FIRST INTERIM REPORT ON PROJECT HINDSIGHT (SUMMARY)

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1. INTRODUCTION

Project HINDSIGHT is a study of the recent science and technology which has been utilized by the Department of Defense in weapon systems. As a consequence, the focus is primarily on the physical and engineering sciences and related technologies. Consideration of contributions from the life, behavioral, or environmental sciences is peripheral.

The study is retrospective in character because the criteria is proven utilization and it is likely that delays of 5 to 10 years, or more, frequently occur between a scientific discovery or an invention and the time of its practical utilization. The effort has two basic objectives: (1) to identify and firmly establish management factors for research and technology programs which have been associated with the utilization of the results produced by these programs; and (2) to measure the overall increase in cost-effectiveness in the current generation of weapon systems compared to their predecessors (when such can be identified) which is assignable to any part of the total DOD investment in research and technology.

The project has been underway for 2½ years and is planned to continue. During the first 1½ years, pilot studies developed and established the techniques of analysis. Throughout the past year, teams of in-house scientists and engineers, working with the voluntary support of contractors, performed the bulk of the data collection. We estimate that about 40 professional man-years were used in collecting and analyzing the data reported here.

2. THE METHOD OF ANALYSIS

The method of analysis has the following steps:

a. A recent weapon system or end-item equipment which is either already in the inventory or is committed to the inventory is selected for study.

b. A team of 5 to 10 scientists and engineers selected for their expertise in the area of the subject system is appointed.

c. The team dissects the system into its subsystems and components to assure systematic analysis, and then identifies each contribution from recent science and technology which, in their judgment, is clearly important either to increased system performance or to reduced cost, compared to a predecessor system when such can be identified. For those cases where no predecessor exists, the contributions (primarily 1945 to date) are those which are judged to be essential to the attainment of a successful system. In making these judgments, the analyzing team worked with the principal contractors involved in the engineering development and production of the system.

An example of such an identified contribution would be the development starting in 1949 of the titanium-aluminum-vanadium alloy used in the compressor blades of the turbo-fan engine in the C-141 transport aircraft. The high and uniform strength-to-weight ratio, the corrosion and erosion resistance, the notch-toughness and creep resistance of this material substantially increased the efficiency and reliability, and reduced the weight and extended the life of the engine compared to what it would have been had one used the steel blades employed in the turbine engine which drives the propellers on the C-130A aircraft (the predecessor system).

d. Once a contribution has been judged to be significant, it is assigned to one of the team members for further study. He identifies the individuals who were the principal contributors, the organizations with which they were working at the time the work was done, the date when the feasibility or practicability of the idea was first demonstrated, the nature of the work (science or technology), the objective of the work, the approximate cost, the funding sources, etc. This material is written up in a uniform format and becomes a part of our permanent data bank of utilized science and technology. We believe we have demonstrated that, with reasonable effort, one can trace the origin of a contribution to a specific time and to particular people. Consider again the example of the titanium alloy used in compressor blades, mentioned above. The development of this alloy was the result of the efforts of individuals in three organizations. Some of the basic work was done in 1949 and 1950 at the Armour Research Foundation, supported by the Army and the Air Force, for military applications. At about the same time, further work was performed at the Battelle Memorial Institute funded partly by the Air Force and partly by industry (the Remcru Titanium Corporation). Over the next 10 years, Remcru and others carried the alloy developed for them at Battelle into production and thus it was available for use in the Pratt and Whitney turbo-fan engine used in the C-141, where we identified it. This material is known to have many other military and commercial applications as well.

It is important to note that this technique is selective in identifying the contributions from recent science and technology. The many important contributions which pre-date the World War II period are not included; nor are the countless results of research that, although indistinguishable in themselves, contribute to the pool of general knowledge of scientists and engineers from which ideas are drawn.

3. DEFINITIONS

Each discrete, identified contribution is called an Event. The duration of an Event includes the period from the conceiving of an idea to the initial demonstration of feasibility or validity. The date of an Event is the end of this period.

In order to provide uniformity of reporting and to facilitate analysis of the data, the following definitions were established for the classification of research activities and for the ascribing of motivation to the identified contributors.

Science: Theoretical and/or experimental studies of new or unexplored natural phenomena.

Science Events are divided into two categories which are determined by the objective of the work:

(a) Undirected Science, in which the objective of the work is the advancement of knowledge for its own sake, without regard for possible application, and

(b) Applied or Directed Science, in which the objective of the work is to produce an understanding of phenomena or specific knowledge which is needed for some particular application or class of applications.

Technology: The conception and/or demonstration of the capability of performing a specific elementary function using new or untried concepts, principles, techniques, or materials, or

The measurement of the behavior of materials and equipment as required for design, or

The first demonstration of the capability of performing a specific elementary function, using established concepts, principles, or materials, or

The development of new manufacturing, fabrication or processing techniques.

The definitions of science make the work substantially synonymous with the current DOD category of Research (6.1), and the definitions of technology make the work substantially synonymous with the current DOD category of Exploratory Development (6.2).

The term "recent" or "new", as applied to science or technology, generally implies "post 1945". However, if an item of science or technology was known to have been used in a predecessor system, "recent" implies an incremental contribution to that science or technology after the engineering design date of the predecessor.

4. THE SYSTEMS STUDIED

Figure 1 lists the 20 systems studied, the number of Events which have been fully analyzed and are included in the present data bank, and indicates the predecessor system, if any. 15 of the 20 systems contributed a total of 638 Events, of which 556 are distinct. That is, 82 Events were identified through more than one system.

The selected systems represent a fairly balanced sample of different types of military equipment.

The list of Events for each system is not exhaustive, but rather contains those Events which the team judged to be most important. The teams estimate that they studied between 30% and 90% of the Events (depending on the system) which, in a more extensive study, would be found worthy of analysis.

We have considerable confidence in the present sample of 556 Events since the properties of the sample have not changed substantially from the time that the data base had less than 100 Events taken from 7 systems.

5. PRINCIPAL FINDINGS

Based upon 556 documented Events in 15 weapon systems, we state the following findings:

a. The Number of Events Per System - A large number of significant science and technology Events (50 to 100 or more) is readily identified as being utilized in the larger systems (reference Figure 1).

b. The Importance of the Events - In the judgment of the technical analysts, it is the synergistic effect of these many Events which is the primary source of the increase in performance or the reduction in procurement cost of the system compared to its predecessor. Without most of the other Events (or their equivalent), any one Event or even a small number, would make little, if any, contribution to a particular system.

c. The Time Distribution of Events - For those systems which have an identifiable predecessor (8 systems, 75% of all Events), the great majority of the Events utilized did not exist at the time the predecessor system was committed to engineering development. This situation can be seen in the Figures referenced in the following paragraphs.

Figure 2 shows the time distribution of the Events in the MK 46 torpedo. The early stages of this program preceding formal development were guided by a well organized technology and system-concept program--the RETORC program. Note that only 11% of the Events judged essential to the performance of the MK 46 existed at the time of the MK 44 prototype. Note also that in spite of the existence of a well organized technology and system-concept program, 19% of the Events occurred after the system design contract was signed--primarily a consequence of changing specifications from the Mod 0 to the Mod 1.

Figure 3 shows the time distribution of the Events in the MK 56-57 mines. This mine development was unusual in that it had an extended stage which corresponds to what we now know as advanced development, culminating in a pilot production of over 100 working models which were used in an exten ive test and evaluation. The drawings were "released for production" in 1958, but regular production was not funded. Between 1958 and 1960, the specifications were changed (the required maximum operating depth was doubled), and in 1960, a production contract was let to the new specifications. Again we see the consequence of a change in specifications: new steels, new methods of sealing leads, and many other innovation changes were needed to make the system useful, and largely account for the 19% of the Events which followed the 1958 release date.

Figure 4 shows the time distribution of the Events in LANCE. For this system, the percentage of Events (42%) following the engineering development contract date, is somewhat above average. In this system, no complete working model had been made before commitment to engineering development. Indeed, in some cases, important subsystems had not been assembled or flight tested.

Figure 5 shows a composite distribution of all systems in which the year zero is the engineering development, system design, or production contract date, whichever came first. Note that, for the 8 systems with identified predecessors, the average predecessor date was earlier by 13 years. We see that only 11% of all the Events occurred 13 or more years before the system being analyzed was designed. Of the Events in this 11%, however, many were not really available to a predecessor system inasmuch as the date of an Event is defined as the "demonstration of feasibility" and, in most cases, considerable further work is needed before the system engineer can confidently include the results into an engineering design.

We note that 37% of the Events occurred after the system was committed either to engineering design or to production--a fair number occurring even 4 or 5 years later.

The time-normalized Event distribution plot of Figure 5 has an interesting form which is probably significant to understanding the RDT&E process. The Events start accumulating about 20 years before the system design date, at a rate which increases steadily. About 2 years before the system design date, the rate of Event production nearly doubles. Following the design date, the rate drops fairly rapidly, reaching a negligible level only after 6 or 7 years.

d. Performing Organizations - The 556 Events were performed by approximately 300 different organizations, sometimes alone and sometimes in a joint effort, in which case credit was shared between the organizations. Our file contains a list of 1,025 people listed as the principal contributors.

We find (see Figure 6) that over the entire period covered by the study, 39% of the Events were performed in DOD in-house laboratories, 49% in industry, 9% in universities, including the research contract centers, 2% was performed in non-DOD Federal laboratories, and less than 1% in foreign laboratories.

It is clear that although the in-house laboratories have made a substantial contribution the relative importance of the in-house laboratory has been declining. As Figure 7 shows, the proportion of Events coming from the in-house laboratories has decreased gradually from about 60% in the early 1940's to about 30% in the last few years. However, this is not necessarily to the discredit of the laboratories. During the 20-year period covered by the study the national scientific and technological community essentially quadrupled in strength while the in-house laboratories were constrained to a growth of about a factor or two. The consequence of the in-house growth is reflected in Figure 8 which shows that there has been about a doubling of Events produced per year in-house as the professional manpower increased.

The university contribution was approximately constant during this period and, therefore, industry has made the relative increase. This is consistent with the fact that industry has enjoyed the greatest increase in funding and in relative funding.

e. Funding - An examination of the funding source for each Event shows (see Figure 9) that DOD direct funding was by far the largest source (87% of the Events). Defense industry (either from profits or from IR&D allowable overhead costs) funded 9%. Thus, one can say that in a very real sense 96% of the Events were funded by dollars appropriated for purposes of defense.

We were surprised to find that non-defense industry funded only 2% of the Events. Further, most of these are the series of 8 Events performed at the Bell Telephone Laboratories on the early development of the transistor. We have classed this organization as commercially-oriented, although for many years it has also been one of the largest defense contractors. The transistor Events have probably significantly affected more types of defense equipment than any other Event or set of related Events.

Another Event of widespread importance to defense which we include in the industrially funded category is the welding of aluminum. (The barrel and chemical container industry was primarily involved.) A close examination of this Event discloses, however, that in the early stages, it received substantial support from the Manhattan District and also from the Navy.

These examples illustrate the fact that the value of Events to defense may differ widely. Thus, simply counting the number of Events in a particular category is only a first-order approximation to the value attributed to that category.

f. Average Cost Per Event - As we have already noted, an Event is regarded as completed at the time that feasibility is first demonstrated. By this definition, the median cost of an Event was found to be about $40,000. However, there is almost inevitably a subsequent cost to carry the idea to the point where it can be used with confidence in engineering design and production. In a small number of cases (15), we have been able to also estimate this subsequent cost and have found that it usually varies from 10 to 20 times the initial cost. In the titanium alloy example, the initial stage of the Event at Armour Research Foundation cost about $50,000 but the subsequent development (industrially financed, in this case) cost well over $500,000.

g. The Objective of the Work Leading to an Event - Finally we turn to a particularly important aspect of the environment surrounding the production of an Event: We ask, what was the objective? This is an important question since it gets at the process by which science and technology are "coupled" to application. We believe the best (and probably the only) way to get at the objective is to personally query the key individuals who either performed the work or were closely involved in its supervision. In 90% of our data base, we have been able to identify the objective or motivation as it was perceived by the participants.

Before discussing the data relating to the Objectives, we find that it is desirable to first categorize the Events as either Science or Technology. This matter can be determined fairly objectively from the nature of the work. In the Science category, the primary result is new knowledge and is similar to the work supported in the present DOD category of Research (6.1). In the Technology category, the primary result is an improved technique, material, component or subsystem, and is characteristic of the work supported in the present DOD category of Exploratory Development (6.2). In the past, and even in the present, much work of this type is associated and funded integrally with the system development process. In this case, it is commonly known as Supporting Technology. However, in categorizing Events as Science or Technology, it is the nature of the work which is determining, not the nature of the funding source.

We found (see Figure 10) that 8% of the Events are categorized as Science and 92% as Technology.

Of the Science Events, the great majority (6.2% of all Events) were applied research, clearly oriented toward a DOD need. Most of the balance (1.5% of all Events), was applied research with a commercial objective. (These were the 8 Events in the transistor sequence at the Bell Telephone Laboratories.) Only two Science

Events (.3% of all Events) were identified that appeared to have a minimum relation to any applied objective. They were the early development of the shock tube at Cornell University and a project in statistical sampling at Wayne University. Incidentally, both of these Events were funded by ONR in the late 1940's.

In the technology category, we find that a substantial number (25% of all Events) had as their objective the development or advancement of "generic DOD-oriented technology." This is technology aimed at a broad category of defense needs and not the needs of a particular system or system concept, such as higher power components for radars, improved explosives, more efficient solid propellants, titanium alloys, and general purpose electronic components. We find that very frequently--in about 75% of the cases--the focus and spur, and often the funding is provided to the technologists by one or more systems under development. Therefore, we could reduce the 25% figure for generic technology by 19%, adding it to the advanced development and system development categories without justifiable challenge. However, the breakout as shown is intended, additionally, to offer an indication of how much of the newly developed technology is inherently multi-useful.

The biggest single source of motivation for technology innovations (46% of all Events) is a system or system-concept in what we would now identify as the Advanced Development stage. In addition, we identify 18% of all Events as being motivated by a DOD system in the stage we now call Engineering Development. Thus, a DOD sysem need motivated 64% of all Events.*

Finally, we note that only 3% of all Events were motivated by a need in a non-DOD end item.

If we identify in Figure 10 the Events which were motivated by a clearly perceived DOD need, we see that they add up to 95% of all Events, and of this 95%, half were motivated by a system in what we now call the Advanced Development stage.

h. <u>Need-Recognition and Technical Initiative</u> - Since it became clear early in the study that technological innovation was highly correlated with need-recognition, we collected additional information about this process. In particular, we separately determined for all technology Events (92% of all Events) the origins of the need-recognition step and of the technical solution itself. We found

* There appears to be no way of finding out with any accuracy what fraction of DOD funds expended over the past 10 to 20 years in the category of science and technology were expended under the condition that the performing organization was primarily exposed to a need in DOD generic technology, a need of a system in the advanced development stage or a need of a system in the engineering development stage. Budget categories are not a reliable indicator of this condition.

that in only 15% of the cases the need was first recognized by the performing research group itself, whereas in 85% of the cases the need was first recognized either by an applications engineering group or an external group associated with the system being considered (a "systems group").

We further found that, where the need was first recognized by the performing research group (15% of the cases), this group was invariably also responsible for the nature of the technical solution. However, even in those cases where the need was first recognized by a "systems group" (85% of the cases), the initiative for the technical solution was still found to be primarily (72% of the time) the sole responsibility of the performing research group, and in the balance of these cases the technical solution was shared by the research group and the "systems group."

Stating the same figures another way, we see that the nature of the technical solution was determined solely by the performing research group 76% of the time and was jointly determined with a systems group 24% of the time.

i. Summary of Findings

(1) Many Events (50 to 100) which are innovations in science or technology, are utilized in a typical advanced system.

(2) These Events are the primary source of the increase in performance or the reduction in cost of the system compared to its predecessor.

(3) The Events begin accumulating about 20 years before the engineering design date of the system which utilizes them. The rate of production increases steadily to a peak one or two years before the system design date, and then decreases gradually reaching zero about six years after this date.

(4) 39% were performed by in-house laboratories, 49% by industry, and 9% by universities. The in-house laboratory contribution has been dropping steadily with time to a recent level of about 30%, due, at least in part, to reduced relative funding and staffing.

(5) 96% of the Events were funded by defense appropriations (directly by DOD 87%, or indirectly by Defense industry 9%).

(6) The median cost per Event to the point of initial demonstration of feasibility was about $40,000. Subsequent costs, necessary to carry the Event to final utilization, appear to be 10 to 20 times this amount.

(7) A clear understanding of a DOD need motivated 95% of all Events. (78% of all Science Events, and 97% of all Technology Events)

(8) For Technology Events, the recognition of need occurred primarily in a "system group" (85% of Events), whereas the technical solution itself was determined primarily by the performing research organization (75% of Events).

6. CONCLUSIONS

In the previous section we have presented the principal facts established by the study and have avoided, as much as possible, the drawing of any inferences. We now wish to extend the discussion to include certain conclusions that appear to be well supported by these facts. Before doing so, however, it is necessary to make two caveats. First, the simple counting of the number of Events in a specified category, as though all Events had equal value, allows only a first-order approximation of the true value of the sum. The recognition of this fact is particularly important in an attempt to make precise estimates of the relative value of a set of Events produced by one source as compared to a set of Events produced by another source.

Second, in some categories, the sample size is quite small and large statistical errors are to be expected.

With these reservations in mind, we can proceed to an interpretation of the factual findings.

Several significant conclusions regarding the system development process as it has been practiced over the past two decades, can be drawn from an examination of the time distribution of Events. As was demonstrated in the composite time distribution of Figure 5, the innovations for a given system begin nearly 20 years before the system design date, but only 11% have accumulated at the 13-year mark, when, on the average a predecessor system was designed. The Events are produced at a steadily increasing rate up until a year or two before the system design date, at which time the rate of production appears to increase significantly. Following the design date the Event production rate drops steadily but does not reach zero until about six years have elapsed.

Our first conclusion is that engineering design of military weapon systems primarily consists of skillfully selecting and integrating a large number of innovations so as to produce, by synergistic effects, the high performance demanded. It appears to us that the rate of accretion of useful innovations paces the time separation between successive systems with a given performance differential. A utilized innovation can occur only when there is a conjunction of three elements: (1) a recognized need; (2) competent people with relevant scientific or technological ideas; and (3) financial support. A deficiency in any one of these elements is therefore the pacing factor in the production of any given utilized innovation.

Second, we conclude that the 37% of the Events which occurred after engineering design was initiated were necessary to the ultimate performance of the system. The process of selecting and integrating a large number of innovations is highly creative and the interactions of the many innovations are frequently very complex and difficult to anticipate. We believe that these late-appearing Events were largely not predictable in advance. In addition to those attributable to the unexpected interactions between innovations some were due to new insights generated in the intense process of system design that offered higher performance or reduced cost. Still others were the consequence of the escalation of formal requirements or specifications in the absence of a proven technological base for their attainment. Whatever the reason it appears that an effort to actually build and operate a complete, working system (not just produce a paper design) generates a burst of innovative activity.

Third, we conclude that at the time of its design the predecessor system was technology-limited. This follows from the fact that on the average only 11% of the science and technology (Events) utilized in the successor system existed at the design date of the predecessor, and many of these were not yet in the state to be used with confidence in engineering design. (In some cases predecessor systems are substantially upgraded over their initial models by retrofitting advanced components based on new technology. Thus, in our example to be discussed later, the C-130-E (1964) has a substantially improved performance compared to the C-130-A (1954), but is still inferior to the C-141-A (1964) which used even more new technology than the C-130-E.)

Fourth, we conclude that the relative efficiency of production of science and technology Events which have been utilized in defense is substantially higher when funded and managed by the Defense Department or defense industry than it is when funded and managed by the non-defense sector of government or industry.

We draw the first support for this conclusion from the funding data in Figure 9, where it is shown that the defense sector funded 96% of the Events, and the non-defense sector funded only 4% of the Events. We estimate that from 1945 to 1963, the defense sector expended about 60% of the U.S. funds in the category of science and technology and the non-defense sector about 40%. Thus, per dollar invested in scientific and technological effort, the defense sector produces many more defense-utilized Events than does the non-defense sector. In particular, the ratio,

$$\frac{\text{(defense-utilized Events produced)}}{\text{(defense-funded and managed research)}} : \frac{\text{(defense-utilized Events produced)}}{\text{(non-defense funded and managed research)}}$$

is

$$\frac{96\%}{60\%} : \frac{4\%}{40\%}$$

or

$$16 : 1$$

That is, science and technology funds deliberately invested and managed for defense purposes have been about one order of magnitude more efficient in producing useful Events than the same amount of funds invested without specific concern for defense needs. Thus, we see that although technological "spin off" into defense weapon systems from the non-defense sector exists, it is very small, and it is quite inadequate to produce the number of innovations needed to make possible the large increases in performance which have been attained.

Our second support for this conclusion is drawn from data on objective or motivation of Figure 10. There, we noted that of the utilized science Events, 75% were motivated by a DOD need as understood by the principal investigators, and of the utilized technology Events, 97% were motivated by a recognized DOD need. It appears that the great majority of defense-utilized Science and Technology Events were the result of a deliberate and successful effort to couple the innovation to the real problems of defense.

We believe that to a considerable degree this conclusion is the logical consequence of the first conclusion which states that it is the synergistic effect of many innovations which produce large improvements, for, in general, an invention has to "fit in" as a part of a system or system-concept along with 50 or 100 other inventions. Hence, innovators, particularly technology innovators, who do not understand the current and anticipated needs, are less likely to produce ideas which are useful. This logical inference is further supported by the data in Figure 10. There we observed that 64% of all the Events had as motivation a DOD system or system concept.

Further insight into understanding the reason why Events funded and managed by defense occur with such a relatively high frequency may be obtained by considering the data in Finding (h). There we observed that for technology Events need-recognition occurred within the performing research organization in only 15% of the cases. In the great majority of technology Events (85%), it required a "system group" of some sort to first perceive and state the need. Thus, since a "systems group" for a defense system is almost invariably closely associated with a defense program, the resulting technology is also similarly associated.

Fifth, we conclude that, in the systems we studied, the contributions from recent (post 1945) research in science were greatest when the effort was oriented. In order to examine the consequence of allowing the scientist to select the problem area to be investigated as an alternative to selection of the area by management, two classes were defined within the study: "Undirected Research", that is, nonoriented research, and "Applied Research", that is, research directed toward the timely gaining of knowledge in areas of specific interest to the sponsor. As used here, these terms are meant to describe the motivation of the research scientist rather than the nature of the work in which he is engaged. For example, we have classified as "Applied Science" a very fundamental and important series of eight transistor-associated basic scientific events occurring at the Bell Telephone Laboratories. We believe that these events are classified correctly because they occurred in a mission-oriented environment and were clearly in support of the mission.

There is no question that over a long time scale undirected research has had great value. The sequence of contributions in atomic and nuclear physics culminating in the discovery of fission in 1939 has had a revolutionary impact on military arms and strategy. Without the organized body of physical science extant in 1930 -- classical mechanics, quantum mechanics, relativity, thermodynamics, optics, electromagnetic theory and mathematics -- none of the science events, and only a fraction of the technological events could have occurred. Thus, in the past, in at least these areas, undirected research has paid off on the 30 to 60 year or more time scale. In our study we see no evidence that this situation has changed. However, the fact remains that the contribution from recent (essentially, post 1945) undirected science to the systems we have studied appears to have been small.

We emphasize that this conclusion does not question the value of scientific research. (Recalling Figure 10, 8% of the identified Events were scientific in nature.) Instead, it focuses on the relative values of alternative practices in the management of scientific research and suggests that the length of time to utilization of scientific findings is decreased when the scientist is working in areas related to the problems of his sponsor.

We believe that the observation regarding the relative times to utilization of oriented as opposed to nonoriented research and the previous conclusion, that the efficiency of production of defense utilized science (and technology) is substantially enhanced when funded and managed by the Department of Defense, cannot be disassociated. Conjointly they demonstrate that both the efficiency of production and the timeliness of knowledge useful to a mission-oriented agency are most readily achieved when that agency funds and manages its own research program.

Sixth, we estimate that the DOD investment in science and technology has had a large payoff, although delayed in time by 5 to 10 years.

To support this conclusion we will give several examples where substantial increases in cost-effectiveness between successive generations of weapon systems have occurred, attributable primarily to technical innovations.

Consider first the comparison of the MK 9 and MK 10 sea mines produced toward the end of World War II and the 1962 - MK 56 and 57 sea mines which replaced them, and whose increased lethality, sensitivity, resistance to countermeasures, operating depth, operating time on station, shock resistance to air drop, and the like are due to the 144 Events* which have been documented. Figure 11 shows the

* Only 67 of these Events have been included in our statistical analysis in this preliminary report.

comparative costs of maintaining a mined harbor at a given level of effectiveness for one month. These calculations, incidentally, are based upon two real examples. Both yield the result that it would cost at least 10 times as much with the old mines as with the new. Also the operation would require about six times as many military personnel.

Consider as a second example the relative effectiveness of the 1954 C-130-A turbo-prop transport compared to the 1964 C-141-A turbo-fan transport. Figure 12 shows that the C-141-A on which we have documented 81 Events, has a ton-mile cost which is only 60% that of the C-130-A. Assuming a 10-year operating life, and an operating range of 1900 miles which is within the capability of the C-130-A, we calculate that the planned fleet of 284 C-141-A's would produce a net savings of over $4 billion compared to doing the same job with a fleet of C-130-A's. We estimate the military manpower needed to operate the C-141-A fleet would be about half that needed to operate the C-130-A fleet.

The dramatic benefits of technological innovation are not always limited to completely new designs. As Figure 12 also shows, the C-130's have been substantially upgraded by retrofitting and by modifications based on 1964 technology.

Our third example is the comparison of two radars. The 1944 SP and the 1964 SPS-48, whose performance depends upon 86 Events. To emphasize the great difference in performance between the two systems, we shall make the assumption that the Fleet requires the performance of the SPS-48, but is forced to obtain the equivalent performance by using SP type technology. The latter could be accomplished through a complicated assembly of 40 SP radars and a very large antenna. This clearly impractical hypothetical system is compared with the compact, reliable and practical SPS-48 in Figure 13. It means, of course, that one simply cannot obtain the SPS-48 performance using SP technology any more than the performance of the NIKE-X radar could be obtained with only the SPS-48 technology. In short, when requirements are rapidly escalating, new science and technology offer the only route to an economic solution.

Suppose, however, that one had constant requirements. What would technology do in this case? We have identified a recent (1965) search and traffic control height-finder radar, the TPN-8, whose range and altitude coverage, data rate and sensitivity are very nearly those of the 1944 SP. We have not performed a HINDSIGHT analysis on the TPN-8, but we believe that it would be found to depend on a set of Events, most of which have been financed by Defense, and many of which probably overlap with the SPS-48 (for one thing, the two radars were developed and produced by the same company). Figure 14 shows the comparison of the two radars. We see that in each of the factors--cost, weight, and reliability--the new radar is five or more times superior to the SP.

We have not attempted to make an exact cost-effectiveness comparison of MINUTEMAN II compared to MINUTEMAN I or of the MK 46 torpedo compared to the MK 44. However, if one were to try to do the same job with the older equipment that is demanded by the advanced requirements which are met by the newer equipment, we estimate that the costs and the military manpower would be higher by factors similar to those we have determined above, namely, by factors of 2 to 10.

We do not know if all the equipments in the U.S. weapons and equipment inventory of some $80 billion procurement cost are as greatly improved by technological innovation over their predecessors as are the cases which we have examined. However, if our examples are at all representative, the approximately $10 billion spent by Defense for science and technology from 1945 to 1963, the period during which 98% of the Events occurred, have been paid back many times over.

Seventh, we conclude that the current productivity of the in-house laboratory is comparable to that of industry. We have reasonably accurate relevant fiscal information only for the period FY-63-65. For this interval, as reported by the NSF in the category of "applied research", in "Federal Funds for Science," the DOD spent about 33% of its money in-house and about 54% in industry. Figure 7, describing the relative productivity of the in-house laboratories demonstrates that the return on investment during this interval correlates well with the level of investment. The decreasing output relative to industry of the in-house laboratories, over the 20-year period, correlates with the relative changes in professional strength of the two categories.

Figure 1. Systems Studied

System	NO. OF* EVENTS	PREDECESSOR SYSTEM
HOUND DOG ASM	23	--
BULLPUP ASM	42	--
POLARIS A 1 SLBM	49	--
MINUTEMAN I ICBM	47	--
MINUTEMAN II ICBM	31	MM I
SERGEANT TBM	20	--
LANCE TBM	127	HONEST JOHN
MARK 46 MOD 0 TORPEDO / MARK 46 MOD 1 TORPEDO	37	MK 44
M-102; 105 MM HOWITZER	2	M2A1

System	NO. OF* EVENTS	PREDECESSOR SYSTEM
AN/SPS-48 RADAR	86	SP
MARK 56 SEA MINE / MARK 57 SEA MINE	67	MK 9 / MK 10
STARLIGHT SCOPE	--	--
C-141 AIRCRAFT	81	C-130
NAVIGATION SATELLITE	26	--
M-61 NUCLEAR WARHEAD	--	--
M-63 NUCLEAR WARHEAD	--	--
XM-409; 152 MM HEAT MP	--	--
FADAC	8	--

20 Studied; 15 Contributed to current data bank.

Total Events = 638
Distinct Events = 556

* Number available as of 15 June 1966

Figure 2. Mark 46 Acoustic Torpedo

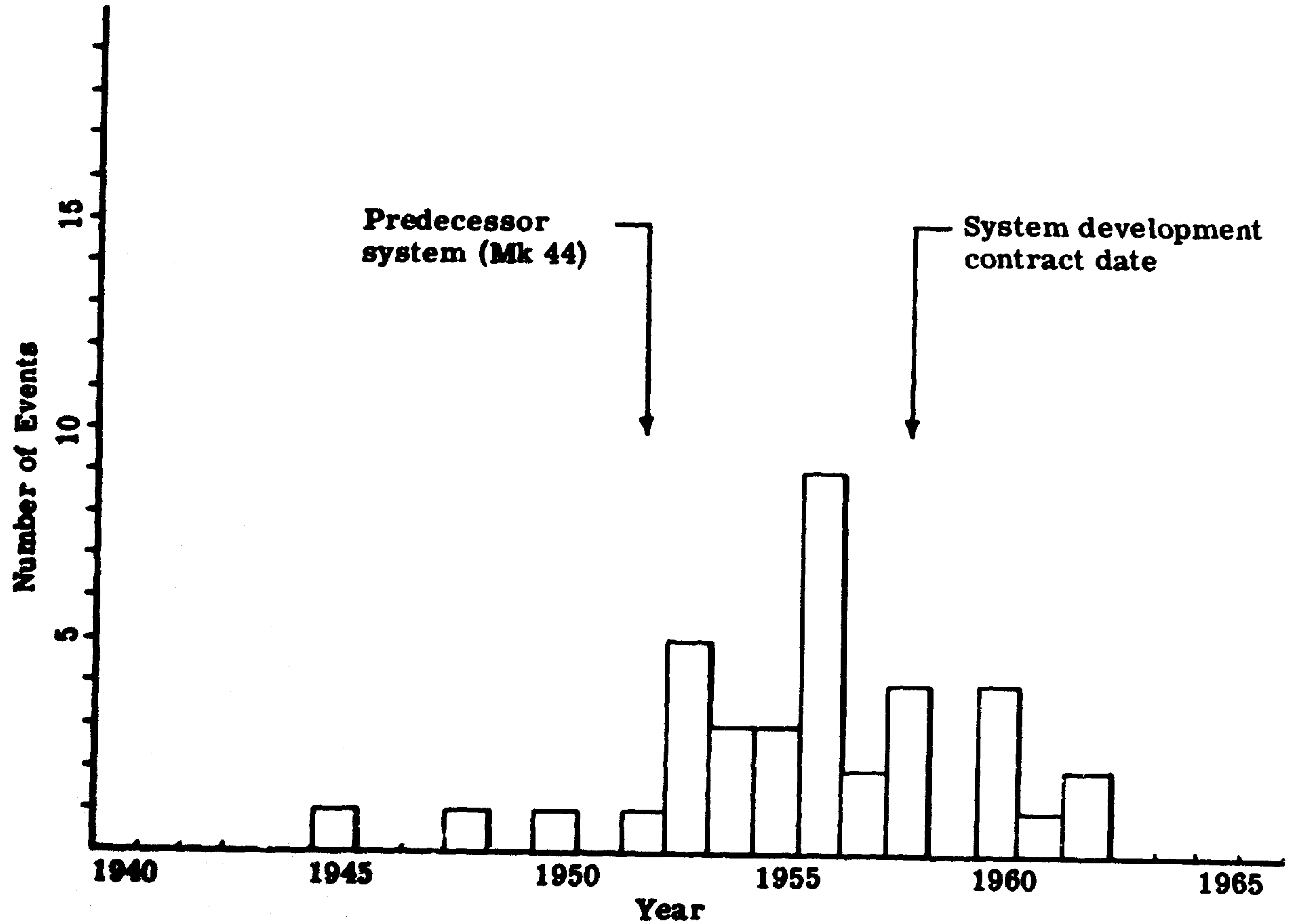
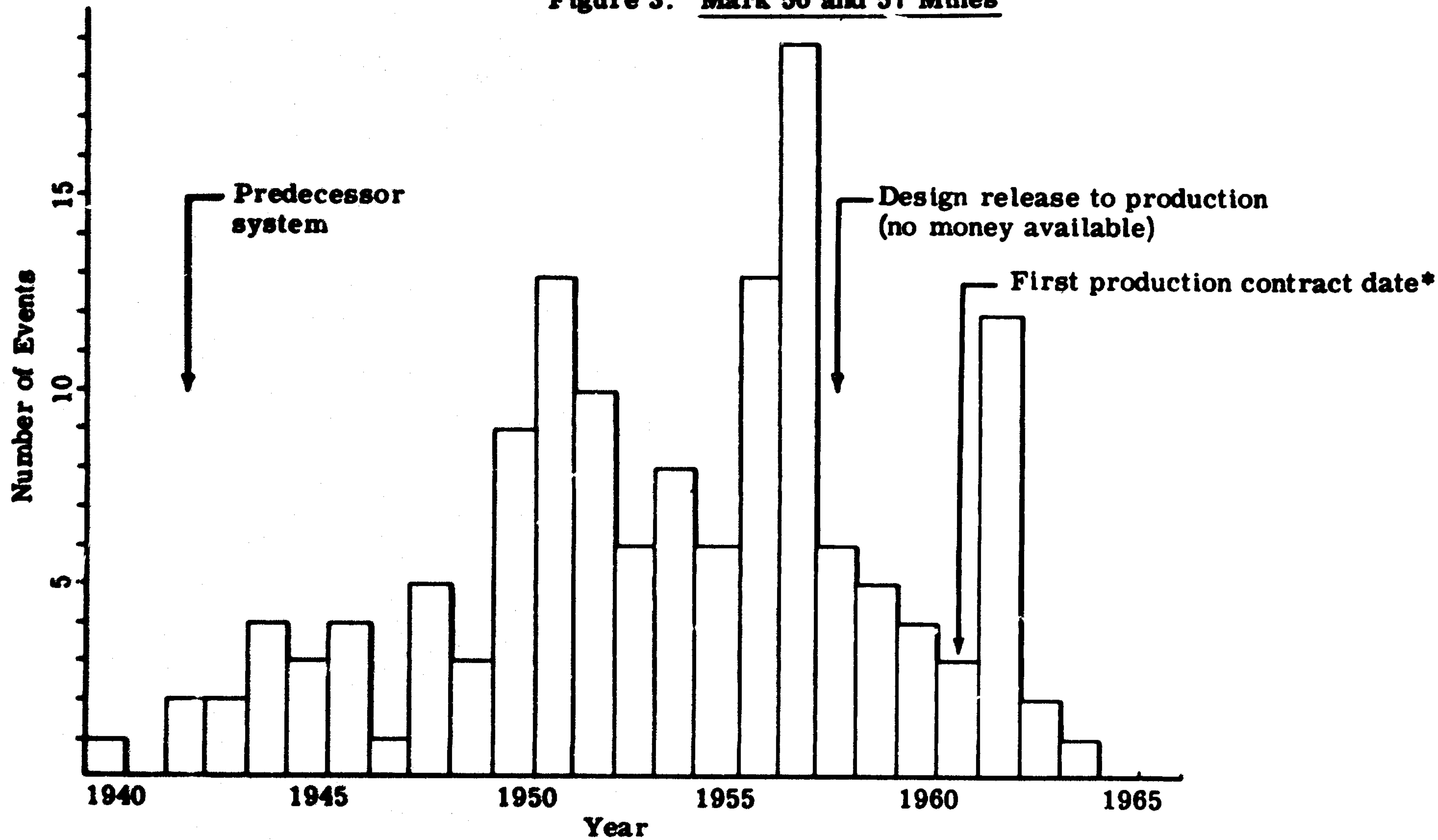


Figure 3. Mark 56 and 57 Mines



Note: *Includes significant specification changes.

Figure 4. LANCE Missile

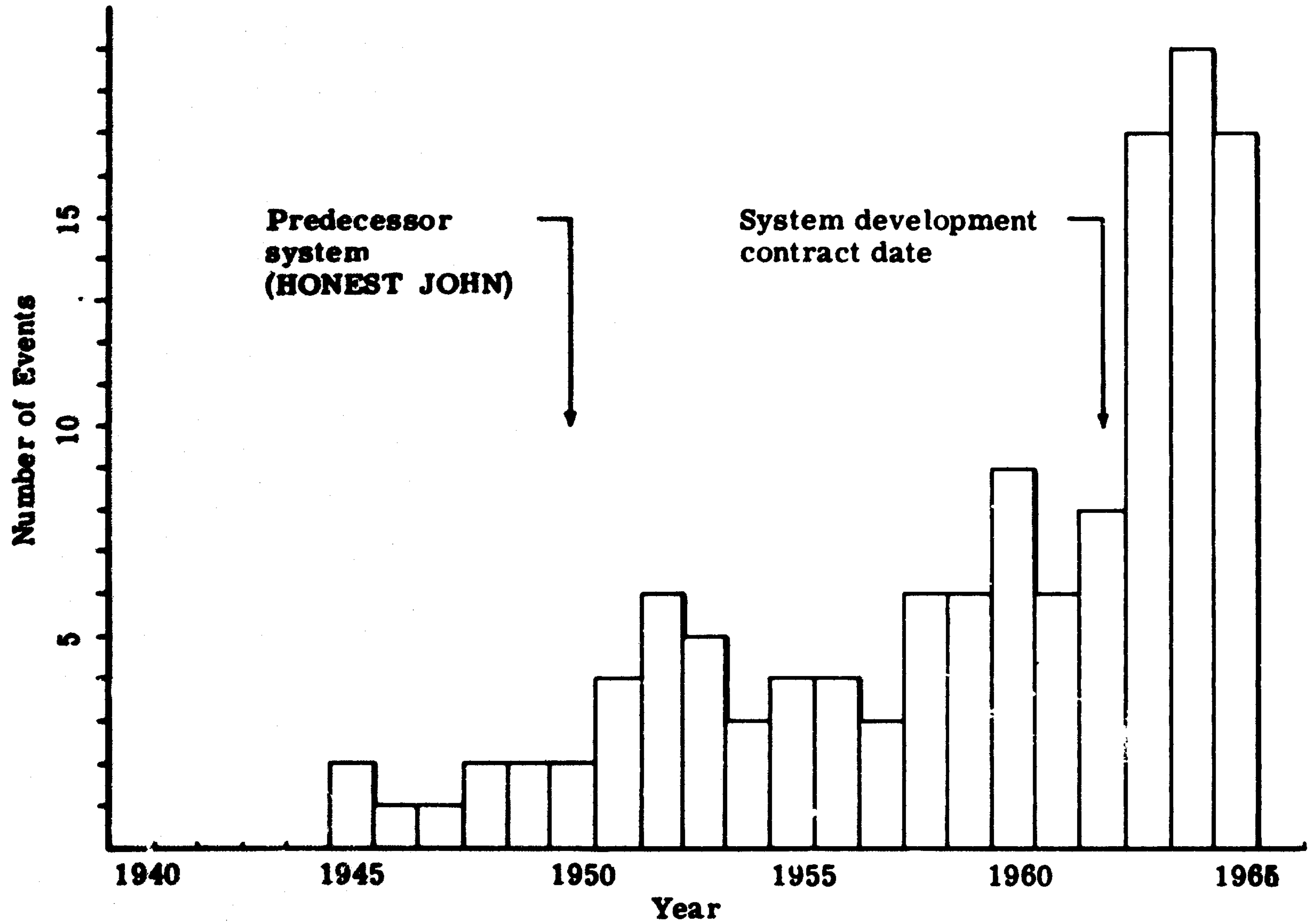


Figure 5. Normalized Distribu'ion of All RXD Events

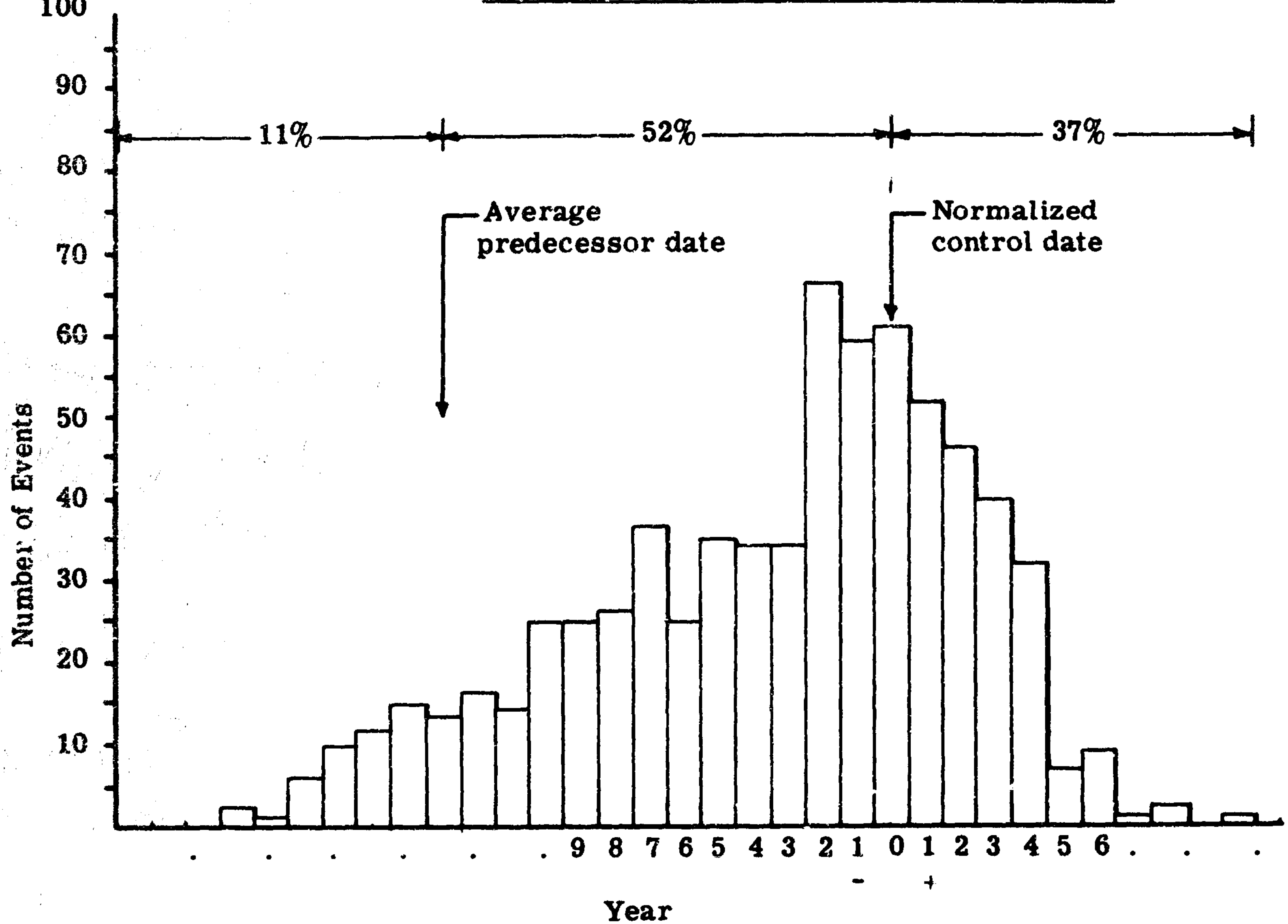


Figure 6. Event Source Distribution

(By Performer)

	(20-year ave.)
• IN-HOUSE LABORATORIES	39%
• INDUSTRY	49%
• UNIVERSITIES (INCLUDING CONTRACT RESEARCH CENTERS)	9%
• NON-DOD FEDERAL	2%
• FOREIGN	1%
	100%

Figure 7. DOD In-House Activity

Percentage of All Events vs. Time (Linear best fit to average of 5. $\sigma = 14.3$)

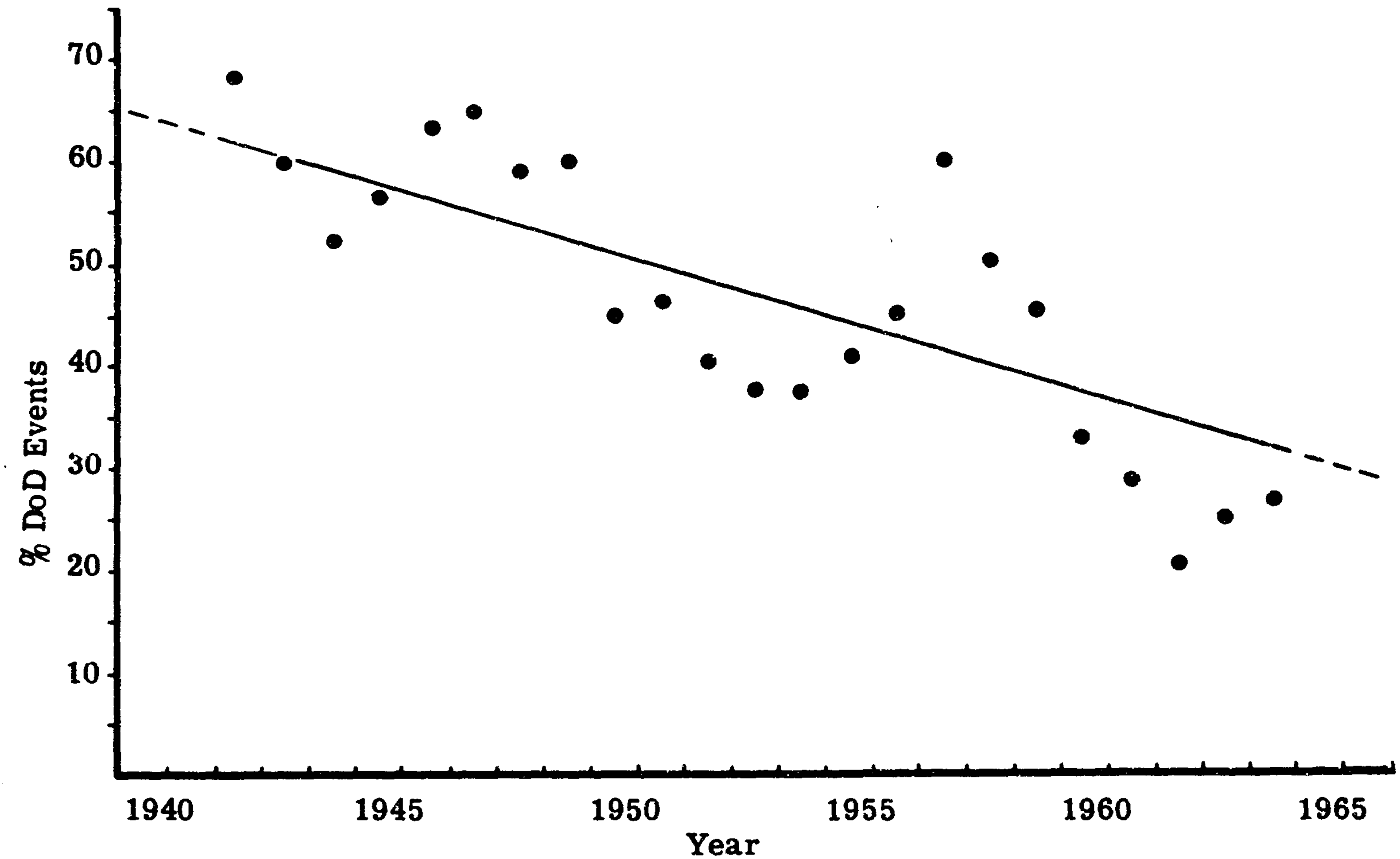


Figure 8. DOD In-House Activity

Number of Events vs. Time (Linear best fit to average of 5. $\sigma = 4.4$)

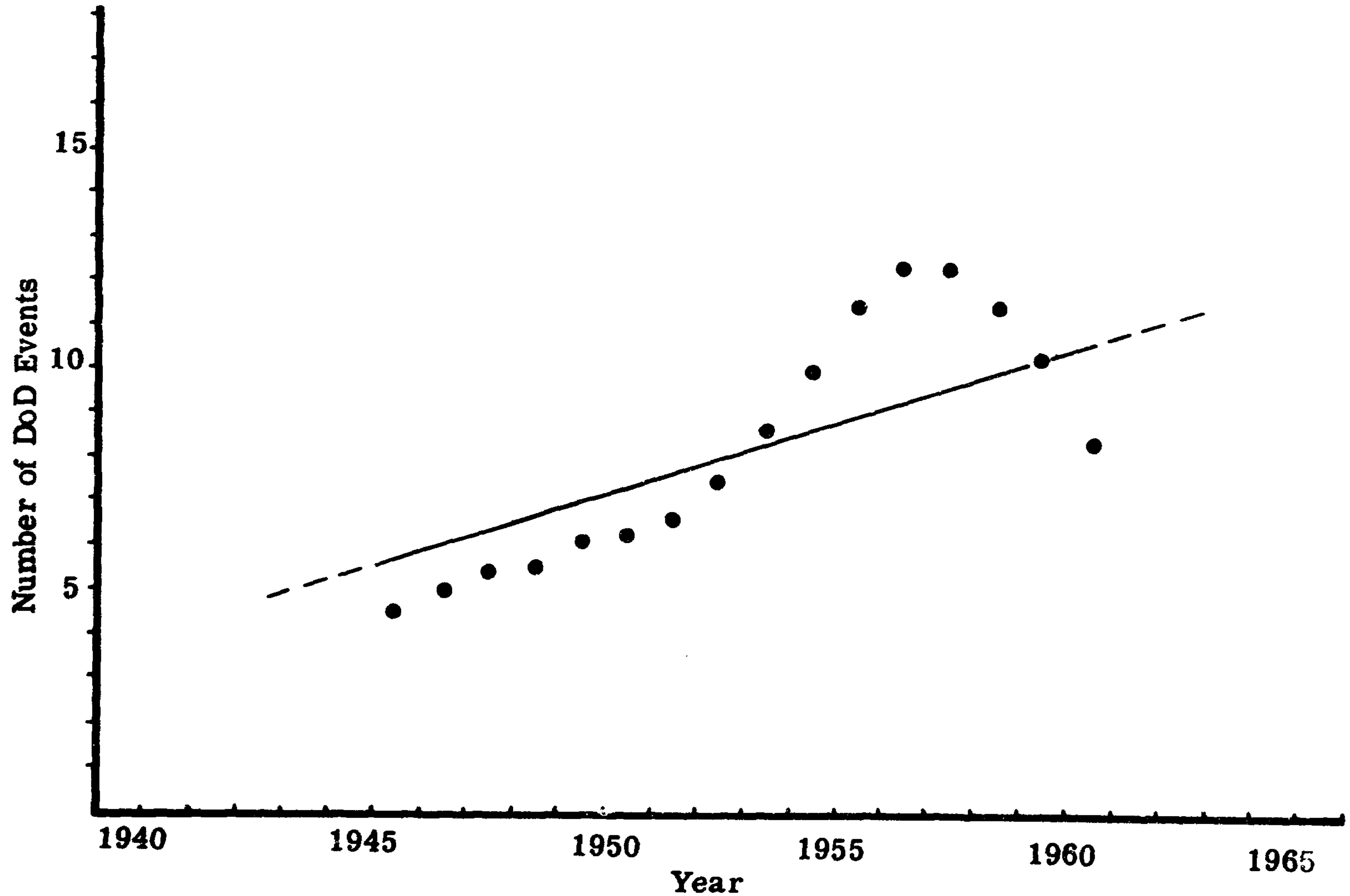


Figure 9. Funding Source Distribution

- DOD DIRECT FUNDING -- 87%
- INDUSTRY, DEFENSE ORIENTED -- 9%
- INDUSTRY, COMMERICALLY ORIENTED --- 2%
- OTHER GOVERNMENT AGENCIES --- 1%
- UNIVERSITIES (STATE, PRIVATE OR FOREIGN FUNDS) --------------------------------- 1%

100%

Figure 10. Research Objective (90% Identification)

		MOTIVATED BY DOD NEED
SCIENCE		
APPLIED - DOD ORIENTED RESEARCH	6.2%	6.2%
APPLIED - NON-DOD RESEARCH	1.5%	
UNDIRECTED RESEARCH	0.3%	
	8 %	
TECHNOLOGY		
GENERIC - DOD ORIENTED	25%	25%
A SYSTEM IN ADV. DEV. OR A SYSTEM-CONCEPT	46%	46%
A SYSTEM IN ENG. DEV. OR OPERATIONAL SYSTEM DEV.	18%	18%
NON-DOD ORIENTED	3%	
	92%	95.2%

Figure 11. Relative Cost for Fixed Effectiveness
Mk 56 Mod 0 vs. Mk 10 Mod 9 Mines

TARGET	MINE	DELIVERY DISTANCE	TOTAL COST 6 MONTH	TOTAL COST 1 YEAR	CONTINUING COST PER MONTH
A	MK 56/0	1500 N.M.	$14.8M	$14.8M	$ 1.2M
A	MK 10/9	1500 N.M.	$74.8M	$150M	$12.5M
B	MK 56/0	700 N.M.	$29.8M	$29.8M	$ 2.5M
B	MK 10/9	700 N.M.	$161.7M	$320.0M	$26.7M

COSTS INCLUDE
INITIAL MI 3
REPLACING MINES
AIRCRAFT OPERATIONS
AIRCRAFT ATTRITION

Figure 12. C-130 and C-141 Cargo Aircraft

	1964 TECHNOLOGY	1954 RETROFIT TO 1964	1954 TECHNOLOGY
	C-141A	C-130E	C-130A[1]
EQUI CAPACITY	284	780	780
COST/TON-MILE[2]	$0.147	$0.182	$0.242
POTENTIAL LOAD	43.4 BILLION TON-MILES	43.4 BILLION TON-MILES	43.4 BILLION TON-MILES
PROJECTED COST	$6.37 BILLION	$7.9 BILLION	$10.5 BILLION
SAVINGS	$4.13 BILLION (C-141A vs. C-130A)	$2.6 BILLION (C-130E vs. C-130A)	

1 - TACTICAL ONLY
2 - DIRECT OPERATING COSTS
SYSTEM SUPPORT COSTS
MILITARY PAY AND ALLOWANCES
DEPRECIATION

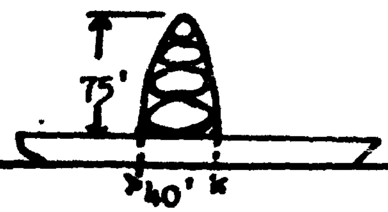
Figure 13. SP and AN/SPS-48 Radars

1944 Technology
SP - RADAR

Development Cost:	$ 10 million
Procurement Cost:	
@ $6.5 million ea. (est.)	$150 million
25 Radars	$160 million
25 DD	375 million
	$535 million

O&M Personnel -- 200 X 25 -- 5,000 men
Ships Crew ----- 200 X 25 -- 5,000 men
10,000 men

MTBF ----- 1 hour (Upper Limit est.)

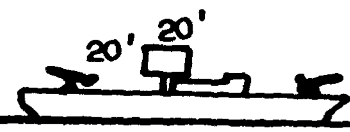


1964 Technology
AN/SPS-48 RADAR

Development Cost:	$18 million
Procurement Cost:	
@ $1.5 million ea. (approx.)	$34 million
25 Radars	$52 million

O&M Personnel -- 20 X 25 ------ 500 men

MTBF ----- 80 hours



Data Rate:
15 scans/min

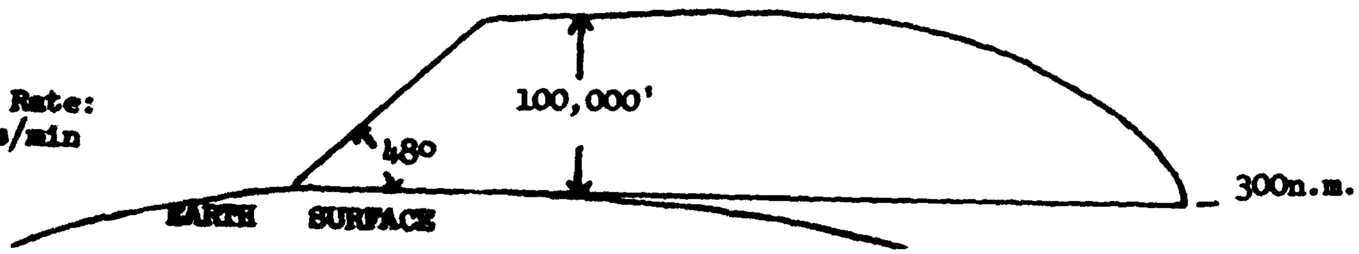


Figure 14. SP and AN/TPN-8 Radars

		SP 1943 TECHNOLOGY		AN/TPN - 8 1961 TECHNOLOGY
RANGE	--(20 M^2 Target)----	35 N.M.	------------------------------	45 N.M.
BEAM WIDTH				
HORIZONTAL	----------	3	------------------------------	3.5
VERTICAL	-------------	3	------------------------------	.37
FREQUENCY	---------------	S Band	------------------------------	X Band
MTBF (Approx)	--------------	10 hrs	------------------------------	100 - 1000 hrs
WEIGHT (Approx)	-----------	9000 lbs	------------------------------	1000 lbs
COST	---------------------	$100,000 (1943)	------------------------------	$50,000 (1965)