Chapter IV.3

THE IDENTIFICATION OF TECHNICAL CHANGE IN THE ELECTRICITY GENERATING INDUSTRY*

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1. Introduction

In recent years there have been a number of empirical studies analyzing technical change. Most of these studies have been carried out on a fairly aggregative level – using industry data at the two-digit census classification level, or else totally aggregate data. The purpose of this study is to analyze technical change at the microeconomic level of the individual plant. There are several reasons for wanting to do so. In the first place, the use of aggregate data involves many inherent limitations which make some types of analysis impossible without the use of some untested identifying restrictions. Commonly used restrictions include the assumption of constant returns to scale, the imposition of strong conditions on the nature and structure of technical change, and an amalgamation of the effects of *ex post* and *ex ante* production decisions. The use of plant data permits one to test some of the restrictions, and to circumvent them if they are not satisfied. Second, some of the problems of aggregation, such as index number problems, can be partially avoided. Furthermore, the role of technical change on a micro level is of itself

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interesting. And although one cannot in general use the results of such a micro analysis to make conclusions about the effects on a macro level, except insofar as the particular industry studied is typical of the economy as a whole, the greater possibilities for analysis associated with a micro study (such as the simultaneous use of cross-section and time-series data) make the results of such a study potentially more reliable than those of a macro study. The emphasis of this study is on the determination of the nature of technical change – particularly with regard to the questions of embodiment and neutrality.

The industry chosen for this study is the electric power industry, with attention being focused on steam electric generating plants. The main reason for choosing this particular industry was that data on operation and costs for individual plants are readily available from the Federal Power Commission. This industry is a very important one in the economy in that its output is used by virtually every other sector of the economy. Also, it is one of the largest industries in the United States – in fact, it is by far the largest in terms of gross capital assets.[1]

There have been a number of other studies of technical change for this industry. A survey of these studies has been made by Galatin (1968). Most of these studies, however, have not gone beyond merely trying to measure the extent of technical change and its effects on individual inputs. They have not given much attention to the determination of the nature of technical change. Barzel (1964) does present some evidence of the effect of disembodied technical change on labor, but he failed to fully recognize the significance of his results.[2] A more recent study by Seitz (1968) indicates that there may be a small bias in technical change for the best practice plants. But those results are by no means conclusive; and since they were more or less incidental to the main purpose of his study, he did not pursue the matter very far.

The traits of this industry are rather distinctive. Its input is much more homogeneous than that of most industries – the plants studied all produce just one product: electricity.[3] Hence the only kind of product differentiation is in the type of customer served (e.g., industrial customers generally require higher voltage than residential customers), which is reflected in the rate structure, and in the time when electricity is

[1]See Federal Power Commission (1964, Part 1, p. 11).

[2]An analysis of the effects of disembodied technical change on individual inputs, using analysis of covariance techniques, is given in Belinfante (1969, Ch. V). The results for labor are similar to those of Barzel.

[3]Plants producing steam as a by-product are not included in the FPC reports.

demanded (unit costs during periods of peak demand are usually greater than at other times). The demand for a firm's output is quite predictable. The daily, weekly, and seasonal demand cycles in a given locality are quite stable, and the growth rate is also fairly steady. There are strongly increasing returns to scale, at least at the plant level.[4] The companies in the industry are regulated monopolies. They are regulated by the Federal Power Commission and state agencies. The apparent rate of technological change, as indicated by plant characteristics and factor efficiency, has been fairly rapid. It is a highly capital-intensive industry. The capital stock of a particular plant tends to increase in spurts at discrete time intervals due to an inherent indivisibility of the machines requiring simultaneous installation of boilers and turbogenerators which can, however, come in almost any size.

These traits may make the results of this study somewhat atypical of the economy as a whole; but, nevertheless, the results might be indicative of the types of things which could be occurring elsewhere in the economy. Most of the traits will tend to simplify the analysis somewhat. However, some of them, particularly the existence of economies of scale, are complicating factors.

2. Notation

The following basic notation will be used throughout this paper:

Y = output (in million kilowatt-hours)
R = capacity (continuous capability, in megawatts)
u = capacity utilization factor (ratio of output per hour to capacity)
t = time (in years)
v = vintage (year of initial operation of the plant)
Σu = past use (sum of past capacity utilization factors)
K = measured capital stock (book value, in thousands of dollars)
q = price index of capital goods (based on the Handy–Whitman Index)
$J = K/q$ = real capital stock (adjusted for price change)
L = operation labor input (in man-years)
M = fuel input (in billions of BTU's)
N = index of maintenance input
r = nominal cost of capital (cash flow rate of return)
$s = qr$ = real cost of capital

[4]See, e.g., McFadden (Chapter IV.1) or Nerlove (1963).

w = wage rate of operation labor (in thousands of dollars per man-year)
m = price of fuel (in dollars per million BTU's)
n price of maintenance (in thousands of dollars per index unit)
C $sJ + wL + mM + nN$ = total cost
U = number of boiler–turbine–generator units in the plant
f = proportion of the fuel input which is coal
c = index of the type of plant construction (0 = conventional, 1 = semi-outdoor, 2 = full-outdoor)
$X_z = \partial X/\partial z$ = partial derivative of X with respect to z
$\dot{X} = \mathrm{d}X/\mathrm{d}t$ = time derivative of X
$\mathring{X} = \mathrm{d}X/\mathrm{d}v$ = vintage derivative of X
$T = Y_t/Y$ = rate of disembodied technical change
$S = Y_v/Y$ = rate of embodied technical change
$\Pi_I = Y_I I/Y$ = relative share of factor I
Π^*_I = average share of factor I (e.g., $\Pi^*_L = wL/C$)

Additional notation will be introduced as we go along.

3. Identification Problems in the Measurement of Technical Change

There are a number of identification problems related to the measurement of technical change. The first set of problems to be considered are those concerning the distinction between embodied and disembodied technical change, and the distinction between technical change and capital deterioration. The problems here are primarily related to the problem of how to correctly measure capital input.

Jorgenson (1966b) has shown that as long as old capital remains productive and new investment takes place, "... there is a one-to-one correspondence between indexes of total factor productivity ... and errors in the price of investment goods ... that can make the rate of growth in measured total factor productivity equal to zero. In view of this correspondence one can never distinguish a given rate of growth in total factor productivity from the corresponding rate of growth in the error in measurement of the price of investment goods."[5] But the growth of total factor productivity can be interpreted as disembodied technical change. And the growth of the inverse of the measurement error of the

[5]See Jorgenson (1966b, pp. 7–8).

price of investment goods can be interpreted as being due to quality improvement in investment goods (for which no "adjustment" has been made), which is normally interpreted as embodied change. Since aggregate data always has productive old capital and positive new investment, Jorgenson concludes that it is impossible to distinguish embodied technical change from disembodied change.

To get around this problem, it is necessary either to find data for a sector where capital only has a one period lifetime and is not replaced until it wears out, or else to find a sector for which no new investment occurs. The latter is a possibility if the problem is approached at a sufficiently disaggregative level. This is the approach used below. Observations are made on individual plants during the period between the time when they first go into operation and the time when the first additional investment is made in the plant. Since no new investment is made in the plant during this period, any observed technical change must clearly be disembodied, because embodied technical change is defined as that technical change which requires new investment in the plant in order for it to occur. In this situation, then, disembodied technical change can be isolated, and hence identified, by using appropriate microeconomic data. Any additional technical change which is observed between plants of different vintages can then be taken to be embodied technical change. A key factor, however, in such an estimation of the rate of embodied change is the choice of an appropriate price deflator for capital. A change in this deflator will cause a corresponding change in the estimates of embodied change.

Hall (1968) has shown that if the rate of embodied technical change is taken to be a constant function of vintage, the rate of disembodied technical change is taken to be a constant function of time, and the rate of capital deterioration is taken to be a constant function of age (i.e., time minus vintage), then it is impossible to empirically distinguish these three effects. This result stems from the nature of the exponential functions which yield constant growth rates and from the fact that there are really only two variables (time and vintage) to which the three effects are related.

Hall shows "that if data on the prices of used machines and the interest rate are available, then the index of embodied technical change and the deterioration function can be identified".[6] However, the prices

[6]See Hall (1968, p. 43).

of used machines are often hard to come by. But there is another way of getting around this identification problem – namely, by reformulating the deterioration function, making use of the data on plant utilization which is sometimes available on a microeconomic level. This technique cannot be used with aggregate data, because the necessary information is not available on an aggregate level. The technique used in this study depends on the observation that a considerable portion of the deterioration of a plant is not due simply to the aging of the plant, but rather it is due to the wear and tear from the accumulated past use of the plant. Admittedly there may be some purely "aging" deterioration, particularly if the plant is not extensively used and gets rusty, etc., from disuse. But for plants that are used reasonably extensively, most of the plant deterioration is undoubtedly of the "wear and tear" variety. Also, to the extent that technological progress is achieved by "learning by doing", accumulated past use might indicate some degree of technical change. However, the extent of this effect is probably small. Thus, by using accumulated past plant utilization to measure deterioration, this identification problem is virtually solved since the effects of time can now be associated solely with disembodied technical change, and the effects of vintage solely with embodied change.[7]

Just as it is possible to eliminate the effects of embodied technical change by choosing the sample in such a way that comparisons are only made between successive annual observations of a given plant (thus holding vintage fixed), it is also possible to largely eliminate the effects of either disembodied technical change or deterioration by an appropriate choice of a sample. Disembodied technical change can be largely eliminated by making cross-sectional comparisons of plants of different vintages within a specific year only. By limiting the observations to one year, all the plants will have equal opportunities to take advantage of the changes in technology which can be reflected in disembodied technical change. Thus, theoretically at least, any observed technological differences between plants of different vintages should be due to embodied technical change. In practice, however, this separation of the effects of the two different types of technical change may not quite be perfect if the plants do not all have equal rates of disembodied

[7]If one accepts the existence of "aging" deterioration and "learning by doing" technical change, then this separation of the effects is not quite complete. However, since all our estimates of the deterioration rate and the rates of technical change had the correct sign, the separation is probably good enough for all practical purposes.

technical change;[8] but such differences are probably small and tend to average out. Thus the effects of this on the estimates of the average rates of technical change are probably relatively negligible. Similarly, plant deterioration effects can be largely eliminated by restricting the sample to comparisons between plants of equal past utilization, i.e., equal values of Σu. For older plants it is practically impossible to find sufficiently close matches of Σu for this purpose, but such matches can be obtained by comparing very young plants – particularly for plants observed in their first full year of operation, for which Σu is near zero. In this case the observed differences between the plants reflect the combined effects of embodied and disembodied technical change; it is not necessary to make any adjustments for plant deterioration. Another advantage of restricting the sample to plants in the first full year of operation is that the *ex post* deviations from *ex ante* plant designs are undoubtedly relatively small for most new plants.

The next identification problem that needs to be considered is one concerning the distinction between the bias of technical change and the elasticity of substitution. In Chapter IV.2, Diamond, McFadden and Rodriguez have shown that in the absence of *a priori* information about the nature of the production function and the nature of technical change, it is impossible to identify the bias of technical change and the elasticity of substitution. This result stems from the fact that the equation (for the case where there are two factors of production, capital and labor)[9]

$$\frac{\mathrm{d}\ln(w/r)}{\mathrm{d}t} = \frac{1}{\sigma}\frac{\mathrm{d}\ln(K/L)}{\mathrm{d}t} + B \tag{3.1}$$

is the only observable relation defining these two effects. The two time derivatives are observable functions of the prices and quantities of the factor inputs. But σ and B are unknown functions representing the

[8]For example, if a plant's rate of disembodied technical change is affected by its learning experiences from its own operations, and if these experiences differ from those experienced at other plants to which it is compared. However, it is assumed here that most disembodied technical change is industry-wide as a result of things such as (i) generally disseminated knowledge of ways of improving operating efficiency (e.g., through trade publications such as *Electrical World*), and (ii) common experiences within the various power companies in learning ways of improving efficiency. Since this is not a competitive industry, the firms in the industry gain no competitive advantage from regarding ways of improving efficiency as "trade secrets"; hence, the dissemination of knowledge about technical change through the industry is probably somewhat faster than in other, more competitive, industries.

[9]"ln" means natural logarithm.

elasticity of substitution and the bias of technical change, respectively. Hence, in the absence of identifying restrictions on σ and B, the effects cannot be identified. One of the simplest identifying restrictions that can be made is to assume that these functions are constants. This is the approach used below. However, Diamond, McFadden and Rodriguez also discuss various other sets of identifying restrictions which can be used to identify the elasticity and the bias. One such set of restrictions assumes that technical change is purely factor augmenting, and that the functional forms of the coefficients of factor augmentation can be represented by a limited number of parameters. This approach has been used by Shapiro (1966) with aggregate time series data. This more general approach was not used here primarily because the analysis for this industry is complicated by two other types of possible bias which are discussed below. It might be noted, however, that in testing for the possible non-constancy of the *ex ante* elasticity of substitution between capital and labor in this industry, McFadden (Chapter IV.1) was not able to reject the hypothesis that the elasticity is constant. At any rate, a solution to this identification problem is possible through the introduction of parameters which can be estimated by regression analysis.

Another important problem is the effect of non-constant returns to scale. Again, without *a priori* information about the nature of the production function and the nature of technical change, there is an identification problem, this time involving the rate of technical change, the rate of plant deterioration, and the degree of returns to scale. In the estimation of disembodied change, the equation[10]

$$\dot{Y}/Y = T + \phi H - D\dot{\Sigma}u, \tag{3.2}$$

which is derived below, demonstrates the relation between these effects. $\dot{Y}/Y$, H, and $\dot{\Sigma}u$ are observable functions of output, input, and plant use, respectively. But T, ϕ, and D are all unknown functions. T represents the rate of disembodied technical change, ϕ represents the degree of returns to scale, and D represents the rate of plant deterioration. A similar relationship holds between embodied technical change and returns to scale.[11] Since this is the only observable relationship between these functions, their effects are not distinguishable unless some identifying restrictions are imposed on them. As in the situation just discussed above, a solution to this identification problem is possible by a

[10]This is the same as equation (5.12).

[11]See equation (6.9).

parameterization of the three unknown functions. This is the approach used below.

If there is a bias in the returns to scale (which is generally the case for non-homothetic production functions) and/or a deterioration bias, then there is an identification problem involving the scale bias, the deterioration bias, the bias of technical change, and the elasticity of substitution. In this case, equation (3.1) should be modified to become

$$\frac{\mathrm{d}\ln(w/r)}{\mathrm{d}t} = \frac{1}{\sigma}\frac{\mathrm{d}\ln(K/L)}{\mathrm{d}t} + \zeta\frac{\mathrm{d}\ln Y}{\mathrm{d}t} + \delta\frac{\mathrm{d}\,\Sigma u}{\mathrm{d}t} + B, \tag{3.3}$$

where ζ is an unknown function representing the bias in the returns to scale, and δ is an unknown function representing the deterioration bias. Again, a solution to this identification problem can be found through a parameterization of the unknown functions. As indicated above, the approach used below is to take the simplest possible parameterization, where the unknown functions are assumed to be constants.

All of the parameterizations involved in these identifying restrictions require "using up" some of the available degrees of freedom. But if the number of parameters is reasonably small there will still be a sufficient number of degrees of freedom left over for testing further hypotheses. Of course, the parameterizations involve the introduction of untested *a priori* assumptions about the nature of the processes involved. However, it is hoped that the assumptions involved are sufficiently general so as to not unduly restrict the validity of the conclusions reached.

4. The Industry and the Data

Only a brief discussion of the industry and the data will be presented here. A fuller discussion may be found elsewhere.[12]

The attention of this study is directed at privately-owned post-World War II steam-electric generating plants. Plants owned by governments (Federal, state, and local) and cooperatives were excluded from the study primarily because of a lack of comparable data, especially with regard to capital costs. Other types of generating plants (hydroelectric, nuclear, gas turbine, and internal combustion engine) were excluded

[12]See Chapter III and the Statistical Appendix of Belinfante (1969). That Appendix contains tables of all of the data used in this study.

because of a lack of direct comparability with the steam plants in the production process.

Currently most of the United States' electricity production is concentrated in plants constructed after World War II. Between 1946 and 1964, 321 plants were constructed, accounting for over 82% of the total steam-electric generating capacity at the end of that period. Since technological obsolescence leads to the operation of plants more than about 15 years old primarily during periods of peak demand only,[13] production is concentrated even more highly in the new plants.

Technological change in this industry has always been fairly rapid. This progress has largely been made possible by developments in high-temperature metallurgy, in the techniques of metal fabrication, and in instrumentation. Important technological developments since the war include an increasing feasible size of generating units, higher steam temperatures and pressures, the use of reheat cycles in the boilers, the use of outdoor or semi-outdoor types of construction for plants, the use of partial or full plant automation, centralization of controls, and greater integration of power systems. The last of these has been made possible by improved transmission lines, and has permitted more economical location of new plants, such as at mine mouths (greatly reducing fuel costs).[14]

These innovations have led to important improvements in factor productivity. From 1945 to 1960, average labor productivity rose from 4.2 kwh per man-hour to 11.0 kwh per man-hour. From 1947 to 1962, the average heat rate fell from 15,600 Btu/kwh to 10,558 Btu/kwh. The average thermal efficiency increased from 21.88% to 32.35%.[15]

However, some of these improvements in productivity were probably due to increasing returns to scale. Based on engineering cost data for 1964, the elasticity of capacity with respect to total cost (an index of returns to scale) can be calculated as ranging from 1.14 to 1.20.[16] Also, some of the improvements in labor and fuel productivity may have been due to the substitution of capital for these factors.

The steam-electric plants produce just one output – electric power,

[13]See Federal Power Commission (1964, Part 1, pp. 119–120).

[14]See Federal Power Commission (1964, Part 1, pp. 64–65), and Federal Power Commission (b) (1966, pp. ix–xi).

[15]See Federal Power Commission (1964, Part 1, p. 67) and Federal Power Commission (b) (1966, p. XXX).

[16]Based on the assumptions that the plant has two units, is operated at 65% of capacity, and incurs a capital service cost equal to 10% of the initial investment cost and a fuel cost equal to 25 cents per million Btu. See Federal Power Commission (1964, Part 1, p. 70).

generally measured in kilowatt hours. The prices (rates) which the companies charge for the electricity are generally set by the companies with the approval of a state regulatory commission. Once the rates have been set, the companies are obliged to supply instantaneously the entire amount of electricity demanded at any time by every customer at the prevailing rates. This means that a company's generating capacity must be at least as large as is required to meet the peak demand.

The main inputs required to produce electricity in steam-electric generating plants, together with their average shares of the total costs of production for the plants used in this study are: fuel – 49%, capital – 39%, operation labor – 7%, and maintenance – 5%. However, there is a considerable amount of variation in these proportions from plant to plant.

The fuels used by the steam plants are coal, gas, and oil, which respectively accounted for 66%, 27%, and 7% of the total electricity generated by these plants in the early 1960's.[17] Many plants are built to be able to burn alternative fuels interchangeably upon short notice. The adaptation of a coal plant to handle gas or oil is relatively inexpensive, but the adaptation of a gas or oil plant to handle coal is rather expensive. This is because a coal-burning plant generally requires 10% to 15% more capital investment, primarily in coal and ash handling equipment and more expensive boiler design. On the other hand, coal has a greater thermal efficiency – typically requiring about 3% to 5% fewer Btu's per kwh than gas, with oil occupying an intermediate position.

In areas with relatively mild climates, such as the South and Far West, there has been a tendency to construct plants with outdoor boilers or with virtually the entire plant outdoors, rather than using the conventional structures housing all of the plant's equipment. This results in reduced capital expenses, but because of the exposure of the plant to the weather, somewhat increased maintenance expenses are required for such non-conventional plants. Thus this provides an opportunity for substitution between capital and maintenance.

The efficiency of each of the plant's machines can be improved by increasing the investment made in them. This is a major source of possible substitution between capital and other factors. Increasing the size of the boiler–turbine–generator units generally also increases efficiency. Thus, for example, one 200 mw unit would be more efficient than two 100 mw units.

[17]See Federal Power Commission (b) (1964, p. XVIII).

There is considerable variation in the unit costs of operation labor. Unit costs tend to fall significantly with the scale of the plant. They tend to rise as the utilization of the plant capacity falls. There is usually not much variation in the number of employees in a given plant as its capacity utilization varies.

Unit maintenance costs tend to fall significantly with scale for plants with capacities up to about 300 megawatts, after which they level off. Labor costs usually account for about 50% to 75% of the total maintenance bill, with considerable variation from plant to plant, but not too much variation for a given plant over time. The labor component is usually somewhat higher for coal-fired plants than for non-coal-fired plants.

The designed capacity of a plant is largely determined by the expected demand for electricity in its service area, and also by the technological limits on plant size at the time it is built. The size limitations are usually quickly exploited as soon as they are expanded because of rapidly increasing demand and because of the extensive economies of scale which exist. However, it is important that a plant not be built too large relative to the demand for its output, because the capacity utilization factor of the plant is an important determinant of its efficiency. Most plants achieve optimal fuel heat rates at capacity utilization factors of around 80% to 90%, with a substantial deterioration in the heat rate occurring for capacity utilization factors below 50%.[18] Also, labor and maintenance inputs show little variation with output, resulting in lower unit costs for higher capacity utilization factors. And of course fixed capital charges do not vary with output at all. Thus it is generally not advisable to build a plant too much larger than the foreseeable demand for its output.

The primary source of the data used in this study was the plant reports of the Federal Power Commission (b). These were supplemented by the company reports of the Federal Power Commission (a), the *Electrical World* cost survey (bi-annual) and the Handy–Whitman Indexes (Whitman, Requardt and Associates, semi-annual).

The sample used in this study consists of 460 annual observations on 80 steam-electric generating plants, with from two to 14 observations per plant. The sample was limited to United States plants which went into service between 1947 and 1959, and which had no generating units added to them in at least the two years following their initial year of operation.

[18]See Zerban and Nye (1956, p. 516).

This was done to avoid as much as possible any confusion as to the chronological vintage of each of the plants. The plants were not observed in the initial year of their operation because during that year they operated only from the date they went into service, and not during the entire year. Hence, the figures for that year are not comparable with those of subsequent full years of operation. Each plant was observed for every full year of operation following the year it went into service. The observations continued through 1961, or until additional units were added to the plant, whichever came first. A number of plants were excluded from the sample because of missing data, including all plants owned by governments and co-operatives.

Probably the most crucial data problem for the estimation of the rate of embodied technical change is the choice of an appropriate capital price deflator. It is necessary to use such a deflator because the reported capital stock figures are expressed in current dollar terms. Thus, in order to make the figures comparable for plants constructed in different years, it is necessary to deflate the vintage cost figures by an appropriate price index to remove the effects of inflation. The index used should only reflect the effects of inflation, and thus should be based on constant-quality components. The index used in this study was based on the Handy–Whitman Index for total steam production plant costs. Since the differences between the six regional Handy–Whitman Indexes have dubious cross-sectional meaning (they all have 1911 = 100), the six figures were averaged to form one composite figure. This composite index was converted to the base 1957–59 = 1.00 for greater ease of interpretation. To allow for the fact that there is some time lag in plant construction, the average value of the index for the two years preceding the first full year of plant operation was used. The items covered by the index correspond very closely with those included in the capital stock figures used here. (The main discrepancy is that the index excludes land, which is usually only a small part of the costs anyway.) Although the description of the index does not clearly state whether constant quality components are used in the computation of the index, an article by Whitman and North (1953) seems to indicate that they probably are. Further light on the appropriateness of this index is provided by the comparison of it with another index of a similar nature which was used by Seitz (1968). This index was computed by Seitz from components supplied by the Bechtel Co. The components were price indexes for materials (steel, concrete, wire, wood, etc.) and labor used to manufacture the equipment of a power plant, and the construction machinery and field labor necessary to build the plant. By its inherent nature, this index is free of the technology and quality of machines problem. A comparison of this index with the Handy–Whitman Index[19] shows that the major discrepancy between the two during the post-World War II period occurs between 1955 and 1962. During the first few years of this period the Handy–Whitman Index rose much faster than the Bechtel–Seitz Index, and during the last few years the Handy–Whitman Index declined while the Bechtel–Seitz Index continued to rise. This discrepancy is easily explained as reflecting the changing profit margins of the electric equipment suppliers. In 1955, the equipment suppliers began the most substantial phase of the collusion involving price fixing which ultimately led to the anti-trust case against this conspiracy in 1960. Thus during the first few years of this period, the suppliers could charge prices resulting in increasingly larger profit margins, until they reached monopoly profit proportions. They then maintained their profits at this higher level until the case broke when the government took action. At that point they were forced to lower their prices again until they achieved more reasonably competitive profit margins in 1962.[20] Since the Bechtel–Seitz Index is based on the prices of the materials used by these equipment suppliers rather than the prices of their finished products, it does not reflect these changing profit margins. Since the rates charged by the power companies during this and subsequent periods were based on the actual cost of this equipment, rather than the lower costs that they would have incurred if the suppliers had been truly competitive, the Handy–Whitman Index is clearly more appropriate than the Bechtel–Seitz Index.[21]

5. The Measurement of Disembodied Technical Change

There are a number of ways to approach the measurement of technical change. Attention here will be focused on a variant of the non-parametric Divisia Index approach popularized by Solow (1957).

The standard non-parametric measure of technical change for a production process with one output, Y, and four inputs, J, L, M, and N,

[19]See Seitz (1968, Ch. III).

[20]See Brooks (1963, Ch. V) and Wall Street Journal (1962).

[21]Even though most of the utilities have subsequently received damage claims corresponding to this price differential, their rate bases in many cases have not been reduced correspondingly. See Metcalf and Reinemer (1967, Ch. VII).

is

$$S + T = \frac{\dot{Y}}{Y} - \Pi_J \frac{\dot{J}}{J} - \Pi_L \frac{\dot{L}}{L} - \Pi_M \frac{\dot{M}}{M} - \Pi_N \frac{\dot{N}}{N}. \tag{5.1}$$

This measure can be derived from the production function

$$Y = g(J,L,M,N,t). \tag{5.2}$$

Under the conditions of cost minimization and constant returns to scale, the relative factor shares are equal to the average factor shares, and the sum of the factor shares is equal to one.

However, for the electric power industry, the direct use of such a measure of technical change is untenable for several reasons. In the first place, there is substantial evidence of increasing returns to scale. Second, a production function such as (5.2) implicitly assumes that the capital input can, in each time period, be determined independently of the level of its input in previous time periods. This violates the durable nature of capital, which is an important consideration for successive observations on a single plant. In particular, for our sample, the observations on each plant are such that the available capital input, J, is the same for all periods of observation on that plant. Thus the capital input is fixed *ex post*, not variable. Third, (5.2) does not take into consideration the capacity limitations of a plant, and the consequences of operating a plant at less than full capacity. Fourth, no account is taken of plant deterioration. Finally, it is not clear that the explicit nature of (5.2) is appropriate for this industry. In testing the nature of the *ex ante* production function, McFadden (Chapter IV.1) found that it is not homothetic in capital and labor. This lack of homotheticity is also implicitly recognized by Barzel (1964) and Galatin (1968), since they note different degrees of returns to scale for different factors of production. It can be shown that a non-homothetic production function must generally be stated implicitly, not explicitly. Thus, it should be given in the more general implicit form

$$F(Y,J,L,M,N,t) = 1. \tag{5.3}$$

Hence, it is apparent that modifications of (5.1) should be considered before it is blindly applied to this industry.

Let us begin by considering variations in output and efficiency of a plant which is in operation and which has no gross investment made in it during its observation period. Any technical change observed for such a plant must be disembodied. Such a plant will face an *ex post* production function relating inputs and output. It is necessary to bear in mind that if the plant is not operated at full capacity, the available capital may not be fully utilized. Let $J^* = h(u)J$ represent utilized capital, where $h(u)$ is some function of the capacity utilization factor. We must also take account of plant deterioration. Since the state of a plant's deterioration is largely determined by how worn out it is from previous use, a reasonable measure of the state of deterioration is the extent to which it has been used in the past, Σu, the sum of past capacity utilization factors. Thus the *ex post* production function can be given as

$$G(Y,J^*,L,M,N,\Sigma u,t) = 1. \tag{5.4}$$

The rate of disembodied technical change is defined as the possible rate of change in output, with no change in inputs or plant condition, i.e.,

$$T = Y_t/Y = -G_t/G_Y Y. \tag{5.5}$$

Before deriving the appropriate computational formula for T, it is necessary to consider the effect of returns to scale on the measurement of the relative factor shares. Assuming that the plant minimizes short-run costs each year, it faces the following Lagrangian problem:

$$\min C = sJ + wL + mM + nN + \lambda[1 - G(Y,J^*,L,M,N,\Sigma u,t)],$$

where sJ is the fixed capital cost, and the Lagrangian multiplier $\lambda \neq 0$. To find the minimum cost for a given level of output in a given year, set $C_L = w - \lambda G_L = 0$, $C_M = m - \lambda G_M = 0$, $C_N = n - \lambda G_N = 0$, and $C_{J^*} = -\lambda G_{J^*} = 0$.

Hence

$$G_L = w/\lambda, \quad G_M = m/\lambda, \quad G_N = n/\lambda, \quad G_{J^*} = 0. \tag{5.6}$$

Now consider the value of the sum of the relative shares of the factor inputs

$$\begin{aligned} \Pi_{J^*} + \Pi_L + \Pi_M + \Pi_N &= \frac{Y_{J^*}J^*}{Y} + \frac{Y_L L}{Y} + \frac{Y_M M}{Y} + \frac{Y_N N}{Y} \\ &= -\frac{G_{J^*}J^* + G_L L + G_M M + G_N N}{G_Y Y} \\ &= 0 - \frac{WL + mM + nN}{\lambda G_Y Y} \\ &= -\frac{1}{\lambda G_Y}\left(\frac{wL + mM + nN}{Y}\right). \end{aligned}$$

The term in parentheses is average variable cost, which can also be written as $(C - sJ)/Y$. Consequently, the sum of the relative shares (with $\Pi_{J^*} = 0$) is

$$\Pi_L + \Pi_M + \Pi_N = -\frac{1}{\lambda G_Y}\left(\frac{C - sJ}{Y}\right). \tag{5.7}$$

Now let $\phi = (\Pi_L + \Pi_M + \Pi_N)/(\Pi_L^* + \Pi_M^* + \Pi_N^*)$, the ratio of the sums of the relative and average shares of the variable inputs. We can also write $\phi = (\Pi_L + \Pi_M + \Pi_N)/(1 - \Pi_J^*)$, since $\Pi_J^* + \Pi_L^* + \Pi_M^* + \Pi_N^* = 1$. But $1 - \Pi_J^* = 1 - sJ/C = (1/C)(C - sJ)$. Hence

$$\phi = \frac{(\Pi_L + \Pi_M + \Pi_N)}{\{(1/C)(C - sJ)\}},$$

or $\Pi_L + \Pi_M + \Pi_N = (\phi/C)(C - sJ)$. Substituting this into (5.7), we have

$$\phi/C = -1/\lambda G_Y Y, \text{ or}$$
$$G_Y = -C/\lambda\phi Y. \tag{5.8}$$

If the production function is homothetic in all variable inputs, then ϕ will be a constant scale parameter. But for a non-homothetic function, ϕ is not in general a constant. Various functional forms are tested in the empirical work reported below.

We are now in a position to compute the rate of disembodied technical change. Taking the time derivative of (5.4), we have

$$G_Y\dot{Y} + G_{J^*}\dot{J}^* + G_L\dot{L} + G_M\dot{M} + G_N\dot{N} + G_{\Sigma u}\dot{\Sigma}u + G_t = 0. \tag{5.9}$$

Dividing through by $G_Y Y$ and noting that $G_{J^*} = 0$, this becomes

$$\frac{\dot{Y}}{Y} + \frac{G_L\dot{L}}{G_Y Y} + \frac{G_M\dot{M}}{G_Y Y} + \frac{G_N\dot{N}}{G_Y Y} + \frac{G_{\Sigma u}\dot{\Sigma}u}{G_Y Y} = -\frac{G_t}{G_Y Y} = T. \tag{5.10}$$

Now, substituting the relations (5.6) and (5.8) into (5.10), we have

$$T = \frac{\dot{Y}}{Y} - \frac{w/\lambda}{C/\lambda\phi}\dot{L} - \frac{m/\lambda}{C/\lambda\phi}\dot{M} - \frac{n/\lambda}{C/\lambda\phi}\dot{N} - \frac{Y_{\Sigma u}}{Y}\dot{\Sigma}u.$$

Letting $D = -Y_{\Sigma u}/Y$, the rate of plant deterioration, this expression becomes

$$T = \frac{\dot{Y}}{Y} - \phi\frac{wL}{C}\frac{\dot{L}}{L} - \phi\frac{mM}{C}\frac{\dot{M}}{M} - \phi\frac{nN}{C}\frac{\dot{N}}{N} + D\dot{\Sigma}u,$$

or

$$T = \frac{\dot{Y}}{Y} - \phi\left(\Pi_L^*\frac{\dot{L}}{L} + \Pi_M^*\frac{\dot{M}}{M} + \Pi_N^*\frac{\dot{N}}{N}\right) + D\dot{\Sigma}u. \tag{5.11}$$

The rate of plant deterioration, D, is not necessarily a constant. It may be a function of various factors. Several factors are tested below. It should naturally be expected that $Y_{\Sigma u}$ be negative, making D positive. Now, if we let

$$H = \Pi_L^* \frac{\dot{L}}{L} + \Pi_M^* \frac{\dot{M}}{M} + \Pi_N^* \frac{\dot{N}}{N},$$

we can rewrite (5.11) as

$$\dot{Y}/Y = T + \phi H - D\dot{\Sigma}u, \tag{5.12}$$

where $\dot{Y}/Y$, H, and $\dot{\Sigma}u$ are measurable, and T, ϕ, and D are unknown functions. Under certain conditions, (5.12) may be amenable to linear regression analysis. A sufficient set of conditions would be for ϕ and D to be linear functions, and for T to be distributed normally and independently of H and $\dot{\Sigma}u$. In applying (5.12) to the annual observations of steam plants, the three measurable variables were estimated by the following approximations:[22]

$$\frac{\dot{Y}}{Y} = \frac{\Delta Y}{\bar{Y}}, \quad H = \bar{\Pi}_L^* \frac{\Delta L}{\bar{L}} + \bar{\Pi}_M^* \frac{\Delta M}{\bar{M}} + \bar{\Pi}_N^* \frac{\Delta N}{\bar{N}}, \quad \dot{\Sigma}u = \bar{u}.$$

The explanation for the last of these is as follows: The discrete equivalent of the time derivative is the change from the first year to the second, $\Delta\Sigma u$. But Σu at the beginning of a year would be the sum of all u's for all previous years, $\sum_{i=v}^{t-1} u_i$, while at the end of that year it would be the sum of all u's for all years, $\sum_{i=v}^{t} u_i$. Assuming that the demand on the plant is roughly spread out evenly during the year, the average value of Σu during the year would be $\sum_{i=v}^{t-1} u_i + \frac{1}{2}u_t$. Hence $\Delta\Sigma u$ between years t and $t+1$ would be

$$\sum_{i=v}^{t} u_i + \tfrac{1}{2}u_{t+1} - \left(\sum_{i=v}^{t-1} u_i + \tfrac{1}{2}u_t\right) = u_t + \tfrac{1}{2}u_{t+1} - \tfrac{1}{2}u_t$$

$$= \tfrac{1}{2}u_{t+1} + \tfrac{1}{2}u_t = \bar{u}.$$

The next problem to be solved is the determination of the functional form of ϕ. The following variables were tested for inclusion in ϕ:[23] $\bar{u}$, $\bar{u}^2$,

[22] If the subscript 1 refers to the first of a pair of consecutive years, and the subscript 2 refers to the second, $\Delta X = X_2 - X_1$ and $\bar{X} = (X_1 + X_2)/2$. The alternative approximations $\dot{Y}/Y = \Delta \ln Y$, etc., could have been used instead, but were found to be less convenient computationally. This alternative was tried in one instance and yielded results similar to those reported below.

[23] $k = J/R$, the capital–capacity ratio.

$\bar{u}^3$, $\bar{u}^4$, $\bar{u}^5$, $\ln \bar{u}$, $(\ln \bar{u})^2$, $(\ln \bar{u})^3$, $(\ln \bar{u})^4$, $(\ln \bar{u})^5$, $\bar{f}$, $\bar{\Pi}_J^*$, $\bar{\Pi}_L^*$, $\bar{\Pi}_M^*$, $\bar{\Pi}_N^*$, k, c, U, v, R, and R/U. The various powers of $\bar{u}$ and $\ln \bar{u}$ were tested to measure the *ex post* scale effects of varying levels of output for a given plant. R, R/U, k, c, U, and v were tested to measure the *ex ante* effects of scale, capital intensity, plant design, and embodied technology. The remaining factors, $\bar{f}$, $\bar{\Pi}_J^*$, $\bar{\Pi}_L^*$, $\bar{\Pi}_M^*$, and $\bar{\Pi}_N^*$, are partly functions of the *ex ante* plant design and partly functions of *ex post* decisions and price changes.

Finally, there is the problem of the determination of the functional form of D. It was felt that the rate of deterioration might increase as a plant becomes older and more worn out. Hence $\overline{\Sigma u}$ was tested for inclusion. In addition, all of the factors tested for inclusion in ϕ were also tested for inclusion in D.

With these functional forms for ϕ and D, (5.12) becomes

$$\begin{aligned}\Delta Y/\bar{Y} = \bar{T} &+ \phi_0 H + \phi_1 \bar{u} H + \phi_2 \bar{u}^2 H + \phi_3 \bar{u}^3 H + \phi_4 \bar{u}^4 H + \phi_5 \bar{u}^5 H \\ &+ \phi_6 (\ln \bar{u}) H + \phi_7 (\ln \bar{u})^2 H + \phi_8 (\ln \bar{u})^3 H + \phi_9 (\ln \bar{u})^4 H \\ &+ \phi_{10} (\ln \bar{u})^5 H + \phi_{11} \bar{f} H + \phi_{12} \bar{\Pi}_J^* H + \phi_{13} \bar{\Pi}_L^* H + \phi_{14} \bar{\Pi}_M^* H \\ &+ \phi_{15} \bar{\Pi}_N^* H + \phi_{16} k H + \phi_{17} c H + \phi_{18} U H + \phi_{19} v H \\ &+ \phi_{20} R H + \phi_{21} (R/U) H + D_0 \bar{u} + D_1 \bar{u}^2 + D_2 \bar{u}^3 + D_3 \bar{u}^4 \\ &+ D_4 \bar{u}^5 + D_5 \bar{u}^6 + D_6 (\ln \bar{u}) \bar{u} + D_7 (\ln \bar{u})^2 \bar{u} + D_8 (\ln \bar{u})^3 \bar{u} \\ &+ D_9 (\ln \bar{u})^4 \bar{u} + D_{10} (\ln \bar{u})^5 \bar{u} + D_{11} \overline{fu} + D_{12} \bar{\Pi}_J^* \bar{u} + D_{13} \bar{\Pi}_L^* \bar{u} \\ &+ D_{14} \bar{\Pi}_M^* \bar{u} + D_{15} \bar{\Pi}_N^* \bar{u} + D_{16} k \bar{u} + D_{17} c \bar{u} + D_{18} U \bar{u} + D_{19} v \bar{u} \\ &+ D_{20} R \bar{u} + D_{21} (R/U) \bar{u} + D_{22} \overline{\Sigma u}\, \bar{u} + \tau, \qquad (5.13)\end{aligned}$$

where $\bar{T}$ is the mean value of T, and $\tau = T - \bar{T}$. Obviously it would be impractical to try to estimate (5.13) directly as it is written, because it contains far too many terms, many of which are undoubtedly not significant.[24] Consequently, it was estimated using stepwise regression, initially forcing $\bar{T}$, ϕ_0, and D_0 into the regression, and then stepwise adding additional terms with coefficients significant at at least the 5% significance level. The following regressions were computed with 379 observations, each calculated from a consecutive pair of years for a

[24]It also suffers from unnecessarily excessive multicollinearity, since many of the terms (e.g., the powers of $\bar{u}$) measure essentially the same thing. Since the primary interest here is in accounting for sources of "nuisance" variation, and not so much in obtaining precise estimates of the "nuisance" parameters, the existence of such multicollinearity is not as severe a problem as it might otherwise be. The use of stepwise regression tends to hold down the number of such multicollinear variables which are actually included in the estimated equations, thus keeping the number of "nuisance" parameters estimated at a minimum.

given plant, on the 80 steam plants in the sample. The stepwise regression results were as follows:[25]

$$\Delta Y/\bar{Y} = \underset{}{0.00063} + \underset{(0.039)}{2.195H} - \underset{(0.0169)}{0.0069\bar{u}} \qquad (\bar{R}^2 = 0.892), \qquad (5.14)$$

$$\Delta Y/\bar{Y} = 0.00694 + \underset{(0.163)}{4.188H} - \underset{(0.332)}{4.148\bar{\Pi}^*_M H} - \underset{(0.0143)}{0.0143\bar{u}} \qquad (\bar{R}^2 = 0.923), \qquad (5.15)$$

$$\Delta Y/\bar{Y} = 0.00766 + \underset{(0.320)}{2.913H} - \underset{(0.501)}{2.389\bar{\Pi}^*_M H} - \underset{(0.128)}{0.587(\ln \bar{u})H}$$
$$- \underset{(0.0139)}{0.0147\bar{u}} \qquad (\bar{R}^2 = 0.927), \qquad (5.16)$$

$$\Delta Y/\bar{Y} = 0.00671 + \underset{(0.318)}{2.928H} - \underset{(0.499)}{2.416\bar{\Pi}^*_M H} - \underset{(0.127)}{0.582(\ln \bar{u})H}$$
$$- \underset{(0.0149)}{0.0029\bar{u}} - \underset{(0.0081)}{0.0171\bar{f}\bar{u}} \qquad (\bar{R}^2 = 0.928). \qquad (5.17)$$

Finally, since the coefficient of $\bar{u}$ in (5.17) is considerably less than its standard error, and since $\bar{u}$ appears elsewhere, the term $D_0\bar{u}$ was dropped, yielding

$$\Delta Y/\bar{Y} = \underset{(0.00375)}{0.00511} + \underset{(0.318)}{2.927H} - \underset{(0.498)}{2.145\bar{\Pi}^*_M H} - \underset{(0.127)}{0.582(\ln \bar{u})H}$$
$$- \underset{(0.0075)}{0.0176\bar{f}\bar{u}} \qquad (\bar{R}^2 = 0.928). \qquad (5.18)$$

None of the remaining terms in (5.13) proved to be significant after the estimation of (5.17) or (5.18). Hence (5.18) is the final estimate of (5.12).

The results emerging from the above regressions are the following: The average rate of disembodied technical change over the sample was a little over 0.5% per year. The estimate has the expected sign, but it is not significantly different from zero at the 5% significance level. It is greater than its standard error, however, and it would be significant at the 20%

[25]The numbers in parenthesis are standard errors. The regression program used did not report the standard errors of the intercept T, but its standard error in equation (5.18) was computed separately with another computer program. The reported coefficients of determination, $\bar{R}^2$, are corrected for degrees of freedom.

level. The rate of deterioration is significantly greater for coal burning plants than for non-coal burning plants, whose average deterioration rate is negligible. Since the average value of $\bar{u}$ over the sample was 0.63 and the average value of $f\bar{u}$ was 0.38, the average rate of plant deterioration ranged from less than 0.2% per year for plants burning no coal to over 1.1% per year for plants burning only coal, with an overall average of about 0.7% per year. For (5.14), $\phi = 2.2$, while for (5.18), $\bar{\phi} = 2.93 - 2.4(0.49) - 0.58(-0.51) = 2.0$, when evaluated at the mean values of $\bar{\Pi}_M^*$ and $\ln \bar{u}$. But under the condition of constant *ex post* returns to scale, we would expect to have $\Pi_L + \Pi_M + \Pi_N = 1$, and hence $\bar{\phi} = 1/(1 - \bar{\Pi}_F^*)$. The average value of $\bar{\Pi}_F^*$ is 0.37, so that $1/(1 - \bar{\Pi}_F^*) = 1.6$. Since this is less than the estimated values of ϕ, the existence of increasing returns to scale in the operation of the plants is confirmed. The function ϕ depends significantly on the capacity utilization factor. The negative sign of ϕ_6 indicates that the degree of returns to scale decreases as output approaches full capacity. ϕ also depends significantly on the share of fuel. The negative sign of ϕ_{14} indicates that the degree of returns to scale decreases as the share of fuel increases. This could be an indication that there are lesser returns to scale for fuel than for the other inputs. This possibility of a bias in returns to scale is explored further in Section 8.

As a test of the stability of the above relationships, the sample was broken down three ways: by vintage, by years of observation, and by the average capacity utilization factor (for the two years involved in each observation). Each of the subsamples was used to estimate a regression of the form of (5.18), i.e.,

$$\Delta Y/\bar{Y} = \bar{T} + \phi_0 H + \phi_6(\ln \bar{u})H + \phi_{14}\bar{\Pi}_M^* H + D_{11} f\bar{u} + \tau. \tag{5.19}$$

No attempt was made to try to reintroduce any of the other variables from equation (5.13). The results of these regressions are shown in Table 1.[26]

For the most part, the estimates tend to be fairly stable. D_{11} has the correct sign in every case. The greatest discrepancy in its estimates, between the last two subsamples, is not statistically significant. The estimates of ϕ are a little less stable – particularly ϕ_6, which has the wrong sign for the most recent vintage plants. This may be due in part to the fact that that subsample is much smaller than the others, a possibility

[26]The reported values of R^2 are not corrected for degrees of freedom.

TABLE 1
Subsample regression estimates of (5.19).

Sample used	$\bar{T}$	ϕ_0	ϕ_6	ϕ_{14}	D_{11}	Sample size	R^2
Entire sample	0.00511 (0.00375)	2.927 (0.318)	−0.582 (0.127)	−2.415 (0.498)	−0.0176 (0.0075)	379	0.93
v = 1947–50	0.01003	2.734 (0.549)	−0.659 (0.229)	−2.270 (0.861)	−0.0245 (0.145)	183	0.89
v = 1951–54	0.00219	3.377 (0.354)	−0.487 (0.133)	−3.113 (0.551)	−0.0121 (0.0079)	143	0.98
v = 1955–59	−0.00240	3.279 (0.977)	0.355 (0.698)	−2.088 (1.441)	−0.0167 (0.0179)	53	0.89
t = 1948/9–54/5	0.01466	2.563 (0.574)	−0.685 (0.283)	−1.929 (0.900)	−0.0263 (0.142)	132	0.89
t = 1955/6–60/1	0.00114	3.156 (0.380)	−0.473 (0.148)	−2.66 (0.593)	−0.0152 (0.0088)	247	0.94
$\bar{u}$ = 0.1–0.6	0.00855	2.315 (0.698)	−0.908 (0.288)	−1.801 (1.002)	−0.0280 (0.0187)	162	0.94
$\bar{u}$ = 0.6–1.0	0.00147	3.012 (0.344)	−0.381 (0.397)	−2.332 (0.534)	−0.0118 (0.0073)	217	0.91

which is supported by the large standard errors of the coefficients for that sample. $\bar{T}$ also has the wrong sign for that subsample, which is probably related to the wrong sign for ϕ_6. But $\bar{T}$ has the correct sign in all of the other cases. However, there is a distinct tendency for $\bar{T}$ to be somewhat smaller in the more recent years, for more recent vintage plants, and for plants operating closer to capacity.

Finally, as a test of the importance of the error specification to the estimates of the coefficients, an alternative specification was tried. This alternative specification corresponds to the theory that the available rate of disembodied technical change is the same for all firms and in all years, but that some of them are better in adapting to it than others. Hence T is a fixed constant for all firms, but the inputs are determined with varying errors from year to year by the plant managers. Consequently, the error occurs in H. If this is the case, then (5.12) becomes $\Delta Y/\bar{Y} = T + \phi(H + \eta) - D\bar{u}$, or

$$H = \frac{\Delta Y/\bar{Y} - T + D\bar{u}}{\phi} - \eta. \qquad (5.20)$$

Using the specification of (5.19) that $D = -D_{11}\bar{f}$ and $\phi = \phi_0 + \phi_6 \ln \bar{u} + \phi_{14}\bar{\Pi}^*_M$, (5.20) becomes

$$H = \frac{\Delta Y/\bar{Y} - T - D_{11}\bar{f}\bar{u}}{\phi_0 + \phi_6 \ln \bar{u} + \phi_{14}\bar{\Pi}^*_M} - \eta. \tag{5.21}$$

Equation (5.21) was estimated by nonlinear least-squares regression techniques. The estimated equation, together with the asymptotic standard errors of the parameter estimates, is

$$H = \frac{\underset{(0.00335)}{\Delta Y/\bar{Y} - 0.00283} + \underset{(0.0066)}{0.0141\bar{f}\bar{u}}}{\underset{(0.343)}{4.859} - \underset{(0.515)}{5096\bar{\Pi}^*_M} + \underset{(0.139)}{0.081 \ln \bar{u}}}. \tag{5.22}$$

The estimates of T and D are slightly smaller in (5.22) than in (5.18), but not significantly so. They again have the correct signs. The estimates of ϕ_0, ϕ_6, and ϕ_{14} are substantially different, however, with ϕ_6 having the wrong sign in the new estimate, and the other two parameters being much larger. Evaluated at the sample means, $\bar{\phi} = 2.3$ for (5.22), compared with 2.0 for (5.18). Thus it appears that the specification of the error term has little influence on the estimates of T and D, but that it is very important in estimating ϕ. For this study, however, the focal point is primarily on the estimation of T and D, with the parameters of ϕ being primarily regarded as "nuisance parameters" which are necessary to take care of the effects of returns to scale.

In summary, the estimation techniques used in this section were based upon the non-parametric Divisia Index approach to the measurement of technical change. However, in order to make this approach applicable to the measurement of disembodied technical change in this industry, it was found necessary to introduce parameters into the measurement process, and then to estimate them with regression analysis. The general pattern emerging from these estimates is that there is a small amount of disembodied technical change in this industry, which on the average probably amounts to less than one percent per year. Counterbalancing this effect, however, is plant deterioration, which probably also amounts to less than one percent per year on the average. Thus these two forces roughly cancel each other out, leaving the average plant as being roughly as efficient at the end of each year as it was at the beginning. Although the parametric estimates of the average rate of disembodied technical change were not statistically significant, the fact that (with one exception) they all had the correct sign reinforces the likelihood that it does exist. And the deterioration effect is significant, for coal burning plants at least, with all of the estimated coefficients having the correct sign.

6. The Measurement of Embodied Technical Change

The measurement of embodied technical change will be approached here in a manner similar to that used for disembodied change. The primary difference is in the way the sample has been chosen. There is also a slight difference in the way that capital is handled.

Ex ante the firm is faced with a production (or plant design) function of the general form

$$g(\tilde{Y},J,\tilde{L},\tilde{M},\tilde{N},v) = 1, \tag{6.1}$$

where $\tilde{Y}$ represents the optimal level of output, and $\tilde{L}$, $\tilde{M}$, and $\tilde{N}$ represent the corresponding optimal levels of the variable inputs. The vintage date, v, represents the current state of technology in plant design.

However, the actual observations on the plants are not on these *ex ante* plant designs, but rather they are on the *ex post* operations of the plants. Consequently, factors affecting the *ex post* deviations from the *ex ante* plant designs must be considered in analyzing the observations. Of course the main cause of these deviations is variations in demand. But a number of complicating factors need special attention. These include plant deterioration, disembodied technical change, and returns to scale. The first two can be eliminated, one at a time, in the manner indicated in Section 3. Returns to scale can be handled in a manner similar to the way they were handled in Section 5. However, because we will be making interplant comparisons here, we can no longer treat capital costs as fixed. This is due to the fact that the observed differences between the different plants reflect differences in their *ex ante* design as well as in their *ex post* operation.

Let us first consider the case where we have observations for a given year for a cross-section of plants of various vintages. In this case t is fixed, so we can ignore the effects of disembodied technical change. An appropriate production function for analyzing and comparing these plants is

$$F(Y,J^*,L,M,N,\Sigma u,v) = 1. \tag{6.2}$$

Again $J^* = h(u)J$ represents utilized capital. For simplicity we will assume here that $h(u) = u$, so that $J^* = uJ$.[27] Since capital costs are fixed

[27] Many of the results discussed below were also estimated using J instead of J^*. The estimates using J were consistently inferior from the standpoints of goodness-of-fit, internal consistency, and the general reasonableness of the magnitudes of the estimates.

ex post, we can define $s^* = s/u$, so that $s^*J^* = sJ$ for a given plant.

The rate of embodied technical change is defined as the possible rate of change in output between plants of different vintages, with no change in inputs, plant condition, or time, i.e.,

$$S = Y_v/Y = -F_v/F_YY. \tag{6.3}$$

Before deriving the computational form for S, it is necessary to consider the effect of returns to scale on the relative factor shares. Assuming that the firms minimize costs, the plants face the following Lagrangian problem:

$$\min C = s^*J^* + wL + mM + nN + \lambda[1 - F(Y,J^*,L,M,N,\Sigma u,v)],$$

where the Lagrangian multiplier $\lambda \neq 0$. To minimize cost[28] for a given level of output, set $C_{J^*} = s^* - \lambda F_{J^*} = 0$, $C_L = w - \lambda F_L = 0$, $C_M = m - \lambda F_M = 0$, and $C_N = n - \lambda F_N = 0$.

Thus

$$F_{J^*} = s^*/\lambda, \quad F_L = w/\lambda, \quad F_M = m/\lambda, \quad F_N = n/\lambda. \tag{6.4}$$

Now consider the sum, ψ, of the relative shares of the factor inputs.

$$\begin{aligned}\psi &= \Pi_{J^*} + \Pi_L + \Pi_M + \Pi_N \\ &= \frac{Y_{J^*}J^*}{Y} + \frac{Y_LL}{Y} + \frac{Y_MM}{Y} + \frac{Y_NN}{Y} \\ &= -\frac{F_{J^*}J^*}{F_YY} - \frac{F_LL}{F_YY} - \frac{F_MM}{F_YY} - \frac{F_NN}{F_YY} \\ &= -\frac{s^*J^* + wL + mM + nN}{\lambda F_YY} = -\frac{C}{\lambda F_YY}.\end{aligned}$$

Rewriting this, we have

$$F_Y = -C/\lambda\psi Y. \tag{6.5}$$

ψ is analogous to ϕ in Section 5, but not quite the same; ψ is essentially just a measure of long-run returns to scale, whereas ϕ was affected by short-run effects. If the production function is homogeneous in all inputs, ψ will be the degree of homogeneity. But for a non-homothetic production function, which this industry probably faces,[29] ψ

[28]From a theoretical standpoint, the cost minimization procedure described here is not totally satisfactory, because it does not completely separate *ex post* and *ex ante* production decisions. However, since it is necessary to take both kinds of decisions into account when comparing different plants, the minimization procedure used here is probably sufficiently good to form a useful basis for the empirical work which follows.

[29]See McFadden (Chapter IV.1).

is not in general a constant, but may be a function of several factors. These factors are not necessarily the same ones that are included in ϕ. Various factors are tested for inclusion below.

We are now in a position to compute the rate of embodied technical change. Taking the vintage derivative of the production function (6.2), we have

$$F_Y\mathring{Y} + F_{J^*}\mathring{J}^* + F_L\mathring{L} + F_M\mathring{M} + F_N\mathring{N} + F_{\Sigma u}\mathring{\Sigma} u + F_v = 0. \tag{6.6}$$

Dividing through by $F_Y Y$ and transposing the last term, this becomes

$$\frac{\mathring{Y}}{Y} + \frac{F_{J^*}\mathring{J}^*}{F_Y Y} + \frac{F_L\mathring{L}}{F_Y Y} + \frac{F_M\mathring{M}}{F_Y Y} + \frac{F_N\mathring{N}}{F_Y Y} + \frac{F_{\Sigma u}\mathring{\Sigma} u}{F_Y Y} = -\frac{F_v}{F_Y Y} = S. \tag{6.7}$$

Substituting the relations (6.4) and (6.5) into (6.7), we have

$$S = \frac{\mathring{Y}}{Y} - \frac{s^*/\lambda}{C/\lambda\psi}\mathring{J}^* - \frac{w/\lambda}{C/\lambda\psi}\mathring{L} - \frac{m/\lambda}{C/\lambda\psi}\mathring{M} - \frac{n/\lambda}{C/\lambda\psi}\mathring{N} - \frac{Y_{\Sigma u}\mathring{\Sigma} u}{Y}.$$

Rewriting this expression and letting $E = Y_{\Sigma u}/Y$, the rate of plant deterioration (not necessarily a constant), we have

$$S = \frac{\mathring{Y}}{Y} - \psi\frac{s^*J^*}{C}\frac{\mathring{J}^*}{J^*} - \psi\frac{wL}{C}\frac{\mathring{L}}{L} - \psi\frac{mM}{C}\frac{\mathring{M}}{M} - \psi\frac{nN}{C}\frac{\mathring{N}}{N} + E\mathring{\Sigma} u,$$

or

$$S = \frac{\mathring{Y}}{Y} - \psi\left(\Pi^*_{\mathring{J}^*}\frac{\mathring{J}^*}{J^*} + \Pi^*_{\mathring{L}}\frac{\mathring{L}}{L} + \Pi^*_{\mathring{M}}\frac{\mathring{M}}{M} + \Pi^*_{\mathring{N}}\frac{\mathring{N}}{N}\right) + E\mathring{\Sigma} u. \tag{6.8}$$

If we let

$$A = \Pi^*_{\mathring{J}^*}\frac{\mathring{J}^*}{J^*} + \Pi^*_{\mathring{L}}\frac{\mathring{L}}{L} + \Pi^*_{\mathring{M}}\frac{\mathring{M}}{M} + \Pi^*_{\mathring{N}}\frac{\mathring{N}}{N},$$

we can rewrite (6.8) as

$$\mathring{Y}/Y = S + \psi A - E\mathring{\Sigma} u. \tag{6.9}$$

Equation (6.9) can be subjected to linear regression analysis under the assumption that S is distributed normally and independently of A and $\mathring{\Sigma} u$, and that ψ and E are linear functions. These assumptions are essentially the same as those made about (5.12) in order to subject it to linear regression analysis.

The observations used to estimate equation (6.9) are based on pairs of observations in a given year (1958) of plants with vintages in adjacent years. Thus, for example, the first observation compares the 1958 performance of a 1948 vintage plant with the 1958 performance of a 1947 vintage plant. Every plant for which a 1958 observation was included in the original sample was used in this analysis. This involved 50 of the 80 plants in the original sample. The year 1958 was chosen because more plants had observations in that year than in any other year. Each of these 50 plants was compared with every other plant whose vintage year was the year preceding or following its vintage year. Thus, for example, each of the seven 1954 vintage plants was compared with each of the seven 1953 vintage plants, and also with each of the five 1955 vintage plants. This resulted in 200 paired observations for the entire sample. For each of these paired observations, the following discrete approximations to the terms in (6.9) were computed:

$$\mathring{Y}/Y = \Delta Y/\bar{Y},$$

$$A = \bar{\Pi}^*_{J^*}\frac{\Delta J^*}{\bar{J}^*} + \bar{\Pi}^*_L\frac{\Delta L}{\bar{L}} + \bar{\Pi}^*_M\frac{\Delta M}{\bar{M}} + \bar{\Pi}^*_N\frac{\Delta N}{\bar{N}},$$

$$\mathring{\Sigma}u = \Delta\Sigma u.$$

Since the estimates for 1958 proved to be fairly satisfactory, it was not felt necessary to carry out the computations for other years. However, if the computations were carried out for other years, the parameter estimates for equation (6.10) should theoretically not be significantly different from those obtained from the 1958 data.

The factors considered for inclusion in the functions ψ and E were essentially the same as those considered for ϕ and D in Section 5. It was not expected, however, that the same factors would be found to be significant. The higher powers of $\bar{u}$ and $\ln \bar{u}$ were not considered here. Also, it was necessary to use average values for the six factors that are fixed for a given plant, but are different for different plants. It might also be noted that here $k = J/R = J^*/Y$. With these functional forms for ψ and E, (6.9) becomes

$$\begin{aligned}\Delta Y/\bar{Y} = {} & \bar{S} + \psi_0 A + \psi_1\bar{u}A + \psi_2(\ln\bar{u})A + \psi_3\bar{f}A + \psi_4\bar{\Pi}^*_{J^*}A \\ & + \psi_5\bar{\Pi}^*_L A + \psi_6\bar{\Pi}^*_M A + \psi_7\bar{\Pi}^*_N A + \psi_8\bar{k}A + \psi_9\bar{c}A + \psi_{10}\bar{U}A \\ & + \psi_{11}\bar{v}A + \psi_{12}\bar{R}A + \psi_{13}(\overline{R/U})A \\ & + E_0\Delta\Sigma u + E_1\bar{u}\Delta\Sigma u + E_2(\ln\bar{u})\Delta\Sigma u \\ & + E_3\bar{f}\Delta\Sigma u + E_4\bar{\Pi}^*_J\Delta\Sigma u + E_5\bar{\Pi}^*_L\Delta\Sigma u + E_6\bar{\Pi}^*_M\Delta\Sigma u \\ & + E_7\bar{\Pi}^*_M\Delta\Sigma u + E_8\bar{k}\Delta\Sigma u + E_9\bar{c}\Delta\Sigma u + E_{10}\bar{U}\Delta\Sigma u + E_{11}\bar{v}\Delta\Sigma u \\ & + E_{12}\bar{R}\Delta\Sigma u + E_{13}(\overline{R/U})\Delta\Sigma u + \epsilon, \qquad (6.10)\end{aligned}$$

where $\bar{S}$ is the mean value of S, and $\epsilon = S - \bar{S}$. Obviously not all of the terms in (6.10) should be included in the equation. Consequently, the equation was estimated by stepwise regression, initially forcing the parameters $\bar{S}$, ψ_0, and E_0 into the regression, and then stepwise adding any additional terms with coefficients significant at at least the 5% significance level. The stepwise regression results were as follows:[30]

$$\begin{aligned} \Delta Y/\bar{Y} &= 0.0336 - \underset{(0.0128)}{0.0131\Delta\Sigma u} + \underset{(0.017)}{1.118A} \qquad (\bar{R}^2 = 0.969), \end{aligned} \tag{6.11}$$

$$\begin{aligned} \Delta Y/\bar{Y} &= 0.0342 + \underset{(0.0153)}{0.0376\Delta\Sigma u} - \underset{(0.0163)}{0.0871\bar{c}\Delta\Sigma u} + \underset{(0.016)}{1.113A} \\ &\qquad\qquad (\bar{R}^2 = 0.973), \end{aligned} \tag{6.12}$$

$$\begin{aligned} \Delta Y/\bar{Y} &= 0.0280 + \underset{(0.0147)}{0.0293\Delta\Sigma u} - \underset{(0.0155)}{0.0863\bar{c}\Delta\Sigma u} \\ &\quad + \underset{(0.033)}{1.247A} - \underset{(0.00004)}{0.00017(\overline{R/U})A} \qquad (\bar{R}^2 = 0.975), \end{aligned} \tag{6.13}$$

$$\begin{aligned} \Delta Y/\bar{Y} &= \underset{(0.0138)}{0.0309} + \underset{(0.0495)}{0.2025\Delta\Sigma u} - \underset{(0.0169)}{0.0582\bar{c}\Delta\Sigma u} - \underset{(0.130)}{0.475\bar{\Pi} j^{*}\cdot\Delta\Sigma u} \\ &\quad + \underset{(0.032)}{1.248A} - \underset{(0.000036)}{0.000174(\overline{R/U})A} \qquad (\bar{R}^2 = 0.977). \end{aligned} \tag{6.14}$$

At this point none of the remaining terms in (6.10) proved to be significant. Hence (6.14) is the final estimate of (6.9). None of the significant factors in the scale or deterioration functions here are the same as the factors found to be significant in the estimation of disembodied technical change. Actually this is not too surprising since the observations there were based on intraplant comparisons and thus primarily reflect short-run differences, whereas here the observations are based on interplant comparisons and thus primarily reflect long-run differences.

The negative sign of the estimate for ψ_{13} indicates that the degree of increasing returns to scale diminishes somewhat as the size of the generating units increases. The final parameter estimates indicate that there are decreasing returns to scale for plants with units averaging over 163 megawatts in size. This figure is slightly exceeded by the largest

[30]In the regressions reported in this section, the values of capacity, R, were converted to an annual basis. The stepwise regression program used did not report the standard errors of the intercepts. The standard error of $\bar{S}$ in equation (6.14) was computed by another program.

plants in the sample. This result is in general agreement with the findings of Nerlove (1963) at the firm level for this industry. He found evidence that the degree of returns to scale diminishes as the firm size increases. This result of a diminishing degree of returns to scale also corresponds to the simple models of long-run cost curves often taught in economics principles courses. The average degree of returns to scale (evaluated at the sample average of $\overline{R/U}$) is 1.13. This is slightly less than the engineering cost estimate reported in Section 4.

The negative sign of E_9 indicates that plants with a greater degree of outdoor construction tend to deteriorate faster. This is in general agreement with the discussion in Section 4. The negative sign of E_4 indicates that plants which are more capital-intensive tend to deteriorate faster. The average value of E (evaluated at the sample averages of $\bar{c}$ and $\bar{\Pi}^*_{j*}$) is -0.015, which has the expected sign.

The estimated average rate of embodied technical change is about 3% per year. This compares with the estimated average rate of disembodied technical change of only about $\frac{1}{2}$% per year. Thus it appears that embodied change is much more important than disembodied change for this industry. This is not too surprising considering the high degree of capital-intensity in this industry. The final estimate of $\bar{S}$ is significantly different from zero.

7. The Measurement of Total Technical Change

Let us now consider the case where we have observations for plants in their first full year of operation. Since the observations are for new plants, we can safely ignore the effects of deterioration from past use. Of course it will not be possible to distinguish between embodied and disembodied technical change for such observations. However, since we already have separate estimates of the rates of embodied and disembodied technical change, our new estimates of the rate of total technical change can be used as a check on the magnitudes of the previous estimates. If the results are consistent, the new estimate of the rate of total technical change should not be significantly different from the sum of the separate estimates of embodied and disembodied change.

An appropriate production function for analyzing and comparing these plants is

$$G(Y,J^*,L,M,N,t) = 1. \tag{7.1}$$

In this case, $t - v = 1$ for all plants. Hence the inclusion of t in (7.1) reflects the effects of both embodied and disembodied technical change. The rate of total technical change, $W = S + T$, can be defined as the possible rate of change of output with no change in inputs or past plant use, i.e.,

$$W = Y_t/Y = -G_t/G_Y Y. \tag{7.2}$$

The effect of returns to scale for this case is similar to the one just discussed. The Lagrangian cost minimization problem yields

$$G_{J^*} = s^*/\lambda, \quad G_L = w/\lambda, \quad G_M = m/\lambda, \quad G_N = n/\lambda. \tag{7.3}$$

And the sum, μ, of the relative shares of the factor inputs is $\mu = -C/\lambda G_Y Y$, so that

$$G_Y = -C/\lambda\mu Y. \tag{7.4}$$

μ represents the degree of returns to scale, and is not necessarily a constant. It is analogous to the functions ϕ and ψ discussed above, but is not necessarily identical with either one. However, a certain amount of similarity with both should be expected. Various factors are tested for inclusion in μ below.

We are now in a position to compute the rate of total technical change. Taking the time derivative of the production function (7.1), we have

$$G_Y\dot{Y} + G_{J^*}\dot{J}^* + G_L\dot{L} + G_M\dot{M} + G_N\dot{N} + G_t = 0. \tag{7.5}$$

Dividing through by $G_Y Y$ and transposing the last term, this becomes

$$\frac{\dot{Y}}{Y} + \frac{G_{J^*}\dot{J}^*}{G_Y Y} + \frac{G_L\dot{L}}{G_Y Y} + \frac{G_M\dot{M}}{G_Y Y} + \frac{G_N\dot{N}}{G_Y Y} = -\frac{G_t}{G_Y Y} = W. \tag{7.6}$$

Substituting the relations (7.3) and (7.4) into (7.6) and rewriting, we have

$$W = \frac{\dot{Y}}{Y} - \mu\frac{s^*J^*}{C}\frac{\dot{J}^*}{J^*} - \mu\frac{wL}{C}\frac{\dot{L}}{L} - \mu\frac{mM}{C}\frac{\dot{M}}{M} - \mu\frac{nN}{C}\frac{\dot{N}}{N}. \tag{7.7}$$

Noting that time and vintage derivatives are equivalent in this case, we can rewrite (7.7) as

$$\dot{Y}/Y = W + \mu A. \tag{7.8}$$

As with equations (5.12) and (6.9), this equation was subjected to linear regression analysis, under the assumptions that W is distributed normally and independently of A, and that μ is a linear function.

The observations used to estimate equation (7.8) are based on pairs of observations of plants in their first full year of operation, with vintages in adjacent years. Thus, for example, the first observation compares the 1949 performance of a 1948 vintage plant with the 1948 performance of a 1947 vintage plant. Each of the 80 plants in the sample was compared with every other plant whose vintage year was the year preceding or following its vintage year. This resulted in 462 paired observations. Discrete approximations for the terms $\dot{Y}/Y$ and A in equation (7.8) were computed in the same manner as the approximations for $\mathring{Y}/Y$ and A in equation (6.9).

The factors considered for inclusion in the function μ were the same as those considered for inclusion in ψ. Thus equation (7.8) becomes

$$\begin{aligned} \Delta Y/\bar{Y} = {} & \bar{W} + \mu_0 A + \mu_1 \bar{u} A + \mu_2 (\ln \bar{u}) A + \mu_3 \bar{f} A + \mu_4 \bar{\bar{\Pi}}{}^*_F \\ & + \mu_5 \bar{\bar{\Pi}}{}^*_L A + \mu_6 \bar{\bar{\Pi}}{}^*_M A + \mu_7 \bar{\bar{\Pi}}{}^*_N A + \mu_8 \bar{k} A + \mu_9 \bar{c} A \\ & + \mu_{10} \bar{U} A + \mu_{11} \bar{v} A + \mu_{12} \bar{R} A + \mu_{13} (\overline{R/U}) A + \eta, \end{aligned} \qquad (7.9)$$

where $\bar{W}$ is the mean value of W and $\eta = W - \bar{W}$. Again, it was expected that only a few of the terms in μ would be significant. Consequently, the equation was estimated by stepwise regression, initially forcing the parameters $\bar{W}$ and μ_0 into the regression, and then adding stepwise any additional terms with coefficients significant at at least the 5% significance level. The stepwise regression results were as follows:

$$\underset{}{\Delta Y/\bar{Y}} = \underset{(0.0078)}{0.0280} + \underset{(0.008)}{1.121A} \qquad (\bar{R}^2 = 0.975), \qquad (7.10)$$

$$\Delta Y/\bar{Y} = 0.0274 + \underset{(0.017)}{1.198A} - \underset{(0.00002)}{0.00011(\overline{R/U})A} \qquad (\bar{R}^2 = 0.976), \qquad (7.11)$$

$$\Delta Y/\bar{Y} = \underset{(0.0076)}{0.0264} + \underset{(0.050)}{1.339A} - \underset{(0.000022)}{0.000097(\overline{R/U})A} - \underset{(0.102)}{0.304\bar{\bar{\Pi}}{}^*_M A} \qquad (\bar{R}^2 = 0.977). \qquad (7.12)$$

At this point none of the other terms proved to be significant. Again the term $\overline{R/U}$ appears with a negative coefficient, reinforcing the conclusion from the estimation of ψ that the degree of increasing returns to scale diminishes as the average size of the plant's units increases. And, as in the estimation of ϕ, the term $\bar{\bar{\Pi}}{}^*_M$ appears with a negative coefficient, indicating that the degree of returns to scale decreases as the share of fuel increases. This is an indication of a bias in the returns to scale. Further analyses of scale biases are carried out in the next section. The average degree of returns to scale (evaluated at the sample averages of $\overline{R/U}$ and $\bar{\Pi}_M^*$) is again 1.13.

The final estimated average rate of total technical change, from equation (7.12), is 2.64% per year. If we add the final estimate of the average rate of disembodied technical change, from equation (5.18), of 0.51% per year to the final estimate of the average rate of embodied technical change, from equation (6.14), of 3.09% per year, we get a total of 3.60%. Thus there is about a one percent discrepancy in the estimates. This difference is not statistically significant, however, and the two estimates of the total rate of technical change are of the same order of magnitude – both being around 3% per year. Considering that the estimates of $\bar{S}$, $\bar{T}$, and $\bar{W}$ were made largely independently of each other, there is a reasonably good agreement among them. It should further be noted that the final estimate of $\bar{W}$ in equation (7.12) is quite significantly different from zero, indicating that technical change is indeed a real phenomenon to be contended with.

Finally, as an indication of the relative importance of increasing returns to scale versus technical change in explaining apparent improvements in productive efficiency, a "naive" model, assuming constant returns to scale, was estimated using this same sample of 466 observations. Under constant returns to scale, the model reduces to $W = \Delta Y/\bar{Y} - A$, since $\mu = 1$. W was computed for each of the 466 observations. The average value of W under this assumption was 0.0410. If we use the estimate of equation (7.12) as the true value of total technical change, this means that the non-constancy of the returns to scale only explains a 1.46% annual increase in average productive efficiency, if we assume that the effects of technical change and returns to scale are additive. Considering that the degree of increasing returns to scale is apparently quite significant, and that there has been a strong upward trend in plant size, this seems to be a rather small amount. It appears to indicate that technical change is more important than increasing returns to scale in explaining the improving efficiency of production. One should not, however, attach too much significance to this result, because it may well be the case that the effects of technical change and returns to scale are not additive in the assumed manner. This might be the case if technical change tends to reinforce and expand the possibilities of returns to scale, so that their effects overlap. Since many of the improvements in this industry have been of the nature of permitting the construction of larger boiler–generator units, this is a definite possibility.

8. The Bias of Technical Change

Another important question regarding the nature of technical change is whether it is neutral or biased. Between a pair of factor inputs, for instance capital and labor, the bias of technical change can be defined as

$$B_{JL} = \left.\frac{\partial \ln(w/s)}{\partial t}\right|_{J/L, Y, \Sigma u \text{ fixed}}, \tag{8.1}$$

if factors are paid proportionally to their marginal products. If technical change is Hicks neutral, then $B_{JL} = 0$. If it is relatively labor saving, then $B_{JL} < 0$, and if it is relatively capital saving, then $B_{JL} > 0$.[31] The biases between other pairs of factors can be defined similarly.

The bias of technical change cannot, however, be considered independently of other relationships which involve the marginal rate of substitution between the factors of production. Probably the most important of these is the elasticity of substitution, σ, between the factors, which might be defined in terms of the relationship

$$\frac{1}{\sigma_{JL}} = \left.\frac{\partial \ln(w/s)}{\partial \ln(J/L)}\right|_{Y, \Sigma u, t \text{ fixed}}. \tag{8.2}$$

The elasticities of substitution between other factors can be defined similarly. The possible effects of interactions with other factors have been ignored here.

If the production function is non-homothetic, there may be a bias in the returns to scale. The scale bias, ζ can be defined as

$$\zeta_{JL} = \left.\frac{\partial \ln(w/s)}{\partial \ln Y}\right|_{J/L, \Sigma u, t \text{ fixed}}, \tag{8.3}$$

and similarly for other pairs of factors. If the returns to scale affects both factors equally, then $\zeta = 0$. If the returns to scale are relatively labor saving, then $\zeta_{JL} < 0$.

Finally, there may also be a bias in deterioration. The deterioration bias, δ, can be defined as

$$\delta_{JL} = \left.\frac{\partial \ln(w/s)}{\partial \Sigma u}\right|_{J/L, Y, t \text{ fixed}}, \tag{8.4}$$

and similarly for other pairs of factors. If deterioration affects both

[31] See Hicks (1932, Ch. VI) and Diamond (1964).

factors equally, then $\delta = 0$. If deterioration is relatively capital using, then $\delta_{JL} < 0$.

If we now take the time derivative of $\ln(w/s)$, we have

$$\frac{\mathrm{d}\ln(w/s)}{\mathrm{d}t} = \frac{1}{\sigma_{JL}}\frac{\mathrm{d}\ln(J/L)}{\mathrm{d}t} + \zeta_{JL}\frac{\mathrm{d}\ln Y}{\mathrm{d}t} + \xi_{JL}\frac{\mathrm{d}\,\Sigma u}{\mathrm{d}t} + B_{JL}, \tag{8.5}$$

and similarly for other pairs of factors.

In order to identify the terms in equation (8.5), it is necessary to make some assumptions regarding their nature. The assumptions that will be made here are that the various biases and elasticities are constants, so that they can each be treated as single parameters in a regression equation. If these terms, particularly B_{JL}, are in fact not constants, then the estimates reported below might be taken as estimates of their mean values.

Before proceeding to apply regression analysis to equation (8.5), however, it is necessary to consider the nature of the underlying relationships involved. Equations (8.1), (8.3), and (8.4), which define the biases, are essentially definitional relationships. On the other hand, equation (8.2) involves a behavioral relationship[32] in which $\ln(J/L)$ is the dependent variable and $\ln(w/s)$ is an independent variable. Consequently, in order to obtain reasonable estimates of the elasticity of substitution, it is necessary to preserve the nature of this relationship between these variables, with $\ln(J/L)$ as the dependent variable.[33] Hence, for estimation purposes, equation (8.5) was rewritten as

$$\frac{\mathrm{d}\ln(J/L)}{\mathrm{d}t} = \sigma_{JL}\frac{\mathrm{d}\ln(w/s)}{\mathrm{d}t} - \sigma_{JL}\zeta_{JL}\frac{\mathrm{d}\ln Y}{\mathrm{d}t} - \sigma_{JL}\delta_{JL}\frac{\mathrm{d}\,\Sigma u}{\mathrm{d}t} - \sigma_{JL}B_{JL}, \tag{8.6}$$

or, using the corresponding approximations for discrete time periods,

$$\Delta \ln(J/L) = -\sigma_{JL}B_{JL} - \sigma_{JL}\delta_{JL}\Delta\Sigma u - \sigma_{JL}\zeta_{JL}\Delta \ln Y + \sigma_{JL}\Delta \ln(w/s). \tag{8.7}$$

[32]Actually, all four equations also incorporate the behavioral assumption that factors are paid in proportion to their marginal products. Strictly speaking, the definitions should be made in terms of these marginal products, rather than in terms of the factor prices. The use of the factor prices (since the marginal products are not directly measurable) in the equations estimated below could mean that there is some errors-in-variables bias in those estimates. No attempt was made to deal with this possible source of bias.

[33]An attempt to estimate equation (8.5) directly, using the total technical change data sample, resulted in very unreasonable estimates of the elasticities of substitution. The estimates of $1/\sigma$ were generally much less than 1, resulting in estimates of σ as high as 12, even though the possibilities of substitution between the factors are fairly limited.

Equations such as this were applied to each of the three samples discussed in Sections 5, 6, and 7.

For the total technical change sample of one year old plants, the deterioration effect is negligible, and can be ignored. Hence equation (8.7) reduces to

$$\Delta \ln(J/L) = -\sigma_{JL}B_{JL} - \sigma_{JL}\zeta_{JL}\Delta \ln Y + \sigma_{JL}\Delta \ln(w/s), \tag{8.8}$$

and similarly for other pairs of factors. As an indication of the effect of the choice of the measure of capital used, each of the three possible measures of capital – J^*, capital used; J, real installed capital; and K, observed capital in vintage dollars – was tried.

The results of the regressions of the form of equation (8.8) for this sample are shown in Table 2. This table gives the estimates and standard

TABLE 2
Estimates for equation (8.8), total technical change.

Dependent Variable	Regression parameters			Biases		
	$-\sigma B$	$-\sigma\zeta$	σ	B	ζ	R^2
$\Delta \ln(L/M)$	−0.0262 (0.0199)	−0.460 (0.014)	0.295 (0.022)	0.0890	1.561	0.77
$\Delta \ln(N/L)$	−0.0081 (0.0295)	0.248 (0.020)	2.189 (0.218)	0.0037	−0.113	0.35
$\Delta \ln(N/M)$	−0.0403 (0.0291)	−0.226 (0.021)	0.203 (0.033)	0.1986	1.113	0.55
$\Delta \ln(J^*/L)$	−0.0101 (0.0181)	0.291 (0.014)	0.717 (0.035)	0.0141	−0.405	0.78
$\Delta \ln(J^*/M)$	−0.0333 (0.0166)	−0.079 (0.011)	0.232 (0.018)	0.1435	0.340	0.30
$\Delta \ln(J^*/N)$	0.0039 (0.0268)	0.064 (0.022)	0.615 (0.058)	−0.0063	−0.104	0.32
$\Delta \ln(J/L)$	−0.0114	0.237 (0.013)	0.755 (0.054)	0.0150	−0.314	0.55
$\Delta \ln(J/M)$	−0.0366	−0.223 (0.013)	0.239 (0.021)	0.1532	0.934	0.53
$\Delta \ln(J/N)$	0.0031	−0.005 (0.019)	0.428 (0.100)	−0.0072	0.013	0.04
$\Delta \ln(K/L)$	0.0032	0.236 (0.013)	0.764 (0.055)	−0.0041	−0.309	0.55
$\Delta \ln(K/M)$	0.0099	−0.224 (0.013)	0.244 (0.021)	−0.0407	0.918	0.53
$\Delta \ln(K/N)$	0.0353	−0.007 (0.019)	0.473 (0.101)	−0.0747	0.015	0.05

errors[34] of the parameters of the regression equation, as well as point estimates of the biases B and ζ, which were found by dividing the appropriate regression parameters by the estimate of $-\sigma$. The last column shows the overall fit of each equation.

Several results emerge from these estimates. The estimated elasticities of substitution are all positive and significantly greater than zero. And, except for labor and maintenance, they are also all significantly less than one. The high elasticity of substitution between labor and maintenance is not very surprising considering the way in which the data for these factors were derived.[35] This estimated high degree of substitution may be due as much to errors in the data as to real substitution between the factors. The choice of the measure used for capital has very little effect on the estimates of σ, except possibly in the case of capital–maintenance substitution, where the estimate using J^* is somewhat higher than the estimates using J or K. The estimates of the elasticity of substitution between capital and labor are very close to the estimated value of about 0.75 found by McFadden in Chapter IV.1. Fuel appears to be much less substitutable than the other factors. The estimated elasticities involving fuel are all between 0.2 and 0.3, whereas the other estimated elasticities are all higher than 0.4. Since these observations are all for new plants, these elasticity estimates are probably closely related to the *ex ante* elasticities.

The biases due to scale generally seem to be much more significant than the biases due to technical change. With the possible exception of the bias between capital and maintenance, the scale bias appears to be significant in all cases. This strongly indicates that the production function is nonhomothetic, which supports the findings of McFadden in Chapter IV.1. The degree of returns to scale appears to be strongest for labor and weakest for fuel. Thus the returns to scale are relatively labor saving and fuel using. The estimated biases are practically the same when capital is measured by J as when measured by K. However, the estimates of ζ are significantly lower when J^* is used. This is not surprising because J^* is much more closely related to Y than are either J or K. The fact that the returns to scale are relatively fuel using helps to explain the negative relationship between the returns to scale and the share of fuel found in Sections 5 and 7.

The biases of technical change are generally quite small. In most cases

[34]The standard errors of the intercept ($-\sigma B$) had to be computed by a computer program that was relatively inconvenient to use. Hence it was only done in a few cases.

[35]See the Statistical Appendix of Belinfante (1969).

they do not appear to be significantly different from zero. There is some indication of a small fuel using bias. This result differs from that of Seitz (1968), who found some evidence of a small fuel saving bias. This difference is undoubtedly due to the difference in our approaches. But in any case, the bias, if any, is small. As to the effect of the choice of the measure of capital, there is little difference in the estimated biases when either J or J^* is used. But the estimated biases are consistently lower (and negative) when K is used. This is undoubtedly due to the generally rising prices of capital goods during most of the period studied. A failure to correct for this would naturally make it appear that there is a relatively capital using bias. Since both J and J^* do correct for these price changes, they are undoubtedly preferable to K as measures of capital.

Equations of the form (8.7) were also estimated for the other two samples.[36] Again, the largest biases were the scale biases, which were also estimated as being fuel using and labor saving. The estimated biases of deterioration and technical change were generally quite small. However, there does appear to be a significant fuel-using bias of moderate size for both deterioration and technical change for the sample used to estimate embodied technical change.

9. Concluding Remarks

It should be noted that the definition of technical change which is used in this study is not the same as that used by some authors. Technical change is often denied as a shift in the production frontier for best-practice plants. One study for this industry which uses such a definition is that of Seitz (1968). The definition of technical change used in this study, however, is a shifting of the production function for average-practice plants. Thus no attempt has been made here to distinguish the best-practice plants from the other plants. As a consequence of this definition, the technical change that has been measured here may be due as much to the better dissemination of already existing knowledge as it is to the discovery of new knowledge.

One might argue that the observed rate of embodied change could be eliminated by choosing an appropriate alternative price deflator which would adjust the apparent capital input just sufficiently to make the

[36]See Belinfante (1969, Ch. VII) for details.

apparent rate of embodied technical change equal to zero. This is one of the major points made by Jorgenson (1966b). A resolution of this problem can only be made by an agreement as to the reasonableness of the price deflator which is used. The choice of the Handy–Whitman Index, which is used in this study, is defended in Section 4. If the chosen index is not accepted as being reasonable and appropriate, however, then this identification problem reduces to the semantic problem of the choice of the appropriate definitions of the terms "embodied technical change", "quality change", and "inflation" as applied to this problem. It might also be noted, however, that it was shown in Section 8 that a failure to correct for changes in the prices of capital goods introduces an apparent capital using bias into the technical change. Thus although it may be possible to choose another capital price deflator which would make the apparent rate of embodied technical change equal to zero, such an apparent zero rate of embodied technical change would also not be neutral in its effect. This result also suggests that it would probably be possible to choose arbitrarily a third capital price deflator which would make embodied technical change apparently exactly Hicks neutral.

It is of interest to compare the estimated rates of technical change and deterioration with the legal depreciation rate (in the 1950's) of 2.7%. The depreciation rate is much larger than the deterioration rate, but it is about the same as the estimated rate of technical change. Thus, although the depreciation rate cannot be "justified" on the grounds of deterioration alone,[37] it is possible to "justify" it on the grounds of obsolescence in the machines due to embodied technical change. It might be noted that the legal lifetime (in the 1950's) of the plants – 37 years – corresponds fairly closely with the average length of time most plants are kept in service. There is a fair amount of variation in the service lives of the plants, however. Some plants are retired as early as 10 to 15 years after they go into service; these presumably are the less efficient plants which become obsolete faster. On the other hand, some plants are kept in service for over 50 years; these presumably are the more efficient plants.

[37]Judged on this basis it clearly gives the electric power companies a tax advantage.