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Innovation Rivalry: Theory and Empirics*

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Abstract: This paper develops the theory of a U relation between seller concentration and R&D investment and integrates the new theory with the traditional expectation of an inverted-U relation. The paper illustrates the U relation, and the integrated U and inverted-U relations, for a single type of R&D performed in most industries, exploiting differences in the degree of structural competition across industries while admitting little if any variation in the type of R&D.

I. Introduction

Scherer (1965, 1966, 1967a, 1967b, 1984) provided seminal analysis of the theory and empirics of innovation rivalry. At the heart of his analysis was rivalry's effects on value (the present value of the streams of profits from innovations) and costs (the present value of the streams of costs of innovative investments).[1] This paper develops and applies a theory of innovative rivalry that is inspired by and grounded in Scherer's seminal analyses wherein the effects of rivalry are to be understood by examining rivalry's effects on value and costs and hence the incentives for R&D investment. We develop the theory of rivalry in research and development (R&D) investment introduced in Scott (2009), and we apply it to test hypotheses about the effects of rivalry on R&D investment. Our theory follows in the line of work initiated in Scherer (1967b), and our empirical analysis follows the literature originating in Scherer (1965, 1967a). We extend the theory and empirics to augment the classic hypothesis test of the inverted-U relation between innovative rivalry and R&D investment with the hypothesis that under specified conditions the relation is a U shape rather than an inverted-U shape.

Following the argument in Scott (2009), our premise is that competitive pressure is perceived differently in structurally competitive markets than in oligopolistic markets. In structurally competitive markets, R&D competitive pressure is perceived as exogenous. In oligopolistic markets, it is perceived as endogenous Nash noncooperative equilibrium. The effect of competitive pressure on R&D will depend on whether competitive pressure is perceived as exogenous or instead as endogenous R&D rivalry. For the particular sample used in this paper, we hypothesize a U relation between R&D investment and competitive pressure. In other words, we hypothesize that greater competition will increase the representative firm's R&D when competitors perceive exogenous competitive pressure, but greater competition will reduce the representative firm's R&D when competitors perceive interactive R&D and reach noncooperative equilibrium strategy combinations. We do in fact find the U relationship in our data.

Many theories imply an inverted-U relation between R&D intensity and seller concentration, assumed to be an inverse measure of competitive pressure, and in the empirical literature, there have been many sightings of the inverted-U relation (Gilbert, 2006; Cohen,

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[1] Baldwin and Scott (1987) place Scherer's seminal contributions in the context of the early literature about R&D and technological change.

2010). Also, previous studies have found the inverted-U relation disappears given sufficient controls for differences in the opportunities for R&D apart from those due to the seller concentration (Gilbert, 2006; Cohen, 2010).[2] Although seemingly contradictory, the many different findings in the literature about the relation between competitive pressure and R&D investment can be explained by a general theory of R&D investment (Scott, 2009).

In this paper, we develop the theory in Scott (2009) and apply it to a hypothesis test with a sample for which the theory supports the expectation of a U relation, in addition to the usual inverted-U relation, between R&D intensity and seller concentration. Our sample and our experiment differ from those about the inverted-U reviewed in Gilbert (2006) and Cohen (2010) because we examine the evidence about seller concentration and R&D investment by focusing on a single type of R&D—the R&D of manufacturing firms aimed at reducing problems created by the emissions of a specific group of chemicals (the U.S. Title III Clean Air Act Amendment chemicals) that are used throughout manufacturing industry. The idea is to look at, broadly speaking, a single type of R&D, but one that is performed by firms that operate in a variety of competitive environments.

Although an inverted-U was observed without the controls, Scott (1984) could not observe, after controls for differences in opportunity for R&D apart from those correlated with seller concentration within broad industries, a link from competitive pressure (as indicated inversely by seller concentration in markets) to R&D behavior.[3] Possibly, we might discern a relation between competitive pressure and R&D for a particular type of R&D—Title III emissions reducing R&D—in a sample of manufacturing firms that do such R&D but do so in a variety of competitive environments. In Scott (1984), the variance in seller concentration within broad industries was not correlated with R&D intensity after firm effects were controlled. Yet, if that variance within the broad industries were correlated with opportunity differences for different types of R&D, a relation between competitive pressure and R&D might have been hidden by the opportunity differences within the broad industries.

[2] Scott (1993, pp. 84-86) discusses several of these studies in the context of Scherer's seminal work.
[3] In his seminal papers, Scherer (1965, 1967a) anticipates this result, showing that the effects of market structure on innovative activity—inputs and outputs—diminish when controls for differences in technological opportunity are included in the empirical specifications and that opportunity differences explain more than differences in market structure. The U.S. Federal Trade Commission line-of-business data used by Scott (1984) allowed a more extensive set of controls, than had previously been possible, because there was more industry detail and then observations of each firm's R&D activity in the various industries where it had R&D.

Given that competitive pressure can have many different theoretical effects, and given that those effects may be very different even within broad industries, even with all of the firm effects and all of the broad industry effects included in Scott (1984), there may not be sufficient control for differences, other than seller concentration, across the narrow industries within each broad industry to allow an effect for competitive pressure to be observed. The Scott (1984) experiment shows that inverted-Us observed in samples examining the R&D activity of many different industries disappear given controls for firm and broad industry effects, yet it may be possible that effects of competitive pressure can be observed in a sample that focuses on a particular type of R&D performed in different competitive environments. The particular type of R&D examined in this paper is product R&D to reduce Title III emissions problems—certainly a more uniform type of R&D than what is observed in the usual cross-industry studies in the literature reviewed by Gilbert (2006) and Cohen (2010). Thus, this paper addresses Scherer's (1965, 1967a) observation that differences in technical opportunity may explain more than differences in structural competition by using data on a single type of R&D performed in most industries, thereby giving us the variance in structural competition with arguably little variance in technical opportunity.

In Section II, we introduce our key hypotheses, and Section III explains the theory. Section IV then presents a statistically significant U relationship between structural competition and R&D investment. Section V concludes by first integrating the U relationship with Scherer's original inverted-U relationship and then testing our theory that is able to predict a non-quadratic relationship between structural competition and R&D intensity. We find a very significant U relationship and, with an appropriately generalized empirical specification, we find a non-quadratic relationship with both the U and the inverted-U appearing in the same data over the different ranges of structural competition as predicted by the theory.

II. Two Hypotheses

In the next section, we explain a theory in which a firm's R&D depends on its relative innovative performance—the probability distribution over the relative performance of its R&D investment and the value of relative performance. The firm's relative innovative performance will depend on its performance relative to the state of the art innovation. Thus, the perception of the anticipated state of the art technology in the post-innovation market will be the linchpin of

the firm's decisions about R&D investment. We use the theory presented in Section III to develop the following hypotheses that imply a U relationship between competitive pressure and R&D investment.

- **Hypothesis 1**: *With structural competition and firms' perception that competitive pressure is exogenous, greater competition will increase the representative firm's R&D.*
- **Hypothesis 2**: *With concentrated market structures and firms' perception that competitive pressure is endogenous (with competitors reaching noncooperative equilibrium strategy combinations), greater competition will reduce the representative firm's R&D.*

Hypothesis 1 follows (1) because we do not observe non-cooperative Nash equilibrium in such cases—with innumerable competitors, the firms in the structurally competitive markets take rivals' behavior as given and ignore the effects of adjustments in their behavior—and (2) because we conjecture that with more competitors, rivals will be focused on the expectation that the state of the art in the post-innovation market will be higher because of the larger number of firms pursuing innovation. We develop Hypothesis 1 further in Section III. We expect that Hypothesis 1, showing the stimulus effect for more structurally competitive market structures, will hold in our sample over the lower range of observed seller concentration.

In Section III, we also explain that we expect, over the higher range of seller concentration, Hypothesis 2 will be supported *in our sample* of firms doing product R&D to reduce toxic emissions. We explain that in our sample rivals' R&D is expected to have a big negative impact on the likely value of the firm's own R&D, and the endogenous Nash equilibrium forces the firms' focus on that effect. We explain the necessary and sufficient conditions for total R&D investment to increase as the number of firms falls.

In sum, the theory to be explained in Section III, in the context of the sample of firms that we describe in Section IV, can support the expectation of a U relationship between structural competition and R&D investment.

III. A Theory of Innovative Investment

We begin with the theoretical description of innovative investment in Scott (2009), but we develop some new results to apply the model to our empirical work.[4] Investment in risky R&D results in innovations—new commercialized processes or products with better technical performance as indexed by the random variable x. The measure, x, of technical performance is necessarily relative technical performance—that is, performance relative to the anticipated state of the art. Better technical performance reflects higher quality of the firm's completed R&D project. The probability distribution for the measure of performance x is given by the probability density f(x; α), where greater values of the distribution's parameter α shift the probability distribution rightward over higher levels of performance.

The parameter α is determined by the amount of R&D investment R and an additional set of explanatory variables X that are referred to as distribution-shifting variables. Thus, α = α(X,R). Greater R&D investment, R, is associated with a greater α. Hence, if a company increases its R&D, its distribution over performance outcomes is shifted rightward over higher values of the index of performance x. The R&D investment R is the present value of the R&D cost schedule chosen by the firm. The details of the R&D cost schedule are described with the partial derivatives and cross-partials for α(X,R).

A company's innovation has a value that increases at a decreasing rate with its technical performance x. The innovation's value is given by V(x; γ), where V given x increases with the parameter γ and the impact of that parameter on V increases with x, and where given the parameter γ, value for relative performance x is positive and increases with x at a decreasing rate. Value increases at a decreasing rate because of diminishing marginal utility for the increased performance measured by x given the parameter γ. The value parameter γ is a function of a set of explanatory variables Z that are referred to as value-shifting variables. Thus, γ = γ(Z). Value reflects the present discounted value of the stream of benefits generated by the innovation; details about the stream of benefits are in the partial derivatives and cross-partials for γ(Z).

Thus, for the i^{th} firm, the expected value E of the investment R is $E = \int V(x;\gamma(Z_{-i},Z_i))f(x;\alpha(X_{-i},X_i,R))dx$, where the subscript i denotes the i^{th} firm and the subscript -i denotes its rivals. The firm chooses R to maximize expected profit (E – R). Table 1 collects the information about the firm's objective function.

[4] A part of our discussion in this section is taken from Scott (2009), and that paper provides the proofs for the six results stated in this section.

Table 1 about here

One can think of competitive pressure as an X variable. For example, let x, the measure of relative technical performance be the relative speed of an innovative computer. Given the state of competition, x is a measure of relative speed—speed relative to the speed for the best alternative computer from the firm's R&D competitors. The measure x is then the ratio of the new computer's speed to the speed of the best alternative. A given R&D investment, R, gives the firm its probability distribution of speed, and hence the distribution of its relative speed—i.e., the distribution f(x) for the performance evaluation x.

More "competitive pressure" means that firms anticipate a more advanced state of the art, and that expectation results in a leftward shift of the probability distribution over the performance outcome for any given amount of R&D. The performance that matters is relative performance—i.e., performance relative to the anticipated state of the art technology. In Figure 1, for the probability distribution on the right, an outcome for x is not the computer's speed itself, but the assessment of the quality, m, of the technical performance represented by the speed. With more competition, for the distribution on the left, the same speed is associated with a lower quality, c, of technical performance, because with more rivals doing R&D the best alternative speed is faster. The probability distribution over x has shifted leftward as competition increases.

Figure 1 about here

For the model of R&D investment grounded in relative innovative performance, Scott (2009) shows that if competitors perceive exogenous competitive pressure (i.e., no strategic interaction), then for a variable that shifts value up as it increases, R&D increases as that variable increases. For a variable that shifts value down as it increases, R&D decreases as that variable increases. Also, for a variable that shifts the probability distribution left as it increases, R&D increases as that variable increases. In contrast, for a variable that shifts the probability distribution right as it increases, R&D decreases as that variable increases. These relationships are summarized with ***Result 1*** and ***Result 2*** in Table 2.

For an example of a value-shifting variable, consider the hypothesis that firm size will have positive effects on the value of innovative investment because larger firms have better marketing, better distribution channels, and more sales of the product embodying innovation

(product or process) with price marked up over post-innovation cost. If firm size increases the value (and also we would expect the increase in value to be increasing in the relative quality of the R&D outcome) of any R&D outcome, then it increases the marginal value of doing more R&D to shift the probability distribution for *x* rightward. Figure 2 illustrates the hypothesis.

Figure 2 about here

For an example of a probability shifting variable, suppose there is more R&D from all other firms and that the firm perceives the greater R&D from others as exogenous competitive pressure in the form of an increase in the state of the art anticipated from best practice. That will decrease the relative quality of any given technical outcome from the firm's R&D. For any given amount of R&D investment by a firm, the distribution over relative quality of technical outcomes has shifted leftward because of the better anticipated state of the art. That leftward shift in the distribution increases the firm's marginal value of doing more R&D. Figure 3 illustrates the effect, on the firm's R&D investment, of the leftward shift in the distribution.

Figure 3 about here

If instead of exogenous competitive pressure there is interactive or strategic rivalry and Nash equilibrium strategy combinations, Scott (2009) shows (and Table 2 summarizes as ***Result 3***) that if a stability condition obtains, where that condition is that any strategic complementarity of rivals' R&D investments is not too extreme, then the sign of the change in the firm's R&D with respect to a value-shifting variable is the same as for ***Result 1***. Also, with interactive rivalry and Nash equilibrium strategy combinations, the sign of the change in the firm's R&D with respect to a probability-shifting variable is the same as for ***Result 2***, and that finding is summarized in Table 2 as ***Result 4***.

Next, to develop an understanding of the U (rather than the customary inverted-U) relation between seller concentration and R&D, Scott (2009) introduces the Schumpeterian condition.

- **The Schumpeterian condition**: The marginal-value-reducing effect (because of post-innovation competition) of rivals' R&D outweighs (1) the positive impact of rivals' R&D

on the marginal value of a firm's R&D resulting from the leftward shift in the probability distribution and (2) the possibly positive impact from complementary rival R&D.

The final two results (summarized in Table 2 as ***Result 5*** and ***Result 6***) from Scott (2009) establish conditions, given interactive rivalry and Nash equilibrium strategy combinations, for the effect of more competitors on the individual firm's Nash equilibrium R&D and on the total R&D in the market.

- ***Result 5*** The sign of the change in Nash equilibrium R&D investment for each firm as the number of competitors increases is negative given the stability condition and the Schumpeterian condition, and the effect becomes smaller as the number of firms in the equilibrium increases.
- ***Result 6*** Total R&D investment could rise or fall as the number of competitors increases. *Result5* implies that the equilibrium R&D investment for each firm will fall as the number of firms increases; however, the total investment in the market could rise given the set of conditions in *Result5*. *Even given that the firm's R&D falls, the total R&D will rise if* a firm's own R&D investments have effects on the marginal benefit of its R&D that are larger in absolute value than the marginal-benefit-dampening effects that result from the R&D investments of its rivals.

The foregoing theory suggests the two hypotheses introduced in Section II. The conjecture supporting Hypothesis 1 is that, given an increase in the amount of exogenous competitive pressure perceived, the R&D-increasing effect of the leftward shift in the distribution for relative performance outweighs the effect of dampened value for relative performance, and the firm increases its R&D investment. Also, if we begin with a Nash non-cooperative equilibrium, we show in the Appendix that if strategic interaction among an industry's R&D rivals decreases as the number of rivals increases, then each firm's reduction in equilibrium choice for R&D becomes vanishingly small as the number of rivals and hence structural competition increases. Thus, in that case too, as long as R&D is profitable, the amount of R&D done *in the industry* will increase as the number of competitors increases. Hypothesis 1,

showing the stimulus effect for more structurally competitive market structures, is expected to hold in our sample over the lower range of observed seller concentration.

We expect, over the higher range of seller concentration, Hypothesis 2 will be supported *in our sample* of firms doing product R&D to reduce toxic emissions because we expect that the Schumpeterian condition will hold in such a sample. We expect that the Schumpeterian condition will hold in our sample because rivals' R&D has a big negative impact on the likely value of the firm's own R&D, and the endogenous Nash equilibrium forces the firms' focus on that effect. Having a "green" product alone would be quite valuable; having one among several green products, much less so. In the Appendix, we explain that for the total R&D investment to increase as the number of firms doing R&D decreases, a necessary but not sufficient condition is that the R&D investments of the firms are strategic substitutes. For total R&D investment to increase as the number of firms falls, a sufficiently strong strategic substitute effect is needed.

Table 2 highlights the key results and conditions for our relative-performance model of R&D investment. In sum, the theory, in the context of the sample of firms that we now describe, can support the expectation that over the range of lower seller concentration, R&D investment will fall, other things being the same, as seller concentration increases, while over the range of higher seller concentration, R&D investment will increase with seller concentration. Moreover, in the Appendix we develop Result 5 and show that as structural competition increases, the reduction in Nash equilibrium R&D for each individual firm is getting smaller and eventually vanishes. That finding would support the smooth shape at the bottom of the U relation between R&D investment and structural competition if the stimulus effect of structural competition takes hold gradually and with increasing force. In any case, the theory can support a U relation rather than the usual inverted-U relation with the bottom of the U being more or less smooth depending on how rapidly the stimulus effect takes over as the range of Schumpeter's prediction shows diminishing reductions in R&D.

Table 2 about here

IV. The Estimated U Relation

We use historical data from a well-documented data set, presenting new estimation and some new robustness statistics using the sample, data and variables, and econometric model in Scott (2003, 2005) where, if needed, clarifications can be found in detailed discussions about the

sample, data, and variables. We reinterpret the findings in terms of our development of the theory of the expected U relation between seller concentration and R&D investment, other things being the same, and here for the first time, the sample, data, and variables are used to adduce in a single estimated equation both the inverted-U and the U relations over different ranges of seller concentration.

Our data about U.S. industrial environmental R&D come from the first of our two surveys—one administered in 1993 and the other in 2001. Both survey instruments are provided in Scott (2003), and the samples and the data we collected are carefully detailed there. The 1993 survey was sent to parent companies in the *Business Week* R&D Scoreboard for that year. Scoreboard companies that year were companies with sales of at least $58 million and R&D expenditures of at least $1 million. The 2001 follow-up survey was sent to a representative group of respondents to the first survey and documented the stability of the environmental R&D investments observed. To estimate the model for this paper, we used the 1993 survey information that we collected from industrial respondents about their environmental R&D, and also additional information that we developed from the *Business Week* R&D Scoreboard, the U.S. Environmental Protection Agency, the U.S. Census, and other sources of information about industrial companies and their industries. In our estimation, we examine for 132 firms the product R&D that is aimed at reducing the emissions of the chemicals targeted by Title III of the U.S. Clean Air Act Amendments of 1990 as chemicals of concern for which new regulations should be developed.[5]

An appropriate procedure for analyzing the determinants of the presence of company R&D aimed at Title III chemicals is Tobit analysis (Maddala, 1983, Chapter 6; Greene, 2003, pp. 764–6). The basic Tobit model makes the following assumptions for the j^{th} observation—here the observations are companies. The model assumes that for the dependent variable y_j and the fixed $1 \times k$ vector x_j of explanatory variables, and an index function $y_j{}^* = x_j\beta + \varepsilon_j$, then $y_j = y^*$ if y^* exceeds 0, while $y_j = 0$ if $y_j{}^* \leq 0$. β is a $k \times 1$ vector of unknown parameters, while ε_j are independently and normally distributed errors with expected value of zero and

[5] Scott (2003) describes Title III of the Clean Air Act Amendments and provides a complete list of the Title III chemicals and a description of their incidence in industry and in the operations of the sampled and the responding firms.

homoscedastic variance σ^2. We check the estimates' robustness to modification of these assumptions.

For the present problem, y_j is either zero or, when positive, it is the observation of ln(*PRD3RDT*) the natural logarithm of the 1992 Title III *product* R&D scaled in thousands of 1992 dollars for the j^{th} of the 132 companies with manufacturing operations. Scaled in thousands, all nonzero R&D values *PRD3RDT* are greater than one. *PRD3RDT* is zero for 95 of the 132 observations. For the remaining 37 observations for which *PRD3RDT* exceeds zero, the mean is $12,395 thousands and the range is from $4 thousands to $367,500 thousands. The Tobit model estimates β and σ^2 using the 132 observations on *PRD3RDT,* described in Table 3, and the explanatory variables that we now describe.

Table 3 about here

The Tobit model uses the following variables which are denoted with the same variable names used in Scott (2003, 2005) to allow easy reference to additional details about the sample, the data, and the variables.[6]

The Company. NTAPC measures the extent of a company's Title III emissions problems. It is the average value of *NTAP*, the number of Title III toxic air pollutants associated with a manufacturing industry, across the four-digit manufacturing Standard Industrial Classification (SIC) industries in which the company operates. *SALES* is the measure of a company's size in 1992. For each company, *SALES* is measured as sales in millions of dollars, for the company's most recent fiscal year as of May 18, 1993.

The Company's Environmental R&D. PRODOTHER is a dummy variable that takes the value one if a company's product R&D to reduce emissions received additional financing from other companies or from the government; otherwise, it equals zero. *COOP* is a dummy variable that takes the value one if the company reported that it had at least some Title III environmental R&D that was performed in a cooperative venture with other firms; otherwise it equals zero.

[6] For example, the average count measure *NTAPC* for toxic pollutants and the average seller concentration measure *CR4C* described below were conscious choices for the best measures of a company's emissions problems and of the seller concentration that would affect its R&D investment decisions. The lengthy discussion about why those measures are the best ones is provided in Scott (2003, pp. 71-73).

DBACKGROUND is a dummy variable that equals one if a respondent reported background research on emissions; otherwise it equals zero. *DPROCESS* is a dummy variable that equals one if a respondent reported process R&D to reduce emissions; otherwise it equals zero.

The Company's Industries. *IMPSC* measures average import competition faced by the company in its industries. The measure of import competition is *IMPS*, the ratio of imports to shipments for each four-digit manufacturing industry. Then, for each company *IMPSC* is the average value of *IMPS* across the four-digit manufacturing industries in which a company operates. *CR4C* measures average seller concentration for a company's industries. The concentration ratio of the value of industry shipments is *CR4*, the four-firm seller concentration ratio as a percentage for each four-digit manufacturing SIC industry. Then, for each company *CR4C* is the average value of *CR4* across the four-digit manufacturing industries in which a company operates. The industry dummy variables are for the two-digit manufacturing SIC industries. For the purpose of defining these broad industry qualitative variables, each company is assigned to the broad industry in which its primary four-digit manufacturing industry is located.

Table 4 provides the descriptive statistics for the explanatory variables used in the Tobit model shown in Table 5. We have considered sample selection, heteroscedasticity, clustering, and endogeneity, and we now discuss each of those issues.

Table 4 about here

Table 5 about here

Sample Selection. Scott (2005) jointly estimates a probit model of selection into the sample simultaneously with the Tobit model shown in Table 5. Although the selection model is well estimated, the jointly estimated models with industry effects show that the correlation of their errors is small and not significantly different from zero, supporting the simpler estimation in Table 5 of the Tobit model alone. Comparing the results reported in Table 5 with the estimates for the full information maximum likelihood joint estimation of the probit model of selection and the Tobit model of Title III product R&D shows that Table 5's results are robust to the control for sample selection.

Heteroscedasticity. The full information maximum likelihood models of the Tobit model with selection for *PRD3RDT* in Scott (2005) assume homoscedasticity of the error in the Tobit model. To check for the presence of different error variance across the observations, we modeled the error variance for the ith observation as a function of the measure of firm size, ln(*Sales*), and four qualitative variables describing broad groups of industries.[7] The likelihood ratio and Wald tests for heteroscedasticity do not reject the null hypothesis that the errors are homoscedastic.[8] For the likelihood ratio test, the chi-squared statistic with 5 degrees of freedom is 4.90; given the null hypothesis, the probability of a greater chi-squared is 0.428. The Wald statistic is 0.723 with 5 degrees of freedom; the probability of a greater value is 0.982 given the null hypothesis.

Clustering. Table 5's second column shows the standard errors with intragroup correlations in the errors in the Tobit model when errors are clustered by primary industry, showing that the essential results for significance are robust to clustering the data—indeed, the statistical significance of the U-relation is greater when the errors are clustered. Greene (2002, p. E21-12) expresses skepticism about the usefulness of clustering the errors in the context of the Tobit model with sample selection as presented in Scott (2005), because ". . . the specification of the censored normal regression model is fairly fragile, and robust estimation of the asymptotic covariance is essentially a moot point."[9] Nonetheless, the procedure can be implemented. Using the software accompanying Greene (2002) and replicating the specifications in Scott (2005) with clustered data gives essentially the same story for the significance of the variables.

Endogeneity. The positively sloped portion of the U relation estimated in Table 5 and illustrated in Figure 4 is attributed to the endogenously determined R&D investments in a Nash

[7] Firm size has often been associated with heteroscedastic error in the empirical literature of industrial organization. For the broad groups of industries, one variable represented chemicals, petroleum, and plastics; another metals and metal fabrication, another machinery and transportation equipment; another electronics and instruments; with the remaining "traditional" industries the baseline case. The variance term for the heteroscedastic disturbance in the Tobit model is modeled as in Greene (2002, p. E21-41). The square root of the variance, σ_i, for each observation's error is equal to σ multiplied times the base to the natural logarithms raised to the power of a linear combination of the variables that determine the different error variances.

[8] These tests are described by Green (2002, p. E21-44).

[9] "The recent literature contains numerous applications of 'robust' covariance matrix estimation. . . . [For] the maximum likelihood estimators of the coefficients in the censored regression models . . . . [i]t is difficult to construct a case for the estimator . . ." (Greene, 2002, p. E21-12).

noncooperative equilibrium given interactive rivalry. Over a sufficiently long time series, of course the numbers of firms themselves will be endogenously determined. However, here we are examining contemporaneous market structure and the concomitant R&D investments of the interactive rivals. Error in the observed R&D spending by a firm is not expected to be correlated with error in the contemporaneous seller concentration, and there is no reason to expect a simultaneity bias in our model. In the empirical application here, it is the rivals' R&D that is endogenous, not the number of firms or seller concentration more generally. Over time, of course, entry and exit are anticipated, the number of firms and seller concentration will evolve, and thus the hypothesis testing becomes more complicated.

The estimates in Table 5 show that environmental product R&D to address Title III pollutants increases with their importance in a company's operations. That effect for *NTAPC* is consistent with R&D-value-increasing effects when pollution problems are more severe. It is also consistent with a probability distribution-shifting effect that would result if with a bigger pollution problem to be solved, the firm's R&D problem is more difficult, resulting in the distribution over relative performance shifting leftward for any given R&D investment.

Larger companies do more Title III product R&D. The result is consistent with greater sales having the R&D value-increasing effect described earlier. The environmental product R&D increases more than proportionately with company size, a result that should be understood in the specific context here—namely, we are observing a very specialized type of R&D (rather than total R&D for each firm) that is performed across many U.S. manufacturing industries.

The Tobit model for *PRD3RDT* shows a negative effect for import competition—measured by IMPSC—on Title III process R&D. The model shows that greater import competition is associated with less emissions-reducing R&D investment, *ceteris paribus*. Possibly, firms find it unprofitable to invest in R&D for improved environmental performance *and* compete with the foreign firms not required to meet emissions standards of U.S. regulations. Jaffe *et al*. (1995) conclude that the competitiveness of firms does not appear to have suffered greatly because of environmental regulation. The result here suggests that there may well be a cost associated with maintaining that competitiveness. Firms facing import competition appear to have cut their environmental R&D.

The reason for the reduction in environmental R&D in the face of import competition is not certain. Import competition could lower the value of good R&D performance because in the presence of import competition expenditures for emissions-reducing product innovations might not be recouped with sufficiently high post-innovation prices in international markets where emissions performance is not valued uniformly across nations. Further, environmental R&D is not mandated by law; it is forward-looking, with product improvements in the future and uncertain. In the present and near-term, companies doing environmental R&D would have to set product prices that meet the prices of foreign competitors who may not incur such R&D expenditures. Greater import competition reduces the pre-innovation margins of domestic firms, leaving fewer internally generated funds for the R&D investments with uncertain payouts.

The positive coefficients for *PRODOTHER* and *COOP* support the hypotheses that funding from others and cooperative activity with others make more valuable the company's own investments in product R&D to improve the emissions performance of products. Also supported are the hypotheses that the outside funding and the cooperative R&D are used with more challenging product R&D projects, shifting leftward the distribution over relative performance, ceteris paribus.

Similarly, the positive coefficients for *DBACKGROUND* and for *DPROCESS* support the hypotheses that investment in background research to understand the emissions themselves and in process R&D make more valuable the applied R&D to improve the emissions performance of a company's products. Further, there is support for the hypotheses that the findings developed with the background research and the process R&D are used with more challenging product R&D.

Title III product R&D is least at intermediate levels of seller concentration because the coefficient on CR4C is negative and the coefficient on its square is positive. The U relation is consistent with the theory that the effect of competitive R&D pressure depends on whether firms perceive that pressure as exogenous, or instead perceive interactive R&D rivalry and reach a Nash noncooperative equilibrium. Using the Tobit model, we can illustrate the relation.

Following the derivation in Maddala (1983, pp. 158–9), with ϕ_j denoting the density function of the standard normal distribution evaluated at $z_j = x_j\beta/\sigma$, and Φ_j denoting the

cumulative distribution function also evaluated at $z_j = x_j\beta/\sigma$, we have for the expected value of ln(*PRD3RDT*) given that R&D is done:

$$E(\ln(PRD3RDT_j) \mid y_j^* > 0) = x_j\beta + E(\varepsilon_j \mid \varepsilon_j > -x_j\beta) = x_j\beta + \sigma(\phi_j/\Phi_j)$$

To illustrate the U relation, the expected amount, in thousands of dollars, of Title III product R&D for a company that performs such R&D is then estimated as

$$E(PRD3RDT_j \mid y_j > 0) = \exp(x_j\beta + \sigma(\phi_j/\Phi_j)),$$

where exp(*p*) denotes the base to the natural logarithms e raised to the power *p*. We then have the Title III product R&D, in thousands of dollars, shown in Figure 4 as a function of seller concentration.[10] Observe that the simulation uses the broad industry effects in the intercept, with other industry effects set to zero, and thus is for the firms operating in broad industries where typically there is less Title III product R&D, but the point is that whatever the industry of operation, the U relation obtains.

Figure 4 about here

Figure 5 uses the information in Figure 4 for a representative firm to illustrate an industry's total Title III product R&D as seller concentration varies. Structural competition stimulates total industry R&D over the lower range of seller concentration, but over the higher range R&D is greater as structural competition is decreased. As explained earlier, the theory predicts positive and negative effects as well as the smooth bottom of the estimated U relation.

Figure 5 about here

V. Discussion

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[10] An analogous estimate of the expected amount of Title III product R&D for a company drawn from the population is $E(PRD3RDT_j) = (1-\Phi_j)0 + (\Phi_j)\exp(x_j\beta + \sigma(\phi_j/\Phi_j))$.

Observe that in the range of seller concentration for which more structural competition reduces R&D, concentration is high and the effect is different from what is observed in the range of concentration where Scherer (1980, p. 429) identified the *"market room factor"*. Scherer's *market room factor* occurs when seller concentration is low rather than high, and it results when there are many firms that reduce the profitability of R&D investment because of the high probability of post-innovation competition from other firms, some that would successfully imitate an innovation and some that would offer competing innovations. Scherer (1980, p. 429) observes (italics in original):

> What we find then is a clash of structural propensities. In terms of the marginal conditions for profit maximization, an increase in the number of sellers is conducive to more rapid innovation. This influence can be called the *stimulus factor*. But in terms of the requirement that expected profits from innovation be non-negative, an increase in the number of firms can, beyond some point, discourage rapid innovation. This influence might appropriately be called the *market room factor*.

Figure 6 illustrates Scherer's *stimulus* and *market room* factors in the relation between seller concentration and R&D investment, other things being the same, and also shows our range of high seller concentration where the oligopolists' R&D efforts are strategic substitutes and the conditions we have identified obtain and result in a *Schumpeterian* positive association between concentration and R&D.

Figure 6 about here

Since both the U and the inverted-U relations can in theory occur, we have added a cubic concentration term to the model in Table 6. Using that polynomial functional form allows us to ask if both relations occur in our sample as seller concentration ranges from very low to very high. Table 6 shows the results of the estimations; both the U and the inverted-U relations are found in the data, but (not unsurprisingly given the fairly small size of the sample) in terms of statistical significance the relations are very faint. To highlight the hint of marginal statistical

significance and thereby to stimulate interest in estimating the relations more precisely in larger samples, the table provides the one-tailed levels of significance.[11]

Table 6 about here

Figure 7 simulates the polynomial relation for an individual firm using the estimates in Table 6. Figure 8 uses the information for the representative firm to simulate at the industry level both the U and the inverted-U relations for total industry R&D as seller concentration and hence the number of firms changes. For very low levels of seller concentration, we would expect and we indeed do find evidence of Scherer's market room effect. Over moderate levels of seller concentration, we find his stimulus effect for structural competition. Finally, over high levels of seller concentration, we observe the effect of Schumpeterian competition among concentrated sellers that increase their R&D investments as seller concentration increases.

Figure 7 about here

Figure 8 about here

In this paper, we have developed a theory to explain when a U relationship between seller concentration and R&D investment is expected. Our U relationship is not a substitute for the inverted-U relation in the literature, but instead complements that story. To the legacy of the literature on the Schumpeterian hypothesis, we add that theoretically both the U and the inverted-U relations can obtain in the right circumstances, and we have shown that both relations can be observed with our sample of firms doing product R&D to reduce the emissions of Title III toxic chemicals.[12] We have addressed Scherer's (1965, 1967a) observation that differences in

[11] Note that Scherer's (1967a, p. 530) seminal presentation of the inverted-U effect had only a modest effect for the squared concentration term, yet the observation led to a large literature.

[12] To establish the theoretical expectation of the presence of both the U and inverted-U relations as seller concentration changes, we have developed the theory in Scott (2009), developing and stating more directly the stability and Schumpeterian conditions. Also with the illustration of both the U and the

technical opportunity may explain more than differences in structural competition. We do so by using data on a single type of R&D performed in most industries, thereby giving us the variance in structural competition with arguably little variance in technical opportunity. We have tested a theory that is able to predict a non-quadratic relationship between structural competition and R&D intensity. We in fact find (a) a very significant U relationship and (b), when allowed by an appropriate specification, a non-quadratic relationship with both the U relationship and Scherer's inverted-U relationship being present over different ranges of structural competition as predicted by the theory.

inverted-U relations over different ranges of seller concentration in the same sample, we have added to the empirical results in Scott (2003, 2005).

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Appendix

The expected value of R&D expenditure R_i to firm i is

$$E = \int V\big(x;\gamma(Z_i, Z_{-i}, Z_R)\big) f\big(x;\alpha(X_i, X_{-i}, X_R, R_i)\big)dx$$

where the variables Z_R and X_R denote the sum of the R&D expenditures of the rivals of firm i.

Note that the variables Z_R and X_R replace the Z and X variables that denoted the extent of competitive pressure in the case of a "competitive" firm facing exogenous competitive pressure. Those variables will be $\sum_{j\neq i}^{n} R_j$ where R_j denotes the investment of the j^{th} firm among n firms.

That is, $Z_R = X_R = \sum_{j\neq i}^{n} R_j$.

The first-order condition for maximizing $E - R_i$ with respect to R_i is

$$\int V \frac{\partial f}{\partial \alpha}\frac{\partial \alpha}{\partial R_i} dx = 1$$

and the second-order condition is

$$\int V \left(\frac{\partial f}{\partial \alpha}\frac{\partial^2 \alpha}{\partial {R_i}^2} + \frac{\partial \alpha}{\partial R_i}\frac{\partial^2 f}{\partial \alpha^2}\frac{\partial \alpha}{\partial R_i}\right) dx = \psi < 0.$$

Displacing the equilibrium by changing Z_i, we derive $\frac{dR_i}{dZ_i}$ as follows:

$$\int \left\{V\frac{\partial f}{\partial \alpha}\left(\frac{\partial^2 \alpha}{\partial R_i \partial X_R}\frac{dX_R}{dZ_i} + \frac{\partial^2 \alpha}{\partial {R_i}^2}\frac{dR_i}{dZ_i}\right) + V\frac{\partial \alpha}{\partial R_i}\frac{\partial^2 f}{\partial \alpha^2}\left(\frac{\partial \alpha}{\partial X_R}\frac{dX_R}{dZ_i} + \frac{\partial \alpha}{\partial R_i}\frac{dR_i}{dZ_i}\right) + \frac{\partial f}{\partial \alpha}\frac{\partial \alpha}{\partial R_i}\frac{\partial V}{\partial \gamma}\left(\frac{\partial \gamma}{\partial Z_i} + \frac{\partial \gamma}{\partial Z_R}\frac{dZ_R}{dZ_i}\right)\right\} dx = 0$$

$$\Rightarrow \frac{dR_i}{dZ_i} = \frac{\int \left(\frac{\partial f}{\partial \alpha}\frac{\partial \alpha}{\partial R_i}\right)\left(\frac{\partial V}{\partial \gamma}\frac{\partial \gamma}{\partial Z_i}\right) dx}{-\psi} + \left(\frac{dR_i}{dX_R}\right)\frac{dX_R}{dZ_i},$$

where

$$\frac{dR_i}{dX_R} = -\frac{\phi}{\psi} = \frac{\int \left\{V\left(\frac{\partial f}{\partial \alpha}\frac{\partial^2 \alpha}{\partial R_i \partial X_R} + \frac{\partial \alpha}{\partial R_i}\frac{\partial^2 f}{\partial \alpha^2}\frac{\partial \alpha}{\partial X_R}\right) + \left(\frac{\partial f}{\partial \alpha}\frac{\partial \alpha}{\partial R_i}\right)\left(\frac{\partial V}{\partial \gamma}\frac{\partial \gamma}{\partial Z_R}\right)\right\} dx}{-\psi}.$$

Appendix Remark 1: Since $\psi < 0$ by the second-order condition, the sign of $\frac{dR_i}{dX_R}$ is that of ϕ. That is, R&D expenditures are strategic complements if $\phi > 0$ and strategic substitutes if $\phi < 0$.

It is reasonable to think that $\frac{dX_R}{dZ_i}$ (and $\frac{dZ_R}{dZ_i}$) should be proportional to $\frac{dR_i}{dZ_i}$ in general, and in the special case of n identical firms we have $\frac{dX_R}{dZ_i} = (n-1)\frac{dR_i}{dZ_i}$ (since in that case $X_R = Z_R = (n-1)R_i$). Making this substitution in the expression for $\frac{dR_i}{dZ_i}$ and rearranging yields Eq. (10) in Scott (2009):

$$\frac{dR_i}{dZ_i} = \frac{\int \left(\frac{\partial f}{\partial \alpha}\frac{\partial \alpha}{\partial R_i}\right)\left(\frac{\partial V}{\partial \gamma}\frac{\partial \gamma}{\partial Z_i}\right)dx}{-\psi} - \frac{\phi}{\psi}\left((n-1)\frac{dR_i}{dZ_i}\right)$$

$$\Leftrightarrow \frac{dR_i}{dZ_i}\left(1 + (n-1)\frac{\phi}{\psi}\right) = \frac{\int \left(\frac{\partial f}{\partial \alpha}\frac{\partial \alpha}{\partial R_i}\right)\left(\frac{\partial V}{\partial \gamma}\frac{\partial \gamma}{\partial Z_i}\right)dx}{-\psi}$$

$$\Leftrightarrow \frac{dR_i}{dZ_i} = -\frac{\int \left(\frac{\partial f}{\partial \alpha}\frac{\partial \alpha}{\partial R_i}\right)\left(\frac{\partial V}{\partial \gamma}\frac{\partial \gamma}{\partial Z_i}\right)dx}{\psi + (n-1)\phi}.$$

Appendix Remark 2: If the strategic interaction is to become irrelevant as n gets large, $(n-1)\phi$ must get smaller as n gets bigger. For n so large that the strategic interaction among firms is negligible, $(n-1)\phi$ should be essentially zero. This means that $|\phi|$ must be decreasing as n increases, quickly enough that even $(n-1)\phi$ vanishes as n gets big. Looking at

$$\phi = \int \left\{ V\left(\frac{\partial f}{\partial \alpha}\frac{\partial^2 \alpha}{\partial R_i \partial X_R} + \frac{\partial \alpha}{\partial R_i}\frac{\partial^2 f}{\partial \alpha^2}\frac{\partial \alpha}{\partial X_R}\right) + \left(\frac{\partial f}{\partial \alpha}\frac{\partial \alpha}{\partial R_i}\right)\left(\frac{\partial V}{\partial \gamma}\frac{\partial \gamma}{\partial Z_R}\right)\right\} dx,$$

it does seem plausible that $\frac{\partial^2 \alpha}{\partial R_i \partial X_R}$, $\frac{\partial \alpha}{\partial X_R}$, and $\frac{\partial \gamma}{\partial Z_R}$ would all become small as the number of firms becomes large and R_i becomes relatively small compared with $X_R = Z_R = (n-1)R_i$.

Displacing the equilibrium by changing X_i, we derive $\frac{dR_i}{dX_i}$ in similar fashion:

$$\int \Bigg\{ V\frac{\partial f}{\partial \alpha}\left(\frac{\partial^2 \alpha}{\partial R_i \partial X_i} + \frac{\partial^2 \alpha}{\partial R_i \partial X_R}\frac{dX_R}{dX_i} + \frac{\partial^2 \alpha}{\partial {R_i}^2}\frac{dR_i}{dX_i}\right) + V\frac{\partial \alpha}{\partial R_i}\frac{\partial^2 f}{\partial \alpha^2}\left(\frac{\partial \alpha}{\partial X_i} + \frac{\partial \alpha}{\partial X_R}\frac{dX_R}{dX_i} + \frac{\partial \alpha}{\partial R_i}\frac{dR_i}{dX_i}\right)$$
$$+ \frac{\partial f}{\partial \alpha}\frac{\partial \alpha}{\partial R_i}\frac{\partial V}{\partial \gamma}\frac{\partial \gamma}{\partial Z_R}\frac{dZ_R}{dX_i}\Bigg\} dx = 0$$

$$\Rightarrow \frac{dR_i}{dX_i} = \frac{\int V\left(\frac{\partial f}{\partial \alpha}\frac{\partial^2 \alpha}{\partial R_i \partial X_i} + \frac{\partial \alpha}{\partial R_i}\frac{\partial^2 f}{\partial \alpha^2}\frac{\partial \alpha}{\partial X_i}\right)dx}{-\psi} + \left(\frac{dR_i}{dX_R}\right)\frac{dX_R}{dX_i},$$

where again

$$\frac{dR_i}{dX_R} = -\frac{\phi}{\psi} = \frac{\int \left\{ V\left(\frac{\partial f}{\partial \alpha}\frac{\partial^2 \alpha}{\partial R_i \partial X_R} + \frac{\partial \alpha}{\partial R_i}\frac{\partial^2 f}{\partial \alpha^2}\frac{\partial \alpha}{\partial X_R}\right) + \left(\frac{\partial f}{\partial \alpha}\frac{\partial \alpha}{\partial R_i}\right)\left(\frac{\partial V}{\partial \gamma}\frac{\partial \gamma}{\partial Z_R}\right)\right\} dx}{-\psi}.$$

Again, with n identical firms we have $\frac{dX_R}{dX_i} = (n-1)\frac{dR_i}{dX_i}$ (since in that case $X_R = Z_R = (n-1)R_i$). Making this substitution in the expression for $\frac{dR_i}{dX_i}$ and rearranging yields Eq. (12) in Scott (2009):

$$\frac{dR_i}{dX_i} = \frac{\int V\left(\frac{\partial f}{\partial \alpha}\frac{\partial^2 \alpha}{\partial R_i \partial X_i} + \frac{\partial \alpha}{\partial R_i}\frac{\partial^2 f}{\partial \alpha^2}\frac{\partial \alpha}{\partial X_i}\right) dx}{-\psi} - \frac{\phi}{\psi}\left((n-1)\frac{dR_i}{dX_i}\right)$$

$$\Leftrightarrow \frac{dR_i}{dX_i}\left(1 + (n-1)\frac{\phi}{\psi}\right) = \frac{\int V\left(\frac{\partial f}{\partial \alpha}\frac{\partial^2 \alpha}{\partial R_i \partial X_i} + \frac{\partial \alpha}{\partial R_i}\frac{\partial^2 f}{\partial \alpha^2}\frac{\partial \alpha}{\partial X_i}\right) dx}{-\psi}$$

$$\Leftrightarrow \frac{dR_i}{dX_i} = -\frac{\int V\left(\frac{\partial f}{\partial \alpha}\frac{\partial^2 \alpha}{\partial R_i \partial X_i} + \frac{\partial \alpha}{\partial R_i}\frac{\partial^2 f}{\partial \alpha^2}\frac{\partial \alpha}{\partial X_i}\right) dx}{\psi + (n-1)\phi}.$$

Appendix Remark 3: Eq. (13) in Scott (2009) has $\frac{\Delta R}{\Delta n} = -\frac{R\phi}{\psi + (n-1)\phi}$, which is negative when the Schumpeterian condition (S-2 in Scott (2009)) holds. This expression gets smaller in absolute value as n increases, not because of the $(n-1)$ in the denominator, but rather in spite of $(n-1)\phi$ decreasing as n increases (from Appendix Remark 2) and because of the $R\phi$ in the numerator (both R and $|\phi|$ get smaller as n gets bigger). Suppose the Schumpeterian condition holds, so $\phi < 0$ and $\frac{\Delta R}{\Delta n} = -\frac{R\phi}{\psi + (n-1)\phi} < 0$. We want to show $\frac{\Delta^2 R}{\Delta n^2} > 0$. That is, $\frac{\Delta R}{\Delta n}$ gets bigger—less negative—as n increases.[13] Since

$$\frac{d}{dn}\left(\frac{-R\phi}{\psi + (n-1)\phi}\right) = \frac{\left(-R\frac{d\phi}{dn} - \phi\frac{dR}{dn}\right)(\psi + (n-1)\phi) - (-R\phi)\left(\frac{d\psi}{dn} + \phi + (n-1)\frac{d\phi}{dn}\right)}{(\psi + (n-1)\phi)^2}$$

we need only show $\left(-R\frac{d\phi}{dn} - \phi\frac{dR}{dn}\right)(\psi + (n-1)\phi) - (-R\phi)\left(\frac{d\psi}{dn} + \phi + (n-1)\frac{d\phi}{dn}\right) > 0$.

Expanding dR/dn, cancelling R, and rearranging, we have

[13] In our discussion here, we are treating n like a continuous variable, but for our purposes that does not create a problem.

$$\left(-R\frac{d\phi}{dn}-\phi\left(\frac{-R\phi}{\psi+(n-1)\phi}\right)\right)(\psi+(n-1)\phi)>(-R\phi)\left(\frac{d\psi}{dn}+\phi+(n-1)\frac{d\phi}{dn}\right)$$

$$\Leftrightarrow -\frac{d\phi}{dn}(\psi+(n-1)\phi)+\phi^2>-\phi\left(\frac{d\psi}{dn}+\phi+(n-1)\frac{d\phi}{dn}\right)$$

$$\Leftrightarrow -\frac{d\phi}{dn}\psi-\frac{d\phi}{dn}(n-1)\phi+\phi^2>-\phi\frac{d\psi}{dn}-\phi^2-\frac{d\phi}{dn}(n-1)\phi$$

$$\Leftrightarrow 2\phi^2+\phi\frac{d\psi}{dn}>\frac{d\phi}{dn}\psi$$

But $\frac{d\psi}{dn}=0$, $2\phi^2>0$, $\psi<0$ by second-order condition, and $\frac{d\phi}{dn}>0$ (if $\phi<0$ then $\frac{d\phi}{dn}$ must be positive if ϕ is to vanish as n gets big as Appendix Remark 2 says it should).

From Section 4 of Scott (2009), $\frac{\Delta(nR)}{\Delta n}=n\frac{\Delta R}{\Delta n}+R=R\left(1-\frac{n\phi}{\psi+(n-1)\phi}\right)=R\left(\frac{\psi-\phi}{\psi+(n-1)\phi}\right)$. Since $\psi+(n-1)\phi<0$ by the stability condition (S-1 in Scott(2009)), the only way that total R&D could increase if the number of firms fell would be if $\psi-\phi>0$. Since $\psi<0$ by second-order condition, this would require not only that $\phi<0$ but also that $|\phi|>|\psi|$.

Appendix Remark 4: From Appendix Remark 1, R&D expenditures are strategic complements if $\phi>0$ and strategic substitutes if $\phi<0$. Therefore, strategic substitute investment is necessary but not sufficient for total R&D to increase as n falls.

Table 1. Relative-Performance Model of R&D Investment: The Objective Function

• The firm's objective function is $\int V(x;\gamma(Z_{-i},Z_i))f(x;\alpha(X_{-i},X_i,R))dx$ – R, where for the ith firm, the value V of its R&D investment R increases at a decreasing rate with its technical performance x.

• The innovation's value is given by V(x; γ), where V given x increases with the parameter γ and $\partial V/\partial \gamma > 0$ increases with x, and given the parameter γ, $V(x) > 0, V'(x) > 0,$ and $V''(x) < 0$.

• The value parameter γ is a function of a set of explanatory variables Z. Thus, γ = γ(Z). Value reflects the present discounted value of the stream of benefits generated by the innovation; details about the stream of benefits are in the partial derivatives and cross-partials for γ(Z). Value increases at a decreasing rate because of diminishing marginal utility for the increased performance measured by x given the parameter γ.

• Investment in risky R&D results in innovations—new commercialized processes or products with better technical performance as indexed by the random variable x. The measure, x, of technical performance is necessarily relative technical performance—that is, performance relative to the anticipated state of the art. Better technical performance reflects higher quality of the firm's completed R&D project. The probability distribution for the measure of performance x is given by the probability density f(x; α), where greater values of the distribution's parameter α shift the probability distribution rightward over higher levels of performance.

• The parameter α is determined by the amount of R&D investment R and an additional set of explanatory variables X. Thus, α = α(X,R). Greater R&D investment, R, is associated with a greater α. Hence, if a company increases its R&D, its distribution over performance outcomes is shifted rightward over higher values of the index of performance x. The R&D investment R is the present value of the R&D cost schedule chosen by the firm. The details of the R&D cost schedule are described with the partial derivatives and cross-partials for α(X,R).

• Thus, the integral is the expected value E of the investment R, and the firm chooses R to maximize expected profit (E – R).

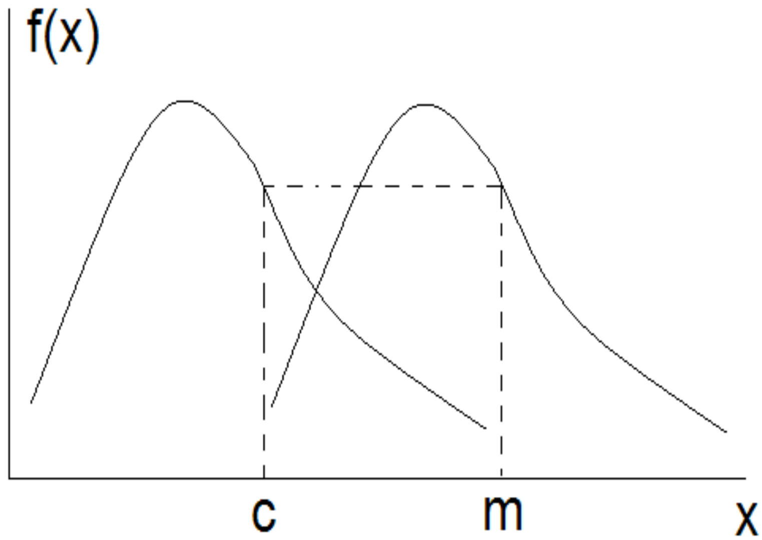


Figure 1. Competitive Pressure and the Probability Distribution for Relative Performance

Figure 2

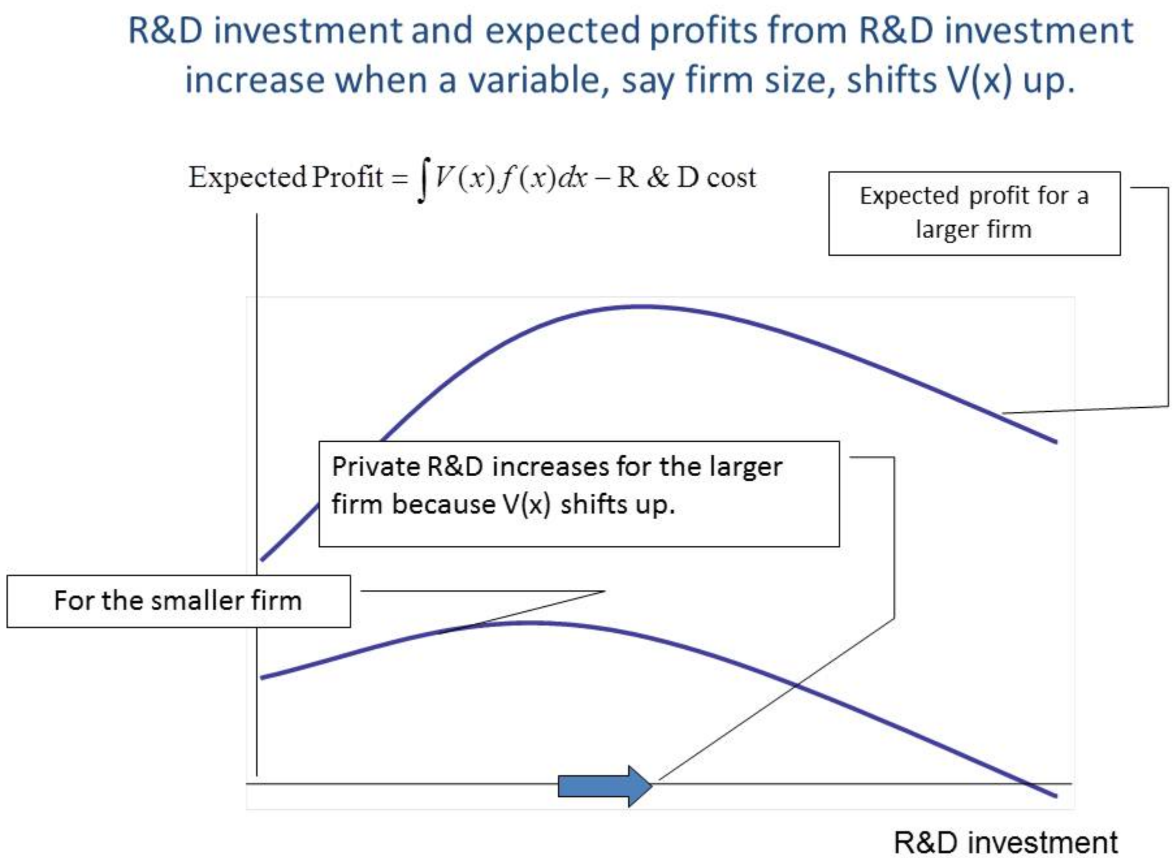

R&D investment and expected profits from R&D investment increase when a variable, say firm size, shifts V(x) up.
Expected Profit = $\int V(x) f(x) dx$ – R & D cost
Expected profit for a larger firm
Private R&D increases for the larger firm because V(x) shifts up.
For the smaller firm
R&D investment

Figure 3

Increased R&D investment when a variable, e.g. other firms' R&D, improves the anticipated state of the art and shifts f(x) for a given level of the firm's R&D leftward.

$$\text{Expected Profit} = \int V(x) f(x) dx - \text{R \& D cost}$$

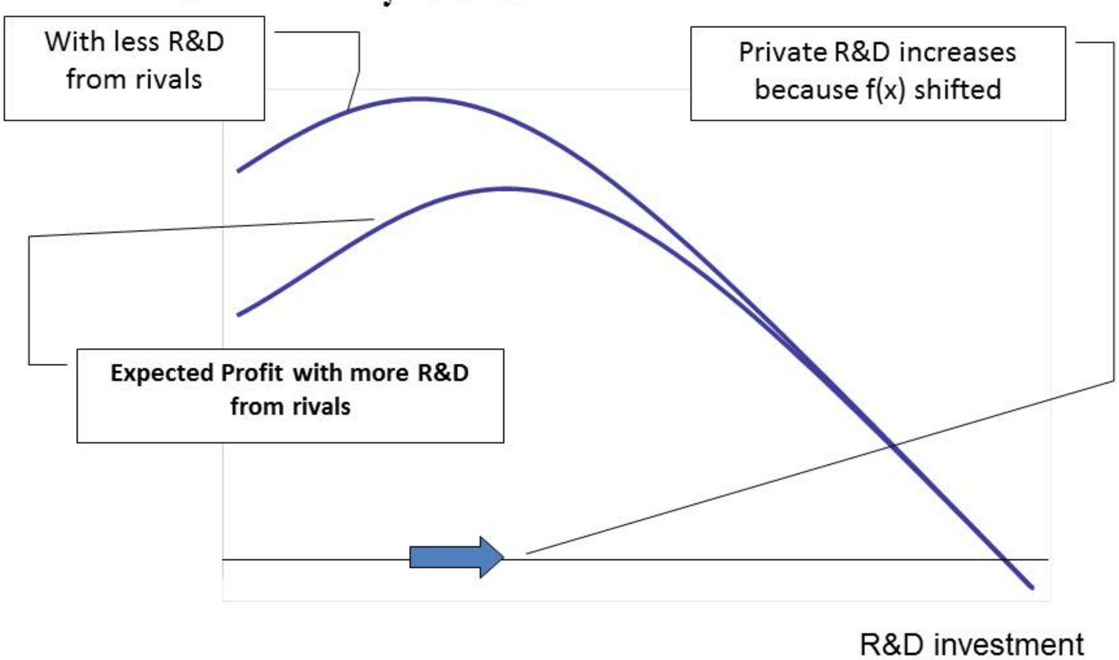


Table 2. Relative-Performance Model of R&D Investment: The Results

For exogenous competitive pressure (i.e., no strategic interaction):

- ***Result 1*** If $\partial V/\partial\gamma > 0$ and is increasing with x, then $dR/dZ_i > 0$ if $\partial\gamma /\partial Z_i > 0$ and $dR/dZ_i < 0$ if $\partial\gamma /\partial Z_i < 0$. For a variable that shifts value up (down) as it increases, R&D increases (decreases) as that variable increases.
- ***Result 2*** If $\partial^2\alpha/\partial X_i \partial R$ has a sign that is the opposite of the sign of $\partial\alpha/\partial X_i$, or alternatively is sufficiently small, then $dR/dX_i > 0$ if $\partial\alpha/\partial X_i <0$ and $dR/dX_i <0$ if $\partial\alpha/\partial X_i > 0$. For a variable that shifts the probability distribution left (right) as it increases, R&D increases (decreases) as that variable increases.

For interactive or strategic rivalry and Nash equilibrium strategy combinations:

- ***Result 3*** With noncooperative Nash equilibrium, the sign for the derivative of R with respect to a value shifting variable Z_i will be the same sign as given in *Result 1* if the **equilibrium is stable** in the special sense that rivals' R&D is not too complementary.
- ***Result 4*** With Nash equilibrium and given the stability condition, the sign for the derivative of R with respect to a probability shifting variable X_i will be the same sign as given in *Result 2*.
- **The Schumpeterian condition**: The marginal-value-reducing effect (because of post-innovation competition) of rivals' R&D outweighs (1) the positive impact of rivals' R&D on the marginal value of a firm's R&D resulting from the leftward shift in the probability distribution and (2) the possibly positive impact from complementary rival R&D.
- ***Result 5*** The sign of the change in Nash equilibrium R&D investment for each firm as the number of competitors increases is negative given the stability condition and the Schumpeterian condition, and the effect becomes smaller as the number of firms in the equilibrium increases.
- ***Result 6*** *Even given the conditions in Result 5 so that the firm's R&D falls, the total R&D will rise if* a firm's own R&D investments have effects on the marginal benefit of its R&D that are larger in absolute value than the marginal-benefit-dampening effects that result from the R&D investments of its rivals.

Table 3. Descriptive Statistics for *PRD3RDT*, Title III Product R&D in Thousands of 1992 Dollars[a]

Variable	Mean	Standard Deviation	Minimum	Maximum	Number of Observations
PRD3RDT	12,395.29	60,312.76	4.00	367,500.00	37
ln *PRD3RDT*	6.1473	2.4838	1.3863	12.8145	37

[a]Note that the distribution of *PRD3RDT* is quite skewed. The average of the natural logarithms corresponds to a much smaller amount of Title III product R&D than the average value for *PRD3RDT*. The logarithms for the minimum and maximum values of course do correspond to the minimum and maximum values for *PRD3RDT*. There are 95 of the 132 responding companies that report they do not do Title III product R&D; the mean for *PRD3RDT* in the 132 observation sample is 3,474.44.

Table 4. Explanatory Variables for the Tobit Model of Title III Product R&D[a]

Variable	Mean	Standard Deviation	Number of observations
ln(*NTAPC*)	3.229	0.6596	132
NTAPC	30.80	19.47	132
ln(*SALES*)	6.375	1.611	132
SALES	2721.09	7721.90	132
ln(*IMPSC*)	– 1.913	0.9178	132
IMPSC	0.2268	0.2963	132
PRODOTHER	0.02273	0.1496	132
COOP	0.09848	0.2991	132
CR4C	36.05	11.27	132
DBACKROUND	0.3182	0.4675	132
DPROCESS	0.4394	0.4982	132
Noncensored observations (*PRD3RDT* > 0)			
ln(*NTAPC*)	3.492	0.6673	37
NTAPC	39.92	23.90	37
ln(*SALES*)	7.190	1.803	37
SALES	6096.21	12971.89	37
ln(*IMPSC*)	– 2.207	0.6899	37
IMPSC	0.1342	0.08355	37
PRODOTHER	0.08108	0.2767	37
COOP	0.2703	0.4502	37
CR4C	33.52	10.69	37
DBACKROUND	0.5946	0.4977	37
DPROCESS	0.7568	0.4350	37

[a]Note that the average of the natural logarithms for a variable does not correspond to the average value for the variable.

Table 5. The Tobit Model for ln(*PRD3RDT*).[a]

Variable	Coefficient (Standard Error)[b]	Standard Error with Intragroup Correlation (clustered errors)[b]
Constant	– 20.0 (8.31)****	5.28*****
ln(*NTAPC*)	2.34 (1.37)***	1.64*
ln(*SALES*)	1.71 (0.566)*****	0.548*****
ln(*IMPSC*)	– 2.82 (1.28)****	0.899*****
PRODOTHER	9.18 (3.54)****	2.35*****
COOP	2.86 (2.27) [c]	1.30****
CR4C	–0.538 (0.295)***	0.256****
$CR4C^2$	0.00539 (0.00362)**	0.00276***
DBACKGROUND	2.85 (1.87)**	1.63***
DPROCESS	2.95 (1.74)***	1.62***
Industry Effects[d]	Yes	
SIGMA	5.29 (0.710)*****	0.543*****
Log likelihood	–143.90	
Chi-square (d.f. =19)[e]	66.99*****	
No. of Observations	132	

[a]The dependent variable for the Tobit model is ln(*PRD3RDT*) for the 37 nonzero observations of Title III R&D and is zero for the remaining 95 observations of companies responding to the survey. Column (1) is the basic Tobit model estimated with StataCorp (2011). Column (2) shows the standard errors estimated using Stata's cluster option for estimating the variance-covariance matrix corresponding to the parameter estimates with the Tobit command. The covariance matrix for the model is adjusted for clustering, allowing for intragroup correlation of the errors in each specified cluster of observations. The clustering of the errors does not affect the estimated coefficients, but changes the standard errors and the variance-covariance matrix of the estimators. The sample of 132 observations contained 15 clusters with each cluster being one of the 15 broad industries listed in note (d) below and with each firm assigned to the cluster that represents its primary manufacturing industry. Six of the 132 firms have a non-manufacturing industry as their primary industry but have significant manufacturing operations too. For purposes of determining the 15 clusters those six firms were assigned to their primary manufacturing industry.

[b]Significance levels for two-tailed tests: * $p \leq 0.20$; ** $p \leq 0.15$; *** $p \leq 0.10$; **** $p \leq 0.05$; ***** $p \leq 0.01$.

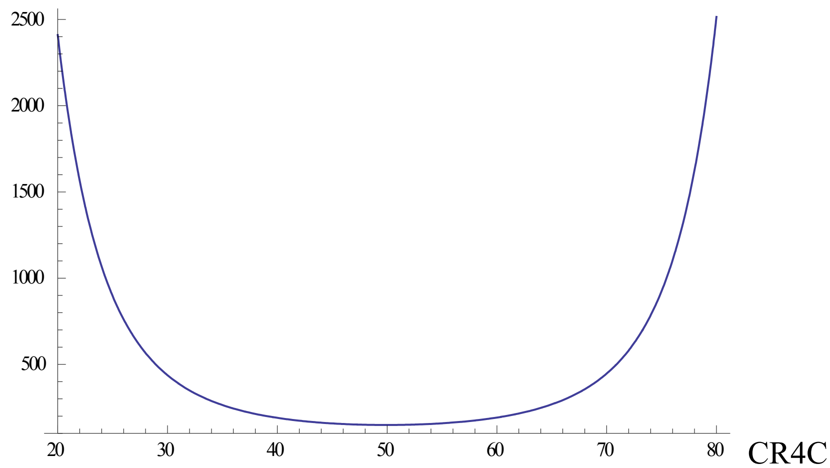
[c]This note is to indicate the p value for the ratio of the coefficient to the standard error for estimated parameters (other than the coefficients for the industry dummy variables) where the ratio is greater than one yet not great enough for a two-tailed p value ≤ 0.20. For the coefficient of *COOP* in specification (1), the p value is 0.21.

[d]Corresponding exactly to the specification used for the two-step estimates of the Tobit model of Title III product R&D with selection into the sample in Scott (2003, Table 6.5, p. 88) and also to the full information maximum likelihood models in Scott (2005) that converged when jointly estimating the models of selection and R&D, industry effects for operations in 10 broad industry categories (food, textiles, furniture, paper, rubber and plastics, fabricated metal, industrial machinery, electronics, transportation, and instruments) were estimated, with operations in the remaining five broad industry categories (lumber and wood, chemicals, petroleum, primary metals, and miscellaneous manufacturing), for which the industry effects were indistinguishable from each other, left in the intercept. There were no respondents with their *primary* activities in five of the broad Standard Industrial Classifications—tobacco, apparel, printing, leather, and stone, clay, and glass.

[e]The likelihood ratio chi-square test of the joint significance of all the variables in the model as described by Greene (2002, p. E21-7); the chi-squared statistic has 19 degrees of freedom.

Figure 4. A Firm's Expected Title III Product R&D Conditional on Performance of Title III Product R&D, as a Function of Seller Concentration, Ceteris Paribus[a]

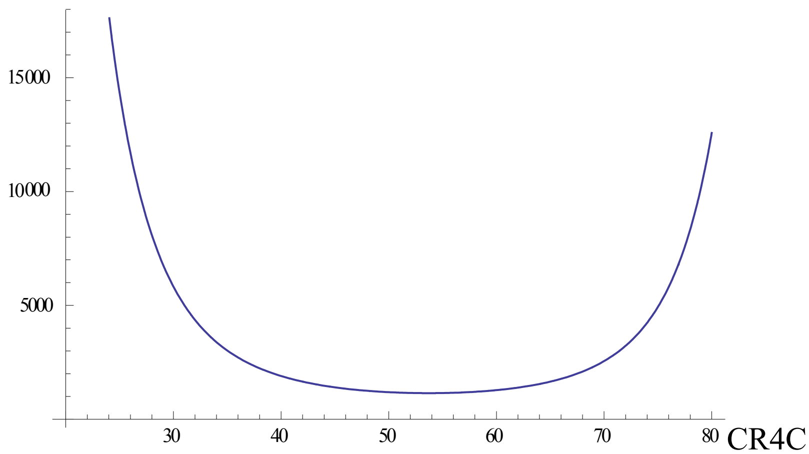
Expected Title III Product R&D (thousands of dollars)



[a]Simulated using the estimation in Table 5 for a firm not in one of the 10 broad industries for which industry effects are estimated (all included industry qualitative variables set to zero, so the broad industry effect reflected in the intercept is used—see the notes to Table 5) with ln(NTAPC), ln(SALES), and ln(IMPSC) set at their means for the sample of firms performing Title III product R&D, and with COOP, DBACKGROUND, and DPROCESS set at 1, and PRODOTHER = 0 (since very few firms, even among those with Title III product R&D, have PRODOTHER = 1).

Figure 5. An Industry's Total Title III Product R&D as a Function of Seller Concentration.[a]

Expected Total Title III Product R&D (thousands of dollars)



[a]Simulated using the results from Figure 4 for the representative firm and using 100/(CR4C/4) for the number of firms at each level of CR4C.

Figure 6. Structural Competition and R&D Investment

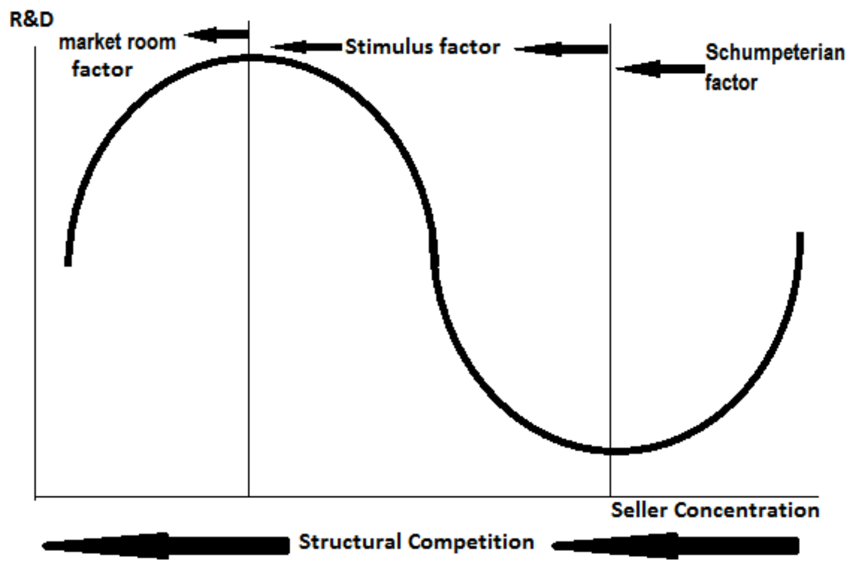


Table 6. The U and the Inverted U in the Tobit Model for ln(*PRD3RDT*).[a]

Variable	Coefficient (Standard Error)[b]	Standard Error with Intragroup Correlation (clustered errors)[b]
Constant	– 33.9 (13.8)*****	10.3*****
ln(*NTAPC*)	1.64 (1.44)**	1.49**
ln(*SALES*)	1.62 (0.560)*****	0.567*****
ln(*IMPSC*)	–2.74 (1.25)****	0.891*****
PRODOTHER	8.72 (3.48)*****	2.22*****
COOP	2.70 (2.24)**	1.21****
CR4C	0.887 (1.11)	0.878*
$CR4C^2$	–0.0305 (0.0274)**	0.0205***
$CR4C^3$	0.000274 (0.000208)***	0.000150****
DBACKGROUND	3.14 (1.87)****	1.63****
DPROCESS	3.15 (1.72)****	1.66****
Industry Effects[c]	Yes	
SIGMA	5.19 (0.696)*****	0.521*****
Log likelihood	–143.02	
Chi-square (d.f. =20)[d]	68.74*****	
No. of Observations	132	

[a]The dependent variable for the Tobit model is ln(*PRD3RDT*) for the 37 nonzero observations of Title III R&D and is zero for the remaining 95 observations of companies responding to the survey. Column (1) is the basic Tobit model estimated with StataCorp (2011). Column (2) shows the standard errors estimated using Stata's cluster option for estimating the variance-covariance matrix corresponding to the parameter estimates with the Tobit command. The covariance matrix for the model is adjusted for clustering, allowing for intragroup correlation of the errors in each specified cluster of observations. The clustering of the errors does not affect the estimated coefficients, but changes the standard errors and the variance-covariance matrix of the estimators. The sample of 132 observations contained 15 clusters with each cluster being one of the 15 broad industries listed in note (c) below and with each firm assigned to the cluster that represents its primary manufacturing industry. Six of the 132 firms have a non-manufacturing industry as their primary industry but have significant manufacturing operations too. For purposes of determining the 15 clusters those six firms were assigned to their primary manufacturing industry.

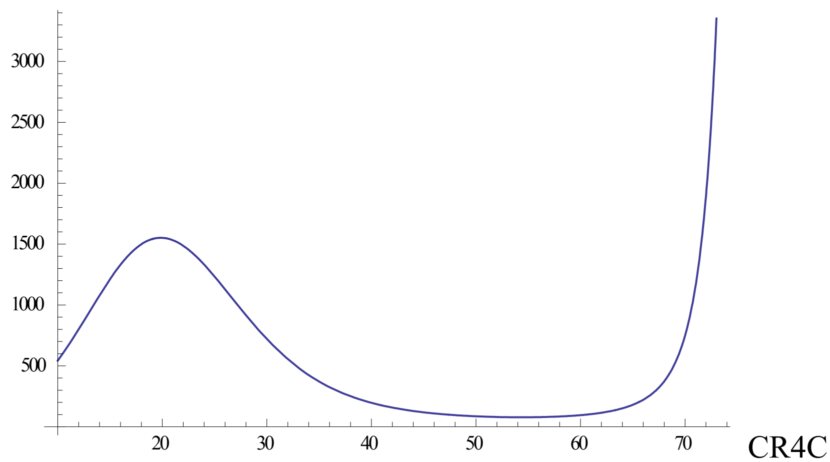
[b]Significance levels for ***one-tailed*** tests: * $p \leq 0.20$; ** $p \leq 0.15$; *** $p \leq 0.10$; **** $p \leq 0.05$; ***** $p \leq 0.01$. With the three terms for seller concentration to estimate a polynomial allowing the illustration of both the traditional inverted-U over the lower range of concentration and the U relation over the higher range, the statistical significance for the concentration terms is certainly not present at anything approaching the usual levels of confidence. Arguably, at this point we are testing a hypothesis with a very clear a priori expectation of a positive sign for CR4C, a negative sign for its square, and a positive sign for its cube, so to show what hint of significance there may be, we have used the one-tailed p values in this table. Doubling them, of course, yields the two-tailed tests.

[c]Corresponding exactly to the specification used for the two-step estimates of the Tobit model of Title III product R&D with selection into the sample in Scott (2003, Table 6.5, p. 88) and also to the full information maximum likelihood models in Scott (2005) that converged when jointly estimating the models of selection and R&D, industry effects for operations in 10 broad industry categories (food, textiles, furniture, paper, rubber and plastics, fabricated metal, industrial machinery, electronics, transportation, and instruments) were estimated, with operations in the remaining five broad industry categories (lumber and wood, chemicals, petroleum, primary metals, and miscellaneous manufacturing), for which the industry effects were indistinguishable from each other, left in the intercept. There were no respondents with their *primary* activities in five of the broad Standard Industrial Classifications—tobacco, apparel, printing, leather, and stone, clay, and glass.

[d]The likelihood ratio chi-square test of the joint significance of all the variables in the model as described by Greene (2002, p. E21-7); the chi-squared statistic has 20 degrees of freedom.

Figure 7. The U and the Inverted-U for a Firm's Expected Title III Product R&D Conditional on Performance of Title III Product R&D, as a Function of Seller Concentration, Ceteris Paribus[a]

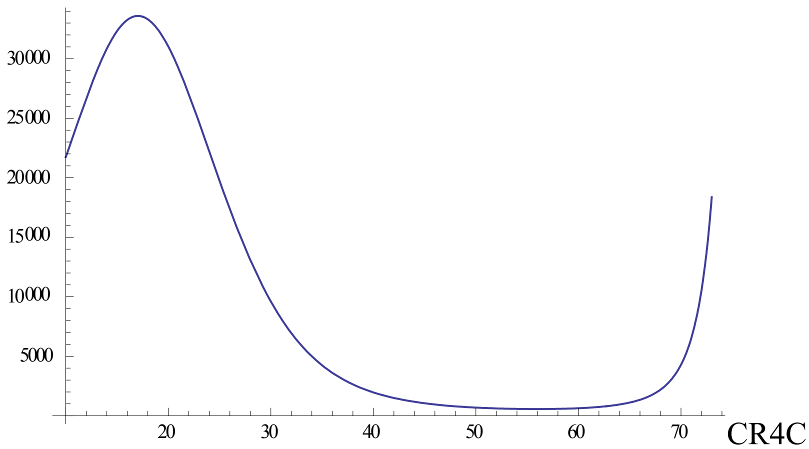
Expected Title III Product R&D (thousands of dollars)



[a]Simulated using the estimation in Table 6 for a firm not in one of the 10 broad industries for which industry effects are estimated (all included industry qualitative variables set to zero, so the broad industry effect reflected in the intercept is used—see the notes to Table 6) with ln(NTAPC), ln(SALES), and ln(IMPSC) set at their means for the sample of firms performing Title III product R&D, and with COOP, DBACKGROUND, and DPROCESS set at 1, and PRODOTHER = 0 (since very few firms, even among those with Title III product R&D, have PRODOTHER = 1).

Figure 8. Illustrating Both the U and the Inverted-U Relation for an Industry's Total Title III Product R&D as a Function of Seller Concentration.[a]

Expected Total Title III Product R&D (thousands of dollars)



[a]Simulated using the results from Figure 7 for the representative firm and using 100/(CR4C/4) for the number of firms at each level of CR4C.