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# Size of Firm, Market Structure, and Innovation

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## 1. Introduction

What are the effects of an industry's market structure on its rate of technical progress? In recent years, economists have become interested once again in this fundamental and classic problem. Debates have taken place over the relative merits of various market structures and the importance of corporate giants in promoting technical change. Unfortunately, little agreement seems to have been reached as yet.[1/]

This paper deals with the following aspects of this problem. First, it investigates the extent to which the largest firms in several industries have been the innovators.[2/] Second, it outlines a simple model that seems to be of use in explaining why these giants accounted for a disproportionately large share of the innovations in some industries, but not in others. Third, it tries to estimate whether fewer innovations would have been introduced if they had been broken up.

Fourth, it tries to determine whether the smaller firms do less innovating, relative to the larger firms, than in the past. Fifth, it shows how, under certain circumstances, historical data identifying the innovators can be used to determine the effect of a change in market structure on how rapidly inventions made outside the industry where they are applicable will be applied.

Of course, the results are by no means free of difficulties. The basic models are often convenient first approximations, and the data are often rough. Nonetheless, the findings -- crude as they are -- contribute to the solution of some important problems, and they should be useful to those interested in the process of technical change and the effects of industrial organization on economic progress.

## 2. Innovation and Size of Firm

A controversy has been going on for some time over the extent to which the largest firms have been the leaders in introducing important new processes and products. Several decades ago, Schumpeter [29] challenged the then prevailing view and asserted that in recent times innovations have been carried out primarily by very large firms. More recently, Galbraith [9], Kaplan [13], Lilienthal [14], and Villard [34] have taken much the same position.

In defense of this view, they cite three primary reasons for the dominance of the industrial giant. First, the costs of innovating are claimed to be so great that only large firms can now become involved. Second, it is alleged that projects must now be carried out on a large enough scale so that successes and failures can in some sense balance out. Third, it is argued that, for innovation to be worthwhile, a firm must have sufficient control over the market to reap the rewards.[3]

This position has been questioned by Mason [22] and others. According to this group, no conclusive evidence supports the view that a disproportionately large share of the significant innovations has been carried out by very large firms. For example, Mason [22] states that "... (W)hether in fact innovation in

[Schumpeter's] sense has generally been the product of the largest firms, during the last few decades of American economic history, is seriously open to question..." (p. 142).

There have been numerous recommendations that empirical studies be conducted to determine the extent to which the largest firms have been the innovators, but because of the considerable difficulties that such studies must face and for other reasons, few such investigations have been carried out.[4] Section 3 presents some empirical findings regarding three basic industries. Although they are very rough, these results should help to fill this important gap.

## 3. Empirical Results

This section estimates the extent to which the largest firms have been the innovators in iron and steel, petroleum refining, and bituminous coal. Of course, these industries may not be entirely representative, but the difficulties involved in obtaining fairly complete data prevented the inclusion of a larger number of industries. To obtain the data, trade associations and trade journals in each industry were asked to list the important processes and products first introduced in the industry since 1918.[5] They were also asked to rank them by importance. Having obtained these lists, we consulted technical journals and corresponded with various firms inside and outside the industry to determine which firm first introduced each innovation commercially and when this took place. This information could be gotten for about 80 percent of the innovations.[6] The results are contained in Tables 1a-1c.

Next, we obtained data regarding the size of each firm in each of the industries. In steel, the ingot capacity of each firm in 1926 and 1945 was obtained;

Table la -- Innovations and Innovators, Iron and Steel Industry, 1919-38 and 1939-58.

**1919-38**

| Innovation | Innovator |
|---|---|
| ustempering | U. S. Steel |
| ontinuous wide strip mill | Armco |
| ontinuous pickling | Wheeling |
| ontinuous galvanizing | Armco |
| echanical scarfing | U. S. Steel |
| ultiple block wire drawing | U. S. Steel |
| utomatic operation of open hearth | Laclede |
| lectronic inspection of tin plate | Jones & Laughlin |
| lectrically welded pipe | Republic |
| olomite gun | Donner |
| oreless induction electric furnace | Heppenstall |
| lectrolytic tin plate | U. S. Steel |
| igh strength alloy steels | U. S. Steel |
| ow tungsten high speed tool steel | Universal & Cyclops |
| Grain-oriented electric steel | Allegheny |
| [illegible]aging steel | Armco |
| 1[illegible]8 stainless steel | Allegheny |
| itriding steels | Ludlum |
| oron treated steels | U. S. Steel |
| alve steels | Ludlum |
| % chrome hot work tool steels | Braeburn |
| Continuous annealing* | Crown Cork & Seal |
| Continuous butt-weld pipe* | Fretz-Moon |
| igh temperature alloys | Timken Roller Bearing |
| ickel bearing electrical steel* | Western Electric |

**1939-58**

| Innovation | Innovator |
|---|---|
| Stretch process for hot reducing tubes | U. S. Steel |
| All-basic open hearth furnace | U. S. Steel |
| Ultrasonic testing | Republic |
| High top pressure blast furnace | Republic |
| Jet tapper | Republic |
| Differential coating of tin plate | National |
| Electric eye for Bessemer turndown | Jones & Laughlin |
| Vacuum melting, | Allegheny Ludlum & Crucible |
| Continuous casting | Allegheny Ludlum & Republic |
| Vacuum degassing (pouring) | Bethlehem & U.S.Steel |
| L-D oxygen process | McLouth |
| Oxygen lancing of open hearth | Bethlehem, National, Jones & Laughlin, Republic, & U.S.Steel |
| Automatic programming of mills | Allegheny Ludlum |
| Killed bessemer steel | U. S. Steel |
| Precipitation hardening stainless steel | Armco |
| Manganese stainless steel | Allegheny Ludlum & Republic |
| Aluminum clad sheets | Armco |
| Titanium treated enameling steels | Inland |
| Columbium treated high strength steel | National |
| Extra low carbon stainless steel | U.S.Steel, Armco, Allegheny Ludlum, Crucible & Republic |
| Closed television circuits* | Babcock & Wilcox |
| Carbon hearth* | Interlake Iron |
| Hot extrusion* | Babcock & Wilcox |
| Szendzimir cold mill* | Signode Steel Strap |

Source: see the text and notes 4,5,6, and 8.

*Innovations excluded from Tables 2 - 5 because innovator had no ingot capacity or because it was engaged primarily in another business. See note 8.

Table 1b -- Innovations and Innovators, Petroleum Refining Industry, 1919-38 and 1939-58.

**1919-38**

| Innovation | Innovator |
|---|---|
| ton-Clark cracking | Standard (N.J.) |
| bs cracking | Shell |
| ed-bed catalytic cracking | Sun |
| pane deasphalting of lubes | Union |
| vent dewaxing of lubes | Indian |
| vent extraction of lubes | Associated |
| talytic polymerization | Shell |
| rmal polymerization | Phillips |
| ylation ($SO_2$) | Standard (N.J.) |
| salting of crude | Ashland |
| drogenation | Standard (N.J.) |
| pe stills and multi-draw towers | Atlantic |
| layed coking | Standard (Ind.) |
| ay treatment of gasoline | Barnsdall |
| monia | Shell |
| hylene | Standard (Ind.) |
| opylene | Standard (N.J.) |
| tylene | Standard (N.J.) |
| anol | Cities Service |
| opanol | Standard (N.J.) |
| tanol | Standard (N.J.) |
| dehydes | Cities Service |
| pthenic Acids | Standard (Cal.) |
| resylic Acids | Standard (Cal.) |
| tones | Shell |
| tergents | Atlantic |
| orants | Standard (Cal.) |
| thyl Chloride | Standard (N.J.) |
| etraethyl lead as anti-knock agent* | Refiners |
| ctane numbers scale* | Ethyl |

**1939-58**

| Innovation | Innovator |
|---|---|
| Moving-bed catalytic cracking | Socony |
| Fluid-bed catalytic cracking | Standard (N.J.) |
| Catalytic reforming | Standard (Ind.) |
| Platforming | Old Dutch |
| Hydrogen treating | Standard (N.J.) |
| Unifining | Union & Sohio |
| Solvent extraction of aromatics | Standard (N.J.) |
| Udex process | Eastern States |
| Propane decarbonizing | Cities Service |
| Alkylation (H Fl) | Phillips |
| Butane isomerization | Shell |
| Pentane and Hexane isomerization | Standard (Ind.) |
| Molecular sieve separation | Texaco |
| Fluid coking | Standard (N.J.) |
| Sulfur | Standard (Ind.) |
| Cyclohexane | Phillips |
| Heptene | Standard (N.J.) |
| Trimer | Atlantic |
| Tetramer | Atlantic |
| Aromatics | Standard (N.J.) |
| Paraxylene | Standard (Cal.) |
| Ethanol | Standard (N.J.) |
| Butadiene | Standard (N.J.) & Shell |
| Styrene | Shell |
| Cumene | Standard (Cal.) |
| Oxo Alcohols | Standard (N.J.) |
| Dibasic acids | Standard (Cal.) |
| Carbon black (oil furnace) | Phillips |
| Glycerine | Shell |
| Synthetic rubber | Standard (N.J.) |
| Ethylene dichloride | Standard (N.J.) |
| Diallyl phthalate polymers | Shell |
| Epoxy resins | Shell |
| Polystyrene | Cosden |
| Resinous high-styrene copolymers | Shell |
| Polyethylene | Phillips |

ource: same as Table la.

* Innovations excluded from Tables 2 - 5 because innovator had no crude capacity or because it was engaged primarily in another business. See note 8.

Table 1c -- Innovations and Innovators, Bituminous Coal Preparation, 1919-38 and 1939-58.

| 1919-38 | | 1939-58 | |
|---|---|---|---|
| Innovation | Innovator | Innovation | Innovator |
| Simon-Carves washer | Jones & Laughlin & Central Indiana | Raymond flash dryer | Enos |
| Stump air flow cleaner | Barnes | CMI drying unit | Hanna |
| Chance cleaner | Rock Hill | Link-Belt separator | Pittsburgh |
| "Roto Louvre" dryer | Hanna | Bird centrifugal filter | Consolidation |
| Vissac (McNally)dryer | Northwestern Improvement | Baughman "Verti-Vane" dryer | Central Indiana |
| Ruggles-Cole kiln dryer | Cottonwood | Vissac Pulso updraft dryer | Northwestern Improvement |
| Rheolaveur | American Smelting | Link Belt multi-louvre dryer | Diamond, Elkhorn, Bethlehem & Eastern Gas & Fuel |
| Menzies cone separator | Franklin County | Eimro filter | United Electric |
| Deister table | U. S. Steel | Dorncofluosolids machine | Lynnville |
| Carpenter dryer | Colorado Fuel & Iron | Parry entrainment dryer | Freeman |
| Froth flotation | Pittsburgh | Heyl and Patterson fluid bed dryer | Jewell Ridge |
| | | Feldspar type jig | Northwestern Improvement |
| | | Bird-Humboldt centrifugal dryer | Clinchfield |
| | | Wemco Fagergrom flotation unit | Hanna, Sevatora, & Diamond |
| | | Continuous horizontal filter | Island Creek |
| | | Cyclones as thickeners* | Dutch State Mines |

Source: same as Table 1a.

in petroleum, the daily crude capacity of each firm in 1927 and 1947 was obtained; and in coal, the production of each firm in 1933 and 1953 was obtained. The data were collected primarily from government documents and trade directories, but in a few cases they had to be gotten directly from the firms.[7] Finally, we determined how many of these innovations were first introduced by the largest four firms in each industry.[8] (Since the recent situation probably differed from that in the pre-war era, innovations that occurred during 1939-1958 were separated from those that occurred during 1919-1938.)

Do the results indicate that the largest firms introduced a disproportionately large share of the innovations? Of course, this depends on what one means by a disproportionately large share. But if the largest firms devoted the same proportion of their resources as smaller firms both to inventive activity and to the testing and development of other people's ideas, if they could obtain applicable results as easily, and if they were as efficient and as quick to apply the results, one would expect their share of the innovations to equal their share of the market.[9] Did they account for more than this?

According to the rather crude measurements in Table 2, the answer seems to vary from one industry to another. Relative to their share of the market, the largest four coal and petroleum firms carried out a large number of innovations. On the other hand, the largest four steel producers carried out relatively few. Thus, if the Schumpeterian hypothesis is taken to mean that the largest firms accounted for a larger share of the innovations than of the market, it seemed generally to hold in petroleum and coal, but not in steel.[10]

Table 2: Percent of Innovations and Capacity (or Output) Accounted for by Largest Four Firms, Steel, Petroleum Refining, and Bituminous Coal Industries, 1919-38 and 1939-58.[a]

| | Steel[b] | | Petroleum[c] | | Coal[d] | |
|---|---|---|---|---|---|---|
| tem | Weighted | Unweighted | Weighted | Unweighted | Weighted | Unweighted |
| | [percent of industry total] | | | | | |
| | Period: 1919-38 | | | | | |
| rocess innovations | 39 | 41 | 34 | 36 | 27 | 18 |
| roduct innovation | 20 | 20 | 60 | 71 | -- | -- |
| ll innovations e/ | 30 | 32 | 47 | 54 | 27 | 18 |
| apacity (or output) | 62 | 62 | 33 | 33 | 11 | 11 |
| | Period: 1939-58 | | | | | |
| rocess innovations | 58 | 64 | 58 | 57 | 30 | 27 |
| roduct innovations | 27 | 27 | 40 | 34 | -- | -- |
| ll innovations e/ | 43 | 51 | 49 | 43 | 30 | 27 |
| city (or output) | 63 | 63 | 39 | 39 | 13 | 13 |

Source: See Tables 1a - 1c.

a/ In the columns headed "weighted", each innovation is weighted roughly according to the respondents' views of its importance. More precisely, each is weighted in proportion to its average rank in the lists obtained. For processes, we suggested that total savings be used to judge relative importance; for new products, we suggested that sales volume be used. Obviously, this is very rough.

b/ Ingot capacity is used to measure each firm's size. The industry is defined to be those firms with ingot capacity, but firms engaged primarily in some other business were excluded. For the earlier period, a firm's size refers to 1926; for the later period it refers to 1945.

c/ Crude capacity is used to measure each firm's size. The industry is defined to be those firms with crude capacity. For 1919-38, a firm's size refers to 1927; for 1939-58, the figures refer to 1947. The product innovations included here are petrochemicals. In each case, the innovator is the first petroleum company that produced it.

d/ Annual production is used to measure each firm's size. The industry is defined to include all who produced bituminous coal. For 1919-38, a firm's size refers to 1933; for 1939-58, these figures refer to 1953. The innovations included here are all new devices for preparing coal. This was the only kind of data we could obtain.

e/ For the weighted data, this is just the unweighted average of the figures for process and product innovations.

## 4. A Simple Model

Why did the largest four firms introduce a relatively large share of the innovations in some cases, but not in others? The differences in this respect may be explained in part by the following sort of model. Consider the innovations of a particular type (i.e., process or product) that were introduced during a given period of time in a particular industry. Letting $\Pi_j$ be the proportion of these innovations introduced by the $j^{th}$ firms in this industry, we assume that

$$(1) \qquad \Pi_j = \begin{cases} 0 & S_j < M \\ \beta_1 + \beta_2 S_j & S_j \geq M \end{cases} ,$$

where $S_j$ is the size (measured in terms of assets) of the $j^{th}$ firm. Of course, $\beta_1$ , $\beta_2$ , and $M$ vary among industries, time periods, and types of innovations, and $\beta_2$ is presumed to be positive.

Firms below a certain size $(M)$ introduce none of the innovations because they lack the volume of production required to use the innovations profitably. (For simplicity, we assume that the minimum size of firm required to use an innovation is approximately the same for innovations of the same type that occur in a particular time interval in a given industry.) For firms larger than $M$, we suppose that the proportion of these innovations introduced by a firm is a direct, linear function of its size.[11/] (For the reasons discussed in Sections 2-3, one would expect $\Pi_j$ to be directly related to $S_j$ .)

Next, we assume that a firm's size has more effect on $\Pi_j$ if the innovations require relatively large investments than if they can be introduced cheaply. Certainly, if the innovations require very large investments, one would expect that larger firms would be required to finance these projects and to take the risks. Consequently, increases in $S_j$ would result in larger increases in $\Pi_j$ than if the innovations were relatively cheap to introduce.[12]

Thus, assuming for simplicity that the minimum investment required to introduce all innovations of a particular type that occurred during a particular time interval in a given industry is I, we suppose that

$$\text{(2)} \qquad \beta_2 = \alpha_1 + \alpha_2 \, I/\bar{S}_M + z \ ,$$

where $\bar{S}_M$ is the average assets of the firms with assets greater than or equal to M , $\alpha_2$ is presumed to be positive, and z is a random error term. The ratio of I to $\bar{S}_M$ (rather than I alone) is used because in the present context the size of the investment must be related to the average size of the relevant firms. Of course, measures other than $\bar{S}_M$ (e.g., M) could have been used instead, but the results would have been much the same as those presented below.[13]

If these assumptions hold, it follows that the proportion of the innovations carried out by the four largest firms should equal

$$\text{(3)} \qquad \Pi = 4/N\ (M) + 4\,\alpha_1\,[\bar{S}_4 - \bar{S}_M] + 4\,\alpha_2\, I\,[\bar{S}_4 - \bar{S}_M] \,/\, \bar{S}_M + z' \ ,$$

where N(M) is the number of firms with assets greater than or equal to M, $\bar{S}_4$ is the average assets of the four largest firms, and z' is a random error term.[14/] Thus, N(M), $(\bar{S}_4 - \bar{S}_M)$, and $I/\bar{S}_M$ determine whether or not the four largest firms introduce a disproportionately large share of the innovations.

According to this model, the characteristics (particularly I and M) of the innovations that can profitably be introduced in a particular industry during a given time interval are exogenous variables determined by the largely unpredictable nature of the technical breakthroughs made previously by members of the industry, equipment manufacturers, independent research organizations, etc. If, on the contrary, these characteristics are influenced by the extent to which the largest firms are the innovators, an identification problem arises in equation (3).

For example, if smaller (larger) firms in the industry, when confronted with various research and innovative opportunities, favor those with small (large) values of I and M, Π may be directly related to I and M although the line of causation is the reverse of that underlying equation (3). Whereas an identification problem of this sort may turn out to be troublesome in some industries, interviews indicate that it is probably of little significance in the industries used here.[15/] Lacking other evidence, we proceed on this perhaps shaky assumption.

To see how well this model can explain the observed difference in Π, we obtained rough estimates of I, M, N(M), $\bar{S}_4$, and $\bar{S}_M$ for the innovations of each type in steel and petroleum during each period. Unfortunately, suitable data of this sort could not be obtained for coal. The results are shown in Table 3. Using these data, we derived least-squares estimates of $\alpha_1$ and $\alpha_2$. Inserting them into equation (3), we have

$$(4) \qquad \Pi - 4/N(M) = \underset{(.00007)}{.00014} \; [\bar{S}_4 - \bar{S}_M] + \underset{(.0063)}{.0289} \; I \; [\bar{S}_4 - \bar{S}_M]/\bar{S}_M ,$$

where the figures in parentheses are standard errors and $z'$ is omitted. As the model predicts, the estimate of $\alpha_2$ is positive and statistically significant.[16]

Figure 1 shows that this equation can represent the data in Table 2 quite well, the coefficient of correlation (adjusted for degrees of freedom) being .88. Of course this model is oversimplified and incomplete, one important omission being the costliness of carrying out research and development. Nonetheless, the model seems useful in understanding the determinants of $\Pi$ and in predicting whether or not the largest firms in a particular industry will introduce a relatively large share of the innovations.[17]

## 5. Dissolution of Corporate Giants

Thus far, we have considered whether or not the largest firms accounted for a disproportionately large share of the innovations. More basically, one would like to know whether fewer innovations would have been introduced during each period if these giants had been broken up. If one is willing to ignore the effects of all factors other than a firm's size on the number of

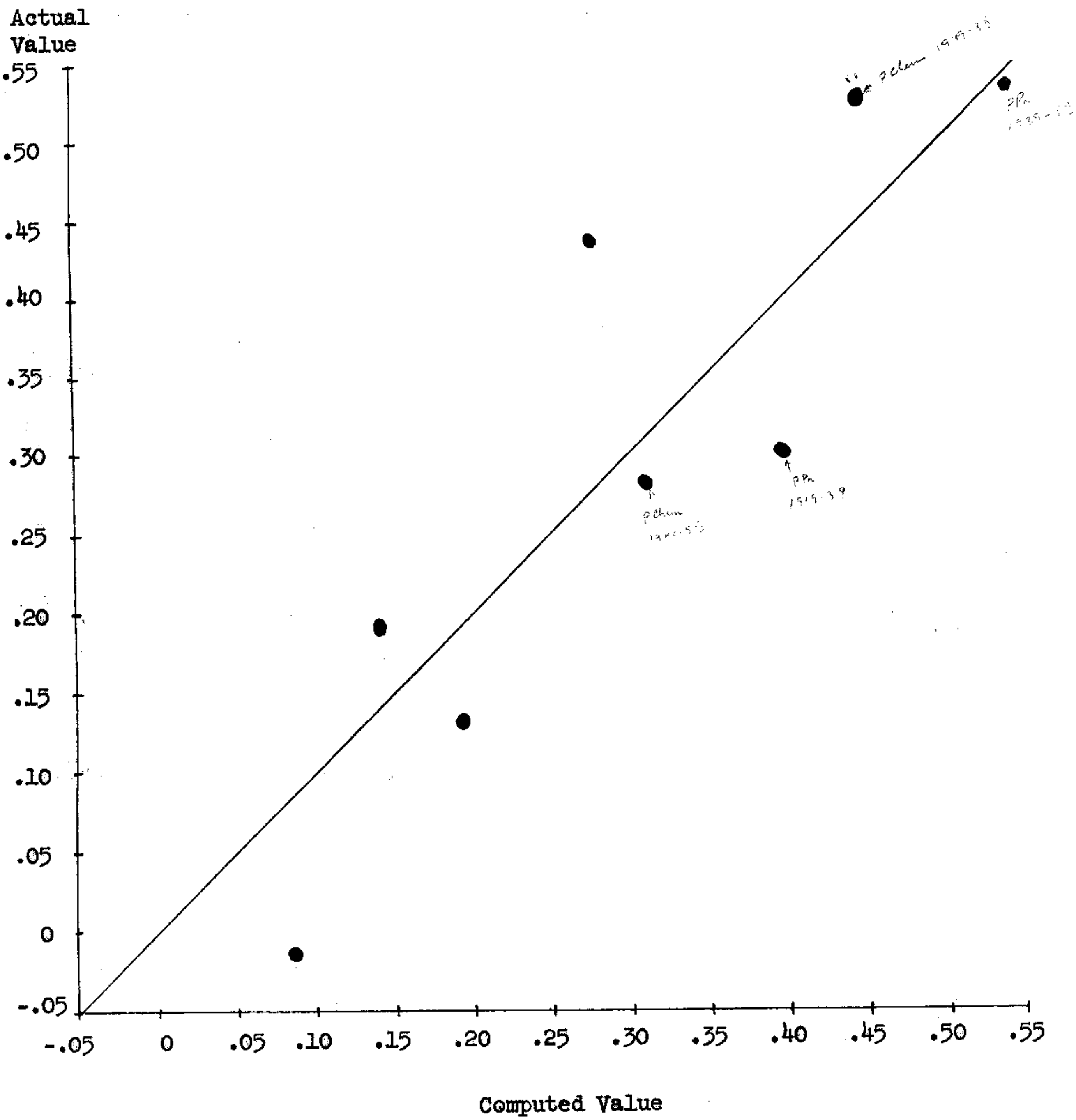
Table 3: Values of M, N(M), I, $\bar{S}_4$ , and $\bar{S}_M$ , Steel and Petroleum Refining Industries, Process and Product Innovations, 1919-38 and 1939-58.

| Industry and Type of Innovation | M | N(M) | I | $\bar{S}_4$ | $\bar{S}_M$ |
|---|---|---|---|---|---|
| | Parameter[1/] | | | | |
| **Period: 1919-38** | | | | | |
| Steel: | | | | | |
| Process | 46.0 | 19 | .60 | 858.5 | 245.2 |
| Product | 47.0 | 18 | .10 | 858.5 | 256.2 |
| Petroleum: | | | | | |
| Process | 10.0 | 81 | 1.75 | 554.4 | 72.6 |
| Product | 18.2 | 50 | 3.30 | 554.4 | 109.2 |
| **Period: 1939-58** | | | | | |
| Steel: | | | | | |
| Process | 26.3 | 29 | 1.30 | 1238.0 | 256.3 |
| Product | 23.5 | 30 | .50 | 1238.0 | 248.6 |
| Petroleum: | | | | | |
| Process | 13.3 | 82 | 1.77 | 1243.0 | 144.0 |
| Product | 36.4 | 34 | 2.08 | 1243.0 | 314.7 |

Source: See note 16.

1/ Symbols: M is the average minimum size (assets) of firms required to use the innovations, N(M) is the number of firms exceeding this size, $\bar{S}_M$ is the average size (assets) of the firms exceeding this size, $\bar{S}_4$ is the average size (assets) of the four largest firms, and I is the average minimum investment required to install the innovations. All but N(M) are expressed in millions of dollars.

Figure 1 -- Plot of Actual Value of $(\Pi - \frac{4}{N(M)})$ Against That Computed from Equation (4), Process and Product Innovations, Steel and Petroleum Refining Industries, 1919-58.




Source: Table 3. The line is a 45° line through the origin.

innovations it carried out, some very rough answers can be obtained, but these results should obviously be treated with the utmost caution.

Assume that during 1919-38 and 1939-58 and for each industry and type of innovation,

$$n_j = \alpha_0 + \alpha_1 S_j + \alpha_2 S_j^2 + \alpha_3 S_j^3 + z'' , \qquad (5)$$

where $n_j$ is the number of innovations carried out by the $j^{th}$ firm, $S_j$ is the firm's size, and $z''$ is a random error term. This model is more useful and convenient than equation (1) for present purposes. Needless to say, the use of equation (5) rather than equation (1) involves no more than a substitution of one sort of approximation for another.[18/]

Let the computed regression of $n_j$ on $S_j$ be $N(S_j)$ and ignore the sampling errors in it. Then, if $N(S_j)/S_j$ is a maximum at or near the size of the largest firm, it would appear on the basis of these assumptions that the dissolution of the largest firms would have resulted in fewer innovations being carried out. On the other hand, if $N(S_j)/S_j$ reaches a maximum far below the size of the largest firm, its dissolution would presumably have had a positive effect.[19/]

Such an analysis is extremely crude, but what do the results suggest? The estimates of the a's are contained in Table 4. In the petroleum and coal industries, the regressions seem to support the Schumpeterean view that fewer innovations would have been introduced if the largest firms had been broken up. (However, in petroleum, many of the estimates of the a's are statistically non-significant.) In the steel industry, the results seem to contradict the

Schumpeterean view; the maximum value of $N(S_j)/S_j$ is always found among relatively small firms.[20]

These findings are not inconsistent with the conclusions reached by others. For example, they lend support to Stocking's assertion that the largest steel producers have not tended to be the technical leaders. Judging by our results, it would be difficult to justify the existence of that industry's giants on the basis of their past performance as innovators.[21]

Finally, four additional points should be noted regarding these results. First, it is possible of course that the average delay in utilizing inventions, not the number utilized would be affected if the largest firms were broken up. Section 7 investigates this possibility in the case where the inventor is not a member of the industry. Second, judging by the correlation coefficients in Table 4, these cubic regressions fit the data quite well in most cases -- but not always. For the innovations in coal and the product innovations in steel in 1919-1938, the correlation coefficients were only about .45, but excluding these three cases, the correlation coefficients average about .80.[22]

Third, the regressions indicate that in almost all cases $n_j$ is an increasing function of $S_j$ throughout most of the relevant range: of course, this is what one would expect. Fourth, the data on which the regressions are based are quite consistent with the estimates of M in Table 2. Firms below a size closely related to M seldom, if ever, introduced an innovation in these industries.[23]

Table 4 -- Least-squares Estimates of $a_0$, $a_1$, $a_2$, and $a_3$, Steel, Petroleum Refining, and Bituminous Coal Industries, Process and Product Innovations, 1919-38 and 1939-58.[1/]

| Industry and Type of Innovation | Estimates $a_0$ | $a_1$ | $a_2$ | $a_3$ | Correlation Coefficient | Number of Firms |
|---|---|---|---|---|---|---|
| | | | Period: 1919-38 | | | |
| Steel: | | | | | | |
| Process | -.003042 | .3998* (.0887) | .07532* (.01830) | .002891 (.000654) | .82 | 101 |
| Product | .08412 | -.0196 (.1164) | .00108 (.02402) | .000271 (.000859) | .49 | 101 |
| Petroleum: | | | | | | |
| Process | -.01274 | 65.845* (13.585) | -3207.26* (984.49) | 59,697.4* (14,674.8) | .72 | 221 |
| Product | .000 | 5.858 (14.525) | 2429.70* (1052.67) | -12,463.2 (15,691.2) | .86 | 221 |
| Coal: | | | | | | |
| Process | -.008859 | .08009* (.02176) | -.02525* (.00877) | .002379* (.000720) | .32 | 639 |
| | | | Period: 1939-58 | | | |
| Steel: | | | | | | |
| Process | -.02812 | .2904* (.0951) | -.01470 (.01394) | .000274 (.000380) | .71 | 68 |
| Product | -.04551 | .3146* (.0588) | -.03779 (.00862) | .000984* (.000235) | .63 | 68 |
| Petroleum: | | | | | | |
| Process | .00056 | 12.962* (5.428) | 258.13 (184.91) | -1,037.6 (1,068.9) | .88 | 269 |
| Product | -.05016 | 81.811* (13.969) | -180.33 (476.67) | 1,119.8 (2,755.5) | .76 | 269 |
| Coal: | | | | | | |
| Process | .01554 | -.01153 (.01916) | .01405* (.00397) | -.0005295* (.0001395) | .46 | 582 |

Source: Tables 1a - 1c.

[1/] The smallest firms were omitted. See note 20.

* Significant at .05 probability level.

## 6. The Changing Role of Large and Small Firms

It is frequently asserted that a small firm now does less innovating -- relative to a large firm -- than it did in the past.[24] Because of rising development costs and the greater complexity of technology, this hypothesis seems plausible for a wide range of industries. Does it seem to hold in steel, petroleum and coal? To help answer this question, we took the average number of innovations carried out by a "small" firm in 1919-38 and 1939-58 and expressed it in each case as a percentage of the average number carried out by a "large" or a "medium-sized" firm. Then we determined whether -- as the hypothesis implies -- the percentage in 1919-1938 was higher than in 1939-1958.

The results -- shown in Table 5 -- suggest that this hypothesis holds in the steel and petroleum industries, but not in bituminous coal. With regard to both process and product innovations and relative to both large and medium-sized firms, the small firms in the steel and petroleum industries seem to have become less important as a source of innovations. This result holds for the weighted data as well as the unweighted. In bituminous coal, the opposite appears to be the case, but there is some reason to think that the data for this industry are biased against the hypothesis.[25]

According to the estimates in Table 2, the decreasing importance of the small firms in the steel industry may have been due in part to an increase in the capital requirements for innovating, but not to an increase in the minimum size of firm which could profitably use the innovations. In the petroleum industry, the situation was just the opposite. Whereas I remained relatively constant, M increased appreciably.

Table 5: Average Number of Innovations Carried Out by a Smaller Firm Relative to That Carried Out by a Larger Firm, Steel, Petroleum Refining, and Bituminous Coal Industries, 1919-38 and 1939-58.[1/]

| Industry, type of innovation and time interval | Number carried out by a small firm as a percent of that carried out by a: large firm | medium-sized firm | Number carried out by a medium-sized firm as a percent of that carried out by a large firm |
|---|---|---|---|
| Steel process: | | | |
| 1919-38 | 0.7 | 0.8 | 8.3 |
| 1939-58 | 0.0 | 0.0 | 7.8 |
| Steel product: | | | |
| 1919-38 | 7.1 | 100.0 | 7.1 |
| 1939-58 | 0.0 | 0.0 | 37.1 |
| Petroleum process: | | | |
| 1919-38 | 0.6 | 3.4 | 18.5 |
| 1939-58 | 0.5 | 2.0 | 23.3 |
| Petroleum product: | | | |
| 1919-38 | 0.2 | 1.3 | 13.3 |
| 1939-58 | 0.1 | 0.6 | 21.9 |
| Coal process: | | | |
| 1919-38 | 0.1 | 0.7 | 11.2 |
| 1939-58 | 0.2 | 2.7 | 6.1 |

Source: Tables 1a - 1c

1/ In steel "large" firms have 4,000,000 tons or more, "medium-sized" firms have 125,000 to 4,000,000 tons, and "small" firms have less than 125,000 tons of ingot capacity. In petroleum, "large" firms have 300,000 barrels or more, "medium-sized" firms have 75,000 to 300,000 barrels of daily crude capacity and "small" firms have less than 75,000. In coal, "large" firms produced 5,000,000 tons or more, "medium-sized" firms produced 500,000 to 5,000,000 tons, and "small" firms produced less than 500,000 tons annually. The size classes obviously are quite arbitrary.

Although the small steel and petroleum firms seem to have become relatively less important, there is no evidence that this was also the case with regard to the medium-sized firms. On the contrary, in 1939-1958 a medium-sized firm introduced, on the average, a greater number of innovations -- relative to the number introduced by a large firm -- than in 1919-1938. The reasons for this are by no means clear, but it may have been that the medium-sized firms increased their research expenditures by a greater proportion than did the large firms. This would be quite consistent with a hypothesis recently put forth by Schmookler [28].[26]

## 7. Market Structure and the Rate of Introduction of Inventions

Suppose that an individual or firm invents a device that could profitably be used in a particular industry, but suppose that the inventor is not a member of this industry and that consequently he must induce some firm in the industry to introduce it or enter the industry himself. For this type of invention, an important question is: what effect would a change in market structure have on the length of time that elapses before someone introduces the invention?

This question has received considerable attention -- both recently and in the past. On the one hand, there are some -- like Bain [2], Brozen [4], Joan Robinson [27], and Stocking [33] -- who believe that inventions would be applied most rapidly under purely competitive conditions. They argue that if many firms exist, there is more protection against an invention's being blocked by the faulty judgment of only a few men. Moreover, they allege that the existence of many competitors will force a firm to seek out and apply new ideas, whereas a live-and-let-live policy may develop otherwise.[27]

On the other hand, there are others -- like Villard [34] -- who think that they would be applied most rapidly if industries contained relatively few large firms. They point out that such firms are better able to finance the introduction of inventions and to take the necessary risks. And they sometimes claim that the larger firms will have better managers who will be more inclined to innovate.

Although each group has some convincing points on its side, there is no evidence that one's arguments are universally more powerful than the others'. And in a particular case we are unable to tell how these factors should be quantified and weighted so that a conclusion can be reached. This section contains some exploratory attempts to devise operational techniques to handle this problem.

Suppose that an industry is composed of $n-1$ firms. If at time $t$ a particular invention of this sort has not yet been introduced, suppose that the probability that the $i^{th}$ firm will introduce it between time $t$ and time $t + \Delta$ is $\lambda_i \Delta$. Suppose that the probability that the inventor or some other new entrant into the industry will introduce it then is $\lambda_n \Delta$. Assume too that there is no collusion among the firms to prevent the application of the technique. That is, assume that the probability that the $i^{th}$ firm will introduce it between time $t$ and time $t + \Delta$ does not depend on whether some other firm decides to do so.[28]

Under these conditions, one can easily obtain expressions for L , the expected length of time that will elapse before the invention is applied, and $P_j$ , the probability that the $j^{th}$ firm will be the innovator.

$$L = \lim_{\Delta \to 0} [\Delta \left\{ 1 - \prod_{i=1}^{n} (1 - \lambda_i \Delta) \right\} \left\{ 1 + 2 \prod_{i=1}^{n} (1 - \lambda_i \Delta) + 3 [\prod_{i=1}^{n} (1 - \lambda_i \Delta)]^2 + \dots \right\} ]$$

(6) $$= (\sum_{i=1}^{n} \lambda_i)^{-1}$$

$$P_j = \lim_{\Delta \to 0} [\lambda_j \Delta \prod_{\substack{i=1 \\ \neq j}}^{n} (1 - \lambda_i \Delta) \left\{ 1 + \prod_{i=1}^{n} (1 - \lambda_i \Delta) + [\prod_{i=1}^{n} (1 - \lambda_i \Delta)]^2 + \dots \right\} ]$$

(7) $$= \lambda_j L$$

Suppose that a change is being contemplated in the size distribution of firms in a given industry. Assume that each firm's size and its value of $\lambda$ have been relatively constant in the recent past. Assume that, once this reorganization is either carried out or dropped, each firm's size and its value of $\lambda$ will again remain relatively constant for some time.[29] Suppose that, if the proposed reorganization occurs, the frequency distribution of firms by size will be n(S). If it does not occur, suppose that it will be m(S). Ignore differences among inventions in a firm's value of $\lambda$ and the possibility that the inventor will enter the industry. Although they complicate things, these matters can be introduced without altering the essentials of the argument.[30]

What effect will the proposed reorganization have on L ? It seems reasonable to believe that a firm's value of $\lambda$ is a function of its size. Suppose that, whether or not the proposed change in market structure occurs, the average value of $\lambda$ for firms of given size will be proportional to the average value in the recent past (the coefficient of proportionality being $\Phi$ ). Of course, whether or not this is true depends on the particular change in market structure and on the characteristics of the industry.[31]

If this assumption holds and if $\lambda(S)$ was the average value of $\lambda$ for firms of size S in the recent past, the expected delay, given that the reorganization occurs, is

$$(8) \qquad L_o = [\Phi \sum_s \lambda(S)\, n\, (S)]^{-1} .$$

And if $\hat{f}(S)$ is the regression in the recent past of the proportion of the innovations of this type that a firm carried out on its size, an estimate of the percentage change in average delay resulting from the proposed change in the size distribution of firms is

$$(9) \qquad C = 100 \left\{ [\sum_s m(S)\, \hat{f}\, (S) / \sum_s n\, (S)\, \hat{f}\, (S)] - 1 \right\}$$

Since $n(S)$ and $m(S)$ are given and $\hat{f}(S)$ can be estimated from past data, the expression in equation (9) can be computed.[32]

As an illustration, consider process innovations in steel. In 1945, suppose that we wanted to estimate the effect of splitting U. S. Steel into seven smaller firms of equal size and keeping the rest of the steel producers at their 1945 size, the alternative being that all firms (including U.S. Steel) would maintain their 1945 size. Assuming that $\lambda_i$ did not vary much from invention to invention and that the relation between the proportion of the innovations of the relevant kind that a firm carried out in the period immediately before 1945 and its 1945 size was like that between the proportion of all process innovations it carried out during 1939-58 and its 1945 size,

$$\hat{f}(S) = -.0022 + .022S - .0011S^2 + .000021S^3 . \quad (10)$$

Since $S = 28$ for U.S. Steel, it follows from equations (9) and (10) that the average delay, according to these rough estimates, would have been decreased by about 20 percent if U.S. Steel had been broken up in this way. Needless to say, these results can only be suggestive, particularly since the $\lambda$'s might have been affected by the reorganization of the industry.[33]

## 8. Summary and Conclusion

This paper reports some theoretical and empirical results regarding the effects of an industry's market structure on its rate of technical progress. Its principal findings are as follows: First, although it is often alleged that the largest firms introduce a disproportionately large share of the innovations, this is not always the case. In petroleum refining and bituminous coal, the largest four firms accounted for a larger share of the innovations than they did of the market. But in steel they accounted for less.

Second, the largest four firms seemed to account for a relatively large share of the innovating in cases where (1) the investment required to innovate was large, (2) the minimum size of firm required to use the innovations profitably was relatively large, and (3) the average size of the largest four firms was much greater than the average size of all potential users of the innovations. A simple model that focused particular attention on these factors could explain most of the observed interindustry and temporal differences.

Third, some very rough estimates suggest that, if the largest firms in the petroleum and coal industries had been broken up, fewer innovations would have been introduced. On the other hand, in the steel industry, their dissolution might have had positive effects. In view of the crudeness of the underlying model, these results should be treated with considerable caution.

Fourth, there is evidence that the smallest steel and oil firms did less innovating -- relative to large and medium-sized firms -- in recent years than in the period before World War II. With the rising costs of development and the greater complexity of technology, this is not surprising. In the coal industry, this is not the case but there are some special factors at work there.

Fifth, under certain circumstances, one can estimate the effect of a proposed change in market structure on the average time interval that elapses before an invention made outside the industry is applied. If a simple model of the innovation process holds, historical data identifying the innovators can be used to estimate these effects. Of course, this technique can only be used under certain circumstances, but it is operational and it should be a useful step toward the general solution of this problem.

Despite their obvious limitations, these results seem both useful and encouraging. Being concerned entirely with innovation, they provide a necessary link between the findings in [20] regarding the effects of a firm's size on the extent and effectiveness of its research activities and the findings in [17] - [19] regarding the effects of a firm's size and an industry's market structure on the rate of imitation. Moreover, they provide an important supplement to the results in [21] regarding the effects of innovation on a firm's rate of growth.

For the first time, data of more than a fragmentary nature have been collected regarding the innovators in several important industries. The usefulness of such data for a wide variety of purposes seems obvious. In addition, models have been devised to help relate these empirical findings to questions bearing on public policy. Further efforts should be made to obtain the theoretical and empirical results so badly needed in the area. Although an industry's market structure is but one of many factors influencing the rate of technical progress, it is important in formulating public policy that we learn more about the direction and magnitude of its effects.

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FOOTNOTES

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1/ For example, see Schumpeter [29], Galbraith [9], Kaplan [13], Lilienthal [14], MacLaurin [16], Villard [34], Mason [22], Mueller [23], Nutter [25], Stigler [32], Bain [2], Brozen [4], Robinson [27], Stocking [33], Jewkes, Sawers and Stillerman [12], Steltzer [31], Schmookler [28], Scitovsky [30], and Fellner [7].

2/ Throughout this paper we shall make the customary distinction between the inventor and the innovator, the latter being the firm that first introduced a new process or product commercially in this country. We are concerned here almost exclusively with innovations, not inventions. For some relevant findings regarding invention and other aspects of technical change, see [17], [18], [19], [20], and [21].

3/ The argument that bigness has become necessary for innovation has probably been stated most bluntly by Galbraith [9]. "Technical development has long since become the preserve of the scientist and the engineer. Most of the cheap and simple inventions.....have been made." (p.91) "[Development] can be carried on only by a firm that has the resources associated with considerable size." (p.92)

If this is so, the largest firms are likely to carry out a disproportionately large share of the inventions; and since (as Schumpeter pointed out) innovation is generally more risky and costly than invention, they are perhaps even more likely to carry out a disproportionately large share of the innovations. Of course, if they do not carry out a disproportionately large share, it does not follow that some minimum size of firm is not required in this area, but it suggests that this argument can not be used to justify the existence of the largest firms -- and they are likely to be the main candidates for dissolution. The problem of defining what is a "disproportionately large" share is postponed to Section 3.

4/ Empirical studies of this sort have been recommended by Mason [22], p. 143; Hennipman [11], p. 456; and Scitovsky [30], p. 108. There are considerable -- and obvious -- difficulties in defining a particular innovation, in singling out the innovators, and in gauging the relative importance of various innovations. In view of these difficulties, any empirical study must be arbitrary in some respects and the results can only be rough approximations.

5/ Of course, the distinction between a process and a product innovation may sometimes be blurred because a new technique that reduces the cost of some product may also alter it somewhat. In such cases, we asked the respondent to make a judgment as to whether the alteration was great enough for it to be considered a new product.

In the case of petroleum refining, the product innovations are petrochemicals. We used a classification of important petrochemicals developed by a major oil company for its internal use. Then sales in 1958 were used to rank them. Some of the classes are very broad, but there is no obvious bias. In steel, innovation in iron ore preparation, handling, etc. are excluded. In the coal industry, the innovations are all new techniques for the preparation of coal. This was the only type of innovation for which data could be obtained at all readily, and it may not be representative of all process innovations in bituminous coal. Most of the results in Table 1c were computed from data and information appearing in Coal Age, a McGraw-Hill publication.

To make sure that the lists were reasonably complete, they were checked with members of the Carnegie engineering faculty and the Bureau of Mines. A few innovations were added to the lists on their recommendation (and some were dropped).

6/ We could obtain data for about 90 percent of the innovations in petroleum refining, about 50 percent of the innovations in the steel industry, and practically all of the innovations in the coal industry. In the case of the product innovations in petroleum refining -- i.e., petrochemicals, the innovator is defined to be the first petroleum company that produced the product commercially from a petroleum base. In a considerable number of these cases, the product had been previously produced by chemical companies. However, the petroleum company generally used a different process than its predecessors. In such cases, the innovations might have been considered as process innovations, but this would have made little difference to the final results.

Although the data on the identity of the innovation are generally reliable, there are a few cases in each industry where the data -- based on the recollections of suppliers, etc. -- may be wrong.

With regard to the rankings by importance, no sales data could be obtained to rank the product innovations in steel. Tariff Commission data for 1958 were used for this purpose in the case of the product innovations in petroleum. In the other cases, ranks were obtained both from respondents and Carnegie (or Bureau of Mines) personnel; and the average of these ranks was used. These data are obviously very rough, but it is noteworthy that in each case the independent rankings were very highly correlated, indicating a considerable amount of agreement.

7/ The daily crude capacity of each petroleum refiner (other than the top twenty companies) in 1927 was obtained from the Petroleum Register. For 1947 it was obtained from a Bureau of Mines circular [5]. The daily crude capacity (domestic and overseas) of the top twenty companies was obtained directly from the firms. The ingot capacity of each firm in 1926 and in 1945 was obtained from the Directory of the American Iron and Steel Institute [1].

For the coal industry, size distributions of firms in the "base states" are provided by Risser [26] for 1933 and 1953. We multiplied the number in each size class -- under one million tons of production annually -- by the ratio of the total production in the country to that in the "base states." A complete count of firms with over 1 million tons produced in 1933 and 1953 was obtained from the Keystone Coal Buyer's Guide. The production of the innovators was also obtained from this source. Risser's data seem to exclude firms producing less than 1,000 tons annually.

8/ In the steel industry, innovations introduced by firms without any ingot capacity or by firms engaged primarily in some other business had to be omitted. To include them on the basis of their ingot capacity would have been to misstate their true size. And no measure of size other than ingot capacity (or pig iron capacity) is readily available for most of the firms in the industry. Such innovations are marked with an asterisk in Table 1a.

In the petroleum industry, a few innovations had to be omitted for much the same sort of reason. In the coal industry, innovations introduced by firms engaged primarily in some other business were not omitted. Such firms account for a large proportion of the industry's output, and the results would not have been altered much in any event if they had been omitted.

9/ Of course, it could also be that they devote more of their resources to inventive activity and less to testing and trying out inventions made by outsiders, and that fewer innovations are produced per dollar of expenditure on the former activity. This is difficult to check. But there is no evidence that it was the case in the steel industry -- the only case where their share of the innovations was less than their share of the market.

The unweighted data suffer from the lack of a clear-cut way to define an innovation and gauge its importance. Conceivably, some of these innovations could be regarded as a set of separate innovations -- not one. If they were, the results using unweighted data would depend on how many elements were recognized in each case.

Of course, the weighted data should eliminate this problem, but the weights are obviously very crude. In addition, the lesser -- and some important -- innovations are excluded altogether; and hence sampling errors (and perhaps biases) are present.

10/ We follow the convention (adopted in most studies of industrial concentration) of using the largest four firms as a basis for concentration measures. In steel, the largest firms' share of the market is their share of the industry's ingot capacity. In petroleum, it is their share of the industry's daily crude capacity. In bituminous coal, it is their share of the industry's (tonnage) production.

Other measures -- e.g., percent of value added or percent of employment -- might have been used instead. But Census data for petroleum in 1935 and 1947 and for steel in 1947 indicate that the results would change only slightly. For 1919-1938, the largest petroleum firms' share of the innovations would have exceeded their share of value added or employment, but the difference would have been somewhat smaller than in Table 2. For 1939-1958, the results in petroleum would have been about the same as in Table 2. For 1939-1958, the largest steel firms' share of the innovations would have been less than their share of the assets or employment, but larger than their share of value added.

Of course, these shares pertain to only one year during each of the twenty-year periods, but this should not cause much difficulty because the rank order of firms by size -- and the share of the market of the largest firms -- is reasonably stable in these industries.

In 1919-38, the difference between the largest firms' share of the innovations and their share of the market was almost always statistically significant in steel and petroleum. In 1939-58, the share of the innovations introduced by the largest firms was closer to their share of the market than in 1919-1938, and often the differences may not have been statistically significant in steel and petroleum. In bituminous coal, there was a relatively small chance that the differences in Table 2 were due to chance in either period.

11/ Of course, a linear function is only a convenient simplification. Up to some point, increases in size may bring progressively greater increases in $\Pi_j$ because a certain minimum size must be attained before a research laboratory can be maintained (assuming that this size exceeds M). See Section 2 and Nelson [24].

Beyond some point, increases in size may result in less than proportionate increases in the number of innovations. Eventually, increases in size result in little further advantage from the viewpoint of the pooling of risks, there is relatively little difference in the ease with which innovations can be financed, and, as is often alleged, the motivation to innovate may become weaker and administrative difficulties may multiply. See Stocking [32].

12/ The results in Mansfield [18] seem to be consistent with this.

13/ Had $I/M$ rather than $I/\bar{S}_M$ been used in equation (2), the results in equation (4) would have been

$$\Pi - 4/N(M) = \underset{(.00009)}{.00013} [\bar{S}_4 - \bar{S}_M] + \underset{(.0010)}{.0032} I [\bar{S}_4 - \bar{S}_M]/M ,$$

and the estimate of $\alpha_2$ would still be positive and statistically significant.

14/ Since the sum of $\Pi_j$ is one, it follows that, if $f(S_j)$ is the number of firms of size $S_j$ ,

$$1 = \sum_{S_j \geq M} (\beta_1 + \beta_2 S_j) f(S_j) ,$$

$$= \beta_1 N(M) + \beta_2 N(M) \bar{S}_M .$$

Thus,

$$\beta_1 = [N(M)]^{-1} - \beta_2 \bar{S}_M .$$

Substituting this expression for $\beta_1$ (and the expression for $\beta_2$ in equation (2)) into equation (1) and summing up the $\Pi_j$ for the four largest firms, we have equation (3). Of course, $z' = z [\bar{S}_4 - \bar{S}_M]$ and $\beta_2$ must be greater than $\left\{N(M) [\bar{S}_M - M]\right\}^{-1}$ . Using the estimates of $\beta_2$ , the latter inequality almost always seems to hold.

15/ According to interviews with executives of engineering associations and research directors of firms, the line of causation has predominately run in the direction presumed by the model. But such evidence is hardly conclusive, and the problem may be more serious than they indicate.

16/ The data in Table 3 regarding $M$ and $I$ were obtained primarily from interviews with officials of engineering associations and firms, although some came from published sources. Estimates were obtained for as many of the innovations in Tables 1a and 1b as possible and the average values of $M$ and $I$ were used in each case. Using the data described in note 7, we determined $N(M)$. Since $M$ was quoted in ingot capacity or crude capacity, we used the ratio of the largest firm's assets to its capacity in 1953 to estimate $M$ , $\bar{S}_M$ , and $\bar{S}_4$ in terms of dollars (rather than capacity). This obviously is a very rough procedure. The estimates of $I$ are in (approximately) 1950 dollars. The weighted data regarding $\Pi$ are used.

17/ Note two things. (1) There is no tendency for the residuals from equation (4) to be positive in one industry or time period and negative in another. They seem quite random in this regard. (2) Even if we include only firms larger than M , the largest four petroleum firms seem to account for a disproportionately large share of the product innovations in 1919-38 and the process innovations in 1939-58. For process innovations in 1919-38 and product innovations in 1939-58, they account for about the "expected" share. Of course, including only firms larger than M , the largest four steel firms fare even worse than in Table 2.

18/ As we pointed out in note 11, equation (1) ignored the fact that $n_j$ might be a curvilinear function of $S_j$; on the other hand, equation (5) ignores the fact that $n_j$ may be zero below some value of $S_j$ . Equation (5) is more convenient here because ordinary regression techniques can be used to estimate the a's , and its disadvantages are reduced by the fact that the very smallest firms are excluded.

19/ There are several obvious difficulties in this sort of an analysis. (1) Although a firm's size influences the number of innovations it carries out, this is not the only factor. The preferences of its management with respect to risk, its profitability and rate of growth, and the size of its competitors may also be important. Thus, if the largest firms had been broken up, their smaller successors would not necessarily have behaved like others of their size in fact behaved.

(2) If the largest firms had been broken up, the innovations that were introduced might have been of a different type. Only the largest firms may have been able to carry out some kinds of innovations. We assume that such innovations were no more important than those that their smaller successors would have introduced. There is no evidence in these industries that an innovation introduced by a larger firm tended to be any more -- or less -- important than one introduced by a smaller firm. But the data are very rough.

(3) If the largest firms had been broken up, changes might have occurred outside the industry. For example, if the largest firms had carried out a relatively large amount of research, there might have been some transfer of research activities to independent laboratories. The amount of inventive activity might not have been greatly affected. The reorganization of the industry might have affected how many of the research results were applied -- and how quickly.

(4) As the literature on cost and production functions clearly shows, there are many difficulties in interpreting least-squares relationships between a firm's size and other variables. Some of these difficulties -- as well as sampling errors -- are present here, e.g., there is an identification problem. For some reason, certain firms may be innovators and as a consequence they may grow more rapidly than others. If so, they may eventually become relatively large and the largest may account for a disproportionately large share of the innovations -- even though size per se brings no particular advantages. This hypothesis is obviously difficult to check.

20/ If $N(S_j)/S_j$ is plotted as a function of $S_j$ , one finds that its maximum occurs at or near the size of the largest firm in almost every case in the coal and petroleum industries. Thus on the average, no combination of smaller firms that in toto equaled the size of the largest firm would carry out as many innovations as it did (if $n_j$ is a function only of $S_j$). However, in the steel industry, $N(S_j)/S_j$ reaches a maximum far below the size of the largest firm (at about 1,000,000 tons of ingot capacity in 1945). Thus, if factors other than a firm's size are ignored, it appears that a combination of smaller firms would carry out more innovations than the largest firm.

The following points should be noted regarding the regressions. In steel, firms with less than 5,000 tons of ingot capacity were omitted in 1919-38 and firms with less than 10,000 tons were omitted in 1939-58. $S_j$ is measured in units of 1,000,000 tons. In petroleum, firms with less than 500 barrels of capacity were omitted, and $S_j$ is measured in units of 10,000,000 barrels. In coal, firms producing less than 100,000 tons annually were omitted and $S_j$ is measured in units of 1,000,000 tons.

Finally, note two other important points. First, all of this pertains only to the existing ranges of firm size. There is no way to tell how firms bigger than the largest existing firm would have behaved. Second, there are substantial sampling errors in the estimates of the a's and consequently in the estimates of the values of $S_j$ where $N(S_j)/S_j$ is a maximum. Particularly in 1939-58, a considerable number of the estimates of $a_2$ and $a_3$ are not statistically significant. Thus, on these grounds too, the results should be treated with caution.

21/ Note two points in this connection. First, the situation in steel in the future may be quite different. In the interviews described in note 16, several executives claimed that U.S. Steel was becoming much more of an innovator than in the past. Second, although U.S. Steel has frequently been criticized on this score, its performance seems to be much better than the second-largest firm -- Bethlehem.

For discussions of the situation in petroleum, see Bain [3]. For both steel and petroleum, see Hamburg [10].

22/ To what extent were the significant innovations in these industries introduced by new firms? According to some authors, society frequently must rely on such firms to be the innovators. E.g., see [6]. In young industries where barriers to entry are relatively weak and the technology is changing rapidly, this may often be true. But in industries like steel and petroleum, where entry was difficult and the technology was relatively well explored, this seems less likely. As it turns out, not one of the innovations for which we have data was introduced by a new firm.

Footnote 22 (Continued)

In the coal industry, the results are the same -- but the data may be biased somewhat. The innovations in the coal industry are new techniques for preparing coal. According to interviews with the Bureau of Mines personnel, such techniques were probably less likely to be introduced by new firms and small firms than many other types. But this bias is unlikely to be great enough to reverse the results in this section. Had it been possible to include other types of innovations as well, the largest firms would probably have continued to account for a disproportionately large share, but the difference might not have been so large. Note that the equipment producers had a very important hand in developing most of these innovations, but the coal producers took the risks involved in introducing them.

23/ Of course, the fact that a few firms below our estimate of $M$ are innovators does not mean that our estimates are incorrect. We assume in Section 4 that $M$ is the same for all innovations, but this really is not the case and our estimates are really of the average value of $M$. Since the estimates are of this sort, the size of some innovators may fall below them.

24/ E.G., see Hamburg [10] for some discussion of this.

25/ In recent years competitive pressures seem to have forced smaller companies to do more preparation of coal. Hence, one might expect them to do somewhat more innovating in this area. But for all areas taken together, this seems less likely.

26/ He asserts that "...given the progressive improvement in the quality of management...given the growing recognition...of the value of research, and given the increasing supply of engineers and scientists, a rise in the relative importance of organized research and development among small and medium-sized firms is perhaps to be expected." See [28], p. 631. Our results could be due in part to such a movement in the past, since it would be expected that the medium-sized firms would react before the small ones.

27/ Of course, these are only a few of the arguments that are submitted. No attempt is made here to present a complete account of the arguments on either side.

28/ All this is assumed to hold only for small $\Delta$. In the analysis below, $\Delta$ tends to zero and terms of higher order would vanish.

We assume that the development work has already been done by the inventor or that it will take about the same length of time regardless of which firm does it. Of course this may not be the case.

We focus attention strictly on the mean delay, but for some purposes higher moments might also be relevant.

29/ This simplification can be relaxed. All that we need to assume is that the future can be divided into epochs within which each firm's size and value of $\lambda$ is relatively constant, that these epochs are very long relative to $L$, and that forecasts are available of the size distribution of firms (given that the reorganization does or does not occur) in each epoch. Then one can estimate the effects in each epoch.

30/ These factors can be introduced in the following way. The relationship between a firm's size and its value of $\lambda$ is likely to differ, depending on the characteristics of the innovation. Thus, one should classify innovations by their capital requirement and other characteristics causing differences in the shape of this relationship. Factors (like the overall profitability of the invention) that cause all the $\lambda$'s to increase or decrease in proportion may be ignored. (If all $\lambda_i$ vary in proportion, the $P_i$ will remain constant, and $\hat{f}(S)$ and the result in equation (9) will be unaffected. Inventions with proportional $\lambda_i$ can be lumped into one class so long as the composition of the class with regard to profitability, etc. is unlikely to change much over time.) Classes should be established so as to maximize differences -- ignoring proportional variations in all the $\lambda_i$ -- in the shape of the relationships. Then $\hat{f}(S)$ can be estimated in each class, the goodness of fit being some indication of how homogeneous the class is. In each class, equation (9) can be used to estimate the percentage reduction in delay. To obtain an overall estimate of the effect on all innovations, one must forecast the proportion of the innovations in the period ahead that will be in each class and estimate the average delay in each class in the previous period. These data -- and the classes -- must often be rough, but it is difficult to see how any technique could be devised that would not require them.

If $\lambda_n$ in the period ahead remains in the same proportion to the average value of $\lambda$ in each size class (whether or not the reorganization occurs) one can easily handle the possibility of new entrants being the innovators. The proportion of the innovations carried out by new entrants is an estimate of $P_n$ in the past -- which equals $\Phi \lambda_1^n$, where $\lambda_1^n$ is the value of $\lambda_n$ in the future. Hence, this proportion can merely be added to both the numerator and denominator of the term in parentheses on the right-hand side of equation (9). Essentially, this assumes that the reorganization will not seriously impede or promote entry into the industry. Whether or not this is true depends on the particular reorganization.

31/ Can the facts in Section 5 be brought to bear on this assumption? Suppose that all the innovations included there were of the type considered here and that $\lambda_i$ did not vary much from invention to invention. According to equation (7), $\lambda_i$ is proportional to $P_i$, and the proportion of innovations carried out by the $i^{th}$ firm is an estimate of $P_i$. As a rough check on this assumption, we took firms that resulted from important mergers in 1925-38 and compared their proportion of the innovations in 1939-58 with those of other firms of their (new) size. If a firm's value of $\lambda_i$ adjusts relatively quickly to a change in its size, as we assume, their proportion should not differ significantly from the others. In fact, this turns out to be the case. Note however, that this is only a crude and incomplete test of this assumption.

32/ Note that this regression should only include data for innovations invented outside the industry.

33/ To derive equation (10), merely divide equation (5) -- after inserting the estimates of the a's in Table 4 into it -- by the number of relevant process innovations during this period, 13. The result equals $\hat{F}(S)$ because we ignore differences in $\lambda_i$ from one invention to another and because we assume the relation between the proportion of the innovations invented outside the industry that a firm carried out and its size was like that for all innovations.

To derive the figure (20 percent) in the text, note that $\sum_S n(S)\ \hat{f}(S)$ is necessarily one because the residuals from a least-squares regression sum to zero. Moreover $\sum_S m(S)\ \hat{f}(S)$ equals $1 - \hat{f}\ (28) + 7\ \hat{f}\ (4)$, since all firms other than U.S. Steel will maintain their size despite the reorganization. Since equation (10) shows that $\hat{f}\ (28) = .21$ and $\hat{f}\ (4) = .07$, it follows that $C = - 20$. Although it is difficult to estimate how much shorter the average delay would be after a 20 percent reduction, it is likely to be at least two years shorter.

Of course, the roughness of this estimate need hardly be labored. Given a major change in market structure of this sort, the average value of $\lambda$ for firms of given size might not be proportional to the average value in the recent past. Instead the relation between the average value of $\lambda$ and a firm's size may be altered by the change in market structure. In addition, the assumptions underlying equation (10) -- and spelled out in the first paragraph of this footnote -- are obviously very rough.