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Quality Issues in the Defense Industry A Case Study

An Essay in

Economics

by

Matthew V. Santoni

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of the Requirements
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I. Introduction

The subject of Department of Defense (DoD) spending is one that always raises a considerable amount of spirited debate. How much is enough? Are we spending too much? Where should the limited resources of society best be allocated? Do the present allocations result in a reasonable return? Much has been said and studied on the macroeconomic question of whether defense spending is "good" or "bad" for the economy.[1] Typically, these studies have focused on defense spending's impact on such macroeconomic variables as employment, GNP, investment and productivity.

On the microeconomic side, it is a bit more difficult to make an a priori judgment on what should be analyzed. The defense industry and the process by which defense goods are bought and sold is often radically different from what might be thought of as a traditional market. Consequently, many micro studies (especially those in the mainstream press) tend to focus on that which is easily observable. Thus, the debate centers on such issues as DoD waste, fraud and mismanagement. During the years of the Reagan buildup it often seemed that one could not pick up a newspaper without reading the following headlines: "Pentagon Pays $640 For Toilet Seat."[2] Or: "Defense Contractors Gouge US Govt $7,400 For Coffee Pot."[3]

Despite this, microeconomics does have a great deal to say about the conduct of defense firms. For example, issues of contract enforcement, monopoly behavior and the nature of individual firm investment (such as how regulatory policy effects research and development expenditures) are all addressed in microeconomic theory.[4] This paper will look at an issue which often generates much criticism when it is not present but at the same time tends to be forgotten otherwise: quality. As already mentioned, the market for defense goods is often characterized by a bilateral monopoly relationship between the buyer and the seller. A bilateral monopoly is defined as a market which is characterized by a single seller and a single buyer. Such a relationship is not uncommon for goods which are highly technical in nature and that require large up front investments in terms of research and development and capital expenditure. Given this, I will focus on the seller and analyze the incentives he or she faces in the decision to provide quality. More formally: what are the incentives for the monopolist to under provide or over provide quality relative to the "social optimum", ie.. that which would be supplied by a Paretian dictator?

In answering this question I will focus on two areas. First, what does microeconomic theory have to say about the issue and what are the relative firm incentives? Secondly, what kind of experience have we witnessed regarding the quality of certain defense items? The empirical evidence that I will present will focus on the case histories of two different DoD programs, the F-15 jet engine and the AMRAAM missile. These two programs provide an interesting cross section of dual sourcing experience. The F100 program started out as single source (hence, monopoly) contract and was then dual sourced (opened up to outside competition) after perceived quality problems arose. The AMRAAM missile started out initialy as a competition but with the understanding that the winner of the competition would transfer its technology to the loser. To what extent did quality issues play a role in the initial contracting for the good? What was the perceived quality of the delivered good before dual sourcing? What quality characteristics did the good acquire after dual sourcing? How do the results square with the predictions of microeconomic theory? These are all questions which I will endeavor to answer.

II. Theoretical Development

What are the intuitive arguments for monopolistic quality adjustment? As a minimum, we will specify an environment in which quality is completely determinable ex post. Simply put, quality is observable as soon as it is supplied. It is easy enough to see that in a competitive outcome the firm would continue to produce quality until the marginal cost of producing quality just equaled the price people would be willing to pay for such quality. This is merely a quality based P = MC outcome. We already know that a monopolist will restrict output. Given this, will the monopolist choose to "stick it to the public" by forcing them to except a higher quality (and thus a higher priced) product then they want? A good example of this would be the situation which existed immediately after WWII. The late fourties and early fifties are generaly recognized as a period of very high demand. To exploit this, car manufacturers began to "load up" cars with lots of extras such as push button transmissions, chrome, and power controls. Alternatively, we can think of a scenario whereby the monopolist "cuts back on costs" by producing shoddy products that the public is forced to buy because of his monopoly power. This criticism is often leveled at public utilities and the TCI story is an example which strikes close to home. TCI is the local cable monopoly and they have been charged with offering poor service and shoddy line quality. From personal experience, every time there is a lightening storm cable service goes out.

Jean Tirole, in his text The Theory of Industrial Organization, sets down a fairly definitive analysis of this problem.[5] I will go through the essential points of his argument here. First of all, Tirole specifies general supply and demand functions:

Demand : $P(q,s)$ $P_q < 0$, $P_s > 0$

Supply : $C(q,s)$ $C_q > 0$, $C_s > 0$ and $C_{qq} > 0$, $C_{ss} > 0$

where: q = quantity of output

s = a measurable level of quality,

and the subscripts denote partial derivatives.

Here the usual assumptions about the structure of costs are made: increasing costs at an increasing rate for both quantity and quality. Notice the sign of P_s. A P_s greater than zero implies that people are willing to pay more for higher quality. Also notice that cross partials for both supply and demand have not been specified. In the case of supply, it is not necessary since our results are independent of the sign of this derivative. In the case of demand, we will see that the sign of its cross partial is crucial to the determination of a monopolist's quality.

First, what would the social planner impose on the market? The social planner's objective is to maximize the total value of production:

$$(1) \quad \max_{q,s} W = \int_0^q P(x,s)\,dx - C(q,s)$$

which yields the following first order conditions for an interior maximum:

$$(2) \quad {}^{dw}/_{dq} = P(q,s) - C_q(q,s) = 0$$

$$(3) \quad {}^{dw}/_{ds} = \int_0^q P_s(x,s)\,dx - C_s(q,s) = 0$$

Equation (2) is the familiar P = MC condition, while Equation (3) determines optimal quality output. Tirole states that (3) "...[is] the partial derivative of gross surplus with respect to quality [set] equal to the marginal cost of producing this quality."[6] The term $P_s(x,s)$ is the marginal willingness (in terms of cash) of consumer x to pay for a unit increase in quality. Thus, the integral of this function over q will be the total valuation of quality in the market for the given quantity. In other words, the integral of the marginal valuations represents the total "price" that the market is willing to pay for quality. Once we look at the relationship in this light it is easier to understand since now price for quality is being set to the marginal cost of quality.

The monopolist approaches this same problem with a completely different set of objectives. He, or she, wants to maximize profits. Using the economic definition of profit, we get the following optimization problem for the monopolist:

(4) $\text{Max}\ \pi(q,s) = q \cdot P(q,s) - C(q,s)$

the first order conditions are:

(5) $d\pi/dq = P(q,s) + q \cdot P_q(q.s) - C_q(q,s) = 0$

(6) $d\pi/ds = q \cdot P_s(q,s) - C_s(q,s) = 0$

Again, equation (5) is a familiar result: MR = MC for the monopolist. Fortunately, (6) is a bit easier to understand then the corresponding condition for the social planner. Here we see that the monopolist sets quantity and quality such that the last marginal consumer is exactly indifferent between the consumption of s quality and not consuming at all. In other words, $MR_s = MC_s$.

To analyze the effect of monopoly on market quality, we would like to compare the two conditions set forth in (3) and (6). A direct comparison between the two is not possible. Both quantity and quality vary between the two conditions. In order to get a meaningful result we must set the quality at a known, fixed value, say q. If we restrict the monopolist and the Pareto dictator to the same output then we can analyze the corresponding quality levels. This is relevant for the defense industry since in the vast majority of transactions quantity is exogenously set; it is contractualy specified. Then, the comparison is:

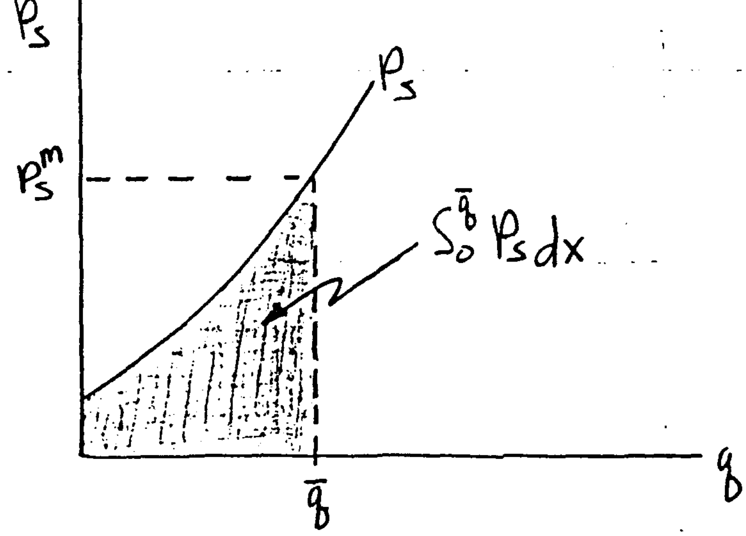
$$\int_0^q P_s(q,s)\,dx \;\begin{matrix} > \\ = \\ < \end{matrix}\; q \cdot P_s \qquad \begin{matrix} \Rightarrow \text{ s under Pareto > monopoly s} \\ \\ \Rightarrow \text{ s under monopoly > Pareto s} \end{matrix}$$

In words, if the total valuation of quality in the market for a given quantity (the left hand side of the relationship) is greater then the monopolist's marginal revenue of supplying that quality (the right hand side) then the monopolist will be under supplying quality. Conversely, if the monopolist's marginal valuation is greater than the market's valuation, then the monopolist will be over supplying quality. When will any of these various conditions hold? The key lies in the cross partial P_{sq}. If this cross partial is positive, the marginal willingness to pay for quality, P_s, is increasing in q and the monopolist will oversupply s.[7] Alternatively, if $P_{sq} < 0$ then P_s is decreasing in q and the monopolist will under supply s. A helpful way to visualize these conditions is to graph P_s versus q. This is done in Fig I. As can be seen in these graphs, the overall comparison depends on the slope of the P_s curve.

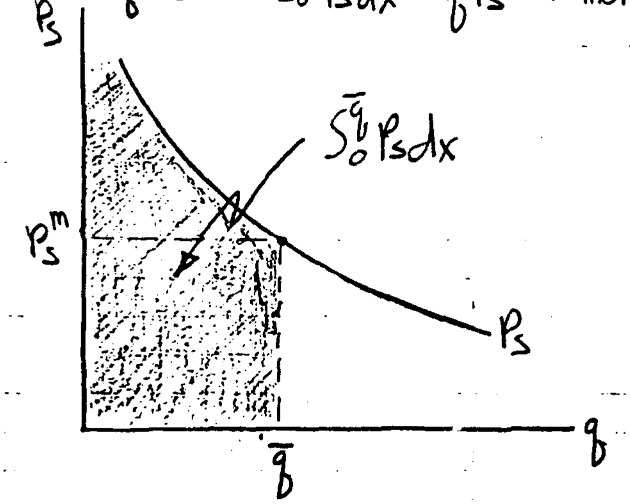
In general, it may be thought that as more is acquired of a certain product the need for quality is less pressing. The prime example of this is the defense industry. For

Figure I

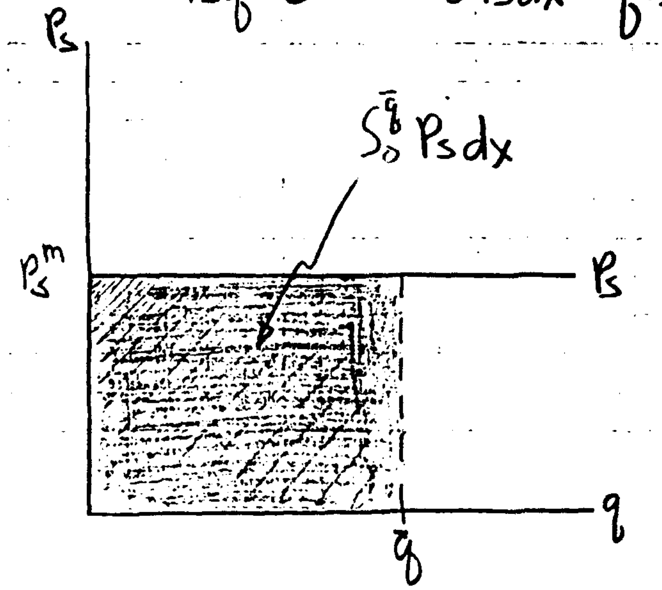
$P_{sq} > 0 \Rightarrow \int_0^q P_s\,dx < q P_s \Rightarrow$ monopolist oversupplies s



$P_{sq} < 0 \Rightarrow \int_0^q P_s\,dx > q P_s \Rightarrow$ monopolist undersupplies



$P_{sq} = 0 \Rightarrow \int_0^q P_s\,dx = q P_s \Rightarrow$ monopolist supplies optimal s!



years the analysis of the military balance between the U.S. and the Soviet Union has focused on the fact that the U.S. seeks to make up for lesser quantity with more quality (in terms of being technologicaly superior). In this sense the U.S. defense establishment may be thought of as having a negative P_{qs} cross-partial. This point will be explored in greater detail later on in the paper.

Supplementing this basic theory are several papers which provide additional insight into the performance phenomena observed in defense contracts. One paper by Thomas Saving lays out conditions in which the monopolist will supply the same amount of quality as a competitive market. Another paper by Ronald Shrieves describes the relationship between market organization and quality in terms of innovation. Lastly, Klein and Leffler describe conditions under which parties to a contract can use market mechanisms as a means of ensuring contractual performance. For each paper I will provide a brief summary of the main points along with an analysis of their applicability to the study at hand.

Thomas Saving's paper, "Market Organization and Product Quality", describes a situation whereby the parameters of supply and demand lead to the monopolist providing the competitive amount of quality, albeit at a lower quantity. Saving starts out with the usual inverse demand function: $p = P(q,s)$ where q is quantity and s is quality. Also, Saving specifies that $P_s > 0$ and $P_{ss} < 0$, or consumers value more quality but at a diminishing rate.[8]

On the cost side, Saving assumes the usual cost function and makes the same assumptions about the convexity of costs as Tirole does. However, Saving then assumes that the market is characterized by a form of constant costs such that the cost function is independent of industry size. Thus, each entering firm has available to it exactly the same cost function as all other firms in the industry. As Saving states, "...the constant cost assumption implies that there are no economies or diseconomies of scale at the industry level."[9] This assumption, coupled with the free (costless) entry and exit of firms allows Saving to derive the result that long run industry average costs are independent of quantity and depend only upon the level of quality.

Saving's final, and most important assumption, has to do with the general inverse demand function previously specified. Saving takes this general function and imposes separability of demand for quantity and quality.[10] In other words, a consumer's demand for quality is completely independent of the level of quantity and vice-versa. Once this condition is imposed, we may intuit the level of quality the monopolist will supply. We know that the monopolist will restrict quantity due to setting marginal revenue equal to marginal cost. Since consumer demand for quality does not change with quantity, the monopolist faces the same demand for quality as the competitive firm. Furthermore, we have also specified that the cost of providing an s level of quality is the same between each form of market organization. It therefore follows that the level of quality supplied by the monopolist will equal that of the competitive firm. Costs for quality are the same. Demand for quality is the same. Quality supplied is the same.

Admittedly, Saving's assumptions of firm independent costs (ie.. all firms have the same cost function) and the separability of demand are a bit restrictive. Relating Saving's results to the defense industry, it would seem to be that they are of limited value. The highly regulatory nature of the defense industry along with the fact that there are often significant economies of scale (especially for big ticket items) does not lend itself to the assumption of constant industry costs. Production processes of many defense firms are proprietary information, to say nothing of matters of national security. Interestingly enough, however, are the several examples of demand separability given by Saving. Two of these examples are generally quite applicable to the defense industry. They are durability and reliability. Saving shows that both of these quality issues can be separated from the demand for quantity; the former additively and the later multiplicatively.[11] As we shall see, quality issues of durability and reliability played a large role in the saga of the F-15 fighter jet engine contracts while reliability problems have plagued the AMRAAM missile development thus far.

The next paper approaches the quality problem from a slightly different perspective. Ronald E. Shrieves, in his paper "Market Structure and Innovation: A New Perspective", evaluates the overall level of quality produced by a firm in terms of its expenditure on research and development. The hypothesis that larger firms possessing some degree of market power have a comparative advantage for innovative activity was first proposed by Joseph A. Schumpeter in 1942.[12]

The theory of relating market structure to innovation basically revolves around a comparison of the relative incentives for innovation in the two alternative forms of monopoly and competition. The incentives issue has to do with the ability and speed with which an innovator's technology is appropriable by competing firms. If the invention is freely and costlessly appropriable by other firms then there are effectively no property rights for the innovator and his or her invention is for all intents and purposes a public good. Under these conditions it is fairly intuitive to see that a competitive firm would have little or no incentive to innovate since it could not recoup its initial investment. The final price of the improved product will not reflect the innovator's efforts because it can be costlessly imitated. If on the other hand, the innovator exercises some degree of market power due to barriers to entry, then the firm can pass on some of the cost of innovation to consumers. As Scherer states,

> "If a product innovation increases industry demand, some portion of the increase will be reflected in the demand curve faced by the individual oligopolist innovator, even with immediate imitation by his rivals."[13]

In this case the firm with market power will produce more innovations then a similar firm in a competitively organized market. An interesting condition on this theory is that for the case where innovation results in a reduction of a firm's marginal cost, this drop must be greater than the corresponding drop in the price of the product.[14]

Contrasting the extreme case of the innovation as public good is the situation where the inventor may fully appropriate the benefits of innovation. In such a situation the inventor's rivals cannot gain access to the new technology or, at least, cannot do so without incurring the same costs as the original inventor. It has been shown that under these conditions a competitive market structure will yield relatively greater incentives to innovate than a monopolistic one. The "story" that is used to defend such a conclusion is as follows: the pre-invention profits of the monopolist represent an opportunity cost to the inventor/monopolist which are not present for the inventor operating in a competitive market.[15]

Using the methodology of Shrieves' it is possible to draw a few conclusions as to what we might expect the nature of innovative effort in the defense industry to be. As mentioned previously, many of the innovations associated with the defense sector are not easily (or legally) appropriated by other firms. The development of a new missile guidance system, for example, is possible for the inventing firm only through massive investments in capital and R&D. The need for large initial investments is a significant barrier to entry for potential competing firms. Indeed, as is stated in several papers, the government must arrange for technology transfers to competing firms for those contracts where the dual sourcing option is being considered.[16] We would therefore predict, under Shrieves' conclusions, that a competitive firm would devote a relatively greater proportion of its expenditures to pursuing innovative activity. It is unfortunate, though, that it is exactly those technologies that are the least appropriable, and thus provide the greatest incentives for innovation to the competitive firm, were we observe the greatest amount of monopolistic structure. Concentration ratios for most of the "high tech" areas of defense production are extremely high. As we shall see, only two companies are able to produce high thrust jet fighter engines.

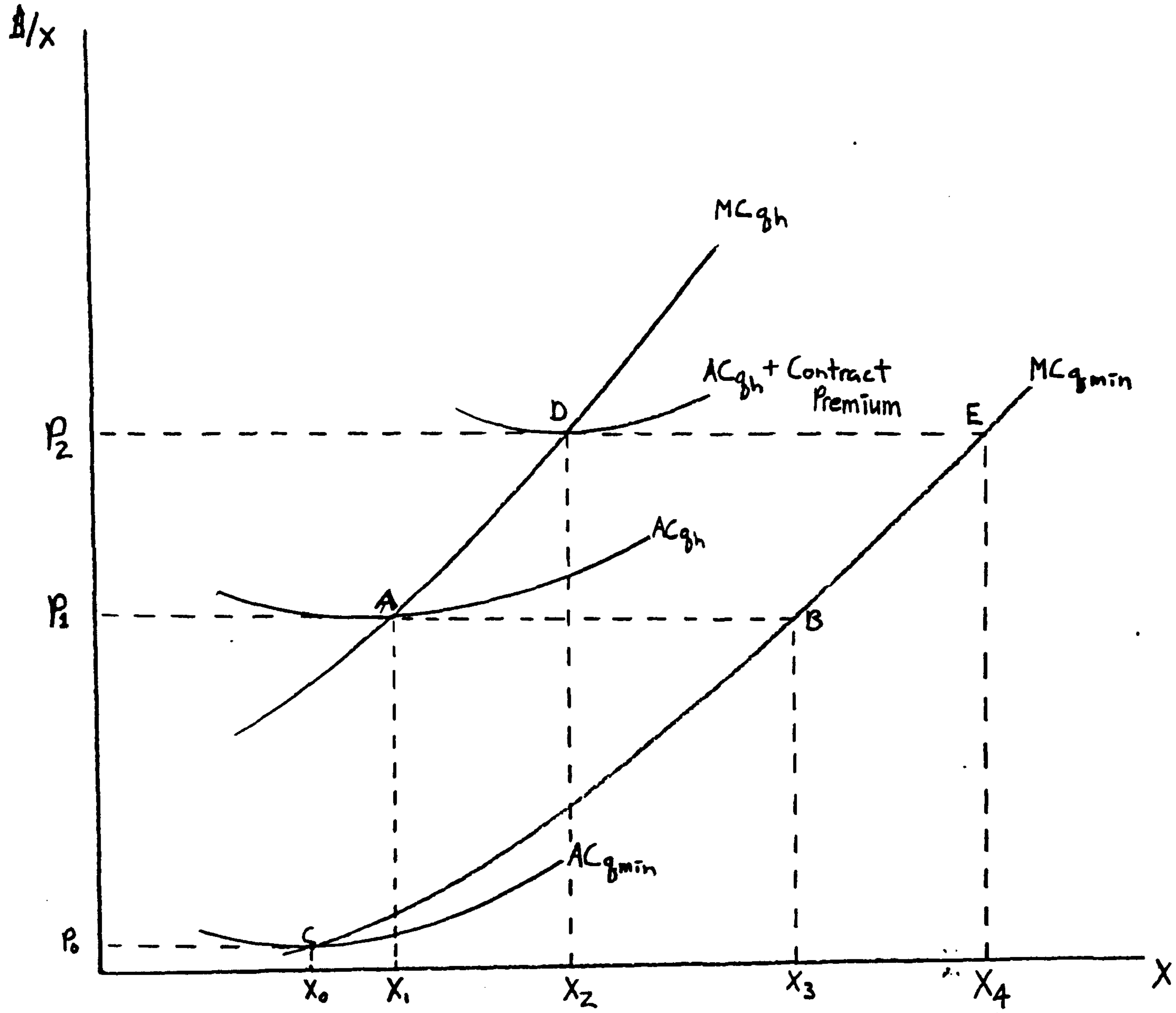
The third area of theory which can give additional explanatory power in the analysis of quality performance in the defense industry is Klein and Leffler's paper on contractual performance. Their paper, "The Role of Market Forces in Assuring Contractual Performance"[17], looks at the conditions under which parties to a contract can use market incentives as a means of enforcing contract stipulations. Boiled down to its essence, Klein and Leffler's hypothesis is quite pleasing intuitively. It is that the buyer basically "bribes" the seller into contractual performance by offering the seller a higher price for the product than would otherwise be obtainable in the free market. As the authors state,

> "A necessary and sufficient condition for performance is the existence of price sufficiently above salvageable production costs so that the nonperforming firm loses a discounted stream of rents on future sales which is greater than the wealth increase from nonperformance."[18]

As is usual in most economic studies, several assumptions are made. First, the authors assume that contracts are not enforceable by the government or other outside force. Since we are dealing with government procurement contracts it may seem that such an assumption immediately disqualifies Klein and Leffler's study from consideration. However, even when such a third party enforcement mechanism does exist, the costs of using the mechanism may be prohibitively high. Market arrangements then become the cheaper method of contractual enforcement. Furthermore, it is assumed that the parties to the contract operate in a repeat sale environment. Examples of repeat sale environments include cars, restaurant, and most non-durable goods. Several other assumptions are then made in order for the repeat sale environment to function. It is assumed that consumers can identify the firm from which they purchase from, property rights are well defined and firms are wealth maximizing and place no value on honesty per se. Also, once a "cheating" firm is found the information is instantly and costlessly passed on to other buyers.[19] A graphical representation of Klein and Leffler's argument is given in Fig.II along with some explanatory notes.

Overall, Klein and Leffler's paper does provide some insight into quality issues in defense procurement contracts. The most restrictive assumption in relation to defense contracting that the authors make is the repeat purchase mechanism. It is not entirely clear that this is a sufficient incentive for certain areas of the industry. On one hand, it can be argued that big ticket defense contracts are so few and far between that the defense firm could treat them as one time purchases. If such is the case then obviously no market incentives exist for contractual performance. Firms would want to cut back on costs and cheat on quality since the potential for future streams of income does not exist. On the other hand (and one is now reminded of the one-handed economist), if the defense firm produces several defense goods or is dependent upon military contracting for a significant portion of its income, then the repeat purchase mechanism is effectively operative. In the case of the AMRAAM missile, repeat-purchases is probably effective. Hughes produces several defense products (Maverick/TOW missile and avionics).

Fig II



Graph taken from Klein & Leffler (1981, JPE)

Notes to Fig II.

1). The key to Klein and Leffler's analysis is that the potential gains from adhering to the contract will outweigh the gains from cheating. In order for this to happen the prospect of repeat sales must exist. Otherwise the market degenerates into an endgame phenomena. In the graph the initial equilibria is at point A where the firm produces high quality at the minimum of its average cost curve and earns a normal return.

2). Point A cannot be supported as an equilibrium because the incentive for the firm is to earn a one period economic profit by producing low quality (with the resuting ACq_{min} and MCq_{min} curves) and continuing to sell at price P_2.

3). The question to ask is whether there exists a price above the competitive high quality one (P_1), by which the firm may earn a positive profit and at the same time satisfy self selection constraints. Specificaly, does the price both a). assure that the discounted stream of income is greater than the one shot cheating profit, and b). does not completely dissipate consumer surplus from the consumption of higher quality. The relevant "areas" for determining such a price are:

a). Premium from cheating : P_1BCP_0

b). Total gains from contract premium : P_1P_2DA

c). Total cheating potential with contract premium : P_0P_2EC

4). The one time gains from cheating are neccessarily always greater than the one period contract premium. This is not the issue. The comparison hinges upon whether the <u>discounted stream</u> of positive profit is greater than that for cheating. Klein and Leffler derive this mathematically and conclude that under very general cost conditions the existence of a performance guaranteeing price is possible.

Now that we have examined some of the theoretical base for the provision of quality by a monopolist, what inferences can we make? The basis for analysis will be Tirole's examination. This examination hinges upon how the demander's valuation for quality varies with quantity. If it is the case that as less is bought, more quality is demanded, then we can expect the monopolist to undersupply quality. Therefore, as we examine the case studies, how has the single sourcing environment affected the provision of quality relative to that experienced in dual sourcing? In addtion, Shrieves' conclusions on firm incentives for innovation will be crucial in the analysis of the AMRAAM missile. We will see how the mandated technology transfer provides a clear example of appropriable innovation. If we except Shrieves' theory, then Hughes (the initial contractor) would have strong economic incentives to under provide quality. Savings makes a case for no adjustments taking place. Critical to his analysis is the assumption that demand for quality and demand for quantity is seperable. Savings' main contribution for our study is his identification of those quality characteristics which may be defined as seperable. Durability and reliability are two such characteristics. We will see that both of these issues play critical roles in the discussion of the case histories.

III. Advanced Medium Range Air-to-Air Missile (AMRAAM) Program History:

The AMRAAM missile has alternately been praised as the missile that will take the Air Force into the next century and damned as a billion dollar boondoggle. To say that the program has experienced difficulties in its development would be an exercise in understatement. The initial concept for the missile began in 1979[1] and as of 1991 there still has not been a firm decision on whether to go ahead with full scale production. This particular program makes an interesting study for my thesis since it provides a case in which the exact nature of the dual sourcing arrangement is not clear. To restate my objective; it is the purpose of this paper to examine the qualitative differences that a monopolist can be expected to introduce in comparison to a competitive market. Since the market for defense goods is rarely ever a clear cut case of pure competition I have chosen to proxy the situation by examining single source (monopolistic) contracting versus dual sourcing ("competitive") contracting.

The saga of the AMRAAM began in 1979 when Hughes and Raytheon were selected for a 33-month "validation phase" to demonstrate technical feasibility. While AMRAAM is officially a joint Navy and Air Force undertaking, throughout the missile's development it has been the Air Force which has called the shots so this account will focus on its role. Scheduling for initial testing of the AMRAAM began in 1980.[2] AMRAAM was first conceived as a replacement for the aging AIM-7 Sparrow missile in response to Department of Defense and Air Force threat projections. Early on in the program both pilots and senior officials in the Air Force expressed strong support for a new air-to-air missile.[3]

It is important to understand the large qualitative leaps in performance that the AMRAAM incorporated because these design characteristics were to later play a large role in the history of the missile's development. The AIM-7 Sparrow, the missile which the AMRAAM is designed to replace, is what is called a "semi-active" radar homing missile. This means that the aircraft which fires the missile must use its radar to illuminate the target. The semi-active missile then uses the illumination to guide itself to the target.[4] There are several disadvantages with this scheme of technology. One is that the attacking aircraft must continue to fly toward the target and keep it illuminated by its radar so the missile can be guided. Thus the pilot and his aircraft are put in serious jeopardy of being shot down themselves because they cannot take evasive action. A further limitation of semi-active technology is that the attacker can engage only one target at a time using this type of missile guidance. If the attacker is outnumbered then he must engage each target separately which reduces his effectiveness. The Sparrow missile was subject to all of these limitations. Furthermore, the Sparrow was found to be of limited effectiveness during the Vietnam war when called upon to engage small, highly maneuverable MiG fighter aircraft.[5]

The AMRAAM, on the other hand, is designed not to have these shortcomings. It is a "fire-and-forget" missile. In other words, the pilot may fire the missile and then turn away from the target. He does not have to keep it illuminated by his radar as with the Sparrow.[6] AMRAAM also addresses the other limitation of previous generations of radar guided missiles. It can engage up to eight separate targets simultaneously.[7] Much of the same technology already existed in the form of the Navy's Phoenix missile. However, the Phoenix has a diameter of 15in. and a weight of 985lbs.[8] The challenge of the AMRAAM program was to squeeze this capability into a package of only 7in. in diameter and 326lbs. Additionaly, a broad range of performance parameters were specified at the initial testing which contributed to the technical complexity of AMRAAM's design.[9] Clearly, AMRAAM had an imposing array of qualitative requirements to fulfill from its inception.

Program testing began in 1980 with a requirement that each competing contractor (Hughes and Raytheon) fire ten shots at live targets. Each shot would impose different stresses on the missile's performance. Also, the contractors could not make each missile "tailor made" to the different tests. Hence, each contractor was to build a general, "generic" missile and test it under varying conditions.[10] The selection of Hughes and Raytheon as competitors was probably based on the fact that these two were the only companies with sufficient experience in radar guided air-to-air missiles. Furthermore, looking at each contractor's previous experience indicates that Hughes was the most likely winner of the contest. While Raytheon did design the Sparrow and Patriot (of Gulf War fame), Hughes was the only defense contractor in the U.S. that had ever built a radar guided missile of the "fire and forget" type, the Navy's Phoenix. By December of 1981 Hughes Aircraft was named as the primary contractor despite the fact that only three missiles were launched instead of the agreed upon ten. As Air Force Brig. Gen. Gerald C. Schwankl, program manager for the AMRAAM, noted, "The results were clean. This was not a coin flip decision."[11] It seems, then, that Hughes was indeed the odds on favorite from the start of the competition.

At this point a few words should be said about the nature of the contracting for the missile's development. Hughes was awarded a $421.2 million fixed-price contract for the fabrication of 94 missiles to be used in the test program.[12] From the start of the development it was understood that as soon as the testing was complete and full-scale production was ready, a second source contractor would be brought on line. The Air Force called this its "leader-follower" concept of acquisition strategy. Plans were ostensibly made to run a separate competition for the purpose of naming a second source supplier. It is not surprising that Raytheon was soon so named given that no other company came forward with a competing design.[13] Additionally, Raytheon would not use the design it developed during initial testing. As part of the leader-follower concept, Hughes would provide technical data and assistance to Raytheon who would then build the missile once full scale production began.[14] Essentially, what was involved was a technology transfer from Hughes to Raytheon. This will become an important point in the analysis of whether monopolistic quality adjustments took place in the AMRAAM program.

Through 1983 the missile's development progressed relatively smoothly. It was not until the summer of 1984 that technical problems began to delay the program. Problems surfaced in three areas: the rocket propellant, transmitter leaks, and software development problems. Despite this the Pentagon remained upbeat. Rear Adm. Isham W. Linder, U.S. Navy director of Defense test and evaluation assured the press that, "None of the problems encountered thus far can be considered show stoppers, and all are technically solvable."[15] Even so, the program development time line was pushed back three months and the last problem identified would prove to be a continuing thorn in the side of AMRAAM. Software problems would plague the program throughout testing and evaluation. It is also significant to note that both the Air Force and Hughes admitted that the complexity of the program was greater than they had expected. While the initial development contract was structured to take such slips into account, any future delays would force the Air Force to renegotiate the contract.[16] Renegotiation of contracts involves substantial additional costs in time and money coupled with the unfortunate reality that the renegotiaton often favors the contractor. The Air Force understandably wants to prevent this from happening. Furthermore, ex ante commitments to renegotiation, or the preception of such a commitment, undermine the credibility of the original contract. If a contractor believes that the Air Force is commited to a policy of renegotiation then the enforcability of the contract is substantialy diminished.

By January of 1985 AMRAAM had slipped a total of 21 months in its development schedule and the DoD along with the House Armed Services Committee initiated an intensive investigation of the program which threatened termination. The main areas of concern were that Hughes had underestimated the test systems cost by 50-100%, the use of a fixed-price contract in a high risk environment, and that Raytheon would not be able to be put on line as a second source contractor until 1987.[17] The DoD's decision at this point was to delay the production decision. Gen. Lawrence Skantze, Commander of the Air Force Systems Command noted, "The program ran into trouble trying to do too many things too fast," and concluded that the problem had more to do with improper scheduling than insurmountable technical obstacles.[18] The Air Force also insisted that the fixed-price contract was still enforceable while suggesting that Hughes would have to come up with the additional $200 million in development costs due to the program's delay. Once again, in spite of what may now seem to be a large body of evidence to the contrary, Air Force officials continued to downplay the technical difficulties of the program. Thomas E. Cooper, assistant secretary of the Air Force for R&D, insisted that, "We think the program has stabilized now....I think we have a reasonably good handle on the program right now."[19]

As if to prove Mr. Cooper correct, AMRAAM successfully completed a series of tests later on in 1985, one which involved shooting down another airplane under difficult conditions. It was also revealed that, other than the delays, AMRAAM was performing in accordance to all contractual specifications with a few exceptions. The exceptions were that the range of the missile decreased slightly, the missile "launch-to-eject" time increased, and the weight increased from 325lbs. to 335lbs.[20]

At this point in the game confidence began to run high among test officials. A November 1985 editorial in Aviation Week and Space Technology pronounced the AMRAAM on "...sound technical footing." Gen. Skantze once more assured a worried Congress and DoD that,

> "Technology is not the program's primary challenge; management issues-cost and schedule are. AMRAAM's development schedule took longer than it should have...We will persevere, for a capable, affordable missile. The cost/technical balance is critical, but the bottom line is that if the program is killed, we will have to go out the next day and reinvent it."[21]

To signal their confidence, both Raytheon and Hughes signed on to another fixed-price contract of $6.2 billion to build 24,335 missiles for both the Air Force and Navy once full scale production began. At the same time two General Accounting Office (GAO) reports on the missile recommended that Congress use caution. A Feb. 1986 report by Frank C. Conahan, Director of the GAO, noted that as of January 1986 only 20 full scale development missiles had been delivered and that of these, half had to be returned to Hughes because of malfunctions.[22] Mr. Conahan also pointed out that several key specifications had not been met (having to do with temperature resistance and radar performance) and concluded by saying that, "There continue to be uncertainties about the cost, schedule, and performance of the AMRAAM program."[23]

Under intense scrutiny testing forged ahead and it appeared that the program may have actually been "out of the woods." Between March and May of 1987 the Air Force conducted five separate live fire tests of the missile, all of which involved shooting down drone targets under varying conditions. All tests were successful except for an April 9 test in which the missile missed its target.[24] Gen. Ferguson, the AMRAAM's program manager during this period of time, who had thus far done an exemplary job of managing a difficult program, expressed hope that a full scale production decision could be had as early as spring of 1989.

Alas, this was not to be. The next year saw a depressingly familiar series of events cast further doubt on the troubled AMRAAM. Almost immediately after Gen. Ferguson expressed guarded optimism, the GAO questioned the validity of the series of five launches. According to the GAO, key aspects of the tests were modified so as to improve the probability of success. Specifically, difficult radar jamming conditions were lessened in severity so the missiles could find their targets.[25] While Air Force officials admitted lingering problems with the missile's software they persisted that this was not unusual.

Next, Hughes and the Air Force decided to push ahead with a complex, four missile launch against four separate targets under heavy jamming conditions. Unfortunately the test was unsuccessful. The Air Force Office of Operational Test and Evaluation noted software and reliability problems. Excessive vibration of the missile when mounted on the F-15 contributed to the reliability difficulties and resulted in a mean time between failure much lower than hoped for. AMRAAM suffered 13 failures in only 750 hours of test time while being carried on the F-15 versus the goal of six failures in 2,000 hours.[26] Predictably, Air Force officials put on a good face. Gen Yates, deputy assistant secretary for acquisition described the AMRAAM's performance as "superb" and insisted that, "The only concerns we have remaining on AMRAAM have to do with captive carry and reliability." Equally as predictable, Congress responded to the Air Force's assurances by cutting back fiscal year 1990 production to 635 missiles from a requested 1,450 missiles.[27]

Meanwhile, Air Force and Hughes designers went back to the drawing board to try and solve the missiles reliability and software glitches. Focus during this time was on a suspected vibration in the AMRAAM when carried by the F-15. In frustration, the Air Force refused to accept deliveries of the missile in February of 1990 until reliability problems were solved. Not until nine months later in May of 1990 was the test finally attempted again, this time successfully. However, this bright spot failed to mollify GAO officials who called for the program's termination. Congress was not impressed either. Both Sen. Dale Bumpers and Rep. Denny Smith lead attacks on the missile from their respective legislative bodies. Further reliability issues continued to plague AMRAAM. Through March of 1990 the AMRAAM averaged a mean time between failure of only 90 hours, less than the 200 hour interim goal and far short of the 450 hour production requirement.[28]

As of this year (1991) the program is still mired in the quicksand of additional testing and low rate production. A decision on full rate production still has not been made although a December 1991 date has been set. During the Gulf War conflict the missile performed surprisingly well. AMRAAM managed to log an excellent mean time between failure figure of 1,300 hours, far exceeding contractual requirements.[29] Given the programs past history, though, it would not be all together unexpected if additional technical problems begin to crop up.

Did Hughes skimp on quality in an effort to cut back on costs? Obviously, such an explanation is far too simplistic. At first glance it may be convenient to dismiss the monopolistic quality adjustment argument out of hand by pointing out that the contract was dual sourced and therefore introduced competition. A closer examination of the contractual realities reveals that this was not necessarily the case. First of all, it appears that Hughes had a significant technology lead in radar guided air-to-air missiles. True, Raytheon does produce both the Sparrow and the Patriot. But, as pointed out earlier, Hughes was the company that developed the Phoenix, a very similar design in terms of the technology used. Moreover, Air Force officials noted that Hughes won the competition handily. It was stopped after only three of the ten planned missiles were fired. Thus, from the very start, the "competition" between Hughes and Raytheon was probably not so competitive and one has to wonder whether Hughes, and the Air Force, knew this all along.

Secondly, once Hughes was named as the primary contractor the nature of the arrangement became that of leader and follower. Hughes had a virtual lock on all of the funds coming from the Air Force. For its development contract Hughes received $421.2 million. In comparison, once Raytheon was named as the second source it received a relatively paltry $43 million.[30] Raytheon did not finally produce a testable missile until late in 1988, fully six years after Hughes. It is important to note that in not one instance during the missile's crucial early design phase did Raytheon ever come up with a competing product development or a more efficient means of production. Later on, when the program had matured greatly, Raytheon did come up with some Air Force sponsored AMRAAM Producibility Enhancements (APREPS). These APREPS, though, were merely incremental improvements to the missile's design for the purpose of increasing reliability and decreasing costs.[31] The APREP program has no consequence on the relative manufacturer share between Raytheon and Hughes. Indeed, Raytheon and Hughes are actually working together on five of the improvements. It is this author's position that Raytheon has never challenged Hughes supremacy in the AMRAAM's development. In essence, Hughes has acted the role of the monopolist throughout the missle's early development.

Recall that under Tirole's argument the key to determining whether a monopolist would under or oversupply quality depended on the sign of the cross partial P_{sq}. If

P_{sq} was greater than zero than the monopolist would oversupply quality and vice-versa. How does the Air Force value quality with respect to quantity? Intuitively, the matter is fairly clear. The Air Force procures weapons systems to defeat a perceived threat. There are basically two ways to defeat a threat; either obtain a great enough numerical superiority that he is overwhelmed or have weapons of a sufficiently higher quality. An examination of the history of past Air Force procurement efforts suggests that the Air Force leans heavily on the latter philosophy.

In WWII the, then, Army Air Force's main fighter was the P-51 Mustang. Over 9000 of these versatile aircraft were eventually produced. During the Korean War the main fighter in use was the F-86 Sabre Jet. About 6000 of these fighters were built. In the Vietnam War, the Air Force's work horse fighter was the F-4 Phantom. Over approximately fifteen years of production 4000 Phantoms rolled off the assembly line. To replace the F-4 the Air Force bought the now famous F-15 Eagle. Total production of these aircraft approached 900 units.[32] Presently, the Air Force is developing the Advanced Tactical Fighter (ATF). Estimated total production of this costly, state of the art fighter is around 600.[33] At the same time the capabilities of these fighters have increased tremendously. Whereas the P-51 struggled to reach 500mph in a dive, todays ATF will be able to cruise supersonically. With such a history, it is reasonable to assume that the Air Force has demanded ever more quality from its fighters as they have bought less of them. Thus, we might think of the Air Force's internal valuation on the P_{qs} cross-partial as negative. As more quantity is obtained, quality valuation decreases. Alternatively, as has been the case with Air Force procurement, as less is bought, quality becomes more important.

Given that we assume a negative P_{qs}, Tirole predicts that the monopolist will under supply quality. After examining the history of the missile's troubled development, this does seem to be the case. While most of the missile's problems stem from scheduling and cost overruns, specified performance has also suffered. As noted earlier, there were three areas of missile performance in which Hughes failed to meet contracted specifications. Furthermore, the missile's reliability has been uncertain.

Overall, though, it is difficult to assess quality adjustment only in terms of Tirole's theory. For one, it is not clear exactly what direction the adjustments, if any, have taken. True, there have been a few performance degradations as well as reliability issues. However, Hughes has actually exceeded contractual requirements in other areas. Also, it appears that AMRAAM's reliability has been steadily improving as the experience in the Gulf War shows. Interestingly enough, reliability is a classic case of demand separability as identified by Saving. Remember that when demand for a quality characteristic is separable from the demand for quantity the monopolist will supply the competitive level of the quality. Thus, in terms of Saving's analysis, the AMRAAM missile roughly followed the predicted outcomes, despite early reliability "teething" difficulties.

An interesting twist to Saving's analysis is provided in the following argument. To the extent that Hughes had proprietary knowledge of the AMRAAM missile we would expect that the company would under provide both reliability and durability. We already know that the monopolist will restrict output. Output is contractualy specified. Reliability and durability can both be thought of as being simply "more" of a product and are thus substitutes for the provision of quantity. It is therefore plausible that Hughes was using these substitute quantity mechanisms to effect its monopolistic tendency to underprovide quantity. Then, as Hughes transfered more of its technology to Raytheon, the cost functions of the two firms became more identical, satisfying Saving's other basic assumption. By the time of the Persian Gulf War most of the technology had already been transfered and we observe that, in terms of reliability and durability, the AMRAAM performed up to snuff. Obviously, there is a fine distinction between the normal evolution of any weapons program and Hughes' monopolistic adjustments. Any given complex weapon system can be expected to have its share of glitches early on.

Even so, I think Saving's results on this matter can be seen as robust.

The other area of theory which can be applied to the AMRAAM development history is Shrieves' conclusions on innovative activity. Shrieves concludes that under conditions where innovations are costlessly appropriable by other firms, a monopolistic market structure will provide greater incentives for innovation then a competitive one. Given the nature of the relationship between Hughes and Raytheon, innovative activity of one firm would immediately be acquired by the other firm. Recall that the Air Force has specified a leader/follower concept for its procurement strategy. Hughes has been forced to turn over its design for the AMRAAM to Raytheon. So far, all improvements to the missile have been made for the general design and are not company specific. Thus, for the APREP program, all improvements will be incorporated into the general design of the missile and both companies will benefit from the innovation regardless of who initially invented it.

It is not difficult to see that under these conditions the incentives to innovate would be relatively greater if the Air Force implemented a policy whereby Hughes and Raytheon were able to appropriate some of the gains from innovation. Innovative activity has not been inordinately low for the AMRAAM. The use of Very High Speed Integrated Circuits, the development of totally new testing equipment and the APREP program all point to a fairly high level of innovative activity. All this does not necessarily rule out Shrieves' conclusions, though. So far, the innovative activity has been toward the fulfillment of contractual obligations (as in the case of the high speed circuits) and for the purpose of reducing costs (as in the case of APREPs). In the first case the innovation came about more because of legal requirements then for economic reasons. In the second case, cost reductions are appropriable by both Hughes and Raytheon (although both companies would have their costs reduced if the Air Force kept up with its policy of technology transfer). The economic implication of this is that to the extent that Hughes and Raytheon continue in a leader/follower relationship, the incentives for innovation to gain market share will be limited. To the extent that the relationship becomes more competitive in the traditional sense, then we will probably see efforts on the part of both companies to differentiate their product through the use of qualitative improvements. It bears repeating, though, that Shrieves' assumptions must hold. The latter implication for product differentiation only holds if Raytheon and Hughes are able to appropriate most, if not all, of the benefits that accrue from new invention.

Finally, after reading of the seemingly endless string of developmental hiccups in the AMRAAM's testing it is difficult not to try and seek out some policy or economic condition in an effort to lay blame. Analyzed in this light, problems of the AMRAAM can be traced back to two basic issues. First of all, certain aspects of the Air Force's credibility in contractual enforcement should be called into question. In certain areas of contractual performance, such as technical specifications, the Air Force took a hard line stand. On other areas, such as meeting deadlines and certain testing conditions, the Air Force adopted a more realistic attitude. It is not surprising, then, that the slippages occurred in those areas where the contractual threat was the least credible. When Hughes ran past a deadline, a new one was simply re-negotiated. Even more troublesome, when Hughes had difficulty passing a test the missile was given a "little lift". This occurred when only three missiles were used in the initial fly off and in subsequent testing, as the GAO noted.[34]

Secondly, many of the bumps in the road can be attributed to technical issues. Air Force program managers and Hughes officials rightly noted that in any highly advanced weapons development program problems and delays will occur. The AMRAAM is a technical achievement of the first order. It takes all of the guidance requirements of semi-active radar missiles that previously were big enough to require mounting on the firing platform and squeezes that into a package 7 inches in diameter and a little over 12 feet in length. Indeed, so much equipment was crammed into the missile's guidance system that heat was damaging the system's electrical components.[35] The need to redesign some of these components using ceramic material and heat sinks was a major source of the early delays. This, and other technical malfunctions, have surfaced regularly and seemingly at random. Yet, one may ask, why has the Air Force insisted that technical problems have been minor? From a more cynical (but realistic) point of view, much of the explanation has to do with who controls the program's purse strings. The Air Force always wants to put on a good face in front of the public and Congress if it wants to keep a weapons procurement contract up and running. Admissions of insolvable technical barriers are a one way ticket to program cancellation. We can therefore interpret much of the Air Force's dogged persistence of the technical feasibility of AMRAAM in its desire to assure future funding.

IV. F-100 Fighter Engine Competition

The F-15 fighter was the most advanced that the Air Force had ever bought when it rolled of the production lines in 1974. It quickly set new records in terms of speed, power, and maneuverability. Many of these records still stand today and the F-15 continues to form the backbone of the Air Force's interceptor force. None of this would have been possible but not for the heart of this airplane, its engine. In able for the new airplane to set records, its powerplant also had to set new records in performance. As in the AMRAAM missile, a significant leap in the state of the art was required. As in the AMRAAM, the program ran into severe questions as to reliability, maintenance and overall quality.

The discussion for the F100 in this part of the paper will follow along similar lines as that of the AMRAAM. A case history of the program will be presented and then analyzed in the light of what we know from theory. Additionally, it will be instructive to draw parallels between the experience of the F100 with the AMRAAM as well as point out those instances when the two experiences have diverged. To what extent can we observe Pratt and Whitney, the engine's manufacturer, making monopolistic quality adjustments? After competition was introduced, ie.. another source was brought on line, to what extent did Pratt begin to provide the "optimal" level of quality? Obviously, the Air Force was not happy with Pratt's performance prior to the 1984 dual sourcing decision. A combination of reliability issues, perceived price gouging and what was judged by the Air Force as Pratt's recalcitrant attitude touched of the competition and resulted in what became known as the "Great Engine War."[1]

There are many similarities between the early stages of the F100 program (before the dual sourcing competition began) and the history of the AMRAAM's development. Like the AMRAAM missile competition, the final contractor for the F100 jet engine was chosen after the Air Force identified two companies with the technological know-how and then evaluated demonstrative prototypes based on performance parameters and the ability to meet design goals. It is significant to note that in both instances there were only two companies able, or willing, to meet the design challenges. In this case General Electric was the other company. While GE lost the first battle, it would ultimately return to take the final round of the engine war.

The F100 started off as a joint Air Force/Navy project. The Air Force wanted the engine for its F-15 and F-16 fighters while the Navy envisioned a derivative of the F100 (the F401) powering its F-14 fighters.[2] The Navy was an early drop out, though, due to program slow downs with the F-14. Unfortunately for the Air Force, the Navy dropped out after a price had already been negotiated for a set number of engines. With the Navy's absence the total number of engines to be procured dropped, raising the unit cost and necessitating renegotiation of the original contract. These renegotiations were performed in sole source conditions and resulted in a price increase of $550 million.[3]

Such a large price hike raises the question as to whether (as it is euphemistically referred to) Pratt was engaging in ex post opportunism. Simply put, was Pratt taking advantage of its position as the sole supplier of F100 engines to effect a transfer of the gains from trade to itself? The idea of opportunism by contracted parties was first formally introduced by Williamson in 1975.[4] The argument is generally stated as "...ex post bilateral monopoly plus bargaining yields under investment in specific assets."[5] Large firm specific investments represent large incentives to the other firm to engage in opportunistic behavior. An example: suppose a power company decides to invest in building a plant directly at the mouth of a coal mine. Suppose that a contract is negotiated by the mine and power companies for the delivery of coal. What would happen if the price was negotiated <u>after</u> the power company had already built its plant in front of the mine? It does not take too much imagination to see that the coal company would try to jack up the price as much as they could. The specialized investment on the part of the power company made them reliant on the coal owners who obliged themselves of the situation.

Even so, several non-opportunistic explanations have been forwarded to explain the increase in price. In defense of Pratt, it is pointed out that a smaller quantity of engines were being sold. Beyond the obvious cost increase due to overhead and learning curve technical efficiencies, the company had already negotiated contracts with all of its sub-contractors based upon the larger quantity. The Air Force's failure to buy this quantity meant that Pratt had to renegotiate all of its parts vendor contracts. So, part of the $550 million was a premium to reimburse Pratt on these renegotiation costs. This explanation does not account for all of the increase, though. If we take evidence of ex post opportunism by Pratt as a reliable indicator of its ex ante behavior, then the conclusion is that a large part of the increase was Pratt appropriating the Air Force's surplus. Pratt's letter of the law attitude toward the contract, its (as we shall see later) less than completely honest parts policy and its obstinate attitude toward fixing engine malfunctions all point to the possibility that Pratt was indeed engaging in opportunistic behavior. In terms of our example, the Air Force was the power company. The presence of a large specific investment by the Air Force in F-15 airframes made them dependent upon Pratt. The Navy dropped out, necessitating a price renegotiation, and the rest is history.

During initial component testing several factors worked against the Air Force getting a quality engine. From the very start it was decided to reduce the testing time for the turbine fan blades. These fan blades are possibly the most critical part in a jet engine since they spin at high velocities, are subjected to extremes of heat and pressure and often come in contact with airborne debris. Thus it is extremely important in an engine development program to establish the durability and reliability of these components. As is usually the case, though, determining the worth of a design's fan blades is quite costly in money and time. E. C. Simpson, former director of the Turbine Engine Div. of the Air Force Aeropropulsion Lab, notes that testing of a jet engine often means rigging it with hundreds of expensive sensors and subjecting it to many hours of valuable wind tunnel analysis.[6] When this fact is combined with the Air Force's need to push timely development of a program and demonstrate progress to Congress, it is not surprising that initial component testing often gets short changed.

Such was the case with the F100's initial testing. Fan testing was cut from 900 to 480 hours, compressor from 1,290 to 804 and combustor testing from 900 to 400 hours.[7] More problems arose when Pratt attempted its first Military Qualification Test or MQT in February of 1973. This test was stopped after 60% of it had been completed due to fan blade problems. Later, an explosion in March of the same year caused extensive internal damage to a test engine as it was being run in a simulated altitude test.[8] Meanwhile, as F100 engines began to self destruct, the development of the F-15 airframe was moving ahead as scheduled at McDonald

Douglas. At this point the Air Force came under intense pressure to finish validation of the F100. Any additional delays in delivery of the engine would slow down development of the F-15, the cost of which McDonald Douglas was able to pass on to the Air Force under the provisions of the airframe contract.[9] In response, Pratt made a subtle but very significant change in the test conditions. The change was made with the blessing of General Bellis, the Air Force program manager for the F100. Specifically, the change involved running the engine at Mach 2.2 at 40,000 feet instead of the contracted Mach 2.3 at 37,500 feet. At first glance this may seem like an even trade off since the engine was being run at a slower speed but higher altitude. However, the engineering fact of the matter is that by running the test at a higher altitude the pressure on the fan blades was reduced by 30%.[10] This lowering of pressure was critical in Pratt being able to successfully complete its second try at MQT.

If one views initial component testing as an accurate indicator of future engine reliability, then we can interpret the reduction in test standards as a direct proxy for the lowering of quality in the F100. The lowering of test standards in the F100 bears a striking resemblance to the same phenomena that was observed in the AMRAAM program. Once again the conclusions about quality adjustment suggested by Tirole hold up.

Remember that we hypothesized in the AMRAAM section the Air Force's internal valuation on quality decreased with quantity, or P_{sq} is less than zero. P_{sq} is the partial derivative of price demand with respect to quality and quantity. A negative value for this cross partial means that as more quantity is bought, less quality is demanded. For a given quantity this is the determining factor on whether or not a monopolist will under supply quality. With the withdrawal of the Navy from the F100 program, the number of engines to be bought declined significantly. With this reduction in quantity, there was a corresponding increase in the Air Force's internal valuation on quality. The "socially optimal" level of quality was negotiated prior to the reduction in quantity. Therefore, relative to this level, once the number of engines to be bought declined Pratt would necessarily under supply quality relative to the Air Force's ex post change in quality valuation.

Admittedly, many other factors were in play. The cost of renegotiating the contract absent the Navy meant that few, if any, additional funds were available for complete testing. As already mentioned, Air Force leadership was under the gun to validate the engine due to the F-15 airframe situation and Congressional pressure. Finally, Gen. Bellis was under a personal mandate from Deputy Secretary of Defense David Packard to avoid program delays and complications. Despite what may seem to be arguments against the Tirole explanation, the economic reasoning for

Pratt's actions remain strong. The early 70's were a time of rapidly expanding inflation. Manufacturers in general were loosing control of the pricing mechanism. With this loss of control, manufacturers, and Pratt, shifted their attention to those product characteristics which were under their control, like quality factors.[11] Between this factor, the reduction in quantity and the Air Force's resulting quality valuation, it is not too difficult to see how Pratt could have been able to manipulate its monopolistic position through qualitative adjustments to the F100 engine in the form of reduced testing and validation.

Three major problems were to afflict the F100 throughout the pre-dual source environment. Perhaps the most serious of these problems was stall stagnation. Stall stagnation occurs when air flow into the engine is either interrupted or disturbed to the point where the engine can no longer function. This causes a momentary "stall" in the engine which often results in shutdown. If the stall is not correctable by an adjustment in the airplane's flight path then it becomes a stagnation and the pilot must then attempt to restart the engine. By July 1977 the Air Force recorded a total of 223 stall stagnations in F100 engines and the number kept rising.[12] Fortunately for the F-15, it had two engines so the pilot could at least keep his plane in the air to restart the engine or make an emergency landing. Pilots of the F-16 were not so lucky. They had only one engine so it is easy to see how serious a problem stall stagnations would be for pilots of this fighter. When the Air Force went to Pratt to try and solve the problem, Pratt displayed more interest in profit generating contract changes than in meaningful design changes. Eventually, several stop-gap measures were implemented which substantially decreased the stall rate. But these measures also required additional maintenance burdens which the Air Force was unhappy to except.[13]

Further difficulties with the engine surfaced. Because the F100 was so clearly superior, in terms of what it was able to do than proceeding engines, pilots began to fly their airplanes in ways not envisioned before the engine's development. This resulted in a dramatic increase in the number of "duty cycles" that an engine was called upon to perform. A duty cycle is defined as any throttle movement which begins at idle, goes to full, and then goes back down to idle or an intermediate setting.[14] A duty cycle is very stressful on an engine because it means that the parts are quickly heated up and then cooled off again, causing thermal fatigue. The increased duty cycle use in the F100 caused cracking and failure of the turbine fan blades. During the F100's development, duty cycle issues were not well understood. Still, there is reason to conclude that Pratt, and the Air Force, chose to ignore what evidence there was. A prominent engineer in the F100 design warned of duty cycle problems but was not heeded. Moreover, the contract for the GE engine for the B-1 bomber which was issued at about the same time, did specifically set out stringent duty cycle requirements.[15]

Lastly, the incidents of stagnation and higher then planned for duty cycle resulted in a high incidence of turbine failure. Turbine failure is a military euphemism for blowing up. Air Force engineers attributed this problem back to cracked turbine blades. An interim solution was found through increased inspections. While this dramatically lowered the occurrence of turbine failures it also had the very predictable result of greatly increasing the burden on maintenance personnel.

A point to be made here is that these were all unanticipated technical contingencies. The engine that Pratt produced was so radically superior to all previous designs that the pilots pushed it very hard. I am not suggesting that Pratt, or the Air Force, should have been able to see all of these problems coming with 100% accuracy. The question to ask is whether the presence of these technical contingencies gave Pratt the incentive for opportunism. Another question to ask is how could have Pratt signaled its good faith intention for contractual performance. Are there things that Pratt could have done to credibly establish its intention to not engage in opportunism? Klein and Leffler suggest that there are. One way that they suggest which is especially applicable to our discussion is through what they call nonsalvageable productive assets.[16] If the seller can invest in capital equipment which can only be used for a particular productive process, then this signals to the buyer that the seller is committed to continuation of the relationship. As Klein and Leffler state,

> "In particular, if the firm uses a production process that has a a nonsalvageable capital element, the normal rate of return on this element of production capital effectively serves as a quality-assuring premium."[17]

The gains to be had from cheating on quality are now reduced by the amount that the seller spent on the nonsalvageable asset.

Expressed in this light, it is not clear whether Pratt ever did send out such signals. Much of the technology for building military jet engines is useful and substitutable for the civilian market and thus is salvageable. Pratt used much of the money that was supposedly being used for F100 improvements on other engines. Not only is there evidence of substitutability in Pratt but in GE as well. Drewes notes that the reason GE was able to provide an alternative was that the Air Force had already funded much of its development through the B-1 program.[18] GE was then able to transfer the technology from the B-1 engine to the F-15 engine alternative. Thus we see that substitutability of productive assets was not unique to Pratt but seems to endemic of the industry as a whole. A final observation on this has to do with the attitude Pratt projected towards its relationship with the Air Force. Much of what Pratt said and implied did not lend weight to the hypothesis that the company much needed the F100. Indeed, we have Robert Carlson, United Technologies vice president (the parent company of Pratt & Whitney), slinging the following stone at the Air Force,

> "[Regarding] the development of two new technology busting commercial engines plus a third engine being developed...Pratt's biggest concern right now is to get those three engines into the market. If the company succeeds, it won't mean a tinker's goddamn whether the F100 stays or goes, not a damn thing."[19]

Given this, we may conclude that there is large body of evidence suggesting that Pratt was not credibly committed to the continuation of the F100 contract and therefore had that much more incentive to behave opportunistically. One area where such activity plausibly occurred was Pratt's spare parts contracting.

Pratt & Whitney's spare parts policy was very questionable. Under the original contract, Pratt was entitled to additional funds from the Air Force under a program known as the Component Improvement Program (CIP). According to Drewes the program was used to, "...cover improvements to such performance characteristics as reliability, maintainability, durability, and operability..."[20] The cost of the CIP was quite high. By 1980 the Air Force had already spent $419.3 million. This money was separate from the money the Air Force spent on spare parts which in 1983 alone amounted to $600 million.[21] By 1983, Pratt's spare parts policies came under heavy fire. At the top of the list was exactly how Pratt spent the money allocated to it under the CIP. Much of it, instead of being used to fund component improvements in the F100, was used to fund development of other engines at Pratt. This is another example of the salvageability of productive assets at Pratt. The argument is made that the work on other engines served to bring about improvements to the F100 through spin-offs. This only serves to reinforce the hypothesis that Pratt was able to transfer its military technology to the civilian market. Other practices which bothered the Air Force included Pratt's policy of forcing the service to buy 80% of its spare parts directly from Pratt instead of going directly to the parts vendors. This became known as the "80% solution".[22] Admittedly, the provisions in the F100 contract that made this possible were Pentagon approved. It is obvious, though, that Pratt was taking advantage of the situation. In 1982 Robert Hancock, a senior civilian contracting officer for the Air Force, uncovered 34 different parts that had quadrupled in price since 1980.[23]

Much of what we observe in Pratt's spare parts policy can be explained in light of Shrieves innovation analysis. In contrast to the AMRAAM case, Pratt definitely had full appropriability of all the gains to be had from innovation. Indeed, Pratt's position was guaranteed by its contract with the Air Force. Under Shrieves' conclusions, the monopolist will therefore produce relatively less innovation then the competitive firm. Recall that the reasoning for this is that under conditions where firms may appropriate all of the potential benefits of innovation, the proper incentive structure is in place for competitive firms while the monopolist's realization economic profit is an opportunity cost. This does appear to have been the case. Despite the millions of dollars that were supposedly used for the purpose of component improvement, stall stagnations, turbine cracks, and turbine failures continued to be problems all the way until 1984 when GE was awarded a lion's share of new engine buys. Some design changes did come about to try and solve these problems. But the most significant changes were those that involved increased maintenance efforts on the part of the Air Force. These are hardly ideal solutions. Note, as well, that Pratt devoted substantial effort into obtaining cash revenue from the Air Force. Such effort took the form of adhering to the strict letter of procurement contracts and exerting control over spare parts acquisition. Given this activity, it is reasonable to suggest that Pratt was indeed generating large amounts of monopoly profit. If one accepts Shrieves' conclusions, the presence of these large profits represent an opportunity cost which inhibits the monopolist from innovation. The spare parts conundrum, combined with the reliability problems already discussed, finally drove the Air Force to seek an alternative to the Pratt F100 design in late 1982.

The story of GE's bid to unseat Pratt begins in March of 1979 when the Air Force agreed to fund initial development of a derivative of GE's F101 engine then being used in the B-1. After some budgetary wars in Congress, funding was finally approved to pursue GE's design. This took the form of a Request For Proposal (RFP). An RFP is an official request by the government to contractors for the supplying of a procurement item. RFPs for the F100 alternative were sent out in Aug of 1981 and by the end of the year the response was so good that the Air Force decided to go ahead with plans for a competition.[24] In contrast to the AMRAAM's story, GE's alternative was a completely different design then the F100. Despite this, it was substitutable for the F100 in the sense that it would fit both the F-15 and F-16 and still meet all technical specifications. The RFPs were strictly voluntary in nature and did not involve technology transfers as in the AMRAAM. The Air Force also did not pre-commit itself to any distribution of the award. Both Pratt and GE were aware that they could be awarded none, all, or part of the final contract.

Now that a fire had been lit underneath Pratt, the company began to make considerable strides in finally improving their engine. In late 1982 Pratt submitted an unsolicited proposal to the Air Force for a substantially improved F100 in trade for a suspension of the competition. The proposal bound Pratt to a fixed-price contract in which many qualitative improvements to the engine were promised. These promises were backed up by warranties and guarantees. Estimates of cost savings to the Air Force ran around $3 billion.[25] It is interesting to note that one year of competition achieved what six years of Air Force badgering and spending could not in the sole source environment. While Pratt's proposal was revolutionary, the Air Force decided to hold out and see what additional gains could be had from a showdown.

In defense of Pratt, we can twist our opportunism story around to suggest that the Air Force was at this point behaving this way. Pratt would certainly make the argument, and with much justification, that they were supplying the correct level of quality. There is no argument that the engine met or exceeded the vast majority of technical requirements. As we have seen, though, perhaps the most important specifications were missed. Once the Air Force realized this, it went about seeking a second source. Just as Pratt tried to appropriate rents from the Air Force during the contract renegotiation, so did the Air Force later on try and appropriate back these rents by insisting that Pratt effect improvements to the engine and threatening the company with a substitute source.

By 1983 competition for the bid was intense. Both companies scrambled to make final changes to their respective designs while mustering support on Capitol Hill. Pratt, in particular, played hard ball politics with many members of Congress and DoD officialdom. Lowell P. Weicker, Senator in whose state of Connecticut the Pratt & Whitney engines would be built, was obviously influenced by Pratt's lobbying as he called for a GAO review of the decision, even before the final decision was made![26] The intensity with which both GE and Pratt went about their business immediately before the Air Force's decision serves to underscore the level of competition which took place. Compared to the "war" which took place between Pratt and GE the competition between Raytheon and Hughes looks fairly tame in comparison. Another point which deserves emphasis is that the Air Force focused largely on reliability and maintenance issues while down playing performance increases. The Air Force's RFP specifically called for all proposals to contain warranty provisions and specified that all designs be guaranteed for not less than 3,000 duty cycles.[27] Finally, on the third of February in 1984 the Air Force announced that GE would be awarded a split buy of 120 engines out of a total of 160, or 75%. GE had effectively rested sole control of the jet fighter engine market from Pratt & Whitney.

Did competition result in a qualitatively better engine? The answer to this question has to be yes. Both designs offer unrestricted use of the duty cycle, are much more maintainable, and contain extensive warranty provisions as well as improved performance. Problems with stall stagnation have been all but eliminated. Furthermore, the competition is not a one time affair. Every year the Air Force re-evaluates each engine in light of any design changes and awards new percentages to each contractor. It was not until three years after the first award in 1984 that

Pratt finally managed to win back a majority percentage of the contract.[28]

The competition which took place between GE and Pratt was real. The present relationship between the two contractors continues to be that of dual sources. These points cannot be emphasized too heavily and are in direct contrast to the experience of the AMRAAM. GE and Pratt continue to do battle with each other every day in the jet engine market place. When, in Nov. of 1987, GE offered an advanced F110 for the F-16, Pratt shot back eight months later with an improved thrust version of its F100-200 (the engine developed during the initial competition).[29] Prior to the introduction of dual sourcing, qualitative problems with the F100 engine cost the Air Force millions of dollars a year. Money spent on innovation in the form of the Component Improvement Program produced little in the way of substantial technological improvement. Now that GE has been brought on line the jet fighter engine market has seen a greatly increased rate of innovative activity and has been marked by continual strides in reliability. Both of these observations square well with the conclusions suggested by Tirole and Shrieves.

Lastly, according to Klein and Leffler the presence of a price well above the minimum average operating cost of the supplier should have been enough to guarantee contractual performance. Remember that by assuring the supplier with a stream of economic profit the buyer may "bribe" the seller into contractual adherence. On one level Klein and Leffler's conclusions were borne out in the case history. Pratt & Whitney never violated the specific letter of its contract. The Air Force never charged that they did. The issue was whether Pratt would fix unanticipated engine malfunctions. Many of the things that the Air Force was asking Pratt to do were never explicitly obligated by the contracts. Yet, as we examined previously, on another level Pratt & Whitney did a fairly poor job of signaling its willingness to the Air Force to continue its contractual relationship.

V. Conclusion/Policy Implications:

After reviewing the case histories of the AMRAAM missile and the F100 engine and reviewing them in the light of economic theory a few general observations may be made. First of all, in both cases the presence of a single manufacturer (or its de facto presence as in the AMRAAM) led to considerable problems. For the AMRAAM, program delays, botched tests and continual re-design were the order of the day. For the F100, the basic problem of stall stagnation resulting in turbine blade failure continued to dog the engine until GE was ready to introduce an alternative. It would therefore seem that the introduction of any amount of competition is a very powerful incentive for the firm. Much has been written on whether the introduction of competition (more specifically, introducing a second source) is always the most cost effective way of doing business. The point is that the initial costs of qualifying and administering a second source often out weigh any potential gains in lowered costs. This is a point well taken if the Air Force must identify the second source and "bring it up to speed". However, if the second source develops a competing technology on its own, as in the F100, then the initial costs are much lower and are almost certainly outweighed by the potential benefits.

The other alternative is for the Air Force to actively pursue the qualification of second sources either through paying for up front capital and research expenditures or by transferals of technology. The AMRAAM missile is a case when the Air Force attempted the latter strategy. Thus far, the performance of the leading technology, Hughes, has been suspect at best. Evaluated in terms of economic theory, technology transfers are not a very efficient means of competition. One, the following technology acquires whatever defects afflicted the leader, and two, all the wrong incentives are broadcast to the leader. One can expect with a high degree of certainty that the leader will not invest in those technologies which would require a large initial investment. In fact, the only innovations that the firm would have the incentive to produce would be those that result in lower costs (assuming a fixed price contract) or those that the firm is under a legal obligation to produce because of contractual performance requirements.

The situation is a classic case of a positive externality. An apple tree in a person's front yard creates a benefit for all of the children in the neighborhood. Unless the owner of the tree is able to appropriate some of the benefits of having the apple tree then chances are that he or she will not take care of it. An exactly analogous situation exists in attempts at technology transfers. The firm's innovation results in a positive benefit accrued to the Air Force. If the firm does not realize any gains from the innovation then there is no incentive to innovate in the first place. Nothing in my research indicates that the Air Force intends to directly compensate Hughes for any of the technology it transfers to Raytheon. Indeed, the Air Force expects Raytheon to use the same technology that Hughes gave it to compete with Hughes. Obviously, Hughes is aware of this. There is certainly a strong incentive on the part of Hughes for opportunistic behavior in the technology transfer. "Yes, Mr. Raytheon, just connect these two wires to the warhead...." Viewed in this light, the Air Force's policy appears questionable at best. To the extent that innovative activity is a proxy for quality, Hughes' disincentives for innovation have contributed to the qualitative problems experienced in the AMRAAM so far. A more economically rational policy would have been to give Hughes some kind of licensing fee for its technology. Hughes would have then been able to appropriate some of its benefits.

The key to understanding the F100 history is that the relationship between GE and Pratt & Whitney is probably about as close to true competition as defense procurement is ever going to get. Both firms are heavily involved in the civilian market. To a large extent, the technology between civilian jet engines and military engines is substitutable. The presence of the civilian market meant that developments in the military technology could produce "spin offs". Spin off potential represents an appropriable pool of positive economic profit. In direct contrast to the AMRAAM missile, GE developed its competing design without help from Pratt. Pratt and GE continue to vie for leadership. The result has been that the F100 has been transformed from a finicky piece of high tech gadgetry to a tough, reliable workhorse that handled the rigors of desert warfare with relative aplomb.

After reviewing the theory and studying the program histories, I believe that strong incentives exist for the under provision of quality in single source environments. The defense market is characterized by ever smaller amounts of higher quality goods. Such a phenomena is directly explainable by Tirole's demand analysis which suggests that the monopolist will under provide quality. The presence of appropriable benefits in innovation again mean that the competitive firm has relatively greater incentives to invent, using Shrieves' conclusions. Lastly, since both reliability and durability are basically more of a particular good and separable in demand from quantity, we know that the monopolist will use these characteristics to restrict his or her true output.

Notes for Sections I & II

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[11] Saving, S.E.J., 863-865.

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[14] Shrieves, J.I.E. 332.

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[9] Griffiths, 1 Dec. 80: 138.

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[16] Kozicharow, 16 July 1984: 23.

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