the heat rate as the capital input variable.

A. Model

Notation: q - instantaneous output (KW)
f - instantaneous rate of fuel input (BTU/hr)
S - capacity of unit (KW)
H - annual heat rate (BTU/KWH)*
Q - annual energy output (KWH)
F - annual fuel consumption (BTU)
r - cost of capital (\$/\$)

s - allowed rate of return (\$/\$)
p_f - price of fuel (\$/BTU)
p - price of output (\$/KWH)
C - cost of capital equipment (unit). Assumed to be a well behaved function of S and H.
* - $\frac{3412}{H} \times 100$ = thermodynamic efficiency (%)

The production conditions are that

$$H \int_o^T q \, dt = \int_o^T f \, dt$$

and

$$q \leqslant S$$

the first condition may be put more concisely as

$$H \; Q = F$$

For a given output the regulated monopolist will attempt to maximize

$$\text{Profit} = pQ - p_f F - rC\,(S, H)$$

subject to the rate of return constraint

$$pQ - p_f F - sC(S, H) \leqslant 0.$$

The standard assumptions that $s > r$ and that the constraint holds with equality are made. To obtain the conditions for maximization, adjoin the constraint to the objective function with the multiplier λ.

$$L = (p - Hp_f)\,Q - rC(S, H) - \lambda((p - Hp_f)\,Q - sC(S, H)).$$

The first order conditions for a regular maximum (considering output fixed) are:

$$\frac{\partial L}{\partial H} = 0 = -\,p_f Q - r\frac{\partial C}{\partial H} + \lambda p_f Q + \lambda s\frac{\partial C}{\partial H}$$

which rearranges to the following:

$$p_f Q + r\frac{\partial C}{\partial H} = \frac{\lambda}{1 - \lambda}(s - r)\frac{\partial C}{\partial H}.$$

The second order conditions for regular constrained maximization require that:

$$\frac{\partial^2 L}{\partial H^2} \leqslant 0,$$

and hence:

$$(-r + \lambda s)\frac{\partial^2 C}{\partial H^2} \leqslant 0.$$

Assuming that efficiency is subject to diminishing returns, i.e., $\frac{\partial^2 C}{\partial H^2} > 0$ and $\frac{\partial C}{\partial H} < 0$ it follows that

$$-r + \lambda s \leqslant 0$$

Hence

$$\lambda \leq 1 \text{ since } s > r.$$

Using the same arguments as Baumol and Klevorick (12), the relation $0 < \lambda < 1$ can be obtained. Using this information in the rearranged form of the first order condition gives the marginal productivity condition if the A-J effect is active:

$$p_f Q + r\frac{\partial C}{\partial H} < 0$$

The condition for a cost minimizer is:

$$p_f Q + r\frac{\partial C}{\partial H} = 0$$

B. The Cost of Capital Equipment

To test this form of the A-J hypothesis, an estimable cost function must be derived from which we can extract the marginal

cost of efficiency. The cost, C, tends to infinity as the heat rate approaches some minimum achievable level (determined by the temperatures and pressures of the cycle). An absolutely perfect cycle using impractical temperatures could at best have a heat rate of 3412 BTU/kwh, which corresponds to 100% thermodynamic efficiency. Considering current metallurgical limitations, in practice this asymptotic heat rate is likely to be in the vicinity of 6,000 BTU/kwh (approximately 57% efficiency). The reasonableness of this assertion is evident in figure VI-1.[8]

For simplicity, a Cobb-Douglas function is used to explain the cost of capital equipment, i.e.,

$$\log[\text{equipment cost/unit}] = A + \alpha C_D + \beta \log[\text{unit size}] + \gamma \log[\text{number of units in plant}] + \delta \log[\text{heat rate} - B].$$

B = asymptotic heat rate $\quad C_D$ = coal dummy

In terms of these parameters the marginal cost is:

$$\frac{\partial C}{\partial H} = \frac{\delta C}{H - B}$$

in which, for practical purposes, the estimate of δ ($\hat{\delta}$) will be used. The quantity $\hat{\delta} C_i$ is a biased estimate of δC due to the stochastic nature of C_i, which requires attention when formulating a test similar to Courville's as will be discussed below.

The data set described as A in the section on Courville's work was used to estimate this equation. Six different values of B were used to demonstrate the insensitivity of the hypothesis tests to this assumption. For detailed discussion, the previously mentioned value of 6,000 was used. The results of the estimation are tabulated in table VI-1. Estimates of more complicated functions and some regressions using another set of data are reported in Appendix C.

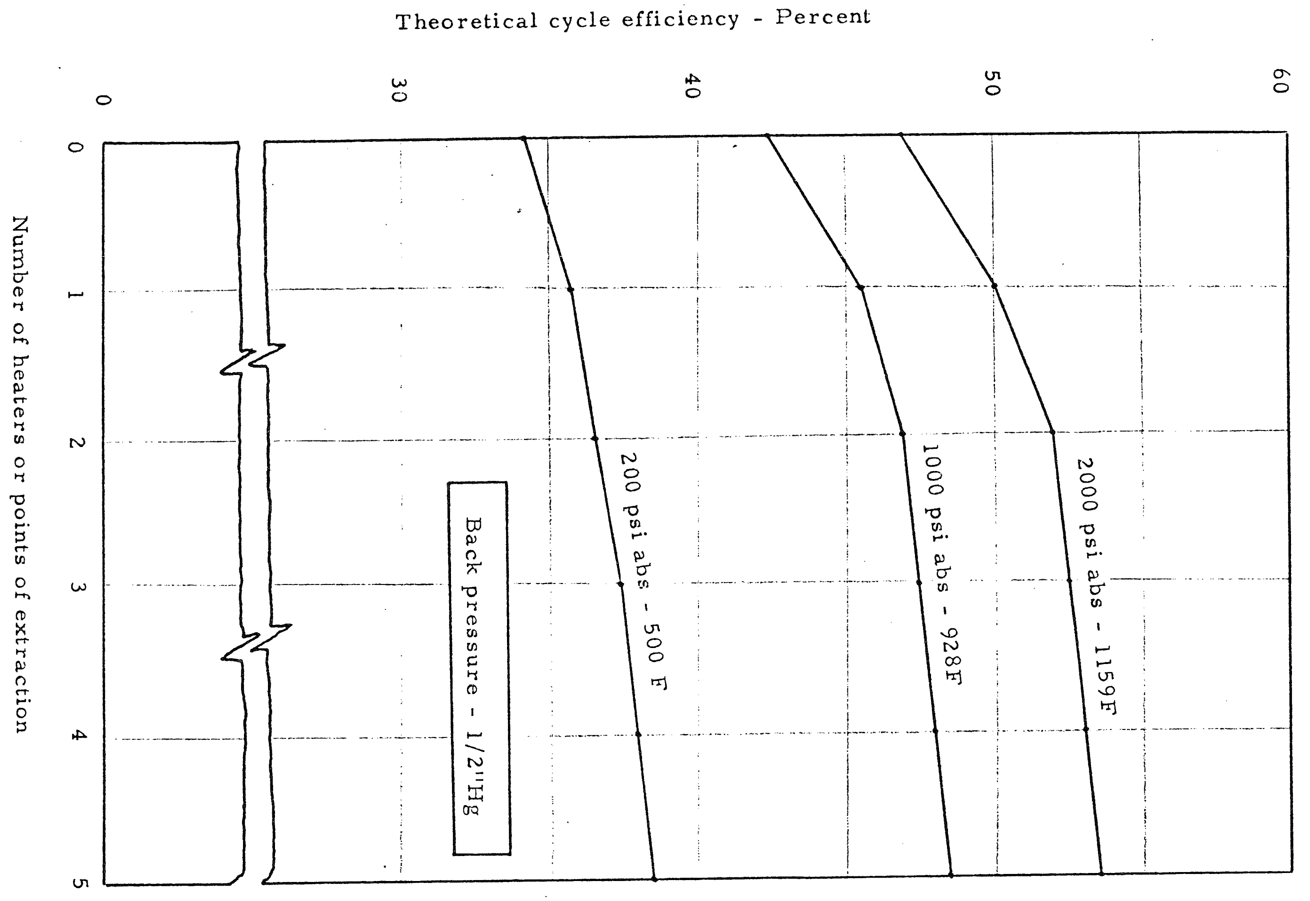

Figure VI-1. Regenerative-cycle efficiency variation with number of heaters. Curves are for ideal cycle.

TABLE VI-1

Estimation of Cost Function for Capital Equipment

B	A	α	β	γ	δ	Std. Error	R
3000	11.947	0.178 (0.081)	0.719 (0.080)	-0.096 (0.090)	-0.666 (0.509)	0.21070	0.933024
4000	10.993	0.178 (0.081)	0.719 (0.080)	-0.096 (0.090)	-0.568 (0.435)	0.21071	0.933016
5000	10.054	0.178 (0.081)	0.719 (0.079)	-0.097 (0.090)	-0.470 (0.360)	0.21072	0.933012
6000	9.113	0.178 (0.081)	0.720 (0.079)	-0.097 (0.090)	-0.370 (0.284	0.21075	0.932994
7000	8.169	0.179 (0.081)	0.722 (0.078)	-0.098 (0.090)	-0.267 (0.206)	0.21080	0.932958
8000	7.173	0.181 (0.081)	0.728 (0.090)	-0.101 (0.090)	-0.155 (0.122)	0.21098	0.932839

Numbers in parentheses are standard errors of coefficients.

$$\log\,[\text{cost/unit}] = A + \alpha C_D + \beta \log\,[\text{unit size}] + \gamma \log\,[\text{number of units}] + \delta \log\,[\text{heat rate} - B]$$

Courville used a t-test directly on his marginal conditions. Unfortunately, another problem, in addition to the bias in the estimate, forces a change in method. Due to the poor estimate obtained for δ (large standard error), the null hypothesis can not be tested with any hope of rejecting it since the limiting value of the t-statistic obtained with increasing cost of capital tends toward $\frac{\hat{\delta}}{\hat{\sigma}_\delta}$, which is not significant. A test of the alternative hypothesis (i.e., undercapitalization) can be performed with some hope of success. Thus, for each plant the following is computed:

$$T_i = \frac{p_{f_i} Q_i + \frac{r\delta C_i}{H_i - B}}{r\hat{\sigma}_\delta C_i/(H_i - B)}$$

While the bias in $\hat{\delta} C_i$ is negligible and supportive of the A-J effect (see Appendix A), unfortunately nothing can be shown about the bias in $\hat{\sigma}_\delta C_i$. This test must thus be carried out under the bold assumption that this is also negligible. The results are presented in table VI-2, which shows the percentage of the sample for which undercapitalization could be inferred (in a one-tailed test) as a function of the cost of capital. (Cost of capital is taken to include the effects of income and property taxation.)

For costs of capital used by others (≈6 to 8%) it does not appear that a case for the A-J effect can be made.

Another approach was also used to test for the A-J effect. If there were no A-J bias, a particular power plant would have equal probability of the quantity

$$p_{f_i} Q_i + \frac{r\delta C_i}{H_i - B}$$

being positive or negative. Hence, a counting procedure can be used to test whether the probability of this term being positive is indeed

TABLE VI-2

T Test of Undercapitalization

Cost of Capital	Percent of Sample which H1 Rejected		
	1%	5%	10%
.0100	100.	100.	100.
.0200	100.	100.	100.
.0300	97.	100.	100.
.0400	87.	92.	97.
.0500	77.	87.	90.
.0600	62.	79.	85.
.0700	28.	69.	77.
.0800	18.	36.	67.
.0900	10.	23.	38.
.1000	5.	18.	23.
.1100	0.	10.	18.
.1200	0.	5.	13.
.1300	0.	3.	10.
.1400	0.	0.	5.
.1500	0.	0.	3.
.1600	0.	0.	0.
.1700	0.	0.	0.
.1800	0.	0.	0.
.1900	0.	0.	0.
.2000	0.	0.	0.
.2100	0.	0.	0.
.2200	0.	0.	0.
.2300	0.	0.	0.
.2400	0.	0.	0.
.2500	0.	0.	0.

H0: $\frac{p_f Q(H - B)/r + \hat{\delta} C}{\hat{\sigma}_\delta C} > 0$

H1: $\frac{p_f Q(H - B)/r + \hat{\delta} C}{\hat{\sigma}_\delta C} \leq 0$

$B = 6000$

$\hat{\delta} = -.370$

$\hat{\sigma}_\delta = .284$

0·5. As before, the problem of bias in $\hat{\delta} C_i$ must be considered. Here the statistic of interest is the median, and it can be shown that the bias here is indeed negligible (appendix A).

The percentage of the sample for which

$$p_{f_i} Q_1 + \frac{r\hat{\delta} C_i}{H_i - B}$$

is negative for a range of r and B is displayed in table VI-3. As the results are insensitive to B, the case B = 6,000 will be examined in detail. These results are graphed on figure VI-2 as is a cumulative binomial distribution with $\mu = .5$ and $n = 39$. The 5% and 10% confidence limits can then be transferred and read as limits on the cost of capital. The cost minimizing hypothesis can only be accepted at the 5% confidence level when the cost of capital lies between 16.4% and 18.6%. This tends to contradict the A-J prediction and even suggest the opposite may be true (i.e., plants have been built with less than the optimum efficiency).

Rather than use the point estimate for δ, in view of its relatively large standard error, the above test was repeated using its 95% lower confidence limit (table VI-4). This was plotted over the central range and changes the 5% confidence limits on cost of capital to 7.2% and 8.0% respectively. This is still larger than the apparent cost of capital in this period that was used by Courville, Spann and Petersen, but with the inclusion of a small property tax it appears that the null hypothesis may be accepted.

Thus, within the limits of the data that are readily available, there seems to be no evidence to support the more carefully formulated version of the A-J hypothesis. In view of the large number of other forms capital bias could take, surely its presence remains an open empirical question. The evidence does not support the notion that electric utilities substitute capital in the form of efficiency of energy conversion for fuel, as the A-J model predicts.

TABLE VI-3

	B					
Cost of Capital	3000	4000	5000	6000	7000	8000
.01	0	0	0	0	0	0
.02	0	0	0	0	0	0
.03	0	0	0	0	0	0
.04	0	0	0	0	0	0
.05	0	0	0	0	0	0
.06	0	0	0	0	0	0.00
.07	0	0	0	0	0.00	5.13
.08	0.00	0.00	0.00	0.00	2.56	7.69
.09	5.13	5.13	5.13	7.69	7.69	10.26
.10	7.69	7.69	7.69	10.26	10.26	10.26
.11	10.26	10.26	12.82	12.82	12.82	17.95
.12	15.38	15.38	15.38	15.38	15.38	17.95
.13	17.95	17.95	20.51	20.51	20.51	25.64
.14	20.51	20.51	20.51	23.08	25.64	28.21
.15	23.08	20.51	20.51	25.64	25.64	30.77
.16	33.33	35.90	33.33	30.77	30.77	33.33
.17	43.59	43.59	46.15	43.59	43.59	35.90
.18	61.54	61.54	58.97	61.54	58.97	38.46
.19	66.67	66.67	71.79	71.79	66.67	48.72
.20	71.79	74.36	74.36	76.92	76.92	64.10
.21	74.36	74.36	74.36	79.49	79.49	71.79
.22	76.92	79.49	82.05	82.05	82.05	71.79
.23	79.49	82.05	82.05	82.05	84.62	82.05
.24	84.62	84.62	84.62	87.18	87.18	82.05
.25	87.18	84.62	87.18	89.74	89.74	82.05

Percentage of Sample Negative

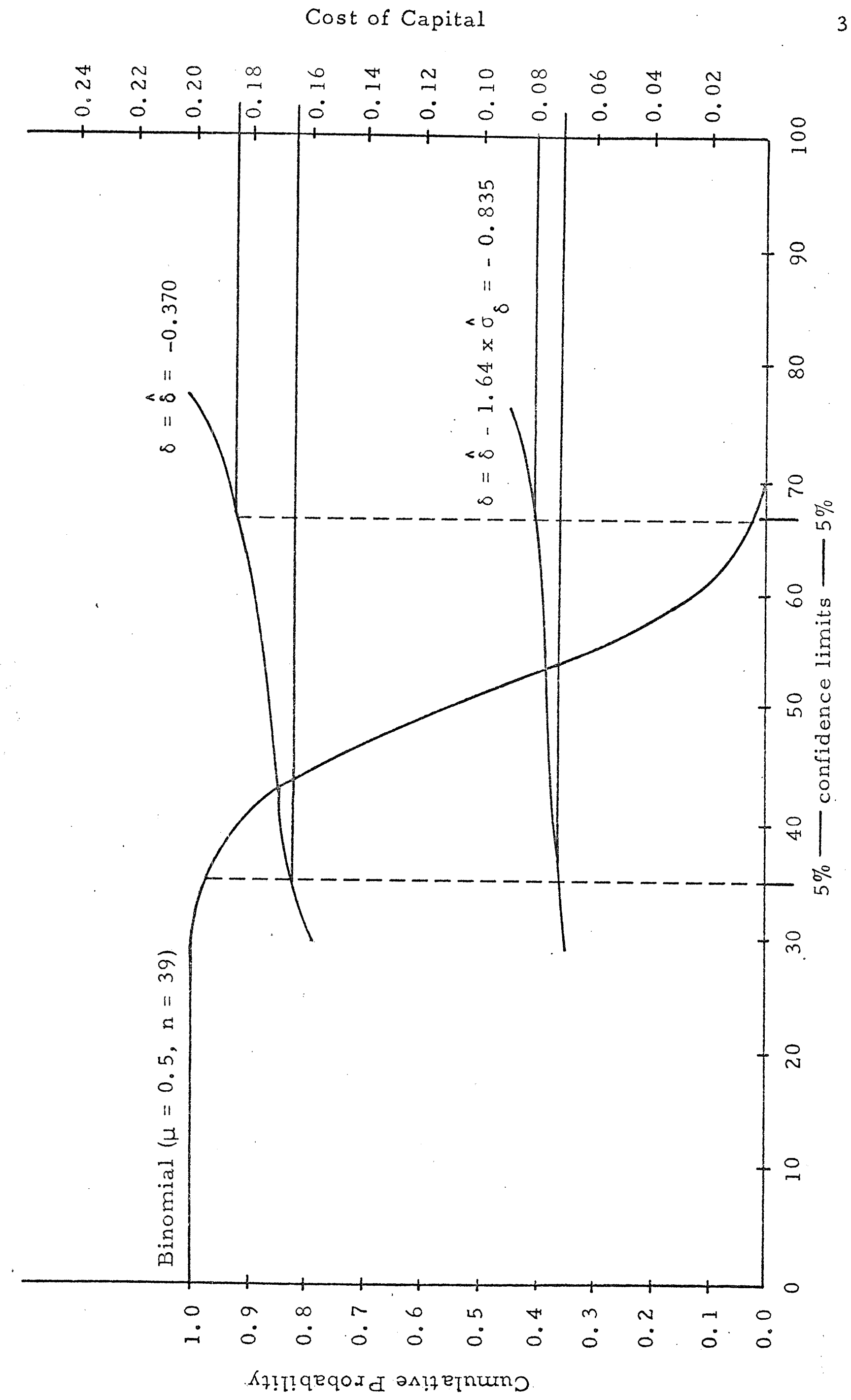

Figure VI-2. % of Sample Negative

TABLE VI-4

Using 95% lower confidence limit for $\hat{\delta}$ i.e., for

B = 6000

δ = -0.835

Cost of Capital	% of Sample Negative
.030	0.00
.032	0.00
.034	0.00
.036	2.56
.038	2.56
.040	7.69
.042	7.69
.044	10.26
.046	10.26
.048	12.82
.050	12.82
.052	12.82
.054	15.38
.056	15.38
.058	20.51
.060	20.51
.062	23.08
.064	23.08
.066	25.64
.068	25.64
.070	28.21
.072	35.90
.074	38.46
.076	43.59
.078	61.54
.080	61.54
.082	66.67
.084	69.23
.086	71.79
.088	74.36

APPENDIX A

Bias in Mean and Median of δC_i

As noted in the text, the quantity $\hat{\delta} C_i$ is a biased estimate of δC_i^*(C_i^* Being the systematic part of C_i). For the purposes of the two tests used in this paper, of principal interest are the biases in the mean, variance and median of this quantity. Unfortunately, it is not possible to evaluate this bias in the variance.

The model that is used to estimate $\hat{\delta}$ is:

$$C_i = e^A e^{\alpha C} D\, S_i^{\beta} N_i^{\gamma} (H_i - B)^{\delta} e^{U_i}$$

in which U_i is assumed to be $N(0, \sigma^2)$ and $E(U_i U_j) = 0$ for $i \neq j$. The least squares estimates of the coefficients (after taking logarithms) will differ from the actual value by a linear combination of the U_i.

$$\begin{pmatrix} \hat{A} - A \\ \hat{\alpha} - \alpha \\ \hat{\beta} - \beta \\ \hat{\gamma} - \gamma \\ \hat{\delta} - \delta \end{pmatrix} = (X^T X)^{-1} X^T \overline{U}$$

As only $\hat{\delta}$ is of interest, the last row of $(X^T X)^{-1} X^T$ can be designated as a vector with elements K_j. These were evaluated and are listed in table A-1; note that none exceed + 0.09.

TABLE A-1

Table of K_i for Data Set A

1	0.0288686
2	0.0441520
3	-0.0724675
4	-0.1183105
5	-0.0979534
6	-0.0914255
7	0.0523532
8	0.0623681
9	0.0493813
10	0.0543095
11	0.0773097
12	0.0277251
13	0.0711023
14	-0.0162539
15	-0.0855611
16	0.0187126
17	-0.0932570
18	0.0304833
19	-0.0103867
20	-0.1180567
21	0.0475740
22	-0.0097923
23	0.0149294
24	0.0900768
25	0.0417682
26	-0.0601037
27	-0.0938723
28	0.0517184
29	0.0505942
30	-0.0009077
31	0.0387931
32	0.0568654
33	-0.0996541
34	0.0451105
35	0.0314857
36	-0.0110669
37	-0.0530851
38	0.0358616
39	0.0106104

The quantity of interest is $\hat{\delta} C_i$, which is equivalent to

$$C_i^* \left\{ \delta + \sum_{j=1}^{n} K_j U_j \right\} e^{U_i}$$

where C_i^* is the nonstochastic part of C_i. The mean of this variable is

$$C_i^* \left\{ \delta \int_{-\infty}^{\infty} e^{U_i} \frac{1}{\sqrt{2\pi}\,\sigma} e^{-\frac{1}{2}\left(\frac{U_i}{\sigma}\right)^2} dU_i \right.$$

$$\left. + K_i \int_{-\infty}^{\infty} U_i e^{U_i} \frac{1}{\sqrt{2\pi}\,\sigma} e^{-\frac{1}{2}\left(\frac{U_i}{\sigma}\right)^2} dU_i \right\}$$

which, after completing the square, gives

$$C_i^* \left\{ \delta + K_i \sigma^2 \right\} e^{\sigma^2/2}$$

To see what the approximate magnitude of this quantity is, substitute the estimates of δ, σ^2 and the worst case K_i (i. e., worst from the point of view of not finding the A-J effect), which gives C_i^* (-0. 374). Since the estimated value is C_i^*(-0. 370), the bias is small and in favor of the A-J effect.

The median of e^{U_i} is unity, so the first term remains unaffected. The second term depends on the median of $U_i e^{U_i}$, which is not easily computed analytically. This was simulated by drawing a sample of size 1, 000 from a $N(0, \sigma^2)$ distribution and computing the variable $U_i e^{U_i}$. The median of this variable, with $\sigma = 0.2107$, was 0. 0034. The worst case, again when the largest K_i is used, yields, on replacement of δ by its estimate, C_i^*(-0. 370 + .000306), which is a bias against finding the A-J effect but of negligible magnitude.

Provided the bias in the variance $\sigma_{\delta} C_i$ is small, these calculations show that the results of the first test are unaffected by the stochastic nature of C_i. The bias in the median is of negligible magnitude so the counting test is also unaffected.

APPENDIX B

The Data Used

1. The data set which is identified as A in the text was constructed by replicating Courville's 1960-1966 vintage plants. As noted in the text a criteria of best year of operation was used. The sample is listed in the following table (table B-1) where the following notation is used.

name - the name as listed in the FPC index
a - the year of observation
b - the capacity of the plant in megawatts
c - the number of units in the plant
d - the plant factor in per cent
e - the heat rate in BTU/kwh
f - the cost of structures in $1,000
g - the cost of equipment in $1,000
h - the annual output in million kwh
i - the total fuel used in 10^6 MBTU
j - the price of fuel in ¢/MBTU
k - type of construction (C = conventional, S = semioutdoor, O = outdoor)
l - coal used as fuel
m - oil used
n - gas

TABLE B-1

Data Set A

Name	a	b	c	d	e	f	g	h	i	j	k	l	m	n
Greene County	68	568	2	73	9401	9461	45603	3634.7	34.169	22.66	C	x		
Cholla	64	115	1	92	9632	1833	18390	931.4	8.946	23.66	O	x		
Helena	66	325	1	69	9902	4170	38653	2166.7	21.424	26.34	O			x
South Bay	68	474	3	74	9788	9219	40451	3082.0	30.169	33.85	C		x	x
Cool-Water	62	65	1	80	9963	797	10333	457.0	4.554	34.15	O		x	x
Cape Kennedy	66	402	1	58	9461	4683	23670	2055.4	19.446	32.30	O		x	
Lansing Smith	68	340	2	75	10019	7022	38808	2231.9	22.342	25.67	C	x		
Harllee Branch	66	299	1	59	9692	6350	25709	1557.8	15.077	30.61	C	x		
Bailly	63	194	1	75	9584	8474	25904	1270.6	12.178	27.14	C	x		x
McDonough	68	598	2	75	9873	7912	43721	3963.8	39.115	25.20	C	x		
Coffeen	66	330	1	78	9930	11066	31948	2258.2	22.408	17.20	C	x		
Breed	66	450	1	80	8957	12824	59884	3155.7	28.256	19.01	S	x		
Neal	69	147	1	72	10090	2962	17024	930.5	9.381	30.48	C	x		x
Cimmaron River	66	59	1	66	12099	917	6304	339.5	4.108	34.55	S			x
Gordon Evans	66	150	1	83	9886	2286	14467	1092.1	10.795	21.65	O			x
Big Sandy	65	265	1	93	8959	6119	31642	2165.0	19.388	16.16	C	x		
Little Gypsy	68	669	2	78	9832	4399	46194	4602.0	45.246	19.25	O			x
Crane	69	400	2	77	9541	16256	48810	2695.2	25.711	31.90	C	x	x	
Chalk Point	67	728	2	76	8700	12225	77220	4823.0	41.958	30.59	C	x		
New Boston	66	359	1	79	9034	4571	27937	2487.1	22.468	32.01	C		x	
Mt. Tom	61	125	1	95	9685	5186	18273	1036.1	10.043	33.60	S	x		
Brayton Point	65	483	2	91	8811	12130	57361	3822.1	33.650	34.77	C	x		
Campbell, J. H.	65	265	1	84	8905	13037	33686	1953.9	17.389	32.10	C	x		
Sibley	64	100	2	78	11476	3180	14423	687.1	7.883	24.74	S	x		
Reid Gardiner	69	228	2	81	9948	3276	27982	1617.5	16.062	28.32	S	x		
Tracey	68	133	2	63	11295	2054	13668	739.0	8.347	36.84	S		x	x
Sunrise	67	82	1	74	9942	2111	9277	525.4	5.222	36.07	S			x
Merrimack	67	114	1	84	9805	5188	17039	833.7	8.167	34.30	S	x		
Hudson	66	455	1	64	9339	5334	66522	2543.8	23.755	31.14	O	x	x	
Mercer	64	653	2	79	8878	11210	100612	4532.4	40.241	27.63	S	x		x
England, B. L.	68	300	2	77	9777	5783	37648	2036.5	19.949	31.20	S	x		
Four Corners	65	634	3	76	10277	3600	75481	4226.0	43.386	13.32	O	x		x
Raveswood	64	800	2	65	9631	20477	90954	4588.8	44.201	34.81	C		x	x
Roxboro	67	411	1	76	9271	8186	27449	2739.8	25.373	27.72	O	x		
Ashville	69	207	1	79	9221	3034	18716	1438.2	13.249	30.93	O	x		
Marshall	68	700	2	99	8690	13751	60949	6359.6	55.263	25.92	C	x		
Northeastern	69	170	1	84	10580	4061	17765	1253.4	13.257	19.33	O			x
Brunner Island	68	768	2	76	9439	11119	68039	5156.7	48.551	25.79	O	x		
Canadys	66	272	2	71	9310	2642	29686	1698.9	15.809	30.86	S	x		x

2. The data used to replicate Spann's plant results is listed in the following table (table B-2). The columns contain the following:

a - the page in the FPC reports from which data come
b - the year of the observation
c - the total cost of the plant in $1,000
d - the fuel cost in $1,000
e - the other production costs in $1,000
f - the total fuel used in 10^6 MBTU
g - the plant load factor
h - the 3 year average rate of return

3. The data set used in discussing Petersen's work is listed in the following table (table B-3). The plant name, state, capacity in megawatts and fuels used are shown.

TABLE B-2

a	b	c	d	e	f	g	h
4	63	20223	1970	570	8.2711	85	6.503
8	63	43221	3854	422	14.9033	53	6.670
13	61	21690	3056	540	9.1147	78	6.333
11	62	12226	1555	326	48.3030	80	5.900
67	63	34520	3307	721	12.1782	79	8.447
43	61	72787	4866	1149	26.0382	67	6.503
85	63	16884	2085	326	9.7927	76	7.087
92	63	37946	2671	809	16.6877	81	9.123
107	62	38001	3857	842	11.6870	75	6.783
100	62	27756	3479	416	16.0419	77	7.320
112	62	23616	3420	569	10.5271	94	8.313
116	63	48469	4577	1029	14.1276	69	6.843
139	63	17871	1878	218	14.4444	69	6.043
86	61	22383	2768	405	6.9575	74	6.023
150	63	115241	11475	2386	38.4321	75	7.123
145	63	23710	2476	673	7.8589	68	6.813
97	64	113680	15393	2354	44.2010	65	5.313
193	62	22385	2109	452	10.4102	69	7.537
201	63	45674	5812	999	21.6205	73	6.537
213	63	19449	2521	266	8.4961	79	7.667
59	61	43682	4497	527	20.6165	57	7.313
15	61	50452	10782	964	32.1942	92	6.653
3	63	116856	17232	1357	66.9311	78	7.860
5	62	25238	5263	445	15.7863	80	6.503
12	62	11425	1718	461	10.6044	65	5.900
31	61	30175	3861	577	11.6941	94	6.773
44	63	47072	9090	768	27.7750	75	8.123
71	63	87250	7187	1673	37.4764	73	6.773
99	63	23195	2531	380	11.5098	78	7.313
147	62	115462	12674	2584	37.5460	70	7.123
153	63	21544	2809	330	12.7305	77	8.050
168	63	27914	3265	400	11.4047	65	6.863
186	63	34889	2238	886	11.0153	50	7.203
207	62	157426	14338	2342	41.9304	79	6.420
265	63	29128	2906	415	10.6659	54	7.270
268	63	35313	1164	699	14.5545	76	6.343
117	63	77324	9904	991	31.1856	75	6.843

TABLE B-3

Plant Name	State	Capacity	Coal	Oil	Gas
Pittsburg	California	951		x	x
Huntington Beach	California	653		x	x
Cameo	Colorado	66	x		
Meredosia	Illinois	300	x		
New Albany	Indiana	450	x		
Lawrence	Kansas	211	x		x
Clay Boswell	Minnesota	128	x		
Gulf Coast	Mississippi	296			x
Bergen	New Jersey	580	x		x
Reeves	New Mexico	175			x
Port Jefferson	New York	400	x	x	
Dunkirk	New York	560	x		
Elrama	Pennsylvania	447			
Bates	Texas	166			x
T. H. Wharton	Texas	323			x
Willow Island	West Virginia	215			
Morro Bay	California	1056		x	x
South Bay	California	474		x	x
Etiwanda	California	911		x	x
Norwalk Harbor	Connecticut	326	x	x	x
P. 'L. Bartow	Florida	494		x	x
Riviera	Florida	738		x	x
Will County	Illinois	1268	x		
State Line	Indiana	972	x		x
Tecumseh	Kansas	346	x		x
Arthur Mullergren	Kansas	133		x	x
Sibley	Missouri	100	x		
Sewaren	New Jersey	841	x		
Barret E. F.	New York	374	x	x	x
Lake Shore	Ohio	512	x		
Conesville	Ohio	434	x		
Portland	Pennsylvania	383	x		
Handley	Texas	523			x
Nelson Dewey	Wisconsin	228	x		
Four Corners	Arizona	634	x		x
Contra Costa	California	1276		x	x
El Segundo	California	1017		x	x
Cool-Water	California	147			x
Valmont	Colorado	274	x		x
Middletown	Connecticut	422	x	x	
Port Everglades	Florida	1255		x	
Wood River	Illinois	650	x		x
Des Moines	Iowa	325	x		x
Graham	Maine	58		x	
England B. L.	New Jersey	299	x		
North Lake	Texas	708			x
Port Wentworth	Georgia	208	x		
Hutchison	Kansas	252		x	x
Little Gypsy	Louisiana	669			x
Wyman Walter F.	Maine	214		x	
Ravenswood	New York	1827		x	x
Brunner Island	Pennsylvania	768	x		
Nueces Bay	Texas	258			x
Webster	Texas	614			x
Stryker Creek	Texas	703			x

APPENDIX C

Some Determinants of the Cost of Capital Equipment

While many of the assertions made previously about the relationships between the various attributes of capital equipment and its cost are deducible from physical principles, some empirical verification is desirable. This appendix reports the results of a number of simple regressions which were run in an attempt to explain the component costs of capital equipment. Two different data sets were used, each of which has its own inadequacies.

The data set earlier described as A (Courville's 1960-1966 group) is used, though the capital costs are disaggregated into structures and equipment. The costs are expressed per unit (rather than per plant), as a unit is the fundamental piece of equipment. This assumes plants composed of identical units, which was in general the case with this sample. No deflator was used on the costs.

The second data set was constructed from the biannual surveys of construction costs published in Electrical World.[9] This survey provides much more disaggregated cost figures than does the FPC reports, but only identifies the plants by number (thus making very tedious the task of combining data sets). A plant appears in the survey each time a unit is added, but the figures reported are plant aggregates. In an attempt to isolate unit characteristics, only those plants in which the units were in the same capacity range were included. As capacity was only reported as an ordinal number, the capacity was computed from the peak output deflated by the utilization factor. Three measures of heat rate are given: the actual net, the actual gross and the design value. None of these proved useful in explaining costs. The reasons are, most probably, that the actual figures suffer from being measured in the first year of operation and that the design data appear to have been very loosely collected (on examination it appears that the questionnaire did not make clear whether net or gross design values were desired). The data spanned the years 1956-1965, and as this included the years of the "electric conspiracy," the Handy-Whitman regional deflators for each account were applied, converting costs to 1949 dollars.

For both data sets log-linear equations were fitted. The restrictions imposed by the functional form are recognized, but the small number of data points, the qualitative nature of the investigation, and the simplicity of estimation are the justification for its use. In these regressions, use was made of qualitative data on fuel type, construction type and geographical location by introducing dummy variables. The results are presented in tables C-1 and C-2, with the absence of an entry meaning that the particular variable was not included in the list of regressors. The standard errors of the estimates are shown in parentheses.

Data Set A:

The results using data set A support the intuitive notions about the determinants of cost. The structural cost is apparently not influenced by the efficiency of the plant. There appear to be both economies of scale with size and number of units housed in the structure. Fully outdoor construction requires significantly less expensive structures, and the use of coal requires significantly more expensive. The cost of equipment has significant economies of scale but is influenced far less than the structural cost by the number of units in the plant. The more efficient a unit the higher

---

TABLE C-1

DATA SET A

Dependent Variable	Estimated Coefficients								R
	C	LUS	LNU	LHR	SOD	FOD	CD	GD	
LSC	6.67	0.867 (0.161)	-0.581 (0.170)	-0.298 (1.352)	-0.159 (0.176)	-0.659 (0.159)	0.229 (0.176)	0.040 (0.238)	0.887
LEC	14.98	0.755 (0.092)	-0.092 (0.097)	-0.995 (0.776)	0.111 (0.101)	0.037 (0.091)	0.171 (0.101)	0.001 (0.136)	0.936

39 observations

Variables: LSC - log [structural cost in $1000]
LEC - log [equipment cost in $1000]
C - constant
LUS - log [unit size in megawatts]
LNU - log [number of units in plant]
LHR - log [heat rate in BTU/kwh]
SOD - dummy equal to one if semi-outdoor construction
FOD - dummy equal to one if full outdoor construction
CD - dummy equal to one if any coal used as fuel
GD - dummy equal to one if only gas used as fuel

TABLE C-2

ELECTRICAL WORLD DATA SET

Estimate of Coefficient

Dependent Variable	C	LUS	LNU	LDH	LAH	CD	GD	PAC	PLT	NCN	SCN	NAT	R
LBC	2.336	0.906 (0.063)	- -	- -	0.155 (0.468)	0.437 (0.061)	-0.220 (0.083)	- -	- -	- -	- -	- -	0.944
LBC	8.242	0.846 (0.067)	- -	-0.454 (0.526)	- -	0.422 (0.060)	-0.207 (0.084)	- -	- -	- -	- -	- -	0.944
LBC	1.771	0.860 (0.065)	0.122 (0.051)	0.228 (0.502)	- -	0.405 (0.066)	-0.131 (0.092)	-0.114 (0.112)	0.063 (0.101)	0.092 (0.069)	-0.027 (0.089)	0.282 (0.067)	0.961
LSC	4.467	0.711 (0.114)	-0.174 (0.133)	- -	- -	-0.081 (0.171)	-0.642 (0.241)	-0.693 (0.295)	-0.667 (0.258)	-0.386 (0.182)	-0.281 (0.231)	0.231 (0.176)	0.799
LTC	- 0.443	0.806 (0.058)	0.144 (0.049)	- -	0.519 (0.412)	-0.037 (0.062)	-0.131 (0.087)	-0.101 (0.108)	0.022 (0.094)	-0.019 (0.066)	-0.098 (0.084)	0.035 (0.064)	0.937
LEC	-11.444	0.989 (0.115)	-0.009 (0.089)	1.447 (0.882)	- -	0.200 (0.115)	-0.158 (0.161)	-0.206 (0.197)	0.050 (0.178)	-0.231 (0.122)	-0.199 (0.156)	0.191 (0.119)	0.866
LMC	-19.664	0.857 (0.222)	-0.306 (0.172)	- -	2.160 (1.701)	0.502 (0.222)	-0.123 (0.311)	1.143 (0.380)	0.184 (0.343)	0.416 (0.235)	0.432 (0.302)	0.732 (0.230)	0.699

86 observations

TABLE C-2 (Continued)

riables:
LSC - log [structural cost/unit in $1,000, FPC acct. no. 311]
LBC - log [boiler cost/unit in $1,000, FPC acct. no. 312]
LTC - log [turbogenerator cost/unit in $1,000, FPC acct. no. 314]
LEC - log [electrical accessories cost/unit in $1,000, FPC acct. no. 315]
LMC - log [misc. equip. cost/unit in $1,000, FPC acct. no. 316]

All deflated to 1949 dollars by the appropriate Handy-Whitman regional index.

C - constant
LUS - log [unit size in megawatts]
LNU - log [number of units]
LDH - log [design heat rate in BTU/kwh]
LAH - log [actual net heat rate in BTU/kwh]
CD - dummy equal to one if any coal used
GD - dummy equal to one if only gas used
PAC - dummy equal to one for Pacific region
PLT - dummy equal to one for Plateau region
NCN - dummy equal to one for North Central region
SCN - dummy equal to one for South Central region
NAT - dummy equal to one for North Atlantic region

The reference dummy for fuel type is oil and oil-gas stations.

The reference dummy for region is the South Atlantic region.

is its cost, but the estimates are not significantly different from zero. The equipment costs increase, as expected, with outdoor construction and the use of coal as a fuel.

Electrical World Data Set:

With the greater disaggregation of costs in this data set, it was hoped that better estimates could be achieved. The results were disappointing in one major respect: no satisfactory variation in costs with efficiency could be obtained. This is apparently due to two factors: the actual heat rates given are plant averages during the startup year of a new unit, and the design values given seem not to be consistently gross or net values. Nevertheless, the results are of some interest with regard to the regional cost variations. The results agree well with the previous data set in several respects. It appears that all cost components are subject to increasing returns with unit size, though electrical accessories only slightly. Only structural cost and miscellaneous equipment have increasing returns with the number of units in a plant. Boiler and turbogenerator costs actually seem to increase with the number of units, a result that is evidence of crowding diseconomies. The regional dummies capture two distinct effects: that due to climate and that due to different costs of local labor and materials. Turbogenerators vary little, as these are usually shipped in a preassembled condition. Boiler costs are significantly more expensive in the North Atlantic region as is miscellaneous equipment. Unfortunately, little can be said concerning the effect of heat rate; not even consistency of sign was obtained. It is mainly for this reason that no further use was made of this data set.

APPENDIX D

Percentage Points for Binomial Distribution
n = 39

% of n	Cumulative Probability
97.4358980	0.
94.8717960	0.
92.3076920	0.0000000
89.7435890	0.0000002
87.1794870	0.0000012
84.6153850	0.0000071
82.0512820	0.0000351
79.4871790	0.0001470
76.9230770	0.0005325
74.3589740	0.0016889
71.7948720	0.0047377
69.2307690	0.0118514
66.6666660	0.0266260
64.1025640	0.0540645
61.5384620	0.0997954
58.9743590	0.1683918
56.4102570	0.2611987
53.8461540	0.3746293
51.2820510	0.5000000
48.7179490	0.6253707
46.1538460	0.7388013
43.5897440	0.8316082
41.0256410	0.9002046
38.4615380	0.9459355
35.8974360	0.9733740
33.3333330	0.9881487
30.7692310	0.9952623
28.2051280	0.9983111
25.6410260	0.9994675
23.0769230	0.9998530
20.5128200	0.9999649
17.9487180	0.9999928
15.3846150	0.9999988
12.8205130	0.9999998
10.2564100	1.0000000
7.6923077	1.0000000
5.1282051	1.0000000
2.5641026	1.0000000

FOOTNOTES

1. Reproduced from (6).

2. This is one possible criticism of Galatin's (5) rather thorough study, as he assumes merit order loading rather than the equating of marginal operating costs (a very difficult task) as his rule for partially loading a plant.

3. This is rather an overstatement, as other qualities are needed for engineering purposes. Features such as power factor, behavior to electrical and mechanical transients and maintenance requirements, etc. are all important but can safely be neglected for the purposes of this study.

4. His inclusion of utilization is quite a reasonable way of handling peak loads.

5. Description of the relative phase of the voltage and current in A-C circuits.

6. Appendix C; 'Bi-annual Steam Station Cost Survey', Electrical World.

7. It is worth noting once again that this is merely a test of whether an individual plant has excess capital in relation to its output. Finding no overcapitalization here does not rule it out as it may

be manifesting itself as early unloading of old plants. The only way to attack this problem is tedious and may be totally impractical as it necessitates checking whether the marginal capital costs did in fact equal the marginal fuel saved over the complete life of the plant. While this point is of extreme importance, it was not recognized by any of the other authors; in this section we will continue to look for the more limited effect they were seeking.

8. Reproduced from (6).

9. An industry trade journal published by McGraw-Hill.

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Acknowledgement

Financial support for preparing this paper was provided by Research Assistantships from EQL and Teaching Assistantship from Sloan Foundation.

The patience and helpful comments of James P. Quirk, David M. Grether and Roger G. Noll are gratefully acknowledged.