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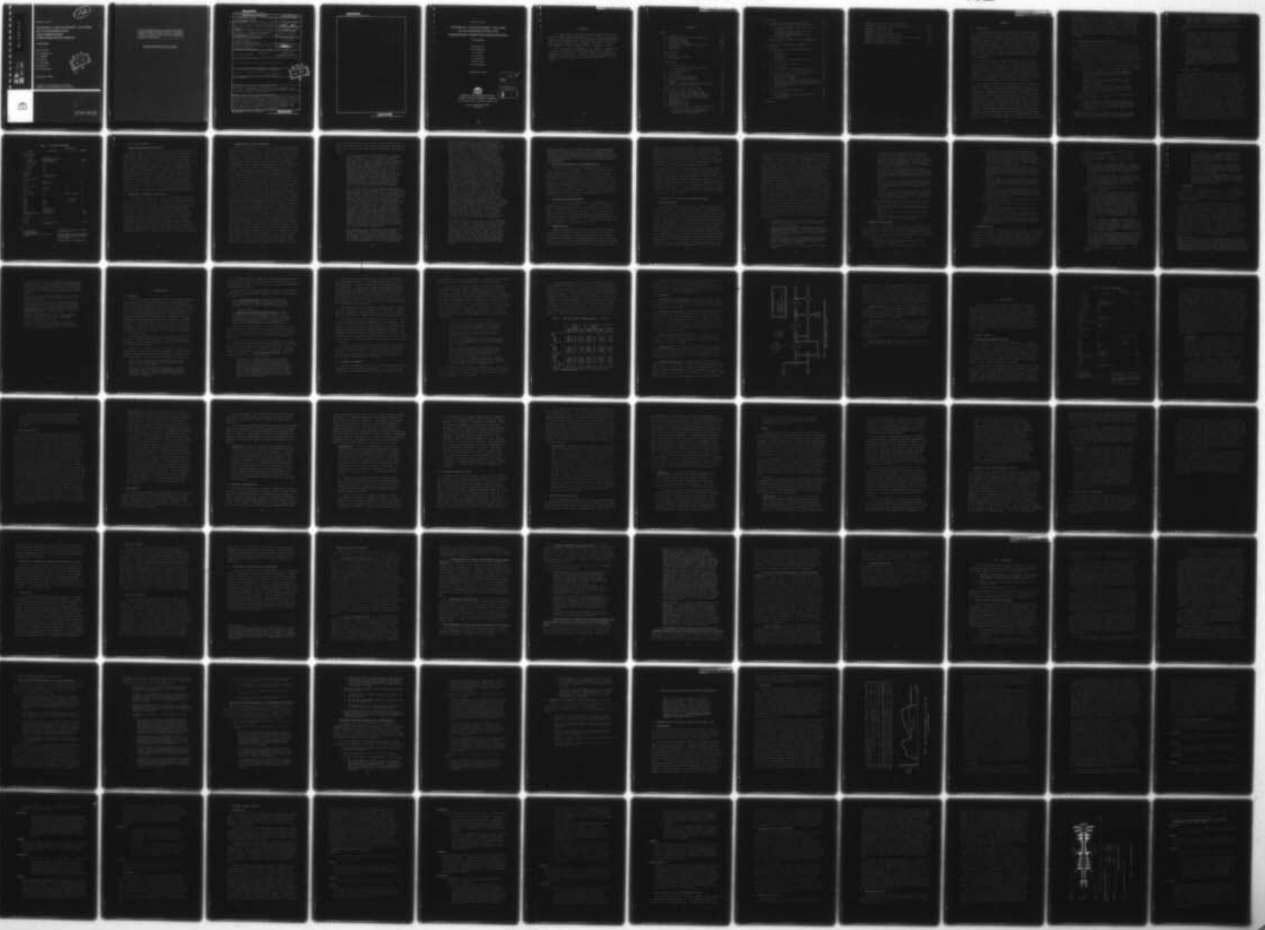
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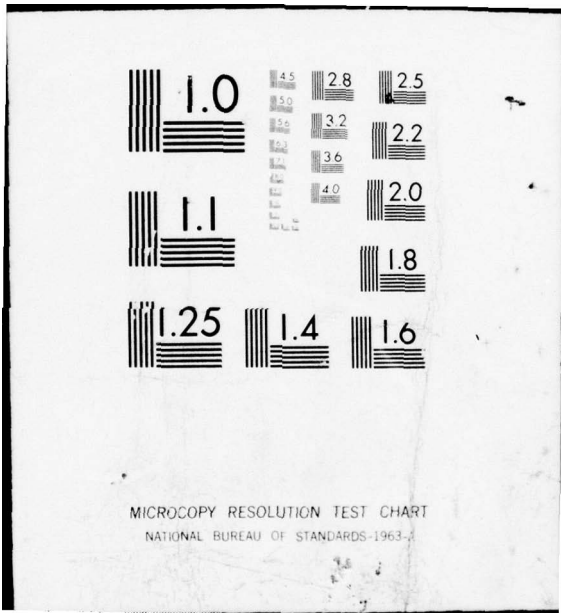
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TECHNICAL AND ECONOMIC ANALYSIS
OF STANDARDIZATION
AND INDEPENDENT
SUBSYSTEM DEVELOPMENT

VOLUME I

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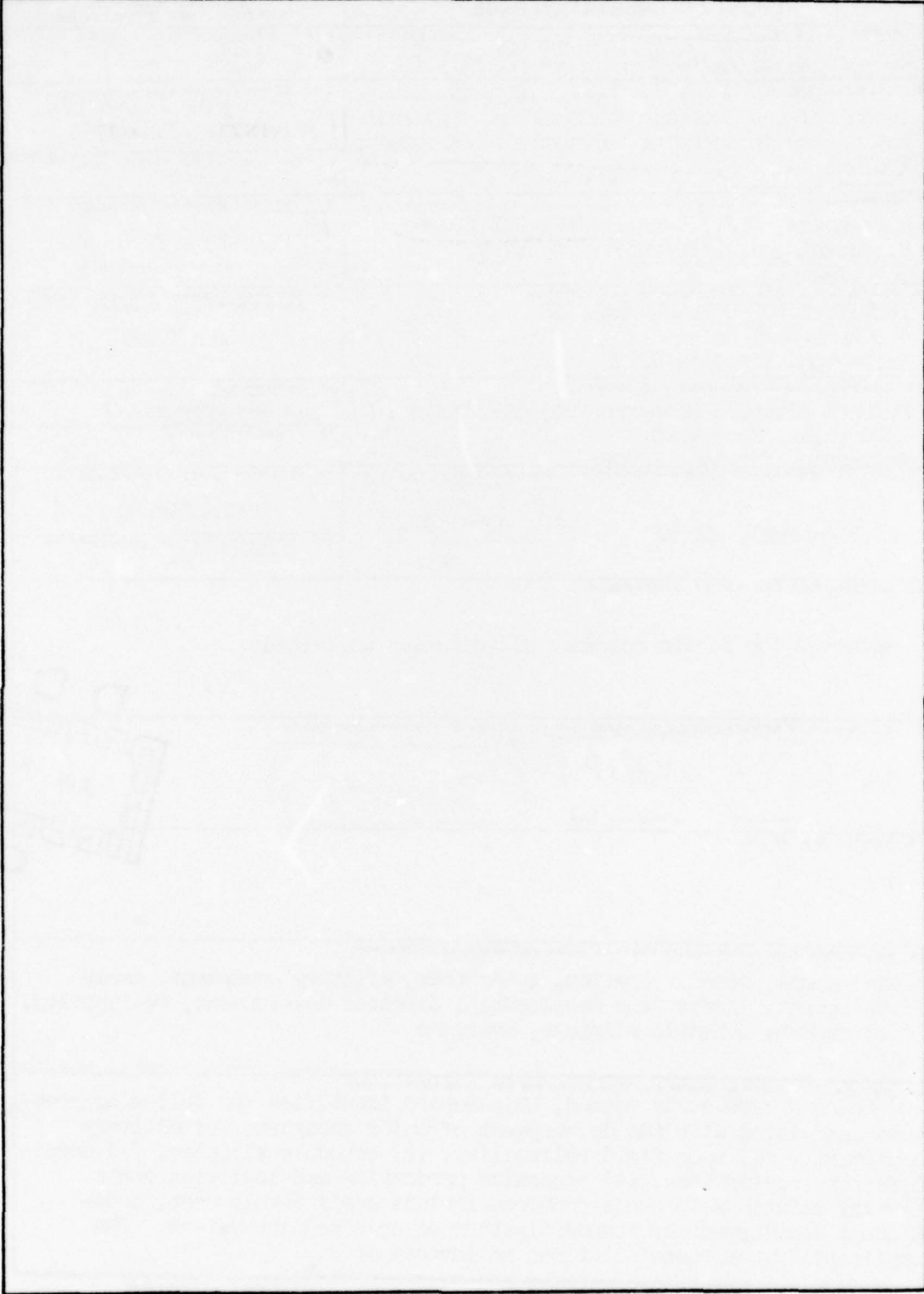
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TECHNICAL AND ECONOMIC ANALYSIS
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December 1976



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FOREWORD

(U) This study (S-474) was conducted by IDA at the request of DARPA, under Task Order T-121: Technical and Economic Analyses of Standardization and Independent Subsystem Development, dated 12 March 1975. Technical cognizance for the task was provided by the Assistant Director (Planning), ODDR&E.

(U) The study is published in two volumes. Volume I consists of the main part of the study, plus the unclassified appendixes (A through H). Volume II, which is published under separate cover, contains the classified appendixes (I, J, K, and L).

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SUMMARY

A. INTRODUCTION

This study examines the development of subsystems by the U.S. military services. However, it examines only two limited aspects of such developments, namely, when they should be initiated and whether or not they should be under the direction of the system program manager. The study focuses on the development of operating hardware (full-scale development) rather than on additions to the technology base. In particular, it emphasizes the development of long leadtime subsystems and items that can be used in more than one system and therefore, might be standardized.

We emphasize that the study deals with no more than the above issues. It does not examine the basic process of subsystem development, including issues of engineering, design or test. The problems that occurred in some of the developments discussed in this study would not be affected by the policies discussed. As stated above, the only issues addressed are the timing of the initiation of subsystem development and the location of responsibility and control for that development.

The primary results of this study are a set of guidelines. They are intended to be of general assistance, but not to be adhered to rigidly in making decisions about initiating early development, independent development, and standardization of subsystems. The primary data base consists of a limited number of case studies of varying quality and completeness. The generalizations we have attempted to draw from the data (case studies) are sometimes contradicted by other, equally credible data. Consequently, the apparent lessons must be viewed with caution. Uncertainties about future systems reduce the applicability of standard market analysis to questions of standardization. The case histories and the limited analytical references that can be drawn from them do not support sweeping general

conclusions. Therefore, to derive the general guidelines, it was necessary to supplement the case study data base with the use of judgment, based on the observations of the various authors. Although the data base is small, the guidelines have nevertheless appeared useful in a number of test cases that were conceptualized to explore their consistency and we consider them as candidates for further consideration and review by ODDR&E.

B. DEVELOPMENT PROBLEMS AND THEIR COSTS

The development of complex military systems is beset by many problems, a limited set of which are dealt with in this study. The problems addressed are all covered by DSARC instructions. Development slip ups seem to occur through excessive optimism, excessive risk-taking, inadequate engineering, or poor program management or the inability of the DSARC Review Committee to adequately challenge the information laid before it.

In the development of major weapon systems, the following problems, which are costly in terms of dollars, have occurred:

1. Poor field reliability of systems, caused by excessive concurrency between the development of the system and the development of its major subsystems.*
2. Schedule slippage of major programs, caused by inadequate or late development of a pacing, critical subsystem.
3. Unsatisfactory performance of a major system, because of the inadequacy of an important subsystem. (In an extreme situation, the entire development may be aborted.)

Possible solutions to these problems may also impact on the following subsidiary problems:

4. Lack of competition in the military equipment market after the award of the development contract or the initial buy. This places the Government at the mercy of the sole supplier and can result in excessive costs.

* This does not imply that the named causes are the only causes of poor field reliability and schedule slippage. In this study, we concentrate on the named causes.

5. Proliferation of subsystems intended to perform similar functions, with attendant high production costs traceable to small volume and high logistics costs traceable to noninterchangeability.

Crude estimates of the dollar impact of these problems are as follows:

- Poor field reliability, resulting from excessive concurrency, is quantifiable for the A-7D aircraft (see Appendix K) and is about 10 to 20% of the total program cost. Assuming that the same proportion holds for all other aircraft, missile, and vehicle systems, the total impact is estimated at \$1-2 billion in FY 76. If ship programs are included, the impact is substantially greater.
- According to Ref. 13, cost overruns, due to all causes defined as the ratio of current estimate to planning estimate, averaged 40% in the five years from 1969 to 1973. If this factor is applied to the 1974 procurement budget (about \$17 billion), cost overruns would amount to nearly \$7 billion. However, only a fraction of this can be attributed to schedule overruns. The GAO, for example, has estimated in Ref. 9 that schedule overruns cost \$3.7 billion in CY 1974.

C. POSSIBLE SOLUTIONS

In this study, we consider in detail a restricted set of possible solutions to the above problems. We make no claim that the subsystem development policies discussed in this report are a panacea for the problems that beset military procurement. At best, the subsystem development policies discussed can deal only with a limited portion of the full spectrum of procurement problems. Nevertheless, we believe that early development, independent development and standardization of subsystems are desirable in some instances. We believe further that we have devised a scheme for identifying such cases. The development of some subsystems requires a long leadtime. One possible way to improve poor field reliability and schedule slippage, caused by concurrent or inadequate development of such subsystems, is to institute a policy of "early development." This policy calls for the development of selected, long leadtime subsystems for a specific system, before there is a system program office and a system manager to sponsor subsystem development. Such a policy

might remedy some of the problem of concurrent or inadequate development. But it carries with it substantial risks. For example, subsystems may be developed to specifications that don't match those needed for the system into which the subsystems must eventually fit. Moreover, in some cases the using system may never materialize. However, the existence of the developed subsystem may then ease the development path of another system specifically designed to use it. The case studies have several examples of this serendipitous occurrence which attests to the general flexibility and continuity of the R&D process.

Another policy that we explore is the development of subsystems by an organization outside the control of the program manager of the system for which the subsystem is earmarked. This is "independent development," in contrast to "directed development," which is under the control of the program manager. Independent development makes it possible to emphasize the design and development of subsystems suitable for use in several systems; thus, subsystem proliferation can be reduced. In some situations, it might lead to standardization of certain subsystems. This would increase the total number of procurable, identical subsystems thereby attracting other vendors to the market. Such a situation could lead to competition and reduced costs to the Government. Independent development and standardization both carry with them the risk that a developed subsystem may not be used.

The described policies are studied in detail in the main part of this report. Developed guidelines for their application are also described. None of the policies conflicts with current DoD or OMB procurement guidelines, although the acquisition structure of the military system tends to discourage such policies, even when they appear desirable.

We reiterate here that this study focuses on engineering (full scale) development. Additions to the technology base through research and advanced development are not under investigation here, although their importance is recognized in arriving

at the "state of the art" that permits the development of successful operating hardware. We note further that the introduction of a component or subsystem into engineering development is usually a commitment to spend at a significantly greater rate on that item than in previous developments of that item. We show in Chapter I that the average DoD project (line item) in engineering development (Category 6.4) is funded at a factor of about 2.4 times the funding of the average project in advanced development (Category 6.3). These averages were taken over the three fiscal years 1973-1975 across the three military services excluding DARPA. There are of course substantial variations from this average factor among the services and especially among projects.

D. ANALYTIC METHODS

Our main analytic tool is a set of case studies. With it we have assessed the contribution that the policies of early development, independent development (ID), or standardization of subsystems might make towards solving the problems we have enumerated. Table 1 shows the particular subsystems, and the using systems, that are central to the case studies.

Each case study includes a summary of the subsystem/system history. It assesses problems that occurred during the development program, or after deployment of the system. It then considers whether ID, early development, or standardization would have been possible, and whether the policies would have been appropriate and beneficial to the particular subsystem/system development. The assessments are qualitative, except in one case where costs are roughly calculated. A set of guidelines is deduced from the case study findings for each of the three types of decisions: whether to undertake early development, independent development, or standardization of subsystems. These guidelines are then applied to the four following subsystems to show how they might be used in making decisions: turboshaft engine, airborne computer, inertial navigator, and correlation guidance system.

TABLE 1. CASE STUDY SUBSYSTEMS

Subsystem	Using Systems	How Acquired ^a					Reference ^c
		1	2	3	4	5 ^b	
I. AIRCRAFT ENGINES							
A. Shaft Engines							
1. T-53	UH-1, AH-1		✓			✓	A
2. T-64	H-53, AH-56A, XC-142, others		✓			✓	B
3. T-700	UTTAS, AAH, LAMPS			✓			V (Ch.)
4. Navy Proposal	UTTAS, AAH, LAMPS, HXM			✓			V (Ch.)
B. Thrust Engines							
1. F-100	F-15		✓				H
2. F-100	F-16					✓	H
3. F-401	F-14		✓				H
II. ROCKET MOTOR							
	SRAM		✓				E
III. TANK ENGINES							
AGT-1500	XM-1 (Chrysler version)					✓	C
AVCR-1360	XM-1 (GM version)					✓	
IV. AUTOMOTIVE TRANSMISSIONS							
X-200	M-113			✓			C
X-300	MICV	} Proposed		✓			C
X-1100	XM-1			✓		✓	C
V. HELICOPTER DYNAMICS							
Bell	UH-1, AH-1		✓			✓	A
Lockheed	AH-56A		✓				B
VI. AIRCRAFT WEAPONS							
Chin gun turret	AH-1		✓	(Adapted from IRAD) ^d			A
GAU-7	F-15		✓				D
VII. RADARS							
APG-63	F-15				✓	(Contractor)	J
WX-200	F-16				✓	(Contractor)	J
SPG-49	Typhon		✓				I
ANSPY-1	AEGIS		✓				I
VIII. AVIONICS							
SCAS	UH-1, AH-1		✓				A
IHAS	Various helicopters				✓		B
ARBS	A-4M, Harrier				✓		G
Proposed standard INS	F-16, C-135, C-141					✓	V (Ch.)
Standard airborne computer	F-18, LAMPS, etc.					✓	V (Ch.)
IX. IR SENSOR							
Standard FLIR	OV-13, UH-1, F-4, etc.					✓	F
X. GUIDANCE							
Aimpoint	Mace, Matador, Pershing II, etc. (Proposed)					✓	V (Ch.) & L

KEY:

- ^a1. Directed development
- 2. Early development
- 3. Independent development
- 4. Independent development and standardization
- 5. Inherited

^bThe second user of a subsystem is considered to have inherited it.

^cExcept for Chapter V, there are appendices giving detailed developmental histories. Note that Chapter V contains guideline tests applied to four new subsystems.

^dIndependent Research and Development (IRAD).

E. CASE STUDY FINDINGS

1. Setting Performance Requirements

A major cause of failure to complete a development is that performance requirements may be set to or beyond the available technology. Examples are the F-401 engine and the GAU-7 gun. Examples of near-failures are the F-100 engine and the SRAM rocket motor. However, it is also possible to mitigate the impact of over-ambitious requirements. In both of these cases, the requirements were reduced and the system development then completed. Counterexamples that illustrate the opposite side of the difficulties caused by excessively ambitious requirements are the T-53 and T-64 turboshaft engines. Both of these subsystems were within the demonstrated state of the art and both were very successfully used in a number of operational systems. In these cases, the flexibility and potential growth had a high payoff, even though the engines may have been less efficient than they might have been in individual applications.

2. Undertaking Engineering Development

A second cause of failure, related to the first above, may be that engineering development is undertaken before sufficient knowledge about the technology is available or because an attempt is made to make several significant technological advances in a single development. Examples are the Typhon radar and the GAU-7 gun. The rocket motor for SRAM was a near-failure that was saved by easing off requirements along with intensive and expensive effort. On the other hand, examples of successful developments are the dynamic system of the UH-1 and the AH-1 helicopter, the UH-1 Stability and Control Augmentation System (SCAS), the Angle Rate Bombing System (ARBS), the standardized Forward-Looking InfraRed (FLIR) system modules, and the APG-63 and WX-200 radars, all of which were based on available technology.

3. Limited Help of Early Development

Early development could help to deal with these causes of failure only in a limited way. An investment in early development of a subsystem could have a high return. But there is no certain way of evaluating this, because the statistics are unavailable. In addition, it is often only clear in retrospect that early development might have led to more flexibility "downstream". The examples suggest that the cost of additional effort may be paid either at the beginning or at the end of a program. The guidelines for early development developed in this study, if carefully used, might help improve the chance of a more orderly system development process with less chance of delay and cost increases. In the case of a long leadtime item, early development would provide more time to exploit the technology, to explore different means of achieving a goal, and to provide an early warning that a goal may not be achievable. In this regard we note that the long development times that are associated with so-called long leadtime items are sometimes over-estimated at least for low risk developments. For example, in the case of engines, the time of development after a demonstration engine has performed satisfactorily is between two and three years. This is exemplified in the development schedule of the T-64 engine (Appendix B, Fig. B-1). After the first engine run, the preliminary flight rating test (PFRT) was completed in less than 15 months. The qualification test was completed in about 33 months. Apparently, flight test engines reflecting the state of the art can be available in a little more than a year, and most of the remaining time is spent in qualifying the engine. Scheduling of this type seems typical for most of the long leadtime items that were included in the case studies, if they represented low risk developments. Guns are perhaps the only exception. They take a longer time to develop, particularly if new ammunition is to be developed also. This suggests that state-of-the-art technology can be made available to a system, without early fullscale development. However, if a large jump in technology is attempted, as in the

case of the F-401 engine, more time is likely to be needed. Early development is one way by which to acquire more development time. On the other hand, early development runs several risks:

- a. *The using systems may not materialize.* An example is the T-64 engine. The requirement specified three intended users. Only one materialized, although other initially unexpected users appeared. The family of automotive transmissions has been available for a substantial time, but is still not used in a field system. However, two of the family have been selected for use in the MICV and the XM-1 tank and therefore are likely to be fielded in the next few years. There are no candidate users for the losing engine in the XM-1 competition, but this can be regarded as a cost in taking different competitive approaches to solve the problem. All other successful subsystems among the case studies actually were used or are likely to be used in operating systems. However, few of these were early developments.
- b. *The potential using system development may be delayed, so that the technology in the early developed system may be obsolete by the time it gets used.* To preclude this occurrence, an early development should have capability for growth or improvement. Alternatively, it should be possible to adjust the user system design to accept the developed subsystem. In some cases, this may mean that the basic subsystem will be overdesigned, so that such improvements can be accepted without redesign. Examples are the T-53 and T-64 engines. Both engines were overdesigned for their first use and were subsequently uprated as power requirements increased. This versatility was useful, but it was obtained at the expense of the potential performance of the first users of the engines. This contrasts with the T-700, a new current state-of-the-art engine that cannot be uprated without extensive further development. The T-700 is light and efficient, but it may not be powerful enough for some of its intended users (as discussed in Chapter V).
- c. *The development goal parameters change before the system is completed.* The degree of this risk depends on how readily the subsystem design can be changed to match new requirements. Every early development in the case studies, including the *de facto* early developments, was originally tailored to performance parameters that were changed when

the using systems' actual characteristics became known. Examples are the T-53, the T-64, the various automotive transmissions, the radars, and the tank engines. The original turboshaft requirements called for too little power, and initial power upratings of 20-30% were necessary. The members of the Army vehicle transmission family are still not used in any operational system. Their power ratings have been adjusted several times in anticipation of the requirements of possible users. In the case of the top-of-the-line (most powerful) transmission, the requirement has tended to increase with time along with the requirement for tank engine power, now 1500 HP, double the power of the current Army heavy tank. In the case of the F-15 and F-16 radars, which were originally company-funded developments, the potential performances actually exceeded the requirements. However, in all early development cases noted above, it was possible to change the characteristics of the subsystem so that it was able to provide the desired performance. Conservative nonoptimized design was essential for these subsystems to have the ability to change without substantial redevelopment. On the other hand, if a substantial performance advance is wanted, it may be necessary to optimize the design for one set of characteristics, after which tailoring to match another set may be difficult. The example here is the T-700 engine, which was optimized for its present power, and cannot be easily uprated for use in other systems. Moreover, the T-700 may not be powerful enough for the systems it is currently programmed for, and a weight limitation has been placed on these systems. Aircraft requirements (and weight) tend to grow during development, and engine power limits obviously interfere with this process. Control of weight growth is clearly desirable, but an absolute limit creates pressure for a new development. Such pressure is becoming observable in the case of the Utility Tactical Transport Aircraft System (UTTAS) and the Advanced Attack Helicopter (AAH) (see Chapter V).

- d. *The subsystem may be rejected by the program manager or prime contractor on the grounds that it is obsolete, or too costly, or that he can provide a better subsystem through new development.* Although this risk was cited to us during interviews of various individuals during the course of this study, the case studies do not shed much light on its validity. Only in one of the cases which were used to test the guidelines (Navy Standard Computer) did we find direct evidence of a prime contractor indicating doubt that a proposed standard subsystem would be as effective as one that they could develop themselves.

Two key problems in the decision regarding early development emerge as: (a) assessing correctly what is "within the state of the art," and (b) judging correctly that there will be other uses for the subsystem if the originally anticipated user does not materialize.

4. Testing for Reliability and Maintainability

Testing for reliability and maintainability prior to deployment tends to be inadequate. The major example among the limited case studies considered here is the A-7D airplane. Early development might contribute to solving this problem, in the sense that it would allow more time for subsystems to mature. Its use is unlikely for the reasons noted under 3 above. Independent development and standardization would help. They could provide more equipment that is better qualified than was originally the case and, therefore, more likely to have better reliability, although even with such equipment a period of operational testing is necessary.

5. Standardization Opportunities

Opportunities for standardization or for the use of standardized equipment are neglected. An example is the A-7D. It used a number of subsystems that could have been drawn from a group of available systems, considered as standard systems, e.g., heads-up display and inertial navigator. The equipment that was used had so low a Mean Time Between Failures (MTBF) that it forced a premature termination of the flight test program, which was to demonstrate reliability prior to IOC.

6. Judgment Errors

Errors in judgment are a factor in many of the decisions represented by the case studies. Such errors occurred at all stages of development. They include the setting of extreme performance requirements, underestimating development time and costs, and not cutting off programs when difficulties indicated that continuing them would not lead to a successful conclusion.

Judgments are an important ingredient in developing military products that use advanced technology. The existence of risk and the possibility of failure are well recognized. The development system favors pushing ahead, even when it is contraindicated. This results in a reluctance to cancel or reorient a program, until it has gone too far. Examples are the GAU-7 gun, the F-401 engine, and the Cheyenne helicopter.

Early development, or independent development and standardization, can contribute only marginally to this judgment problem. Potentially, early development of long leadtime subsystems can provide a better probability of success, or at least an early warning that a particular approach might have to be changed. But good judgment is needed to act adequately on such warnings. Similarly, the use of standard items helps to offset the uncertainty and risk of developing new subsystems, although it may upset the match between the original requirement and the final system to some degree.

F. GUIDELINES FOR SUBSYSTEM DEVELOPMENT DECISIONS

I. Early Development

Early development can take place in either deliberate or nondeliberate ways. Deliberate ways would include the decisions we are discussing here; nondeliberate ways would include the use of developed subsystems in the conception and development of new systems for which the subsystems were not originally contemplated. By our definition, it must be done in advance of system definition. Consequently, it carries with it the risk of specifying subsystem performances that may not match the system requirements that eventually evolve. Note that system requirements are not immutable. They are derived through a process of analysis, negotiation, and compromise, which reflects considerations of military threats, environments, technical possibilities, and budget issues. The process does not stop with an initial system specification. Since the use of advanced technology involves risk, the initial requirements' specification may turn

out to be too ambitious technically or too costly, and the adjustment of one or more performance parameters may be necessary to achieve an operating system. Such adjustments were made in a number of the cases we examined. This risk is not restricted to early development. Even when a great deal of information about a system is available, the initial subsystem goal parameters may not match the system requirements as ultimately stated. Another risk is that the system itself may never be approved or that, even if it is, the program manager may elect to develop another subsystem, rather than use the developed subsystem. Still another risk is that technology developments may make an early developed subsystem obsolete before it can be used. On the other hand, an early development may make available a long leadtime subsystem that otherwise might seriously delay an IOC or, as in the case of the T-64, it may make available a subsystem which another system, not originally contemplated, can incorporate. Through more available time, it might also produce a more mature subsystem and, thereby, reduce the need for Product Improvement Programs (PIPs). Also, it may forestall a premature system development decision by indicating a risk that may be unacceptable. These considerations lead to the following guidelines for deciding whether a subsystem should undergo early development. The decision maker should determine that:

- a. The subsystem is of the type that requires a long development leadtime relative to the development time of other subsystems.
- b. At least one, and preferably several, potential user systems are identifiable. Note that the detailed characteristics of the user system may not be known at the time that the decision to develop the subsystem is taken.
- c. No subsystem alternatives are available that would permit the system to be cost-effective in a minimally acceptable set of missions of the type for which the system is envisioned.
- d. Integration will not be a major problem. In other words:

1. The subsystem performance characteristics are alterable over a reasonable range, without requiring major development effort; the scaling laws governing changes in the performance of the subsystem are well understood or can be clarified during subsystem development. Alternatively, system requirements are of sufficient flexibility to accept the developed item.
 2. The subsystem can be repackaged without major development effort, allowing it to fit into the system without integration problems. Or, if such repackaging appears impossible, the system can be designed without difficulty to accept the subsystem.
 3. The environment of the using system will not adversely affect the performance of the subsystem. If the normal system environment is a problem, a controlled environment for the subsystem will be available.
 4. Conversely, the environment generated by the subsystem will have no adverse impact on the system or other subsystems. Alternatively, the environmental impact of the subsystem is controllable by appropriate packaging.
- e. System obsolescence stemming from technology changes in subsystem area will not be serious, because:
1. No developments are in view that will obsolete the subsystem, before the system development is started, or
 2. "Form, fit, and function" principles are applicable, or
 3. Expected benefits in the utility period of the subsystem exceed the expected costs.

2. Independent Development

Independent development (ID) is generally undertaken with the intention of developing a standard subsystem. The guidelines for such a case are stated under "Standardization" below. Sometimes, ID is undertaken without an intention to standardize and the applicable guidelines are as follows:

- a. More than one potential using system, including retrofits, is identifiable.
- b. Integration will not be a major problem. In other words:

1. The subsystem performance characteristics are alterable over a reasonable range, without requiring major development effort; the scaling laws governing changes in the performance of the subsystem are well understood or can be clarified during subsystem development. Alternatively, system requirements are of sufficient flexibility to accept the developed item.
 2. The subsystem can be repackaged without major development effort, allowing it to fit into the system without integration problems. Or, if such repackaging appears impossible, the system can be designed without difficulty to accept the subsystem.
 3. The environment of the using system will not adversely affect the performance of the subsystem. If the normal system environment is a problem, a controlled environment for the subsystem will be available.
 4. Conversely, the environment generated by the subsystem will have no adverse impact on the system or other subsystems. Alternatively, the environmental impact of the subsystem is controllable by appropriate packaging.
- c. The subsystem design parameters are adequately specified. In other words:
1. System design is complete enough to specify the subsystem, or
 2. System will be designed around the characteristics of the subsystem, or
 3. Subsystem is part of a family, whose characteristics span the expected system requirements.
- d. No subsystem alternatives are available that would permit the system to be cost-effective in a minimally acceptable set of missions of the type for which the system is envisioned.

3. Standardization

Among the cases examined in this study, several independently developed subsystems were standardized. Nevertheless, the basis on which the military services decide whether a subsystem should be independently developed and standardized is unclear and inconsistent. To be a candidate for independent development and standardization, a subsystem must satisfy the following conditions:

- a. More than one potential using system, including retrofits, is identifiable.
- b. Subsystem technology is mature and well in hand.
- c. The potential market is large enough. In other words:
 - 1. The market may be only large enough to support a single supplier for several years. Independent development and standardization are then appropriate, only if future prices can be adequately protected by devices such as a long-term pricing agreement.
 - 2. The potential market may be large enough to support two or more suppliers. Independent development and standardization may then be appropriate, provided that suitable steps (e.g., form, fit, and function standardization) are planned to ensure continuing competition.
- d. The projected overall benefits of standardization exceed its disadvantages:
 - 1. Whenever feasible, the cost-benefit analysis should include a comparative (but not necessarily an absolute) life cycle cost (LCC) analysis of standardized and nonstandardized equipment, including RAM (Reliability, Availability and Maintainability) and logistics. The maintenance concept must be sufficiently well defined to permit the determination of costs and required configuration control. In other words, if contractor repair is contemplated, form, fit, and function standardization is adequate. But if service repair is envisaged, detailed configuration control inside the repairable module is needed.
 - 2. If the LCC cannot be reliably estimated, the cost-benefit study should attempt to look at least several years into the future. It should use the cost of reliability improvement warranties or any other applicable technique as a proxy for LCC. The maintenance concept must be adequately defined for a meaningful result.
 - 3. If a cost advantage cannot be found, the advantage that might be obtained from the potential of a more attractive set of procurement policies should be considered. An example is continuation of competition after deployment through split buys. To be valid, the analysis must account for the maintenance concept and the required configuration control.
- e. Integration will not be a major problem. In other words:

1. The subsystem can be repackaged without major development effort, allowing it to fit into the system without integration problems. Or, if such repackaging appears impossible, the system can be designed without difficulty to accept the subsystem.
2. The environment of the using system will not adversely affect the performance of the subsystem. If the normal system environment is a problem, a controlled environment for the subsystem will be available.
3. Conversely, the environment generated by the subsystem will have no adverse impact on the system or other subsystems. Alternatively, the environmental impact of the subsystem can be controlled by appropriate packaging.

4. Discussion

We recognize that the guidelines are not easy to apply, although we have applied them to several cases (as discussed in Chapter V) and they appear to be useful. It is clear that they require knowledgeable, unbiased judgments, if they are to be successfully used.*

Moreover, the military procurement system has a built-in bias against independent or early development. Independent development is discouraged by a lack of funding. We have been told in interviews that it is also discouraged by the difficulty of getting program managers to accept developed items for their systems. Such a difficulty is compounded by the economic incentive given to prime contractors to develop new items, instead of using existing ones. The case studies provide little data to support these statements, but they appear to be common impressions supported by logical inference. If it is real, this bias has a deleterious effect on the costs, operability, and timeliness of major U.S. military systems.

* Chapter V describes situations as they were perceived by IDA at the time of writing this report. During the course of this research project, some of these programs changed in significant ways. Hence the facts as well as the conclusions relating to specific subsystems may no longer be relevant. Nevertheless, we stress the purpose of Chapter V, which is to illustrate the method of using the guidelines and not to present an assessment of these programs.

Standardization of subsystems and components tends to happen only when the procuring service takes special action to make it happen. Even more, it may require a strong central organization with technical and procurement competence to guide the standardization effort. The development and use of a standardized subsystem depend on certain factors. To a large degree they depend on the organization of the procuring service and the attitudes of the program manager and the prime contractor, rather than on the intrinsic merits of using a standard item. The Army, through its commodity command system, seems to have the best organization for promoting standardization. Yet, even the Army has no methodical way of selecting subsystems and components, or even selecting commodity areas, in which standardization efforts should be concentrated.

The difficulties are multiplied manifold in the question of commonality between the military services. Our investigation uncovered only two areas in which an organized effort to achieve interservice coordination is authorized--munitions and FLIRs. The AMRAD (Air Munitions Requirements and Development) committee, attached to ODDR&E, is responsible for interservice munitions standardization. So far its efforts seem to have had mixed success, despite the fact that it has access to the highest level at the Pentagon for making its recommendations (Ref. 10). The FLIR standardization program has reached an advanced status because of the technical capability, professional standing, procurement skill, and persistence of the Army's Night Vision Laboratory (see Appendix F) and because of the strong backing by ODDR&E.

G. SUGGESTIONS

1. Primary

As a consequence of this study, we believe that substantial benefits can be derived from the selective use of early development, independent development and standardization of subsystems.

Nevertheless, such a use is not a panacea for the problems that affect military procurement of high technology systems. Considering the limitations and, sometimes, the contradictory nature of the available data, we suggest that ODDR&E review the guidelines offered in this study with a view toward verifying, modifying, and then implementing them. Potential implementation actions that might be undertaken, with a final set of guidelines, are:

- a. Use of Guidelines by DDR&E. Through its powers to approve or disapprove subsystem development, ODDR&E can encourage ED, ID, and standardization of subsystems when appropriate. The guidelines can be used as a basis for deciding and encouraging the early development and standardization of subsystems.
- b. Dissemination of Guidelines to Service Development Commands. The initiative for subsystem development often comes from the development commands of the military services. Therefore, the guidelines should be disseminated to such commands for comment and possible use.
- c. Use of Guidelines in the DSARC Process. This process initiates the development of a major system. But it is usually too late for it to become involved in early-development decisions. However, both DSARC Review I and DSARC Review II are charged with considering the use of available subsystems versus the development of new subsystems. To the extent that these reviews tend to favor developed systems, the military services should be encouraged to undertake the early development of subsystems, when they meet the right conditions. Accordingly, the DSARC reviews might indicate the desirability of having developed subsystems available, when conditions are favorable.
- d. Encouragement of Standardization Efforts. Subsystem standardization does not tend to occur, unless a competent, persevering organization is leading the effort. Accordingly, subsystem standardization under appropriate guidelines, might be encouraged by designating lead organizations (e.g., service laboratories or procurement agencies) in each area of interest and providing specific program funding for justified standardization efforts.

2. Secondary

The following suggestions concern aspects that indirectly affect subsystem development:

- a. Restrict advances in the state of the art, during an engineering development, to only one undemonstrated characteristic. If several advanced characteristics have been demonstrated individually, but not in the same piece of hardware, proof of the concept should be demanded before engineering development is undertaken.
- b. Use more realistic demonstrations of proof of concept before accepting a new subsystem in an engineering development.
- c. Increase emphasis on questions of reliability and availability at DSARC III. In particular, attention should be given to future plans for reliability improvement after system operation begins and independent judgement of the realism of the plans and the prospects for their success.
- d. Explore the opportunity to use a lead-the-force plan to provide RAM data, before deployment of the next major system. If the plan is used, carry it through to completion.
- e. Examine the tradeoffs between highly optimized subsystems vs. subsystems capable of being tailored for various uses, paying particular attention to new turbine engines.

I. INTRODUCTION

A. OVERVIEW

Current procurement practices in the U.S. military services discourage the engineering development of subsystems, except as part of a total system under the control of a system manager. Little subsystem development takes place unless there is a "home" for it. There are exceptions, and some occur among subsystems that perform certain functions which are clearly common, i.e., communication, navigation, sensing, and computing. But even among such apparently common functions, there is an excessive proliferation of equipment that is developed by or for prime contractors to perform these functions in specific systems. Sometimes, a subsystem that has been developed for one system is adopted for another, but there is no consistent mechanism by which this occurs.

The latest DoD directives on acquisition provide brief mention of subsystem developments. We quote these here and then discuss their implications for the various alternatives we consider in this study.

Directive No. 5000.26, dated 21 January 1975 (Ref. 1), describes the makeup, duties, and guidelines for the Defense Systems Acquisition Review Council (DSARC). Only two points in this document mention subsystems explicitly. These are:

DSARC I (10). *The use of currently available subsystems versus development of new subsystems, has been or will be considered.*

DSARC II (8). *The approach for selection of major subsystems has been clearly identified and the program has considered the use of currently available subsystems versus new development (including test and support equipment).*

Of course, there are a number of other guidelines in this directive which imply that consideration should be given to subsystems, but the above two are the only places where subsystems are mentioned explicitly.

Subsystems are also mentioned twice in the DoD Instruction on Selected Acquisition Reports (SAR) No. 7000.3, dated October 1975 (Ref. 2):

B.1. Program Highlights. Briefly summarize the significant developments in the program including the current status of related systems and key subsystems, except for those covered by separate SARs...

C. Technical Section

Operational/Technical Characteristics. These characteristics are to be grouped as "operational" or "technical." The list should include the characteristics for which DCP thresholds exist, principal performance requirements of the contract, meaningful characteristics pertaining to key subsystems, and any other characteristics considered significant.

A reasonable interpretation of these statements is that they recognize the existence of, and need for, subsystems and provide instructions that they be considered, but they do not constitute a policy for early or independent development of subsystems.

Of the various recent procurement documents that we have seen, only one provides explicit policy guidelines for the kinds of subsystem developments we discuss in this study. This is the recent publication of the Office of Management and Budget (OMB) on the subject: Major System Acquisitions, (Ref. 3). Paragraph 11-j of this document states:

Development of subsystems that are intended for use in a major system should be restricted to less than fully designed hardware until the subsystem is identified as part of a system candidate that has been selected for full-scale development. Exceptions may be authorized by the agency head if the subsystems are long lead time items that fulfill a recognized generic need or if they have a high potential for common use among several existing or future systems.

In the cases we examine here the first sentence of this guideline has been observed with high consistency, while the second sentence has been honored more in the breach than in the observance. As we discuss later, the acquisition system has a built-in bias against full-scale engineering development of subsystems that might qualify as exceptions, under this guideline although it is clear that such bias is not derived from explicit procurement policy. Nevertheless, the exceptions are the basic subject of this study which sets forth guidelines for identifying such exceptions.

Considerations in this study are limited to major subsystems and components such as propulsion, transmission, communications, navigation, airborne radars, etc., and to development beyond demonstration or feasibility (engineering development).

The primary vehicle for analysis is a series of case studies of the development history of different types of systems. The selection of system types for case study was more or less arbitrary, constrained only to include systems that represent all three military services and a range of different missions. The findings are based primarily on this limited set of cases. But we believe that the case studies have helped to focus our efforts on the essential issues relevant to the questions we have tried to answer.

However, we caution the reader that the methodology falls short of substantiating the findings with proof. We do relate findings to specific cases. But because the number of cases is limited, we have used our judgment in determining the importance and generality of the findings.

B. STATEMENT OF PROBLEM

The military services have no coherent mechanisms for early development of long leadtime subsystems. In fact, some major subsystems became available early through processes that might

be characterized as being accidental. In addition, no systematic method is used to select subsystems for standardization.

The following practices prevail in the development and acquisition process: Program managers and prime contractors undertake to develop what is needed for the system for which they have responsibility; there is no consistent way of achieving coordination among program managers and contractors to determine where commonality would be possible and beneficial. Occasionally, development of a long leadtime item, such as an aircraft engine, is funded on a speculative basis. But, most often such a development is intended for a specific use. Among the systems examined in this study, common usage of subsystems is exceptional; institutional arrangements tend to maintain this situation.

These practices contribute to several problems:

1. Poor field reliability of systems, which may be caused by excessive concurrency (which reduces test time) between the development of the system and development of its major subsystems.
2. Schedule slippage of major programs, caused by inadequate or late development of a pacing, critical subsystem.
3. Unsatisfactory performance of a major system, because of the inadequacy of an important subsystem. (In an extreme situation, the entire development may be aborted.)
4. Lack of competition in the military equipment market after the award of the development contract or initial buy. This places the Government at the mercy of the sole supplier and often results in excessive acquisition costs.
5. Proliferation of subsystems intended to perform similar functions, with attendant high production costs traceable to small volume and high logistics costs traceable to noninterchangeability.

In this study, we examine the feasibility and utility of ameliorating these problems through early development of subsystems and, where appropriate, through independent development and standardization of subsystems.

We emphasize that a decision to move a development project from advanced development (6.3) status to engineering development (6.4) is a major one. It normally implies a commitment to increase the rate of funding as well as a commitment to produce operating hardware. The potential magnitude of the increase in funding is estimated in Table 2 which presents the service expenditures in RDT&E Categories 6.3 and 6.4 for the fiscal years 1973-75. The average DoD project in engineering development is funded at a level which is about 2.4 times the funding of the average project in advanced development. The table shows substantial variations from this average factor among the services. There are also substantial variations among projects.

TABLE 2. MILITARY RDT&E APPROPRIATIONS, FY 1973-75

	Category 6.3			Category 6.4			\$/Item Ratio 6.4/6.3
	Total \$M	Items	\$M Item	Total \$M	Items	\$M Item	
ARMY							
1973	408.3	48	8.51	498.5	33	15.11	1.78
1974	473.6	45	10.52	531.2	41	12.96	1.23
1975	<u>515.9</u>	<u>46</u>	<u>11.21</u>	<u>518.2</u>	<u>41</u>	<u>12.64</u>	<u>1.13</u>
Total Army	1397.8	139	10.06	1547.9	115	13.46	1.34
NAVY							
1973	492.4	86	5.72	798.3	50	15.97	2.79
1974	541.0	82	6.60	1029.1	47	21.90	3.32
1975	<u>599.5</u>	<u>82</u>	<u>7.31</u>	<u>1199.3</u>	<u>50</u>	<u>23.99</u>	<u>3.28</u>
Total Navy	1632.9	250	6.53	3026.7	147	20.59	3.15
AIR FORCE							
1973	383.1	43	8.91	964.6	41	23.53	2.64
1974	390.0	39	10.00	921.4	34	27.10	2.71
1975	<u>506.1</u>	<u>40</u>	<u>12.65</u>	<u>988.1</u>	<u>39</u>	<u>25.33</u>	<u>2.00</u>
Total Air Force	1279.2	122	10.49	2874.1	114	25.21	2.40
Total All	4309.9	511	8.43	7448.7	376	19.81	2.35

SOURCE: Defense/Space Daily, October 17, 18, 23 and 24, 1974.

A simplified representation of the development process is shown in Fig. 1. The flow from the technological base to a hardware production program is taken through several decision points that are related to subsystem development. These decision points provide the focus for this study.

C. DEFINITIONS

Independent Development (ID). Development of items outside the control and funding of a major system program manager any time after the program office has been created (post-DSARC I). Standardization may follow ID.

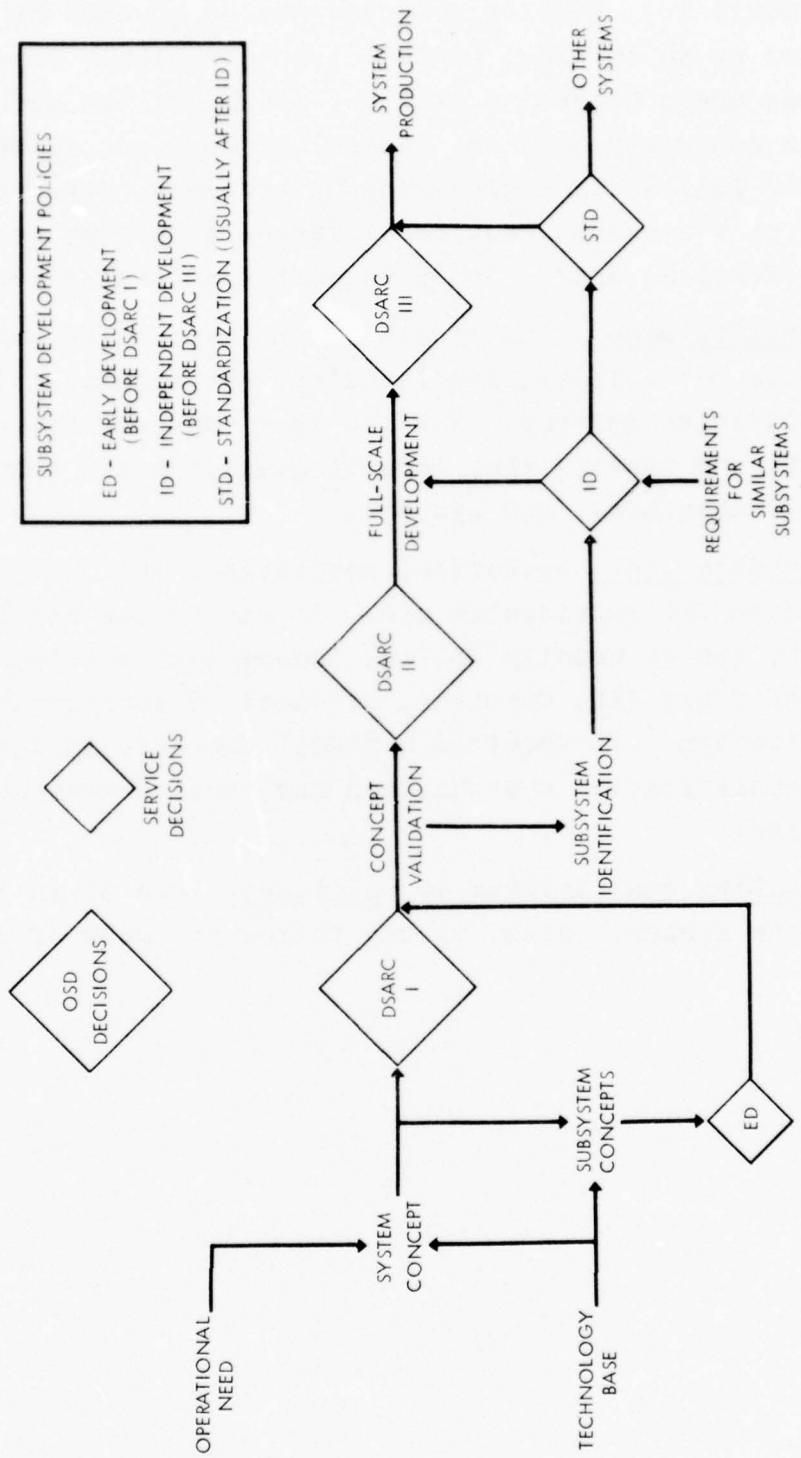
Early Development (ED). Initiation of full-scale development of items prior to the creation and funding of a major program office and before identification of a specific using system. Such development would occur before DSARC I in systems that meet the cost threshold. ED is speculative, since the subsystem may not be used even though it achieves its development goals. It would be the exception cited in Paragraph 11-j of the OMB circular quoted earlier.

Directed Development. Development of items for a major system under the control and direction of the system program manager. This would be consistent with the first sentence of Paragraph 11-j quoted earlier.

Technology Base. Knowledge and capability to develop and produce military hardware. Results from all previous research and development and production activities in the nation. It includes foreign contributions, insofar as information access is available and used.

Beyond Technology Base. Initial stages of development to address potential alternate solutions to a specific mission area need (6.3B)*. If they are successful, work will proceed to full-scale engineering development (6.4) for completion of developmental work. [All 6.3B work is post-DSARC I, if program is large

*These are references to DoD budget category paragraph numbers.



SUBSYSTEM DEVELOPMENT POLICIES

ED - EARLY DEVELOPMENT
(BEFORE DSARC I)

ID - INDEPENDENT DEVELOPMENT
(BEFORE DSARC III)

STD - STANDARDIZATION (USUALLY AFTER ID)

FIGURE 1. Decision Points for the Various Subsystem Development Policies Considered in This Study

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enough to merit it. Smaller programs may be covered by Program Memoranda or by an informal DSARC I type decision. Does not include gray areas between 6.3A and 6.3B, where the nature of the work is generally 6.3A and technology does not support decision for full-scale engineering development, although the complexity of the system requires a large technology prototype, e.g., Navy Vertical and/or Short Takeoff and Landing (VSTOL).]

Operability Base. The knowledge and capability that lead to acceptable reliability, availability, and maintainability (RAM) in operating systems. Results from previous research, development, and testing that include qualification testing of components, subsystems, and systems.

Standardization. Selection, adaptation, and qualification of a subsystem for multisystem use. It may follow any form of development, but it usually follows independent development. It may be of form, fit, function, or detailed configuration and specification. It requires a formal process, including extensive qualification testing, and may require contractor qualification.

Commonality (multisystem or multiuse). Use of an item in more than one system. Also, it may follow any mode of development.

II. CASE STUDIES

The manner in which the various subsystems considered in this study were acquired is summarized in Table 1. Further details are given in Chapter III. In Table 1 we have tried to indicate which of five acquisition methods was most applicable to each subsystem, although in some cases more than one may have been instrumental in bringing the subsystem into existence. Most of these acquired subsystems are discussed in detail below, along with our observations. The acquisition methods used by each of the military services are described in brief at the end of the chapter.

A. AIRCRAFT ENGINES

1. Turboprop and Turboshaft Engines

The acquisitions of two types of engines were examined: the T-53 and T-64. The T-53 was initially an early development, contracted for by the Army Ordnance Corps before a system design requirement was acknowledged. The only identification of need in this case was that the Army would require a four-place, turbine powered helicopter. About six months after this initial specification, the Army decided that it needed a more powerful engine, and the initial design was scrapped.

Even after this, the T-53 engine was modified several times in the course of its user system (UH-1) development to increase its power. One of these upratings occurred after extensive field operations, by the Army, of a large number of aircraft, which indicated that increased power would be desirable. Fortunately, it was possible to uprate the engine without major new development.

TABLE 1. CASE STUDY SUBSYSTEMS

Subsystem	Using Systems	How Acquired ^a					Reference ^c
		1	2	3	4	5 ^b	
I. AIRCRAFT ENGINES							
A. Shaft Engines							
1. T-53	UH-1, AH-1		✓			✓	A
2. T-64	H-53, AH-56A, XC-142, others		✓			✓	B
3. T-700	UTTAS, AAH, LAMPS			✓			V (Ch.)
4. Navy Proposal	UTTAS, AAH, LAMPS, HXM			✓			V (Ch.)
B. Thrust Engines							
1. F-100	F-15	✓					H
2. F-100	F-16					✓	H
3. F-401	F-14	✓					H
II. ROCKET MOTOR							
	SRAM		✓				E
III. TANK ENGINES							
AGT-1500	XM-1 (Chrysler version)					✓	C
AVCR-1360	XM-1 (GM version)					✓	
IV. AUTOMOTIVE TRANSMISSIONS							
X-200	M-113		✓				C
X-300	MICV	} Proposed	✓				C
X-1100	XM-1		✓		✓		C
V. HELICOPTER DYNAMICS							
Bell	UH-1, AH-1		✓			✓	A
Lockheed	AH-56A		✓				B
VI. AIRCRAFT WEAPONS							
Chin gun turret	AH-1		✓	(Adapted from IRAD) ^d			A
GAU-7	F-15		✓				D
VII. RADARS							
APG-63	F-15			✓	(Contractor)		J
WX-200	F-16			✓	(Contractor)		J
SPG-49	Typhon		✓				I
ANSPY-1	AEGIS		✓				I
VIII. AVIONICS							
SCAS	UH-1, AH-1		✓				A
IHAS	Various helicopters				✓		B
ARBS	A-4M, Harrier				✓		G
Proposed standard INS	F-16, C-135, C-141					✓	V (Ch.)
Standard airborne computer	F-18, LAMPS, etc.					✓	V (Ch.)
IX. IR SENSOR							
Standard FLIR	OV-13, UH-1, F-4, etc.					✓	F
X. GUIDANCE							
Aimpoint	Mace, Matador, Pershing II, etc. (Proposed)					✓	V (Ch.) & L

KEY:

- ^a1. Directed development
2. Early development
3. Independent development
4. Independent development and standardization
5. Inherited

^bThe second user of a subsystem is considered to have inherited it.

^cExcept for Chapter V, there are appendices giving detailed developmental histories. Note that Chapter V contains guideline tests applied to four new subsystems.

^dIndependent Research and Development (IRAD).

The T-64 engine was developed by the Navy on a speculative (ED) basis. At the time that the development contract was initiated, the engine had no specific "home." The specification called for an engine in a particular horsepower range, suitable for powering three types of future Navy aircraft, none of which was in development. The specification also called for multi-purpose capability (turboshaft and turboprop) and for a capability to grow in power. The major users of the engine were the various versions of the H-53 helicopter; it was also selected for use in a number of fixed wing aircraft. It might have had another user, the AH-56A Cheyenne, but that program was cancelled for reasons not related to the engine. One other point worth noting is that the compressor section of this engine had been developed by General Electric under IRAD and was one of the bases on which the contract award was made. In the full subsystem testing, this compressor developed problems and had to be reengineered.

OBSERVATIONS: The rating target initially selected for the design power of the T-53 engine was too low and resulted in a loss of some engineering effort. Moreover, even after the system was completely defined and the requirements were much better known, the design power was found to be inadequate. The ability to change the engine's characteristics, particularly its power, was a highly useful feature of this engine design.

The notion of flexibility in performance and function in the initial specification of the T-64 engine had a high payoff, in providing a useful multipurpose engine in a timely way. The flexibility permitted multiple uses of the engine, since it could be tailored with minimal development effort to different applications. However, this flexibility was not obtained without penalty: for any single use, the engine was probably heavier and less efficient than if it had been designed

specifically for that use. A requirement for power upgrading during the Cheyenne program was easily met. Another observation that ensues from the T-64 case is that a component, no matter how highly developed and tested as a component, must be integrated and tested with its operating system before its suitability and operability can be certified.

2. Turbofan Engines

The engines for the F-15 and F-14B aircraft were under development by the same contractor at the same time. A 75% increase in design thrust-to-weight ratio was to be achieved through the use of new technology. When technical problems appeared that looked unsolvable, the requirements for the F-15 engine (designated the F-100) were relaxed somewhat, and time and resources were made available to complete the development.

The problems of the engine for the F-14B (designated the F-401) were not as simple to solve. The engine was to use the same engine compartment and air inlet that housed the TF-30 engine, which was being used to power the F-14A. It was intended to have more thrust than the TF-30, although its air flow and size were limited to the same envelope as that of the TF-30. To save weight, the engine's structural rigidity was compromised, which resulted in compressor-blade tip rubs. Significantly, these problems were experienced in the engine testing program during the airplane program. If the engine were to be qualified in time for incorporation in the F-14B program, hurried, expensive, high-risk developments of a number of new components would be necessary. The decision was made to terminate the development program of the F-401 engine for the F-14B, although the engine itself remained in advanced development. The Navy investigation, after the termination, found that the technology base was insufficient to meet the goals of the development; also, attempts to advance the component technology in this development involved steps that had not been demonstrated.

OBSERVATIONS: A new engine development that involves a significant advance in technology may require several years of lead time over that of an airframe. Sometimes, requirements are unrealistic, and performance goals that are set a priori cannot be achieved within the time schedule. In the case of the F-401 engine, requirements for very light weight led to structural deficiencies (engine too flexible) and to a materials mismatch. In part, this was attributable to misjudging the technology base, which stemmed from the interpretation of the results from the advanced engine technology demonstrator.

The problems were exacerbated by an inadequate knowledge of aerolastic phenomena scaling, which is a major problem for advanced engine designs. Extensive testing and development of full-scale articles must be provided over the range of operating conditions. Furthermore, program rigidity should be avoided. That is, there should be flexibility to make changes in specifications during development, without a major revision of the contract. A small relaxation in a performance requirement can yield a large improvement in such a factor as aeroelastic stability, e.g., moving away from the blade flutter boundaries. If the F-401 engine development had started earlier, or if the component technology base had been further advanced, the engine development program might have met its objectives. An alternative would have been to back off from the performance and installation requirement (as was done with the F-100 engine) and accept an engine whose performance would not be sufficiently better than the engine already being used in the F-14A. This alternative, which would have been difficult to justify, was turned down by the Navy.

Finally, we note that changes in mission performance requirements, occurring between the original engine request for proposal and the source selection time, cause long-range problems (i.e., component improvement programs).

B. SRAM ROCKET MOTOR

The SRAM (short-range attack missile) system used no on-the-shelf subsystems or major components, because the requirements were so stringent that advances in the state of the art were needed to meet them. The SRAM rocket motor involved several significant advances in technology. These included a solid rocket motor capable of cycling on and off and a high total impulse in a relatively small volume. Both features had not been demonstrated in a single motor prior to this development. Because of the intense competition for the development contract for the SRAM motor, the competitors greatly underbid (factor of 10-11) the development costs. Since this was to be a fixed-price contract, they clearly had the expectation of recouping excess development costs from the production contract. Technical difficulties during development were followed by litigation among the prime contractor (Boeing), the Air Force, and the rocket developer (Lockheed), with Lockheed claiming it should receive more money for developing the motor despite the fixed-price contract. One basis for the Lockheed claims was that the specifications had changed very late in the proposal period and that the contractor did not have adequate opportunity to study them before the proposal had to be submitted. The system came perilously close to failure during development, because of the rocket motor problem. However, in the end, some remission of the performance requirement (reduced range at low altitude) and some renegotiation of the contract terms resulted in a system that performed essentially as required.

OBSERVATIONS: The SRAM case illustrates two sides to the important question of development risk. On one side, the development risk was very high, because the required rocket motor was highly sophisticated and depended on technology that was not in hand. If the rocket motor development could have been started earlier, much of the grief might have been avoided, and development costs might have been reduced. (The need to take multiple approaches to meet the schedule on such a complex development is very costly.) On the other side, the rocket motor might have received early development without a detailed knowledge of the characteristics of the system in which it was to be used. Then, significant environmental problems (such as heat soak or vibration), which could only have been determined by a detailed system-requirements study, might have been neglected. It is difficult to state which side predominates. It appears that the procurement was undertaken without an adequate technology base, particularly in solid-fuel rocketry. And a further demonstration of rocket capability should have been requested before such stringent requirements were specified. Minor easing of the volume restrictions might have notably decreased the development risk of this program. We note, however, that these statements are made in the face of the fact that the SRAM appears to be a successful development, which in the end met its (adjusted) performance, cost, and schedule.

C. TANK ENGINES

Two engines are candidates for powering the XM-1 tank, currently under development. The AGT-1500 engine is a 1500-hp turbine engine, which has had substantial testing (over 8000 hours), including 12,500 miles in vehicular operation. This engine appears to be ready for adaptation to the XM-1 tank, and production planning has started.

The second engine, the AVCR-1360, is a piston engine with a variable compression ratio. It will provide about the same power as the AGT-1500 will and is in about the same state of development.

Both engines have been inherited from previous tank programs that have been canceled. In fact, development of both engines ceased for awhile, but it was revived when the possibility of their use revived. Both engines were partially developed under IRAD and technology base funding as well as funding from tank programs. For the XM-1 tank, we consider the engines to be inherited.

OBSERVATIONS: *The XM-1 tank has two comparatively low-risk engine options as a result of development work undertaken previously for canceled tank programs. If neither of these engine developments had been started as early as they had they might still have been started in 1972, with the expectation that they would be ready for system production by 1979. But the risk of development would have been higher, and there would have been no developmental engine on which to base system decisions. These early developments resulted in the early availability of the engines, which influenced the tank system decisions, and significantly reduced the risk in developing the new tank.*

D. AUTOMOTIVE TRANSMISSIONS

The Army has developed a family of transmissions that were intended for use in a variety of armored vehicles. These include the ARSV (Armed Reconnaissance Scout Vehicle), the M113A1 APC (Armored Personnel Carrier), and the MICV (Mechanized Infantry Combat Vehicle). The largest member of the transmission family is the X-1100, which is being developed for both versions of the XM-1 tank, as well as for retrofit into the improved M-60 tank.

It fits these different roles by using a modular design in which different input sections, adaptable to the characteristics of the different engines, are utilized. The members of the transmission family also have parts that are interchangeable with commercial transmissions. From the large volume of data on commercial truck and car transmissions, the manufacturer of these transmissions has developed methods and data for predicting the performance and the reliability of each component. Experience has shown that this information is scalable to components and subsystems of different ratings, though it is still necessary to perform total systems testing in each new type of vehicle.

OBSERVATIONS: A family of transmissions has been developed by the Army largely through independent development, by TACOM or its predecessor organization although various members of this family are linked to specific vehicles that use them. The development of the family was assisted by the ability of the contractors to scale up power ratings, an ability that stems from the knowledge gained from extensive commercial development. It appears that the scaling can be applied, not only to performance factors, but also to reliability and durability.

Usually in military transmissions, which are designed for low-volume production for a specific system, the provision for growth is less than that typical for commercial products. Modifications are paid for by the military customer; incentives do not exist to create designs capable of growth.

Despite the ability to predict reliability and performance in scaling to different sizes, it is necessary to run full system qualification tests, since other components in the system might impact on the performance and RAM of the system. At least, in the automotive area,

it appears possible to design components and subsystems to a tentative specification, while allowing for future growth. Such designs can be tested and debugged. Then, if it becomes necessary to change the specification somewhat to meet the needs of the system, the subsystem or component can be redesigned. The new design will not require as much testing as will the original design, because the original testing results will still be applicable. Thus, it should be possible to fund such long lead items in advance of the time when a final specification is known, and decrease the need for concurrency in the development of components and system. The system designer would then proceed to design his system with lower risk and with some likelihood of overall savings. The savings would accrue, because concurrent development sometimes creates a need for multiple simultaneous approaches to increase the likelihood of timely success, a need that is obviated when a developed subsystem is at hand.

E. HELICOPTER DYNAMIC SYSTEMS

In this section, we refer only to the helicopter drive and rotor systems. The engines discussed earlier are not included. The dynamic system of the UH-1 helicopter was developed, as part of the aircraft system by the prime contractor. The AH-1 used the dynamic system that had been developed for the UH-1, but with a different fuselage configured around it. However, by the time the AH-1 development had been started, the dynamic system had gone through some evolution, and the contractor's knowledge of it was relatively mature. But in any case, the AH-1 helicopter inherited its dynamic system from the UH-1, and no scaling was necessary to make the adaptation. Instead, the AH-1 was scaled to the available dynamic components.

In the case of the AH-56A (Cheyenne), the circumstances were somewhat different. The Cheyenne development depended on a new technology that had been successfully demonstrated on a smaller prototype vehicle. In fact, the successful prototype was the basis for the system proposed by the contractor. In the course of this development, the contractor tried to scale up the old system. But he ran into difficulties: specifically, serious rotor control instabilities in certain flight regimes. Although the existence of such instabilities had been recognized in the earlier vehicle, it had been possible to configure the flight envelope around such conditions, thereby avoiding them. This was not possible with the larger prototype machine, and disaster resulted.

OBSERVATIONS: *Helicopter dynamic systems are the primary basis for helicopter design and performance. Consequently, they do not seem to be good candidates for early development. But certain components of the dynamic systems, such as transmissions, might be candidates for early development provided their scaling is well understood (see discussion under automotive transmissions above). In addition, the scaling of helicopter dynamic systems does not appear to be a well understood art; therefore, it is necessary to test and qualify dynamic system components at their full size. The Cheyenne failure might not have occurred, if the technology base had been developed to support it, or further analysis and testing had been accomplished. In this case, early development might not have been possible, but it would have been better to have held up the development until more knowledge was available about these kinds of systems.*

F. HELICOPTER WEAPON SYSTEMS

Helicopter weapon systems have constituted existing ground or airborne weapons adapted to helicopter airframes. At first, such adaptations were relatively primitive (e.g., hard-mounting machine guns or rocket pods on landing skids). Then, after

the deficiencies of this type of adaption were recognized in the early 1960s, the combined efforts of helicopter manufacturers and weapon manufacturers resulted in flexible side mounts, turrets, and universal pylons on which a variety of weapons could be carried and operated. This activity eventually produced the first attempt at an integrated prototype gunship, in which two M-60 machine guns were installed in a turret, chin-mounted on an H-13 (Sioux Scout helicopter). The aircraft was configured with tandem seating to reduce drag; also, side-arm flight controls were installed to provide space for the gunner's sight. This demonstration prototype, which had been assembled under IRAD funding, became the basis for a full-scale weapon helicopter development, the AH-1. The demonstration also evoked the concept of the AAFSS (Armed Aerial Fire Support System). This was to be a highly sophisticated helicopter weapons aircraft, but its development was never completed (see Appendix B). The Armed Attack Helicopter (AAH), presently in prototype competition, is also an outgrowth of this earlier development. Even in this case, however, no new weapons have been developed expressly for this system.

OBSERVATIONS: Typically, helicopter weaponeering has involved the integration of an existing weapon and a fire control system with a helicopter airframe. No weapon has been developed exclusively for helicopter use. Rather, weapons have been adapted to this use, sometimes after solving complex integration problems.

The typical behavior of the industry has been to develop prototype systems under IRAD and then to interest the military in funding full-scale development. While, in some cases, the developments may have involved significant changes in the peripheral equipment used for the weapon system, they did not involve developing new weapons. In none of the cases was the aircraft development significantly impeded by a weapon development,

since the weapons had been developed under other programs and were available for inheritance by the helicopter weapon systems.

G. RADARS

The weapon system radars that we have looked at in this study include the ASG-18 intended for the F-108, YF-12, F-111B, and F-14A. Originally in 1959, this radar was a concurrent development for the F-108 airplane. However, when that airplane program was canceled, the radar development was continued for use in the YF-12 (1960), then in the F-111B (1962), and finally (1967) in the F-14A. Although the radar was changed somewhat for each application, in its final role in the F-14A it had a mature design that could provide the required performance.

The APG-63 radar, which is used on the F-15 airplane, is a descendant of the ASG-18. But it employs some modes of operation that are different from those of the ASG-18. The design was based originally on company funded and IRAD funded work and was selected in 1968 after a funded competition, which involved flying brassboard radars developed for competitive flight evaluation.

Similarly, the radars for the F-16 and F-18 originated from independent work on new radars, which were brought to a stage of laboratory demonstration and then funded by the Air Force for use on flying brassboard radars tailored to the F-16 requirements. Both these radars are built to accept modules that will increase their performance.

OBSERVATIONS: *Each of the F-14A, F-15, and F-16/18 radars benefitted from previous government support on other radar programs. The F-14A and F-15 radars are lineal descendants of the ASG-18, originally developed for the F-108 (canceled) and later used in the YF-12 and F-111. The F-14A radar is a somewhat improved ASG-18.*

The F-15 radar represents an interpolation in performance within the performance boundary of the F-14A radar, but with a new medium PRF mode. The two F-16 radars evolved from company-funded developments, as well as substantial previous government support of operational and brassboard radar developments.

The F-15 and F-16 radars are examples of radar developments within the maximum performance supported by the available technology base or state of the art. Experienced contractors can be expected to develop such radars with low risk. Also, when the state of the art is not being advanced, contractors can make tradeoffs that permit flexibility and compromises that can reduce costs. Moreover, when the state of the art is well advanced compared to what is demanded of it, the radar procurement offers little risk to the scheduled development of the aircraft.

Generally, in the latest developments of these radars, the contractors had available several viable approaches for each subsystem. Although, in some cases, there were substantial differences in the components selected by the different contractors for the same function, both outcomes were satisfactory. The previous-development history of these aircraft radars can be considered as independent development that led to the F-15, F-16, and F-18 radars, although there was concurrent development to refine the specific configurations in each case.

Finally, it appears that when the state of the state of the art in radar is well advanced compared to the performance demands that are made upon it (i.e., the contractors are working within the state of the art and not advancing it), the development can emphasize the

aspects that are often neglected in advancing the state of the art such as producibility, cost, and RAM. Conversely, if the state of the art is being pushed, one can expect these other factors to suffer as the contractor concentrates on meeting performance specifications, particularly if he is limited to a single unsatisfactory choice of a radar component. Under such circumstances, a contractor may slip schedules and costs while trying to make such a component work properly. In the cases of the F-15, F-16, and F-18 radars, the state of the art was sufficiently mature, the technology sufficiently advanced, and the packaging well developed. As a result, there was no large problem in integrating the radars within the physical constraints of the aircraft and retaining radar performance, despite the relatively small radome that limited the antenna size.

H. FORWARD-LOOKING INFRARED SENSORS (FLIRS)

During the 1960 decade, FLIRS achieved very good performance. But the market was limited and unit prices were high. With strong encouragement from ODDR&E the Army's Night Vision Laboratory (NVL) at Ft. Belvoir, the lead laboratory in the infrared area, studied the market and concluded that the market for FLIRS could be increased considerably and prices reduced significantly through a major standardization effort. NVL used its position as the major service funding agency for infrared R&D to force the standardization of IR related detectors and then the development of designs to form the basis for a standardization effort. Apart from the development of suitable designs, the NVL program included adequate documentation and the development of second production sources for the various modules that composed the designs. In the program, it became clear that the repair philosophy dictated the requirement for documentation. "Form, fit, and function"

standardization might have been adequate for throwaway modules. But for modules that were to be repaired by the military services rather than by the contractor, it was necessary to control the configuration and to acquire detailed information on the internal structures of the modules.

The program to develop a standard FLIR and an adequate production base took five years. The reduction in price that the program has yielded is significant. In the case of the TOW, the FLIR system cost has been reduced from \$60,000 to \$11,000 (Ref. 4). Although few standard FLIRs have been produced to date, contracting has been completed by the Army for a large number of these systems.

OBSERVATION: NVL had the advantage of having no competition from other service organizations in the infrared area. It was necessary for NVL to maintain its continuity of purpose for five years to accomplish the standardization. It was also necessary to find ways of ensuring volume production by two or more suppliers to maintain competition. This entailed the development of a suitable production data package and an industrial base. It was also necessary to define the repair philosophy early so that configuration control could be implemented, if necessary, for service repair. It is clear from this example that a strong central guiding organization, capable of developing both technology and an industrial base, is essential to successful standardization.

I. SERVICE ACQUISITION METHODS

The military services use different methods for the acquisition of subsystem hardware. In the Army, a formal paper such as an ROC (Required Operational Capability) provides the authority and budget to ensure that standardized items are developed and used. An ROC is developed to cover some kinds of capability such as aircraft survival, target sensing, and navigation for a variety of aircraft.

The Navy's system is similar to that of the Army, except that funding for commodity development and procurement must come from the system program. This creates scheduling problems, since the funds are not usually made available to the commodity manager until sometime after the program has been funded. Moreover, the Navy commodity manager does not have the authority to force standardization decisions. Instead, he must persuade the program managers to accept standard items. Only in relatively few instances has the Navy commodity manager obtained advance funding, so that he can independently develop a standard item for inclusion in a number of systems.

The Air Force does not use a commodity command organization. However, it has undertaken a program to develop certain standard items (e.g., inertial navigators), which are to be used in new aircraft and also to be retrofitted in some old ones. The program is using the services of ARINC, Inc., a private firm that was originally set up by the commercial airlines to provide such services. ARINC plans to use the same basic technique for the Air Force as it has used in developing airline equipment specifications.

III. DEVELOPMENT OF LONG LEADTIME ITEMS

A primary consideration in an early development decision, with respect to the acquisition of major subsystems whose development time is long relative to the other parts of a systems, is whether the subsystem should be the development pacing item in the system of which it is to be a part. Major programs require about 7 to 12 years for system development to deployment; major components often require about 5 to 10 years of development time. These two time periods can be concurrent to some extent. But excessive telescoping of these times has led to problems, because important system functions have been based on components that were not always suitable in the field. For critical components, it is desirable to demonstrate their ability to perform under field conditions, before the system concept is firmly decided. This means that for these critical components, the lowest risk is incurred when component development and system development times are consecutive. But this is difficult, because developments are not normally done in a leisurely manner. Rather, they are pushed to get useful hardware as rapidly as possible, once the decision has been made to go ahead with development. There are several reasons for this acceleration in development: existing hardware tends to become obsolete and to need quality upgrading, new technology promises to make substantial improvements, and the threat is perceived to need offsetting.

Long leadtime items are acquired in a variety of ways. We describe eight of these below. Note that methods E through H represent deliberate ways in which long leadtime hardware has

been acquired in the past; methods C and D represent nondeliberate, almost accidental, ways in which long leadtime items have been acquired. Frequently, a subsystem comes into existence via a combination of these methods.

A. DEVELOPED UNDER THE PROGRAM (CFE)

In this case, the contractor develops a subsystem as part of the contract for the major system and supplies the subsystem to the program as contractor furnished equipment (CFE). Quite often, the subsystem is designed and fabricated by a subcontractor who works to specifications laid out by the prime contractor. Obviously, in this case, the time to initial operating capability (IOC) must include the sum of subsystem development time and the integration time. But there may be some opportunity for some time telescoping through close collaboration of the contractors, so that system integration can be started as soon as the subsystem design is available.

B. DEVELOPED UNDER THE PROGRAM (GFE)

This is a variant of the case above, except that the subsystem contractor is responsible to a Government manager rather than to the prime contractor. The subsystem is supplied as GFE, by the Government, to the prime contractor who is still responsible for integrating it into the system. The essential difference between this mode and the one above is responsibility. The prime contractor is not responsible for the quality of equipment provided through GFE sources.

C. DEVELOPED UNDER PRIOR SYSTEM PROGRAM

Sometimes, a long leadtime item becomes available in a timely fashion, because development was initiated for a different system and the item was found to be suitable for a new one (e.g., F-100 engine used in F-16 airplane). This might also

happen because a program was canceled, and some of the major components were determined to be suitable for a follow-on system. This occurred in the case of some components of the mobility subsystem of the XM-1 tank, including the engine, suspension, and transmission.

D. ADOPTION OF INDEPENDENT RESEARCH AND DEVELOPMENT (IRAD)

Contractors are continually performing IRAD, which often results in a subsystem or component feasibility demonstration. Most often, this seems to be applied to product improvement. But occasionally it results in the concept of a new subsystem that is then contracted for as CFE. The UH-1 and the AH-1 dynamic systems represent examples of subsystems that were improved through contractor IRAD. The AH-1 is an example of a new system that was conceived partly under IRAD, using the basic UH-1 with a new fuselage design.

E. PROTOTYPING

A number of long leadtime items are procured by starting development during the program definition phase. Such items are independently developed, even though they are clearly intended for a particular "home" system, because the system program office was not organized when the development was initiated. However, in the program definition phase, enough information is developed about the system characteristics and requirements to allow the development of long leadtime subsystems to start in advance. The F-100 engine and the radar for the F-15 airplane are examples of this method. Their development was started during the F-X program definition phase that led to the F-15 airplane, and prototypes were in test stages before the F-15 system program was initiated. Since a specific user system was identified, we consider the engine and radar to be early developments rather than independent developments.

F. EQUIPMENT FAMILIES

The X-1100 transmission for the XM-1 tank illustrates another deliberate way in which early development might occur. The X-1100 transmission is the largest member of a family of X-series transmissions for heavy military vehicles. The design is modular, to permit maximum parts commonality with other members of the transmission family, while retaining compatibility with different applications. It can be used with either the turbine or diesel version of the XM-1. In the development of this family of transmissions, experience was gained in scaling up designs and hardware. This made it possible to develop the X-1100 rapidly, largely from the X-700, a smaller transmission that had been developed earlier. Early full-scale engineering development, in this case, provided two benefits: a family of subsystems that could be used in several vehicles, and the technical background and know-how to readily scale these subsystems to different requirements.

G. MODULAR DEVELOPMENT

Another deliberate way in which early development takes place is through modularization of the system. This makes it possible to change or improve the performance of a system by substituting different components or subsystems. To some extent, this is true of any system; however, the essential characteristic here is that the system is deliberately designed with interfaces that permit components to be readily exchanged, often through a plug-in or bolt-on mechanism, and new system integration is not required. The Standard missile is an example of this kind of development. It has a long history of being upgraded and provided with new capabilities through the exchange of bolt-on subassemblies, a practice that is in keeping with a philosophy adopted by the system manager many years ago. Thus, development risks in the Standard missile program were restricted to

small pieces of the system. Yet, overall, a sophisticated operational system emerged from the process. As another example, the Westinghouse WX-200 radar, which has been selected for the F-16 airplane, can augment its basic capability by adding modular subassemblies to a determined electrical bus structure.

H. DELIBERATE DECISION FOR EARLY DEVELOPMENT

The fourth deliberate way of developing a long leadtime subsystem or component, for use in an undefined system, is simply to make a decision to do so.* Obviously, a system development cannot be completed in less time than it takes to develop its longest leadtime component. Subject to such a limitation, it is possible to reduce time to IOC by telescoping (overlapping) development so that the total, elapsed system development time is less than the linear sum of the times needed to complete each development separately. However, telescoping development time entails certain risks and costs. This is especially true, if the system's requirements demand high performance of its components (many of which are likely to be new and unproven), or if extensive system integration is required. Since this type of early development is of principal interest in this study, we shall discuss it in detail here.

* In this discussion, we use the term "long leadtime" to refer to components or subsystems whose development time is significantly greater than other parts of a system. We assume that, through previous experience, it is possible to identify such subsystems and to accurately estimate their development times, before an upcoming system's characteristics are known in detail.

1. Reasons for Early Development

A decision to undertake the early development of long leadtime subsystems can be made for the following reasons:

a. To Reduce Time to System IOC. The early initiation of developing the longest leadtime item permits the reduction of the time to IOC by whatever amount the subsystem takes to develop over the next longest leadtime item. Additional time savings can be realized through early development, since the existence of a subsystem fixes one set of system parameters. That is, if a subsystem design exists, other components with which it interacts can be defined more easily, and integration may be smoother. On the other hand, with concurrent development, as the subsystem is developed and difficulties are experienced, it is often necessary to modify interface specifications and then interacting components; thus, an interactive procedure is started that can lead to increased effort, costs, and schedule changes. The existence of a subsystem provides a partial base to the remainder of the system design; also, it reduces the amount of concurrent development that might be needed to complete the system by the IOC data. This can reduce costs as well, since the greater a high risk development is rushed the more it is necessary to try a number of approaches to find one that will work. The potential for waste in such circumstances is obvious.

b. To Reduce Development Risk. The availability of a critical subsystem (or the fact that one is well along in development) reduces the risk of the system development program encountering difficulties or of being unsuccessful. Also, system performance can be estimated more accurately. On the other hand, an unsuccessful attempt at early development of a subsystem may prevent initiating the development of a system that critically depends on the subsystem. At the very least, the failure to develop a subsystem during early development

should lead to an earlier search for a different approach. This would avoid costs due to the disruption of the total system development while waiting for the subsystem to reach a satisfactory level of development.

c. To Reduce Need for Product Improvement Programs (PIPs) After IOC. Telescoping of development time often results in systems being delivered with inadequate RAM (Reliability, availability, and maintainability). The PIPs that are undertaken to correct these items are costly; meanwhile, the operational utility of the systems is degraded or nonexistent. Combat aircraft systems that should be operating at about 70% availability rates may have substantially poorer availability, and in some cases may be grounded because of the poor RAM of one major subsystem. This is illustrated by the case of the A-7D (see Appendix K). Considerable savings might have been achieved, either by delaying IOC or by initiating development of the critical subsystems earlier and working the problems out during the system development.

d. To Support Industrial Base. Military purchases effect a significant amount of irregularity, which reduces the capability and willingness of industry to support the military. Slack times are used to make additions to the technology base through R&D funding, but the funding is not sufficient to take up all the slack between major developments. Early development of major subsystems could be used to even out some of this varying workload and make for a more competitive and more responsive industrial base.

2. Early Development Risks and Their Avoidance or Minimization

The decision to undertake the early development of long leadtime subsystems carries with it implicit risks. Such risks and their avoidance or minimization are as follows:

a. Subsystem Development May Not be Used. Either the system in which the subsystem is to fit may not come into existence, or the program manager may decide to develop the subsystem himself. Thus, the subsystem development may be completely wasted. At best, it represents a costly addition to the national technology base, which might be regarded as providing an additional management option.

To some extent, the likelihood that developed subsystems will be used can be enhanced by:

1. Selecting only those subsystems for full-scale engineering development that are applicable to more than one potential system, and for which there is a clear need and little competition. Examples include turbine engines of a particular thrust or power class, and radar systems with a particular resolution and range.
2. Developing only those systems that offer significant advances in desirable qualities (advancing the state of the art), so that a program manager would prefer not to take the risk of developing his own subsystem.
3. Mandating the subsystem's use through the system development contract and through procurement. While this takes away some of the program manager's autonomy, by eliminating one of his choices, it also reduces his responsibility for the success of the system. (This approach was taken with several subsystems to reduce the program cost of the B-1.)
4. Providing the prime contractor with economic incentives to use available subsystems or, at least, remove incentives to develop new ones.

b. Subsystem Target Parameters May be Poorly Chosen, Since Using System Information is Incomplete at Time of Subsystem Design. This is often cited as a major risk of early development. But there is evidence that it is not restricted to subsystems developed prior to system definition. Moreover, the risk can be made insubstantial for many kinds of subsystems:

1. Even after a system is fully defined, many parameters are found to be poorly chosen. Engines, for example, must often be upgraded after field experience proves that the aircraft are underpowered. Mission requirements are added or changed during, and even after, development. Hence, system definition does not guarantee that the subsystem parameters have been well chosen. Flexibility in the design of a subsystem, so that it can be easily tailored to the needs of the potential using system, will minimize this problem.
2. Another way to minimize the problem is to design the subsystem in such a way that it consists of a core part, for use in a number of application modules that are tailored to meet specific system requirements. Development and testing can be carried out on the core part in full. Then, only the application module will have to be designed and tested when the final system specification becomes known. Even when such an approach is infeasible, development and testing that are done for a tentative specification can save time and money, when the final specification becomes known and the subsystem must be reengineered and retested. Existing subsystems that are modified in this way are likely to provide reliability faster and at less expense than would be obtainable by completely developing a new subsystem.
3. The optimization of the using system should be less rigid so that it can accept a less specialized subsystem. A system development can be severely compromised by its dependency on the performance of a newly developed subsystem. If a subsystem's development potential is not realized, it may be necessary to field the system with less than adequate performance in one or more aspects of its mission activity. If the state of the art is being pushed in a number of areas, the risk is compounded and the chances of success are greatly diminished. Some retreat from the demand for extreme performance would be helpful in reducing such risks.

c. Environment of Using System is not Fully Known and, Therefore, Subsystem Specifications Cannot be Drawn Up in Advance. This may be true of a system such as SRAM, which used advanced technology and components that did not exist at the time development was started. Therefore, some aspects of the environment

such as vibration and temperatures may not have been known. However, for many systems it should be possible to define the environment in sufficient detail for subsystem specification. Also, the using system can be flexible to the extent that it could be designed to provide a suitable environment for the subsystem. Thus, there is a tradeoff between designing a subsystem for the system environment and designing the system to provide a more suitable environment for the subsystem.

d. An Early Developed Subsystem Will Depend on Older Technology. This is obvious but necessary for long leadtime items, if the system time to IOC will be short. The fact that technology is old is immaterial. New technology has no value, except in conferring desired characteristics on the subsystem and systems in which it is employed. Only where the technology is changing rapidly is this a significant risk. In some technologies (e.g., avionics) the subsystem can be designed for form, fit, and function, so that if the technology should change rapidly during the development period, it would be possible to make the change without disaster occurring in the system design. The result may be a component or subsystem whose characteristics are not as optimized as they otherwise might have been (e.g., heavier, larger, more power demanding). But it would not be necessary to change the basic system design to incorporate new technology. Avionic subsystems seem to be adaptable to form, fit, and function design principles. But other subsystems, such as engines, are not adaptable to such treatment because of integration difficulties.

e. Lack of Funding. The military budget is tight, and it is difficult to fund items that are considered unessential. Unfortunately, early developments are likely to fall in such a classification, despite the likelihood that they might result in later savings. We note that the Commission on Government Procurement as well as the Congress of the United States have both expressed some opposition to these kinds of developments

(Refs. 5, 6). This opposition is of concern and must be considered, but it does not affect the basic arguments that support the need for these kinds of developments. The OMB has provided the basis for exception in Circular A-109 (Ref. 3).

f. Lack of Motivation. It has been argued that people are not motivated to perform well, if they are uncertain about the eventual utility of their work. It is hard to give credence to this kind of argument, when most military procurement competitions present this risk to all the contenders. One might make the opposite point that the motivation to do a good job can be very high, since the better the result the greater the likelihood that it will be used. We regard this as a nonsubstantive argument against performing early development.

IV. GUIDELINES

In this chapter we synthesize the findings of the case studies (Chapter II) and relate them to the possible benefits that might follow from making one of three decisions:

1. Whether to undertake early development of a subsystem (before the program has been initiated and the characteristics of the system are scarcely known)
2. Whether to develop a subsystem independently of a system program
3. Whether to standardize a subsystem.

Suggested guidelines to follow based on each of these decisions, have been developed and are included here. Their application in several real cases is described in the next chapter.

A. RESOLUTION OF DEVELOPMENT PROBLEMS

In the discussion below, we note the kinds of development problems that occurred in the various cases we examined. Then, we indicate whether any of the types of decisions noted above might be relevant in dealing with such problems. We believe that most of the problems discussed in this synthesis are more generally found than in the limited set of cases we examined. Any of these problems might arise in future military system developments, and any of the forms of development or standardization might be helpful in averting them as indicated.

1. *Poor reliability resulting from excessive concurrency between system development and major subsystem development.*

One outcome of forcing a system development to be completed in too little time is poor field reliability. The problem can

be exacerbated by the practice of emphasizing high performance at the expense of reliability, availability and maintainability (RAM).

One solution to this type of problem would be to delay the IOC until the system has demonstrated adequate RAM. But this is a solution that is seldom used by the military services. The preference has been to field the system on time and to remove its deficiencies in the course of operations through Product Improvement Programs (PIPs). Sometimes, this practice is extremely expensive if not disastrous. The A-7D, for example, has been grounded by the Air Force for an extended period of time, because of engine problems that were never adequately worked out prior to IOC.

We stress here that excessive concurrency is not the only cause of poor field reliability, and that the various subsystem development policies that are the subject of this study would not avert such problems by themselves in all cases. Nevertheless, it is clear that the early development of those subsystems types that are known to have RAM problems would be helpful, by reducing concurrency and providing more time to work out difficulties through the processes of TAF (test, analyze and fix).

Independent development in itself would not help, because it does not provide more time. But using a standard subsystem that might have been developed earlier could be helpful, because a standard item's RAM can be expected to be better than that of a newly developed item. However, in a climate of procurement, where new systems are required to substantially outperform old ones, the use of standard subsystems is severely circumscribed.

2. *Schedule slippage of major programs caused by inadequate or late development of a pacing critical subsystem.*

3. *Unsatisfactory performance of a major system caused by inadequacy of an important subsystem (in an extreme case the entire development may be aborted).*

These two problems are clearly interrelated and are discussed together. The absence of a critical subsystem when it is needed can occur, because the required subsystem performance may be beyond the demonstrated state of the art, or because the state of the art is misinterpreted. Engineering development of systems that require advancing technology is risky. Yet taking such a risk may be the only way in which adequate performance can be achieved to meet mission requirements. This raises the question of whether hardware requirements that involve advancing technology should be specified for new systems. We do not examine this policy here, but we attempt to indicate some of the cost. Our case studies include system development programs that were not completed due to failure in achieving adequate original estimates, programs that required longer development time than was expected and aborted programs (in some individual developments all three occurred). In some cases, where "successful" operating hardware was eventually produced, it was necessary to relax requirements to obtain an operating system.

One way to deal with this problem is to restrict engineering development only to the truly demonstrated state of the art. If advances are needed in a particular area, advanced development programs aimed at demonstration should be undertaken. The problem here, of course, is that this delays the introduction of new systems.

Early development offers a partial solution to this dilemma, but it requires foresight to determine that a need exists. If such a need can be identified, ED of those subsystems wherein the requirement to advance the state of the art is recognized might be undertaken. If funding is available,

multiple approaches might be used to improve the likelihood of success, although multiple approaches are clearly more costly.

System development should not be initiated until advanced state-of-the-art developments show substantial promise of success. If an early development is unsuccessful, another means can be tried, or at least there will be an indication that system development should not be initiated. In fact, this is supposed to be the function of the concept validation stage following the DSARC I review of any major program. However, sometimes, the pressures of the schedule combined with the optimism of the program manager result in a premature approval for full-scale development, when there may still be some gaps in the validation.

Early development cannot substitute for poor judgment or overoptimism. It can only increase the likelihood that development time can be advanced sufficiently to meet a goal, or alternatively to provide a warning that such a goal may be too ambitious. A disadvantage of using ED for this purpose is that the system will have to be designed to use the developed subsystem rather than an optimum subsystem that might have been derived if the system had been more adequately defined before the subsystem development started. Otherwise, the development would be wasted. While in principle, overall optimization seems desirable, in practice most military hardware is used in a variety of ways, many of them unpredicted. Extreme optimization means extreme specialization, thus limiting utility and increasing development risk, even though the system might perform well in the one hypothetical situation for which it is optimized. Moreover, mission requirements are often changed, thereby reducing extreme optimization to an empty and perhaps counterproductive exercise. In sum, ED offers a partial solution to these two problems, but is not a substitute for good judgment and must be applied judiciously.

Independent development, since it offers no time advantage, would not help here. And standardization is applicable only in the sense that use of a standard subsystem could help avert the problem, but such a subsystem is unlikely to provide the necessary performance.

4. *Lack of competition in the military equipment market occurs after initial buy. This places the government at the mercy of the sole supplier and can result in excessive costs.*
5. *Proliferation occurs in subsystems intended to perform similar functions, with attendant high production costs traceable to small volume, and with high logistics costs traceable to noninterchangeability.*

We have identified these problems as subsidiary ones that may be impacted upon by one or more of the proposed approaches to averting the primary problems discussed above. In fact, the primary way of maintaining competition and of reducing proliferation of military subsystems is through standardization. This broadens the potential market for an individual item by pooling a number of requirements. And it helps maintain competition by ensuring that all contractors are bidding to supply the same item. However, the standardized item may limit the performance of the system, since it is likely to represent a state of technology that is earlier than one that could be available from a later development. Also, note that a standard item, though independently qualified, may interact with other parts of the system to cause unanticipated system problems. Hence, it is clear that all subsystems should not be standardized or independently developed. This is discussed further under the guidelines below.

Early development can potentially contribute to reducing problems 4 and 5 by providing subsystems that might be candidates for standardization; but, most commonly, standardization is a consequence of ID.

B. SUBSYSTEM DEVELOPMENT POLICY GUIDELINES

1. Selecting Candidate Subsystems for Early Development

In Chapter III we presented major arguments for and against undertaking early development of long lead time subsystems, before a specific using system has been defined in detail. The arguments are summarized as follows:

- Early development runs a strong risk of improperly specifying the required system performance, since it must be done in advance of system definition and, in fact, in advance of concept validation. However, this risk is not unique to early development. Even when a great deal of information about a system is available, the subsystem parameters can be poorly chosen.
- The system itself may never be approved, or even if it is approved, the program manager may elect to develop another subsystem rather than use the developed subsystem.
- Technology developments may make an early development subsystem obsolete before it can be used. On the other hand, where technology seems mature, an early development may make available a long lead time subsystem to avert a delay in IOC. Through providing more development and testing opportunity, early development might also produce a more mature subsystem and thereby reduce the need for PIPs.
- Early development may forestall a premature system development decision by indicating a risk that may be unacceptable.

In Section A of this chapter we have discussed the rationales for how Early Development might help to avert the major development problems that occurred in the various cases we examined. There is no data base from which these rationales can be quantified. But we believe that we have presented enough information to justify the conclusion that ED of subsystems should be practiced selectively. We believe that the presented information permits the specification of guidelines for selecting candidates for ED. Except for cost-benefit

arguments, the following guidelines are qualitative and require the exercise of mature, informed judgment in their application to qualify any candidate for early development:

- a. The subsystem is of the type that requires a long development lead time relative to the development time of other subsystems.
- b. At least one, and preferably several, potential user systems are identifiable. Note that the detailed characteristics of the user system may not be known at the time that the decision to develop the subsystem is taken.
- c. No subsystem alternatives are available that would permit the system to be cost-effective in a minimally acceptable set of missions of the type for which the system is envisioned.
- d. Integration will not be a major problem. In other words:
 1. The subsystem performance characteristics are alterable over a reasonable range without requiring major development effort; the scaling laws governing changes in the performance of the subsystem are well understood, or can be clarified during subsystem development. Alternatively, system requirements are of sufficient flexibility to accept the developed item.
 2. The subsystem can be repackaged without major development effort, allowing it to fit into the system without integration problems or if such repackaging appears impossible, the system can be designed to accept the subsystem.
 3. The environment of the using system will not adversely affect the performance of the subsystem. If the normal system environment is a problem, a controlled environment for the subsystem will be available.
 4. Conversely, the environment generated by the subsystem will have no adverse impact on the system or other subsystems; alternatively, the environmental impact of the subsystem is controllable by appropriate packaging.

- e. System obsolescence, stemming from technology changes in the subsystem area, will not be serious because:
 - 1. No developments are in view to obsolete the subsystem, before the system development is started, or
 - 2. "Form, fit, and function" principles are applicable, or
 - 3. Expected benefits in the utility period of the subsystem exceed the expected costs.

2. Selecting Candidate Subsystems for Independent Development

Independent development is generally undertaken with the intention of developing a standard subsystem. The guidelines for such a case are stated under the next category (Subsection 3). Sometimes ID is undertaken without an intention to standardize, and the applicable guidelines are as follows:

- a. More than one potential using system, including retrofits, is identifiable.
- b. Integration will not be a major problem. In other words:
 - 1. Subsystem performance characteristics are alterable over a reasonable range, without requiring major development effort; the scaling laws governing changes in the performance of the subsystems are well understood, or can be clarified during subsystem development. Alternatively, system requirements are of sufficient flexibility to accept the developed item.
 - 2. The subsystem can be repackaged without major development effort allowing it to be fitted into the system without integration problems. If such repackaging appears impossible, the system can be designed to accept the subsystem.
 - 3. The environment of the using system will not adversely affect the performance of the subsystem. If the normal system environment is a problem, a controlled environment for the subsystem will be available.

4. Conversely, the environment generated by the subsystem will have no adverse impact on the system or other subsystems; alternatively, the environmental impact of the subsystem is controllable by appropriate packaging.
- c. Subsystem design parameters are adequately specified. In other words:
 1. System design is complete enough to specify the subsystem, or
 2. System will be designed around the characteristics of the subsystem, or
 3. Subsystem is part of a family, whose characteristics span the expected system requirements.
 - d. No subsystem alternatives are available that would permit the system to be cost-effective in a minimally acceptable set of missions of the type for which the system is envisioned.

3. Selecting Candidate Subsystems for Standardization

In paragraph A of this chapter, we have indicated how standardization might help overcome problems caused by unsatisfactory subsystem performance or proliferation of subsystem types. Without a quantified data base, we conclude that standardization of major subsystems should be practiced selectively. The guidelines for such selection follow.

To be a candidate for independent development and standardization, a subsystem must satisfy the following conditions:

- a. More than one potential using system (including retrofits) is identifiable.
- b. Subsystem technology is mature and well in hand.
- c. The potential market is large enough. In other words:
 1. The market may be only large enough to support a single supplier for several years. Independent development and standardization are then appropriate, only if future prices can be adequately protected by devices such as a long-term pricing agreement.

2. The potential market may be large enough to support two or more suppliers. Independent development and standardization may then be appropriate, provided that suitable steps (e.g., form, fit, and function standardization) are planned to ensure continuing competition.
- d. The projected overall benefits of standardization exceed its disadvantages:
1. Whenever feasible, the cost-benefit analysis should include a comparative (but not necessarily an absolute) life cycle cost (LCC) analysis of standardized and nonstandardized equipment, including RAM and logistics. The maintenance concept must be sufficiently well defined to permit determination of costs and required configuration control. In other words, if contractor repair is contemplated, form, fit and function standardization is adequate. If service repair is envisaged, detailed configuration control inside the repairable module is needed.
 2. If the LCC cannot be reliably estimated, the cost-benefit study should attempt to look at least several years into the future. It should use the cost of reliability improvement warranties or any other applicable technique as a proxy for LCC. The maintenance concept must be adequately defined for a meaningful result.
 3. Where a cost advantage cannot be found, the advantage that might be obtained from the potential of a more attractive set of procurement policies should be considered. An example is the continuation of competition after deployment through split buys. To be valid, the analysis must account for the maintenance concept and the required configuration control.
- e. Integration will not be a major problem. In other words:
1. The subsystem can be repackaged without major development effort, allowing it to fit into the system without integration problems. If such repackaging appears impossible, the system can be designed without difficulty to accept the subsystem.

2. The environment of the using system will not adversely affect the performance of the subsystem. If the normal system environment is a problem, a controlled environment for the subsystem will be available.
3. Conversely, the environment generated by the subsystem will have no adverse impact on the system or other subsystems; alternatively, the environmental impact of the subsystem is controllable by appropriate packaging.

C. ENHANCING THE PROBABILITY THAT A SUBSYSTEM WILL BE USED

The fact that a subsystem has been developed does not mean that it will get used; however, some strategies do exist for improving the likelihood that the developed subsystem will get used:

1. Mandate the use of the subsystem through the system contract, or through rulings of the Secretary of Defense or the Secretaries of the Military Services.
2. Persuade the program manager, through whatever means are available, that he should accept the developed subsystem.
3. Provide economic incentives to the prime contractor to use the developed subsystem (or disincentives to develop a new subsystem).
4. Reduce the level of system optimization and performance extremes (design to cost).
5. Emphasize RAM, development cost, and low risk in the system specification.

V. APPLICATION OF GUIDELINES TO POTENTIAL PROCUREMENTS

NOTE: This chapter describes situations as they were perceived by IDA at the time of writing this report. During the course of this research project, some of these programs changed in significant ways. Hence, the facts as well as the conclusions relating to specific systems may no longer be relevant. Nevertheless we stress the purpose of this chapter, which is to illustrate the method of using the guidelines and not to present an assessment of these programs.

A. STANDARDIZATION OF INERTIAL NAVIGATION SYSTEMS (INS)

1. Introduction

The Aeronautical Systems Division (ASD/RW) at Wright-Patterson AFB is currently working on the problem of standardizing inertial navigation systems. ASD is assisted in this endeavor by its contractor, ARINC Research Corporation.

The Air Force is studying the use of an "ARINC characteristic" for the INS procurement. Unlike a military specification, an ARINC characteristic is evolved from forums attended by the users and producers. One of the major objectives of such a characteristic is to open up the market for competition, by making it possible for any producer to qualify his wares according to the characteristic and then sell them to interested parties. In the case of the Air Force, the purpose is to establish a specification for an INS that will be useful across a variety of aircraft types for an indefinite time. To allow the designs to take advantage of technology advances, the characteristic employs an approach known as "form, fit, function";

that is, it specifies the input, output, external shape and size, and the environmental conditions, but it leaves the internal structure of each module unspecified.

2. INS Market

ARINC has performed a market analysis for inertial navigation systems. The INS quarterly buys are listed in Fig. 2. Figure 2 however, does not include all possible buys. The total USAF market might include buys for the A-10, and new versions of the F-15. The number of units procured thru 1985 then might be as high as 4000. (Ref. 11). While this is a large market for INS, realistic competition must be maintained. If only one vendor is available, then competition disappears and standardization becomes a rather limited concept, namely, one-company standardization. One problem now facing ASD/RW is reflected in the following discussion.

A large part of the market for INS is in the F-16 aircraft; an ongoing program. The USAF Systems Projects Office for the F-16, and General Dynamics, have picked the Singer-Kearfott Division as their inertial supplier for the F-16. The inertial unit is the SKN-2400. Because the F-16 is on a tight schedule, it will be necessary to buy the first two lots (lot 1, 34 units; lot 2, 112 units) from Singer-Kearfott, before their competitors, can modify and qualify a suitable unit. This means that Singer-Kearfott may have an opportunity to benefit from a learning curve, before another supplier can get into production. There is also a further problem peculiar to the F-16 and its equipment. Because coproduction was agreed to by the United States for the F-16, Norway will be building 70% of the electronics and assembling and testing 37%. Only one firm in Norway is capable of producing such high-technology equipment. This firm will not find it advantageous to work with two prime contractors, each of which will need only half the volume required for the F-16, since it eliminates any chance of achieving economies

	76	77	78	79	80	81	82	83
C-141	20 10 76	84 84 86 90	90 30					
KC-135		25 25	25 25 45 45	45 45 58 53	58 58 58 58	58 64		
F-16			6 18	26 35 39 46	49 57 60 60	46		
AMST							3	10 11 15 15 ...
TOTALS	20 10 76	84 84 111 115	115 55 51 63	71 80 97 104	107 115 118 118	104 64	3	10 11 15 15 ...
+20% SPARES	12 91	100 100 133 138	138 66 61 76	85 96 116 125	128 138 142 142	125 77	4	12 12 13 18 ...

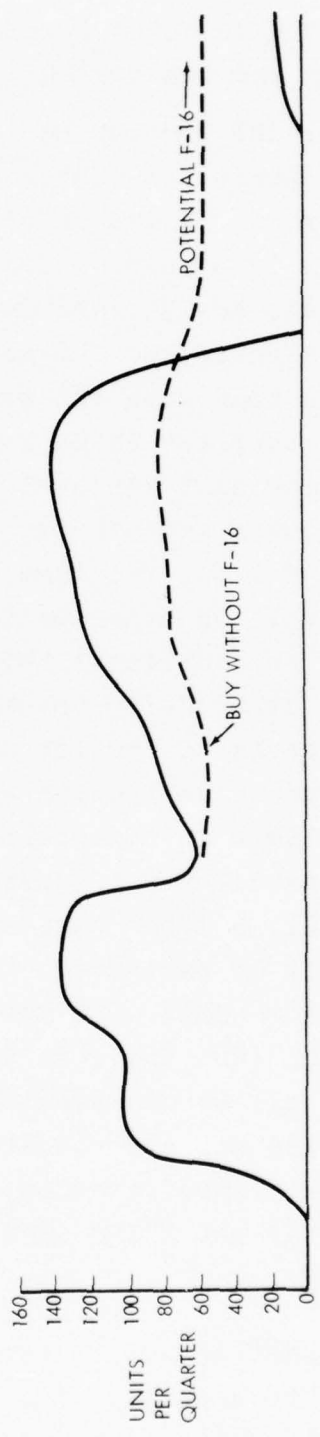


FIGURE 2. Most Probable INS Procurements, Source: ARINC, 1976.
(in units per quarter)

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of a scale attainable with a single prime contractor. Thus, the coproduction requirement increases the problem of creating competition on the F-16. And without the F-16 INS contract, the market may not be attractive enough for other producers to invest in modifying and qualifying a unit.

Another INS program has been initiated by the Warner-Robbins Air Logistics Center by its award of a contract to the Delco Electronics Division of General Motors. Such a contract could result in a multimillion dollar program to outfit the Air Force's C-141, KC-135, and C-135 fleets with the Carousel IV INS, (a version of the INS now being used by the commercial carrier) rather than with the standardized (by the Air Force) INS. The initial contract calls for prototyping, installing, and flight testing dual Carousel IV systems in one C-141 aircraft. It also includes options for the production of dual systems, plus spares for the Military Airlift Command fleet of 275 C-141s, as well as other options to provide single Carousel systems for an additional 739 Strategic Air Command KC-135 tankers and other C-135 transports. The primary purpose of this contract is to provide military transports with sufficiently accurate navigation capability to satisfy FAA requirements for flight in controlled airspace across the Atlantic Ocean, a capability not currently possessed. If this program is successful, a large part of the market for the ARINC standard INS will be satisfied. However, it is our understanding that the Delco units will meet the commercial aircraft INS specification (No. 561), so to that extent at least the transport units will be standardized. There is some possibility that the units may also be designed to meet the forthcoming ARINC military specification, but this is yet to be decided by Delco after the ARINC open forum process is completed.

3. Progress

A strawman INS characteristic has been drafted by ARINC, distributed to industry, and discussed at length in several forums attended by representatives of industry and government.

The strategy being employed by ASD/RW is interesting, and it may provide a useful guideline for other standardization efforts. The Air Force is considering instituting "split buys" of the standardized systems. These are buys that are spread out over a substantial period and are awarded periodically with full recognition of the vendor's performance during the preceding buys. This practice can generate intense and continuing competition reminiscent of the situation in the commercial airline equipment market. It is unlike the usual military approach of the large single buy, which may spell the end of all competition and result in the complete dependence of the government on the sole supplier. The approach already seems to be having an impact since the bid prices of proposed units are now under \$60,000 in comparison to \$100,000 in previous Air Force buys (Ref. 11).

A careful study has been made by ARINC of the advantages and disadvantages of standardization. But a complete LCC analysis has not proven feasible, largely because adequate cost data have not been available, particularly for the operation and maintenance phase. ARINC has been able to compare acquisition costs for two different alternatives and also to compute long-term warranty costs for several alternatives. Using the reliability improvement warranty (RIW) concept, they have been able to look ahead for three to four years under RIW, followed by three to four years under a warranty follow-on option. Since fleet installation takes about two to three years, this adds up to eight to eleven years. ARINC has also done parametric analyses of procurement costs plus installation costs; thus, it was able to outline the conditions under which a split-buy strategy would have economic advantages. It is important to note that such model studies did indeed give useful guidance for procurement policies and actions, even though the LCC calculation was not realistically possible.

Another issue that the ARINC standardization program raises is the cost of providing unused capability. If the standard INS

has a form, fit, and function specification it will have an identical set of input and output functions. For example, the C-141 requires a special display drive; the F-16 does not. Other aircraft may require updates from doppler or a satellite positioning system. Since the standard unit will be used in different types of aircraft, not all the inputs and outputs will be used in each application. Thus each unit may have additional investment and operating costs over what it would have it if it were tailored for each aircraft type. These additional costs may be offset by savings due to identical servicing requirements and complete interchangeability. Another way to resolve this problem is to use a modular design that would permit the subsystem to be tailored for each application through plug-in units.

4. Application of Proposed Guidelines

We examine here the utility of the proposed guidelines on standardization (Section B.3, Chapter IV) by applying them to the ongoing Air Force effort to standardize the INS.

Guideline

- a. *More than one potential using system, including retrofits, is identifiable.*

Comment

This condition has been met, since the using subsystems (i.e., the F-16, A-10, KC-135, C-141, AMST, and other planes) have been identified.

Guideline

- b. *Subsystem technology is mature and well in hand.*

Comment

This condition is being met. The proposal is to standardize the mature technology of the SKN-2400, not the less mature technologies of Micron, GEANS, or the laser gyro.

Guideline

c. The potential market is large enough:

- 1. The market may be only large enough to support a single supplier for several years. Independent development and standardization are then appropriate, only if future prices can be adequately protected by devices such as a long-term pricing agreement.*

Comment

A long-term contract, guaranteeing availability of the SKN-2400 at a fixed price, is under consideration. Thus, this condition is being met.

Guideline

- 2. The potential market may be large enough to support two or more suppliers. Independent development and standardization may then be appropriate, provided that suitable steps (e.g., form, fit, and function standardization) are planned to insure continuing competition.*

Comment

The potential market here is large enough to support two or more suppliers over a period of several years; however, the timing of the projected buys is such that one supplier could get a commanding position in the market through production experience, well before another supplier can establish itself. On the other hand, a second supplier, by repackaging its INS to meet the ARINC characteristic, could be an important source of competition. Consequently, the conditions of this guideline are being met.

Guideline

- d. The projected overall benefits of standardization exceed its disadvantages:*

1. *Whenever feasible, the cost-benefit analysis should include a comparative (but not necessarily an absolute) life cycle cost (LCC) analysis of standardized and nonstandardized equipment, including RAM and logistics. The maintenance concept must be sufficiently well defined to permit determination of costs and required configuration control, in other words, if contractor repair is contemplated, form, fit, and function standardization is adequate. But if service repair is envisaged, detailed configuration control inside the repairable module is needed.*

Comment

A complete life cycle cost analysis has not proven feasible. Thus, the conditions for this alternative guideline are not satisfied.

Guideline

2. *Where LCC cannot be reliably estimated, the cost-benefit study should attempt to look at least several years into the future, using the cost of reliability improvement warranties or any other applicable technique as a proxy for LCC. The maintenance concept must be adequately defined for a meaningful result.*

Comment

Extensive studies of reliability improvement warranties (RIW) have been undertaken, mainly by ARINC. Contractor maintenance, either at depot level or (for the C-141) at the intermediate level, is envisaged. In the case of the C-141, only one contractor is envisaged. He would be free to modify the individual modules as long as the form, fit, and function standardization remains intact. Moreover, the contract requires him to bring all functioning INS equipment to a single configuration, when the Air Force

decides to switch to organic maintenance. Thus, this guideline is being followed.

Guideline

3. *Where a cost advantage cannot be found, the advantage that might be obtained from the potential of a more attractive set of procurement policies should be considered. An example is the continuation of competition after deployment through split buys. To be valid, the analysis must account for the maintenance concept and the required configuration control.*

Comment

ARINC has performed a number of model studies of the effects of such procurement policies, as the continuation of split buys after deployment. Thus, this guideline is being followed.

Guideline

- e. *Integration will not be a major problem. In other words:*
 1. *The subsystem can be repackaged without major development effort, allowing it to fit into the system without integration problems. If such repackaging is not possible, the system can be designed without difficulty to accept the subsystem.*

Comment

System integration problems are to be explored for the Air Force, in connection with the INS, under the next phase of the contract with ARINC. There is the possibility of using several different options within the same box, versus the possibility of using separate boxes. Moreover, the need for a vertical channel is paramount on a fighter plane or a cargo plane with precision airdrop capability, but it is

superfluous on other planes. All these issues must be resolved, and they are to be studied. Other more severe forms of integration difficulties, in which the plane interferes with the function of the INS, are not expected. It is our judgment that the problems noted above will be favorably resolved; therefore the guideline is being followed.

Guideline

2. *The environment of the using system will not adversely affect the performance of the subsystem. If the normal system environment is a problem, a controlled environment for the subsystem will be available.*
3. *Conversely, the environment generated by the subsystem will have no adverse impact on the system or other subsystems; alternatively, the environmental impact of the subsystem is controllable by appropriate packaging.*

Comment

Environmental problems are not expected to arise with respect to the INS; consequently, the conditions that satisfy this are considered fulfilled.

5. Conclusions

Since all the guidelines are being followed (with the possible exception of e.l.--packaging--which is being investigated) the standardization program that ASD/RW has initiated should be pursued. The potential market is large enough even though part of it will be satisfied by the selection of Carousel IV INS units for the Air Force transports. Moreover, there is some possibility that the Carousel IV INS, through repackaging, could be made to meet the forthcoming ARINC standard thereby providing another potential INS supplier for fighter and attack aircraft.

B. STANDARD AIRBORNE COMPUTER

1. Introduction

The avionics division at Naval Air Systems Command (NAVAIR) develops and provides various equipment to NAVAIR project managers. At present, its funding comes entirely from program managers. Accordingly, its initiatives are constrained to be brief and very specific.

The director of the avionics division is trying to obtain funding as a line item in the 6.4 budget, to be called Avionics Components and Subsystems. If successful, this would provide him with greater flexibility and enable him to develop a broader range of equipment for standard use.

Currently, the avionics division is developing the AN/AYK-14 as a standard airborne computer under funding from the project managers for the F-18 and Light Airborne Mobile Platform System (LAMPS) Mk III. The decision to provide such funding was made by the Commander, NAVAIR, supported by the Assistant Secretary of the Navy (R&D). The overall Navy market has been surveyed. It is estimated that 6000 such computers will be required in 1982.

Under the present procurement strategy, a single contractor will provide the initial engineering model, a production data package, and options for production copies, priced in FY-77. Then, a second source will be given the production data package and will be required to build to performance specifications. There are now about 20 different computers in the naval aviation inventory of contractor furnished equipment (CFE). They have different word lengths, different languages, different spare parts, and different maintenance requirements. Thus intuitively, one concludes that the standardization will be beneficial from a cost point of view. This conclusion, however, is tempered by the possibility that competition may be limited because of the procurement conditions. The present solicitation for the computer

calls for an emulation of the UYK-20 shipboard computer so as to have a minimal impact on existing software. However, the F-18 prime contractor has indicated that the combination of required software, lack of floating point capability, memory capacity, and base addressing capability will not be satisfactory for the aircraft needs. In addition only one company supplies and supports the UYK-20. Either more memory or a more efficient machine language is necessary. Due to limitations of the computer physical envelope there is some doubt that the additional capacity can be included. Moreover, the potential for upgrading the computer for technology advances such as "double density" memory modules would be severely limited. Thus a major reason (existing software and support) for specifying that the new computer should emulate the UYK-20 may be nullified.

2. Application of Proposed Guidelines

Guideline

- a. *More than one potential using system, including retrofits, is identifiable.*

Comment

This condition is being met, because it is already planned for the F-18 and LAMPS Mk III to use the computer; also, HARM, and several other major programs have been identified in the market survey.

Guideline

- b. *Subsystem technology is mature and well in hand.*

Comment

The use of a mature LSI technology and existing software is planned. Thus, this guideline is being followed. However, there is some question that the resulting computer will be satisfactory for the F-18.

Guideline

- c. *The potential market is large enough. In other words:*
1. *The market may be only large enough to support a single supplier for several years. Independent development and standardization are then appropriate, only if future prices can be adequately protected by devices such as a long-term pricing agreement.*
 2. *The potential market may be large enough to support two or more suppliers. Independent development and standardization may then be appropriate, provided that suitable steps (e.g., form, fit, and function standardization) are planned to insure continuing competition.*

Comment

The market has been surveyed and found large enough (6000 computers by 1982, or \$180-\$240 million) to support two or more suppliers. Standardization at the card level, and the decision to "second-source", may provide competition, but the present solicitation tends to heavily favor only one contractor. This guideline may not be followed under the present solicitation.

Guideline

- d. *The projected overall benefits of standardization exceed its disadvantages:*
1. *Whenever feasible, the cost-benefit analysis should include a comparative (but not necessarily an absolute) life cycle cost (LCC) analysis of standardized and nonstandardized equipment including RAM and logistics. The maintenance concept must be sufficiently well defined to permit determination of costs and required configuration*

control, in other words, if contractor repair is contemplated, form, fit, and function standardization is adequate. If service repair is envisaged, detailed configuration control inside the repairable module is needed.

2. Where LCC cannot be reliably estimated, the cost benefit study should attempt to look at least several years into the future. It should use the cost of reliability assurance warranties or any other applicable technique as a proxy of LCC. The maintenance concept must be adequately defined for a meaningful result.
3. Where a cost advantage cannot be found, the advantage that might be obtained from the potential of a more attractive set of procurement policies should be considered. An example is the continuation of competition after deployment through split buys. To be valid, the analysis must account for the maintenance concept and the required configuration control.

Comment

The cost-benefit assessment has been only intuitive here, but it appears reasonable. The use of reliability assurance warranty is contemplated. However the problem of a second source supplier is not resolved. Thus this guideline may not be followed.

Guideline

- e. Integration will not be a major problem. In other words:
 1. The subsystem can be repackaged without major development effort, allowing it to fit into the system without integration problems. If such repackaging appears impossible, the system can be designed without difficulty to accept the subsystem.

2. *The environment of the using system will not adversely affect the performance of the subsystem. If the normal system environment is a problem, a controlled environment for the subsystem will be available.*
3. *Conversely, the environment generated by the subsystem will have no adverse impact on the system or other subsystems; alternatively, the environmental impact of the subsystem is controllable by appropriate packaging.*

Comment

The conditions for this guideline do not seem to be met at least for the F-18, which is currently the primary user system. This stems from the use of inefficient software and space limitations in the computer box. This problem must be corrected before the conditions of this guideline can be considered to be met.

Overall Comment

Although standardization of an airborne computer intuitively seems desirable, this particular standardization program seems to have some problems created by the details of the solicitation. In its present state it does not follow the guideline that assures control of costs through competition or pricing strategy, the guideline that assures integration with the using system, and the cost-benefit guideline. Until these issues are resolved this standardization program does not appear to be justified.

C. NAVAIR PROPOSAL FOR A NEW TURBOSHAFT ENGINE

The Office of Propulsion, Naval Air Systems Command (NAVAIR), is considering the development of a new turboshaft engine with a power rating of 2200 horsepower. One potential user system

is in engineering development, two are in advanced development, and one is in the conceptual stage. In addition, there are two possibilities for retrofit. Therefore, this proposed development can be categorized as either early development or independent development. This provides an opportunity to examine the proposed development under two separate sets of guidelines.

1. Potential Users of a New Engine

The Army is developing a helicopter known as the Utility Tactical Transport Aircraft System (UTTAS) and an Advanced Attack Helicopter (AAH). The UTTAS has passed through the DSARC II review, and two contractors are competing for the engineering development contract. The AAH has passed the DSARC I review and is scheduled for the DSARC II shortly. Two contractors are also competing for the AAH. Both of these aircraft are powered by a common engine, a prototype of the T-700, which is a current technology engine rated at 1536 horsepower (Ref. 12). The T-700 is in its final qualification testing, and prototypes of the engine are already being operated on the UTTAS and AAH flying prototype aircraft.

The Navy is planning to develop a Light Airborne Mobile Platform System (LAMPS). The LAMPS, which has been through the DSARC I review and is close to DSARC II, would use the same airframe as that of the UTTAS; it is expected that at least the first buys of LAMPS would be powered by the T-700 engine.

There is a fourth potential helicopter development, the Marine Corps HXM, which has not had a DSARC I review yet. The present concept of the HXM is that it will use the same airframe as that of the LAMPS, but since it is likely to be heavier than the LAMPS, the HXM may need more power.

2. Need for a New Engine

The problem with the T-700 engine, according to the NAVAIR Office of Propulsion, is that it may be underpowered for its

proposed uses under some conditions, because the engine's performance degrades (as in all turbine engines) with increasing temperature and altitude. On a standard hot day (95° F, 4000 ft altitude), for example, the engine can produce only 1163 hp. Considering the planned gross weight of the aircraft, this is barely enough power to maintain level flight with one engine out. Thus, the NAVAIR Office of Propulsion has expressed concern that the UTTAS and AAH, if powered by the present T-700 engine, will have only marginal capabilities. This is especially true of the AAH, which is intended to be operated in the "nap of the earth,"* where any sudden decrease in operating capability could easily result in disaster. It is also a possible problem for LAMPS which, as a Navy aircraft, is required to hover at maximum gross weight on a hot day and to take a waveoff with one engine out. In a third case, the proposed Marine Corps transport, the HXM, will be heavier than either the LAMPS or UTTAS, in which case it would need either more power or have less range.

In view of these factors, the NAVAIR Office of Propulsion believes that a more powerful engine should be developed for these aircraft. The proposed new engine might also be used as a retrofit in aircraft that now are powered by the T-58 engine, including the H-3 and H-46. It is expected that it will offer a 25% improvement in specific fuel consumption (SFC) in these aircraft. In addition, the newer technology engine is expected to offer significant benefits in reliability, availability, and maintainability. The primary sources of these benefits are a modular design that allows easy replacement of parts, and better materials that will have longer life.

3. New-Engine Proposal

The NAVAIR Office of Propulsion proposes to develop a new current technology engine, normally rated at 2200 hp. Several

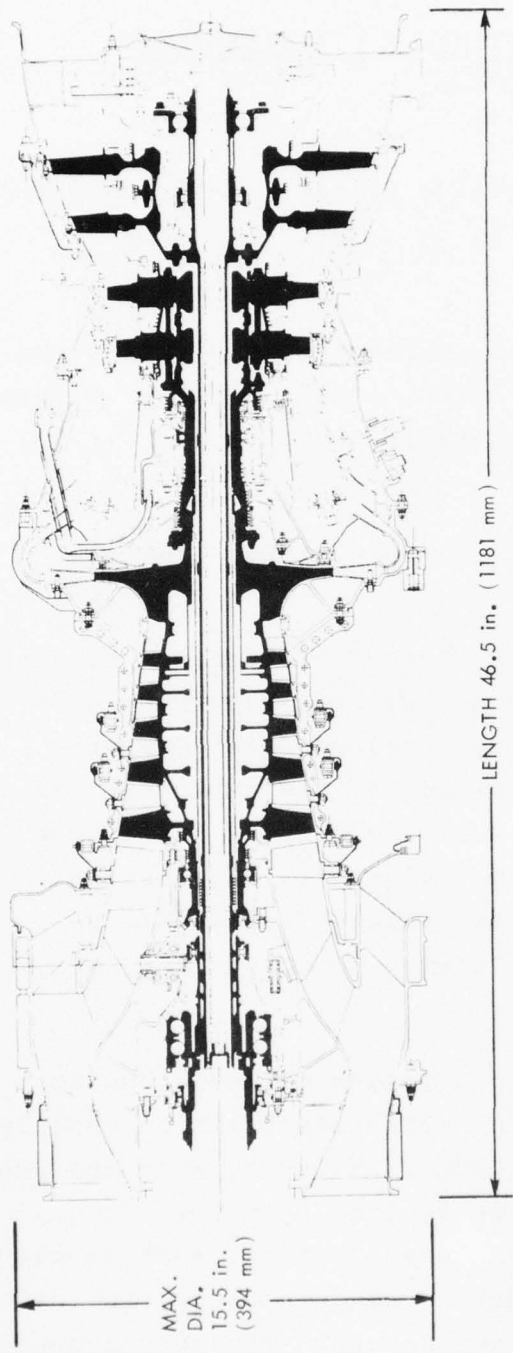
* At tree top level and below.

possible engine designs are candidates for this proposed development. One of them is the T-700 itself, which might be uprated. However, the uprating potential of the T-700 is limited. Its manufacturer has proposed a two stage uprating that would increase its power to about 2050 HP. This would involve the use of advanced state of the art technology. NAVAIR believes it could develop an engine with 2200 hp within the same physical envelope as that of the T-700. It also believes that the proposed engine will offer a small improvement in military power sfc (from 0.46 to 0.44). These beliefs are based on demonstrations that have been made with partially developed engines, some of which were in the competition that was won by the T-700 and whose development has continued under IR&D.

To produce 2200 hp within the same envelope as the T-700 would require either a significant advance in technology or another major change in the engine to get more air through. One possibility is a reduction in the size of the integral inlet particle separator, a large assembly forward of the compressor. (See Figure 3.) While this elaborate mechanism is considered necessary for many army operations, its utility for most naval operations is not clear. Use of a smaller separator would permit the addition of extra compressor stages within the same envelope.

We estimate that the development of a new engine of this type would cost from \$30 to \$150 million. The lower figure is applicable to the upgrading of an existing engine, such as the T-700. The higher figure is applicable to a totally new development. Full-scale development of one of the partly developed engines would probably cost something between those extremes.

The decision is whether the Navy should develop this new engine for any of the potential uses mentioned earlier: for the second buy of UTTAS, second buy of AAH, second buy of LAMPS, for the HXM, or as a replacement for the T-58 in two existing aircraft. We consider the decision in two ways, first as an



- INTERMEDIATE SHAFT HORSEPOWER (SLS) _____ 1536 _____ (1536)
- SFC _____ 0.469 _____ (0.213)
lb/shp/hr kg/shp/hr
- WEIGHT _____ *400 lb _____ (181 kg)

*Includes integral inlet separator

Source: General Electric T700 Turboshift brochure, December 1973.

7-6-76-12

FIGURE 3. T-700 Engine Specifications

independent development for the UTTAS, LAMPS, and AAH, and second, as an early development for the HXM.

4. Application of Proposed Guidelines for Independent Development (UTTAS, LAMPS, AAH)

Guideline

- a. *More than one potential using system, including retrofits, is identifiable.*

Comment

Without considering retrofits, three potential using systems have been identified: UTTAS, LAMPS, and AAH. Therefore, this guideline has been satisfied.

Guideline

- b. *Integration will not be a major problem. In other words:*

 1. *Subsystem performance characteristics are alterable over a reasonable range, without requiring major development effort; the scaling laws governing changes in the performance of the subsystem are well understood, or can be clarified during the subsystem development. Alternatively, system requirements are of sufficient flexibility to accept the developed item.*

Comment

The history of turbine engine development leads one to the general belief that engine performance can be readily changed over a considerable range. However, such changes, generally power upratings, are derived from two primary sources. One source is technology advances, such as high-temperature materials and turbine blade cooling that permit increases in turbine inlet temperature. The second source is simply over design, allowing engine power to grow with only minor changes.

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DEC 76 M KAMRASS, J J BAGNALL, J L BEEBE DAHC15-73-C-0200

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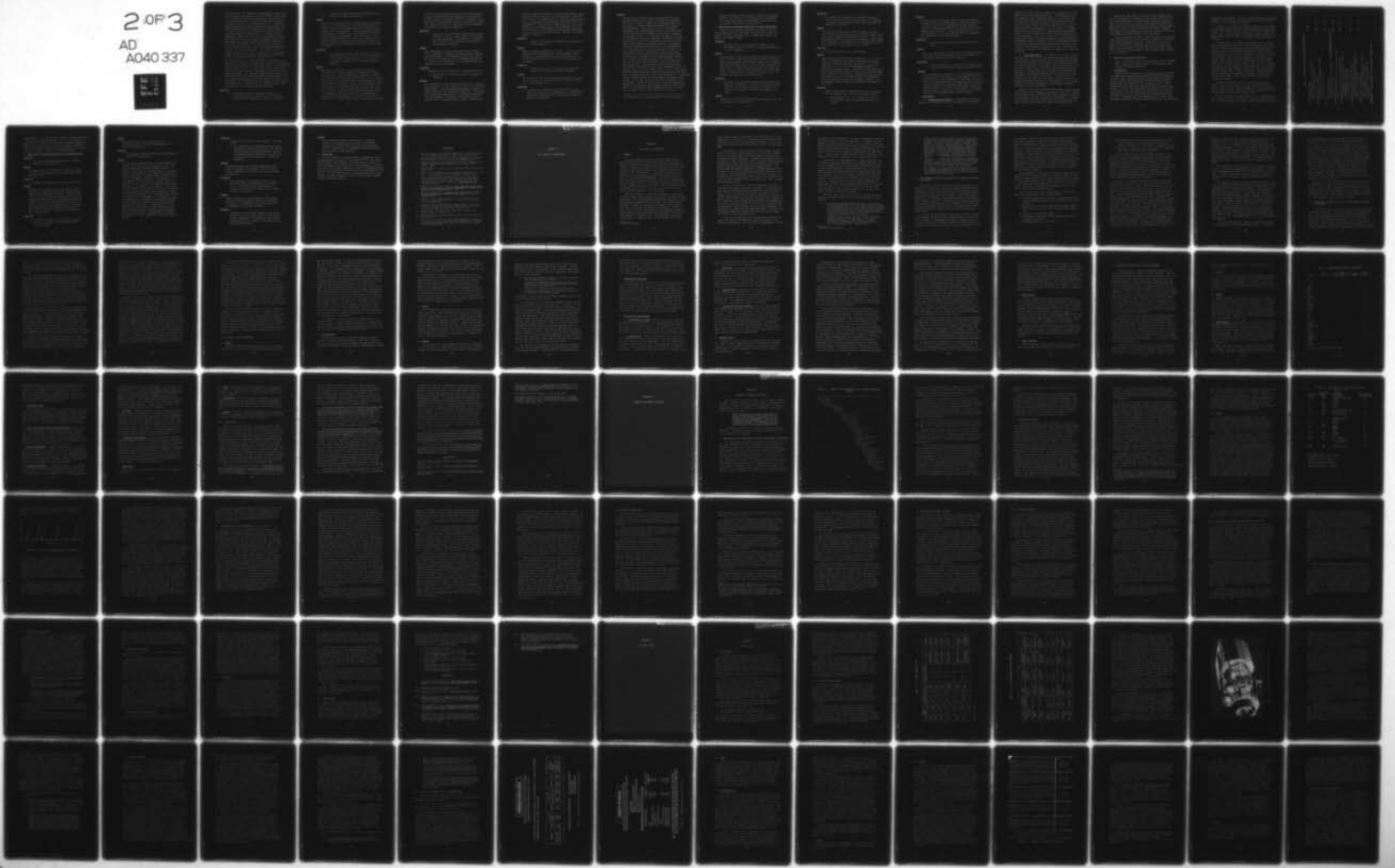
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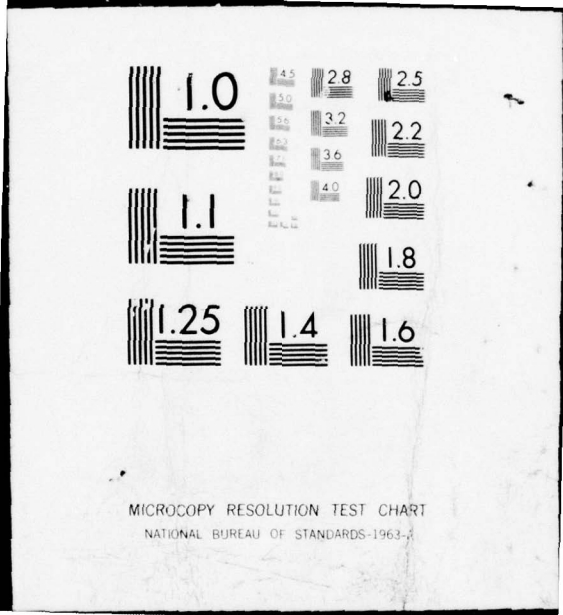
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We believe that the increases in engine power through technology advances are likely to be more limited in the future, since technology improvements beyond the present base are becoming more difficult. This means that the upgrading of an engine will tend to become more difficult. Performance gains stemming from initial overdesign could continue, but this would mean that such engines would be larger and less efficient than they might otherwise be. Hence, potential system performance is traded off for flexibility in subsystem use. Although, in the past, this tradeoff has been made typically in the direction of subsystem flexibility, the demand for improved systems performance coupled with fewer opportunities for gains from technology advances, may change this direction. The T-700 engine presents some evidence that this is happening. The outcome of such a trend could be the tailoring of the system to the available subsystem, which is the major alternative to having flexibility in subsystem performance characteristics.

The scaling laws seem to be reasonably well understood for engines that involve no more than minor advances in technology. However, there is evidence that engine design is more of an art than a science (Ref. 7). Engine efficiency is often highly sensitive to minor changes. Changing an engine from a demonstrated prototype to a production design sometimes results in unacceptable losses of efficiency which then generates a need for further development to bring the engine performance to an acceptable level. Nevertheless, with respect to the proposed Navy engine, the conditions for this guideline seem to have been met since it is to use current technology.

Guideline

2. *The subsystem can be repackaged without major development effort, allowing it to fit into the system without integration problems. Or if such*

repackaging appears impossible, the system can be designed to accept the subsystem.

Comment

The proposed Navy engine is to have the same outer envelope as that of the current T-700. The major problem may be changing the particle separator which could involve relatively elaborate development. Infrared suppression system changes may be necessary, but would probably not require major programs to accomplish. (The T-58 engine is also about the same size as that of the T-700.) Because of the particle separator problem, the requirements dictated by this guideline may be troublesome in both new and retrofit aircraft.

Guideline

3. *The environment of the using system will not adversely affect the performance of the new subsystem. If the normal system environment is a problem, a controlled environment for the subsystem would be available.*

Comment

The major environmental factors in which the Navy is interested are: salt, operational temperatures, thermal cycling due to mission requirements, vibration, torsional moments, flight loads, thermal environments in the vicinity of the engine, and inlet and outlet characteristics. With the exception of the salt problem, the environmental factors of interest to the Army are much the same as those of the Navy. However the Army has additional concern over flying dust and debris generated by helicopters operating close to the ground. This has resulted in the development of screens and particle separators to protect the engines (See Fig. 3). In this case the Army's environmental problem

could affect the proposed engine since the engine may not be able to develop the target power within the current envelope unless the particle separator is reduced in size. Thus there is considerable question as whether this guideline can be followed in the case of the two Army systems for which the new engine is suggested.

Guideline

4. *Conversely, the environment generated by the subsystem will have no adverse impact on the system or other subsystems. Alternatively, the environmental impact of the subsystem is controllable by appropriate packaging.*

Comment

The environmental concerns associated with the engine (i.e., temperature, controls, auxiliary power, vibration, and noise) appear to be engineering matters that create no new types of problems in the considered applications. As a result, the requirements for the guideline are considered to have been satisfied.

Guideline

- c. *Subsystem design parameters are adequately specified.*
 1. *System design is complete enough to specify the subsystem.*

Comment

The requirement of this guideline has been met. However, we reiterate one of the lessons that were derived from the case studies: a specification may change as a result of added requirements or operational experience. This seems to be especially characteristic of aircraft powerplants. During development, the weight of an aircraft tends to increase over the original design weight. Sometimes, in

addition, demands are made for increased performance. These factors require an increase in installed power. Therefore, the ability of an engine to grow in power has usually turned out to be valuable, although such an engine may not be as lightweight or efficient as it might have been, had it been designed for one power rating. The alternative is to restrain the aircraft requirements to weight and performance values that fit the available engine. However, this seldom happens in practice.

Guideline

2. *System will be designed around the characteristics of the subsystem.*

Comment

This is covered in guideline c.1 above. In this case, it means primarily maintaining the aircraft weight and performance at a level suitable for the available power. Since the conditions for c.1 are met, this guideline does not apply.

Guideline

3. *Subsystem is part of a family, whose characteristics span the expected system requirement.*

Comment

The requirement for this guideline has not been satisfied. But it does not have to be satisfied, if either of the c.1 or c.2 requirements is met.

Guideline

- d. *No subsystem alternatives are available that would permit the system to be cost-effective in the minimally acceptable set of missions of the type for which the system is envisioned.*

Comment

On paper and in official terms, the condition for this guideline cannot be met under the present circumstances. The reason is that a subsystem that apparently meets the requirement is already under development and is almost fully qualified. This subsystem is the T-700 engine. Presumably, the considerations raised by the NAVAIR Office of Propulsion have been examined by the project managers and in DSARC reviews. The resultant decision is that the T-700 engine will provide sufficient performance to enable the aircraft to meet the requirements that have been imposed. The additional performance margin to accommodate a hot-day, one-engine-out condition is a new requirement that apparently has not been accepted and included in the system specification. Similarly, the Navy operational requirements for hot-day hover and single-engine waveoff are either met or waived, and further marginal performance in these operations becomes a new requirement. Therefore, we conclude that the condition for this guideline has not been met. Nevertheless, we feel impelled to add that previous experience with aircraft developments have frequently led to a need for higher power. In fact, the requirement for higher power was sometimes expressed after the first buy of production aircraft (e.g., UH-1, Appendix A). Previously, the new requirement was met by increasing the engine power rating. In the case of the T-700, such a course may not be practicable. Hence, we believe that it will be essential to maintain close control on the weight growth of the user aircraft, or to modify hot-day operating procedures to ensure flight safety with the T-700 engine, or to do both.

Although the condition for this guideline has not been met in a formal sense, the requirements to determine whether the

above alternatives are satisfactory should be considered further. If they are not satisfactory, the requirement for a new engine should be generated, and then the conditions for the guideline would be met.

5. Application of Proposed Guidelines for Early Development

These early development guidelines are applied only to the potential use of the proposed new engine in the HXM helicopter, which we assume will have a higher gross weight than that of the UTTAS or LAMPS.

Guideline

- a. *The subsystem is of the type that requires a long development lead time relative to the development time of other subsystems.*

Comment

The development time for a new turbine engine is about five years. This is longer than the development time of most aircraft subsystems, and certainly longer than the development of the airframe itself. There is some uncertainty in the need for a time of five years in which to uprate the T-700. But the T-700 is not considered to be a good candidate for uprating; so, on balance, the condition for the guideline is considered to have been met.

Guideline

- b. *At least one, and perhaps several, potential user systems are identifiable. Note that the detailed characteristics of the user system may not be known at the time that the decision to develop the subsystem is taken.*

Comment

The HXM concept permits the proposed new engine to meet the requirements of this guideline.

Guideline

- c. *No subsystem alternatives are available that would permit the system to be cost-effective in a minimally acceptable set of missions of the type for which the system is envisioned.*

Comment

If the HXM is indeed heavier than the other aircraft, it will need more power, which can be obtained by either using three T-700 engines or developing the new one. But a careful design and cost study should be conducted, before making such a decision. The conditions for this guideline may be met, depending on the results of such a study.

Guideline

- d. *Integration will not be a major problem.*

Comment

This guideline was discussed as guideline b (1, 2, 3 and 4) under the independent development discussion preceding. The same conditions that were discussed in b (1, 2 and 4) apply here. In b (3) the army operating environment creates a different problem. The HXM will presumably operate in a naval environment and therefore the particle separator would not be so crucial. Furthermore, since the HXM is presently only in the concept stage, a larger engine envelope could be included in the design if needed. Hence the proposed engine follows the integration guideline in this case.

Guideline

- e. *System obsolescence, stemming from technology changes in the subsystem area, will not be serious because:*
 - 1. *No developments are in view that will obsolete the subsystem, before the system development is started.*

Comment

Some potential developments, such as the use of ceramic turbine materials and high pressure compressor stages, are in view. However, the incorporation of these types of advances in developed engines is not likely before the new engine can be developed. Hence, obsolescence is not a limiting factor, i.e., the conditions for this guideline are considered to have been satisfied.

Guideline

2. *"Form, fit, and function" principles are applicable.*

Comment

Form, fit, and function concepts are not applicable to the question of engine obsolescence, because an engine is a very highly integrated piece of machinery.

Guideline

3. *Expected benefits to be realized in the period of utility of the subsystem exceed the expected costs.*

Comment

If the conditions of either e.1 or e.2 guideline would not be satisfied, we would then do a cost benefit study, in which the cost of the development, acquisition, and operation of the new engine would be compared with the acquisition and operation of existing engine types over the expected period of utility of the intermediate technology. However, since the conditions of guideline e.1 are satisfied, the cost benefits study is not applicable.

6. Conclusions

- a. Independent Development. The guidelines have been applied to the possible use of the proposed Navy turboshaft

engine in the AAH, UTTAS, and LAMPS, all of which are in some phase of the system development cycle. The new engine meets the conditions of all guidelines except b.3 which says that the environment will not affect the subsystem and d which states that no subsystem alternatives are available. In the case of b.3 the problem lies in the Army's need to operate aircraft in dirty environments. In the case of d, an engine that meets the requirements is already in engineering development. In fact, prototypes of that engine are being used to power prototypes of two of the aircraft (i.e., UTTAS and AAH). On the other hand, as we have indicated previously perhaps the requirement should be changed in view of the previous history of helicopter weight and performance demands increasing over values that were originally envisioned. But, unless the requirement is changed, the conditions for guideline d cannot be satisfied.

b. Early Development. The guidelines for early development have been used to test the possibility that the proposed engine should be developed with its intended application being the HXM, assuming that the HXM would be significantly heavier than either the UTTAS or the LAMPS. The proposed engine satisfies the conditions of all the mandatory guidelines, except guideline c, which states that no subsystem alternatives are available. In this case we are not sure since there is one alternative that needs investigation: the possibility of using three T-700 engines. If, based on study, such use is feasible and cost-effective, the development of the new engine cannot be justified, according to the guideline condition; otherwise, it can be justified.

Each of these "iffy" possibilities provides only a partial justification for developing a new engine at this time. We see no defensible way to combine the two sets of partial justifications to make a "whole", unequivocal justification. It should be justified in one case or the other by the means indicated above, after which it might be used in both applications.

Besides the HXM, UTTAS, and AAH, the other possible uses for the new engine are retrofits to two aircraft (H-3 and H-46) that are now powered by the T-58 engine. The basic reason for such a retrofit would be to provide performance benefits that might result from a 25% improvement in specific fuel consumption. Basically, this would mean an increase in aircraft range and in payload, or in a combination of the two. But the T-700 would offer this improvement without further development.

Another possibility offered by the new engine is a significantly better RAM than that of the T-58. Again, the T-700 without further development would be a candidate for this role, since its RAM would be representative of the new technology. Hence, the development of the new engine on the basis of lower fuel consumption or better RAM in the H-3 and the H-46 aircraft is not justified.

D. CORRELATION GUIDANCE SUBSYSTEMS

Note: Classified aspects of these devices are not included here. They are discussed in Part 2 of this study, which includes classified appendices.

1. Introduction

Research and development on a correlation guidance subsystem began three decades ago at Goodyear Aerospace Corporation. The first model, Automatic Terrain Recognition and Navigation (ATRAN), was the first system to use the principle of radar map-matching for navigation, and it weighed 1200 lb. Early development was intended for application in the Matador cruise missile. By 1953, the weight had been reduced to 250 lb, and the subsystem was incorporated into the Mace cruise missile. Approximately 250 units were deployed in Europe between 1958 and 1965. Subsystems were also designed for the Navy's Triton and Regulus missiles, but these major systems were canceled during

research and development. In 1975, Martin Marietta subcontracted Goodyear to build a radar map-matching system, using a Correlatron tube for the Pershing II missile.

Correlator performance has improved greatly over the years. Also volume, weight, lifetime, and reliability have greatly improved. These improvements are attributed mostly to the Correlatron tube. The culmination of this set of developments is a system called Aimpoint, whose development history is summarized in Table 3.

Unfortunately, one significant parameter has not dramatically improved over the years. This is subsystem unit production cost, which was \$30k for the Mace guidance system and is expected to be in the \$50k-\$60k range for the Radar Guidance (RADAG) system for Pershing II. However, if inflation is taken into account, the unit cost increase may in reality be a unit cost decrease. Most electronic subsystems, such as aircraft radars, have experienced unit cost increases of much larger factors (4-5) over the past 20 years. The cost of the Correlatron tube is a small fraction of the subsystem cost. Produced by the Electron Tube Division of ITT, this tube is expected to cost \$5k-\$8k per unit in small quantities. However, the production cost would be expected to decrease to \$2000 per tube for 2000 unit orders, and to less than \$1000 per tube for 10,000 unit orders.

The most important feature of the Correlatron is the nearly instantaneous comparison of real-time and reference images. This provides a search capability that was lacking in earlier systems, which required a reference image and thus precluded operation over large bodies of water.

At least 11 potential applications of the Correlatron tube are envisioned and one is currently planned for operational use. The technical feasibility of many of the applications has been

TABLE 3. HISTORY OF AIMPOINT DEVELOPMENT CONTRACTS*

HITTING MISSILE STUDY	1964
- PROJECT FORECASE - HIT FROM STANDOFF	
- UNVEILED CORRELATRON APPROACH	
DEVELOPMENT AND TEST PROGRAM	1965 - 1968
- BREADBOARD XY & XYZ CORRELATRON HARDWARE	
- C-130 & UH-IF FLIGHT TEST	
L ³ STUDY	1968 - 1969
- LAB TEST CAPABILITY	
- INTERFACED TO MODEL 55 XYZ TRACKER & QUICK DEMONSTRATION VIA UH-IF	
SRAM/"OPTAG" SUPPORT STUDY	1968 - 1969
- MODEL 55 AT BAC ON SIMULATOR FOR ADVANCED SRAM	
DEVELOP AND TEST A MISSILE CONFIGURED AIMPOINT	1969 - 1970
- RECONFIGURED OAC DESIGN; DAY/NIGHT CAPABILITY	
- INTEGRATED WITH STABLE MOUNT	
- UH-IF HELICOPTER FLIGHT TEST	
SNAP-AND-GO AIMPOINT OPERATION AND TEST	1970 - 1971
- STRAPDOWN OAC, ELECTRONIC STABILIZATION	
- COMPATIBLE WITH PAVESTORM III "REQUIREMENT"	
AIMPOINT DROP TEST EVALUATION	1971 - 1974
- REVISED REQUIREMENT FOR DUAL MODE CAPABILITY	
- TIED TO PAVESTORM III EVALUATION	
- COMPETITIVE TEST EVALUATION AT WSMR	

* Reference: Private communication--Goodyear Aerospace Corp.

demonstrated. It is not possible to design a single subsystem, or even a single Correlatron tube, that could be used for all applications. A modular Aimpoint optical guidance subsystem, however, has been proposed by Goodyear Aerospace Corporation for glide or powered vehicles. We have subjected this subsystem to the guideline conditions for standardization.

2. Application of Proposed Guidelines For Standardization

Guideline

- a. *More than one potential using system, including retrofits, is identifiable.*

Comment

The condition of this guideline has been met, subject to Aimpoint being chosen over its competitors as the guidance system.

Guideline

- b. *Subsystem technology is mature and well in hand.*

Comment

Aimpoint is the culmination of more than 10 years of successful development and testing. Therefore, the device itself meets this criterion. However, high volume production has never taken place; so far, all production has occurred in a semilaboratory setting. However, this aspect would affect the selection of Aimpoint instead of its standardization. Therefore, the condition for this guideline is considered to have been met subject to the same qualification as that of guideline a.

Guideline

- c. *The potential market is large enough to support at least one contractor, and preferably two, for several years.*

Comment

The subsystem meets the criterion for this guideline, subject to the same qualification as that under guideline a.

Guideline

d. The projected overall benefits of standardization exceed its disadvantages.

Comment

If more than one system were to use the Aimpoint subsystem, there would be an opportunity for unit cost reduction through increased production orders. In addition, there would be the opportunity for reducing support costs, since the using systems would share a common reconnaissance imagery format, and data collection and processing assemblies. Consequently, it is our judgment that the condition for this guideline would be met by standardization, provided the decision was made to use Aimpoint on two systems. We have not attempted to deal with the use of Aimpoint in relation to other kinds of automatic guidance systems. Also, we raise one cautionary note. At present there is only one maker of these subsystems. If a decision is made to standardize, the question of procurement strategy must be carefully considered, as we have discussed previously in this report. Otherwise, there is the danger of the Government being at the mercy of the one contractor, unless a long-term pricing arrangement can be worked out. Alternatively, or perhaps in addition, it may be desirable to qualify a second source.

Guideline

e. *Integration will not be a major problem. In other words:*

1. *The subsystem can be repackaged without major development effort, allowing it to fit into the system without integration problems. If such repackaging appears impossible, the system can be designed without difficulty to accept the subsystem.*

Comment

Integration feasibility has been demonstrated in at least two systems (see Appendix L, Part 2 of this study). Therefore, the condition for this guideline has been met.

Guideline

2. *The environment of the using system will not adversely affect the performance of the subsystem. If the normal system environment is a problem, a controlled environment for the subsystem will be available.*

Comment

Based on experience, the environment of the using systems should not adversely affect the performance of Aimpoint. Consequently, the condition for this is considered to have been satisfied.

Guideline

3. *Conversely, the environment generated by the subsystem will have no adverse impact on the system or other subsystems. Alternatively, the environmental impact of the subsystem is controllable by appropriate packaging.*

Comment

Since Aimpoint depends on the the use of a passive sensor, its interaction with the rest of the system should be no different from that of any other passive sensor. Therefore, it is considered as having satisfied the criterion for this guideline.

3. Conclusions

All the criteria or conditions for the guidelines for the standardization of Aimpoint are considered to have been satisfied, subject to the condition that the guidance method is in fact the method for choice for two or more systems. As we have noted above, this choice depends not only on performance factors, but also on the potential for setting up for large quantity production. We also caution against standardizing without a procurement strategy, designed to protect the Government against contractor monopoly pricing.

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APPENDIX A

UH-1 AND AH-1 HELICOPTERS

APPENDIX A

UH-1 AND AH-1 HELICOPTERS

I. SUMMARY

The developmental history of the UH-1 (Huey) utility helicopter and its AH-1 (Huey Cobra) gunship derivative can scarcely be separated from the recent history of the Army, and from the advocacy role played by the helicopter contractor and a group of Army officers who were enthusiastic about an enhanced role for Army aviation. This advocacy resulted in a contract to Bell Helicopter to produce the first version of the UH-1 as a "medevac"* helicopter. However, contract for this development was held up initially, since the requirement, even when combined with two secondary missions, involved only a small number of production aircraft. Then, the Army aviation enthusiasts came up with a rationale for a new mission that would require thousands of utility aircraft.

The first production Hueys were delivered to an armored cavalry division, where doctrine and tactics for their use were developed. Also, new performance needs were recognized. Hence, the UH-1A was superseded by the UH-1B, a more agile machine because of changes in the engine and dynamic system that had been made as a result of the initial experience. Each new model of the aircraft (there are about 20 different versions) was designed to a somewhat different requirement and had somewhat different characteristics. The development was mainly evolutionary: a change in one or two components at a time.

* Medical evacuation.

Such changes involved either IR&D by the contractor or, if the capability was believed to be satisfactorily demonstrated, the development was directed by the program manager. Such a capability demonstration was often the objective of the contractor's IR&D.

The improvements that started as IR&D included a larger chord rotor blade, larger diameter rotor, a new rotor airfoil section, new blade production method, weapons installations, and uprated dynamic components. Primarily, the impetus and the capability to make these improvements came from the manufacturer, who maintained close contact with the military users of the machines and noted their desires and dissatisfactions. Contractor IR&D was aimed at improving or adding something to the aircraft, for which the manufacturer detected there was a need or desire. Such development might be carried to the point of demonstration, at which point the purchaser would decide to include the new characteristic in the latest buy. Then, a directed development ensued.

In the entire history of the UH-1 aircraft, only one independent development was directly relevant. This was the initial engine development contract awarded by the Army Ordnance Corps in 1951 to Lycoming, to develop a 480-shp (continuous rating) turbine engine for a four-place helicopter. Within six months, this contract was amended to increase the horsepower to 600. Before a 600-shp engine was qualified a second amendment was made to develop an engine for the H-40, the prototype utility helicopter which needed 770 shp; thus, the independent development was turned into directed development. Moreover, even the 770-shp engine was uprated after some operational experience with the first production buy.

After the airframe and turbine engine were initially combined, two further developments occurred that might be considered revolutionary. The first was the development of a chin

gun turret by Emerson Electric, working in cooperation with Bell, and both of them on their own IR&D funds. The second was the gunship fuselage, developed by Bell on its own after losing the AAFSS (Armed Aerial Fire Support System) competition to Lockheed. Again, it was the Army aviation contingent that decided it needed this aircraft in Vietnam, following the Bell demonstration. And this was a primary factor in Bell's receiving a production contract over objections from a number of sources.

Other items were developed early. These constituted GFE (government-furnished equipment) to the prime contractor, e.g., avionics equipment, sighting and tracking equipment, and some of the flight equipment, including instruments. We have not examined these in detail in this study, since they were available equipment insofar as the prime contractor was concerned. In a number of cases, it was necessary for Bell to repackage some of these subsystems to fit and integrate them into the aircraft. Examples, which we class as being independently developed, are the "comnav"* system being installed in current model aircraft as part of the Army avionics plan, the night vision equipment, and survival equipment that is part of the Army's aircraft survivability program.

From this case study of the Bell Huey and Huey Cobra, we draw the following conclusions about the development of subsystems:

- a. Contracted independent development was not a factor in the developmental history of these aircraft. Nearly all developments were done under IR&D by the contractor or a major subcontractor. They were taken to the point of demonstration and, if the customer accepted them, they were followed by either a production contract or a directed development for the next buy.
- b. Standard subsystems were GFE that had been developed for general use in Army aircraft. These were developed independently under commodity programs (avionics, survivability) that were responsive to ROCs (Required Operational Capabilities).

* Communication/navigation.

- c. Prime contractor behavior was to expand its envelope of expertise. Unless it was required to adapt subsystems, either by contract or lack of in-house expertise, it tended to develop what it needed. Major exceptions were the engine and weapons. In these cases, the contractor established close working relations with those who had the capability and, in some cases, performed joint IR&D projects with such contractors. In at least one case, the contractor developed a new subsystem, when available off-the-shelf equipment could have performed the function.
- d. A close relationship with the operators, and aggressive advocacy by the prime contractor and some of its military clients, were decisive factors in the original development of the Huey and the follow-on development of its improvements and derivatives.
- e. The transfer of technology from the technology base was readily accomplished by the contractor, through an incremental approach that relied substantially on IR&D and directed development.

II. DEVELOPMENT HISTORY OF THE HUEY (UH-1) SERIES OF UTILITY HELICOPTERS

Experience in Korean military operations provided an impetus for developments to improve helicopter operating characteristics. Helicopters of the Korean era were powered by reciprocating engines; they had relatively low payload-to-empty-weight ratios, low climb rate capability, and poor hovering performance at altitude, although their endurance was satisfactory. However, there was a greater need for payload and hovering capability than there was for endurance in the operations for which helicopters seemed suited. It appeared that turbine engine characteristics would help in achieving this desired performance.

In 1951, the Army Ordnance Corps contracted with Lycoming Engine Company to develop a gas turbine engine for helicopter use. This was an independent development, although there was a fairly specific use in mind--a four-place machine capable of carrying two patients on litters as well as an attendant inside

its fuselage. Other desired characteristics were increased smoothness (decreased vibration) and reduced maintenance. Another requirement was that the helicopter be air transportable. In addition to the medevac mission, there were secondary missions of staff and command utility and helicopter instrument training. Also, from Korea came the requirement for hovering capability at high altitude on a hot day (5000 ft, 95° F). The gas turbine engine, whose initial target horsepower was 480 (600 take off), was believed to be a primary means of resolving this diverse set of requirements. Within six months of the award of the original contract, the Army decided it would need more power and the contract was amended to develop a 600-shp (military rating) engine.

The requirement to develop the actual helicopter was later generated by the Airborne Board at Ft. Bragg, except that the question remained whether the new aircraft should have a turbine or reciprocating engine. The missions named for the helicopter to fly indicated a requirement for a total of 150 to 200 aircraft. More than 20 proposals were submitted, four of them from the Bell Helicopter Corporation.

Bell's "homework" prior to submitting its proposals had been done largely under IR&D. This included:

- Close coordination with Lycoming to interchange information on helicopter and engine requirements and interactions
- Installation of a French-made turbine engine (under an Air Force contract) in the previously piston-powered H-13
- Research on metal rotor blades
- Development of methods to use honeycomb materials in airframe structures
- Simplification of the rotor hub

- Development of an elevator control system with a non-linear connection to the cyclic controls, thereby reducing sensitivity to c.g. (center of gravity) travel
- Evolution of simplified logistic concepts for helicopter maintenance, based on Korean experience.

Bell was awarded a development contract in 1956, on the basis of one of its proposals that specified a turbine engine. This award created considerable controversy, in which Bell's competitors and high Army officials became embroiled. The essential argument was that a new machine should not be developed, since there was a requirement for only 150 to 200 aircraft. Such a low quantity did not justify a development program, because an already developed transport helicopter, the H-34, could accomplish the named missions. The contract award was put in limbo by the Army Chief of Staff.

Later on, a new mission requirement evolved, which came about through the studies of a group of Army aviation enthusiasts led by General H. Howze. The requirement was for a small tactical troop transport, which in concept could provide air mobility to fighting forces in small units, perhaps of squad size. Studies initiated by the Army aviation group through the Army's Chief of R&D indicated the technical, economic, and military feasibility of this concept. The outcome was a potential requirement for 3000 aircraft, whose individual airframe cost was to be under \$100,000. The development contract that had been in limbo was finally released to Bell, who developed the wholly new airframe for \$15 million. It was also recognized that the engine to be produced under the contract that had been given to Lycoming earlier would not be powerful enough for the proposed helicopter. Therefore, a new contract amendment was made to "grow" the engine to 770 shp. The original 600-shp engine was never qualified. In addition, by maintaining close liaison with the field when the prototypes were flying, Bell

managed to get most field corrections incorporated in the pre-production UH-1. The first group of production aircraft (UH-1As) went to Ft. Campbell in 1959, where they became part of division equipment. At that time, General Westmoreland was the Deputy Division Commander. At this point, the aircraft had the Lycoming T-53-1A engine, which was rated at 770 shp. Its missions included instrument training, medical evacuation, and administrative troop lift (seven-place). Its maximum gross weight was 7200 lb. A total of 173 UH-1A aircraft were produced.

The performance of the aircraft was not completely satisfactory. Greater payload would have been desirable. In addition, an argument was raised about the productivity of the aircraft. Because of the small payload, it was not considered cost-effective in comparison with the larger transport helicopters.

The Director of Army Aviation, then General von Kann, decided to "grow" the vehicle by improving the components. Bell first developed an improved rotor system. Blade chord was enlarged from 15 to 17 and then to 21 inches. Transmissions were tested at higher power. Engine power was increased to 860 shp. The upgraded aircraft broke a number of records for helicopter performance, which seemed to provide the justification for the B model, a growth version of the UH-1A aircraft and engine. This new aircraft was intended to be capable of flying the previous missions as well as a new mission (fire support). Three engine versions were used in the B model, starting with the T-53-L-5 with 960 shp, and ending with the L-11 with 1100 shp. The maximum gross weight increased from 7200 lb to 8500 lb. This permitted about a 500-lb increase in the payload.

In 1963, Bell proposed a change to stretch the fuselage but to continue to use the same dynamic system. Eventually,

this stretched fuselage was combined with a larger rotor to become the D model. Gross weight was increased to 9500 lb.

At about this time, the West German Government came in with a request for 350 utility helicopters and a competition was held among Bell, Sikorsky, and Vertol, which was to be settled by a flyoff. Bell apparently held its own, until it was decided to run part of the flyoff at high altitude. Bell engineers felt their engine was not powerful enough to perform well at high altitude. Meanwhile, Lycoming, with whom Bell had been maintaining its continuing close relationship, had developed the T-53 engine to where it had tested one that could be rated at 1400 shp. Although the engine had never been flown, it was brought to Germany and installed in the flyoff aircraft. This gave a clear advantage to Bell, who easily won the flyoff with the demonstration of the altitude capabilities of its helicopter.

From time to time, other modifications have been made to the UH-1 basic aircraft, in response to new capabilities requested by users. These requirements have been met by variations in power, dynamic components, and by changes in internal configuration and auxiliary equipment. The users include the U.S. Army, Navy, Air Force, Marines, and the military forces of Canada, Germany, Iran, and other countries.

III. DEVELOPMENT HISTORY OF THE AH-1 ATTACK AND FIRE-SUPPORT HELICOPTERS

In the early 1960s, the Army put rockets and machine guns on utility helicopters. The earliest efforts were reminiscent of the early weapon delivery modes of aircraft during World War I, when bombs might be thrown over the side and pilots would shoot at each other with pistols. In the case of the helicopter, machine guns or rocket pods were hard-mounted on the skids. Later, combined efforts of Bell and Emerson included the development of rocket and machine gun kits for side mounting,

turrets for nose mounting, and a universal pylon on which a variety of stores and weapons could be mounted. The weapons aircraft required a crew of four, they had high drag (the Huey had a wide fuselage with side-by-side seating), and the payload was low.

Bell, with the IR&D funds, sponsored the development of an integrated prototype gunship, using the Model 207 (H-13) Sioux Scout as a test bed. The gunship had two M-60 machine guns installed in a chin turret, which had been developed by Emerson Electric, also under IR&D. It had tandem seating and side-arm controls that provided a space for the gunner's sight. A honeycomb floor served as structural mounting for the chin turret, thus providing a structure that minimized vibration and absorbed turret recoil loads. In January 1964, pilots of the 11th Air Assault Division evaluated the aircraft and recommended that the Army develop a special-purpose helicopter, using the same configuration but with turbine power.

The requirement for the Armed Aerial Fire Support System (AAFSS) evolved from this evaluation. The Transportation Corps and the Secretary of the Army decided to hold a competition to develop a prototype. Lockheed proposed the Cheyenne. Bell proposed the Warrior, a two-place tandem machine that would use the same dynamic components as the UH-1C would use, but with a new fuselage to provide better performance, and with the weapon system integrated into the machine. Lockheed won the contract award with its Cheyenne which promised better performance and less maintenance than did the Bell machine, primarily because of an advanced technology (though unproven), rigid rotor system.

After the development contract was awarded to Lockheed, Bell decided to build its proposed gunship secretly, on its own. This decision was made in January 1965 and the ship, now called the Huey Cobra, was supposed to fly that year. At first, the Army ignored Bell's work, but by then the Vietnam commitment

was growing and the need for gunships was being emphasized. At that time, the Hueys (UH-1s) were being used as gunships, with machine guns being fired through open side doors and with rocket pods attached to the side. Also, the aircraft was considered to be too slow for gunship use and, because the weapon system was not truly integrated with the machine, the total system was clumsy and ineffective. Visits of Bell personnel to the battle areas, and discussions with combat arms people indicated that the Cobra concept would match the mission requirements. Although the Transportation Corps wanted to stop the program, calling the Cobra a high-risk development, General Westmoreland was convinced of the need and he provided the requirement for the Huey Cobra.

Army doctrine at that time was explicit in denying the use of armed helicopters for assaulting enemy forces. Close support was to be supplied by Air Force fighters. Combat helicopters were to be used for such missions as moving troops and weapons, for observation, and for reconnaissance. Some arming of aircraft or helicopters for self-protection and for use in armed reconnaissance was legitimate. But the concept of using helicopters as the means of delivering of heavy firepower or close support in assault missions was a disapproved notion, although a number of Army-sponsored studies and combat development groups had been examining such concepts. There was opposition to this requirement from the Transportation Corps and from Bell's competitors, who were effectively shut out from competing against a development that was all but completed and a requirement considered to be immediate. The Army Chief of Staff found it difficult to veto a request that had its origins in Vietnam combat and was supported by General Westmoreland, Vietnam combat veterans, and the combat arms groups. The contract for the AH-1 was let.

Controversy over the eventual outcome of this use of helicopters in Vietnam continues. Helicopter losses to enemy weaponry were significant, and it is not yet clear whether gunship helicopters provided significant assistance in Vietnam. Analysis of this particular controversy is beyond the scope and purpose of this paper. The present situation is that the Army is now running a competition for an advanced version called the Advanced Attack Helicopter (AAH), which has succeeded the AAFSS as the next-generation Army combat aircraft. AAFSS development was stopped after the Cheyenne rigid-rotor concept ran into technical and financial difficulties (see Appendix B). Meanwhile, the technology of arming helicopters has developed to where an individual helicopter can be made capable of delivering a considerable variety of ordnance with only minor changes, most of which are possible in the field. In addition, considerable attention has been paid to methods of augmenting survivability against surface-launched weapons through a formal aircraft survivability program.

The foregoing narrative represents the basic background leading to acceptance and development of integrated armed helicopters. Our interest is not in the merits of the concept but in the nature of the process, particularly where improvements and new capabilities were incorporated in the hardware itself. The Bell machines illustrate nearly all the possible ways in which such improvements and new capabilities occur. The next section addresses a number of the subsystems that have been incorporated or improved in the Huey helicopter and its derivatives.

IV. HISTORY OF HUEY SUBSYSTEMS

A. Engine

The T-53 engine, which has powered almost all the Hueys and Huey Cobras, was started as an independent development by

the Army Ordnance Corps. At that time, the independent concept was a four-place helicopter capable of hovering "out of ground effect" on a hot day. Although there was no specific design, an estimate of the weight of the aircraft led to a specification of 480 shp (continuous rating) for the engine. Lycoming started this development in 1951. Within six months, the contract was amended to increase the rating to 600 shp, causing Lycoming to scrap all the work up to that point and start afresh. However, a 600-shp engine was never qualified. The requirement for the aircraft grew, and eventually the need for a more powerful engine was realized with the design of the H-40. When the Bell design requirements became better known, Lycoming increased its engine horsepower from 600 to 720 and then to 860, although it was flat-rated to 770 to meet the capabilities of the original Huey dynamic system. This engine, the T-53-L-1A, was installed in the UH-1A aircraft. For the UH-1B, the power of the T-53 was increased twice, to 960 and then to 1100 shp; this was the L-11 engine. The L-13 engine, originally developed for the UH-1C, was rated at 1400 shp. This engine version is used in all the Bell gunships. Development of the T-53 has continued, and the engine is now capable of producing 1700 shp, but there is no program for it at present.

The upgrading of the T-53 engine is characteristic of turbine engines. It was achieved by a variety of devices that include the use of higher temperature materials in turbine components, additional turbine wheels, and improved compressor and stator blading to increase pressure and air flow.

B. Transmissions

The Huey transmission has had four changes, intended to upgrade its power-transmission rating. This was achieved by the use of duplex and triplex bearings, strengthening the case, increasing the number of planetary gears, thickening the flanges,

and increasing the oil cooling capacity. Despite these substantial changes in power-handling capacity, the transmission's external appearance is much the same as the original. These product improvements were directed developments, related to new versions of the aircraft.

Transmission development is continuing at Bell with the intent to provide transmissions that will operate for a reasonable period of time (30 to 45 minutes) without lubrication. Thus, if the lubrication system is damaged, there is a good chance of the vehicle being flown to a safe recovery point. Three such transmissions are now being fabricated for testing. It is possible that they will be used on a new machine called the Advanced Attack Helicopter (AAH), for which Bell has a contract to produce vehicles for a flyoff. At the present time, this transmission development is primarily IR&D, although there is some Navy 6.2 support in the development.

C. Rotors

The original Bell rotor had a chord of 15 inches and a diameter of 44 feet. New requirements prompted Bell to develop larger rotors, ranging up to 48 feet in diameter and 27 inches in chord. These various sizes of rotors were used in the different aircraft, to emphasize performance characteristics that might be desired for different missions. Other work included the development of a new high efficiency airfoil, and production methods for making the new airfoil, which required higher tolerances than did the original. The concept of the new airfoil was developed under IR&D, but its application to the Huey was done as directed development.

D. Weapons

In all cases, the basic weapons were either in existence, or they were developed independently of the aircraft. This included the M-60 machine gun, 2.75-inch rocket, 40-mm grenade

launcher, and such guided weapons as the SS-11 and TOW (tube launched, optically tracked, wire guided) missiles. However, the installation of these weapons on the aircraft required directed development, because there was a substantial integration problem. This included:

1. The need for turrets and hard points that would provide an adequate field of fire
2. Avoidance of interference with any of the aircraft components and structure including damage from recoil, muzzle blast, and vibrations
3. Provision of ammunition storage and feed systems
4. Avoidance of electromagnetic interference with any of the aircraft's electronic systems.

In addition, the fire-control and stores management systems had to be integrated with the aircraft.

The development of the TOW system perhaps typifies the process of development with the Bell aircraft. To operate the TOW adequately from an unstable platform, such as a helicopter, requires a stabilized sight. Such a sight development was undertaken by MICOM, as a prototype conceptual program independent of the TOW development. Bell supplied the platform for the stabilized sight system but otherwise was not involved in the program. When this program was completed, Bell proposed an ECP (engineering change proposal) to install the TOW on the AH-1. The TOW airborne tracking unit, which was different from the MICOM unit, was to be used along with a stabilized mirror instead of stabilized optics. This concept had been developed by General Electric for the Cheyenne helicopter, and it represented an additional capability over the MICOM unit, because the mirror system could accept any optical signal, including FLIR (forward looking infrared), laser, and conventional optics.

The TOW pods and launchers were both directed development. The pods were developed by Hughes, and the slewable launchers were developed by Bell. Since the TOW is to be launched from

the helicopter in a hover, and the attitude of the aircraft will vary with wind and aircraft weight, the launchers must be vertically slewable to permit launching the weapon at the correct angle for "capture" by the gunner's control system. Thus, the integration of the TOW system to the aircraft was, in itself, a development problem.

E. Stabilizing Subsystems

Although Bell built a stabilizing system as early as 1952, no such system was used on any of the Hueys until Bell sold some to the Italian Government, who needed an overwater hovering capability at night. For this purpose, Bell developed a system called SCAS (stability and control augmentation system). This system is now used on the Cobra, where it improves weapon aiming accuracy and helps reduce drag by permitting the elimination of the stabilizer bar. Although other manufacturers had developed such devices, Bell decided to develop its own, which it claimed saved weight and was easier to integrate into the helicopter. Bell claims that its better unit stemmed from its better understanding of the dynamics of its machine.

F. Survivability Enhancement

1. IR Suppression System. This is a system to reduce the vulnerability of the aircraft to an infrared-seeking missile. It controls the temperature of the exhaust and engine surfaces that might be "seen" by a missile. The system is highly integrated with the aircraft configuration, and it includes a mixer to dilute and cool the exhaust gases and exposed engine surfaces.

2. Landing Gears. Bell's preconception of its own superior capability to design components for its own aircraft was borne out in the case of landing gears. Bell had subcontracted the design and production of the landing gear for the prototype machines. But it received what it considered to be a high-weight gear. Consequently, Bell developed its own design, which

used an energy absorber principle involving the shearing of metal. This saved 250 lb of dead weight.

3. Fuel Cells. A safety assessment of helicopter operations resulted in a development of crashworthy fuel cells. This development was sponsored by the Army's Aviation Laboratories and was intended as a retrofit for all Army helicopters, particularly the Hueys, which were exposed to considerable enemy fire in their missions. The penalties associated with this survival measure are reduced fuel capacity, increased empty weight (about 130 lb on the AH-1G), and increased airframe cost.

4. Armored Seats. During the Vietnam war, there was a desire to reduce the vulnerability of the aircraft and crew to ground fire. The outcome was an armored seat development. Actually, the armor material had been developed earlier by other manufacturers. Bell designed seats for its aircraft, but subcontracted the fabrication to another manufacturer.

5. Other Survivability Programs. Bell has been developing gears and transmissions that are capable of surviving oil pressure loss for about 30 to 40 minutes. Also, Bell is working on programs to reduce the vulnerability of flight control systems and the tail boom. These programs are all part of a general product improvement program, being conducted partly under IR&D with some sponsorship by the military service. This program may result in the development of vulnerability reduction kits that could be retrofitted to existing aircraft. These Bell programs tend to complement the Army's aircraft survivability program discussed below under standard items.

G. Standard Items

A number of items included in the helicopters are standard GFE. These include flight instruments, batteries, the starter, alternator, motor generators, hydraulic accumulators, and hydraulic pumps. However, components such as control actuators are Bell-designed.

Communication and navigation developments are being handled through the Army aviation plan, which is a time-phased plan that is independent of any particular aircraft schedule. The plan is to develop standard integrated equipment for installation in the aircraft. This has resulted in the redesign of the aircraft, particularly around the instrument panel, to accept the new equipment. Thus, an independent development is being done on equipment that is to become a standard package.

Similarly, there is an Army program for aircraft survivability, in which standard equipment is being developed and procured for installation on various Army aircraft. This program illustrates how the Army has created a structure to independently develop equipment and to standardize it for use in performing similar functions on different aircraft. The program was initiated as a result of experience in Vietnam with some of the survivability equipment installed on Army aircraft and used before that conflict ended.

The survivability philosophy has three objectives: (1) reduce aircraft detectability, (2) reduce the enemy's weapon hit probability, and (3) increase the recovery probability. A cost-effectiveness study was done to indicate how these objectives should be implemented. The study examined the missions and operating environments for each type of Army aircraft, making an allowance for the fact that some aircraft of the same type might not have the same set of missions depending on their assignment. Various subsystem candidates were considered in the study. The outcome was a set of specific recommendations for equipping the Army's aircraft with a number of survival means. These recommendations were translated into a ROC (required operational capability) for aircraft survivability equipment, which became the operative document in this area after approval by the Assistant Chief of Staff for Force Development (ACSFOR). The responsibility for implementing this ROC then devolved to the Army's Office of Research, Development,

and Acquisition. A five-year program and a budget were developed and approved. The survivability program then became a line item (in fact several lines) in the Army's budget, representing an expenditure of some \$500 million through 1980.

This five-year program is related to the individual aircraft procurement programs, so that the required items will be available in time for inclusion in the various aircraft being procured. In addition, some retrofits on existing aircraft will be timed to take place when those aircraft are in shops for overhaul or modification for other purposes. The program will develop, test, qualify, and procure equipment and a number of subsystems for Army aircraft. These include two radar warning receivers, a false-pulse infrared suppression device, a flare dispensing system, engine exhaust deflectors and mixers, a chaff dispensing system, camouflage paint schemes, armored seats, dual control systems, and low reflectance canopies. As noted above, not all of these items will be installed on each aircraft. Instead, the aircraft will be outfitted with equipment appropriate to their missions and operating environment. Thus, for example, two UH-1 aircraft with different assignments might have different survivability equipment.

The survivability program cuts across the various aircraft programs, and it must interface with the system program managers to ensure that scheduling and integration take place as needed. An officer in the Army's Office of Research, Development, and Acquisition, who is designated a DASC (Department of the Army System Coordinator), is assigned to each aircraft program. The DASC coordinates the survivability and other commodity-type programs with the aircraft program manager to make sure that the directives for including the equipment are properly implemented.

The survivability equipment is being developed independently of aircraft programs with 6.3 or 6.4 program funds. As part of the development work, the equipment is integrated and tested in the aircraft to ensure that it fits and works properly

in the aircraft's operating environment and that it does not interfere with other subsystems. In some cases, the equipment that is being developed is currently planned for only one type of aircraft. This is true, for example, of the flare decoy system that will be installed only in the CH-47 aircraft. Also, the configurations of the various mixers for diluting the exhaust gasses are highly specific to the aircraft, although the same engine configuration will be used on both the AH-1 and UH-1. Nevertheless, the developments are under the control of the survivability program office and are, therefore, independent developments.

H. Night Vision

A need is emerging for a high-resolution FLIRs with a narrow field of view for accurate weapon aiming. Also, there is a supplementary need for a wider field of view for the pilot, who must avoid obstacles while flying low at night. Several programs are under development in this area. One is a Marine Corps program called NOGS (night optical gun sight). In addition, the Air Force uses an operational FLIRs on C-130 gunships and the Navy uses one on its S-3 ASW aircraft. Bell has no special part in these programs, but it does monitor them for their potential for incorporation of its aircraft.

Another possible independent development, by Northrop, is a gated laser for use with a low-light-level TV system. The intent here is to overcome the limitation of infrared system resolution and to reduce "crosstalk" between detector components.

I. Control System

Bell is developing a helicopter fly-by-wire system under IR&D, which might be applicable to any of its aircraft.

V. INTEGRATION PROBLEMS OF HELICOPTER WEAPONS

Helicopters have a number of characteristics that make them poor candidates for weapon delivery platforms. They vibrate significantly more than do fixed-wing aircraft, and they have deflection and bending modes that create serious bore-sighting problems. Since their complex structures have many modes of vibration, resonance with rapid firing weapons can cause wild gyrations, if not structural failure, of the helicopters. The usual preventive measure is to control structural stiffness. But it is nearly impossible to tell in advance which part of the structure is going to provide the problem. Rockets and missiles provide overpressures that can erode or damage structural parts and skin. In addition, they create debris that can damage the parts of the aircraft. Some weapons, such as the WECOM 30, are considered to have too much recoil for a helicopter. Because the attitude of a helicopter is a function of its speed, helicopter weapons cannot be fixed in elevation without degrading their performance.

The fire-control systems present some problems, particularly in space needs. The original system was a pantograph that mechanically pointed the weapons in the direction the gunner aimed the sight. The sights have become more sophisticated with a need for an optical path to the gunner. When the gunner was moved to the rear seat to improve the pilot's ability to fly "nap-of-the-earth," the sighting system that conducted sensings from a nose sensor to the gunner had to be repackaged. Since helicopter control is sensitive to c.g. location, changing one component may require changes in the location or arrangement of other components.

Further work is being done to improve the helicopter for night fighting. Devices such as low-light-level TV and FLIR have been tested. Now Bell has a contract to add the TOW to the aircraft. Actually, this is not a new concept, since the

SS-11 wire-guided missile had been fired from the aircraft many years ago.

VI. RESULTS

The results of the case study of the UH-1/AH-1 subsystems are listed in Table A-1. Histories of the subsystems are divided into three major categories in the table: source, development route, and requirement. The subheadings under each category indicate how each subsystem was derived, and they are defined below.

A. Source

1. Prime. The prime contractor receives the basic contract for the development and production of the system, in this case the UH-1 series of aircraft, and is responsible for the design and manufacture of the aircraft, the integration of all subsystems and components in the airframe, including GFE and CFE (contractor-furnished equipment). Components and subsystems that are not supplied as GFE may be purchased by the contractor from other vendors. However, the prime contractor is responsible for the quality of all CFE.

2. Subcontractor. A subcontractor is chosen by the prime contractor to **supply** hardware that is to be used on the aircraft. The subcontractor may also design the hardware, or it may simply manufacture the hardware to the prime contractor's design and specifications. Normally, the engine is carried as GFE; however, the engine is such an integral part of the aircraft and, in this case at least, Bell and the engine manufacturer worked so closely together that the engine was GFE only in a formal sense.

3. GFE. Government-furnished equipment includes subsystems and equipment such as "comnav" avionics, survivability equipment, flight instruments, and certain electrical and hydraulic

TABLE A-1. DERIVATION OF UH-1 AND AH-1 SUBSYSTEMS

Subsystem	Source			Development Route				Requirement			
	Prime	Sub	GFE	IR&D	Product Improvement	Directed Development	Available	Independent Development	Firm	Preliminary	Generic
T-53		✓						✓		✓	
T-53-L-1A			✓			✓			✓		
-L-5			✓		✓				✓		
-7			✓		✓				✓		
-9			✓		✓				✓		
-10			✓		✓				✓		
-13			✓		✓				✓		
Transmissions											
Original	✓					✓			✓		
Up-rated	✓				✓				✓		
Fail-Safe	✓			✓	✓					✓	
Rotors											
Original	✓			✓					✓		
New Sizes	✓				✓				✓		
New Airfoil	✓			✓						✓	
Production Method	✓			✓						✓	
Weapons											
Turrets		✓		✓						✓	
Fire Control		✓		✓						✓	
Integration	✓					✓			✓		
Sighting & Tracking			✓					✓	✓		
Stabilizer											
1-2 Model	✓					✓			✓		
Improved	✓				✓					✓	
Cabin											
UH-1	✓					✓			✓		
AH-1	✓			✓						✓	
Survivability											
IR Suppress	✓					✓			✓		
EW			✓				✓				✓
Landing Gear	✓					✓			✓		
Fuel Cells	✓					✓			✓		
Armored Seats	✓					✓			✓		
Vulnerability Reduction	✓			✓						✓	
Night Vision											
NOGS			✓					✓			✓
FLIR			✓					✓			
Laser-LLLTV			✓					✓			
Flight Equipment											
Instruments			✓				✓				✓
Motors, Generators			✓				✓				✓
Accumulator			✓				✓				✓
Actuators	✓					✓			✓		
Comnav			✓					✓			✓
Flight Control											
Fly by Wire	✓			✓							

Note: Some available items may have been earlier independent development.

operating components. In general, such equipment is specified in the contract awarded to the prime contractor, who is responsible for ensuring that the equipment is properly integrated into the aircraft. In some cases, however, the development program for the equipment may have included the testing of the equipment in each aircraft to ensure that it could be appropriately integrated and qualified.

B. Development Route

Five possible routes, leading to the development of a subsystem, are recognized here. It is possible that more than one of these routes would be taken in developing a particular subsystem. Moreover, the different routes are not always clearly distinguishable from each other. In assigning the routes in this case study, a certain amount of judgment has been exercised.

1. IR&D (Independent Research and Development). This is R&D that a contractor might do to produce new military products, or to make improvements to those already produced. IR&D is funded from contractor overhead, a practice allowed by the Government. The funding is limited to an overall proportion of each contractor's defense business and is not supervised by the Government, except in accounting for the total.

2. Product Improvement. Product improvement is a form of directed development that is aimed at improving the characteristics of the system or subsystem. Here, it is distinguished from directed development to indicate that it has improvement as a goal rather than the accomplishment of something new and, therefore, it uses a partial or incremental approach. Some IR&D might also be considered to be in this category.

3. Directed Development. A subsystem fits into this development category, if it is developed specifically for the first system in which it is to be incorporated. Therefore, its development parameters are determined by the program manager, who

is responsible for the overall performance of the system. Program managers seem to prefer this approach, because they feel that they can do a better job of integrating and optimizing the system with subsystems designed explicitly for the system. However, the development risks are higher and the cost is usually greater. On the other hand, an off-the-shelf subsystem is sometimes expensive and provides better performance than a particular system requires. In such cases, a low-risk, low-cost directed development might be justified.

4. Available. Subsystems become available from earlier developments, because they happen to be capable of meeting the requirements for the new system, or because they are standardized in view of the functions they perform (i.e., their functions are general enough for a number of systems to use them). Such subsystems are often GFE, but they need not be, unless the contract calls for it. Note that an "off-the-shelf" item is not necessarily sitting on the shelf. It must be manufactured to an existing design, which means that time must be allowed for procurement, manufacturing, testing and inspection.

5. Independent Development. A subsystem developed this way is developed independently of the particular system to which it might be fitted. It is, in fact, often developed as a standard item that is to be fitted to a number of systems, where the performance of a common function might be required. Independent development might also be undertaken early, to provide a component of a system for which the lead time is too long. However, this presents problems in that the requirements might change during the system development and, thus, provide a subsystem designed to the wrong specification.

C. Requirement

Three types of requirements for a subsystem development are recognized.

1. Firm. There is a specific requirement for the subsystem. The desired performance for the subsystem has been specified and the using system has been chosen, although it may not yet be fully designed.
2. Preliminary. There is a general requirement for the subsystem in the sense that approximate performance parameters have been generated, but the system is not yet fully defined and the system requirement has not yet received official sanction.
3. Generic. There is a general requirement for the subsystem function, and equipment developed to perform this function will be used in several different types of systems.

VII. CONCLUSIONS

First, it is clear that all of the modes we have identified have occurred in this series of developments of the UH-1 and AH-1. It is also clear that little of what might be called independent development occurred. The only cases in which it did occur are those in which the subsystems had a general application, and so they were being developed as standard units for incorporation in a number of types of aircraft. These include the stabilized tracking unit, electronic warfare subsystems, the "comnav" system (part of an overall Army avionics program), night vision equipment, and survivability items. All other GFE (not including engines) were earlier system developments. The one exception is the first Lycoming engine contract, which was turned into a directed development after the aircraft was more clearly defined and it turned out that the original requirements would have provided an inadequate engine.

This leads to the first conclusion. Independent development (contracted) was not a factor in the developmental history of the UH-1/AH-1 aircraft. Unless the prime contractor was required to adapt subsystems to its design, either by contract or

lack of in-house expertise, it tended to develop what it needed. There were a few items that the contractor accepted for integration into its aircraft, after they had been developed; however, these received special treatment in order to make the adaptation. This included the weapon systems, which had to be installed in turrets for useful adaption to the helicopter, and optical sights, which must be carefully integrated into the aircraft if they are to perform properly.

The second conclusion is that the standard subsystems used by the contractor in its aircraft were usually GFE that had been developed for general-purpose use in Army aircraft. Virtually every other subsystem and its improvements were developed by the prime contractor, either under IR&D, product improvement, or directed development; most of the developments consisted of modifications to the basic aircraft to change its characteristics for different mission requirements.

The third conclusion then is that the prime contractor provided the bulk of product improvement developments and tried to extend its envelope of expertise. Only where a new capability was required (e.g., weapon delivery) did the contractor go outside his field of competence to obtain the necessary subsystems. Even then, there was substantial prime contractor input to integrate these new subsystems into the aircraft. Here also, the degree of the prime contractor's contribution varied. In some cases, it was simply handed a subsystem that it had to fasten to the aircraft. In other cases, such as fuel cells and armor, the prime contractor used basic materials that had been developed by another industrial company as a basis of design for its own aircraft. At other times, the prime contractor worked closely with a weapons system manufacturer to design an interface, whereby the weapon could be installed on the aircraft.

Some other observations are worth noting here. The UH-1 and its derivatives are examples of the impact that an aggressive

contractor can have on the development, utilization, and modification of a system. Bell tended to ignore the formal progenitor of system requirements, the Transportation Corps. In fact, it regarded them almost as an enemy. Bell set up good working relationships with the users, Army Aviation and Combat Development personnel. It provided them with information on performance and technical possibilities that resulted in the development of new tactical concepts in which helicopters were employed as a major means of military mobility. These concepts led to the use of armed helicopters that provided mobile tactical firepower. In the course of developing and realizing these concepts, Army Aviation and Bell ran into stiff opposition from sources that include the Air Force, the DOD, the Army's Transportation Corps, and Bell's competitors. The purpose of noting these events is not to make Bell appear to be heroic; instead, it is an attempt to describe how things happened in this particular case.

This leads to the fourth conclusion. A close relationship with the users and aggressive advocacy by the prime contractor and some of its military clients were decisive factors in the original development of the Huey, and the follow-on developments of its improvements and derivatives.

Finally, we conclude that the transfer of technology from the technology base was readily accomplished by the contractor through an incremental approach that relied substantially on IR&D and directed development.

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APPENDIX B

HISTORY OF CHEYENNE HELICOPTER

APPENDIX B

HISTORY OF CHEYENNE HELICOPTER

This section reviews the history of the Cheyenne (AH-56A) aircraft. Emphasis is placed on the genesis of requirements in an effort to discover whether earlier development of critical subsystems, or the use of available components, might have effected a different outcome.

The historical portions were pieced together from a combination of sources, and it is impossible to attribute completely the source of each piece of information. The most comprehensive account of the Cheyenne's history is contained in Ref. B-4, which was used as a major source for the data presented herein.

A calendar of events in the Cheyenne's history is given in Table B-1. Appropriate events are amplified and discussed in the remainder of the appendix.

I. EVOLUTION OF THE REQUIREMENT FOR ARMY-OWNED ARMED HELICOPTERS

The involvement of the United States in the Korean War in the early 1950s saw the first extensive use of helicopters in military activity, and it started military planners thinking about their further use. The notion of helicopters as fighting vehicles was given further impetus by a "roles and missions" dispute between the Army and the Air Force. A major issue in this dispute centered on the mission of close air support. In the late 1950s, the dispute was temporarily resolved by an agreement between the Secretaries of the Army and Air Force to restrict Army fixed-wing aircraft to 5000 lb gross weight. Exceptions to this limitation were granted for the Caribou and the Mohawk, neither of which was a threat to the Air Force monopoly

of the close air support mission. However, in 1966, the Air Force took over the Caribou as an intratheater transport, while giving up all claims to helicopters designed and operated for intratheater movement and supply of Army forces.

In addition to the exclusive right to perform the close support function, in a kind of "Catch-22" arrangement, the Air force also retained the right to apportion aircraft to missions. The Air Force doctrinal order of mission priority was: air defense, interdiction, and then close support. Moreover, the Army had considerable skepticism about the Air Force's capability to perform close support usefully with the high-speed jet aircraft it was procuring.

Thus, the Army could neither select, nor own, nor control the use of aircraft in supporting ground operations. Naturally, the Army became interested in acquiring its own armed vehicles.

The 1961 Berlin crisis resulted in an increased emphasis on giving the Army increased capability to fight major wars both in Europe and in Asia. President Kennedy, interested in providing more flexibility in possible responses after the era of "massive retaliation", called for an increased budget for Army aircraft.

Aircraft armament at this time was relatively primitive. Rocket launchers and machine guns had been hard-mounted on the landing skids of the UH-1 utility helicopters and were being used for suppressive fire. But because of the unstable nature of helicopters, and the difficulty of controlling attitude and speed independently of each other and independently of the wind during hover, such weapon installations were ineffective. In addition, the 1961 guidelines would not permit arming a helicopter with more than one weapon at a time. Thought was being given to the use of helicopter rockets as a kind of artillery for suppressive fire, and also to the use of the SS-11, a French developed wire-guided missile, which offered a

promising way to attack small hard targets such as tanks and bunkers.

Several more ingredients were added to what was becoming a boiling pot of Army aviation. The United States was providing minor assistance to the South Vietnamese Government. Some of this assistance involved the use of a few helicopters. But the war in South Vietnam was not going well. In October 1961, President Kennedy sent General Maxwell Taylor and Walt Rostow to Vietnam to examine the situation. One of the conclusions of this visit was to call for a larger U.S. effort. Helicopters were to play a major part in such an effort.

II. TECHNOLOGY ADVANCES

In the 1950s and early 1960s, a number of technology advances to armed helicopters were made. Suitable turbine engines were developed, and improved rotor blades, honeycomb materials, and simplification of rotor hubs were occurring. Schemes for vertical thrust, other than pure rotor lift, were evolving. The Army sponsored the fabrication and testing of a number of flight vehicles that used several different principles to achieve vertical takeoff or landing (VTOL). One of these schemes was the compound helicopter. The vehicle was equipped with a rotor for hovering and vertical motion, and a wing and propulsive means other than the rotor so that the rotor could be unloaded in forward flight. The compound machine potentially offered a number of significant advantages over conventional helicopters and fixedwing aircraft, while seemingly having only minor disadvantages of its own. For example, a compound helicopter could slow down rapidly while attacking a surface target, thereby increasing target tracking time. By increasing thrust, the aircraft could accelerate while tracking a target, without going into the nose-down position of conventional helicopters. The separation of forward propulsion from the rotor permitted hovering in a range of pitch attitudes, thereby making

it easier to aim rockets and acquire the TOW missile after launch. In addition, the "unloaded" rotor had the potential for increased range and speed and lower fuel consumption. Considerable maintenance benefits from "unloading" the rotor were also expected.

In 1962, the U.S. Army Aviation Laboratories (AvLabs) awarded rotorcraft research contracts to five U.S. manufacturers for testing compound aircraft of various configurations. These contracts had the goal of determining fundamental aerodynamic and dynamic limitations, which contribute to performance limits of compound rotorcraft that employ shaft driven rotors. One of the five manufacturers was Lockheed, which had built a rigid rotor aircraft known as the XH-51A. Development of this concept had been started by Lockheed with a radio-controlled model, which subsequently led to the design and construction of the manned vehicle. The first flight of the XH-51A occurred in 1959 and was followed by a highly successful test program. By 1962, the XH-51A had been shown to have satisfactory stability, control, handling, vibration, and stress and loading characteristics up to a speed of 175 knots. A dynamic instability problem had been noted under certain conditions of flight, but this was not considered to be a difficult problem, since the performance envelope could be adjusted to avoid such conditions. Scaling problems in this characteristic were not anticipated.

The results of the AvLabs program were used by the Army in establishing performance specifications for the Advanced Aerial Fire Support System (AAFSS). Continuing its work with the XH-51A, Lockheed in 1964 was awarded a contract with the Army to further evaluate the XH-51A, setting a speed goal of about 200 knots.* Up to this point, Lockheed's system was performing

* By 1969, the XH-51A had been flown at speeds up to 263 knots, a limit reported to be caused by compressibility effects on the advancing blade. It was proposed to slow down the rotor as a means of achieving 300 knots in level-flight speed; even 350 knots looked feasible, if the rotor could be slowed down sufficiently.

well, showing considerable promise for achieving the high speeds and other characteristics desired by the Army in a gunship.

There were applicable developments in other fields as well. Suitable avionics, including helicopter stability augmentation systems, navigation systems, terrain avoidance, and a variety of weapons, were becoming available for armed helicopters. Army planners and conceptual thinkers had a great deal of material to consider for use in future Army systems.

III. ENGINE

The T-64 engine, which was selected for use in the Cheyenne, is discussed here in some detail, since it was an early independent and speculative development that was undertaken by the Navy in anticipation of multiple system requirements. This particular GFE subsystem created no problems for the AAFSS development; instead, it was a positive asset.

The T-64 engine has been used in over a dozen types of Navy and civil aircraft as shown in Table B-2. Development of this engine was initiated by the Navy in 1956-57, at a time when there was no specific user for the engine but a set of possible applications instead. These applications were specified in a 1956 Navy Bureau of Aeronautics Requirement (Ref. B-1) as a High Speed Assault Transport Helicopter, an ASW Helicopter, and a Carrier Based AEW Fixed Wing Aircraft. The Navy had in mind a number of other possible uses for the engine, including a replacement for the AD fighter, but these were not named in the requirement. The requirement describes briefly the missions, estimates the weights of the aircraft, and specifies an initial rating for the engine of 2650 hp (military) and 2250 hp (normal). The requirement also explicitly states that the design should allow growth in these ratings up to 3500 hp and 3000 hp, respectively. The development schedule called for turboshaft qualification by the middle of 1961 and turboprop

TABLE B-2. APPLICATIONS OF T-64 TURBINE ENGINE
(From Ref. B-2)

<u>Dash No.</u>	<u>Max. Rated Power</u>	<u>Aircraft Designation</u>	<u>Engines/Aircraft</u>
-1(-3)	3080	XC-142A Tiltwing VTOL HH-53B	4 2
-6	3080	CH-53A	2
-7	3925	HH-53C	2
-7A	3936	(Growth version of -7)	
-10	2850	SHIN MEIWA PS-1	4 ^a
		KAWASAKI P-23	2
-16	3925	AH-56A	1
-413	3925	CH-53D RH-53D CH-53G	2 2 2
-415	4380	RH-53D CH-53E	2 3
-820	3060	DHC-7 BUFFALO	2 ^b
		G-222 (AERITALIA)	2 ^c
-P4D	3400	G-222 (AERITALIA)	2 ^d

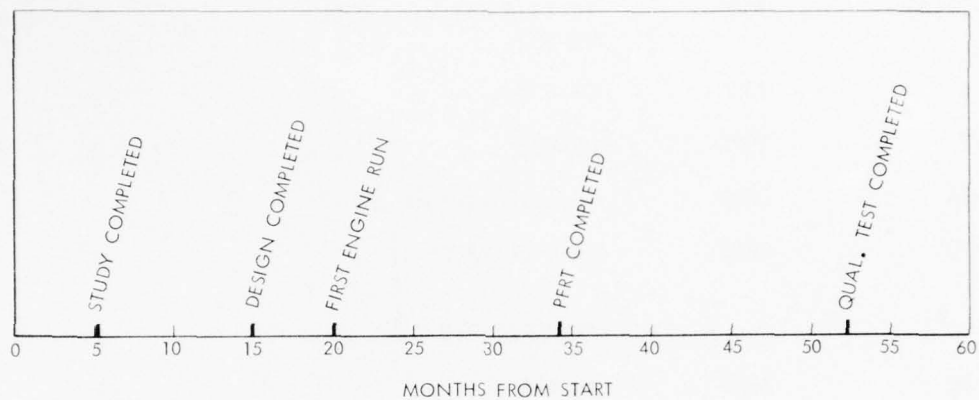
^aProduced in Japan under license.

^bCanadian-built airplane.

^cItalian prototype airplane.

^dItalian production airplane.

qualification by the middle of 1963. Total development cost was to be about \$61 million. The engineering development schedule is shown in Fig. B-1.



3-16-76-2

FIGURE B-1. Engineering Development Schedule for T-64 Engine

The General Electric proposal to develop the engine included the use of a compressor that GE had developed with its own money. The development contract was awarded to GE in 1957. Some time after development had started, the Navy decided that the engine should have somewhat more power than was originally called for. In this case, there was no need for a design change, since the engine was already providing a higher power output. Eventually, the first version of the engine qualified at 2810 hp.

Early in the qualification period, a few problems were encountered, including combustor failure, lubrication difficulty, and compressor blade weakness. The fixing of these problems added two years to the original development time. However, this may have been more of a help than a hindrance, at least

to the contractor and perhaps to the Navy, since no application for the engine was ready when the development was originally to have been completed. But during the time extension, the Navy decided to use the engine in the CH-53 helicopter. It also was selected for use in the XC-142 tiltwing transport and the DHC-7 Buffalo transport. As early as 1961, the engine was being flown in a test-bed DHC-4 Caribou, a 3-ton, fixedwing aircraft that the Army wanted to use as an intratheater transport. The Caribou had originally been built with piston engines, which provided rather mediocre performance. With the turbine engines, its performance was little short of spectacular, particularly its short-field capabilities. However, this aircraft became a victim of the Army/Air Force "roles and missions" dispute and never survived the prototype stage.

A Navy 1963 annual report (Ref. B-3) shows that there were no significant differences between the original performance values of the engine, as conceived in 1956, and the values that would be characteristic of fleet T-64 engines, except in the engine weights. The turboshaft engine was 20% lighter than the original requirement, and the turboprop engine was 3% heavier. Moreover, the development cost, despite the nearly two-year delay, was less than 5% over the estimated cost.

In the follow-on program, the engine was successively up-rated several times to a final value of 4380 hp. This growth was achieved primarily by cooling the first-stage turbine rotor and stator. Possible growth beyond 5000 hp is considered possible by cooling the second-stage turbine. Consistent with the multiuse requirement, the T-64 engines were qualified to operate at from 100 degrees nose-up to 45 degrees nose-down. Eventually, T-64 variants were used in a number of versions of the H-53 helicopter and several other applications. By February 1974, a total of 1800 T-64 engines had been produced in the United States. In addition, production was licensed in Germany, Italy, Britain, and Japan.

By the time the Cheyenne competition was started, the T-64 was fairly widely used and the Cheyenne requirements were well within its range, even after they had been changed from about 3400 to over 3900 hp. The Cheyenne application involved only some repackaging of the gearing, which represented a minor change for this engine.

IV. DEVELOPMENT OF THE REQUIREMENT (Refs. B-4, B-5)

In August 1962, the Army Tactical Mobility Requirements Review Board (also known as the Howze Board for the General who was chairman), called for increased air mobility for Army units through the creation of air mobile fighting units. The Board also recommended development of tactical air vehicles, including close support aircraft. The Bell Helicopter Corp., using IR&D funds, developed a prototype integrated gunship, using as a test bed its model 207 (H-13) Sioux Scout, which was an Army reconnaissance vehicle. The prototype gunship had two M-60 machine guns installed in a chin turret, which had been developed by Emerson Electric. It also had tandem seating and side-arm controls, thereby providing a space for a gunner's sight. Despite the Bell development, no existing aircraft was considered capable of meeting the requirements that had been expressed by the Howze Board. The Army thought about procuring an interim machine, which would involve some modification of existing aircraft. However, in 1963, Army Secretary Vance instructed the Army to "lift its sights" and to develop an optimal aerial weapons system. In June 1963, a project management office was established for the Fire Aerial Support System (FASS), which later became known as the Advanced Aerial Fire Support System (AAFSS). In October 1963, Secretary Vance requested the Department of Defense to reprogram about \$2.5 million in FY 64 funds from the interim to the advanced program.

The AAFSS requirements specification process began in 1963 with the establishment of a QMDO (Qualitative Material Development Objective.) This QMDO, which was approved in April 1964, would be evaluated for technical feasibility and cost-effectiveness. The various possible performance factors and capabilities would be traded off, in an attempt to create an optimum system for the missions and environments that were envisioned. Following approval of the QMDO, the Army was to firm up the requirement for the system and to develop the overall specifications. Project management responsibility was given to the Army Materiel Command. Because the Army was undergoing a reorganization at that time, the AAFSS project manager was also given responsibility for formulating the concept. This stage of the program was supposed to result in a Qualitative Materiel Requirement (QMR), which would then be followed by a Program Change Request (PCR) requesting Congress to authorize the new program and to appropriate money for it. A detailed plan for accomplishing the program, called a Technical Development Program (TDP), would also be developed. However, this sequence was not followed for the AAFSS. The PCR and the TDP were first submitted in November of 1963, which was before the QMR was approved and even before the QMDO was approved. The QMR itself was not approved until November 1964, several months after the Program Definition proposals had been submitted. An in-process review held in January 1966 established that the Cheyenne would meet all stated requirements. This finding came about despite the fact that new requirements, particularly in ground support and test equipment, had already begun to appear. This resulted from the Army's accelerating the project, partly in response to the Vietnam buildup.

The missions envisioned for the AAFSS included escort of air mobile columns and their protection during landing or evacuation of an objective, surveillance and security (including reconnaissance by fire), and highly discriminatory fire in close

proximity to ground forces (including antitank fire). The capability to perform a 50-nmi radius assault mission under IFR conditions was desired. The close support role, although the Army was careful not to call it that, was to be integrated under the control of the ground force commander with ground weapon systems.

The system concept for accomplishing these missions was a helicopter escort aircraft capable of flying at ground level ("nap of the earth"), in virtually all weather conditions, at speeds of 210 to 220 knots. The machine was also to be capable of hovering for the purpose of training weapons on ground targets for extended periods of time. This characteristic required an automatic stability and control system, plus flexible weapon systems capable of being trained on the target regardless of aircraft attitude. High maneuverability was essential, yet the aircraft needed armor to protect vital components.

Hard points were required for ordnance and extra fuel tanks, since self-ferrying from CONUS to possible theaters of war was envisioned. An advanced avionics system, such as the Navy's IHAS (Integrated Helicopter Avionics System), would be needed for the 50-nmi radius mission. Other kinds of needed equipment included a doppler navigation system, as well as terrain avoidance and terrain-following radar systems. In addition, the aircraft had to fly fast enough to be capable of escorting heliborne forces. The CH-47, one of the principal vehicles used in transporting heliborne forces, had a maximum speed of 164 knots and cruised at 141 knots. The escort aircraft were required to be faster. A dash speed of 220 knots and a cruise speed of 210 knots were the original development goals. Later, these were reduced to 212 and 196 knots, respectively, and then to 200 and 186 knots, respectively, as the extreme difficulty of attaining such speeds in the AAFSS vehicle became more apparent.

The AAFSS had a dual purpose turret, which was capable of using either a 7.62-mm minigun or a 40-mm grenade launcher. It was also equipped with a belly turret for a 20- or 30-mm cannon. Both of these turrets were trainable in azimuth and elevation. Optical sights would automatically track a target after being locked-on. The turrets were slaved to these sights. Also, the gunner's seat could be turned to permit the gunner to follow the target.

The Army had also been considering an automode version of the AAFSS that would have additional capabilities, such as automatic flight control and station-keeping capability. But the cost and weight of the equipment for these capabilities were considered to be too great. Initially, night vision was not part of the contract, and a passive IR system was selected to provide some night capability. However, when the role of killing mechanized vehicles was added, the TOW missile and a night vision system were added to the required equipment.

There was insufficient time and staff to adequately study the AAFSS requirement in the various cognizant offices of the Army. These offices had authority to add requirements without supplying the necessary funding, but unfortunately the Army had no effective mechanism for eliminating requirements that accumulated during concept formulation. No one in the Army, except the Chief of Staff, had the authority to eliminate an unnecessary or unwise requirement. (Although the project manager may want to eliminate unnecessary items, he cannot without an agreement from the generator of the requirement, an action that is not likely to happen.) Thus, the requirements tended to grow during the Project Definition Phase and even up to the issuance of the belated QMR. By this time, tremendous momentum had been built up in the program, especially within the Army, and it would have taken a great effort to interfere at such a point.

V. THE AAFSS COMPETITION

The AAFSS was to be developed and procured under a scheme of "Total Package Procurement." Although the requirement was initially biased toward a compound helicopter, it was later changed so as not to preclude tiltwing and tiltengine configurations.

Twelve proposals for the AAFSS were received by the Army, of which nine were for various types of compound helicopters. The others were tiltpropeller or tiltwing aircraft, on which prototype developments were ongoing.

On 1 March 1965, Lockheed and Sikorsky were selected to receive contracts for the "Project Definition Phase" of the program, which was to last six months. Since both Lockheed and Sikorsky had proposed rotary-wing type machines, the Army apparently had rejected the configurations that involved fixed wings. Not least among the reasons for rejecting fixedwing aircraft was the old Army/Air Force "roles and missions" agreement, which limited Army fixedwing aircraft weight to 5000 lb. The Army feared that a fixedwing configuration would run into Air Force opposition, whereas a rotor craft would be much more difficult for the Air Force to oppose.

Representative Otis Pike had this to say about the Army's selection: ". . . the Army has chosen to go (the compound helicopter) route because the top of it goes round and round and they know they are not going to get into the roles and missions fight with the Air Force if they go the helicopter route. Whereas if they go the fixedwing route and call it close air support--see, anything that goes round and round provides suppressive fire, this is part of the semantic ritual that we go through, and anything that has fixed wings and

shoots the same guns provides close air support--and this the Army is not allowed to do."*

There were additional reasons for not selecting tiltwing or tiltpropeller aircraft. These technologies were not as well developed and, hence, not as familiar as rotor technology. Also, these VTOL configurations generated higher downwash velocities that would intensify the problems of operating from unprepared fields.

After the evaluation of the project definition phase reports, Lockheed was selected for engineering development, because its vehicle included the rigid rotor technology, promised lower costs, and its management proposal was considered to be superior. On 3 November 1965, Lockheed was chosen to build ten AAFSS prototypes.**

Under the total package procurement plan, Lockheed assumed total responsibility for logistical support and program management and gave performance guarantees. However, there were no predetermined penalties for "failure to achieve;" instead, the contract called for "equitable adjustment". Correction of deficiencies after delivery of the aircraft was also provided for in the contract.

Also included in the contract was the production option, which gave the Government the right to purchase 375, 500, 1000, or 1500 AAFSS vehicles at specified prices. These prices depended not only on the number ordered but also on the delivery

* Rep. Otis Pike, Hearings, Armed Services Committee, House of Representatives, pp. 8183-8184, 8 March 1966.

** In the public announcements made of this award, Lockheed claimed: a rigid rotor was needed to provide a stable platform for armament accuracy, with a speed possibility of about 350 knots, and at a unit price of \$500,000 in a large production run.

schedule. More significantly, the specified prices also increased each day that the Government delayed in signing the production contract. After 31 December 1967, if the Government had not signed the contract, the prices would be subject to complete renegotiation. This latter provision held whether or not Lockheed's performance on the development contract was satisfactory. This arrangement was to lead to major difficulties for the Army.

The rigid-rotor technology, which was one of the features the Army judged important in awarding the Cheyenne development contract to Lockheed, had worked well for the XH-51A, although the aircraft had exhibited some problems of instability and lack of controllability in certain flight regimes. Other helicopter manufacturers had tried rigid rotors and had abandoned them. The dynamic characteristics of rigid rotors were not completely understood at the time of the contract award to Lockheed. But in 1965, no one felt impelled to challenge the award to Lockheed on this technological question, a circumstance that would have tragic and expensive consequences.

Meanwhile, although the Army had decided to forego an interim armed helicopter, events were working to offset that decision. Commanders in Vietnam were requesting interim gunships, not being willing to wait for the AAFSS, which would not be operational before 1968 at best. When the 1st Cavalry Division was deployed in Vietnam in the summer of 1965, the interim-armed helicopter became a combat requirement. The Bell Huey Cobra was chosen for this role, because it could be available in a short time (it had already been demonstrated in Vietnam), and because it had a great deal of commonality with the UH-1 systems then being used extensively in Vietnam.

VI. CHEYENNE DEVELOPMENT PROGRAM

The Lockheed XH-56A (Cheyenne) development program started off well, with the first airframe rolling out and static testing getting started ahead of schedule. Progress at rollout time indicated that all objectives would be met. The first flight was also ahead of schedule, and no significant hardware problems had yet appeared.

As noted earlier, the production price of the aircraft would increase for each day that the production option was not exercised. The delivery schedule would also be slipped correspondingly. The first barrier to exercising the option was lack of funds, because the Department of Defense withheld them. The DOD wanted the Army to avoid a commitment, at least until after the aircraft had flown and systems testing had been initiated, thereby presumably minimizing the risk. Moreover, the DOD wanted to obligate funds at the slowest production schedule, which meant that the first production vehicles would not become available until 1970. In urging the slower pace, the Secretary of Defense noted that the Army had yet to develop an integrated force plan for the Cheyenne.

The Army was in a tight position. It had no funds to commit for production and yet, if it did not make such a commitment by the expiration date, it would eventually be forced into a sole source negotiation. When the expiration date passed, the Army convinced Lockheed to extend the option period for a short time, during which a last-ditch negotiation was held with the DOD. The outcome of this negotiation was that DOD would permit the Army to exercise the option, but the Army would have to reprogram the money from its current budget, which meant the deletion or reduction of other programs. The program that felt the pinch the most was the AH-1 Cobra, which had been planned as the interim gunship.

VII. TECHNICAL PROBLEMS

At the time the Cheyenne production option was exercised, the development program appeared remarkably trouble-free. But by May 1968, a few months after the production contract had been signed, technical difficulties started to appear. In May, a Cheyenne made an emergency landing after the pilot noticed something wrong. The landing damaged the rotor and fuselage. In August, the rotor of a test aircraft struck the canopy and fuselage. These were early hints that gyro-induced rotor instability would occur in the Cheyenne flight envelope, although it had been possible to avoid them in the smaller XH-51A.

The problems were severe enough for Lockheed to convene a Blue Ribbon Committee to advise it on the rotor instability problem. Some members of this committee advised Lockheed to study the problem analytically and in a wind tunnel, before deliberately provoking the conditions in flight. Unfortunately, the advice was not heeded. To compound the error, Lockheed also failed to install crew escape equipment or telemetry equipment in the test aircraft, omissions that were to result in tragedy.

Other problems were related to the performance of the aircraft. The addition of the TOW missile increased the drag substantially over the original Lockheed estimate. More power was required, but this put the transmission under greater stress than had been anticipated and caused considerable downtime, thereby stretching out the flight test program.

Avionics problems were also appearing. The AH-56A had a high proportion of GFE, and a number of problems occurred in interfacing this equipment with the aircraft. The stability augmentation system and the weapons control system were the most notable contributors in this regard. The computer, which had been adopted from the Navy's IHAS (integrated helicopter avionics system) program, was also experiencing malfunctions.

Lockheed claimed that GFE deficiencies were to be blamed for slowing progress on the helicopter development program.

In response to these difficulties, a system manager office was created by the Army. This office was to monitor the program and resolve difficulties as they arose. The importance of the program to the Army was indicated by the fact that it named a major general as the system manager.

On 12 March 1969, one of the Cheyenne prototypes exploded in midair and crashed, killing the pilot. There was some evidence that this was a flight envelope expansion mission, although Lockheed claimed it was not. On April 12, the Army sent Lockheed a "cure" notice on the production contract, which listed 11 items, not all of which were related to the gyroscope-rotor instability problem. The contractor was directed to reply within fifteen days. Lockheed responded with a 430-page report.

In addition to technical difficulties that occasioned the Army's cure notice, the Lockheed contract costs were soaring. The R&D costs of the 10 prototype machines had risen to \$193.5 million compared with the original estimate of \$77.5 million. Moreover, despite the "fixed" price contract, production vehicle unit costs had reached \$2.2 million from \$992,000. Lockheed blamed this primarily on the delay in exercising the production option. It stated that although it had extended the option at the request of the Army, the subcontractors were not obligated to do so and, therefore, Lockheed could not guarantee its subcontractors' prices. Lockheed wanted to negotiate a new contract, while the Army wanted to maintain the old agreed-upon unit price.

Since the proposed fixes did not convince the Army that Lockheed could solve the technical problems or meet the promised delivery schedule, and since costs were becoming excessive, the Army terminated the production contract.

The termination of the Cheyenne production resulted in the release of funds for other purposes, and the Army soon contracted with Bell for another 200 Cobra gunships for Vietnam.

VIII. CHEYENNE DEVELOPMENT CONTINUES (Refs. B-6, B-7)

After the fatal crash on March 12, Lockheed and the Army tried to restructure the program. The contract was rewritten, and performance specifications and schedule and cost projections were made more realistic. However, this restructuring avoided the resolution of the dynamic-system problem. The problem had been identified as being caused by the inability of the mechanical gyro system to differentiate between rotor flapping and inplane rotor motion. Under certain conditions of flight, which unfortunately were within the desired envelope of the Cheyenne, this contamination of the gyro signal would result in a rapid divergence of the rotor blade angles of attack and cause the rotor to go out of control. In the AH-56A, this happened so rapidly that there was no opportunity for the pilot to correct the situation after the condition had started.

Lockheed proposed to deal with this problem by developing an advanced control system, which was capable of discriminating between the two conflicting input forces. However, because contract litigation was going on in which the primary area of contention was the rotor system, this solution to the problem could not be contracted for directly, since it might appear that Lockheed would be admitting to the deficiency in the earlier rotor. Eventually, this new control system was developed by Lockheed as a rotor improvement program and it worked well (Ref. B-8).

Some other facts bear on the outcome. Most of the GFE came from the various Army Commands. The Avionics were supplied by ECOM, weapons by ARMCOM, TOW by MICOM, and aircraft subsystems by AVSCOM. Since the AAFSS was in fact an advanced

concept, very little standard equipment was being used. In fact, some equipment (e.g., communications gear) had not become available yet. Hence, when difficulties started to emerge, the general behavior within the Army was to avoid admitting to any error whatsoever. The Army believed that in such an integrated system any admission of being wrong anywhere would immediately make the Army responsible for the contractor's overrun.

Lockheed continued its work with the Cheyenne with some hope that the difficulties would eventually be ironed out and a later production decision might be made. The misfortunes continued however. On 17 September 1969, a Cheyenne prototype, which was being tested in the Ames low-speed wind tunnel, disintegrated, injuring two technicians and destroying the 10th prototype vehicle. Efforts continued for about two more years, during which time a base of knowledge about rigid rotor characteristics was built up. In 1971, the Army again turned down a production decision on the AH-56A. In 1972, all efforts on the machine were abandoned and Lockheed went out of the helicopter business.

IX. CHEYENNE SUBSYSTEM DEVELOPMENTAL OPPORTUNITIES (Ref. B-6)

In this section, we examine the history of the AAFSS, as recounted above, for opportunities in which early or independent development of subsystems occurred and to determine whether such developments might have been beneficial to the program. This approach is taken with complete recognition of its after-the-fact nature. In hindsight, one is bound to have a better perspective on the decisions that were made, without compensating empathy for the pressures and situations that were forcing such decisions. We make this examination solely to help generate guidance for the future and not as a critique of past actions.

A. Airframe--Dynamic System

The dynamic system, including the rotor, power gearing, and controls, was a major basis for Lockheed's award of the development and production contracts for the AAFSS. Although rigid rotors had been conceived by others at an earlier time, no one had seriously proposed their use before Lockheed did. The rigid rotor concept, the first model of which first flew in a test-bed aircraft in 1959, appeared to be a breakthrough in aircraft dynamic systems. Testing on the XH-51A and other Lockheed aircraft was very successful and indicated a great potential for the concept. At this point, about 1962 or 1963, the Army might have initiated the development of a family of rigid rotor dynamic systems. The first systems might have been used in the AH-56A, with other versions earmarked for use in future helicopters and perhaps even retrofitted to existing ones. Even from the current time perspective, this does not seem to be a particularly good idea for the following reasons.

- a. The research on rigid rotors was incomplete, and the state of the art would not support fullscale development of this type of system.
- b. Retrofitting to current aircraft would need substantial study, since helicopters and their systems are highly integrated machines.
- c. Speculation on the characteristics of future helicopters would be very nebulous and would not yield a high probability of success in the selection of appropriate target characteristics for development.
- d. Limited development funding was available.

It is concluded that the speculative development of dynamic components for helicopters does not have a high potential payoff and, therefore, would not have been a desirable approach in the pre-AAFSS days.

We note in support of this conclusion that the first conception of the AAFSS requirement, combined with the applicable technology, occurred about 1963-64 with a desired delivery date

of 1968. This highly optimistic schedule probably resulted from a combination of wishful thinking, on the part of the Army, and the apparently clear success of the XH-51A compound helicopter. And it gave rise to expectations that scaling up to a different vehicle, using the same principles, would be a simple job.

B. Engine and Transmission

The engine selected for the Cheyenne was the T-64-GE-16, rated at 3435 shp.

During the Cheyenne development program, it was found that a higher power would be needed, because the aircraft drag had grown beyond expectations. The engine manufacturer quickly produced a modification of the engine, designated the 712 version, which was rated at 3925 shp. Unfortunately, this created a problem with the transmission, which had been designed for the lower power and could not be as easily uprated as could the engine. The result was a significant delay in the flight test program, because of the down time caused by the transmission.

Here we have an illustration of an independent development (the engine) that was originally developed for multiple purposes, and that was capable of being readily tailored for use in this aircraft and retailored after the original specification had changed. On the other hand, the transmission, which was all new, was incapable of being easily modified. If AAFSS production had continued, a modified transmission design would have been required, although it is likely that the new design would have been a stepped-up version of the original one. The experience points up the value of designing versatility and flexibility into a subsystem or component.

C. Avionics and Mission Equipment

We include in this category the communications sets, navigation sets, weapons systems, and radar equipment that were

necessary for the aircraft to accomplish its mission. A considerable amount of this equipment was developed independently of the AH-56A by various Army commands, including ECOM, MICOM, ARMCOM, and AVSCOM. This equipment was supplied as GFE to Lockheed. In most cases, the intention of the Army was to develop equipment that could be installed in a variety of aircraft. The IHAS was one of the items jointly developed by the Navy and the Army. The IHAS computer had a high failure rate. In some cases, the equipment did not become available in time for incorporation in the developmental aircraft. Independent development of this equipment seems to have been a hindrance rather than a help in the case of AAFSS. This may provide some argument for initiating such independent developments earlier, and testing them more fully before attempting to incorporate them in a new vehicle. But then the risk is present that the development will not represent the latest state of technology.

X. DISCUSSION

The Cheyenne program, although a failure itself, illuminates several facets of the independent development question. In the case of the T-64 engine, an early development was initiated in 1957. This engine was specifically required to have a multiuse capability and a growth capability. In fact, it was qualified before it was selected for use in a system. Moreover, at the time of design, none of the aircraft for which it was being considered even had a preliminary design. All that was wanted was an engine in a particular power range. This engine became very successful. It was used in several aircraft. Eventually, it was selected for the AAFSS application, a development that failed but not because of the engine.

On the other hand, the IHAS was being developed separately and independently, also with the intention of being used

in a number of Army and Navy helicopters. Its selection created problems for the AAFSS development, since the IHAS computer had a high failure rate. Unfortunately, the IHAS was a new development then, and the bugs had not been fully worked out.

Other equipment intended for incorporation in the Cheyenne was under the control of the various Army commands. These were simultaneous, independent developments that were to be supplied to the prime contractor as GFE. Apparently, some of this equipment was not ready at the time the prime contractor needed it. But, except for the IHAS, it appears that this equipment worked satisfactorily and was suitably integrated into the aircraft.

The major failure in the Cheyenne was in the rotor system. This development was directly under the control of the prime contractor and cannot be considered as an independent development. The Cheyenne rotor was simply an extension of the technology that Lockheed had developed and operated successfully in a smaller aircraft.

The transmission was a problem component, since it was required to operate at higher power than it had been designed for, and it resulted in slowing down the developmental flight schedule of the Cheyenne.

XI. CONCLUSIONS

We can draw some general conclusions about independent development from the examination of the Cheyenne subsystems. In the case of a long lead time item such as the engine, early development was essential. The T-64 was highly successful and useful in developing the Cheyenne for two reasons. The engine was mature enough to assure its reliability and its design was such that it could be easily uprated if necessary. The

IHAS was not completely developed and, therefore, its reliability was not yet assured. The rotor scaling was not understood; the transmission design had no provision for growth. These conclusions suggest the following rules for assuring the successful application of early developments.

- a. Start as early as possible.
- b. Plan for growth in the original design.
- c. Avoid specialization and plan for a range of uses in the original design.
- d. Fully understand the rules for scaling.
- e. Ensure that the potential market justifies the development.
- f. Demonstrate a flight test vehicle before committing to the subsystem end use.
- g. Expect some required integration effort, even for well-developed subsystems.

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APPENDIX C

THE XM-1 TANK

APPENDIX C

THE XM-1 TANK

I. INTRODUCTION

In recent years, there have been three new main battle tank programs, namely, the MBT-70, XM-803, and XM-1. The MBT-70 was a joint program with the Federal Republic of Germany (FRG). It entailed an attempt to build all new components rather than use existing ones. This policy was one of the factors contributing to its demise. But the overwhelming reason for the program's failure was that there was no single decision-maker in charge. Simple decisions, e.g., whether to use metric or English fasteners, could not be made.

The second program, the XM-803, was a revised MBT-70 program, aimed at meeting only the U.S. requirement, not the FRG requirement. It continued to support many of the components initiated under the MBT-70 program. It died when the costs escalated, and when doubts arose over the real advance represented by the XM-803 over the product-improved M-60 tank. The cancelation action, however, did allow a large sum of money to be used further development of component technology.

The third program, the XM-1 tank, was initiated in 1972, when the Army formed the Main Battle Tank (MBT) Task Force at Ft. Knox to define a tank that would:

- Be greatly superior to the M60A1E3 tank.
- Constitute a low- to medium-development risk.

The MBT task force prepared a "Material Need" document and a "Development Concept Package." To accomplish its mission, the task force also prepared a "shopping list" of low risk and

moderate risk components. These components became candidates for incorporation into the XM-1 tank system. Many of them came from the M-60 tank series. Others were developed under the technology base funding at the TACOM laboratories and were then slated for the MBT-70 program. Upon the program's cancellation, they were continued for the XM-803. These components were further developed under terms of the cancellation of the XM-803, which provided substantial funds for the continued development of tank components.

The XM-1 tank is being developed in two configurations: the Chrysler version with a turbine AGT-1500 engine, and the General Motors version with a diesel AVCR-1360 engine. It is now nearing the end of the advanced development stage. Table C-1 compares the XM-1 tank with other tanks of relatively recent vintage, and Table C-2 compares major components. Some of these components, namely, the two competing engines and the X-1100 transmission are discussed here.

II. AGT-1500 TURBINE ENGINE

The formal beginnings of the AGT-1500 were in 1965, when an RFP called for a regenerative 1500-hp turbine. AVCO was selected out of eight or nine competitors. The development was the outgrowth of several years of research studies and hardware installation testing. The engine configuration was established by USATACOM design and performance specification, representing an advanced engine considerably beyond the state of the art.

The AGT-1500 turbine is specified to deliver 1500 hp, at 100° F, and is specifically designed for powering the heavy class of military vehicles. Significant advantages over current engines include: light weight, small size, quiet operation, low fuel consumption, ease of cold starting, higher net output, reliability and durability (2 to 4 times greater than previously attainable), and a favorable life cycle cost advantage.

TABLE C-1. U.S. TANKS COMPARATIVE DATA

Tank	Combat Weight Tons	HP	HP/Ton	Road Speed, mph	Range Miles	Primary Armament	Basic Weapon Load, rds	Rate of Fire, Rounds/min	Fire Control	Suspension
M-48A3	52	7500	14.4	30	310	90mm (rifled)	62	6	Optical range finder-ballistic computer	Conventional torsion bar
M-48A5	53	7500	14.1	30	300	105mm (rifled)	43*	6	Optical range finder-ballistic computer	Conventional torsion bar
M-60A1	53	7500	14.1	30	310	105mm (rifled)	63	6	Optical range finder-ballistic computer	Conventional torsion bar
M-60A2	57.3	7500	13.8	30	280	152mm gun/launcher (rifled)	46	4	Ruby LRF electric ballistic computer gun stab	Conventional torsion bar
M-60A3	57.3	7500	13.8	30	310	105mm (rifled)	63	6	Ruby LRF solid state ballistic computer gun stab	Tube over bar & conventional torsion bar
XM-1	58	1500	25.7	35-40	275-325	105mm (rifled)	40-50	6-8	Neodymium LRF solid state digital/analog computer stabilized bar, line of sight & gun	Hydropneumatic & torsion bar or tube over bar & torsion bar

* Redesign with goal of 60.

TABLE C-2. U.S. TANKS--COMPARISON OF MAJOR COMPONENTS

Component	Minimum Requirement	Tank				Baseline System	Leopard 2
		XM-1 Crysler	XM-1 General Motors	XM-1 General Motors	XM-1 Crysler		
Engine (model) Type Horsepower	Not specified	AGT 1500 Gas turbine 1500 hp	AVCR 1360B Air cooled diesel 1500 hp	AVCR 1360B Air cooled diesel 1500 hp	AVDS 1790 Air cooled diesel 750 hp	MB873 Liquid cooled 1500 hp	
Transmission Steer Type	Not specified	Allison X1100 Hydrostatic steer Torque conv. drive	Allison X1100 Hydrostatic steer Torque conv. drive	Allison X1100 Hydrostatic steer Torque conv. drive	Allison, CD 850 Differential steer Torque conv. drive	RENK Hydrostatic steer Torque conv. drive	
Suspension Type Roadwheels	Not specified	Tube over bar & conventional torsion bar 14 dual	Hydropneumatic & torsion bar 12 dual	Hydropneumatic & torsion bar 12 dual	Tube over bar & conventional torsion bar	Conventional torsion bar 14 dual	
Ballistic Computer	Type not specified	Digital	Analog	Analog	Analog	Analog	
Laser Range Finder	Type not specified	Neodymium	Neodymium	Neodymium	Ruby	Neodymium	
Stabilization	Type not specified	Vertical sight azimuth turret	Full sight stab.	Full sight stab.	Add-on stab. Gun only	Full sight stab.	
Night Vision Type Range	Thermal	Thermal	Thermal	Thermal	I ²	I ² w/thermal pointer	
Main Weapon	105-120mm	105mm	105mm	105mm	105mm	120mm (SB)	

The engine configuration (Fig. C-1) consists of a twin spool, concentric, counterrotating compression section, followed by variable nozzles and two free-power turbines. A cylindrical heat exchanger (recuperator) wraps around the reduction gears and the concentric exhaust-diffuser section on the output end of the turbine, adding almost nothing to the engine's length and width. A single-can, tangential-scroll combustor had a single ignitor plug and fuel nozzle, which can be serviced from the top of the engine. The accessory section provides direct top accessibility to all engine and user power takeoff accessories, for ease of maintenance in tank installations. The 3000-rpm maximum output speed permits engine use with a variety of standard and advanced transmissions. Minimal engine cooling requirements (15 to 40 hp) make substantially greater net power available for propulsion. The engine is adequately protected by standard, compact two-stage static air cleaners, with servicing beyond a 20-hour interval.

The first TACOM contract was for 30 months, and it required the production of 30 engines (5 development; 20 prototype; 5 final configuration). Actually, 20 engines had been built by the end of the TACOM contract (July 1969) for the total cost of \$21 million.

The first engine developed only 1200 hp. A zeroth stage was added to the compressor to get more mass flow (increased from 9.7 to 11.7 lb/sec) through the engine. It was estimated that another 20% growth could take place in the same engine envelope, which was fixed mainly by the MBT-70 requirements and has been extended only slightly since. In retrospect, it can be said that the original design of the engine was a flexible one; it allowed a 50% growth in output shaft horsepower.

The components that paced most of the turbine engine's developments were the compressor, recuperator (a heat exchanger), combustor, and the turbines. Peculiar to the automotive

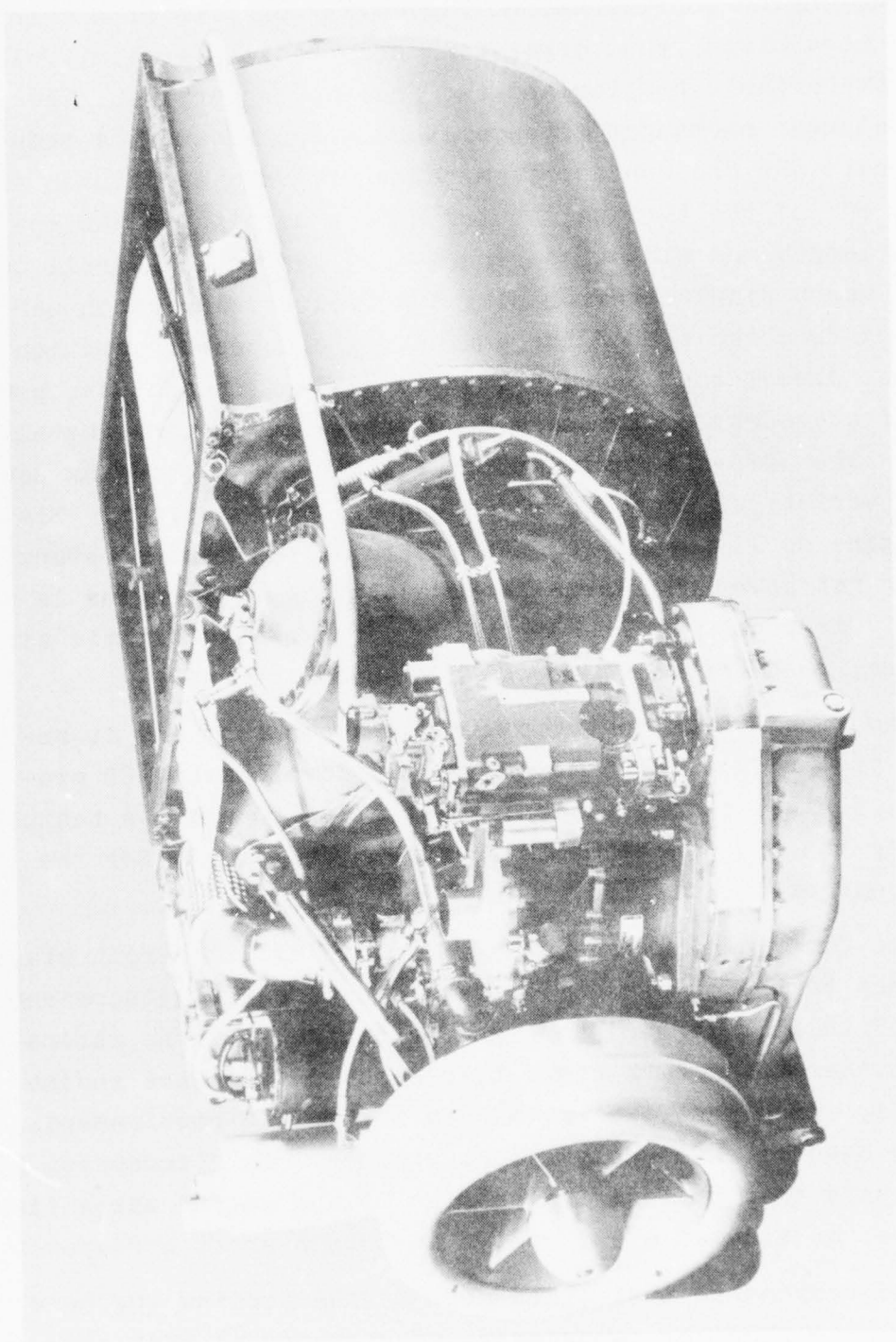


FIGURE C-1. AGT-1500 Turbine Engine Configuration

application were the stationary recuperator, the single-can combustor, and the variable-power turbine inlet nozzles. These three components were beyond the state of the art of the mid-1960s. The main concern of the development effort was to achieve better fuel economy at intermediate power level (60 to 80% of full power), using the recuperator.

The recuperator that AVCO uses is of a unique design, which entails a large number of welds. For manufacturing, it requires the development of new repetitive welding system. The function of the recuperator is to heat air emerging from the compressor by about 200° F. The recuperator is essential to achieve fuel economy comparable to a diesel. The initial version of the recuperator was developed by AVCO with its IR&D funding, with no direct assistance from TACOM, and it was a basic ingredient in its winning proposal.

The variable-geometry turbine nozzles permit a shift of power to the gasifier turbine for rapid acceleration. They also maintain high exhaust temperature and recuperator efficiency under partial power, and can "slow open" for protection against destructive overspeed on loss of load.

The turbine inlet temperature is 2180° F. This development effort, for fuel economy, pushed materials technology for the high pressure turbine beyond the state of the art at the beginning of the program. By 1973, a better material (WASPALLOY) was developed and put into use. Even so, the turbine blades had to be air-cooled.

During the July 1969 to May 1971 period, the funding was slow. Little work was accomplished, but the organization was kept intact. Then, the spending rate accelerated under a TACOM contract for \$11.8 million (May 1971-January 1974) and with a follow-on contract from Chrysler for \$11.5 million (July 1973-April 1976). These two contracts were both under the XM-1 program funding. The first provided for the development

of the engine for generic tank applications (i.e., operation in a modified T-48 test rig). The second provided the funds for the specific adaptation of the engine to the XM-1: namely, specific dimensions, fault isolation and maintenance indicators, special fasteners, a power turbine speed governor, a revised accessory gearbox, and mating with the XM-1 electrical system. As of 1 July 1975, the AGT-1500 had a total of 8340 engine test hours, including 12,500 vehicular miles. Currently, a "design to cost" production cost estimate is being worked out.

The fluctuating funding is believed to have had the effect of substantially extending the duration of the overall program. Competent personnel estimate that had the funding and the major system objectives been reasonably steady, the engine would have been ready for operational tests in a total of five years and for production in a total of seven years.

Our conclusions with respect to the AGT-1500 turbine are as follows:

- a. Independent research and development played an important role in the development of the AVCO recuperator.
- b. TACOM technology base funding was responsible for some of the early development work of the AGT-1500.
- c. Funding for earlier tank programs, which were later cancelled, supported much of the early development of the AGT-1500.
- d. The XM-1 tank has a turbine engine as an option, largely as a result of development work undertaken previously for the cancelled MBT-70 and the XM-803 tank programs. Had the engine development waited until 1972, then the engine could still have been ready for production by about 1979, but there would have been no development engine on which to base system decisions. The early development did result in the early availability of a development engine, which influenced the tank system decisions.

III. AVCR-1360 ENGINE

The development of the 1100-in³ displacement (CID) diesel started in 1958 for the T-95 tank (42 tons), in a development program that lasted 2.5 years and cost the Government about \$3.2 million. The 90° V, four-cycle, air-cooled, 12-cylinder engine, provided 600 hp. Seven engines were produced. They logged a total of 6000-7000 hours, including some time in the developmental T-95 tank in the test field. The engines were stored in 1959, when the T-59 program was discontinued.

In 1961, TCM brought the idea of a variable compression ratio (VCR) piston to TACOM, and obtained a \$50,000 contract. Under this contract, a piston was built to fit the 1100-CID engine. It was developed in a one-cylinder configuration, and it yielded power equivalent to 750 hp for 12 cylinders in 1961, 900 hp in 1962, and 1100 hp in 1963. In 1963, a 12-cylinder version was built and it logged about 3000 miles, in a tank, at 1000 hp. During FY61-FY64, the funding made available by TACOM was about \$2.3 million; it was adequate funding.

(A brief technical description of the VCR piston is as follows. If the peak firing pressure is plotted as a function of the load, the resulting graph is usually a rising straight line. The VCR piston, like any other piston, has a connecting rod to which the piston is fastened by a pin. The height of the piston above this pin is variable, however, and it is controlled by the peak firing pressure. As long as this pressure remains under 1900 psi, the piston remains in its extended position, giving a large compression ratio. As soon as the peak firing pressure reaches 1900 psi, the piston begins to retract, giving a lower compression ratio. This retraction results in holding the peak firing pressure constant at 1900 psi, even as the load increases up to a point that would have produced 3800 psi with a normal piston. This feature and the resulting

lower range of peak firing pressures result in less stress being placed on the piston and the other engine components, and they lead to lower engine weight per horsepower.)

With the beginning of the MBT-70 program in 1965, GM gave an engine subcontract to TCM for \$13 million. As part of this subcontract, three 90° V engines were built for use in transmission development. They were delivered within 1 year, and each could produce 1200 hp or more. Then, the engine was redesigned to 120° V to lower its silhouette. This engine was being used with the Renk hydrokinetic transmission. To achieve the required power output (1475 hp), the engine had to be supercharged. Originally, the engine had only turbochargers; mechanical, gear-driven Roots blowers had to be added. These high-speed blowers reflected a substantial advance in technology and they posed some reliability problems. Towards the end of the MBT-70 program, the secondary option engine, (Daimler-Benz MB-873Ka) was finally selected for the MBT-70 in order to attain the reliability objectives. It was a 2400-CID engine of conventional technology, and represented less of a technological advance. Then, in December 1968, the MBT-70 program was cancelled. West Germany continued to fund TCM for a year for providing AVCR-1100 engines to its pilot tanks.

The XM-803 program began in April 1970, and GM continued funding the AVCR-1100 under subcontract. With the XM-803 program, there was a change from the Renk hydrokinetic transmission (with a torque converter) to the XHM-1500 hydrostatic-hydraulic transmission. With the latter transmission, the low-speed torque requirement could be met with a 1250-hp output. Thus it was possible to remove the engine parts of questionable reliability (e.g., the Roots blowers). It was also feasible to lower the exhaust temperature below the 1800° F it was running in the MBT-70. This led to improved reliability in the engine, at the cost of considerable risk in the unproven hydrostatic transmission.

The XHM-1500 hydrostatic-hydromechanical transmission specified for the XM-803 differed from the usual hydrokinetic transmission. The torque converter-range pack combination was replaced by a variable-displacement hydrostatic pump, coupled to a fixed-displacement hydrostatic motor. Such an arrangement offered infinitely variable ratios, continual operation under optimum performance conditions, and a lower silhouette. Unfortunately, it was also more complex, costlier by about 50%, heavier, and had little flexibility. This lack of flexibility, stemming from incompressible nature of oil, often resulted in broken shafts and the resultant failure of the entire propulsion system. It was the lack of flexibility, plus the added cost and greater weight, that later led to the replacement of the XHM-1500 by the X-1100 in the XM-1 tank.

When the XM-803 program terminated in December 1971, TCM had one year of direct Army funding for the VCR engine. Then, the engine passed the stiff 400-hour NATO test. Total funding during this one year was \$2.1 million.

With the advent of the XM-1 program, the hydrostatic transmission was abandoned in favor of the X-1100, which, like the Renk, is a hydrokinetic one. Since the vehicle now had a weight of 58 tons and considerable requirements for agility, the engine requirement was changed to 1500 hp. Thus, the engine was uprated to 1360 CID and the Roots blowers had to be used again. This development is now said to be proceeding satisfactorily. The test-and-fix procedure is yielding a Duane reliability growth curve with a 0.5 slope as desired. This engine is now designated as the AVCR-1360.

Our findings with respect to the AVCR-13600 engine are as follows:

- a. The VCR piston was invented under independent research and development and was developed under a TACOM technology base contract.

- b. The VCR engine was developed under a succession of MBT-70, XM-803, and XM-1 tank programs, with some TACOM technology base funding added. It had to be modified substantially to fit the XM-1 tank.
- c. The VCR piston, superchargers, and an improved injection pump, made possible the doubling of the power output of the old AVDS-1790 engine by the new AVCR-1360, while reducing the weight by 5% (see Fig. C-2).
- d. The AVCR-1360 is said to have a growth potential of 30% (see Fig. C-3).
- e. The availability of the AVCR-1100 development engine, in fairly well-developed, low-risk form, was what led to its adoption for one of the two competing versions of the XM-1. It would not have been available in such a form, except for the precursor MBT-70 and XM-803 programs.

IV. X-FAMILY OF ARMORED VEHICLE TRANSMISSIONS

This section deals with the X-200, X-300, X-500, X-700, and X-1100 hydrokinetic transmissions and the lessons that were learned in their development.

The model number in the X-family corresponds generally to the lower end of the range of horsepower values that the particular transmission is designed to handle.

All the members of the X-family of transmissions are crossdrive transmissions. They feature a hydraulic torque converter in combination with a planetary range package for propulsion, a hydrostatic pump and motor unit with combining planetaries for differential steer control, and integral, power-assisted brakes. An automatic converter lockup clutch is employed at the higher vehicle speeds to connect the converter pump and turbine directly. The range section consists of hydraulically-applied clutches and planetary gearing, providing four forward speeds and two reverse speeds. The hydrostatic steer consists of a differential steer system, controlled by a hydrostatic pump and motor. The integral brakes are of the multiple-plate, oil-cooled variety.

PRODUCTION COST

GREAT SIMILARITY EXISTS BETWEEN CURRENT
PRODUCTION M60 ENGINE & AVCR-1360-1

I.E. BOTH ARE:--AIR COOLED, DIESEL, OPEN CHAMBER, V-12, OHV ALUMINUM,
MODULAR, SEP. CYL. CONST., MIL DESIGN

MODEL	GHP	WEIGHT (LBS)	LBS/HP	NO. OF		S/HP	S/LB	FY-72 SELLING PRICE
				PARTS	P/N			
AVDS-1790	750	4650	6.2	8497	1255	32.70	5.28	24,600(ACT.)
AVCR-1360	1500	4462	3.0	7825	1381	20.00	6.70	30,000*(EST.)

*PRINCIPAL DIFFERENCES ARE:-- INJ. SYSTEM (X-PUMP)
VCR PISTONS
SUPERCHARGERS

FIGURE C-2. Comparison of AVDS-1790 (M-60) and AVCR-1360 Engines

GROWTH POTENTIAL

EXPECTED XM-1 LIFE IN EXCESS OF 20 YEARS
REQUIRES POWER GROWTH & FLEXIBILITY FOR NEW:

- WEAPONRY
- MOBILITY REQUIREMENTS
- ANCILLARY VEHICLES (SP GUNS,
HET, AVLB, ETC.)

AMPLE MARGIN EXISTS IN THE AVCR-1360

<u>KEY PARAMETERS</u>	<u>@ 1500 GHP</u>	<u>CURRENT STATE OF THE ART</u>
RPM	26-2800	3000
PISTON SPEED (FT/MIN)	21-2340	2500
EXH. TEMP (°F)	1500	1600
CYL. PRESS. RISE RATE (PSI/°)	125	175
CYL. PEAK PRESS (PSI)	2050	2200
ROD BR'G LOAD (PSI)	7000	10,000
MAIN BR'G LOAD (PSI)	5200	7500

❖ WITHOUT EXCEEDING THE STATE OF THE ART,
THE AVCR-1360 CAN BE DEVELOPED TO 1800 GHP

FIGURE C-3. GROWTH POTENTIAL OF THE AVCR-1360

A. X-200

The X-200 was developed in 1968 by Allison, under the ARSV program, for use in the FMC tracked vehicle. Two pilot transmissions were designed, fabricated, and carried through lab and vehicle development on GM funding. TACOM then funded a 6000-mile performance and durability evaluation in an M113A1 vehicle. Subsequently, the transmission was selected for the tracked version of ARSV, where 7 units accumulated more than 28,000 miles of engineering development testing prior to program cancellation. The X-200 transmission remains a candidate for a product-improved M113 vehicle.

B. X-300 and X-500

The X-300 and the X-500 started out as two distinct transmissions, but were later merged into a single unit with a range of 250-550 hp. It is now the alternate transmission for the MICV. The following paragraphs give its history in some detail.

The X-300 transmission study effort originally began (under the technical supervision of the U.S. Army Tank Automotive Command) in 1962. The first generation unit, the X300-1, was subsequently designed, component-tested, and fabricated in 1964. Laboratory, dynamometer, durability, and vehicle testing continued through 1967. During this period, 2250 vehicle miles at 340 net horsepower and 20 tons, 269 laboratory development hours, and 8000 simulated durability miles, were accumulated. Concurrently, the X500-1 program accumulated 60 hours and 6341 vehicle miles at 550 net horsepower and 25 tons.

In 1968, a program began to redesign the X-300 and X-500 transmissions, based on the experience gained during the first generation testing. A common concept was employed, and commercial components were adopted so that a maximum commonality of parts, consistent with sound and proven design practices, was obtained. The results of this effort were the X-300-4 and

X500-4 transmissions. A follow-on fabrication and test program was also undertaken and completed. A total of 208 development hours and 2810 miles in an M109 test vehicle, at engine levels of 340 and 515 net horsepower and vehicle weights of 19 to 22 tons, respectively, have been accumulated on the -4 configurations. More than 1000 of these miles were run at the 515 net horsepower level.

The X300-4 design was subsequently optimized to meet the anticipated MICV requirements in late 1971 and early 1972. This optimized unit has undergone 30 hours of laboratory calibration and development testing and has operated approximately 1400 miles in an M109 test bed. The major portion of this operation has been at a 600-ghp level. The latest operation has been at a lower, 480-ghp level. Primary test activity has been concerned with performance and fuel economy comparisons at various power levels and hydrostatic steer system evaluations. As of April 1974, the major problem had been with the commercially supplied hydrostatic steer unit. But subsequent vendor design modifications have apparently eliminated this problem. The optimized transmission, X300-4A, was on durability test at General Motors Proving Grounds in an M109 test rig vehicle during 1974. Fabrication of two new X300-4A transmissions was undertaken under TACOM contract. Minor design revisions have been incorporated to meet MICV vehicle installation requirements.

Thus, the latest X-300 units available are the product of 12 years of continual design, development, and test, including 560 laboratory development hours, 8000 simulated durability miles, and 11,700 vehicle miles at power levels to 600 ghp and weights to 25 tons.

C. X-700

The X-700, which was a cross-drive model for the retrofit of the M-60 tank, was a concept only. It evolved into the X-1100 design.

D. X-1100

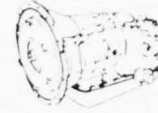
The X-1100 is the largest member of this transmission family. It is now being developed for both versions of the XM-1 tank (i.e., for the GM-AVCR-1360 diesel engine and the Chrysler AGT-1500 turbine engine). It is also planned for use as a retrofit for the M-60 product-improved tank with the AVDS-1790 diesel. The X-1100 fits these different roles by using a module design, in which different input sections, adaptable to the characteristics of the different engines, are utilized. It would be equally adaptable to the Daimler-Benz MB-873 engine.

Both the X-200 and the X-300 have 40% of their parts interchangeable with the AT-540 and HT-700 commercial transmissions, respectively. Thus, these parts were already developed; they required only repackaging for use in the X-1100. More importantly from a production point of view, these parts are available from relatively high volume tooling.

In the new commercial series, the AT transmission was developed first, followed by the HT, and finally the MT. Descriptions of these transmissions are given in Fig. C-4.

The large volume production of commercial truck and car transmissions has made it possible for Detroit Diesel Allison (DDA) to develop detailed data banks and methods which can be used for predicting both the performance and the reliability of each component in probabilistic terms. DDA has also evolved a computer-based methodology for simulating an entire transmission system and obtaining both performance and reliability predictions. This requires typical duty-cycle information, i.e., information about the torque and speed input to the transmission during the typical use for which the vehicle is intended. Such information is obtained experimentally for some vehicles and is then scaled for use with other related types of vehicles.

The AT 540 is a fully automatic transmission with 4 forward ranges and 1 reverse range. While the AT 540 is the smallest transmission in the Allison Automatic family, it is **not** an upgraded passenger car automatic. It is a compact, yet rugged medium-sized automatic designed specifically for trucks which may be used with both gasoline and diesel engines up to 200 net HP. Some typical applications where the AT 540 is a real bonus to the truck owner and driver are: beverage delivery/dump/school bus/rental/farm/sanitation/utility and van delivery.



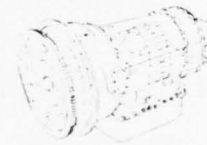
The MT 640 with 4 forward ranges and 1 reverse range will accommodate gasoline or diesel engines up to 250 net HP. The MT 640, with its wide range for medium-heavy trucks, is fully automatic which provides proven job performance in the toughest highway hauling jobs. Following are some good examples of where the MT 640 improves truck performance and driver efficiency: armored car/beverage delivery/feed lot/fire truck/furniture delivery/refrigerated van/school bus/sight-seeing bus/tractor and trailer spotter.



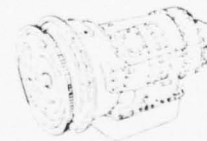
The MT 650, which has 5 forward ranges and 1 reverse range, is an extremely versatile truck transmission. It may be used with both gasoline and diesel engines up to 250 net HP. In addition . . . the MT 650 is designed for on/off highway service. The MT 650 has an added manually selected extra low first range, which provides exceptional gradeability. The following are some typical applications where the MT 650 saves time and money: dump/exploration vehicle/fuel oil delivery/grain truck/lumber truck/refuse packer/transit mixer and tow tractor.



The HT 750CR (close ratio) is designed for heavy-duty on-highway trucks. It is a member of the biggest automatic series within the Allison Family. The HT 750CR has five forward ranges and one reverse range and may be used with diesel engines up to 400 net HP. The HT 750CR is designed primarily for over-the-road (line-haul) tractor/trailer applications where maximum efficiency and productivity are especially important.



The HT 750DR (deep ratio) is specifically engineered for on/off highway operations. This transmission has five forward ranges (an extra low first gear for off-highway applications) and one reverse range. The HT 750DR may be used with diesel engines up to 400 net HP. Here is a partial list of the applications for the HT 750DR: single box and trailer dump/equipment hauler/off-highway tractor/refuse vehicle and transit mixer.



Note: Multiple speed axles and/or auxiliary gearing are available for application with the AT 540, MT 600 and HT 700 Series Transmissions. With the Allison Automatic, extra gearing is used as range extenders only, not for split-shifting.

FIGURE C-4. Commercial Series Transmissions

Detroit Diesel Allison (DDA) found that about 75% of the reliability, maintainability, and durability work on components and also on vehicle transmissions was directly transferable from one model to another (information obtained from F. Blair, DDA Div., GM Corporation). This is particularly significant, since the AT series is rated at only 200 hp, while the HT series is rated at 400 hp. System integration tests, however, must be done for each vehicle.

Similar cases of growth have been found in other transmissions. The TX-100 three-speed transmission (propulsion only) was rated at 175 nhp in a 24,000-lb M113A1 tracked personnel carrier. It was then uprated to 209 nhp for the 28,000-lb Dutch AIFV (Armored Infantry Fighting Vehicle). The required component changes, which entailed the use of proven commercial items, understandably did not cause any serious new reliability problems.

A similar uprating occurred with the XTG-250 transmission first used for the Sheridan M-551. Although originally designed for eventual use of 34,000 lb and 250 nhp, the development took place at 30,000 lb and 209 nhp at 35 mph. Subsequent changes raised these parameters to 36,000 lb and 248 nhp at 44 mph for the production vehicle. The uprating was accomplished by increasing brake and steer clutch capacities and by revising the heat treatment of gears. As finally used in Vietnam with anti-mine armor plate and extra ammunition, the vehicle weighed 43,000 lb.

It would appear that, in automotive transmissions, scaling laws for individual components are reasonably well understood. Thus, when a design is tested at one rating, much of the reliability information is applicable to a scaled-up or scaled-down version.

New designs are usually made with an eye to the economics of production. For commercial designs that are to be produced in large volume, special tools make up the large-cost item, whereas materials are less significant. Thus, housings are usually designed with extra space for more clutch plates, etc., which may be required for higher power or greater torque in a later model. On the other hand, in military transmissions that are designed for low volume production for a specific system, size and weight are optimized for the individual system. Here is less provision for growth than is typical of the commercial product. Every modification is, of course, paid for by the military customer and, thus, is a potential source of income. Consequently, there is an incentive for the designer to create designs with less room for growth.

The DDA simulation methodology makes it possible to predict reliability on scaled versions of existing hydrokinetic transmissions. But, as of yet, it does not permit reliability predictions on hydrostatic transmissions, largely because of shock waves, ram effects, and other system phenomena occurring in incompressible fluids in the hydrostatic transmission. These phenomena depend on the total system configuration, not just on the cumulative actions of the individual components assembled into the system.

E. Findings

It has often been found practicable to increase the input rating of commercial hydrokinetic automotive transmissions by a large factor (about two), without changing the basic technology. All that is required is to decrease the torque ratio of the torque converter, add clutch plates and lubrication, or improve the heat treatments.

In such cases, reliability and durability work carried out on the lower rated transmissions was applicable, to a great extent, to the higher rated versions. A successful design could be scaled either up or down, with minimal risk. Only system integration tests had to be done again for each vehicle. It is believed that these findings are typical, not only of hydrokinetic transmissions, but also of other military subsystems, where the component and subsystem scaling laws are reasonably well known for both performance and reliability. However, they do not hold for subsystems, such as hydrostatic transmissions, where system effects are dominant.

V. CONCLUSIONS AND RECOMMENDATIONS

There is considerable similarity in the development histories of the two engines and the X-family of transmissions. Each new design had considerable growth potential, and this growth took place as the development objective shifted. No major reliability problems developed as a result of this shift. This suggests that an automotive component or subsystem can usually be designed with growth in mind. The design can then be engineered, built, tested, and debugged. And the resulting debugged design can be altered to meet a changed specification, without requiring a complete retest program for the component, although a system integration test program will be required.

The reasons for growth potential design are clear in the case of hydrokinetic transmissions: the reliability and performance scaling laws for individual components are well known. The effects of integrating these components into a system are not dominant. Thus, the extrapolation of reliability information is quite meaningful. Apparently, a similar rationale holds for piston engines, and to a much lesser extent for turbines. However, it breaks down when system effects become dominant, as shock waves do in hydrostatic transmissions and as thermal and vibration effects seem to in some turbine engines.

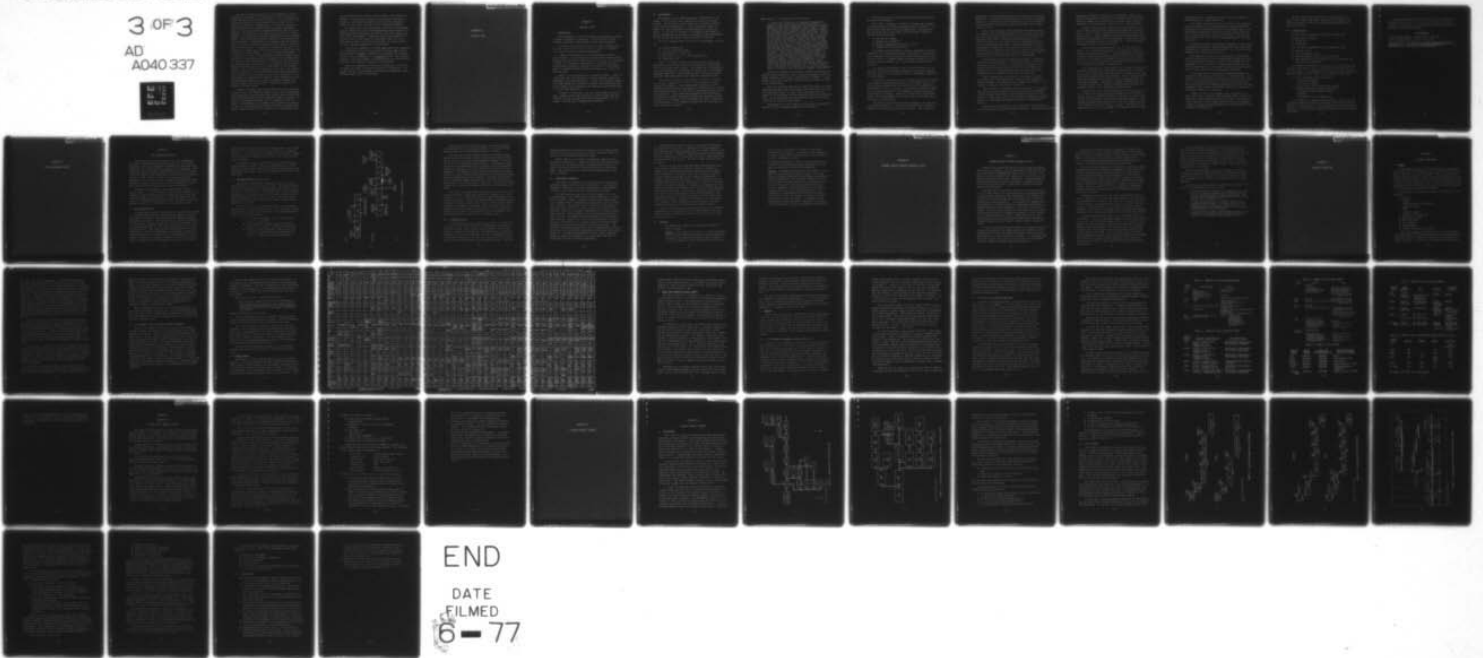
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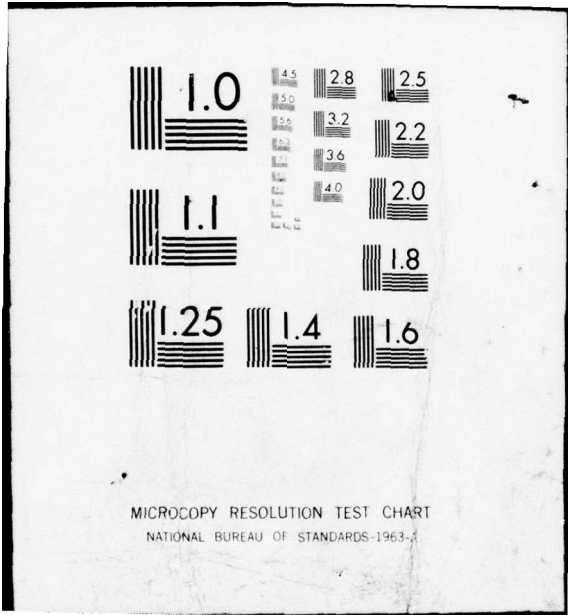
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The above conclusion holds for such industries, as the automotive one, where a new design can be made to provide for future growth without excessive penalty. It also requires that both the reliability and performance scaling laws for components be either well understood, or at least be capable of being formulated and verified during the early development phase; it also requires that system integration effects not be dominant. In such cases, the need may be clear for a certain system to be developed, whose exact specifications are indeterminate. Also, some long leadtime components or subsystems may need developing. Consequently, we recommend that the development of such long leadtime items be started, using a very tentative specification. A component or subsystem can then be developed to a design based upon this tentative specification but allowing for future growth. It can be tested and debugged. If it then turns out that the specification needs changing to meet the needs of the system, then the component can be redesigned. But the resulting redesign will not require as much testing as the original one, because much of the original testing and debugging information will still be applicable to the modified design. Thus, it should be possible to fund such long leadtime items in advance of the date when the final system specification is known, and to decrease the need for concurrency in the development of components and system. With components and subsystems made available by an early development process, the system designer can then proceed to design the system with a minimum of overall risk.

Another conclusion that can be drawn from this case study is that, often, the incentive system is such that new designs have relatively little provision for growth, even though allowing for such provision may be technically feasible and may not entail any unreasonable added cost or increase in size or weight. Accordingly, we recommend that in drawing up specifications for new component or subsystem designs, consideration should always be given to the inclusion or a requirement that

the new design allow room for future growth. The decision on whether to include such an item in the specification must be based on a cost-benefit tradeoff for each case, giving due weight to the issues outlined in the preceding paragraphs.

The study shows that independent research and development plays an important role in the uninhibited, early invention of new devices and components, and that 6.2 and 6.3A funding supports early development. These new devices and components often serve as the very basis for new system ideas, as in the AVCR engine, where their early development is a precondition for the ultimate development of a new system.

Just as the existence of certain new devices and components is a prerequisite for the development of certain new systems, the existence of mature components and subsystems is a prerequisite for the development of a low-risk system. This requires extensive early development, including substantial RAM work for selected, long leadtime components and subsystems.

Thus, we recommend the services' sponsorship of early development for some long leadtime devices and components. For a few critical, long leadtime components and subsystems, early RAM work should also be undertaken.

APPENDIX D

THE GAU-7 GUN

APPENDIX D

THE GAU-7 GUN

I. INTRODUCTION

The development of the F-15 fighter was preceded by nearly a decade of studies and analyses. In the course of these studies, a need for a new aircraft cannon was identified.

To minimize concurrency in the new fighter program, the Air Force undertook early development of some of the high-risk subsystems before airframe development.

A QMR was developed for a high performance aircraft cannon (HIPAC). This resulted in contracts with Aeronutronics Division of Philco-Ford Corporation and with G.E., in the summer of 1967, for competitive developments. In January of 1968, Aeronutronics accepted a proposal from IITRI for the development of a high-performance telescoped round with a fully combustible case.

Phase I of the program was a conceptual design. Phase II (1969-1970) was a continuation of the gun design, ammunition development, and gun fabrication. Phase III covered the design of a feed system and a shutoff to select the contractors who would complete the development and undertake the manufacturing of the gun and ammunition.

In Phase IV, which was to be the final stage of development, problems arose that could not be solved under the constraints of time, funding, and special requirements for the weapon. And the GAU-7 program was terminated.

II. DEVELOPMENT

The design of a gun system requires coordination of the design of the aircraft, gun, ammunition, feed, and storage systems. Historically, it has taken 8 to 11 years to develop a new gun and new ammunition. If the ammunition exists already, then gun development proceeds smoothly in about six years. In the case of the GAU-7, a concurrent development of gun and ammunition was planned, and several of the requirements for the gun and ammunition exceed the state of the art.

The GAU-7 program began with a set of requirements calling for:

- Caseless ammunition
- A fully telescoped round
- High velocity: ~ 4000 fps
- High rate of fire: ~ 5000 rounds per min
- Lightweight gun

Phase I of HIPAC included conceptual design and gun and ammunition tests, which called for the firing of some rounds from a single-shot test fixture. This phase was to demonstrate technical feasibility, including the feasibility of telescoped caseless ammunition. Philco-Ford and G.E. were prime contractors and IITRI and Hercules were ammunition subcontractors.

The primary purpose of telescoping a round is to reduce the volume of ammunition carried. Various degrees of telescoping are possible. Full telescoping is where the total round is essentially the same length as the projectile. Partial telescoping is where the round may be considerably longer than the projectile. Full telescoping presents some difficulties. It requires a special ignition time history, enabling the projectile to move forward into the chamber and seal, followed by the development of full chamber pressure and the propellant of the round from the barrel.

With respect to telescoping, IITRI reported:

"The barrel entrance for telescoped combustible-cartridge case rounds must be carefully designed. The reason for this care arises from two conditions directly related to telescoped combustible-case rounds. First, the combustible case provides a soft launching platform for the projectile, guiding it into the barrel. Second, the telescoped feature of the design means that the projectile must travel its entire length before it is completely within the barrel, which means that, compared to a standard configuration round, the round velocity at the time it is completely within the barrel is high. Third (and related to the second point), it is desired to project the round out of the telescoped combustible case as fast as possible to obturate the barrel and prevent blow-by from the propellant ahead of the projectile (in the annular section surrounding the projectile in the case). Under these conditions it is possible to generate a transient projectile jump that causes a deviation between the axis of the projectile and barrel. If, under such a condition of misalignment, the round engages a rifling in the barrel, subjecting it to a rotational couple, projectile balloting can result. Thus, when the projectile leaves the muzzle it may have a spin about some undetermined axis. In effect, the yaw at the muzzle is a function of the yaw in the barrel, which is dependent upon the barrel entrance conditions."

IITRI also observed that previous firings with 30-mm combustible case ammunition, with a specially designed barrel entrance geometry, gave stable round-to-round launches. It proposed to make the 25-mm HIPAC barrel entrance similar to that of its 30-mm design.

The term "caseless ammunition" means that there is no non-consumable external shell surrounding the propellant, and that the propellant itself, or some other consumable material, serves as the container for the propellant, primer, and projectile. An acrylic fibre and nitrocellulose were used in the round, and a residue problem arose.

The absence of a hard case also introduced the problem of sealing the hot combustion gases into the chamber.

The residue and the sealing problems became major issues during this development.

The Phase II program, in 1969-70, included the finishing of the gun design and continuing ammunition development. G.E. and Hercules were active in the program also. Aeronutronics was confident that all problems could be solved. The main problems in Phase II were

- Sealing the chamber
- Sealing the firing pin
- Residue accumulation and metal erosion
- Designing the feed mechanism.

The sealing problem affected the gun performance, because leakage of the hot propellant gases eroded metal and increased the tolerances, thereby reducing the gas pressures and the projectile velocity. Reduced chamber pressure mitigated the sealing and erosion problem, but it also reduced the projectile velocity.

The residue accumulation lead to a short firing life for the gun. The corrosive gases leaking past the seals, coupled with the deposit of the residue, lead to considerable reduction in burst length.

Problems in the ammunition feed system arose from the merging of the feed section and the gun. A principal concern (of the military sponsors) was the possibility of the ammunition getting wet or too hot or cold. A protective coating was added to the rounds, which had to be stripped off before the round could enter the chamber. This was an additional complication. Rounds were being damaged in the feed, and the stripping mechanism was not working well.

The high firing rate of the GAU-7 demanded a gun that was externally driven, i.e., the action was separately powered as opposed to guns driven by recoil or hot gas. This required a

uniformity of firing times that was not present in the caseless ammunition. Rounds were being damaged in the feed, and jamming occurred. It was hard to get the velocity up to the specified value, because of the need to reduce the action time to raise the rate of fire.

Early in the program, IITRI calculated the driving loads. It concluded that the bearing stress on the driving force, and the shear acting across the base of the band, could be alleviated with high copper content rotating-band compositions. IITRI recognized, at the start, that the centrifugal stresses in the rotating band represent a critical design area, and it recommended consideration of a welded overlay band. The Air Force, however, insisted to the end on a *plastic* rotating band. The plastic band never worked, and this became a major obstacle and an important factor in the future of the program.

Another major problem surfaced at this time: round survivability and vulnerability. The rounds burned, but they did not explode unless confined. Rounds would be confined in the aircraft, which became a major issue with the airframe contractor later on. Several methods for quenching fires were considered, but no decisions were made at this point.

Phase II ended with the firing of the Phase II fixture (4500 r/m) with a 25-round burst. The burst was limited by residue buildup. The problems that followed the program to the end were set by the conclusion of Phase II.

Phase III was to establish proof of principle. It included the first contract award for feed system design to accommodate 150-250 rounds. The rights to the telescoped caseless round concept of IITRI were sold to the Brunswick Corporation, during Phase III, and Brunswick became the supplier of ammunition to Philco.

Hercules (G.E.'s partner in the competition) was permitted to supply rounds to Philco-Ford for evaluation. Aerojet Corporation's

Shillelagh companion round was also considered. Philco considered the Brunswick round to be structurally better than the Hercules' round, but the Hercules' round was better from the standpoint of environmental protection, e.g., waterproofing.

Although the Philco gun could fire at the design rate but only in short uneven bursts, Philco's attitude was very optimistic. At this time, a restaffing took place at Philco-Ford Aeronutronics. People formerly occupied with the reentry programs were transferred to the gun program. A shootoff at Eglin AFB was scheduled for the end of Phase III. The F-15 aircraft contractor had not yet been selected.

Philco-Ford Aeronutronics beat G.E. in the shootoff at Eglin. G.E. encountered problems in the shootoff that Aeronutronics would have later on. The gun weight was reevaluated. A 150-lb reduction was desired, because the Air Force wanted the GAU-7 to be similar in weight to the 20-mm cannon. This was to pose a major problem in reliability, because weight had to be reduced from highly stressed parts.

The requirement for light weight in a high-performance gun demanded removing metal from highly stressed parts. Furthermore, since the gun was externally driven, uniform action times and rapid ignition times were required. Both of these requirements were unachievable, because of the pulse-pulse mode of propellant burning. Variations in timing, stemming from lack of round repeatability, leads to jamming, broken rounds, and possible damage to the lightweight stressed parts.

Phase IV was to be the development of the actual gun. All of the Phase III work involved prototypes and test fixtures. Philco could not improve the Phase III product by 30%, and now it started to design a new gun, with separate chambers. The weight requirement was unrealistic, since the weight goal was well beyond the state of the art for guns. Furthermore, the ammunition was *not* to be changed. The decision was that Phase

III ammunition was considered not bad, and now it should be made producible in large quantities.

The design problems now began to surface. The ammunition had to be burned in the "nonstop" mode to achieve ballistic performance, but the seals required a pulse-pulse mode. Sub-specification ammunition would work the gun seals properly, but it would lose about 1000 fps in velocity. This problem was caused mainly by the fully telescoped aspect of the caseless round.

The new gun design, with separate chambers and two seals, compounded the problem. Design alternatives that could have minimized seal problems were not tested, e.g., the M-61 reciprocating bolt, front load revolvers.

The proposed solution to the survivability and vulnerability problem was to eject the ammunition storage box after a fire warning and before explosion. This proposal was not acceptable to the Air Force. Satisfactory solutions to the GAU-7 problems were not forthcoming by the deadline imposed by the F-15 SPO, and the GAU-7 program was terminated.

It is important to recognize the coupling between the problems of the gun and the problems of the ammunition. The problem of the gun sealing propellant would not have occurred, if a fully telescoped caseless round had not been required. The poor sealing of the chamber permitted gas blowby, and the subsequent metal erosion and residue deposition contributed to the short firing life of the gun.

Toward the end of the program, some tests were run at Eglin AFB, using a plastic cased cartridge with a copper rotating band. This round did duplicate the GAU-7 ballistics on a test fixture, but the copper band could not be considered further, because the program demanded caseless ammunition and a plastic rotating band.

The mass production rounds made in large quantity for Phase IV had larger dimensional variations than those of the test rounds made for Phase III, and this contributed to the sealing problem too.

III. OBSERVATIONS

The principal requirements of the gun system were:

- Ballistic performance
- Firing rate
- Gun weight

The specific requirements for the ammunition were:

- Caseless round
- Fully telescoped round
- Low vulnerability and high survivability
- High resistance to environment (e.g., waterproof, and temperature insensitive).

The apparent objectives in specifying the fully telescoped, caseless round were to save on volume and to preclude the use of shell cases. The consequences of specifying fully telescoped, caseless ammunition are listed here according to the source:

- Full telescoping caused problems in:
 - Projectile seating
 - Sealing the chamber
 - Pulse-pulse mode of propellant burning.
- Caseless ammunition caused problems in:
 - Sealing the chamber and firing pin
 - Residues
 - Survivability and vulnerability.

In retrospect, it appears that yielding on some of the requirements might have saved the program. But it would have diminished the superiority of the new weapon over what was already available, thereby reducing the justification for the new weapon development.

Early development might have been helpful by exposing the problems earlier. But it is not clear that this would have prevented the failure, since the problem symptoms were ignored during the directed development.

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APPENDIX E

THE SRAM WEAPON SYSTEM

APPENDIX E

THE SRAM WEAPON SYSTEM

This appendix reviews the history of SRAM, emphasizing the problems encountered during development of one critical subsystem. The high performance specified for the system precluded the use of off-the-shelf components or subsystems. Each subsystem required significant advances in the state of the art and not just repackaging. Without definite specifications to work toward--not only in the usual performance parameters but in volume, weight, vibration environment, power required, radiation hardening, etc.--the independent development effort would not have produced usable components.

Information contained in this appendix was obtained chiefly from A. H. von der Esch, who was general manager of the Lockheed Solid Propellant Division during the entire SRAM development program, and from John R. Smith of Boeing, who was head of the SRAM Systems Engineering from the first concept development activity to the delivery of the 1000th missile.

I. SYSTEM DESCRIPTION

The SRAM weapon system (also known as the WS-140A) consists of a nuclear-armed missile, airplanes that support, control, and launch the missile, specialized ground support equipment, and trained personnel. The missile can be launched throughout a wide envelope of carrier aircraft speeds and altitudes, with its flight programmed for one of many trajectory and velocity profile options. The trajectory may be semiballistic for maximum range or low-level performance, controlled by either an inertial system or an altitude sensor. The weapon's velocity profile, shaped by a two-burn, variable interval solid rocket, may be programmed to provide maximum velocity over the last 10

miles, maximum average velocity, or maximum range. The target may be at any azimuth from the launch airplane, including to the rear. A given missile is uncommitted to a specific target, until the target coordinates are fed into the missile during launch countdown.

Currently, both the B-52 and FB-111 aircraft are operational carriers of SRAM. The B-1 is expected to be a SRAM carrier and is designed with three identical weapon bays, each 180 inches long, with a capacity of eight SRAM missiles on rotary racks.

II. PROGRAM HISTORY (See Fig. E-1)

The Specific Operational Requirement (SOR) that led to SRAM was issued by the Air Force in 1964. The Boeing Company was one of two winners of a System Definition Contract, covering work in 1965 and 1966. In November 1966, a total package procurement type contract was let to Boeing, covering the design, development, test, and evaluation of the whole system. Boeing had near-complete control over system design and subcontractor selection.

The first step in developing SRAM was to put together a specification tree that identified all major functional equipment and the equipment's interactions. The equipment was divided into three categories:

- Air Vehicle Equipment (AVE), which consists of missile components
- FB-111 and B-52 Carrier Aircraft Equipment (CAE), which consists of SRAM system avionics
- Aerospace Ground Equipment (AGE), which consists of all dedicated ground equipment necessary for SRAM operation and maintenance.

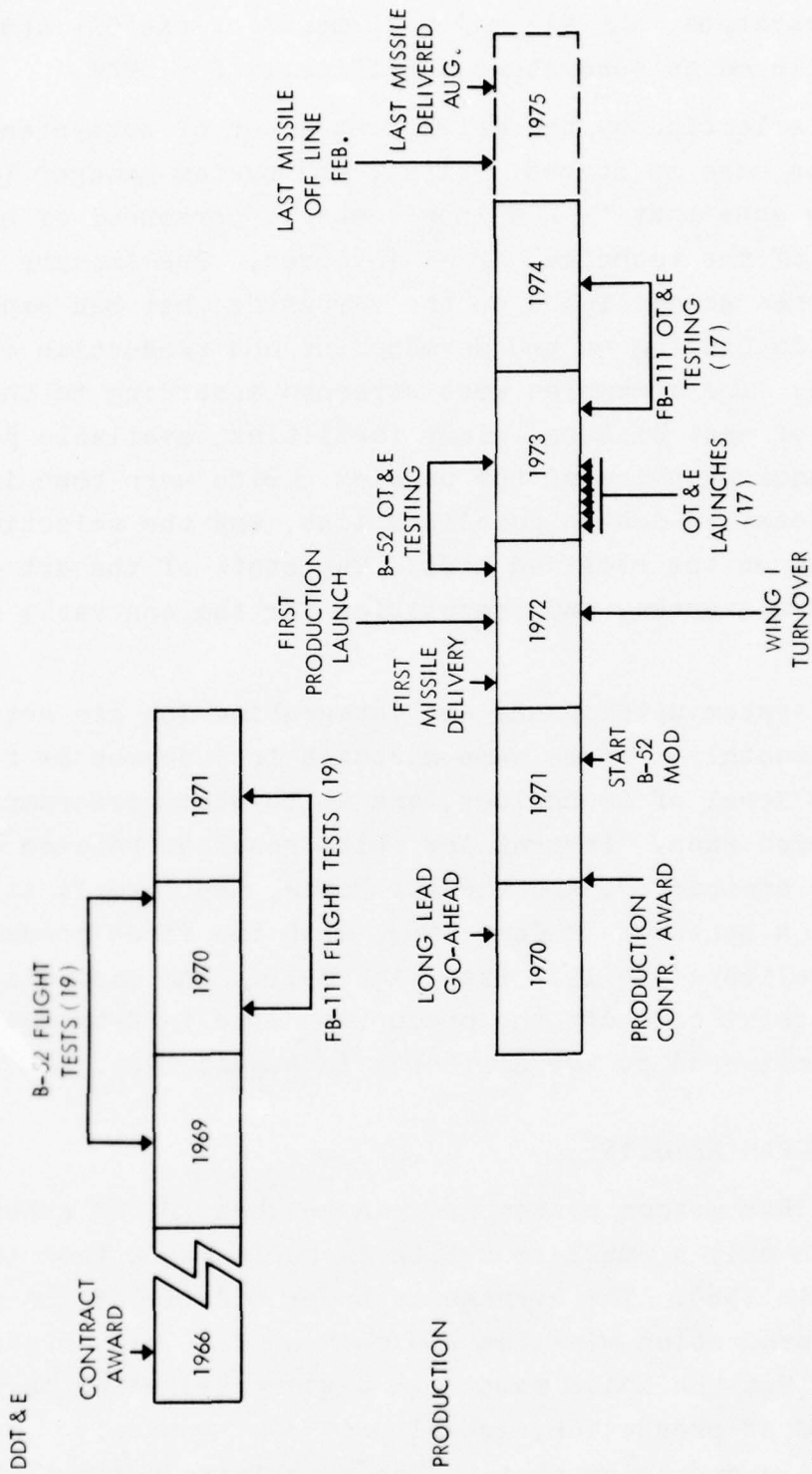


FIGURE E-1. Program Phasing

Major sections of the AVE are what are usually referred to as subsystems, but all major elements of the CAE and AGE were developed as subsystems specifically for SRAM.

The selection by the prime contractor of subsystem suppliers was done in stages. First, the system manager (Boeing) had to be sure that he had knowledgeable personnel of his own for each of the technical areas involved. Preliminary screening was then accomplished on the companies that had expressed interest in bidding on the development and production of each subsystem. The companies were screened according to the usual criteria of past history, plant facilities, available personnel, and the understanding of the problem. Bids were then invited on very detailed design specifications, and the selection was made based on the received bids. The state of the art was being pushed in all areas, and competition for the contracts was intense.

The system development and integration job did not go completely smoothly. There were mistakes in judgment as to the available level of technology, and as to what performance could be delivered when. Several law suits resulted between supplier, the prime contractor, and the Air Force. But the first launch occurred on schedule in June 1969, with the first production missile delivered in 1972 (see Fig. E-1). The last missile in the 1500 total came off the production line in February 1975 and was delivered to the Air Force in August 1975.

III. PROGRAM RESULTS

The SRAM weapon system program reached IOC on schedule in 1972, with only a small reduction in performance from that envisioned in 1964. The average cost per missile of the first block of production missiles was much higher than originally planned. But the costs went down a steep "learning curve" and, at the end of production, actual unit cost was below the predicted value and below that of the negotiated price. The only

incentive provision in the prime contract was for radar cross-section reduction, under which the prime contractor earned almost all of the available incentive award.

Today, SRAM is a successful, operational system with no recognized deficiencies. Other than shooting down the aircraft that carry it, no high-confidence military weapon exists, of either the United States or the Soviet Union, to counter the SRAM. The Air Force has no modifications planned and no SOR for a successor.

IV. DEVELOPMENT PROBLEMS

Most major new systems have some problems in meeting the original schedule and product specifications. But increased management attention, with minor reallocation of development resources, will usually provide satisfactory solutions.

The SRAM system exemplifies this philosophy, but to an extreme degree. The weapon system required advances in a number of technical areas: guidance, radar cross-section reduction, flight control subsystems, and propulsion, which was the most critical. The system concept was based on achieving not only high total impulse in a given volume, but also the delivery of thrust in two pulses, separated by a variable-length time interval. Rocket restarts had been accomplished before, but not at the low temperature and pressures associated with high altitude. Several new technical problems were introduced here, and the difficulty of solving them was seriously underestimated in the system planning and definition phase. The problems of getting adequate bulk specific impulse and a nozzle liner that could withstand temperature cycling were particularly difficult. No previous development effort, either contract-funded or IRAD, had progressed to a point where the level of technology could be reliably extrapolated.

The competition for the contract to develop and produce the SRAM motor was intense. Competitors were the leaders in the industry, including Lockheed, Hercules Powder, Thiokol, and Aero-Jet General. Lockheed, through its propulsion subsidiary, won the competition to develop the motor with a fixed price bid of approximately \$6 million. The next closest bid was for \$7 million.

By the time the motor was qualified, approximately three years later, Lockheed had spent \$66 million. During the height of the development problems, when motors were consistently blowing up test stands, the prime contractor (Boeing) had more engineers working on the propulsion subsystem at Lockheed than Lockheed did itself. Another indication of the technical difficulty in this area was the inability of Thiokol, during the production phase, to qualify as a second source of motors, even after being given a \$12 million contract and much of Lockheed's know-how. Eventually, the motor was developed with only a minor compromise in low-level performance. The two-pulse concept is working as planned, and the operational reliability is high. Lockheed recovered most of its development contract losses during the production phase, but subsequently dropped out of the solid propellant business.

Serious development problems also existed in the guidance subsystem and in components of the flight controls, but none came as close to causing the program to fail as did the propulsion problem.

V. FINDINGS

- a. The SRAM system used no off-the-shelf subsystem or major component.

Comment: This should be expected. A high-performance, high-technology system such as SRAM would probably not incorporate any existing subsystem except, possibly, one that represents so much development time and cost

that to reject it would be to make the new system economically infeasible. There was no such subsystem for SRAM, unless the launch platforms (B-52 and FB-111) could be considered as such.

- b. The specific operational concept and the physical environment for a weapon system are critical in the design and evaluation of important subsystems.

Comment: The SRAM system provides the example, in the case of the propulsion subsystem, where, if a high specific-impulse motor had been developed independently without knowledge of the heat soak problem or even of the very severe volume limitation, it probably could not have been used. To develop a high technology piece of hardware, with the intention of producing a standard item, is a very risky undertaking. The likelihood of understanding the relative importance and utility of all the possible specification parameters appears very low indeed. For example, these parameters include vibration, resistance to radiation, total observables, volume, and required operating time.

APPENDIX F

FORWARD-LOOKING INFRARED SENSORS (FLIRs)

APPENDIX F

FORWARD-LOOKING INFRARED SENSORS (FLIRs)

Forward Looking InfraRed sensors (FLIRs) have been developed over a long period. By the midsixties, FLIRs already had good performance, rivalling low light level TV (LLLTV). The market was poor, however; most buys were for only one or a few units at extremely high prices (\$500,000). Volume production was unknown, and there was no real hope of lowering the unit price as long as each unit required R&D, followed by custom design and fabrication.

The Night Vision Laboratory (NVL) at Ft. Belvoir had been set up by the Army as the lead laboratory in the infrared area. It had already a well-developed organization for dealing with both R&D for new technology and the translation of new technology into volume production. It achieved this capability by developing the required production engineering methods and by standardizing the required product to increase the volume required. This was proven during the long (more than five years) and successful effort to standardize Generation I and Generation II image intensifier tubes. During that effort, tubes with 18-mm, 25-mm, and 50-mm photocathodes were developed as a standard family, and were used in a great variety of applications.

In its role as lead Army laboratory in infrared, NVL, with strong encouragement from ODDRE, studied the market for FLIR systems, both in existing applications and in new areas that might open up, if the price were to plummet. It concluded that the market would really open up, if the cost of FLIR systems could be lowered to between \$10,000 and \$50,000.

NVL, still with the strong encouragement of ODDRE, used its position as the major service funding agency for infrared R&D to force the standardization of FLIR-related detectors using HgCdTe, a material that can attain suitable detectivity at 77°K. The deciding factor here was the relatively high temperature of operation and the moderate cooling load.

NVL was then instrumental in initiating a triservice study, sponsored by the Joint Logistics Commanders, on the modularization and standardization of building blocks for FLIR system. An NVL study team defined the requirements for the various building blocks and invented some designs suitable for modulation, including an oscillating scanner. Honeywell and TI were asked to brassboard these designs; TI produced a suitable prototype. With the backing of the Joint Logistics Commanders, NVL was then able to proceed with the standardization effort, using the TI system.

Throughout this program, the Army supported NVL both because of the logic of its actions and because NVL was the Army's lead laboratory in infrared. The Navy had no centralized view on this subject, although Admiral Kidd did back NVL. The Air Force was less cooperative; at one point it tried to have a different FLIR system one designed with serial scan by Honeywell adopted as the common FLIR system for all tactical applications.

Certain approaches were the key to attaining success in this effort. First, a procurement approach had to be developed, in parallel with the technological effort, to ensure the development of volume production capability by several contractors. Suitable data packages had to be obtained from TI, and their validity had to be checked in house by actually building the various modules from them. This took much effort--and some 3000 engineering changes! Once a valid production data package was available, a second volume production source had to be found for each module. Thus, competition--and lower prices--were assured.

In this program, it became clear that the repair philosophy dictated the data requirement. For throwaway modules, form, fit, and function standardization is sufficient. But for every module that must be repaired by the Government (as opposed to repair by the contractor), configuration control is essential, and detailed information on the internal structure of the module is required to permit repair. Thus, part lists, drawings, etc., are needed.

NVL had the advantages of the full support of ODDRE and of having no other service organization as significant competitors in the field of infrared. But NVL also had to provide the Government with a continuity of purpose in this five-year endeavor.

Our conclusions with respect to developing subsystems similar to the FLIR systems are as follows:

1. To provide the real benefits of standardization, ways have to be found to ensure volume production by two or more suppliers and continuing competition. This entails the development of a suitable production data package and an industrial base.
2. A repair philosophy must be defined early in the standardization process. If service repair is contemplated, then configuration control must be implemented inside each module; form, fit, and function standardization is not sufficient.
3. A strong central guiding organization, capable of developing both technology and an industrial base, is central to a successful standardization effort.

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APPENDIX G

AIRCRAFT SUBSYSTEMS

APPENDIX G

AIRCRAFT SUBSYSTEMS

I. SUMMARY

A preliminary analysis of aircraft subsystem development was carried out by examining the history of three military aircraft: The A-4, F-15, and F-17/F-18. The A-4 series has a 20-year history, the F-15 is just getting into squadron service, and the F-17/F-18, which evolved from the T-38/F-5 series, are in the prototype development stage. Despite the different life-cycle phases these aircraft are in, there are some similarities in the programs that are worth examining.

The principal categories of subsystems considered in this study are:

- Avionics
 - Radar
 - Communications and navigation
 - Weapons control
 - ECM
 - Digital computers
 - Heads-up displays (HUD)
- Mechanical systems
- Secondary power
- Fuel Systems
- Escape systems
- Landing gear wheels and brakes

Among the programs considered here are a few examples of early development, although generally subsystem development is concurrent with the program (and might be a repackage of existing equipment). According to the definitions established

for this task, early development or independent development does not usually play a major role in these acquisition processes; exceptions might be such long leadtime items as engines and radars. The aircraft prime contractors exhibit clear preferences for particular modes of subsystem development and acquisition. They look first for suitable equipment already in production. However, for first-line aircraft, many critical items are not available and have to be developed. The contractors themselves prefer to control the development of critical items as CFE. This is an obvious and natural preference from the standpoint of the prime contractor. After an item becomes developed, it might become GFE and be made available to other systems, although this outcome appears to occur in very few cases.

In some instances, the aircraft and engine R&D programs are carried on under project names, or designations, that are different from the ultimate designation of the program (e.g., the F-15 airplane went through a long program definition study phase known as the F-X). During this study phase, both engine and radar developments were started, although they were not completed before the airframe development program began. We consider these to have been early developments of long leadtime items.

Another early (though unsuccessful) development associated with the F-15 was the GAU-7 gun. The experience with this gun indicates that high-risk items should not be tied to a particular program. Delays in the development of the item can threaten delays in the aircraft, thereby forcing the program manager to substitute proven technology of lower performance than considered desirable.

Some recent experiences indicate that high-risk items should not be tied to a major system program (technology demonstration should be independent). But major programs are an

important source of funds, and new programs are catalysts for ideas on new developments beyond the technology demonstration stage. The aircraft companies identify areas where particular incremental developments or applications would benefit their projects, and they use IR&D funds in many instances. The companies will seek contracts for followon R&D (especially technology demonstration), not only for the funding, but also for a form of endorsement or qualification of the equipment in terms of the sponsor's project report, assuming that the equipment passes the qualification tests.

While designers will tailor and custom design systems to get better performance and will try to avoid performance penalties associated with standard parts, components, or subsystems, prototype budgets are often inadequate and can cause short cuts that are regretted later.

II. A-4 AIRCRAFT SERIES--DOUGLAS AIRCRAFT COMPANY

The A-4 was designed in the early 1950s by the Douglas Aircraft Company (El Segundo) as a carrier-based attack plane. Douglas (El Segundo) created many new aircraft designs in the early 1950s. One new aircraft design per year was typical, and they were pushing the limit of that technology, i.e., the aircraft itself was the limit. The subsystems were relatively simple and the equipment could be made by the company itself, although it chose not to make small standard parts. For example, Douglas made its own landing gear. After a prototype was built and tested, it farmed out the fabrication, from the company drawings, to subcontractors. This "make it inhouse" philosophy was typical of the El Segundo Division. On the other hand, the Santa Monica Division of Douglas was oriented towards commercial aircraft and tended to buy subsystems from outside suppliers.

The A-4 was designed with the El Segundo philosophy. It was equipped with unsophisticated electronics and with meager navigation equipment. The basic communications and electronics weighed 120 lb, originally. As experience was gained with the airplane, it was decided that more electronics and avionics were needed.

There were two ways to develop these items:

- a. They could be planned as GFE from the beginning, or
- b. They could begin as CFE, where the company had responsibility for development. Later this equipment would become GFE, after the development problems had been solved.

Douglas preferred the latter mode.

The new equipment for the A-4 required going to subcontract competitions among specialist houses. And the equipment bought in this way usually had very specific functions.

Table G-1 shows the evolution of the A-4 and its subsystems. The A-4 changes were always short-term improvements. There was no long-range plan for these developments, because each modification to the A-4 was made for the next buy, which was a small number of aircraft. With the exception of the engine and the AN avionics equipment, most of the subsystems were developed specifically for the A-4.

Some specific systems are singled out for discussion, because they illustrate some general points that are worth noting.

A. Escape System

The Douglas Aircraft Company develops and sells escape systems. In concept, each one differs slightly from the next. This requires new development and new design, and there is non-recurring money spent on qualification testing. For example, the divergence from the aircraft must be tested for each escape system, which requires zero-zero trials and sled tests. Even

ITEM	1954	1955	1958				1961	1965	1964		1967	
	A-4A	A-4B	A-4P ARG AP	A-4Q ARG NAVY	A-4S	A-4C	A-4E	A-4F	A-4G	A-4H	A-4I	A-4J
ENGINE	J65-W-16A	J65-W-16A J65-W-20	J65-W-16A	J65-W-20	J65-W-20	J65-W-20A J65-W-20 J65-W-420	J52-P-8A, 8B J52-P-8A, 8B	J52-P-8A, 8B J52-P-408	J52-P-8A, 8B J52-P-8A, 8B	J52-P-8A, 8B	J52-P-8A, 8B	J52-P-8A, 8B
THRUST	7,700 #	7,700 # 8,400 #	7,700 #	8,400 #	8,400 #	7,700 # 8,400 # 8,400 #	8,500 # 9,300 #	9,300 # 11,200 #	8,500 # 9,300 #	9,300 #	9,300 #	9,300 #
TOTAL INTERNAL FUEL CAPACITY	5,400 LBS 800 GAL	5,400 LBS 800 GAL	5,400 LBS 800 GAL	5,400 LBS 800 GAL	5,400 LBS 800 GAL	5,400 LBS 800 GAL	5,400 LBS 800 GAL	5,400 LBS 800 GAL	4,488 LBS 660 GAL	5,400 LBS 800 GAL	4,488 LBS 660 GAL	5,400 LBS 800 GAL
SELF STARTER	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO
FUELING PROBE	NO	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES
AIR REFUELING STORE	NO	YES	YES	NO	NO	YES	YES	YES	YES	YES	YES	YES
VSCP	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO
APC AN/ASN-54	NO	NO	NO	NO	NO	YES	YES	YES	PROVISIONS	NO	NO	NO
OXYGEN SYSTEM	5 LITER	5 LITER	5 LITER	5 LITER	10 LITER	10 LITER	10 LITER	10 LITER	10 LITER	10 LITER	10 LITER	HI PRESSURE GASEOUS
ROCKET (7) EJECTION SEAT	ESCAPAC-1	ESCAPAC-1A-1 STENCIL MOD	ESCAPAC-1A-1 STENCIL MOD	ESCAPAC-1A-1 STENCIL MOD	ESCAPAC-1A-1 STENCIL MOD	ESCAPAC-1A-1 STENCIL MOD	ESCAPAC-1A-1 STENCIL MOD	ESCAPAC IC-3 IP-3 (7) IG-3 (7)	ESCAPAC IC-3 IP-3 (7) IG-3 (7)	ESCAPAC IC-3 IP-3 (7) IG-3 (7)	ESCAPAC IC-3 IP-3 (7) IG-3 (7)	ESCAPAC IC-3 IP-3 (7) IG-3 (7)
NOSEWHEEL STEERING	NO	NO	NO	NO	NO	NO	NO	YES	YES	YES	YES	YES
SPOILERS	NO	NO	YES	YES	YES	NO	YES (3)	YES	YES	YES	YES	YES
DRAG CHUTE	NO	NO	NO	NO	YES	NO	NO	NO	NO	NO	NO	YES
JATO (2)	NO	NO	NO	NO	NO	SOME PROVISIONS ONLY	SOME PROVISIONS ONLY	PARTIAL PROVISIONS	PARTIAL PROVISIONS	PARTIAL PROVISIONS	PARTIAL PROVISIONS	PARTIAL PROVISIONS
UPPER AVIONICS COMPARTMENT	NO	NO	NO	NO	NO	NO	YES	YES	NO	PROVISIONS ONLY	NO	PROVISIONS ONLY
APCS	NO	NO	NO	NO	NO	YES	YES	YES	YES	YES	YES	YES
RADAR	NO	NO	NO	NO	AN/APG-145	AN/APG-53A	AN/APG-53A	AN/APG-53A	AN/APG-53A	AN/APG-53A	AN/APG-53A	AN/APG-53A
NAVIG. COMPUTER	NONE	AN/ASN-19A	NO	AN/ASN-19A	DECCA TYPE 72 DOPPLER/TANS COMPUTER DISP.	AN/ASN-19A	AN/ASN-19A (EARLY A-4E) AN/ASN-41	AN/ASN-41	AN/ASN-41	AN/ASN-41	AN/ASN-41	AN/ASN-41
COMMUNICATIONS	RT-355/ASQ-17 (AN/ARC-27A)	RT-355/ASQ-17 (AN/ARC-27A)	CNA-4 (BEND IX) RTA-41B RNA-25C	ARC-109 DHP 612P-2D WOP	PTR 377 UHP/WOP RT AN/ARC-159	RT-355/ASQ-17 (AN/ARC-27A)	RT-355/ASQ-17 (AN/ARC-27A)	AN/ARC-51A AN/ARR-69	AN/ARC-51A AN/ARR-69	AN/ARC-51A AN/ARR-69	AN/ARC-51A AN/ARR-69	DUAL ARC-51A AN/ARR-69
TACAN	AN/ARN-21D	AN/ARN-21D	AN/ARN-21D	AN/ARN-21D	AN/ARN-52(V)	AN/ARN-21D	AN/ARN-21D (EARLY A-4E) ARN-52 (V)	AN/ARN-52(V)	AN/ARN-52(V)	AN/ARN-52(V)	AN/ARN-52(V)	NO
ADP	AM-1260/ ASQ-17 (AN/ARA-25)	AM-1260/ ASQ-17 (AN/ARA-25)	OPA-73	OP-203	OP-206	AM-1260/ ASQ-17 (AN/ARA-25)	AM-1260/ ASQ-17 (AN/ARA-25)	AN/ARA-50	AN/ARA-50	AN/ARA-50	AN/ARA-50	AN/ARA-50
RADAR ALTIMETER	NO	AN/APN-141	NO	PROVISIONS ONLY	AN/APN-141	AN/APN-141	AN/APN-141	AN/APN-141	AN/APN-141	AN/APN-141	AN/APN-141	AN/APN-141
DOPPLER AN/APN-153	NO	NO	NO	NO	SEE NAVIG. COMP. ABOVE	NO	SOME	YES	YES	YES	YES	YES
ILS (8)	NO	NO	NO	SIRT-1	NO	NO	NO	AN/ARA-63	NO	NO	NO	NO
RADAR IDENTIFI- CATION (IFF)	RT-354/ASQ-17 (AN/APX-68)	RT-354/ASQ-17 (AN/APX-68)	NO	AN/APX-79	PTR 446	RT-354/ASQ-17 (AN/APX-68)	RT-354/ASQ-17 (AN/APX-68)	AN/APX-64(V)	AN/APX-64(V)	AN/APX-64(V)	AN/APX-64(V)	AN/APX-46
AIMS	NO	NO	NO	NO	NO	PROVISIONS APC-482 (1)	PROVISIONS APC-482 (1)	PARTIAL PROVISIONS	PARTIAL PROVISIONS	NO	NO	NO
STRIP CAMERA	NO	NO	NO	NO	YES	NO	NO	NO	NO	NO	NO	NO
BOMB RACES	3	3	3	3	5	3	5	5	5	5	5	5
EGN	NO	NO	NO	NO	NO	PROVISIONS	PROVISIONS	PROVISIONS	SOME	NO	NO	NO
LABS	AERO 18B	AERO 18B	NO	NO	NO	AN/AJB-3	AN/AJB-3 AN/AJB-3A	AN/AJB-3A	AN/AJB-3A	AN/AJB-3A PROVISIONS	AN/AJB-3A PROVISIONS	AN/AJB-3A PROVISIONS
CP-741/A	NO	NO	NO	NO	YES	NO	YES	YES	YES	NO	NO	NO
SPECIAL WEAPON	YES	YES	NO	NO	NO	YES	YES	YES	YES	NO	NO	NO
SIDEVINDER (4)	NO	TWO STATION BY APC-203	NO	PROVISIONS	TWO STATION	TWO STATION BY APC-203A	TWO STATION BY APC-431	TWO STATION BY APC-431	NO	FOUR STATION	FOUR STATION	FOUR STATION
BULLPOP	NO	PROVISIONS	NO	NO	NO	PROVISIONS	PROVISIONS	PROVISIONS	PROVISIONS	PROVISIONS	PROVISIONS	NO
GCBS	NO	SOME PROV.	NO	NO	NO	PROVISIONS	PROVISIONS	PROVISIONS	PROVISIONS	NO	NO	NO
AN/APN-154	NO	NO	NO	NO	NO	YES	YES	YES	NO	NO	NO	NO
SHRIER	NO	NO	NO	NO	NO	LIMITED SHRIER	YES	YES	YES	PROV.ECP-2005 DATA REC.	PROV.ECP-2005 DATA REC.	NO
VALLEYE	NO	NO	NO	NO	NO	NO	PROVISIONS	PROVISIONS	SOME PROV.	NO	NO	NO
GUNS	20 MM 200 RDS	20 MM 200 RDS	20 MM 200 RDS	20 MM 200 RDS	30 MM 300 RDS	20 MM 200 RDS	20 MM 200 RDS	20 MM 200 RDS	20 MM 200 RDS	20 MM 200 RDS	20 MM 200 RDS	20MM/200RDS 300M/300RDS
VDS & HUD & VDMS	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO
LASER SPOT TRACKER	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO
BULLDOG	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO

(1) APC-482 UPDATES A-4C/E AVIONICS TO A-4P CONFIGURATION.

(2) P/N 5818116-501 JATO INSTL ALTER EQUIP KIT, WHEN INCORP INTO A/C & PARTIAL PROV. P/ATC WILL PROVIDE COMPLETE JATO CAPABILITIES. THIS IS A UNIVERSAL KIT.

(3) APC-442 INC. POILERS.

(4) APC-509 & RE PARTS

TABLE G-1. EVOLUTION OF THE A-

	1967				1969				1970							
	TA-40	A-4H	TA-4H	TA-4J	A-4K	TA-4K	A-4L	A-4M	A-4N ARC-518 MOD	A-4N I, II	A-4N/M	TA-4P/N	TA-4J/N	A-4N PT-74	A-4N PT-74	TA-4P
	J52-P-8A, 8B	J52-P-8A, 8B	J52-P-8A, 8B	J52-P-8A, 8B	J52-P-8A, 8B	J52-P-8A, 8B	J65-M-70 J65-M-120	J52-P-408	J52-P-408	J52-P-408	J52-P-8B	J52-P-8B	J52-P-8B	J52-P-408	J52-P-408	J52-P-408
	9,300 #	9,300 #	9,300 #	8,500 # 9,300 #	9,300 #	9,300 #	8,400 # 8,400 #	11,200 #	11,200 #	11,200 #	9,300 #	9,300 #	9,300 #	11,200 #	11,200 #	9,300 #
	4,408 LBS 660 GAL	5,400 LBS 800 GAL	4,408 LBS 660 GAL	4,408 LBS 660 GAL	5,400 LBS 800 GAL	4,408 LBS 660 GAL	5,400 LBS 800 GAL	5,400 LBS 800 GAL	5,400 LBS 800 GAL	5,400 LBS 800 GAL	5,400 LBS 800 GAL	4,408 LBS 660 GAL	4,408 LBS 660 GAL	5,400 LBS 800 GAL	5,400 LBS 800 GAL	4,408 LBS 660 GAL
	NO	NO	NO	NO	NO	NO	NO	YES	YES	NO	NO	NO	NO	NO	NO	NO
	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES
	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES
	NO	NO	NO	NO	NO	NO	NO	SOME APC-545	YES APC-545	SOME	NO	NO	NO	YES	YES	NO
	NO	NO	NO	PROVISIONS	NO	NO	YES	PROVISIONS	PROVISIONS	NO	NO	PROVISIONS	PROVISIONS	PROVISIONS	NO	PROVISIONS
	10 LITER	HI PRESSURE GASOUS	HI PRESSURE GASOUS	10 LITER	10 LITER	10 LITER	10 LITER	10 LITER	10 LITER	10 LITER	10 LITER	10 LITER	10 LITER	10 LITER	10 LITER	10 LITER
	ESCAPAC IC-3 IP-3 (7) IG-3 (7)	ESCAPAC IC-3 IP-3 (7) IG-3 (7)	ESCAPAC IC-3 IP-3 (7) IG-3 (7)	ESCAPAC IC-3 IP-3 (7) IG-3 (7)	ESCAPAC IC-3 IP-3 (7) IG-3 (7)	ESCAPAC IC-3 IP-3 (7) IG-3 (7)	ESCAPAC-1A-1 STENCIL MOD	ESCAPAC IC-3 IP-3 (7) IG-3 (7)	ESCAPAC IC-3 IP-3 (7) IG-3 (7)	ESCAPAC IC-3 IP-3 (7) IG-3 (7)	ESCAPAC-1A-1 STENCIL MOD	ESCAPAC IC-3 IP-3 (7) IG-3 (7)	ESCAPAC IC-3 IP-3 (7) IG-3 (7)	ESCAPAC IC-3 IP-3 (7) IG-3 (7)	ESCAPAC IC-3 IP-3 (7) IG-3 (7)	ESCAPAC IC-3 IP-3 (7) IG-3 (7)
	YES	YES	YES	YES	YES	YES	NO	YES	YES	YES	NO	YES	YES	YES	YES	YES
	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES
	NO	YES	YES	NO	YES	YES	NO	YES	YES	YES	NO	NO	NO	YES	YES	NO
	PARTIAL PROVISIONS	PARTIAL PROVISIONS	PARTIAL PROVISIONS	PARTIAL PROVISIONS	PARTIAL PROVISIONS	PARTIAL PROVISIONS	SOME PROVISIONS ONLY	COMPLETE PROVISIONS	COMPLETE PROVISIONS	PARTIAL PROVISIONS	PARTIAL PROVISIONS	PARTIAL PROVISIONS	PARTIAL PROVISIONS	COMPLETE PROVISIONS	NO	PARTIAL PROVISIONS
	NO	PROVISIONS ONLY	NO	NO	YES	NO	YES	YES	YES	YES	YES	NO	NO	YES	YES	NO
	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES
	AN/APG-53A	AN/APG-53A	AN/APG-53A	WIRING ONLY	AN/APG-53A	AN/APG-53A	AN/APG-53A	AN/APG-53A PROVISIONS	SHRIKE/WALLEYE PORTION OF AN/APG-53A	AN/APG-145	AN/APG-53A	AN/APG-53A PROVISIONS	AN/APG-53A PROVISIONS	SHRIKE/WALLEYE PORTION OF AN/APG-53A	AN/APG-145 PROVISIONS	AN/APG-53A PROVISIONS
	AN/ASN-41	AN/ASN-41	AN/ASN-41	AN/ASN-41 PROVISIONS	AN/ASN-41	AN/ASN-41	AN/ASN-19A	AN/ASN-41 PROVISIONS	AN/ASN-41 PROVISIONS	AN/ASN-41	AN/ASN-41	AN/ASN-41 PROVISIONS	AN/ASN-41 PROVISIONS	AN/ASN-41 PROVISIONS	AN/ASN-41 PROVISIONS	AN/ASN-41
	AN/ARC-51A AN/ARR-69	DUAL ARC-51A AN/ARR-69	DUAL ARC-51A AN/ARR-69	AN/ARC-51A AN/ARR-69	AN/ARC-115 (VHP-AM) AN/ARR-69	AN/ARC-51A AN/ARR-69	AN/ARC-115 (VHP-AM) AN/ARR-69	AN/ARC-51A AN/ARR-69	AN/ARC-159 AN/ARR-69 AN/ARR-114 (VHP-AM)	DUAL ARC-51A AN/ARR-69	AN/ARC-51A AN/ARR-69	AN/ARC-51A AN/ARR-69	AN/ARC-51A AN/ARR-69	AN/ARC-159 AN/ARR-69 AN/ARR-114	DUAL ARC-51A AN/ARR-69	DUAL ARC-51A
	AN/ARN-52(V)	NO	NO	AN/ARN-52(V) AN/ARN-84	AN/ARN-52(V)	AN/ARN-52(V)	AN/ARN-52(V)	AN/ARN-52(V) AN/ARN-84	AN/ARN-52 AN/ARN-84	NO	PROVISIONS ONLY	PROVISIONS ONLY	PROVISIONS ONLY	AN/ARN-84	NO	NO
	AN/ARA-50	AN/ARA-50	AN/ARA-50	AN/ARA-50	AN/ARA-50	AN/ARA-50	AN/ARA-50	AN/ARA-50	AN/ARA-50	AN/ARA-50	AN/ARA-50	AN/ARA-50	AN/ARA-50	AN/ARA-50	AN/ARA-50	AN/ARA-50
	AN/APN-141	AN/APN-141	AN/APN-141	AN/APN-141	AN/APN-141	AN/APN-141	AN/APN-141	AN/APN-141(6) AN/APN-194(6)	AN/APN-141(6) AN/APN-194(6)	AN/APN-141(6) AN/APN-194(6)	AN/APN-141	AN/APN-141	AN/APN-141	AN/APN-141(6) AN/APN-194(6)	AN/APN-141(6) AN/APN-194(6)	AN/APN-141
	YES	YES	YES	PROVISIONS	YES	YES	NO	PROVISIONS	PROVISIONS	YES	YES	YES	PROVISIONS	PROVISIONS	PROVISIONS	PROVISIONS
	NO	NO	NO	NO	NO	NO	NO	AN/ARA-63 (8)	AN/ARA-63	NO	NO	NO	NO	AN/ARA-63	NO	NO
	AN/APX-64(V)	AN/APX-46	AN/APX-46	AN/APX-64(V) AN/APX-72	AN/APX-72(V)	AN/APX-72(V)	AN/APX-64(V)	AN/APX-72(V)	AN/APX-72(V)	AN/APX-72(V)	AN/APX-64(V)	AN/APX-72(V)	AN/APX-72(V)	AN/APX-72(V)	AN/APX-72(V)	AN/APX-72(V)
	NO	NO	NO	PARTIAL PROVISIONS	NO	NO	PROVISIONS APC-482	PROVISIONS	PROVISIONS	PROV. EXCEPT KIT + SEC	PROVISIONS APC-482	PROVISIONS APC-482	PROV. EXCEPT KIT + SEC	YES	YES EXCEPT KIT + SEC	YES KIT
	NO	NO	NO	NO	NO	NO	NO	NO	NO	PROVISIONS	NO	NO	NO	NO	PROVISIONS	YES KIT
	5	5	5	5	5	5	3	5	5	5	5	3	3	5	5	5
	NO	NO	NO	NO	PROVISIONS	NO	PROVISIONS	PROVISIONS	IMPROVED PROVISIONS	PROVISIONS	PROVISIONS	NO	NO	IMPROVED PROVISIONS	PROVISIONS	NO
	AN/AJB-3A PROVISIONS	AN/AJB-3A PROVISIONS	AN/AJB-3A PROVISIONS	AN/AJB-3A PROVISIONS	AN/AJB-3A PROVISIONS	AN/AJB-3A PROVISIONS	AN/AJB-3A	AN/AJB-3A	AN/AJB-3A	NO	AN/AJB-3A	AN/AJB-3A	AN/AJB-3A	AN/AJB-3A	NO	AN/AJB-3A
	NO	NO	NO	PROVISIONS	PROVISIONS	PROVISIONS	YES	YES	YES	NO	NO	PROVISIONS	PROVISIONS	YES	NO	NO
	NO	NO	NO	NO	NO	NO	YES	YES	YES	NO	NO	NO	NO	YES	NO	NO
	FOUR STATION	FOUR STATION	FOUR STATION	NO	TWO STATION	NO	TWO STATION BY APC-203A	TWO STATION BY APC-509	TWO STATION BY APC-509	FOUR STATION	FOUR STATION	NO	NO	TWO STATION	FOUR STATION	NO
	PROVISIONS	NO	NO	NO	PROVISIONS	PROVISIONS	PROVISIONS	PROVISIONS	YES	PROVISIONS	PROVISIONS	PROVISIONS	PROVISIONS	NO	PROVISIONS	PARTIAL PROVISIONS
	NO	NO	NO	NO	NO	NO	PROVISIONS	YES	YES	NO	PROVISIONS	PROVISIONS	PROVISIONS	YES	NO	NO
	NO	NO	NO	NO	NO	NO	YES	YES	YES	NO	PROVISIONS	NO	NO	YES	NO	NO
	PROV. EXP-2005 DATA PKG.	NO	NO	PROVISIONS	PROVISIONS	PROVISIONS	YES	YES	YES	YES	YES	PROVISIONS	PROVISIONS	YES	YES	PARTIAL PROVISIONS
	NO	NO	NO	NO	NO	NO	PROVISIONS	PROVISIONS	PROVISIONS	PROVISIONS	PROVISIONS	NO	NO	PROVISIONS	PROVISIONS	NO
	20 MH 200 RDS	20MH/200RDS 30MH/300RDS	20 MH 200 RDS	20 MH 200 RDS	20 MH 200 RDS	20 MH 200 RDS	20 MH 200 RDS	20 MH 400 RDS	20 MH 400 RDS	30 MH 300 RDS	20 MH 200 RDS	20 MH 200 RDS	20 MH 200 RDS	20 MH 400 RDS	30 MH 300 RDS	20 MH 200 RDS
	NO	NO	NO	NO	NO	NO	NO	NO	NO	VDS & HUD	NO	NO	NO	HUD ONLY	VDS & HUD	NO
	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	PROVISIONS	NO	NO
	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	PROVISIONS	NO	NO

(4) APC-509 A-4H SIDEWINDER KITS TO BE MANUFACTURED BY NAMP, PUNLA.

(5) CONTRACTOR EQUIVALENT (CPE) INSTALLED.

(6) EITHER AN/APN-141 OR AN/APN-194 TESTED.

(7) APC-489 IP-3/ACC-256 IC-3.

(8) APC-463 AN/

TABLE G-1. EVOLUTION OF THE A-4 AIRCRAFT AND ITS SUBSYSTEMS

1974-1975

	TA-4B/R	TA-4J/R	A-4H PT-74	A-4H PT-74	TA-4J/R PT-74	A-4H PT-74 (SUPP)	A-4H PT-75	A-4EU	TA-4EU
WT	J52-P-88	J52-P-88	J52-P-408	J52-P-408	J52-P-88	J52-P-408	J52-P-408	J52-P-408	J52-P-408
WGT	9,300 #	9,300 #	11,200 #	11,200 #	9,300 #	11,200 #	11,200 #	11,200 #	11,200 #
FUEL	4,488 LBS 660 GAL	4,488 LBS 660 GAL	5,400 LBS 800 GAL	5,400 LBS 800 GAL	4,488 LBS 660 GAL	5,400 LBS 800 GAL	5,400 LBS 800 GAL	5,400 LBS 800 GAL	4,488 660
	NO	NO	YES	NO	NO	YES	NO	PROV. ONLY	PROV. ONLY
	YES	YES	YES	YES	YES	YES	YES	YES	YES
	YES	YES	YES	YES	YES	YES	YES	YES	YES
	NO	NO	YES	YES	NO	YES	YES	YES	YES
	PROVISIONS	PROVISIONS	PROVISIONS	NO	PROVISIONS	PROVISIONS	NO	NO	NO
FUEL	10 LITER	10 LITER	10 LITER	10 LITER	10 LITER	10 LITER	10 LITER	10 LITER	10 LITER
ESCAPAC	ESCAPAC IC-3 IP-3 (7) IO-3 (7)	ESCAPAC IC-3 IP-3 (7) IO-3 (7)	ESCAPAC IC-3	ESCAPAC IC-3	ESCAPAC IC-3	ESCAPAC IC-3	ESCAPAC IC-3	ESCAPAC IC-3	ESCAPAC IC-3
	YES	YES	YES	YES	YES	YES	YES	YES	YES
	YES	YES	YES	YES	YES	YES	YES	YES	YES
	NO	NO	YES	YES	YES	YES	YES	YES	YES
PROVISIONS	PARTIAL PROVISIONS	PARTIAL PROVISIONS	COMPLETE PROVISIONS	NO	PARTIAL PROVISIONS	COMPLETE PROVISIONS	NO	NO	NO
	NO	NO	YES	YES	NO	YES	YES	YES	YES
	YES	YES	YES	YES	YES	YES	YES	YES	YES
AN/APG-53A	AN/APG-53A PROVISIONS	AN/APG-53A PROVISIONS	SHRIKE/MALLETE PORTION OF AN/APG-53A	AN/APG-145 PROVISIONS	AN/APG-53A PROVISIONS	SHRIKE/MALLETE PORTION OF AN/APG-53A	AN/APG-145	AN/APG-145	AN/APG-145
AN/ASN-41	AN/ASN-41 PROVISIONS	AN/ASN-41 PROVISIONS	AN/ASN-41 PROVISIONS	AN/ASN-41	AN/ASN-41	AN/ASN-41 PROVISIONS	AN/ASN-41	SEE WDNS BELOW	SEE WDNS BELOW
AN/ARC-51A	AN/ARC-51A AN/ARR-69	AN/ARC-51A AN/ARR-69	AN/ARC-159 AN/ARR-69 AN/ARR-114	DUAL ARC-51A AN/ARR-69	DUAL ARC-51A AN/ARR-69	AN/ARC-159 AN/ARR-69 AN/ARR-114	DUAL ARC-51A AN/ARR-69	DUAL ARC-159 ARC-115 VHP (5) ARC-114 VHP HP R/T	DUAL ARC-159 ARC-115 VHP (5) ARC-114 VHP HP R/T
PROVISIONS	PROVISIONS ONLY	PROVISIONS ONLY	AN/ARR-84	NO	NO	AN/ARR-84	NO	AN/ARR-84	AN/ARR-84
AN/ARA-50	AN/ARA-50	AN/ARA-50	AN/ARA-50	AN/ARA-50	AN/ARA-50	AN/ARA-50	AN/ARA-50	AN/ARA-50	AN/ARA-50
AN/APN-141	AN/APN-141	AN/APN-141(6) AN/APN-194(6)	AN/APN-141(6) AN/APN-194(6)	AN/APN-141(6) AN/APN-194(6)	AN/APN-141(6) AN/APN-194(6)	AN/APN-141(6) AN/APN-194(6)	AN/APN-141(6) AN/APN-194(6)	AN/APN-141(6) AN/APN-194(6)	AN/APN-141(6) AN/APN-194(6)
	YES	PROVISIONS	PROVISIONS	PROVISIONS	PROVISIONS	PROVISIONS	PROVISIONS	NO	NO
	NO	NO	AN/ARA-63	NO	NO	AN/ARA-63	NO	YES	YES
AN/APX-72(V)	AN/APX-72(V)	AN/APX-72(V)	AN/APX-72(V)	AN/APX-72(V)	AN/APX-72(V)	AN/APX-72(V)	AN/APX-72(V)	AN/APX-72(V)	AN/APX-72(V)
PROVISIONS	PROVISIONS APG-482	PROV. EXCEPT KIT & SEC	YES	YES EXCEPT KIT & SEC	YES EXCEPT KIT & SEC	YES	YES EXCEPT KIT & SEC	YES EXCEPT KIT & SEC	YES EXCEPT KIT & SEC
	NO	NO	NO	PROVISIONS	NO	NO	PROVISIONS	YES	YES
	5	3	5	5	5	5	5	5	5
PROVISIONS	NO	NO	IMPROVED PROVISIONS	PROVISIONS	NO	IMPROVED PROVISIONS	PROVISIONS	PARTIAL PROVISIONS	PARTIAL PROVISIONS
AN/LTB-3A	AN/LTB-3A	AN/LTB-3	NO	AN/LTB-3	AN/LTB-3	NO	NO	NO	NO
PROVISIONS	PROVISIONS	YES	NO	NO	YES	NO	NO	NO	NO
	NO	NO	YES	NO	NO	YES	NO	NO	NO
NO	NO	TWO STATION	FOUR STATION	NO	TWO STATION	FOUR STATION	FOUR STATION	FOUR STATION	FOUR STATION
PROVISIONS	PROVISIONS	NO	PROVISIONS	PARTIAL PROVISIONS	NO	PROVISIONS	NO	NO	NO
PROVISIONS	PROVISIONS	YES	NO	NO	YES	NO	NO	NO	NO
NO	NO	YES	NO	NO	YES	NO	NO	NO	NO
PROVISIONS	PROVISIONS	YES	YES	PARTIAL PROVISIONS	YES	YES	NO	NO	NO
NO	NO	PROVISIONS	PROVISIONS	NO	PROVISIONS	PROVISIONS	PROVISIONS	PROVISIONS	PROVISIONS
NO	20 MH 200 RDS	20 MH 200 RDS	20 MH 400 RDS	30 MH 300 RDS	20 MH 200 RDS	20 MH 400 RDS	30 MH 300 RDS	20 MH 400 RDS	20 MH 400 RDS
NO	NO	NO	HUD ONLY	VDS & HUD	NO	HUD ONLY	VDS & HUD	VDS & HUD	VDS & HUD
NO	NO	NO	PROVISIONS	NO	NO	PROVISIONS	NO	NO	NO
NO	NO	NO	PROVISIONS	NO	NO	PROVISIONS	NO	NO	NO

TOTALLED.

(7) APC-489 IP-3/ACC-256 IC-3.

(8) APC-463 AN/ARA-63.

G-5/G-6

C1-788
REVISED 4/75

though escape systems are well developed and different models may use some common elements, a development and qualification program is needed for each system, because the systems are tailored to each aircraft type.

B. Angle Rate Bombing System (ARBS)

The ARBS (Addendum 1) originated as a specific solution to the problem of the A-4 not having a satisfactory air-ground weapon delivery system. The Navy had been pressuring the Marine Corps to adopt the A-7 airplane, instead of modifying the A-4. But the Marine Corps could not support the A-7 system, because of its cost. Through modification of the A-4 airframe, visibility was increased, and performance was improved by installing a new engine. The Marines also wanted to add a new weapon delivery system that would provide good delivery accuracy.

To develop this new system, the Marine Corps funded a development program at NOTS, China Lake. Feasibility testing of the new system occurred in the early 1970s, and a flyoff between two contractors, Martin and Hughes, was held. Hughes won the development contract. But further demonstration is planned to show performance and reliability. The hardware for the next demonstration is to be available in 1977, after which full-scale development will start. The IOC, however, is not expected for several years. In contrast with the ARBS development program of the Marine Corps, which will take from seven to nine years, McDonnell Douglas claims to have developed, in two years, an equivalent system for the Israeli Air Force. The Navy has shown little interest in expediting the Marine Corps ARBS development, since it regards it as benefitting only the Marine Corps.

Nevertheless, the general bombing system that will result from the development program could also be used in other aircraft, such as the AV-8A and the A-10. However, each of these

aircraft, would have to use a buffer to provide an interface between the equipment and the sensors, since each aircraft has different sensors. A new "heads-up" display would also be needed. Thus, although there is some potential for commonality, additional development would be needed to realize this potential.

The case of the ARBS illustrates how interservice politics can influence technological developments. It also illustrates how a lack of interface standardization imposes additional buffer equipment requirements, thereby inhibiting the potential common use of equipment, such as the ARBS.

C. Engines

Pratt & Whitney proposed to McDonnell Douglas an upgrading of the J52 engine for the A-4. The proposal was a result of a direct request from Grumman in 1968 for more power for the EA6B. Pratt & Whitney wanted to enlist Douglas to broaden the customer base. At that time, the Navy was thinking about cutting out the A-4 program, but the Marine Corps decided to buy the A-4M with a new engine; then Grumman backed away from their request.

III. F-15 AIRCRAFT--MCDONNELL DOUGLAS (Mac-Air)

The F-15 is the outgrowth of years of studies, beginning with followons for the F-100 and continuing through the F-X. Most of the avionics equipment in the F-15 was CFE, except the IFF. The Air Force specified the performance requirements, although the final contract specified certain equipment; for example, in the case of the ARC-109 radio, Mac-Air wrote the specifications and then requested bids, looking in particular for equipment already in production. The evaluation procedure considered costs, but a low bid was not the only criterion. Except for the radar and inertial navigation systems, fixed-price bids were sought. The radar and the inertial navigation

systems (INS) were CPFIF. In these instances, Mac-Air tried to get equipment that was available within state of the art and not beyond it. However, in the case of the INS, the size and weight were beyond the state of the art, but not performance. Mac-Air designed the interfaces for the avionics. It believes that the computer, which processes data from the subsystem, should be a part of the subsystem; for example, the radar, INS, or ADC should each have its own computer, and a central computer should be avoided.

The F-15 radar program started two years before the F-15, using requirements generated in previous studies (e.g., F-X). These included a threat study, mission study, and a requirement for one-man operability. There were also weight restrictions for the prototype. The dish size and antenna type were specified. The "look-down" requirement meant that the side lobes had to be small. Two flying prototypes were contracted for and were flown on a B-66. Under the F-15 contract, Mac-Air decided upon the winner of the flyoff.

In the F-X program, a new gun was specified. Philco and GE both developed guns and ammunition, using a caseless ammunition concept. Then, a vulnerability problem developed with respect to the ammunition. The aircraft, in effect, was sitting on a bomb. The Air Force program manager decreed that the gun development program would be canceled, if the problem was not worked out and if the developed gun was not available for installation on the 176th F-15. Philco was selected to complete the gun program, although it had done a poor job with the M-39 gun. Mac-Air's viewpoint is that the program was ill conceived. It believes that guns should be GFE, common to other aircraft. The GAU-7 program, tied to a particular aircraft, was a mistake. (see appendix D)

Examples that are given to illustrate the role of IR&D in developing systems and components for the F-15 make a reasonable

case for the IR&D work being focused by application and for the prime contractor being in a good position to assign priorities to applications and problems. There was a requirement from the SPO that undemonstrated hardware could not be put into the F-15; therefore, it was to Mac-Air's advantage to seek contracts for hardware demonstrations.

IV. F-5/F-17/F-18--AIRCRAFT-NORTHROP

In Northrop designed aircraft, the subsystems are tailored specifically to the aircraft. Consequently, in the case of the F-5, it was necessary to repackage the outside procured escape system, which then had to be requalified. The Martin Baker seat for Iranian aircraft had to be modified to fit the F-5. In the case of armament, the racks are GFE. The MAU40 had a special weapons' capability that was not needed. The MAU50 was developed for the F-5 (14-in. spaces and 1000-lb store capability). The MAU40 was centerline mounted; the MAU50 was pylon mounted. The AIM-9 launcher on the wing tip was CFE. The standard launcher would not fit, and a new shell had to be developed. Northrop will develop new launchers, with a contract to Hughes, because the Government could not provide them on schedule. Northrop claims that slow Government response is the main reason why initial procurement goes CFE.

The NORSIGHT fire control system (FCS) was developed in-house with company funds. It was later licensed to Chicago Aerial Industries. Besides being used on the F-5/A/B, it was also used on the A-9 and A-10 aircraft. The FCS for the F-5E was developed especially by Emerson, the subcontractor, with radar systems components derived from the B-52 tail gun radar. The antenna, however, was tailored to the aircraft. The lead computing sight was developed specifically by GE for the F-5E, and was also used on the F-4E. The laser designator for the F-5 is a repackaged "Pave Way" from the F-4.

The T-38/F-5 aircraft are the antecedents of the F-17/F-18. Tables G-2, G-3, G-4, and G-5 show the selection evolution of the fire control system, electrical system, escape system, and the engine. Table G-6 shows the evolution of weapons capability, and Table G-7 gives weapons store station capacity.

The J85 engine was developed for the Quail missile and later man-rated. The F-5 influenced the J85 program, and IRAD funds were used to increase engine thrust.

The Air Force wanted to use the Air Force-developed but unproven ACES seat in the F-17. Northrop resisted and held fast for the proven Stancel seat. The Air Force proposed that the ACES be used in the F-16, but General Dynamics chose the Stancel seat, so the ACES seat is still an orphan development.

Bendix built an Air Force-developed lightweight, high performance air data computer. Four items were delivered to the Air Force and two of them were used by the YF-17 program.

In 1974, the air combat fighter (ACF) had, as prospective suppliers for inertial navigation systems, Singer, Litton, and Delco. The Litton system was the most advanced, but did not use proven technology. General Electric selected the Singer SKN2400. Again, the tradeoff between risk and performance was settled in favor to low risk. (This raises a question of what "off-the-shelf" means?) For the YF-17, Rockwell built a special radar with range and range rate--gunnery radar, a derivative of a Navy gunboat radar.

Aircraft contractors are reluctant to let anything change the external shape of an aircraft and generally with good reason. For example, putting in the M-61 gun deepened the F-17 fuselage and, consequently, reduced the directional stability with angle of attack. Strakes had to be added to improve the stability. The fuselage change could have been avoided by modifying the ammunition drum and making it smaller. But Northrop did not want to modify the proven gun system at this

TABLE G-2. GROWTH OF T-38/F-5 FIRE CONTROL SYSTEM

<u>Aircraft Model</u>	<u>Fire Control System</u>	<u>Remarks</u>
T-38A	None	No armament capability
N156F	AN/ASG-20 radar AN/AAR-18 I/R search Mark I bomb director system Optical sight Missile release computer	Range only radar Fixed sight
F-5A/B	NORSIGHT	Unstabilized manual depressed (iron) sight
CF-5A	LCOSS	Feranti ISIS-N LCOSS 1st-order linear predictor-A/A guns A/G bunt delivery
F-5E/F	AN/APQ-153/APQ-157 Fire Control Radar AN/ASG-29 LCOSS	A/A search, boresight steering and ranging radar A/A gunnery - manual and nonmanual target modes D/F mode A/A guns A/A missile mode A/G manual depressed, roll stabilized recticle
F-5E/F Saudi Improvement	AN/APG-153 (mod)/APQ-157 (mod) FCR AN/ASG-29 (mod) LCOSS	Additions: Flat plate antenna Frequency agility Angle tracking CRT/DSC for Maverick Missile dogfight mode 40 mile A/A scale Off-boresight acquisition Pipper slaving

TABLE G-3. GROWTH OF T-38/F-5 ELECTRICAL SYSTEM

<u>Aircraft Model</u>	<u>Generator System Capacity</u>	<u>Prime Mover Source</u>
T-38A	115/200 v, 320 to 480 Hz, 3 phase, 8-10 kva 2 generators per A/C	NAD-designed 2-speed gearbox Prime moved by the engine
N-156F	115/200 v, 320 to 480 Hz, 3 phase, 8-10 kva 2 generators per A/C	NAD-designed 2-speed gearbox Prime moved by the engine
F-5A/B	115/200 v, 320 to 480 Hz, 3 phase, 8-10 kva 2 generators per A/C	NAD-designed 2-speed gearbox Prime moved by the engine
CF5A/D	115/200 v, 3 phase, 400 Hz, 15 kva, 2 generators per A/C	Sunstrand CSD prime moved by the engine
NF5A/B	115/200 v, 3 phase, 400 Hz, 15 kva, 2 generators per A/C	Sunstrand CSD prime moved by the engine
F-5E/F	115/200 v, 3 phase, 320 to 480 Hz, 13-15 kva, 2 generators per A/C	NAD-designed 2-speed gearbox Prime moved by the engine

TABLE G-4. GROWTH OF T-38/F-5 ESCAPE SYSTEM

<u>Aircraft Model</u>	<u>Configuration</u>	<u>Remarks</u>
T-38	<u>Northrop Seat</u> <ul style="list-style-type: none"> • M-5 catapult • 28-ft, C-9 parachute • Powered seat/man strap separator • Arm, leg, and calf supports • Automatic sequencing 	Escape envelope limited, since M-5 catapult did not incorporate any rocket thrust. High speed limited by tail clearance (A/C later retrofitted with M-9 rockets). Envelope: 120 knots minimum @ zero Altitude. Limited high speed.
T-38 N-156F F-5A/B	<u>Northrop Seat</u> Same as above, except M-9 rocket/catapult	Rocket sustainer provides increased escape envelope and tail clearance. Envelope: 120 knots minimum @ zero altitude up to 600 knots.
F-5E (Basic)	<u>Northrop Seat</u> Same as above except M-38 rocket/catapult	<ul style="list-style-type: none"> • Adjustable thrust vector provides seat stabilization, reducing seat pitch rotation. • Increased catapult thrust, resulting in higher aircraft separation velocity. Envelope: 120 knots minimum @ zero altitude up to 600 knots.
F-5E/F (Iran)	<u>Martin Baker Seat - MK-IRQ-7A</u> <ul style="list-style-type: none"> • Separate rocket and catapult • Drogue chute (stabilization, deceleration, and separation) • Powered inertial reel • 24-ft parachute with antisquid • Leg strap restraint 	<u>Escape envelope:</u> <ul style="list-style-type: none"> • Zero speed at zero altitude up to 600 knots. • Chute canopy full inflation at 150 knots = 3.5 sec.
F-5E/F Saudi Arabia & F-5E USAF	<u>Northrop Improved Seat</u> <ul style="list-style-type: none"> • M-38 rocket catapult • Drogue chute (stabilization, deceleration, and separation) • 28-ft parachute, with ballistic spreader (or pull-down vent) • Faster automatic sequence, resulting in faster chute inflation. 	<ul style="list-style-type: none"> • 50 knots at zero altitude up to 550 knots • Seat stabilized with drogue @ catapult burnout • Chute canopy full inflation at 150 knots = 3.1 sec.

TABLE G-5. GROWTH OF T-38/F-5 ENGINE

<u>Aircraft Model</u>	<u>Engine Design</u>	<u>Thrust Level Military/Maximum, lb</u>	<u>Engine and Airframe Installation Changes</u>
T-38	J-85-9E-5	2680/3850	Basic
N-156F	YJ85-9E-13	2720/4080	New Supersonic inlet
F-5A/B	J85-9E-13	2720/4080	Same as above
GF-5/NF-5	J85-9E-15	2925/4300	Added auxiliary T.O. doors
F-5E/F	J85-9E-21	3500/5000	Increased induction system size
F-5B Saudi Arabia	J-85-9E-13	2720/4080	Added auxiliary T.O. doors

TABLE G-6. GROWTH OF T-38/F-5 WEAPONS CAPABILITY

<u>Aircraft Model</u>	<u>Store Stations</u>	<u>Guns</u>	<u>Missiles</u>	<u>Fire Control System</u>
T-38	1 CL pod	-	-	
N-156F	3 Pylons 2 Wing tips	Two 50-caliber M-3 gun pods (wing pylons)	2 AIM-9s	NORSIGHT
F-5A/B	5 Pylons 2 Wing tips	Two 20-mm M-39s (F-5A only)	2 AIM-9s 4 AGM-12Bs (Bullpup)	NORSIGHT
NF-5A	5 Pylons 2 Wing tips	Two 20-mm M-39s	2 AIM-9s 4 AGM-12Bs (Bullpup)	NORSIGHT ARW-77 missile radio control
F-5E/F	5 Pylons 2 Wing tips	Two 20-mm M-39s One 20-mm M-39(F)	2 AIM-9s	Fire control Radar Lead computing sight
F-5 Saudi Arabia	5 Pylons 2 Wing tips	Two 20-mm M-39s One 20-mm M-39(F)	2 AIM-9s 4 AGM-65As (Maverick)	Improved Radar Lead Computing sight Laser designator (F-5F)

TABLE G-7. GROWTH OF T-38/F-5 WEAPONS STORE STATION CAPACITY (1b class)

<u>Aircraft Model</u>	<u>Wing Tip</u>	<u>Outboard</u>	<u>Inboard</u>	<u>Centerline</u>
T-38		-	-	500 (luggage pod)
N-156F	450	-	1000	2000
F-5A/B	450	750	1000	2000
NF-5A	450	750	1000 2000*	2000
F-5E/F	450	1000	2100	3000
F-5 Saudi	450	1000	2100	3000

* At reduced load factor for 275-gallon tanks

point. Also, the accessory gear box and the afterburner are tailored to fit the shape of the F-17 aircraft, although the basic engine is designed to meet the aircraft performance requirements.

ADDENDUM 1

(Appendix G)

THE ANGLE RATE BOMBING SYSTEM

The Angle Rate Bombing System (ARBS) is an improved weapon delivery system. It consists of a dual-mode sensor/tracker, a head-up display for the pilot, and a digital computer for weapon release computation. The dual modes of the sensor/tracker are TV and laser spot tracking.

Bombing systems for attack aircraft that use unguided weapons require the accurate determination of weapon release conditions, together with a means for presenting this information to the pilot.

Early bombing systems used the aircraft fixed sight. Later improvements used sensor inputs, e.g., air speed, barometric altitude, and radar range.

Recently developed advanced systems use doppler-inertial velocity measurements obtained from the aircraft inertial platform, e.g., A-7E. These technological advances bring with them additional cost and complexity.

Developments in air-ground tracking systems permit their application to the tactical bombing problem. The basic idea is to provide the weapon delivery computer with target line-of-sight angles and angular rates. These measurements are obtainable from a gyro-stabilized tracking head, which locks on to a target and tracks it. The computer also requires inputs of aircraft attitude, true air speed or ground speed, and weapon ballistic characteristics. The tracker can use a TV system or a laser spot tracker and laser target designator.

In FY65, the Naval Weapons Center (NWC) began preliminary studies of an ARBS. The experimental development led to hardware that was based on a gyrostabilized TV tracker, which could be carried externally on an A-4 at the center station.

This program was developed independently of prior angle rate bombing systems (e.g., Trim, Shed-light), which were designed for level flight tactical bombing.

Flight tests with the two-axis tracker revealed problems in tracker performance and stability. Analyses indicated that these problems could be fixed by providing roll stabilization (i.e., a 3-axis tracker). The 3-axis tracker study and development continued through FY69. In FY70 the work on designing, testing, and evaluating two prototype 3-axis TV trackers was continued. Flight testing and system definition work was started, and in FY71 the NWC conducted a program to demonstrate technical feasibility and tactical utility of ARBS for naval aircraft. (This system differs from the previous angle rate systems in that it is designed for single-seat aircraft (i.e., the pilot uses it), and the aircraft can be maneuvering or jinking while attacking.

In FY72, NAVAIR was directed by OPNAV to stop funding the ARBS development. There was no "home" for the system and no Navy funds were available. The Air Force Avionics Laboratory funded the program during this period and kept the advanced development program alive.

In FY73, the USMC entered the picture, and tradeoff studies were initiated leading to an engineering development program with Navy funding resumed. OPNAV directed that the ARBS be usable in the HARRIER and the AX although the A-4 was still the first priority. Prototype systems were developed and flight tested through FY75, ending with a source selection, based on a flyoff, in early FY75.

The ARBS requirements included

- Laser target designator system (LTDS) compatibility
- Accuracy of 10 mil or better for unguided ordnance
- Dual mode, e.g.:
 - Day-visual
 - Night-laser designator
- Backup delivery modes, e.g., fixed sight
- Maximum use of off-the-shelf items.

Hughes Aircraft won the flyoff competition against the Martin Company, and it will build nine systems. The timetable for the ARBS program with Hughes is:

April 1975	Contract with Hughes signed
September 1975	Design review
March 1976	First test item due
August 1976	First A4-M test
November 1976	T&E
Date deleted	Release to production
Date deleted	First production items due

The analysis of the ARBS leads us to these observations:

- The Navy was aware that the ARBS could be used in several different aircraft, and it required that multi-aircraft-use considerations be included in the engineering development.
- The procurement of the A4-M and the development of ARBS for the A4-M by the USMC were in direct conflict with the Navy's interest in reducing the unit cost of its A-7s by increasing the A-7 production run.
- The ARBS flyoff competition and the lengthy development program were a consequence of the differing interests of the Navy and the Marine Corps. In effect,

the flyoff demonstration was a compromise, and the program was able to continue in advanced development without a commitment for implementation.

- Although the program has suffered delays in reaching the production stage, it is not clear that this was harmful. The equipment will be extensively tested prior to release to production.
- The ARBS was an independent development. It entered engineering development with a "home" in the Marine Corps A4-M, and with a specific directive that it be suitable for use in AX and Harrier.
- From its beginning to the delivery of production hardware, the ARBS program will have spanned many years. In contrast, the Israeli A4-Ns were supplied with a Lear-Siegler weapon delivery system, in which the radar and inertial components were developed in a 2-year program by using concurrent development and production.

APPENDIX H

FIGHTER AIRCRAFT ENGINES

APPENDIX H

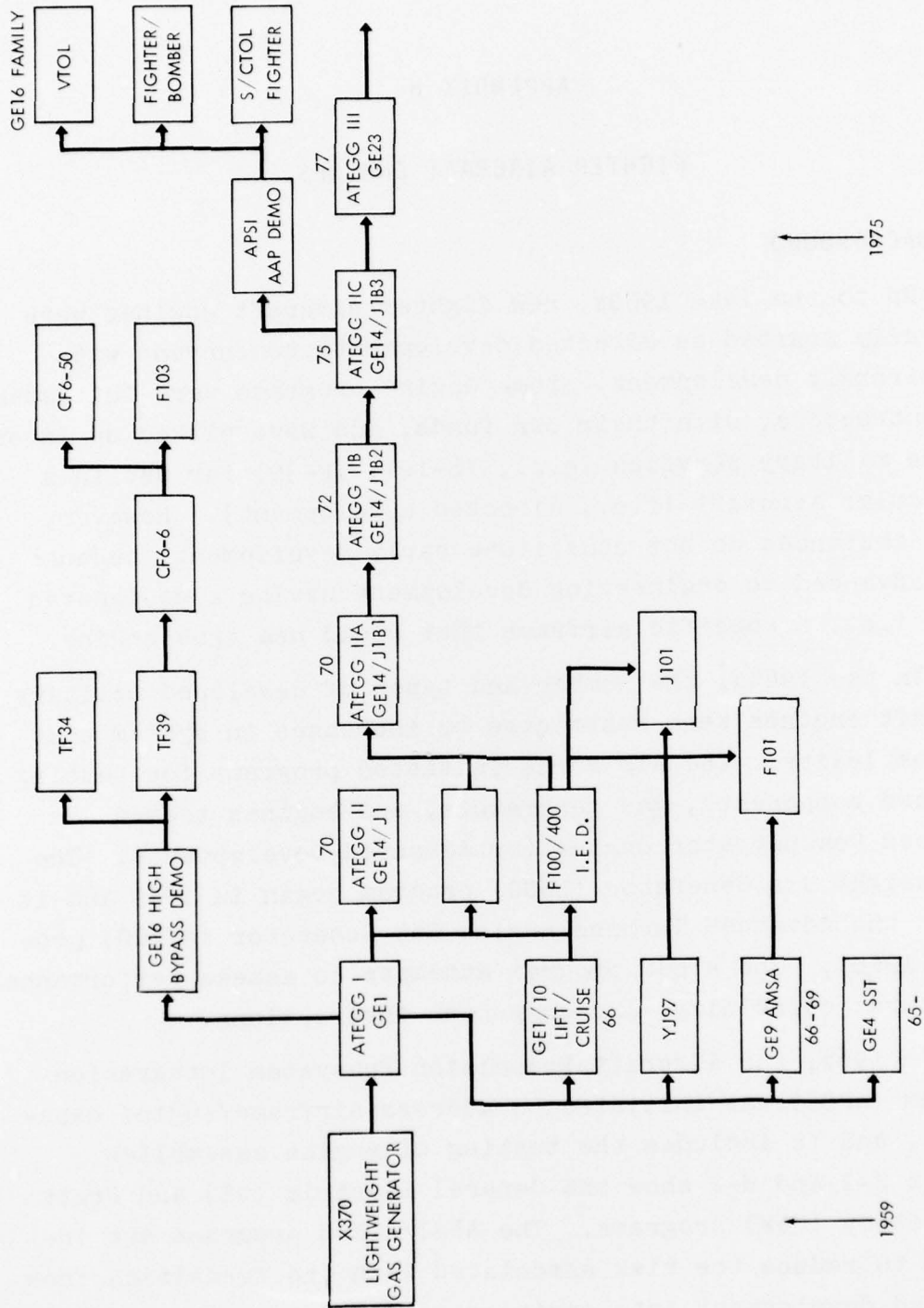
FIGHTER AIRCRAFT ENGINES

I. BACKGROUND

Up to the late 1950s, new fighter aircraft engines were generally started as directed developments concurrent with new aircraft development. Some engine programs were initiated by contractors, with their own funds, and were picked up later by the military services (e.g., YS-101, TF-30) for use in a particular aircraft (i.e., directed development). However, these instances do not constitute early development, because they advanced to engineering development having a designated home, i.e., a specific airframe that would use that engine.

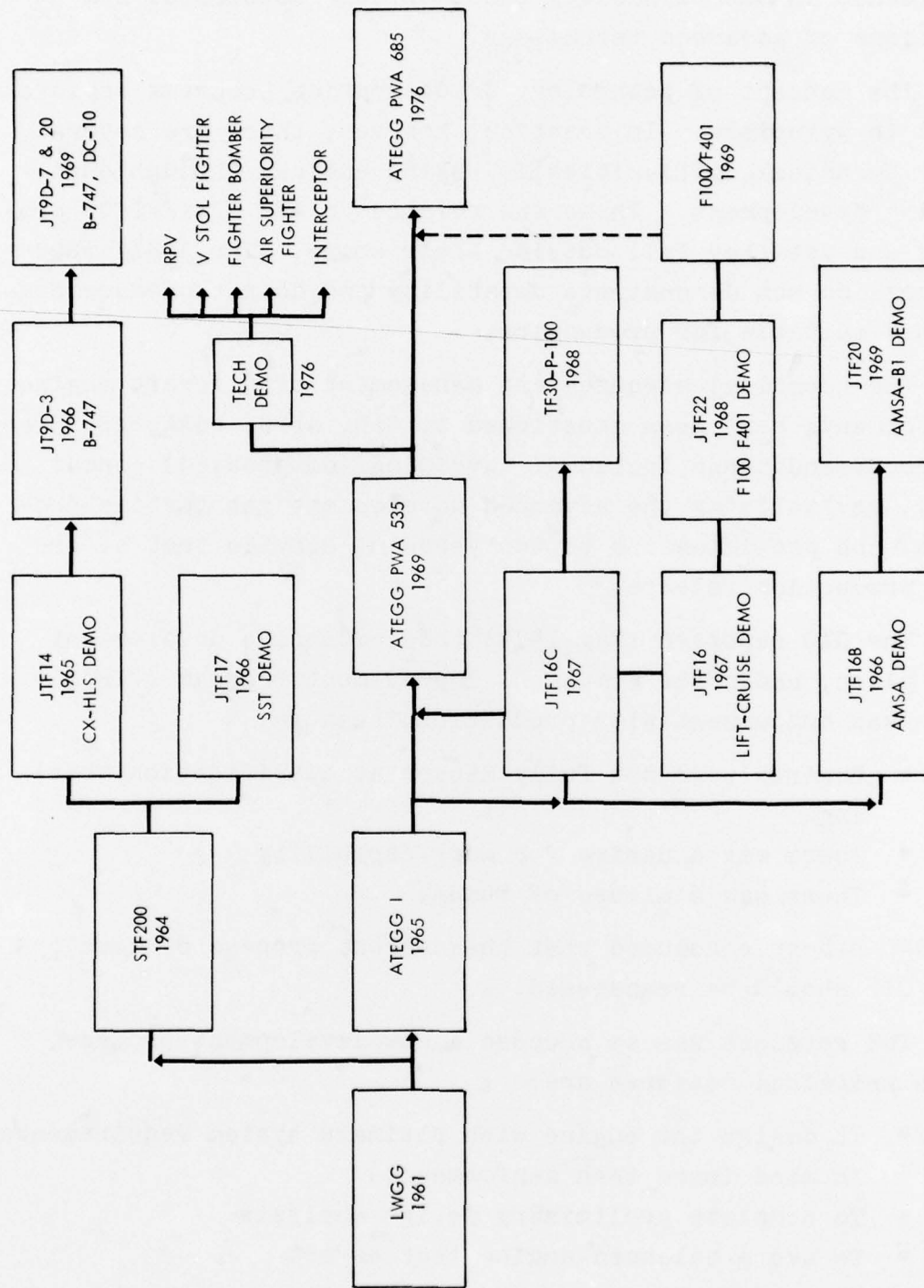
In the 1960s, the number and types of developed military aircraft engines were restricted by increases in system cost and complexity. The Air Force initiated programs for testing advanced components, gas generators, and engines termed Advanced Demonstrator engines or Advanced Developments. The Lightweight Gas Generator (LWGG) program began in 1959 and it led to the Advanced Turbine Engine Gas Generator (ATEGG) program (1965). The ATEGG program attempts to assess performance, structural capability, and component interactions.

In 1968, the Aircraft Propulsion Subsystem Integration Program (APSI) was initiated to address airframe/engine capability, and it includes the testing of engine assemblies. Figures H-1 and H-2 show the General Electric (GE) and Pratt and Whitney (P&W) programs. The APSI/ATEGG programs are intended to reduce the risk associated with the transition from advanced development into engineering development. A goal of the APSI/ATEGG concept was to give industry and the Government



Source: ASD Aeropropulsion Laboratory.
3-22-76-16

FIGURE H-1. General Electric ATEGG Family Tree



Source: ASD Aero-propulsion Laboratory.
3-22-76-17

FIGURE H-2. Pratt and Whitney Advanced Engine Programs - Technology Transfer

confidence in the technology base, through successful demonstrations of advanced technology.

The concept of technology demonstration programs appears sound in principle. In practice, however, there are several major technical difficulties in taking engines through engineering development. These are related to the APSI/ATEGG programs and yet they fall outside their scope. The APSI/ATEGG programs do not demonstrate durability and do not produce components suitable for production.

The technical adequacy and management of aircraft engine developments have been questioned by GAO, AFLC, USAF/SAB. The SAB recommendations included: avoiding (compressed) concurrency, revitalizing the advanced development gas turbine programs, and providing one to two years of service test before full production release.

The GAO reported (May 1974) that extensive development took place, under the Component Improvement Program (CIP), which was concurrent with production, because:

- Engines were not fully mature at qualification testing
- There was a desire for more capability
- There was a misuse of funds.

The GAO report concluded that the current process of development/CIP should be reassessed.

The response was to propose a new development process, whose principal features are:

- To design the engine with ultimate system requirements in mind (more than performance)
- To complete preliminary design analysis
- To use a balanced engine test effort
- To conduct mission usage related endurance tests

- To give a full flight-envelope aeromechanical demonstration
- To demonstrate TBO/MOT
- To demonstrate the life limit
- To give a comprehensive logistic demonstration
- To give a performance and stability demonstration.

The ASD phases of the new and current development processes for engines and airframes are illustrated in Figs. H-3 and H-4. A Navy version of an idealized engine development process is given in Fig. H-5.

II. F-401 EXAMPLE

One of the most important examples of a program that was hurt by technical failures is the engine development for the F-14B. In 1968, the FX program office, which was working towards a new Air Force fighter, awarded competitive contracts for \$50 million each to P&W and GE. Each company was to build two prototype engines: one for Air Force application and the other for the Navy for the F-14B. The Air Force engine was designated the F-100 and the Navy engine was called F-401. The engines for the Air Force and the Navy F-14B were to be developed under a joint program and were to use a common gas generator. The fans and turbines were to be specially tailored to suit the F-15 and F-14B requirements.

The competition was won by P&W. The P&W prototype engines were designs that were based on J-58 and JT-9D technology, i.e., compressor JT-9D, variable inlet J-58, and turbine J-58. The exhaust nozzles and controls were new. A lightweight design was required, and the design thrust/weight (T/W) was to be 7, an increase from the T/W of 4 for previous engines.

In each case, technical problems appeared, and the engines did not reach their original specification goal for performance and durability. In the case of the F-100 engine for the F-15,

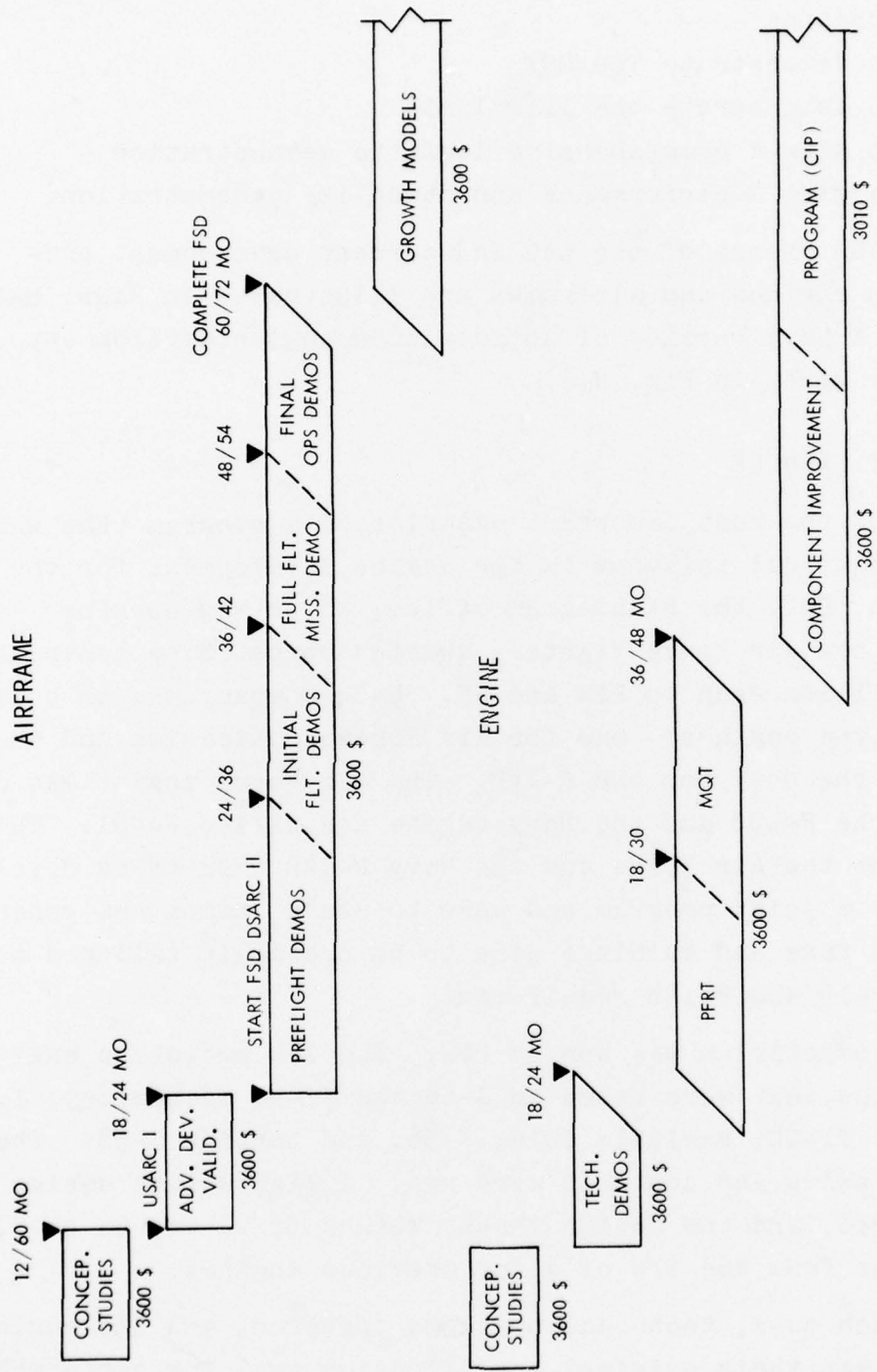


FIGURE H-3. Current Development Process (ASD Phases)

Source: ASD Aero-propulsion Laboratory.
3-22-76-18

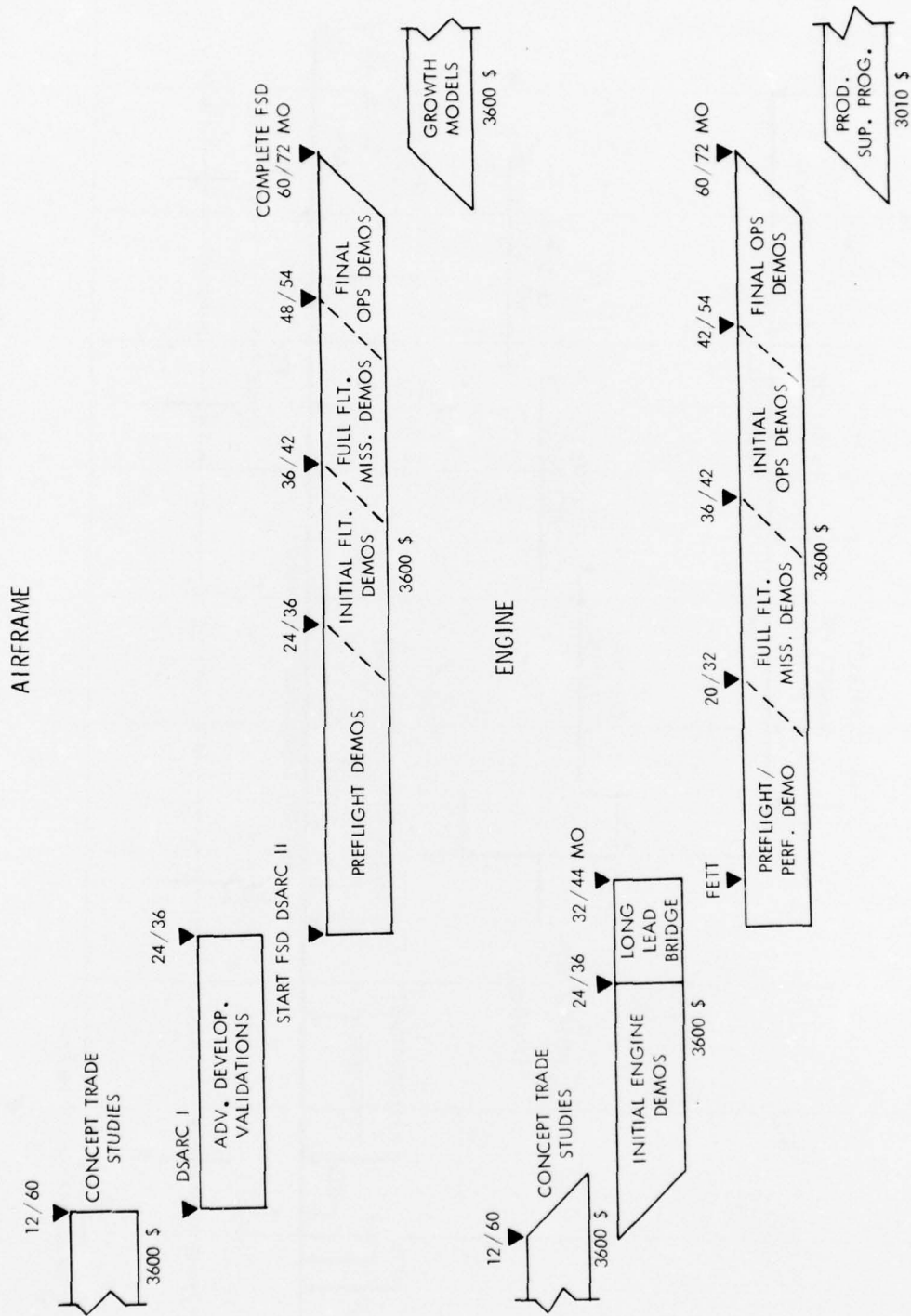


FIGURE H-4. New Development Process (ASD Phases)

Source: ASD Aeropropulsion Laboratory.
9-22-76-19

the requirements were slightly relaxed, and time and resources were made available to complete the development. In the case of the F-401 engine (F-14B), the performance of the engine (and, therefore, the F-14B) could not be reduced because of the possible loss of program support by Congress. The existence of a backup system, i.e., the TF-30 engine and the F-14A, served to reduce the sense of urgency regarding the F-401, because Fleet Air Defense could be maintained with the F-14A and Phoenix weapon system.

The F-14B program was cancelled, due to a combination of cost escalations and engine difficulties. The Navy subsequently conducted a review of the F-401 engine development at the request of Admiral Hopkins (AIR-93).

The principal conclusions of that review are:

- More effort should be expended in category 6.3 in areas other than performance so that the transition from demonstrated technology to production hardware is not as difficult nor time consuming.
- Establish realistic goals achievable within allocated time and dollar figures.
- Insufficient technology base existed when F-401 program was undertaken. This occurred because of a 10-year reduction in R&T effort preceding F-401 contract initiation.

During the course of the program, there were changes in the engine component performance requirements that pushed the needed component technology beyond the demonstrated technology. These changes were caused by deficiencies in the overall engine performance. The components of the P&W engine that won the competition would not meet the upward revised requirements, and new developments had to start with a compressed schedule.

The F-401 engine called for:

- Higher pressure ratio
- Higher turbine inlet temperature
- Variable aerodynamic component
- Reduced size afterburner
- Lightweight construction.

To meet the overall performance requirements, the F-401 design would be pushing the state of the art in component performance, with little margin for further improvement based on existing technology. The F-401 engine, as built, exhibited performance deficiencies that were attributed mainly to component interactions. These interactions were unanticipated because of an inadequate technology base.

The Navy evaluation of the F-401 pointed out that although the performance deficiencies were distributed throughout the engine and not assignable to a single component area, the principal sources of performance loss were compressor efficiency, overall turbine efficiency, and nozzle velocity coefficients.

It was also pointed out that the lightweight engine technology and structural innovations demanded by the high thrust/weight requirement resulted in engine flexibility. This flexibility required increased operating clearances of rotor blades and seals to reduce rub caused by structural deflections.

The contractor attempted to regain the performance loss, caused by leakage and component interaction, by improving the component performance. But the components, i.e., fan, compressor, combustor, turbine, and nozzle, were already close to their technological limits, and correcting deficiencies and improving performance amounted to new developments.

Time, money, and effort could eventually correct the deficiencies. But the Navy decided that the gain was not worth the extensive additional funding at that time.

Program areas were related to R&T programs in the study for Admiral Hopkins. That study recommends increased R&T effort in:

- Durability assessment
- Off-design performance estimation
- Fracture mechanics
- Titanium fires
- Technology base for system performance--cost/weight/performance sensitivities.

III. OBSERVATIONS

- A new engine development requires several years lead time over an airframe, if several advances beyond the demonstrated state of the art are required.
- Requirements are sometimes unrealistic. Performance goals set *a priori* are sometimes unachievable within the time schedules.
- The requirement for very lightweight engines leads to structural deficiencies, e.g., engine flexibility and materials mismatch.
- The problems in the transition from technology demonstrations to production hardware are more difficult to resolve than is generally admitted by the developers.
- At present, the scaling of aeroelastic phenomena is a major problem for advanced engine designs. Extensive testing and development of full-scale articles must be provided over the range of flight/operating conditions.
- There was a misjudgment of the technology base, because of the interpretation of APSI/ATEGG results.
- Endurance tests should be part of source selection.
- Program rigidity should be avoided. There should be flexibility to permit changes in specifications during development, without major revision of the contract.

A small relaxation in performance requirement can yield a large improvement in aeroelastic stability, e.g., moving away from blade flutter boundaries (although in this case relaxation of the requirement may have been politically infeasible).

- Changes in aircraft and mission performance requirements that occur between the original engine proposal and source/selection time cause long-range problems, i.e., Component Improvement Program (CIP).

