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A RAND NOTE

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The Cost and Performance Implications of
Reliability Improvements in the F-16A/B Aircraft

John B. Abell, Thomas F. Kirkwood,
Robert L. Petruschell, Giles K. Smith

March 1988

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→ This Note suggests the magnitude of the effects of policies and strategies to enhance reliability of Air Force aircraft weapon systems. Using the F-16A/B fighter aircraft program as a case study, the authors found that the benefits of improved reliability include (1) a reduction in base-level maintenance manpower requirements, (2) increased capability to generate sorties, (3) lowered costs for procurement and repair of engines and spare parts, and (4) reductions in the resources (both equipment and manpower) required to deploy a combat unit to an overseas site.

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PREFACE

The work reported in this Note is intended to support the formulation (and evaluation) of policies and strategies to enhance the combat effectiveness of Air Force aircraft weapon systems through improvements in reliability and maintainability (R&M). RAND's overall R&M studies comprise three tasks:

1. Develop methods to quantify the full range of R&M effects on the operational capabilities and lifecycle costs of weapon systems.
2. Develop acquisition strategies to achieve specified levels of R&M.
3. Improve the way R&M specifications are written and the measurement of R&M in force status reporting systems.

Reliability improvements carry both costs and benefits, as do improvements in maintainability. Thus, in effect, four separate factors are involved in overall R&M studies. This Note focuses solely on efforts to estimate part of the effect of one of those four factors, selected benefits that could be obtained from improved reliability. Using the F-16 A/B fighter aircraft program as a case study, it was found that the benefits of improved reliability include:

- A reduction in base-level maintenance manpower requirements,
- Increased capability to generate sorties,
- Lowered costs for procurement and repair of engines and spare parts, and
- Reductions in the resources (both equipment and manpower) required to deploy a combat unit to an overseas site.

This research is being conducted under the Project AIR FORCE Resource Management Program project entitled "Reliability and Maintainability" and should be of interest to senior Air Force officials concerned with acquisition and logistics management.

SUMMARY

The reliability of an aircraft's systems and subsystems determines to an important extent its need for support resources and its ability to continue operating when resources are limited. In the work described in this Note, which comprises several different studies accomplished over a two-year period, Monte Carlo simulation models were used to estimate some of the benefits of a postulated twofold or fourfold improvement in the reliability of the F-16 A/B aircraft. The specific benefits estimated include:

- Reductions in base-level maintenance manpower requirements.
- Enhanced sortie generation capability.
- Reductions in the cost of engines and certain spare parts.
- Improvements in squadron deployment flexibility.

The amount of estimated benefits is substantial, totaling more than \$1.2 billion in lifecycle costs for engines and spare parts alone.

A twofold improvement in the overall reliability of the aircraft (a 50 percent reduction in the rate of maintenance actions on all components of the aircraft) could reduce maintenance manpower requirements an estimated 9 percent, given the same level of flying activity. A fourfold improvement could theoretically reduce manpower requirements by nearly twice that.

Virtually all of the manpower savings occur in the Component Repair Squadron, such as reducing the requirements for avionics technicians by about a fourth and for propulsion technicians by about a third, accompanied by modest reductions in certain other skills. Including training costs, the manpower reductions from a twofold reliability improvement represent an annual savings of about \$5 million per 72-PAA F-16 A/B wing.

The most important benefit of improved reliability lies in its effects on combat capability. Improving reliability increases both sortie generation capability and the probability of individual mission accomplishment. The reduction in maintenance manning described above can, in fact, be traded off against an estimated 17 percent increase in wartime sortie generation capability with current manning levels.

The effects of improved reliability (through lowered aircraft component removal and repair rates) on the capital costs of spare engines and engine modules, and the costs of procurement, depot-level repair, and condemnations of certain recoverable spare parts for the F-16 A/B program were also estimated.

Both twofold and fourfold reliability improvements just in the F-16's fire-control and propulsion system components (as reflected by a 50 percent reduction in component removal rates) were analyzed. Given a constant 80 percent aircraft availability goal, **the twofold reliability improvement alone would yield an estimated cost savings of \$1.2 billion** (in constant, undiscounted FY 84 dollars) over the 13-year period from 1978 through 1990.

Even more important than the dollar estimate of potential savings in capital costs, however, was the **identification of the effects of database churn**, the yearly change in the database used to calculate the numbers of spare parts needed and their cost. It results from the addition of entirely new parts, the exchange of new parts for parts currently in inventory, and changed characteristics of various parts (e.g., demand rates) over the time period. Analysis of the 1982, 1983, and 1984 databases shows that churn alone can induce the need for annual expenditures on spare parts equal to 16 to 21 percent of the total cost of all the spares in the system. The implications of this finding are important in estimating the costs of spare parts needed for the F-16 A/B over its lifecycle and are probably equally important when applied to other weapons systems over their lifetimes.

Improving reliability decreases both the number of personnel and the tonnage of spare parts and equipment required to support short-term tactical deployments of aircraft. The postulated twofold reliability improvement would reduce by approximately 40 tons the bare-base deployment support required for a 24-PAA F-16 A/B squadron. Although seemingly large in absolute terms, this tonnage represents only about 5 percent of the total tonnage required by the squadron and includes only selected tractors, trailers, and loaders for handling munitions and towing aircraft. Thus improved reliability does not dramatically affect deployment support requirements.

Table S.1 translates the twofold reliability improvement into monetary terms for three of the individual benefits: reduced maintenance manpower requirements; lower capital costs for engines and spare parts; and the reduction in lifecycle costs of spare parts. It excludes, however, the modest cost savings achieved by reducing deployment requirements by 40 tons. The table also reflects a rough estimate of the savings in the capital cost of War Reserves Spares Kits (WRSK). Two alternative ways of applying the benefits are shown, either reducing manpower or increasing the sortie rate.

Table S.1

AGGREGATE BENEFITS OF TWOFOLD IMPROVEMENTS IN RELIABILITY, FY 78-FY 90
(Billions of FY 84 \$)

Category of Benefit	Estimated Wartime Sortie Rate per Aircraft per Day	Direct Savings from Reduced Maintenance Manning	Engines, Modules, and Recoverable Spare Parts Cost Savings	WRSK Investment Cost Savings ^a	Reduction in Lifecycle Costs of Spare Parts
Manpower reduction	3.0	0.3	1.2	0.2	1.7
Sortie capability increase	3.5	0.0	1.1	0.1	1.2

^aDoes not include replenishment or other lifecycle costs.

The first line of Table S.1 shows the savings if the reliability improvement is used to reduce maintenance manpower requirements without lowering wartime sortie generation capabilities. It would be possible to save a total of \$300 million (about \$5 million annually per 72 PAA wing for each of the eight USAF F-16 A/B operational and training wings), plus about \$1.4 billion in capital costs and repair costs for spare parts. Assuming that the total force was built up during the first half of the 1978-1990 time period, the total estimated savings in lifecycle costs would be roughly \$1.7 billion.

The sortie capability data in Table S.1 are based on the assumption that all of the benefits of improved reliability would be realized in terms of increased sortie rates. This would cause a slight reduction in the savings in capital costs for spares and WRSK.

Both cases are extremes in the sense that all of the benefits of the postulated reliability improvements are applied in only one way. Nevertheless, the data provide some insights into the dramatic size of the tradeoffs that might be possible.

Another way to view the savings in capital costs for engines and recoverable spare parts, WRSK, and the lifecycle cost of spare parts would be to use them to reduce the overall size of the USAF F-16 A/B force; fewer aircraft would be needed for the same sortie generation rate. Alternatively, the savings could be used to purchase additional aircraft. Used this way, the \$1.7 billion savings in lifecycle costs would translate into approximately two additional 72-PAA F-16 wings.

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Dr. King made especially important contributions to the estimates of the churn in the Air Force's recoverable item database that made it possible to translate capital costs of recoverable POS into lifecycle costs. He was supported in this effort by Virginia Mattern.

CONTENTS

PREFACE	iii
SUMMARY	v
ACKNOWLEDGMENTS	ix
FIGURES	xiii
TABLES	xv

THE COST AND PERFORMANCE OF IMPLICATIONS OF RELIABILITY IMPROVEMENTS IN THE F-16 A/B AIRCRAFT

Introduction	1
Analytic Approach	2
Maintenance Manning and Sortie Generation	3
The Effects of Reliability on the Lifecycle Costs of Engines, Engine Modules, and Recoverable Spares	7
Deployment	12
Overall Benefits	15

Appendix

A. ESTIMATING THE BENEFITS OF IMPROVED RELIABILITY ON MAINTENANCE MANPOWER REQUIREMENTS AND WARTIME SORTIE GENERATION CAPABILITY	19
Personnel Estimates by Skill Area	19
Methodology	23
How the TSAR Model Works	24
The Scenario, Assumptions, and Analyses	26
Overview of the Estimating Method	27
Personnel Requirements Estimated with TSAR	29
Estimating Day-Shift Flightline Personnel	31
Estimating Support Shop and Night-Shift Flightline Personnel	34
Accounting for Indirect Work	36
Personnel Not Estimated with TSAR	36
Dealing with Random Numbers and Multiple Trials	37
B. ESTIMATING THE EFFECTS OF RELIABILITY ON THE LIFECYCLE COSTS OF ENGINES, ENGINE MODULES, AND RECOVERABLE SPARES	39
Introduction	39
The Capital Costs of Engines and Engine Modules	41
Estimating the Effects of Enhanced Reliability on the Capital Costs for Recoverable Spare Parts	42
Estimating Lifecycle Costs of Recoverable Spares	47

C. THE EFFECTS OF IMPROVED RELIABILITY ON DEPLOYMENT	
REQUIREMENTS	64
Types of Equipment and Personnel Deployed	64
Equipment that Need Not Be Deployed by Airlift	64
Air-Delivered Support Equipment	66
Deployed Personnel	66
Potential Reductions Due to Improved Reliability	66
Method of Determining Savings in Support Equipment	69
Using TSAR to Model the Potential Savings	70
Conclusion	73
REFERENCES	77

FIGURES

1. Total Maintenance Personnel Savings vs. Sortie Rate for Reliability Improvement Factors of 1X, 2X, and 4X	5
2. The Effects of Improved Reliability on F-16 A/B Total Investment and Lifecycle Costs, Fiscal Years 1978 through 1990, 0.16 Churn	10
3. Savings in Deployed Equipment	14
4. Savings in Deployed Personnel	14
5. Effect of Sortie Rate and Reliability on Total Weight of Support Equipment ..	15
A.1. Avionics Maintenance Personnel, F-16 A/B Wing	21
A.2. Airframe and AGE Maintenance Personnel, F-16 A/B Wing	22
A.3. Propulsion Maintenance Personnel, F-16 A/B Wing	23
A.4. Loaders, Weapons Release, and Gun Maintenance Personnel, F-16 A/B Wing	24
A.5. Munitions Maintenance Personnel, F-16 A/B Wing	25
A.6. Probability that the Number of Personnel Working is Less than or Equal to P	33
C.1. Deployed Support Items	68
C.2. F-16 Deployment Support	70
C.3. Effect of Sortie Rate and Reliability on Total Weight of Support Equipment ..	74
C.4. Maintenance Personnel	75
C.5. Savings in Deployed Equipment Weight per Squadron	76
C.6. Savings in Deployed Personnel per Squadron	76

TABLES

S.1. Aggregate Benefits of Twofold Improvements in Reliability, FY 78-FY 90	vii
1. Effect of Improved Component Reliability on Base Level Maintenance Personnel by Organization	6
2. Effect of Improved Component Reliability on Base Level Maintenance Personnel by Skill Group	6
3. How Design Reliability Might Have Affected the F-16 A/B Program Total Investment and Lifecycle Costs, FY 78 Through FY 90, with an 0.16 Churn Factor	11
4. How Design Reliability Might Have Affected the F-16 A/B Program Total Investment and Lifecycle Costs, FY 78 Through FY 90, with an 0.21 Churn Factor	11
5. How Design Reliability Might Have Affected the F-16 A/B Program Total Investment and Lifecycle Costs, FY 78 Through FY 90, with an 0.10 Churn Factor	12
6. Aggregate Benefits of Twofold Improvements in Reliability, FY 78-FY 90	16
A.1. Summary of Personnel Estimates by Case and Aggregate Skill Area	20
A.2. Identification of Analyses, 5 Waves per Day	27
A.3. Source of F-16 Maintenance Manpower Estimates, Summary Table	30
A.4. Source of F-16 Maintenance Manpower Estimates, Deputy Commander for Maintenance	31
A.5. Source of F-16 Maintenance Manpower Estimates, Aircraft Generation Squadron	32
A.6. Source of F-16 Maintenance Manpower Estimates, Component Repair Squadron	34
A.7. Source of F-16 Maintenance Manpower Estimates, Equipment Maintenance Squadron	35
A.8. Sorties Achieved vs. Sorties Scheduled by Case	38
B.1. Scenario for Engine and Engine Module Requirements Computations	41
B.2. Engine and Engine Module Requirements	42
B.3. Inferred Mapping of Federal Stock Class into Aircraft System	44
B.4. Scenario Data for Computing Recoverable POS Requirements	45
B.5a. Capital Costs of Recoverable Spares to Maintain 80 Percent Aircraft Availability	47
B.5b. Capital Costs of Pipeline Plus Safety-Level Stocks for the Fire Control and Propulsion System Components	48
B.6. Assumptions Underlying the 1983 to 1984 Computation	52
B.7. Composition of the 1983 to 1984 Capital Requirement	52
B.8. Assumptions Underlying the 1983 to 1985 Computation	53
B.9. Results of the 1983 to 1985 Computation	53
B.10. Assumptions Underlying the 1984 to 1985 Computation	54
B.11. Results of the 1984 to 1985 Computation	54
B.12. Effects of Changing Component Unit Prices	55
B.13. Assumptions Underlying the 1982 to 1983 Computation	55
B.14. Composition of the 1982 to 1983 Capital Requirement	56
B.15. Assumptions Underlying the 1982 to 1984 Computation	56
B.16. Results of the 1982 to 1984 Computation	57

B.17.	Results of the 1983 to 1984 Computation Following the 1982 to 1983 Procurement	57
B.18.	Effects of Changing Component Unit Prices	58
B.19.	Comparison of Effects of 1982 to 1983 Churn with Effects of 1983 to 1984 Churn	58
B.20.	F-16 A/B POS Investment Requirements by Fiscal Years, for 1978 Through 1990	60
B.21.	The Effects of Reliability and Churn on the Lifecycle Costs of Recoverable Spares	61
B.22.	Lifecycle Condemnation and Depot Repair Costs FY 78 Through FY 90	62
C.1.	Deployment of 24 F-16s	65
C.2.	Weight of Support Material Not Included in UTCs	65
C.3.	Deployed Support and Maintenance Items	67
C.4.	Deployed Personnel	69
C.5.	Support Items Used in TSAR Analysis	72

THE COST AND PERFORMANCE OF IMPLICATIONS OF RELIABILITY IMPROVEMENTS IN THE F-16 A/B AIRCRAFT

INTRODUCTION

In recent years there has been a growing consensus that U.S. weapon systems would benefit from better reliability and maintainability (R&M). Numerous studies and reviews have concluded that procedural deficiencies in the acquisition and support process have led to serious R&M deficiencies in our operational systems. Early in 1985, the Air Force responded to the problem by organizing a new headquarters office, the Special Assistant for Reliability and Maintainability, headed by a brigadier general. The office reports both to the Deputy Chief of Staff for Logistics and Engineering and to the Deputy Chief of Staff for Research, Development and Acquisition.

Increasing attention is being paid to R&M requirements in the development specifications for weapon systems. In the early 1960s, the development specification for the F-111 aircraft contained no mention of reliability and only a brief qualitative statement about maintainability. The comparable specification for the F-15, issued nearly a decade later, included a paragraph on reliability, but again it was entirely qualitative. When full scale development was initiated on the F-16 in the mid-1970s, the specification contained several quantitative requirements for reliability and maintainability at both the system and subsystem levels.[1] The specifications for more recent new aircraft starts, such as the C-17, contain extensive requirements for R&M, backed up by warranties that will penalize the manufacturer if those required levels of performance are not achieved.[2]

Because there are costs associated with the achievement of higher levels of R&M, it is important to quantify the benefits of specified levels of improvement so that sensible R&M goals can be set in weapon system development programs. Eventually some sort of yardstick will be needed to compare the costs of increasing R&M performance with the benefits that would be achieved.

This Note addresses only the problem of estimating the benefits and only those benefits associated with enhancing reliability, not with improved maintainability. It is intended to provide some insights into the magnitude of savings achievable by improving reliability in order to help USAF set future reliability goals and allocate resources to reliability improvement programs. Reliability improvements can yield such benefits as reductions in procurement and repair costs for spare parts or improvements in combat capability.

In late 1984, a special task group was formed in Headquarters USAF to recommend approaches to improving R&M. It defined a set of criteria for evaluating the benefits, including:

1. *Manpower.* The acquisition, training, and maintenance costs of support manpower, especially in skills for which the Air Force competes with the civilian economy.
2. *Readiness.* The measure of the number of sorties by fully mission-capable aircraft that can be launched in a specified period of time, or the sortie rate that can be sustained under some specified set of operational conditions.
3. *Dollar costs.* The investment and operation-and-support costs of the force.
4. *Mobility.* Measured by the amount of maintenance equipment required to support the deployment of combat units to "bare" bases.
5. *Dependability.* The probability that all critical systems will continue to function properly throughout the mission.
6. *Vulnerability.* Measured by the amount of support resources that are vulnerable to loss in a combat environment.

These criteria, of course, are interrelated. For example, an improvement in reliability can be reflected in increased sortie rate, or reduced maintenance manning, or reduced spares levels, or some combination of all three; and the effects on support costs will depend on the particular mix of actions taken to derive the benefits of the improvement. Thus it is not possible to assess each potential benefit independently. However, by examining a mix of possible benefits under different assumptions it is possible to gain some useful insights into the magnitude of the benefits that can be achieved.

ANALYTIC APPROACH

In three largely independent studies reflected in this Note, we considered information about four of the six criteria for evaluating the benefits of reliability: manpower, readiness, the dollar costs (at least for spare parts), and mobility. We focused on the F-16 A/B fighter aircraft. One study examined the tradeoff between maintenance manning and sustainable sortie rate; the second addressed the lifecycle investment costs for engines and engine modules and the lifecycle procurement, depot-level repair, and condemnation costs of recoverable spare parts; and the third analyzed mobility requirements. The first and third

studies considered reliability improvements affecting the entire aircraft, while the second study (detailed in App. B) dealt with the F-16's propulsion and fire control systems. Summaries and results of each of the three analyses follow. Discussions of methodology and further details concerning results can be found in the three appendices.

MAINTENANCE MANNING AND SORTIE GENERATION

Among the most important consequences of improved reliability are opportunities for reduced requirements for support resources, for increased aircraft availability, or some combination of the two. In this study, the Theater Simulation of Airbase Resources model (TSAR), a detailed Monte Carlo simulation model, was used to estimate the tradeoffs between base-level maintenance manpower requirements and sortie generation capability.[3,4,5] This was done by varying the rates of maintenance actions three ways: by setting them equal to current Air Force experience (the 1X case), then to one half of those values (the 2X case), and then to one fourth of those values (the 4X case), thus postulating twofold and fourfold improvements in the reliability of all components of the aircraft. A twofold reliability improvement simply means that half as many failures, component removals, or maintenance actions occur as before. In this study we varied only the reliability parameters and did not modify any of the maintenance networks—the set of maintenance actions specified to the model.

Using input values obtained from Headquarters TAC, the model produced estimates of maintenance manning requirements consistent with current Air Force manning documents and sortie generation rates. With the model so calibrated, we systematically varied the desired sortie rate and determined the maintenance manning needs for each rate, first at the current reliability levels, then for each of the two postulated reliability improvements.

Our analysis encompasses base-level maintenance manning requirements for a 72-PAA F-16 wing. The manpower requirements examined include those of the Deputy Commander for Maintenance (DCM), the Aircraft Generation Squadron (AGS), the Component Repair Squadron (CRS), and the Equipment Maintenance Squadron (EMS). The wing was assumed to be operating in place during a seven-day surge in activity under simulated wartime conditions. Modeling of the base case—about three sorties per aircraft per day with current component reliability—produces estimated manning requirements that are very close to the current manpower authorizations of 72-PAA F-16 wings.

Sorties were air-to-ground, lasting 1.7 hours on the average, and all flying was during daylight hours. Each aircraft was scheduled to fly five sorties per day, at 0600, 0900, 1200, 1500, and 1800 hours. Aircraft were launched in flights of four, but if four were not

available, flights of three were acceptable. Flights of less than three aircraft were scrubbed. Delays of up to 30 minutes were allowed in meeting the scheduled takeoff times. Non-mission-critical maintenance was deferred until the end of the flying day.

All resources other than personnel (e.g., fuel, support equipment, spare parts, and munitions) were assumed to be available in sufficient quantities that they did not limit the scheduled flying program. The results reflect balanced mixes of the skills required; no skills were in either long or short supply.

The results are shown in the curves in Fig. 1. Considering the base case, we estimate that a twofold improvement in the reliability of all components could either reduce maintenance manning requirements by 9 percent or increase sortie production by 17 percent. Of course, some of the benefits could be taken in reduced manning and the rest in increased sortie production. At a fourfold reliability improvement, maintenance manning requirements could be reduced 16 percent or the sortie rate increased 30 percent. The curves suggest how such tradeoffs could be made over a range of improvements up to four times greater than present reliability and a range of sortie rates from about 1.5 to 4.0.

Table 1 shows the potential manpower savings, by organization, for the reference case and for the 2X and 4X improved-reliability cases at an operating rate of slightly over three sorties per day. A twofold improvement in reliability saves roughly 8 percent in manpower, and a fourfold improvement saves about 14 percent.

The small difference between these numbers and the ones quoted above in describing Fig. 1 results from slightly different assumptions about the sortie rate.

Organizationally, the manpower savings occur mostly in the Component Repair Squadron (CRS). Some slight savings occur in the Aircraft Generation Squadron (AGS), almost none in the Equipment Maintenance Squadron (EMS), and none at all in the office of the Deputy Commander for Maintenance (DCM). A twofold improvement in reliability yields a 25 percent reduction in CRS manning and a 7 percent reduction in AGS manning. We have assumed that DCM manning is necessary overhead that is independent of component reliability and sortie rates. These results indicate that EMS manning is also largely independent of component and subsystem failure rates.

Savings by aggregate skill area are shown in Table 2. A more detailed breakdown is shown in Figs. A.1 through A.5 and the accompanying discussion in App. A.

The requirements for avionics technicians can be reduced by 24 and 38 percent, respectively, for twofold and fourfold reliability improvements. Similarly, propulsion technicians can be reduced by 32 and 50 percent, and Airplane General (APG) manpower and Aerospace Ground Equipment (AGE) manpower by 14 and 26 percent, respectively.

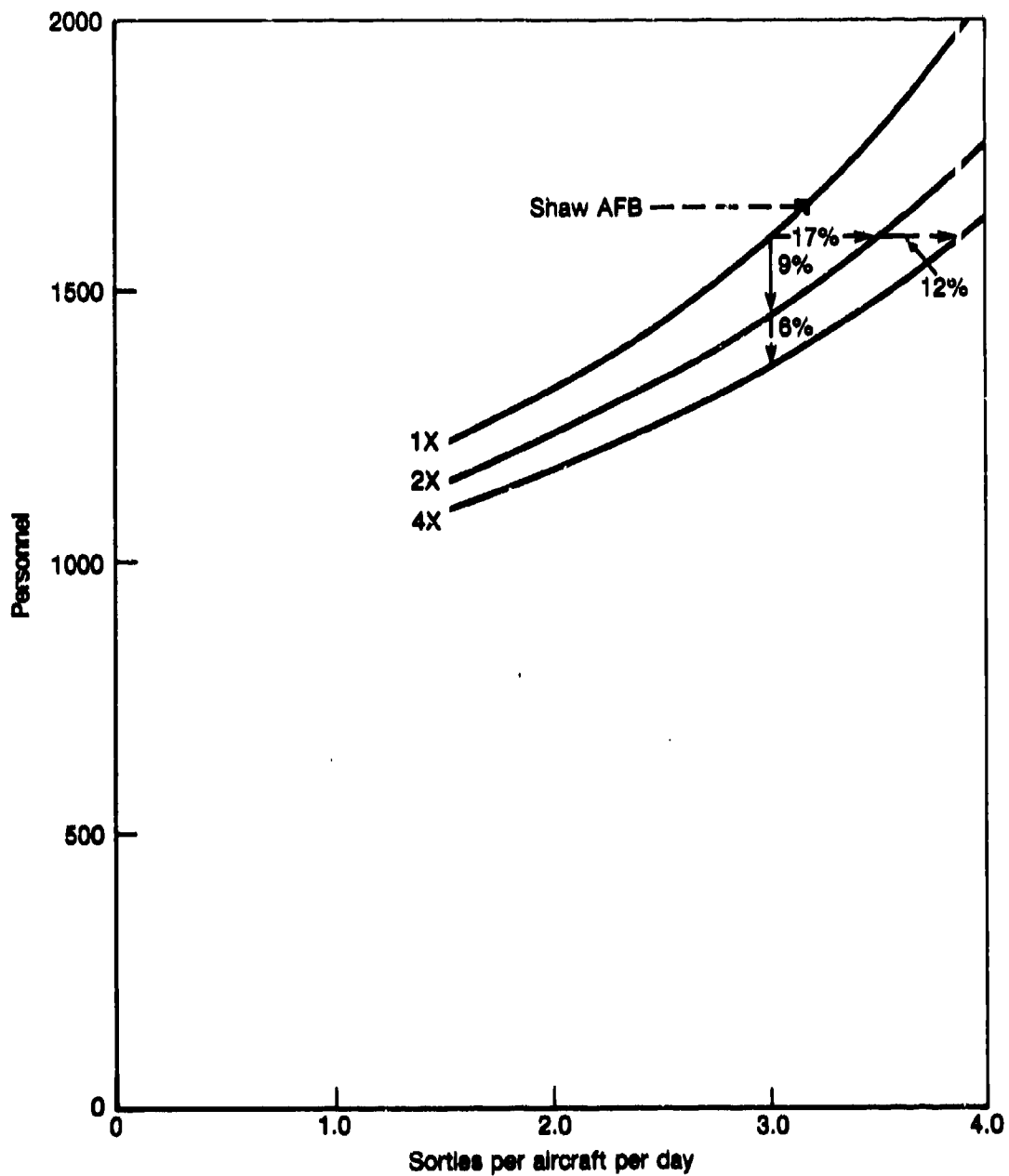


Fig. 1—Total maintenance personnel savings vs. sortie rate for reliability improvement factors of 1X, 2X, and 4X

Table 1

EFFECT OF IMPROVED COMPONENT RELIABILITY ON BASE LEVEL
MAINTENANCE PERSONNEL BY ORGANIZATION^a

Organization	Reliability Improvement Factor				
	1X	2X	4X		
	3.2 S/A/D ^b	3.3 S/A/D	Difference %	3.3 S/A/D	Difference %
Deputy Commander for Maintenance	142	142	0	142	0
Aircraft Generation Squadron	798	750	-7	693	-13
Component Repair Squadron	297	222	-25	183	-38
Equipment Maintenance Squadron	399	395	-1	392	-2
Total Maintenance Personnel	1636	1509	-8	1410	-14

^a72-PAA F-16 A/B wing operating in place during a seven-day surge.

^bSorties per aircraft per day.

Table 2

EFFECT OF IMPROVED COMPONENT RELIABILITY ON BASE LEVEL
MAINTENANCE PERSONNEL BY SKILL GROUP

Skill Area	Reliability Improvement Factor				
	1X	2X	4X		
	3.2 S/A/D ^b	3.3 S/A/D	Difference %	3.3 S/A/D	Difference %
Avionics	229	175	-24	142	-38
Propulsion	127	86	-32	63	-50
Aircraft General and AGE ^c	357	309	-14	266	-26
Crew Chiefs, Weapons and Munitions Handlers	923	939	+2	939	+2
Total Maintenance Personnel	1636	1509	-8	1410	-14

^a72-PAA F-16 A/B wing operating in place during a seven-day surge.

^bSorties per aircraft per day.

^cAerospace ground equipment.

Highly skilled maintenance personnel, such as avionics and propulsion technicians, are much more likely to be in short supply in the future and are more expensive to train and retain than those in most other skills. A twofold improvement in component reliability could make possible a reduction of 54 avionics technicians for a single wing, from 229 down to 175. For the roughly eight three-squadron equivalent F-16 A/B wings in the Air Force today, that would amount to a reduction of 430 avionics technicians. Similarly, we might save a total of about 330 propulsion technicians and 380 airframe and AGE technicians. All of this adds up to over 1,100 skilled maintenance people that the Air Force might be able to either do without or use for other purposes.

The requirements for other maintenance manpower change little as a result of reliability improvements. Although some fraction of the overhead and supervisory personnel could be reduced if the requirement for other (direct) personnel were reduced, such gains would be modest at best.

We have also made rough estimates of the possible commensurate reduction in the annual operating cost for the wing. The savings are \$5 million and \$7 million per wing, respectively, for the postulated twofold and fourfold improvements, or roughly 2-3 percent of a single wing's \$250 million total annual operating cost.

THE EFFECTS OF RELIABILITY ON THE LIFECYCLE COSTS OF ENGINES, ENGINE MODULES, AND RECOVERABLE SPARES

The reliability of an aircraft's systems to an important extent determines its need for support resources. Logisticians have long argued that those needs should be considered early in the conceptual phase of a weapon system's life and should influence the levels of reliability that become an inherent part of the aircraft's design characteristics.[6]

The work described below attempts to quantify the relationships between reliability (as reflected by component removal and repair rates) and:

- Capital costs for engines, engine modules, and recoverable spare parts;
- Total lifecycle costs (capital costs of replenishment and depot-level repair, and replacement costs for condemned parts) for recoverable spare parts.

Substantial reductions in capital costs and lifecycle costs might have been achieved if the F-16 A/B's fire control and propulsion systems (the two systems in the aircraft with the greatest effects on support cost and system performance) had been designed initially with

greater reliability. The lifecycle costs estimated here are based on postulated twofold and fourfold improvements in component reliabilities for only the components of these two systems. The Logistics Management Institute's Aircraft Availability Model (AAM) was used for this analysis.

We estimate a potential total savings in these cost categories of \$1.2 billion (in constant, undiscounted FY 84 dollars) over the 13-year period from 1978 through 1990, assuming only that the propulsion and fire control systems had been twice as reliable as they actually were. (This estimated saving is roughly the equivalent in FY 84 dollars of the flyaway cost of 100 additional aircraft. The magnitude of these numbers in a program of the dimensions of the F-16 A/B program suggests the benefits of enhancing the reliability we design into our weapon systems.)

Churn

In performing this study, we identified the importance of the effects of *churn* in the annual database used to calculate the numbers of spare parts and their costs. *Churn* is the year-to-year change in the database caused by the addition of entirely new parts, exchanges of new parts for existing parts, and changes in the item characteristics of existing parts (e.g., price, specifications). Random changes in item characteristics tend to create additional capital cost requirements; however, whether such changes actually result in additional costs depends on the asset position of the item (the total number of spares of the item in the inventory system) as well as the direction and magnitude of the changes in the item's characteristics as reflected in the requirements database. Consider two items, A and B, whose asset positions are consistent with past estimates of their pipeline values. Now suppose the requirements database reflects changes in the characteristics of both items such that the estimated pipeline of item A increases and that of item B decreases compared with the estimates made using past databases. The computed requirement of item A will then be increased by the computational system to maintain a constant level of aircraft availability, and the computed requirement of item B will be zero. The "excess" of item B will contribute less to increasing availability, other things equal, than the "shortage" of item A detracts from it. Thus, on balance, random changes tend to induce the need for additional assets.

The database used by the Air Force to compute capital costs of recoverable spare parts is not a model of a steady-state system, and it should not be thought of as such. If it were a steady-state system, then accurate estimates of the cost of spare parts for all future years of a weapon system's life could be made very early in its lifecycle. Clearly, that is not the case.

Instead, from year to year there are many changes in the database, creating the need for investments in recoverable spare parts beyond those just to replace spares that have been condemned as not economically repairable. This additional annual investment is required to maintain the specified level of system performance. Our techniques for estimating churn so as to account explicitly for the changes in item characteristics in the database are discussed in detail in App. B. The main points are summarized below.

The USAF database is subject to all of the dynamics that affect the world it represents. If there were no changes from year to year in the numbers and types of items in the database and in the characteristics of individual items, the annual requirement for spare parts would consist only of replacements for parts that had been condemned (assuming no other changes in the force posture, aircraft availability rate, or flying hour program).

The extent to which the database changes from year to year is substantial, however, even in the fairly benign peacetime environment. In wartime, the rate of change is likely to be compounded by changing characteristics of the operational scenario. Planners must be able to estimate with accuracy the lifecycle costs of the recoverable spare parts needed to maintain a specified level of aircraft availability across the life of the weapon system. And we believe this ability depends on the ability of planners to quantify churn and to estimate its effects on annual investment requirements over time.

In accounting for the churn phenomenon, we developed a measure of the effect of churn on the computed annual capital cost of recoverable spare parts. We call this measure the *churn factor*, which is simply the estimated cost of replenishment spare parts (as opposed to initial spares) needed to maintain a specified level of system performance, divided by the total capital cost (the total cost of all stock levels at all locations in the supply system). In other words, it is the proportion of the total capital costs spent on additional spare parts just to keep up with database dynamics.

In estimating lifecycle procurement costs for recoverable spares, we computed the dollar amount of churn and the associated churn factors using three consecutive USAF D041 databases (those actually used by the Air Force to compute investment requirements for recoverable spares). This resulted in the computation of two churn factors, 21 percent and 16 percent. The first reflects the churn between the September 1982 and September 1983 databases, and the second reflects the churn between the September 1983 database and the one for September 1984.

Results

In the tables below and in Fig. 2 we summarize the estimated effects of improved reliability on F-16 A/B investment costs. As can be seen by comparing the tables, the effects of churn in the calculations for recoverable POS are substantial. In fact, the magnitude of the effects of churn are especially remarkable when they are contrasted with analytic results derived from the view that the database is a model of a steady-state system.

Table 3 summarizes the effects with a 0.16 churn factor (based on the 1983 and 1984 databases). A twofold reliability improvement could result in a total cost reduction of \$1.2 billion, and a fourfold reliability improvement would result in a \$1.8 billion savings. Table 4

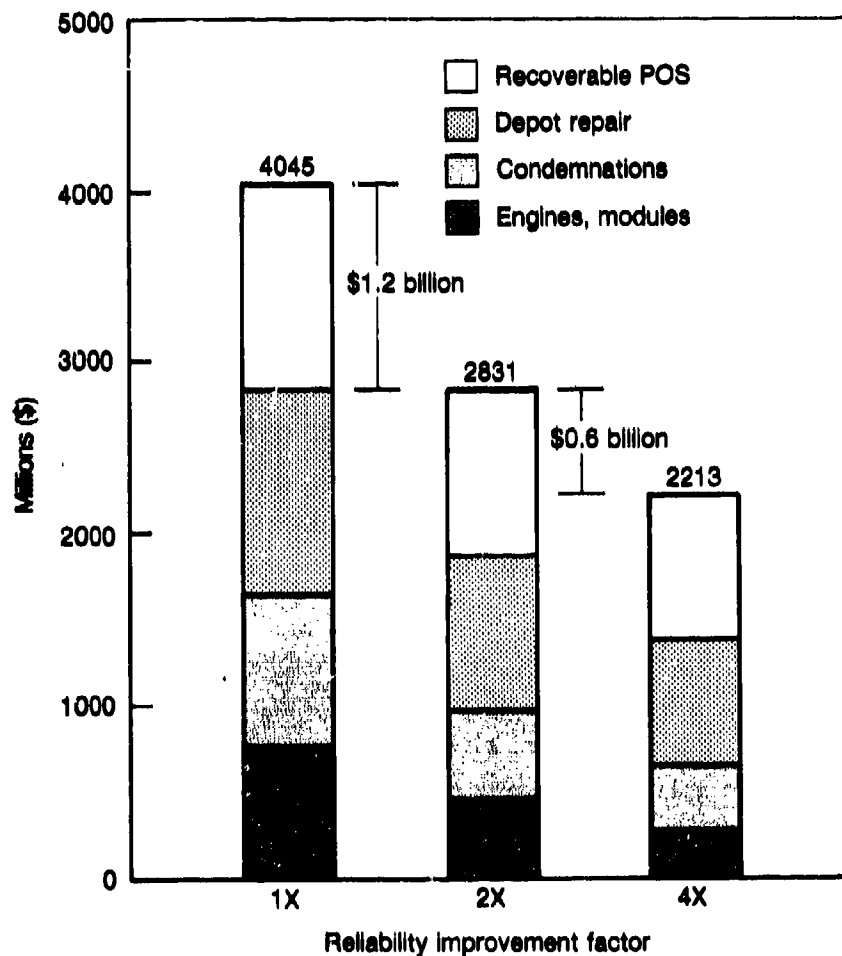


Fig. 2—The effects of improved reliability on F-16 A/B total investment and lifecycle costs, fiscal years 1978 through 1990, 0.16 churn

Table 3

HOW DESIGN RELIABILITY MIGHT HAVE AFFECTED THE F-16 A/B
PROGRAM TOTAL INVESTMENT AND LIFECYCLE COSTS,
FY 78 THROUGH FY 90, WITH AN 0.16 CHURN FACTOR
(Million \$)

Investment Category	Reliability Improvement		
	1X	2X	4X
Recoverable POS	1245	977	839
Depot-level component repair	1175	870	718
Condemnation replacements	837	536	385
Engines and engine modules	788	448	271
Totals	4045	2831	2213

Table 4

HOW DESIGN RELIABILITY MIGHT HAVE AFFECTED THE F-16 A/B
PROGRAM TOTAL INVESTMENT AND LIFECYCLE COSTS,
FY 78 THROUGH FY 90, WITH AN 0.21 CHURN FACTOR
(Million \$)

Investment Category	Reliability Improvement		
	1X	2X	4X
Recoverable POS	1506	1182	1015
Depot-level component repair	1175	870	718
Condemnation replacements	837	536	385
Engines and engine modules	788	448	271
Totals	4306	3036	2389

is based on a churn factor of 0.21 (based on the 1982 and 1983 databases) and Table 5 on a churn factor of 0.10 (an arbitrary lower churn factor chosen by the researchers to help illustrate the potential range of churn's effects). Even with a churn factor of 0.10, a twofold reliability improvement would result in a savings of almost \$1.2 billion, and a fourfold reliability improvement would produce a \$1.7 billion savings.

The reason for including a table of results for a churn factor of 0.10 is simply that both the 0.16 and 0.21 estimates of the churn factor from the three successive databases seem quite high and could be due to a handful of aberrant items. Indeed, in the estimate made from the 1983-1984 computation, 50 line items accounted for 64 percent of the dollar

Table 5

HOW DESIGN RELIABILITY MIGHT HAVE AFFECTED THE F-16 A/B
PROGRAM TOTAL INVESTMENT AND LIFECYCLE COSTS,
FY 78 THROUGH FY 90, WITH AN 0.10 CHURN FACTOR
(Million \$)

Investment Category	Reliability Improvement		
	1X	2X	4X
Recoverable POS	901	707	607
Depot-level component repair	1175	870	718
Condemnation replacements	837	536	385
Engines and engine modules	788	448	271
Totals	3701	2561	1981

amount of churn. Further estimates of churn from examination of additional databases could be higher or lower. Thus it is difficult to infer a single churn factor that can be used reliably to estimate lifecycle costs, based on the results of only two estimates of the dollar amount of churn. These tables should be viewed, then, as a sort of sensitivity analysis showing how lifecycle costs for recoverable spare parts vary as a function of the churn. As shown in these three tables, it is the recoverable POS costs that are affected by the churn in the database.

Using the churn factor of 0.16, Fig. 2 presents a bar chart showing the reliability effects from Table 3.

Based solely on this study, it is difficult to guess how the estimates of churn in the lifecycle costs for F-16 A/B recoverable POS might differ from those made for a different weapon system. However, we believe it is an experiment worth replicating on several other weapon systems.

DEPLOYMENT

Improvements in reliability would allow reductions to be made both in the amount of equipment and spare parts and in the number of support personnel required to support the overseas deployment of a squadron. We investigated this effect by examining bare-base deployment requirements reflected in Wing Mobility Materiel Lists for 24-PAA F-16 squadrons.[7]

The support equipment covered by this analysis does not represent all of the tonnage needed: fuel, armament, housing, and food were excluded, for example. These items actually represent far more total tonnage than equipment items, but it is likely they would be available locally or from sites where they have been prepositioned much closer to the overseas deployment area, thus obviating the need for delivery from the CONUS.

Starting with the basic material list, we used the TSAR model to estimate the possible reduction in support equipment and spare parts, as well as maintenance personnel, that could be achieved with either a twofold or a fourfold improvement in the reliability of all of the components of the F-16 A/B weapon system. The estimated reductions in mobility requirements are expressed in terms of tons of material and numbers of people. At a twofold reliability improvement, the savings for a 24-PAA Squadron range from approximately 30 tons of equipment and 20 personnel when the sortie rate is two sorties per aircraft per day to as much as 60 tons of equipment and 100 personnel at four sorties per aircraft per day.

The combined effect of sortie rate and reliability on the weight of equipment and the number of personnel deployed with a squadron of 24 aircraft is shown in Figs. 3 and 4. As in the analysis of maintenance manpower requirements and the cost of spare parts described above, most of the benefit is achieved with the twofold reliability improvement, with less marginal benefit obtained from the fourfold improvement.

The actual amount of savings, especially in tons of material, appears large. However, those savings are a small fraction of the total deployment effort because only a small fraction of the total material required is affected by changes in reliability. Most of the deployment tonnage is due to tractors, trailers, and loaders for handling ammunition and moving the aircraft. Improving reliability does not reduce the need for such equipment; in fact, if improved reliability generates more sorties, there may be need for more tractors, trailers, and loaders. The variation in total weight of support equipment deployed with an F-16 squadron is shown in Fig. 5. Doubling reliability yields only about a 5 percent reduction in total deployment tonnage.¹

¹If this case study were on the F-15, whose Avionics Integrated Systems test equipment is deployed with the aircraft, a much greater airlift savings might have been realized during deployment.

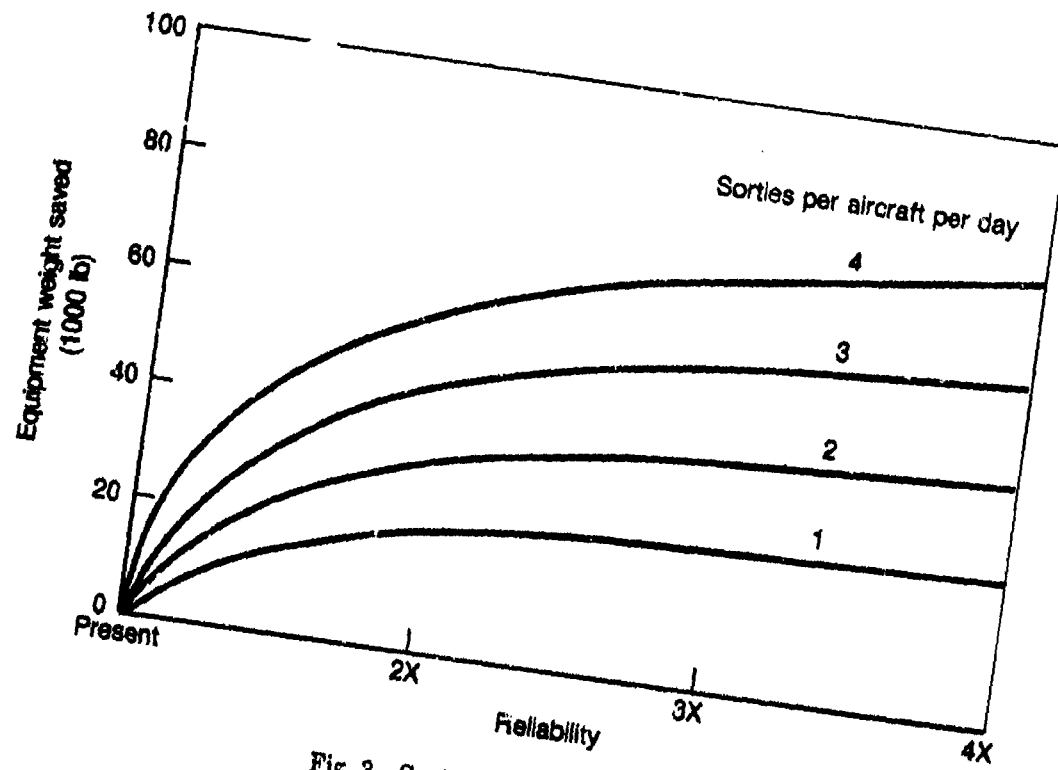


Fig. 3—Savings in deployed equipment

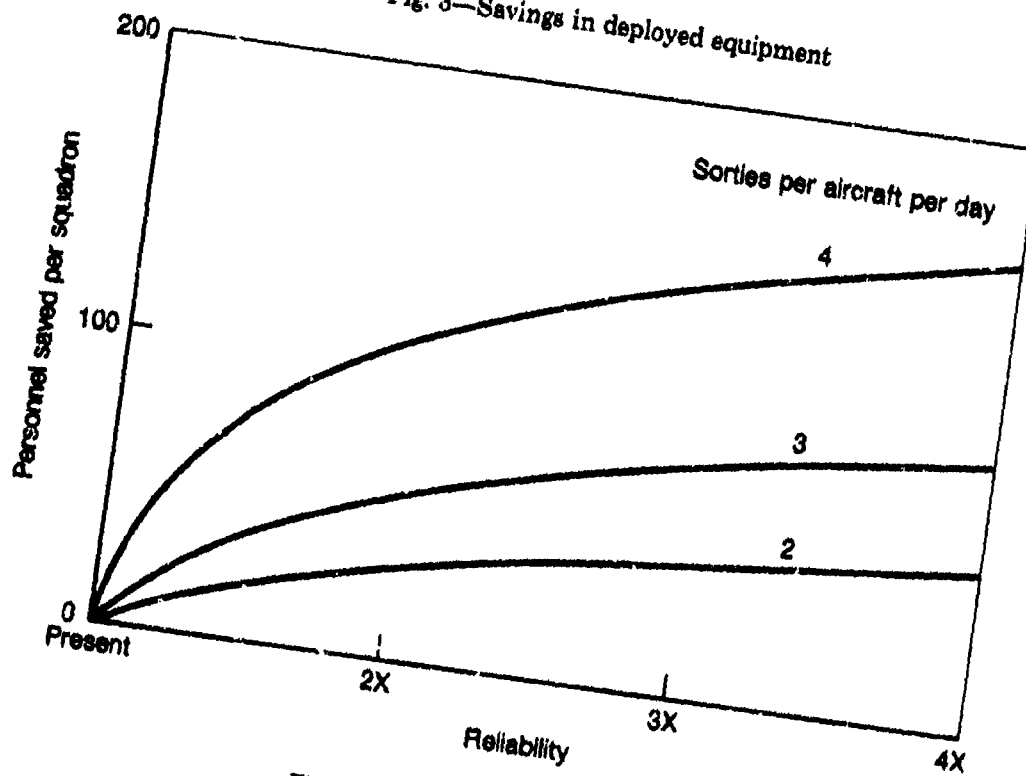


Fig. 4—Savings in deployed personnel

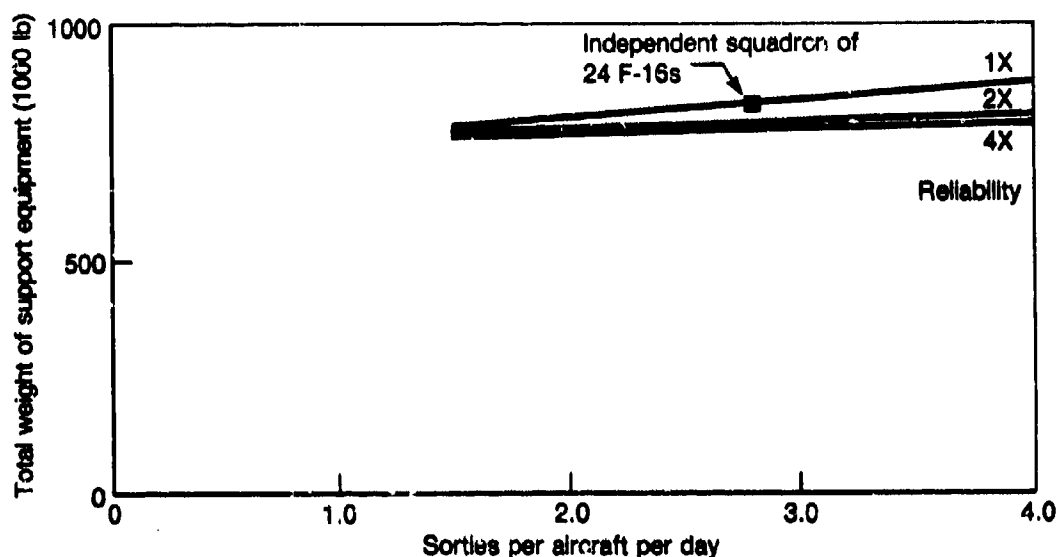


Fig. 5—Effect of sortie rate and reliability on total weight of support equipment

OVERALL BENEFITS

We believe that the most important benefit of improved reliability is enhanced combat capability. In the discussion that follows, the gains in wartime sortie generation capability achievable through reliability improvements are compared with other benefits. As previously shown, doubling the reliability of all components of the aircraft would yield an estimated 17 percent increase in wartime sortie generation capability given current manpower levels. Alternatively, the worth of the cost savings could be applied to acquiring additional aircraft. Or the capability increase from improved reliability could be used to reduce the number of aircraft required to accomplish a given sortie generation capability.

Although such estimates are highly dependent on the specific scenario considered as well as the estimating models used, they do provide some sense of the importance of reliability improvements and some insight into the relationship between reliability and wartime sortie generation capability. An added dimension of improving reliability is increased dependability; once launched, a more reliable aircraft has an improved chance of accomplishing its mission.

Table 6 (which is the same as Table S.1 in the Summary) translates the manpower, spares, and wartime sortie generation benefits of a two-fold reliability improvement into monetary terms, based on an assumption of no change in flying activity. We have excluded the value of the modest 40-ton per squadron savings in deployment equipment requirements, although the table does reflect a rough estimate of the savings in capital costs for War Reserves Spares Kits (WRSK) that would be realized from the postulated twofold reliability improvement if wartime sortie rates remained the same. Two alternative ways to apply the benefits are shown, either simply reducing manpower or increasing the sortie rate.

Manpower

The first line of Table 6 reflects the assumption that the reliability improvement is exploited solely by reducing maintenance manpower while keeping wartime sortie generation capability constant. This would make it possible to save a total of \$300 million (about \$5 million annually per wing for each of the eight operational and training wings), plus about \$1.4 billion in spare parts repair and capital costs. Assuming that the force was built up over the first half of the 1978-1990 time period, the total estimated savings in lifecycle costs would be roughly \$1.7 billion.

Table 6

AGGREGATE BENEFITS OF TWOFOLD IMPROVEMENTS IN RELIABILITY, FY 78-FY 90
(Billions of FY 84 \$)

Category of Benefit	Estimated Wartime Sortie Rate per Aircraft per Day	Direct Savings from Reduced Maintenance Manning	Engines, Modules, and Recoverable Spare Parts Cost Savings	WRSK Investment Cost Savings ^a	Reduction in Lifecycle Costs of Spare Parts
Manpower reduction	3.0	0.3	1.2	0.2	1.7
Sortie capability increase	3.5	0.0	1.1	0.1	1.2

^aDoes not include replenishment or other lifecycle costs.

Sortie Capability

The data in the second line are based on using the reliability improvement to achieve a 17 percent increase in wartime sortie generation rates. It results in fewer spare parts being needed and an investment savings for WRSK, but no savings at all in manpower.

Both cases are extremes in the sense that all of the benefits of the postulated reliability improvements are derived in only one way; nevertheless, the data provide some insights into the dramatic dimensions of the tradeoffs that might be possible.

Force Size

Another way to view the savings in capital costs for engines and recoverable spare parts, WRSK, and the lifecycle costs of spare parts would be to use it to reduce the overall size of the USAF F-16 A/B force; fewer aircraft would be required to accomplish the same sortie generation rate. Alternatively, the savings could be used to purchase additional aircraft. Used this way, the \$1.7 billion savings in lifecycle costs would translate into approximately two additional 72-PAA F-16 wings.

Appendix A

ESTIMATING THE BENEFITS OF IMPROVED RELIABILITY ON MAINTENANCE MANPOWER REQUIREMENTS AND WARTIME SORTIE GENERATION CAPABILITY

This appendix describes the methods used to estimate the benefits of improved reliability on the maintenance manpower requirements for a 72-PAA F-16 A/B wing and on the wing's ability to generate sorties under simulated wartime conditions (while operating in place during a seven-day surge in activity).

Maintenance personnel include those assigned to the Deputy Commander of Maintenance, the Aircraft Generation Squadron, the Component Repair Squadron, and the Equipment Maintenance Squadron, but only those normally included in DOD Program Element 27133 (F-16 squadrons).

As described in the text, we concluded that a postulated twofold improvement in reliability enables an 8 percent reduction in maintenance manpower, and a fourfold reliability improvement enables a 14 percent manpower reduction.

A full summary of personnel estimates by skill area for 12 analysis cases is shown in Table A.1 and discussed below. How the 12 cases were constructed is discussed on pp. 26-27.

PERSONNEL ESTIMATES BY SKILL AREA

Although we did make separate estimates for each combination of individual AFSCs and maintenance organization, we have found the results more meaningful after grouping the estimates by aggregate skill category. Our final estimates are presented by skill category and case, along with the achieved sorties, in Table A.1. The notes to the table describe the relation between the major skill categories and AFSCs.

For each case, the total personnel were presented in Fig. 1. Results for the more interesting skill categories are presented graphically in Figs. A.1 through A.5. The reader should be aware that the results for the separate skill categories do not stand alone; rather they help detail the total personnel requirements shown on Fig. 1 and discussed earlier. In other words, the relationship shown on Fig. A.1 for avionics maintenance personnel is completely dependent on having the appropriate number of all other kinds of maintenance personnel available simultaneously. The numbers derived from Figs. 1 and A.1 through A.5 differ slightly from the numbers shown earlier on Tables 1 and 2 because, as noted in Sec. I, slightly different assumptions were used about the sortie rate.

Table A.1

SUMMARY OF PERSONNEL ESTIMATES BY CASE AND AGGREGATE SKILL AREA

Analysis Case	Avionics	Airframe & AGE	Propulsion	Crew Chiefs	Loaders	Munitions	Struct Repair	Wheel /Tire	DCM and OH	Total	Sorties Per Aircraft Per Day
1 x 24	171	191	94	219	115	91	26	12	338	1257	1.67
2 x 24	137	166	68	216	99	91	26	12	338	1153	1.67
4 x 24	104	150	57	216	97	95	25	12	338	1094	1.67
1 x 32	189	221	100	228	140	146	26	12	338	1400	2.22
2 x 32	154	195	78	225	131	146	26	12	338	1305	2.22
4 x 32	127	166	61	222	127	146	25	12	338	1224	2.22
1 x 48	229	256	127	243	167	238	26	12	338	1636	3.18
2 x 48	175	223	86	243	164	242	26	12	338	1509	3.28
4 x 48	142	190	63	240	154	246	25	12	338	1410	3.31
1 x 64	269	288	152	267	202	337	26	12	338	1891	3.72
2 x 64	198	250	95	261	198	343	26	12	338	1791	3.87
4 x 64	169	213	74	258	185	340	25	12	338	1614	3.95

Notes: Aggregate Skill Areas include the following AFSCs.

Avionics: 326X4 Automatic Test Station
326X6 Fire Control System
326X7 Auto Pilot/Instruments
326X8 Communications/Navigation/Electronic Countermeasures
404X1 Photographic

Airframe & AGE: 423X0 Electrical
423X1 Environmental
423X2 Egress
423X3 Fuel Systems
423X4 Pneudraulics
423X5 Aerospace Ground Equipment Maintenance

Propulsion: 426X4 Engine

Crew Chiefs: 431X1 Crew Chiefs

Loaders: 426G0 Gun Servicing
462L0 Loaders
462W0 Weapons Release

Munitions: 464X0 Munitions Assembly
464X1 Missile Maintenance

Structural Repair: 427X0 Machinist
427X1 Corrosion Control
427X2 Non-destructive Inspection
427X4 Welder
427X5 Structural Repair

Wheel/Tire: 431R1 Repair and reclamation
431W1 Wheel & Tire

DCM & OH: Deputy Commander for Maintenance and Overhead
338 = Total that could not be estimated by TSAR

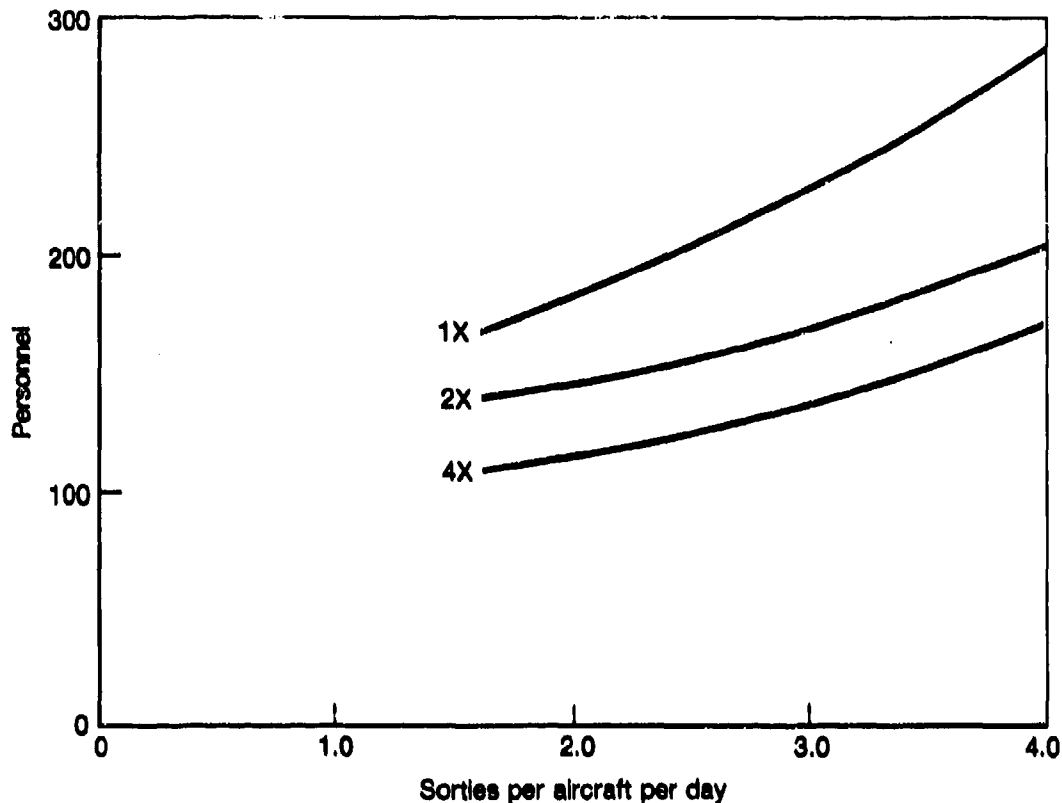


Fig. A.1—Avionics maintenance personnel, F-16 A/B wing

The largest single effect of improved reliability on personnel requirements is in the avionics skill group (see Fig. A.1). At roughly three sorties per aircraft per day, a twofold improvement in reliability results in a reduction of approximately 59 personnel, 26 percent of the number in this group. A fourfold improvement yields a further reduction of 31 personnel, 18 percent of the required avionics maintenance personnel. As reliability improvements are made, the requirements for avionics maintenance personnel are less sensitive to increases in sortie rate. With no change in reliability (the 1X case), moving from two to three sorties per aircraft per day results in a 25 percent *increase* in avionics maintenance personnel requirements. However, had reliability been improved by a factor of two (the 2X case), the required increase would have been only 18 percent.

Airframe and Aerospace Ground Equipment personnel (see Fig. A.2) behave somewhat differently. At about three sorties per aircraft per day, a twofold reliability improvement results in a savings of 32 personnel, approximately 13 percent of the total airframe and AGE personnel, while the fourfold improvement in reliability gives an

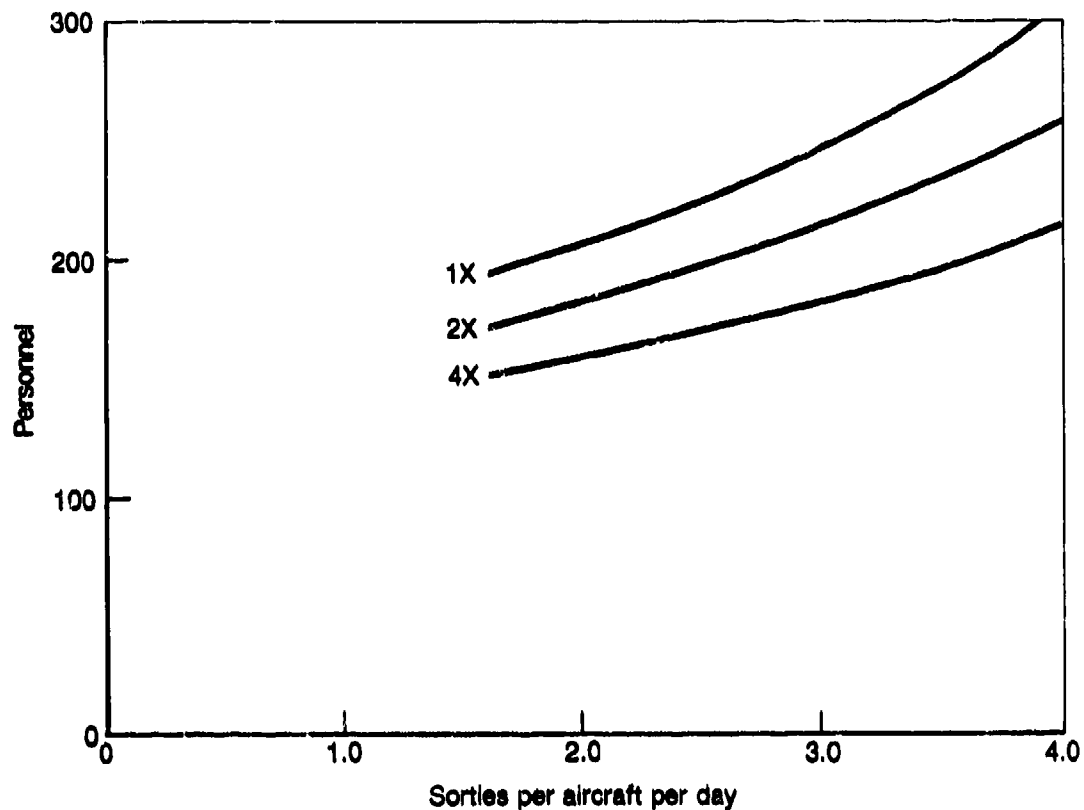


Fig. A.2—Airframe and AGE maintenance personnel, F-16 A/B wing

additional saving of about the same amount. We still see the decrease in the sensitivity of personnel requirements to sortie rate with improvements in reliability, but not nearly so much as in the case of the avionics technicians. This group behaves differently in the model largely because in our analysis, the AGE maintenance personnel who make up a large fraction of this group are only indirectly influenced by reliability improvements, and the other members of this group are the various airframe systems people who span many different AFSCs. For each AFSC, certain minimum numbers of personnel are always required on each shift.

Propulsion maintenance personnel requirements (see Fig. A.3) behave much like the avionics skill group. At three sorties per aircraft per day, a twofold reliability improvement reduces the requirement by 38, or about 32 percent of the total; a fourfold improvement saves only an additional 19 personnel, or another 23 percent. Again, improvement in reliability reduces the sensitivity of personnel requirements to increases in sortie rates.

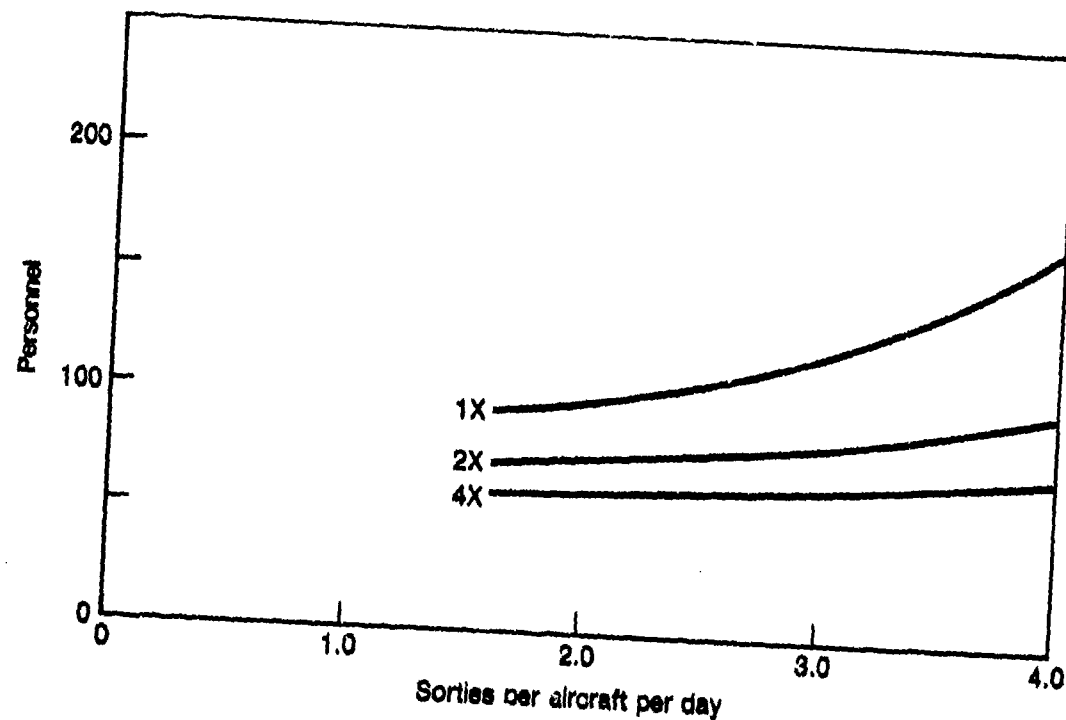


Fig. A.3—Propulsion maintenance personnel, F-16 A/B wing

The remaining maintenance personnel requirements (not including those for supervisory and overhead people) show little change as a result of improved reliability (see Figs. A.4 and A.5). However, the requirement for these personnel is largely a function of sortie rate independent of reliability. The curves on Fig. A.5 are heavily influenced by the constant requirement for 156 dedicated crew chiefs independent of sortie rate.

METHODOLOGY

Our estimates were made using a RAND simulation model called TSAR (Theater Simulation of Air Base Resources). [3,4,5]

The following discussion includes a short description of the TSAR model, our choice of scenario, the key assumptions, and the analyses themselves, plus a discussion of the overall estimating method.

Methodologically, not all of the maintenance manpower associated with the F-16 A/B wing was estimated using TSAR. As described in detail below, we used two different estimating methods depending on whether the personnel were assigned to the flightline or to

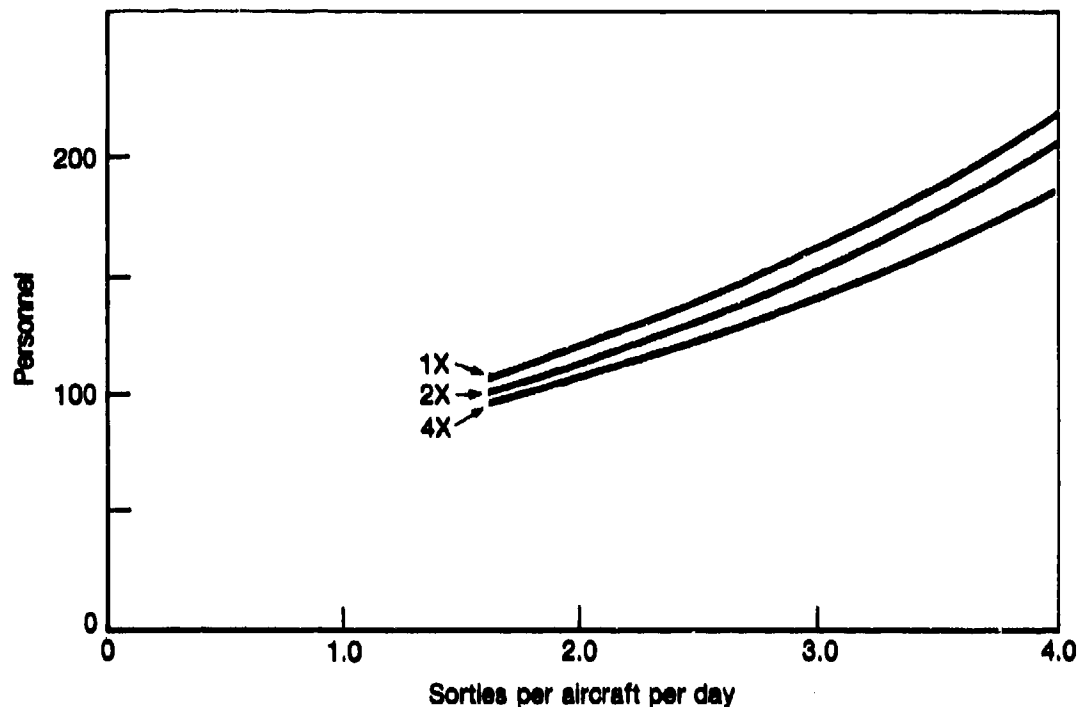


Fig. A.4—Loaders, weapons release, and gun maintenance personnel,
F-16 A/B wing

the support shops. Then we describe how we handled data on personnel not simulated by TSAR, followed by how we accounted for indirect work. Finally, we discuss how we dealt with variations caused by the random numbers and multiple trials inherent in the simulation.

HOW THE TSAR MODEL WORKS

The TSAR model was used to make most of the personnel estimates presented here. TSAR is a large Monte Carlo simulation model similar to the Air Force's Logistics Composite Model (LCOM). Both models were developed by RAND.

For this analysis, TSAR was used in one of its simplest modes—no base damage, no chemical warfare, a single operating base, etc. We simply simulated flying and maintenance activities for a wing of 72 F-16s during a seven-day wartime surge in an otherwise benign environment—no losses to attrition and no battle damage. Sorties were scheduled and TSAR attempted to fly them according to the schedule. As the sorties were flown, the model generated requirements for maintenance people, equipment, spare parts, fuel, ammunition, and the like, in order to fuel, arm, launch, recover, and repair aircraft and component parts.

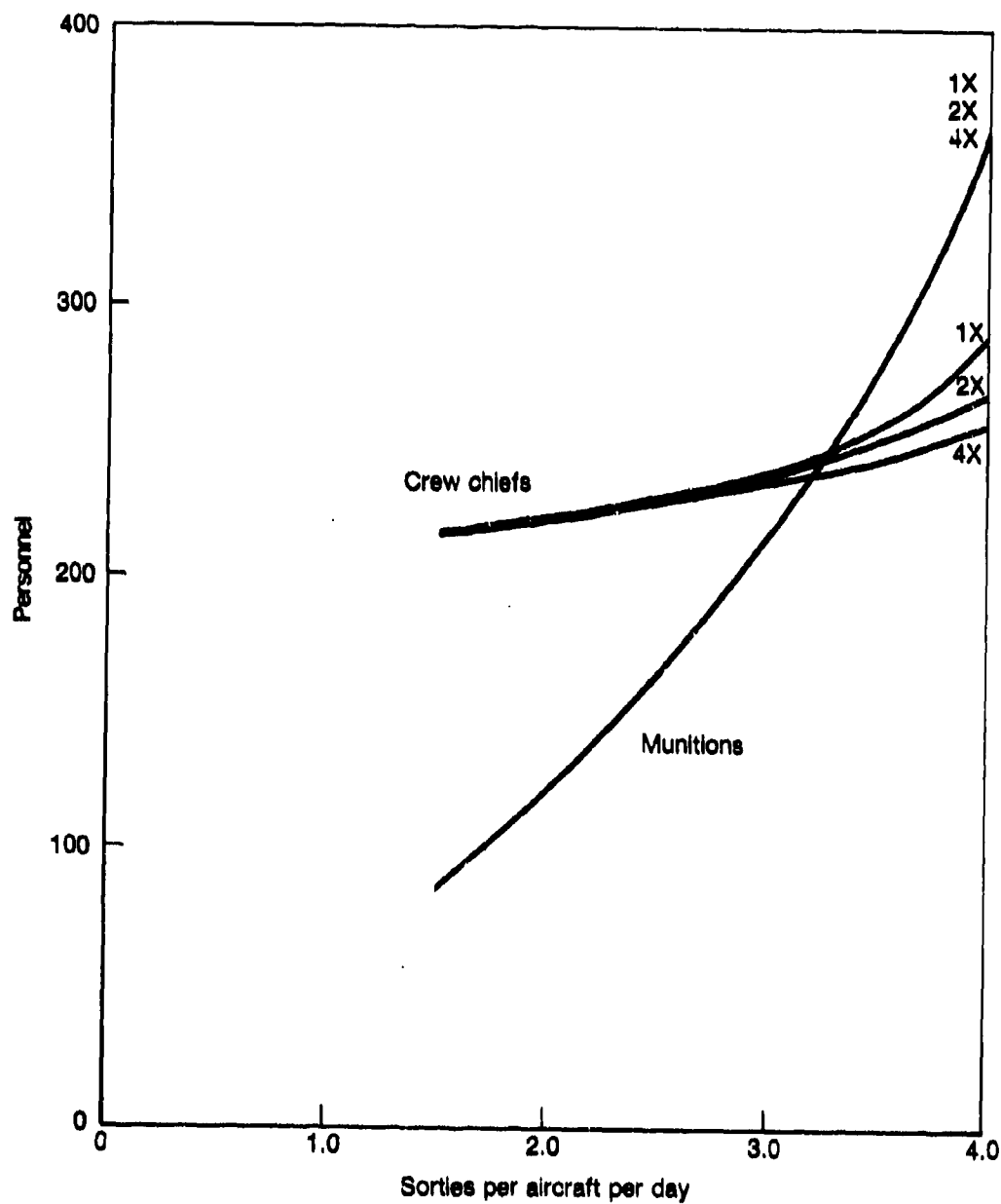


Fig. A.5—Munitions maintenance personnel, F-16 A/B wing

Similar to LCOM, TSAR represents on-equipment aircraft maintenance tasks by using *on-equipment task networks*. There is a separate network for each important aircraft system or subsystem—e.g., fire control system, propulsion, landing gear, vertical stabilizer assembly, primary flight control electronics. There are 84 of these networks for the F-16 A/B in LCOM and in TSAR. Associated with each network is a probability that it will be entered on any given sortie; once a network is entered, probabilities are again used to select the alternative paths through it.

After each sortie, a random draw is made for each network to determine whether the maintenance tasks represented by that network will be required. To reflect improved component reliability, we simply reduced the probability that the on-equipment network would be entered. The probabilities used to calculate personnel requirements assuming no-change-in reliability (the 1X case) were obtained from Headquarters, Tactical Air Command (LCOM/XPM). They reflect TAC experience with the F-16 A/B during the last six months of 1984, adjusted by TAC to reflect the differential use of a few aircraft systems in wartime vs. peacetime (for example, electronic countermeasures (ECM)).

For each maintenance task, the probability of occurrence, the expected time to complete the task, the number and kind of maintenance people needed to accomplish it and the probability that a spare part would be required, and any requirement for AGE were specified individually. When parts are replaced, the faulty parts are sent to intermediate-level maintenance (ILM) to be repaired or, if beyond the capability of ILM, to the next higher echelon (Centralized Intermediate Repair Facility (CIRF), depot, or contractor) for repair. Repair procedures and maintenance resource requirements—people, parts, and AGE—are also specified for each parts repair procedure for every part repaired in ILM.

THE SCENARIO, ASSUMPTIONS, AND ANALYSES

We simulated the operation of a single F-16 A/B wing (three squadrons of 24 aircraft each) fighting in place during a seven-day wartime surge, but with no aircraft attrition and no damage to the base. All sorties were air-to-ground and lasted an average of 1.7 hours. We tried to launch aircraft in flights (groups) of four, but accepted flights of three when four aircraft were not available. Otherwise, the entire flight was canceled. We allowed a 30-minute launch window (the flight could be launched any time during the 30-minute window before being scrubbed).

The model assumed that an unlimited supply of pilots was available, and no restrictions were placed on the availability of any nonpersonnel resources. Non-mission-critical maintenance was deferred until after the flying day if performing it

sooner would disrupt the flying schedule. However, cross-utilization training was not considered.

Twelve analyses were specified to span an interesting range of reliability improvements and sortie generation capability. These 12 cases are identified in Table A.2. Detailed maintenance personnel estimates were made for each case.

Table A.2

IDENTIFICATION OF ANALYSES, 5 WAVES PER DAY
(72-PAA F-16 A/B wing)

Scheduled Sorties per Wave ^a	Reliability Improvement Factor		
	1X	2X	4X
24	1 x 24	2 x 24	4 x 24
32	1 x 32	2 x 32	4 x 32
48	1 x 48	2 x 48	4 x 48
64	1 x 64	2 x 64	4 x 64

^aWaves scheduled at 0600, 0900, 1200, 1500, and 1800 hours each day.

The number of sorties scheduled to be launched in each of the five waves was set at 24, 32, 48, and 64, or an average total of 1.67, 2.22, 3.33, and 4.44 sorties per aircraft per day. As will be seen later, TSAR did not actually fly all of the scheduled sorties. The model aborts some flights before launch, and resource constraints sometime prevent an aircraft from being ready to fly at the time a sortie is scheduled.

We also examined three different levels of reliability. The 1X case reflects recent TAC experience with the F-16 A/B fleet. The 2X case reflects cutting the failure rates for the 1X case in half, and the 4X case cuts the failure rates in half again. We refer to 1X, 2X, and 4X as Reliability Improvement Factors.

Combining each of the four sortie generation schedules with the three reliability improvement factors yields the 12 analyses shown in Table A.2. For example, combining the 1X reliability improvement factor with a scheduled 48 sorties per wave results in the 1X 48 case.

OVERVIEW OF THE ESTIMATING METHOD

Both TSAR and LCOM have been used extensively by RAND and the Air Force to estimate maintenance manpower requirements. The usual approach, at the outset, is to provide the models with a flying scenario, an organizational description, an operating policy, a set of failure probabilities, and a *baseline set of resources* (number and kind of personnel,

AGE, spare parts, etc.). Usually several trials are then run using these resources and the results are examined to suggest possible changes in the initial resource set.

Both models provide an extensive set of indexes to describe how the weapon system in question performed during the simulations. These indexes include: the fraction of scheduled sorties actually achieved, number of maintenance tasks performed, number of shortages of each type of spare part, number of shortages of AGE, and average utilization rate for each type of personnel.

The analyst who examines these performance indexes looks for choke points or places where resources were provided but not used. On a particular trial, the analyst may find that several aircraft were grounded for lack of parts, or that there were not enough fuel trucks, or that aircraft were grounded because not enough people were available to perform a particular maintenance task. The analyst may also observe, for example, that the initial manning level provided four "widget fixers" but that they were never used. These insights then can be used to adjust baseline resources up or down in an attempt to *balance* the resource mix. The simulation is then rerun using a revised set of resources. Until a stable situation is achieved, the model may be run many times. Once stability is achieved, the analyst presumes that the resources are matched to the activity simulated and that the model will generate a reasonable estimate of the *requirements*.

The richness of detail allowed in the simulation models is a virtue because a great deal of realism is created. However, that detail makes it very difficult for the analyst to trace any problems encountered in the output performance indexes to their root causes. For example, the analyst may observe that avionics maintenance technicians in the support shop are being underutilized and suspect that too many technicians were provided. However, the real reason for this underutilization might have been that not enough power carts were provided to allow the flightline specialists to troubleshoot and remove the components that would otherwise have to be sent in for repair. There are just so many possible constraints on system performance that it is almost impossible to determine precisely which one is operating at any moment, and hence determine what to do about it.

Because TSAR and LCOM are Monte Carlo models, they must be run many times to sort out the effects of random variation from effects due to the controlled parameter values. Thus, using these models in the traditional way to estimate resource requirements becomes largely a matter of cutting, fitting, and iterating—a very time-consuming and expensive process and one not easily replicated.

We ran TSAR a bit differently in this analysis in order to reduce many of these difficulties. Instead of loading the model with a baseline set of resources (people) at the outset, we provided unlimited resources and let TSAR tell us what resources it actually utilized during the simulation. Also, at the outset we modified TSAR so that, at the end of each simulation time step (a three-minute period), data on the actual number of people assigned to the tasks (categorized by their specialty, shift, organization, and work place) were output. Later we used these data to make our personnel estimates. Exactly how is explained below in the sections starting with *Estimating Day-Shift Flightline Personnel*.

Another analytic problem inherent in the use of any large Monte Carlo simulation model is that every trial run yields a different answer, and it is difficult to decide whether the differences are due to changes made in the input values or to chance alone. The usual solution is to make many trials with the same input values and then average the results in some way to reduce the effects of chance. However, with models as large as TSAR or LCOM (with many random variables), that approach can be quite expensive. We have not found a simple solution to the random variation problem, but we did develop a method for working with it systematically and efficiently. We made many trials but, rather than averaging all the trials with the same input values, we used a regression approach to simultaneously average all the trials for all cases.

As noted above, each analysis is associated with a scheduled (desired) flying program, although just scheduling sorties does not guarantee that they will actually be flown. Even with unlimited resources, they seldom all are, either in reality or in the TSAR model, because of realistic time constraints and scheduling requirements that preclude the aircraft from flying constantly. Thus, having estimated the maintenance personnel required for a given sortie schedule does not actually tell us how many sorties we could actually generate. To derive the sortie generation capability of a given mix of maintenance people, we loaded our personnel estimates back into TSAR along with the scheduled sorties from which the personnel were estimated and then ran TSAR again to observe the sorties that were actually achieved. This will be described further in the section *Dealing with Random Numbers and Multiple Trials*.

PERSONNEL REQUIREMENTS ESTIMATED WITH TSAR

As noted above, we actually used two different personnel estimating methods within TSAR. Reasoning that launching of aircraft was the paramount task, we provided sufficient flightline personnel during the flying day so that seldom if ever would a demand for maintenance people go unsatisfied by the model. In other words, we manned the flightline

to peak requirements during this period. During nighttime on the flightline and at all times in the support shops, however, we felt that such immediacy was not required. So, for those situations, we provided only enough manpower to ensure that the workload received was accomplished sometime, we did not care when, during the shift.

Maintenance personnel are defined as all personnel in an F-16 A/B wing normally assigned to the Deputy Commander for Maintenance, the Aircraft Generation Squadron, the Component Repair Squadron, and the Equipment Maintenance Squadron. On many bases, such personnel might be augmented in order to provide maintenance support to tenant organizations on the base, but all such additional personnel were specifically excluded from our model.

Table A.3 presents a summary of the split by squadron of maintenance people estimated with TSAR and those estimated outside the model. Tables A.4 through A.7 provide a breakout of these figures by organization and organizational structure code. Estimates for the staff of the Deputy Commander for Maintenance as well as for several organizations within the three squadrons could not be made with the TSAR model because it does not deal with those functions. The numbers shown in the tables are those estimated outside of TSAR and were obtained specifically from the Unit Manpower Documents for the F-16 A/B wing at Shaw AFB during the 4th quarter of fiscal year 1986. These figures, totaling 338 people, were included, unchanged, in all of our estimates. The entire DCM staff was treated in this way. Also the people not dealt with in TSAR perform primarily supervision and overhead functions.

Table A.3

SOURCE OF F-16 MAINTENANCE MANPOWER ESTIMATES,
SUMMARY TABLE^a

Organization	Shaw AFB	Simulation
Deputy Commander for Maintenance	142	—
363rd Aircraft Generation Squadron	105	TSAR
363rd Component Repair Squadron	44	TSAR
363rd Equipment Maintenance Squadron	47	TSAR
Total	338	

^aIn organizations in which a number is shown for Shaw and TSAR is not indicated, we have estimated the manpower counting the personnel in the Unit Manning Documents (PEC 27133), FY 86 position, for 363rd Tactical Fighter Wing, three 24-PAA F-16 A/B Squadrons. In organizations in which a number is shown for Shaw and TSAR is also indicated, we have estimated manpower using both Unit Manning Documents and TSAR, because the model does not deal with all possible functions within that organization.

Table A.4

SOURCE OF F-16 MAINTENANCE MANPOWER ESTIMATES,
DEPUTY COMMANDER FOR MAINTENANCE^a

OSC ^b	Organization	Shaw AFB	Simulation
JN	Command	4	—
JNB	Training Management	3	—
JNBA	Training and Administration	7	—
JNBB	Development and Application	14	—
JNF	Maintenance Management	1	—
JNFA	Maintenance Systems Analysis	13	—
JNFB	Administration	7	—
JNFC	Programs	5	—
JNH	Quality Control	3	—
JNHA	FCF Weight Balance	2	—
JNHB	Inspection	24	—
JNHC	Technical Order Distribution	2	—
JNHE	Product Improvement	1	—
JNI	Maintenance Control	3	—
JNIA	Maintenance Operations Control	23	—
JNIB	Maintenance Plans	9	—
JNIBB	Combat Plans/Mobility	1	—
JNIC	Materiel Control	2	—
JNICA	Maintenance Supply Liaison	9	—
JNICC	Repair Cycle Monitor	11	—
JNID	Consolidation Engineering Maintenance	9	—
Total		142	—

^aTSAR is not indicated because the model does not deal with any functions within the DCM staff. We have estimated manpower using the Unit Manning Documents (PEC 27133), FY 86 position, for 363rd Tactical Fighter Wing, three 24-PAA F-16 A/B Squadrons.

^bOSC is the Organizational Structure Code.

ESTIMATING DAY-SHIFT FLIGHTLINE PERSONNEL.

Flightline personnel are responsible for doing on-equipment aircraft maintenance, uploading (and, when necessary, downloading) munitions, fueling, and otherwise recovering aircraft after a sortie and preparing it for the next sortie. Included in this category are the crew chiefs, various equipment maintenance specialists, and loaders.

Their primary responsibility is to recover the aircraft after each sortie and to prepare the aircraft to be launched on the next sortie. Many aircraft must be launched nearly simultaneously (within a 30-minute window). Thus, the workload is subject to extreme fluctuations. For short periods of time all available personnel will be required; at other times, they will have little to do. This fluctuation makes for low manpower utilization rates

Table A.5

SOURCE OF F-16 MAINTENANCE MANPOWER ESTIMATES,
AIRCRAFT GENERATION SQUADRON^a

AFSC	OSC ^b	Organization	Shaw AFB	Simulation
	AA	Command	3	—
	AZ	Squadron Section	8	—
	SA	General Supervision	11	—
	SAA	Load Standardization	28	—
	SA_	AC Maintenance (3 AMUs)	43	TSAR
431X1	SA_A	Crew Chiefs	1	TSAR
	SA_B	Flight Line Specialists	3	TSAR
462X0	SA_C	Weapons, Flight Line	6	—
462X0	SA_CA	Loading	—	TSAR
462X0	SA_CB	Maintenance	—	TSAR
Total			105	

^aIn organizations in which a number is shown for Shaw and TSAR is not indicated, we have estimated the manpower counting the personnel in the Unit Manning Documents (PEC 27133), FY 86 position, for 363rd Tactical Fighter Wing, three 24-PAA F-16 A/B Squadrons. In organizations in which only TSAR is indicated, we have used the model alone to estimate manpower. In organizations in which a number is shown for Shaw and TSAR is also indicated, we have estimated manpower using both Unit Manning Documents and TSAR, because the model does not deal with all possible functions within that organization.

^bOSC is the Organizational Structure Code.

but probably reflects wartime requirements adequately. This fluctuation requires that personnel be provided to meet approximately peak flightline manning (rather than average) demands. Therefore, our estimating methods have been tailored to provide the number of personnel needed to meet peak demands.

Each simulation provides sufficient data to prepare a probability distribution like the one shown in Fig. A.6 for each type of person working on the flightline during the daytime. The sample distribution shown is for crew chiefs in one Aircraft Maintenance Unit (AMU). Actually, a separate distribution is prepared for each AMU. The number of men observed to have been working per shift (during the simulation) is indicated on the horizontal axis. The vertical axis indicates the cumulative frequency or probability that this number or fewer will have been working at any time during the shift. The curve reflects the probability distribution obtained from a single simulation run and is used as follows:

Suppose that it was desired to provide enough crew chiefs so that only five out of every 100 times would there be a need for more of them than were provided. In other words, we would man according to a 95 percent peak cutoff criterion. The number of people required is then estimated by selecting the 95 percent point on the vertical axis,

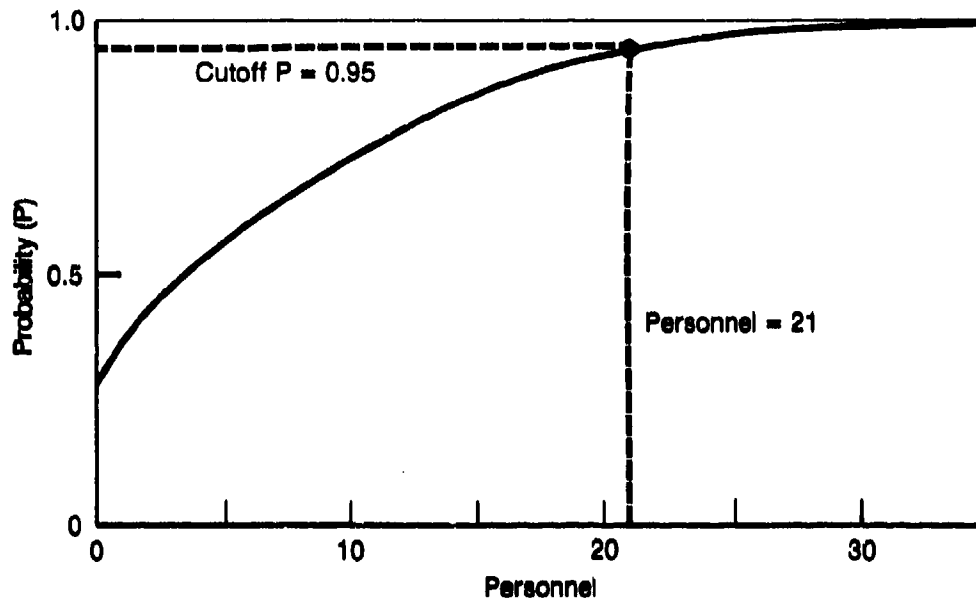


Fig. A.6—Probability that the number of personnel working is less than or equal to P

reading over to the curve and down to the horizontal axis as illustrated in Fig. A.6. For this example, 21 crew chiefs would have provided the desired capability in the simulation.

As noted above, separate estimates are made for each personnel type (AFSC) in each of the three AMUs. The observed workload will probably have been different among AMUs during the simulation, so each AMU will be found to have required a different number of people of the same specialty. We know that in another simulation, the AMU that had required the largest number of people previously might now require the fewest. That is simply the luck of the draw. Actually, there is no difference between the AMUs, so for determining requirements, we chose the maximum number of people required by any of the three AMUs and assigned that number to each AMU.

Obviously, the number of people assigned is a function of the cutoff criterion. After some initial discussions with people in the Tactical Air Command, we came to the conclusion that something like a 99 percent cutoff criterion would most nearly approximate Air Force policy and practice. We used this cutoff value in some early runs to *calibrate* the model and, by comparing our results with UMD figures, found that our estimates were a bit on the high side. We also did some experimenting by making personnel estimates using different cutoff criteria and then loading those people into TSAR and redoing the simulation.

Table A.6

SOURCE OF F-16 MAINTENANCE MANPOWER ESTIMATES,
COMPONENT REPAIR SQUADRON^a

AFSC	OSC ^b	Organization	Shaw AFB	Simulation
	AA	Command and Supervision	2	—
	AZ	Squadron Sectioning	5	—
	SC	Supervision	5	—
	SCB	Accessory Maintenance	3	—
423X4	SCBE	Pneumatics	—	TSAR
423X1	SCBF	Environmental Systems	—	TSAR
423X3	SCBH	Aircraft Fuel Systems	1	TSAR
423X2	SCBI	Hydraulic Systems	—	TSAR
423X0	SCBJ	Electrical Systems	—	TSAR
	SCD	Propulsion	5	—
426X4	SCDA	F-100 Jet Engine	1	TSAR
426X4	SCDB	Test Cell	—	TSAR
	SCE	PMEL-Type 11	1	—
	SCF	Integrated Avionics	3	—
326X4	SCFA	Automatic Test Station	3	TSAR
328X3	SCFC	EW Test Station	—	TSAR
404X1	SCFD	Sensor/Photos Systems	—	TSAR
	SCFF	Type 4 PMEL	15	—
Total			44	

^aIn organizations in which a number is shown for Shaw and TSAR is not indicated, we have estimated the manpower counting the personnel in the Unit Manning Documents (PEC 27133), FY 86 position, for 363rd Tactical Fighter Wing, three 24-PAA F-16 A/B Squadrons. In organizations in which only TSAR is indicated, we have used the model alone to estimate manpower. In organizations in which a number is shown for Shaw and TSAR is also indicated, we have estimated manpower using both Unit Manning Documents and TSAR, because the model does not deal with all possible functions within organization.

^bOSC is the Organizational Structure Code.

We observed the resulting sortie production and noted that we could reduce the cutoff percent from 99 to 95 percent with no distinguishable effect on sortie production; when we dropped it to 90 percent and lower, sortie production decreased noticeably. We finally settled on a 95 percent cutoff criterion and have used that value in the analyses presented here.

ESTIMATING SUPPORT SHOP AND NIGHT-SHIFT FLIGHTLINE PERSONNEL

Support shop personnel include all of the technicians assigned to the Component Repair Squadron and the Equipment Maintenance Squadron. For the most part, the people in these shops are insulated from the flightline by the base spares. When an aircraft returns

Table A.7

SOURCE OF F-16 MAINTENANCE MANPOWER ESTIMATES,
EQUIPMENT MAINTENANCE SQUADRON^a

AFSC	OSC ^b	Organization	Shaw AFB	Simulation
	AA	Command and Supervision	2	—
	AZ	Squadron Section	6	—
	SB	Equipment Maintenance Supervision	7	—
	SBA	AGE—Flight Line Equipment	6	—
423X5	SBAA	Repair and Inspection	—	TSAR
423X5	SBAB	Service/Pickup/Delivery	—	TSAR
423X5	SBAD	Nonpowered Support	—	TSAR
	SBB	Maintenance	3	—
	SBBA	Aircraft Inspection	—	TSAR
431X1	SBBC	Repair and Reclamation	—	TSAR
	SBE	Armament Systems	3	—
462X0	SBEA	Maintenance	—	TSAR
462X0	SBEB	Alternative Mission Equipment	6	—
462X0	SBEC	Armament Support Equipment	—	TSAR
461X0	SBG	Munitions Systems Support	1	TSAR
461X0	SBGB	Munitions Control	10	—
	SBGC	Line Delivery	2	—
461X0	SBGCA	Handling	—	TSAR
461X0	SBGCB	Munitions Maintenance	—	TSAR
461X0	SBGCC	Equipment Maintenance	—	TSAR
461X0	SBGE	Missile Maintenance	—	TSAR
	SBGF	Material Production	2	—
	SBGFA	Storage and Handling	—	TSAR
	SBGFB	Inspection	—	TSAR
	SBH	Fabrication	2	—
427X4	SBHA	Metals Processing	—	TSAR
427X5	SBHB	Structural Repair	—	TSAR
427X3	SBHC	Survival Equipment	—	TSAR
427X0	SBHE	Machine Shop	—	TSAR
427X1	SBHF	Corrosion Control	—	TSAR
427X2	SBHG	Nondestructive Inspection	—	TSAR
Total			47	

^aIn organizations in which a number is shown for Shaw and TSAR is not indicated, we have estimated the manpower counting the personnel in the Unit Manning Documents (PEC 27133), FY 86 position, for 363rd Tactical Fighter Wing, three 24-PAA F-16 A/B Squadrons. In organizations in which only TSAR is indicated, we have used the model alone to estimate manpower. In organizations in which a number is shown for Shaw and TSAR is also indicated, we have estimated manpower using both Unit Manning Documents and TSAR, because the model does not deal with all possible functions within that organization.

^bOSC is the Organizational Structure Code.

from a sortie needing repair, the most likely sequence of events is for the flightline people to recover the aircraft, diagnose the problem, and either fix it or remove and replace a faulty component with a serviceable spare from base supply. At that point, the aircraft is flyable again. The faulty part is then sent to the support shops for repair, but exactly when it is repaired is not an important factor in determining when the particular aircraft can fly again. Because spares are likely to be limited, however, the part must be repaired in a reasonable time and returned to supply in serviceable condition.

All of this leads to a different criterion for manning the support shops. Our calibration runs led us to choose the maximum total manhours required for the shift (day and night) over the seven days in the simulation. The manhours actually used during the unconstrained simulation run were calculated, from TSAR output data, for each personnel type (AFSC) in each of the support shops. The appropriate maximum manhours were selected and manning requirements were calculated by assuming that men were available for work 12 hours per day seven days per week.¹ The same method was used to estimate night-shift personnel for the flightline. As before, manning for each specialty in each AMU was calculated separately, and the maximum across the three AMUs was given to each AMU.

ACCOUNTING FOR INDIRECT WORK

All of the manpower estimates made using TSAR were inflated to account for indirect work by using the currently acceptable Air Force factors of 0.82 direct and 0.18 indirect.² Normal Air Force practice is to vary these figures slightly among the different specialties, but we applied the same figures across the board.

PERSONNEL NOT ESTIMATED WITH TSAR

Activities that generate requirements for administrative, overhead, and certain other kinds of maintenance personnel are not simulated with TSAR. For most of these, we simply used figures from the Unit Manpower Document for Shaw AFB (4th quarter, FY 86 position). At that point the F-16 wing at Shaw was operating similarly to our simulated wing. Tables A.4 through A.7 indicate by organization and OSC exactly which requirements we took directly from the Shaw UMD and which were estimated using TSAR. As indicated, the entire DCM staff and 338 people in all were estimated in this way.

¹AFR 26-1, Vol. III, (C1), Table 1-2. Standard Air Force Workweeks and Manhour Availability, p. 1-3.

²Ibid.

An additional requirement for 156 dedicated crew chiefs was calculated outside the model. We added one crew chief per aircraft per shift for a total of 144 and another 12 for end-of-runway duty.³

DEALING WITH RANDOM NUMBERS AND MULTIPLE TRIALS

As with any Monte Carlo simulation model, numerous trials are required simply to distinguish between variation in the results caused by variation in the random number streams and that caused by changes in the values of the inputs. After considerable experimentation we decided on five trials for each of the 12 analysis cases. Given that there are roughly 2000 sorties flown per trial, this meant that we simulated approximately 120,000 sorties. The differences between cases were usually more significant than the variation from trial to trial for the same case.

Several methods were tried in an effort to make our final estimates vary smoothly and reasonably with changes in the component reliability and sorties flown. For example, it is not reasonable to determine that there is a requirement for more maintenance personnel when the component failure rates used were lower and the sortie schedule was the same. Occasionally, there were two trials whose outcomes would be inverted in that way.

We first ran five trials for each of the 12 analyses (four sortie schedules times three reliability improvement factors) and preserved the detailed output from TSAR for each of these 60 trials. Using these data, we then estimated personnel requirements by AFSC and organization for each of the 60 trials. At that point we regarded each combination of AFSC and organization as a separate database and ran a separate regression for each using the equation

$$P = \alpha + \beta-1 \times \text{SORTIES} + \beta-2 \times \text{WORK} + \beta-3 \times \text{SORTIES} \times \text{WORK} ,$$

where: P = personnel in a specified AFSC and organization,
SORTIES = scheduled sorties,
WORK = 1.0, 0.5, 0.25 for reliability improvement
factors of 1X, 2X, and 4X, respectively.
 α and $\beta-1, -2, -3$ = parameters estimated

The particular form of the regression was chosen after we plotted the initial personnel estimates for each AFSC against the reliability improvement factor and sortie schedule. All

³Per our discussions with maintenance personnel in the 388th Tactical Fighter Wing at Hill AFB during the summer of 1985.

of the plots indicated the same general relationship (for each reliability improvement factor, people were a linear function of SORTIES, but the level and the slope were increasing functions of WORK). The equation chosen was selected because it was among the simplest forms we could find to express the desired overall relationship. Most of the time we obtained R^2 values above 90 percent. With the coefficients estimated, we used the regression equations to adjust the number of maintenance personnel required.

At this point, with a refined and largely consistent set of personnel estimates, we turned our attention to the following problem: Thus far, personnel requirements had been estimated from planned sorties but what we really wanted was to calculate personnel requirements *as a function of sorties actually flown*. Therefore, we now loaded our personnel estimates back into TSAR (for each of the 12 analysis cases) and ran 10 more trials for each case, or a total of 120 trials, in order to observe the sorties actually produced. Our final estimate of sorties produced was obtained by averaging the sortie production over the 10 trials for each case. The results are shown in Table A.8.

We made one more refinement by repeating the regression analysis, but this time using the achieved rather than the scheduled sorties. We then adjusted the results for expected availability and added in the people not dealt with in TSAR—the dedicated crew chiefs and the supervisory and overhead personnel.

Although we are sure that the estimates presented here are not "accurate" in any definitive sense, we believe that they present a realistic picture of the savings in maintenance manpower that can be expected from improving aircraft component reliability.

Table A.8
SORTIES ACHIEVED VS. SORTIES SCHEDULED BY CASE

Case	Scheduled Sorties per Aircraft per Day	Achieved Sorties per Aircraft per Day
1 x 24	1.67	1.67
2 x 24	1.67	1.67
4 x 24	1.67	1.67
1 x 32	2.22	2.22
2 x 32	2.22	2.22
4 x 32	2.22	2.22
1 x 48	3.33	3.19
2 x 48	3.33	3.26
4 x 48	3.33	3.31
1 x 64	4.44	3.72
2 x 64	4.44	3.87
4 x 64	4.44	3.95

Appendix B

ESTIMATING THE EFFECTS OF RELIABILITY ON THE LIFECYCLE COSTS OF ENGINES, ENGINE MODULES, AND RECOVERABLE SPARES

INTRODUCTION

In this study, we have estimated the effects that enhanced reliability of selected aircraft systems and subsystems would have on the costs for engines, engine modules, and recoverable spare parts for the F-16 A/B aircraft. *Recoverable* spare parts are those that are repaired when they fail rather than being discarded (as consumable parts are). Inventories of spare parts comprise both *peacetime operating stocks* and war reserve materiel (WRM). The portion of war reserve materiel intended to be deployed in wartime with operational units is usually maintained in air-transportable containers and constitutes what is called *war reserve spares kits*. The focus of this work is on *recoverable* POS, but a rough estimate was also made of the effects of enhanced reliability on capital requirements for recoverable spares in the WRSK.

The effect of improved reliability on costs was examined in two separate analyses: The first estimated the potential effect of increased reliability on reducing the capital costs of the F-16 A/Bs engines, engine modules, and POS. The second extended the first by estimating the effect of increased reliability on the total lifecycle costs of their recoverable POS (the capital costs of acquiring enough recoverable spare parts to initially fill the entire spare parts resupply pipeline—including removal from an aircraft, through repair facilities at the base or depot, to final return to the base or condemnation when beyond economical repair—plus the costs of replenishing the inventory system with new spare parts). Lifecycle costs thus include initial procurement of spare parts, the costs of repairs at the depot, and the cost of replenishment spares to replace those that have been condemned in order to keep the inventory system operating at some desired level of performance. The computation of requirements for recoverable spare parts is done with computerized computational systems, each of which contains a model of the resupply system.

In the model, when a component in an aircraft is deemed to have failed, it is removed and sent to the base's repair shop. If a serviceable spare is available, that spare is installed on the aircraft immediately. Meanwhile, the failed part is either repaired at the base and added to its supply of spare parts or designated as *not-repairable-this-station* (NRTS) and

shipped to the next level, which is depot repair, along with an order that a replacement be sent to the base to replenish its serviceable stock.

At the depot, the failed part is repaired and returned to a base or placed in inventory. If it is beyond economical repair, it is *condemned* and a replacement is usually ordered from the manufacturer. At all times, the model attempts to keep the number of spare parts available throughout the entire supply system at or above the authorized stock level. For example, whenever the number of components on hand at the base plus those on order (minus those already ordered to make up for existing shortages in aircraft) falls below the authorized stock level, another spare is ordered immediately.

Condemnation costs refer to the replacement costs of spare parts that are beyond economical repair and are disposed of. As used in the model, a *pipeline* is defined as the expected number of spare parts in *resupply*—in base repair, depot repair, in transit between depot and base, or awaiting replacement after condemnation. When we occasionally refer to sections of the resupply pipeline—e.g., "the base repair pipeline" or the "order-and-ship pipeline"—we simply mean the expected number of components undergoing base repair or in transit from the depot to the base.

The analytical techniques used to estimate the effects of enhanced reliability on the capital and replenishment costs of engines, engine modules, and recoverable spare parts are discussed in this appendix. The two analyses were done about 1-1/2 years apart.

The first study estimated the reduction in the capital costs of engines, engine modules, and recoverable spares that might have been achieved if the F-16 A/B aircraft's fire control and propulsion systems had been initially designed with greater reliability. By *capital costs* we mean the total cost of all initial stock levels in the supply system, given a specified, steady-state description of the flying hour program, aircraft force structure, item characteristics, and aircraft availability goal. We postulated twofold and fourfold improvements in component reliabilities for these two systems.

The second study attempted to extend our estimates of capital costs for recoverable spares to include their total lifecycle costs from the initial investment for procurement through depot-level repair and stock replenishment to eventual disposal.

Clearly, cost reductions constitute only one class of benefit to be derived from improved reliability. Enhanced combat capability through improved mission performance and higher sortie generation rates are also achievable.

This appendix is divided into two main sections: The first covers the case of estimating capital costs for engines and engine modules. The second major section deals with recoverable spare parts. It describes how capital costs were estimated, then discusses

problems encountered in inferring lifecycle procurement costs of recoverable spares (the additional capital cost of replacements needed just to maintain a certain level of performance in the face of changing demands and changes in the characteristics of parts—e.g., demand rates) from our knowledge of initial capital costs. Then we suggest a way of estimating the lifecycle costs of recoverable spares. After that we discuss their lifecycle depot-level repair and condemnation costs.

THE CAPITAL COSTS OF ENGINES AND ENGINE MODULES

The estimate of initial capital costs for engines and engine modules was done by Headquarters, AFLC/XRS, using Mod-METRIC, the model the Air Force itself uses to compute such requirements. Our computation is literally a replication of the Air Force's. The resulting estimates were scrutinized by personnel at the Acquisition Logistics Division and Headquarters, AFLC. The scenario shown in Table B.1, which was used for this computation, approximates the F-16 A/B force structure and flying hour program in the third quarter of fiscal year 1985. The flying hour program specified assumes equal utilization rates for all aircraft.

AFLC computes two requirements for engines and engine modules. The first is for POS; the second is the wartime requirement based on providing for 30 days of removals at wartime rates. AFLC's stated requirement, subject to later adjustment, is simply the larger of the two numbers. In our computation, the wartime requirement was invariably the larger

Table B.1

SCENARIO FOR ENGINE AND ENGINE MODULE REQUIREMENTS COMPUTATIONS

Base	PAA	Order-and- Ship Time	Flying Hours per Month
McEntire	24	10	670
USAFE A	72	15	2000
USAFE B	72	15	2000
PACAF A	48	15	1340
Hill	121	10	3370
Shaw	48	10	1340
Nellis	93	10	2590
Eglin	3	10	80
MacDill	84	10	2340
Luke	51	10	1420
Edwards	16	10	450

of the two. The computed peacetime requirements were \$462 million, \$280 million, and \$170 million for the current (1X), the twofold (2X), and the fourfold (4X) reliability cases, respectively. Table B.2 reflects the wartime requirements, which were 60-65 percent higher for each case.

The computation of investment requirements for engines and engine modules was done for the time when the combination of force posture and flying hour program yielded the greatest requirement—the third quarter of fiscal year 1985. In contrast to the case of recoverable spare parts, which is discussed below, initial capital cost constitutes the total investment cost requirement for engines and engine modules over the lifecycle of the weapon system. Also, the phenomenon of *churn*, the substantial year-to-year changes in the database used to support the computation of requirements for recoverable POS, is not a concern in these calculations of engine requirements because engines and engine modules are not included in the recoverable spares database but engine recoverable spare parts are. Thus, the engine and engine module capital costs in Table B.2 already represent total lifecycle investment costs. As can be seen, at a twofold reliability improvement, the potential saving in capital costs is approximately \$340 million.

ESTIMATING THE EFFECTS OF ENHANCED RELIABILITY ON THE CAPITAL COSTS FOR RECOVERABLE SPARE PARTS

The capital cost for recoverable spare parts is the cost of providing sufficient stock to fill the recoverable spare parts supply pipeline and protect against demand variability. The requirements computational method presumes a given (specified) steady-state system description and specified level of performance.

Table B.2

ENGINE AND ENGINE MODULE REQUIREMENTS

Reliability Factor	Requirement (\$ millions)
1X	787.8
2X	448.1
4X	270.7

Our estimates of the capital costs for recoverable spares were made using the Logistic Management Institute's Aircraft Availability Model. The logic of the model is consistent with that planned for the Air Force's computation of recoverable item requirements.[8]

AAM is an analytical model based on probabilistic and economic concepts. It produces expenditure vs. availability curves by relating procurement and repair costs to aircraft availability rates.

By ranking aircraft spare parts as candidates for procurement and repair in decreasing order of benefit per cost, AAM optimizes aircraft availability for any given funding constraint and produces optimal "shopping lists" and repair requirements by component, for any specified funding level.

AAM considers an aircraft "available" as long as it is not awaiting repair, replacement, or shipment of a recoverable component. However, such other circumstances as the need for on-aircraft maintenance or a lack of consumable spare parts may prevent an aircraft from performing its mission. Thus, *availability* is not a complete measurement of mission readiness.

Our approach to estimating capital costs as a function of reliability consisted of several steps:

1. Specify the force structure and aircraft utilization rates consistent with the AAM's average base assumption.
2. Using the Air Force's current DO41 database, compute the *stockage posture* (total stock levels of all recoverable spare parts required to achieve an estimated 80 percent aircraft availability rate during peacetime).
3. Compute the baseline capital cost of this stockage posture using the current unit price extended over the total quantity of each line.
4. Postulate improved reliability for just the subsets of items associated with the propulsion and fire control systems, and recompute the stockage posture for 80 percent availability (for both 2X and 4X reliability improvements).

Up to this point, we are dealing only with initial capital costs. Therefore, this procedure does not account for condemnation costs nor for the costs caused by churn in the database over time (e.g., items being deleted from the database, new items being added, and existing item characteristics changing). These issues, as well as depot-level repair and condemnation costs, are addressed below.

To use AAM in step 1, we first attempted to determine the stock numbers associated with each of the two aircraft systems, propulsion and fire control, through use of the WUC-NSN dictionary that matches the work unit codes used in the maintenance data system with national stock numbers. However, we found that the dictionary did not contain work unit codes for many items, so we finally used federal stock class (FSC) as a surrogate for WUC. We inferred the first two digits of the WUC from a cross-tabulation of FSC with WUC. This mapping supports the use of the FSC for our purpose; the estimate appeared to be quite good in the sense that each of the federal stock classes chosen for inclusion in one of the two systems had a very high proportion of applications to that system. Table B.3 shows the mapping.

A few of these FSCs are exclusive to the propulsion and fire control systems (1270 and 2840, for example). Most are not. Those that are not were chosen for inclusion based on the high *proportion* of their applications to these two systems. Certain other FSCs also applied to the systems but were excluded because those particular applications represented only a small proportion of their total applications.

In step 2 we computed the required stockage posture. The analysis consisted of several steps.¹ First, an F-16 database was extracted from the March 1984 DO41 database.

Table B.3

INFERRED MAPPING OF FEDERAL STOCK
CLASS INTO AIRCRAFT SYSTEM

Propulsion System	Fire Control System
2840	1270
2915	5841
2925	5985
2935	5990
2995	6605
6340	
6685	

¹ This discussion draws heavily from Ref. 11.

This file contained only those components applicable to the F-16. For F-16 components that also were common to one or more other model-design aircraft as specified in the March 1984 DO41 database, prorated condemnations and demand rates were used.

We then examined the F-16 A/B force structure from FY 78 through FY 90 (the period covered in available Air Force planning documents). As time passes during this period, the F-16 A/B aircraft used by USAF are turned over to the Air National Guard and replaced by the F-16 C/D. This "migration" of the F-16 A/B results in a changing force posture. The number of F-16 A/B aircraft locations grows over time while the number of aircraft per location diminishes.

Because the force configuration has implications for resource requirements, we also determined for each resource category (engines, engine modules, and recoverable spares) the time when the combination of programmed flying hours and force structure would yield the greatest investment requirement. As noted above, the third quarter of FY 85 was found to be the most demanding for each of the resource categories examined.

We then modified this F-16 database to reflect the force configuration and activity levels extracted from the USAF planning documents. They are summarized in Table B.4.

AAM asset levels (the number of recoverable spares in the model) were set to zero, except for the expected number of items in the condemnation portion of the supply pipeline. This was done because we were interested in estimating the *capital* cost of stock levels to support a specified 80 percent aircraft availability under assumptions of alternative system reliability. The resulting capital costs computed by the AAM for stock levels in the supply pipelines (plus safety levels) were then offset by the condemnation pipeline quantities, leaving only the safety level portions. This was because we did not wish to include any replenishment costs in our estimates (such as those represented by asset condemnations).

Table B.4

SCENARIO DATA FOR COMPUTING RECOVERABLE POS REQUIREMENTS

Item	All F-16s	F-16A	F-16B
Number of aircraft	627	533	94
Hundreds of flying hours per quarter ^a	527	448	79

^aFlying hours based on 11 bases, 57 aircraft per base, and 84 flying hours per aircraft per quarter, an abstraction of the USAF planning factors.

For technical readers, it may be of interest to note that the next stage of the procedure was to produce a variable-safety-level (VSL) file from our modified F-16 database. In producing the VSL file, 4953 national stock numbers (NSNs) were processed, 3589 of which had F-16 applications and 1364 of which had no application but did have F-16 system management codes (SMCs). These 1364 items were not allocated safety stock in the marginal analysis—only enough assets were computed to fill the supply pipeline; 296 NSNs that had only F-16C or F-16D applications were dropped in the processing, reducing the NSN count of the VSL file to 4657. This VSL file was then input to the AAM model. Each time the model was run, it computed procurement requirements only, ignoring repair requirements. The variance-to-mean ratios used were derived from Sherbrooke, [9] but departed from his method in that the weighted resupply time was used in lieu of a fixed time period. For each item, the variance-to-mean ratio was specified to be:

$$V/M = 1.0 + ax^b, \text{ where}$$

x = expected number in resupply (the pipeline),

a = 0.1535, and

b = 0.5785.

The goal of this exercise was to estimate the savings in the extended costs of all stock levels in the system that might have been realized if the F-16's propulsion and fire control systems had been developed with better reliability characteristics. Thus we compared the current total recoverable peacetime operating stock investments required (the 1X case) with those needed when the reliability of each system was increased by a factor of two (2X) and by a factor of four (4X). The resulting curves also portray the various combinations of capital costs at reliability factors ranging all the way from 1X to 4X. In this exercise, a fourfold reliability improvement to the fire control system, for example, was modeled by multiplying by 0.25, the resupply pipelines of all components whose FSCs are shown in the righthand column of Table B.3, while a twofold reliability was modeled by multiplying the pipeline by 0.50. (This assumes that the resupply pipeline is a linear function of component removal rate.)

For step 3, Table B.5a summarizes the capital costs required to support an 80 percent aircraft availability rate for the F-16 force, given the scenario specified in Table B.4, with three levels of reliability for the fire control and propulsion systems. In Table B.5a, the entry in the first row, first column, is the estimated baseline investment cost associated with the

Table B.5a

CAPITAL COSTS OF RECOVERABLE SPARES TO MAINTAIN
80 PERCENT AIRCRAFT AVAILABILITY
(Million \$)

Fire Control System Reliability Factor	Propulsion System Reliability Factor		
	1X	2X	4X
1X	627.3	573.3	541.0
2X	545.5	492.4	461.0
4X	505.7	453.5	422.7

Baseline Investment = \$627.3 million.

Savings = baseline - entry (investment costs after improved reliability).

component removal rates in the USAF's DO41 database. The entry in the second row, third column, for example, represents the costs that result from an increase in reliability by a factor of two for the fire control system and a factor of four for the propulsion system. Other entries in the table are interpreted similarly. Again, these estimates represent only *the capital costs for recoverable spares required to fill resupply pipelines, plus safety levels*. As pointed out previously, they do not include the costs of condemnation replacements nor the costs induced by churn in the database—changes in weapon system configuration, item configuration, or item characteristics.

The results of step 4 are presented in Table B.5b. It summarizes these same pipeline and safety-level costs for the fire control and propulsion system components. These are a subset of the costs shown in Table B.5a and the data are arranged similarly to those in Table B.5a.

ESTIMATING LIFECYCLE COSTS OF RECOVERABLE SPARES

In this section, we discuss some of the problems involved in extending these findings to lifecycle cost estimates for recoverable spares.

The lifecycle costs of recoverable spares include procurement, depot-level repair, and condemnation costs. The work described here was undertaken about a year after the estimates in the previous section were made. Thus, there are some differences in the assumptions made about flying hour programs and force structure simply because the data sources had been revised between the two analyses.

Table B.5b

**CAPITAL COSTS OF PIPELINE PLUS SAFETY-LEVEL STOCKS FOR
THE FIRE CONTROL AND PROPULSION SYSTEM COMPONENTS^a**
(Million \$)

Fire Control System Reliability Factor	Propulsion System Reliability Factor		
	1X	2X	4X
1X	174.6	152.8	141.9
2X	137.1	115.4	104.5
4X	127.1	105.4	94.5

^aExcludes \$160 million in fixed insurance costs and related costs not associated directly with the demand for spare parts.

Baseline Investment = \$174.6 million.

Savings = baseline - entry (investment costs after improved reliability).

The Problem of Estimating Lifecycle Procurement Costs²

Estimating lifecycle procurement costs for recoverable spares is difficult because of the dynamics of the database itself. The database, in fact, changes dramatically from year to year. This churn considerably increases the lifecycle costs of recoverable spare parts. Consider the case in which there is no stock in the system and we wish to compute the mix of stock levels that would minimize the cost of achieving some specified level of aircraft availability. We define the planning horizon involved in such computations as the average procurement lead time for the spare parts to be acquired in order to fill those stock levels and have set that lead time at 24 months.

As previously discussed, the LMI Aircraft Availability Model is designed to solve this optimization problem.[8] Let's say we apply the AAM to this problem (based on an initial no-asset position) and determine that the level of investment required is, for example, \$600 million in recoverable spares for the F-16 A/B force to achieve an aircraft availability rate of 80 percent. Suppose, too, that we wish to determine how much additional investment would be required each year to maintain that 80 percent availability rate across an indefinite future planning horizon. If we run AAM a second time using the same database (the VSL file), but this time compute only the additional investment that would be required a year later, the result would be a fairly small investment requirement. In fact, the requirement would be only that associated with the cost of condemnation replacements, given a constant force structure and flying hour program.

²The discussion that follows is based largely on Ref. 12.

If we waited for a year before computing the investment needed to maintain the specified level of performance, however, the database on which our computations are based would have changed in many ways in the intervening year. For example, the force structure might not have evolved as we had originally planned, or the flying hour programs might have changed, or items formerly applicable to the aircraft would no longer be applicable, and new items would have appeared in the database that were not there before. Moreover, many item characteristics themselves would have changed, such as the NRTS rates, repair times, component removal rates, order-and-ship times, unit prices, etc. With all the changes, computation of the investment required to maintain the specified level of system performance is likely to be dramatically different from that using the previous year's database.

As a practical matter, the investment requirement is likely to be far higher for two reasons: First, if an item's supply pipeline requirements decrease, some of the stocks of that item on hand do not contribute much to aircraft availability because they are less likely to be needed; second, if the number of items in the pipeline increases, additional investment is required to provide the same level of performance as before. Intuitively, such random changes in the factors influencing item pipelines occur across many items and tend to induce the need for substantial additional annual investments in order to sustain a specified level of performance.

The magnitude of the effects of churn is really rather remarkable when contrasted with analytic results derived from the naive viewpoint that the requirements database models a steady-state system. It clearly does not. The database is subject to all of the dynamics that affect the real world that it represents. Those dynamics are substantial even in a fairly benign peacetime environment and are likely to be compounded by rapidly changing circumstances in wartime. We believe that planners should be able to accurately estimate the lifecycle procurement costs of the recoverable spares needed to maintain a specified level of availability across the life of a weapon system. Doing so requires that churn be quantified, assigned a dollar value, and incorporated into estimates of annual investment requirements for replenishment spares.

In accounting for this churn, we developed a measure of its effect on the computed annual investment requirement. This churn factor is simply the computed additional investment caused by the churn alone divided by the total capital costs. In other words, it is the proportion of the total capital costs (the total cost of all stock levels at all locations in the system) spent on additional spares just to keep up with database dynamics.

The Analytic Design

In estimating total lifecycle procurement costs for recoverable spares for the F-16 A/E, we estimated the dollar amount of churn in successive years, the churn factors, and their effects on additional annual investment requirements. What we learned is undoubtedly not unique to this program, however, and we believe it can and should be applied in principle to virtually all weapon system programs.

The method we used to estimate the dollar amount of churn, and ultimately the churn factor, involved the use of two sets of D041 databases. For the first estimate, we used the databases for September 1983 and September 1984 (shown in the tables as the 83S and 84S databases). Ignoring most of the technical details of database processing involved, we will describe the method of estimating the churn and the churn factor, using the 1983 and 1984 databases. The method consists of the following major steps:

1. Using the 1983 database, we computed the investment required in 1984 (which we will refer to as the \$83S4 costs) to buy the spare parts to fill the optimal mix of stock levels throughout the system to yield an 80 percent aircraft availability rate at the point beyond 1984 of an average 24-month procurement lead time, in about mid-1986. We based the calculation on the assumption that there was no stock in the system at the start. This yielded the \$83S4 capital cost estimate.
2. Then, again using the 1983 database, we computed the investment required in 1985 (the \$83S5 costs) to maintain the same 80 percent aircraft availability 24 months later, in mid-1987, assuming that the mix of spares that emerged from the 1983 to 1984 computation had actually been procured. This yielded the additional funding required in 1985 on the basis of 1983 data—the \$83S5 amount shown in the tables later in this section.
3. Using the 1984 database, we then computed the investment required in 1985 to maintain the same 80 percent aircraft availability in mid-1987, again assuming that the mix of spares that emerged from the 1983 to 1984 computation was actually procured. This yielded the additional funding required in 1985 on the basis of 1984 data—the \$84S5 amount shown in the tables.
4. Thus, our estimate of the dollar amount of churn (the amount due to the change in the database between 1983 and 1984) was simply made by subtracting \$83S5 from \$84S5. The churn factor is the additional dollar amount of investment induced by churn divided by the total capital cost (\$83S4), and is calculated as $[(\$84S5 - \$83S5) \div \$83S4]$.

The costs of additives and condemnations were excluded, although the costs of safety levels for the condemnation pipelines were included. Additives are requirements that are determined outside the formal computational algorithms of the D041 system, and are also beyond the scope of the AAM used in this analysis. Thus the data discussed here do not reflect the effects of aircraft modification programs. (Condemnations and depot-level repair costs are discussed separately below.)

In our analysis, the \$83S5 costs were estimated using the flying hour program for mid-1987 that was current as of September 1983, but only with program changes and condemnations accounted for. When the \$84S5 costs were estimated, the flying hour program for mid-1987 that was current as of September 1984 was used, along with the 1984 database that reflected many changes in item applicability and characteristics from the 1983 database.

This estimate of additional annual investment fails to account for the fact that AFLC does not actually buy the mix of spares suggested by the requirements computation; in execution, managers modify the recommended buy quantities for various of reasons. These judgmental modifications may cause even more turbulence in requirements determination than estimated by the method described here. Our estimating technique assumes that, in the above case for example, the mix of spares computed in the 1983 to 1984 computation actually was procured.

The individual components included in this analysis were selected from the D041 data system based on application data that tied them to the F-16 A/B aircraft. If no application record could be found, the system management code (SMC) was used. If a component was selected on the basis of SMC alone, no safety level was computed by the AAM because application data are required in order to support the computation of safety level requirements. The 1983 database contained 3121 components with F-16 A/B applications and an additional 1441 components that, although without data reflecting an F-16 A/B application, were included on the basis of SMC. Factors applicable to common components were prorated to the F-16 A/B based on usage.

The two analyses described in the discussion that follows estimated the dollar amounts of churn on the basis of both the churn from the 1983 to the 1984 databases and the 1982 to 1983 databases.

Estimating the Dollar Amount of the 1983 to 1984 Churn

Step one produced the 1983 to 1984 computation; Table B.6 reflects the flying hour program and aircraft force posture assumed for our computation, 18 months past the end of fiscal year 1984.

As shown below, the \$83S4 capital requirement turned out to be \$527.1 million. Table B.7 reflects the breakdown of this investment.

Table B.6

ASSUMPTIONS UNDERLYING THE 1983 TO 1984 COMPUTATION (Number of bases = 11)

Aircraft	Flying Hours (hundreds)	Number
F-16A	443	538
F-16B	73	93
Totals	516	631

Table B.7

COMPOSITION OF THE 1983 TO 1984 CAPITAL REQUIREMENT (Million \$)

Pipeline requirements	184.7
Safety levels ^a	183.7
Negotiated levels ^b	105.2
Insurance requirements ^c	53.5
Total \$83S4 requirement	527.1

^aSafety levels protect against variability in the number of items in the pipeline.

^bNegotiated levels represent additional spares required because of judgments applied by supply officers and managers in the field.

^cInsurance requirements are intended to provide protection against unforecast demands.

Table B.8

**ASSUMPTIONS UNDERLYING THE
1983 TO 1985 COMPUTATION
(Number of bases = 14)**

Aircraft	Flying Hours (hundreds)	Number
F-16A	426	528
F-16B	73	93
Totals	499	621

Step two was the \$83S5 computation. As explained before, the computation is based on the assumption that the mix of spares emerging from the 1983 to 1984 computation was actually procured. That mix constituted the starting asset position for the 1983 to 1985 computation. The flying hour program and force posture assumed are shown in Table B.8. Table B.9 shows the 1983 to 1985 computational results.

The slight decrease in programmed flying hours and projected force size for fiscal year 1987 is probably largely offset by the increase in the projected number of F-16 A/B bases. As reflected in Table B.9, the additional funding in fiscal year 1985 to maintain the 80 percent aircraft availability goal is \$9.8 million, less than 2 percent of the \$527.1 million capitalization investment. (Recall that this \$9.8 million requirement excludes condemnation replacements.)

In step three we use the 1984 database to compute the \$84S5 costs. Table B.10 reflects the underlying assumptions current as of September 1984; Table B.11 shows the results.

Table B.9

RESULTS OF THE 1983 TO 1985 COMPUTATION

Additional insurance, negotiated, and pipeline requirements	7.6
Safety level	2.2
Total \$83S5 requirement	\$9.8 million

Table B.10

ASSUMPTIONS UNDERLYING THE
1984 TO 1985 COMPUTATION
(Number of bases = 13)

Aircraft	Flying Hours (hundreds)	Number
F-16A	430	531
F-16B	74	95
Totals	504	626

Table B.11

RESULTS OF THE 1984 TO 1985 COMPUTATION

Additional insurance, negotiated, and pipeline requirements	59.9
Safety level	26.9
Total \$84S5 requirement	\$86.8 million

In step four we subtracted the \$83S5 requirement from the \$84S5 requirement to determine the dollar amount of the 1983 to 1984 churn. This totaled \$77 million (\$86.8 - \$9.8 million), a rather substantial 14.6 percent of the \$83S4 capital cost, and almost eight times that assumed in the 1983 to 1985 computation.

Compensating for Changing Component Unit Prices

In an effort to understand how much of the estimated dollar amount of the 1983 to 1984 churn might be due to changing component unit prices between the 1983 and 1984 databases, we compared the 1983 database item by item with the 1984 database. Surprisingly, on the average, for the set of components considered, the 1984 prices were lower. The results are shown in Table B.12.

Thus the dollar amount of churn due to changing unit prices of components is, in this particular case, insignificant.

The churn factor is the estimated dollar amount of the 1983 to 1984 churn divided by the \$83S4 level of capitalization: $\$77.2 \text{ million} \div \$475.1 \text{ million} = 0.162$ (for \$84S).

Table B.12

EFFECTS OF CHANGING COMPONENT UNIT PRICES

Computation	Prices in Actual Database Dollars (million \$) ^a	Prices in September 1984 Database Dollars (million \$)
1983 to 1984	527.1	475.1
1983 to 1985	9.8	9.6
1984 to 1985	86.8	86.8
Estimated Effect	77.0	77.2

^a"Actual" database dollars are the unit prices reflected in the database used in each of the three computations.

Estimating the Dollar Amount of the 1982 to 1983 Churn

Using the September 1982 and September 1983 databases, we replicated the analytic steps described above, this time simply making all of the calculations one year earlier. The selection of components included in the analysis was based on the same criteria as before. The 1982 database contained 2958 components with data reflecting an F-16 A/B application and an additional 1358 components that were included in the analysis because of the SMC.

In step one we computed the capital costs for 1982 to 1983. Table B.13 reflects the flying hour program and aircraft force posture assumed for this computation. Table B.14 reflects the 1982 to 1983 capital investment required to achieve an 80 percent aircraft availability rate (based on the assumption of no spare parts in the system initially). The \$82S3 capital requirement turned out to be \$457.7 million. Table B.14 reflects the breakdown of this investment.

Table B.13

**ASSUMPTIONS UNDERLYING THE
1982 TO 1983 COMPUTATION
(Number of bases = 11)**

Aircraft	Flying Hours (hundreds)	Number
F-16A	461	553
F-13B	74	90
Totals	535	643

Table B.14

COMPOSITION OF THE 1982 TO 1983
CAPITAL REQUIREMENT
(Million \$)

Pipeline requirements	171.4
Safety levels ^a	150.1
Negotiated levels ^b	95.3
Insurance requirements ^c	40.9
Total \$82S3 requirement	457.7

^aSafety levels protect against variability in the number of items in the pipeline.

^bNegotiated levels represent additional spares required because of judgments applied by supply officers and managers in the field.

^cInsurance requirements are intended to provide protection against unforecast demands.

Step two began with the assumptions underlying the estimation of the \$82S4 requirement—the additional funding required in 1984 based on the 1982 data (shown in Tables B.15). Table B.16 shows the results of the 1982 to 1984 computation.

Again, as in our estimate of the dollar amount of 1983 to 1984 churn, the changes in flying hour program and force posture on the one hand and number of bases on the other tended to be offsetting. The additional investment of \$7.1 million required to maintain the 80 percent aircraft availability goal is quite modest, only about 1.5 percent of the total capital cost.

Table B.15

ASSUMPTIONS UNDERLYING THE
1982 TO 1984 COMPUTATION
(Number of bases = 10)

Aircraft	Flying Hours (hundreds)	Number
F-16A	485	573
F-16B	71	83
Totals	556	656

Table B.16

RESULTS OF THE 1982 TO 1984 COMPUTATION

Additional insurance, negotiated, and pipeline requirements	7.0
Safety level	0.1
Total \$82S4 requirement	\$7.1 million

In step three we used the 1983 database to compute the \$83S4 costs, based on the assumption that the mix of spares that emerged from the 1982 to 1983 computation was actually procured and constituted the starting asset position for this 1983 to 1984 computation. Refer to Table B.6.

Table B.17 shows the results of this new 1983 to 1984 computation; the estimated additional requirement is \$117.5 million. The result differs from the one previously described as the 1983 to 1984 computation (see Table B.7) because the starting asset position is not zero but rather the result of buying the mix of spares suggested by the 1982 to 1983 computation.

In step four we determined the dollar amount of the 1982 to 1983 churn by subtracting the \$82S4 requirement from the \$83S4 re-wpquirement: $\$117.5 - \$7.1 = \$110.4$ million. This is more than 24 percent of the \$82S3 capital investment and over 16 times that assumed in the 1982 to 1984 computation. The difference is even more dramatic when viewed in the context of the 7.1 percent decrease in flying hour program.

Table B.17

RESULTS OF THE 1983 TO 1984 COMPUTATION
FOLLOWING THE 1982 TO 1983 PROCUREMENT
(Million \$)

Additional insurance, negotiated, and pipeline requirements	73.1
Safety level	44.4
Total \$83S4 requirement	\$117.5 million

Compensating Again for Changing Component Unit Prices

Actual database dollars were again translated into constant database dollars, this time 1983 dollars. The results are shown in Table B.18. In this case the changing unit prices of components had no effect whatever on the dollar amount of the churn.

The churn factor is the estimated dollar amount of the 1982 to 1983 churn divided by the \$82S3 capital cost: \$110.4 million ÷ \$522.0 million = 0.211 (for \$83S).

Table B.19 compares the two estimates of dollar amount of churn, compensating in each case for changing component unit prices.

Table B.18

EFFECTS OF CHANGING COMPONENT UNIT PRICES

Computation	Prices in Actual Database Dollars (Million \$)	Prices in September 1984 Database Dollars (Million \$)
1983 to 1984	457.7	522.0
1983 to 1985	7.1	7.1
1984 to 1985	117.5	117.5
Estimated Effect	110.4	110.4

Table B.19

COMPARISON OF EFFECTS OF 1982 TO 1983 CHURN WITH EFFECTS OF 1983 TO 1984 CHURN

Time Period	Capitalization	Estimated Amount ^a	Churn Factor ^b
1983 to 1984	\$475.1 million	\$ 77.2 million	0.162 (\$84S)
1982 to 1983	\$522.0 million	\$110.4 million	0.211 (\$83S)

^aEstimated dollar amount of churn.

^bEstimated dollar amount divided by total capital costs.

Estimates of the Dollar Amount of Churn

Given the variability in computed capital cost levels, it is hardly surprising that the estimates of dollar amounts due to churn differ as much as they do. The best we could have hoped for was that the estimates of those amounts as a percentage of capital cost (the churn factors) would have been closer. That would have been encouraging in terms of the

feasibility of using such estimates to project lifecycle procurement costs for recoverable spares. However, it is not clear, based on these estimates alone, that this method provides a sound basis for such cost projections. The dynamic changes in the database from year to year are dramatic indeed and need to be explicitly accounted for in any use of the database to project future investment requirements for recoverable spares.

Despite our concerns about whether we had in fact achieved estimates of the dollar amount of churn that could reasonably be viewed as representative of the amounts that would actually be experienced across the life of this weapon system, we did apply them to the estimate of lifecycle procurement costs on the assumption that a replication of these analyses would yield *roughly* comparable estimates. Thus, the following discussion of the possible magnitude of lifecycle procurement costs of recoverable spares for the F-16 A/B program may be viewed as somewhat hypothetical. We believe that it will suggest the magnitude of savings in such costs that might be achievable through reliability improvements is very substantial indeed, much more so than would be the case in the world seen as a steady state system.

The Estimate of Lifecycle Procurement Costs for Recoverable Spares

First, since we knew only total flying hours for fiscal years 1980 through 1983, we assigned the flying hours in a way that is consistent with a linear buildup of the force posture. For the fiscal years from 1984 through 1990, we extracted the flying hours from USAF documents. This results in the flying hours by fiscal year shown in Table B.20. Next, we adjusted the capital required for each fiscal year so that it was proportional to the \$83S4 capital costs computed using the 51,600 flying hours (a quarterly figure) shown in Table B.6. This adjustment raises the capital required in FY 84 to achieve an 80 percent aircraft availability rate in FY 86 from the \$527.1 million shown in Table B.7 to \$564.5 million. The capital costs for every other year are in the same proportion to the flying hours for that year as in FY 86.

The estimates contained in Table B.20 are based on the simplifying assumption that an investment in spare parts in any particular fiscal year is reflected in aircraft availability two years later.

The required annual investments shown in Table B.20 are based on the churn factors reflected in the column headings. In addition to showing the annual investment resulting from the two churn factors we calculated, we also have included estimates of the annual investment that would be required if the churn factors were 0.100, or even 0.0 (as if there were no churn and no dollar amounts of churn, and all program data were known with

Table B.20

F-16 A/B POS INVESTMENT REQUIREMENTS BY FISCAL YEARS, FOR 1978 THROUGH 1990

Fiscal Year	Flying Hours	Capital Costs	Additional Investment Required (million \$)			
			Churn Factor = 0.211	Churn Factor = 0.162	Churn Factor = 0.100	Churn Factor = 0.000
78	0	0.0	83.0	83.0	83.0	83.0
79	0	0.0	100.5	96.4	91.3	83.0
80	32496	83.0	118.0	109.9	99.6	83.0
81	64991	166.0	135.5	123.3	107.9	83.0
82	97487	249.0	237.1	220.8	200.2	167.0
83	129982	332.0	158.0	133.5	102.6	52.7
84	195402	499.0	129.2	102.2	68.0	12.8
85	216020	551.7	100.6	72.9	38.0	0.0
86	221041	564.5	90.1	63.4	29.5	0.0
87	213782	546.0	89.0	63.5	31.2	0.0
88	203960	520.9	73.0	48.5	17.5	0.0
89	195776	500.0	68.3	45.4	16.5	0.0
90	183079	467.5	63.9	42.5	15.4	0.0
91	171205	437.2				
92	160102	408.9				
Total			1505.9	1244.9	900.7	564.5

certainty). The inclusion of these additional churn factors (0.100 and 0.0) reflects our uncertainty about the accuracy of our estimates of the dollar cost of churn and uncertainty whether we have actually bracketed the "true" cost. To us, the 0.211 factor seems especially high. The inclusion of the two additional factors helps to show the sensitivity of lifecycle cost estimates to the value of the churn factor.

The required additional annual investments are computed by deducting the total capital required one year in the future from that required two years in the future, and then adding to that the dollar amount calculated by multiplying the churn factor by the capital required one year in the future. In computing the estimated additional investment required in FY 83 with a churn factor of 0.211, for example, we deduct \$499.0 million from \$551.7 million, to get \$52.7 million, which is the increase in capital cost, and then add to that 0.211 times the total capital required in FY 84 ($0.211 \times \$499.0 \text{ million} = \$105.3 \text{ million}$, and $\$52.7 \text{ million} + \$105.3 \text{ million} = \$158.0 \text{ million}$).

In summary, these investments are based on the assumption that, to maintain a specified level of performance from one year to the next, we must not only buy condemnation replacements but we must also invest an additional amount to overcome the effects of churn in the database. However, whether a single numerical constant such as the "churn factor" can be used over time to represent that additional investment requirement must be a subject of additional and more thorough research. If it is feasible to model the process in this way, then estimates of lifecycle procurement costs for recoverable spares requirements could be made quite early in a weapon system's lifecycle. More important, perhaps, such an approach could be especially useful in the planning, programming, and budgeting system (PPBS).

In Table B.21 we show the lifecycle procurement costs of recoverable spares as a function of the churn factor and reliability level. Obviously, the highest capital cost required in any single year in the life of a weapons system only hints at the total lifecycle cost of its recoverable spare parts.

Estimating Lifecycle Condemnation and Depot Repair Costs

Our estimate of the lifecycle costs for condemnation replacements and depot level repairs of recoverable spares were computed from the three different databases, 1982, 1983, and 1984. They were based on a cumulative total flying program of 1,484,950 hours and 269,057 hours for the F-16A and F-16B, respectively. The results are shown in Table B.22.

The averages shown in the bottom line of Table B.22 are the best estimates of lifecycle condemnation and depot repair costs that can be made with these three databases. However, the behavior of the sequence of estimates of condemnation replacement costs

Table B.21

THE EFFECTS OF RELIABILITY AND CHURN ON THE LIFECYCLE COSTS OF RECOVERABLE SPARES (Million \$)

Churn Factor	Reliability Improvement		
	1X	2X	4X
0.211	1505.9	1182.1	1015.0
0.162	1244.9	977.2	839.1
0.100	900.7	707.0	607.1

Table B.22

LIFECYCLE CONDEMNATION AND DEPOT REPAIR COSTS
FY 78 THROUGH FY 90
(Million \$)

Database	Condemnation Costs		Depot Repair Costs	
	Database	84S	Database	84S
82S	983.4	1072.1	988.0	1231.1
83S	937.2	897.7	1226.4	1228.9
84S	542.4	542.4	1065.2	1065.2
Averages		837.4		1175.1

suggests that the use of the \$837.4 million average could be misleading. The substantial decrease in the annual estimates of condemnation costs over these three databases is due largely to changes in the condemnation costs associated with the engine overhaul program. These changed from \$645.7 million to \$544.5 million to \$250.6 million from the 1982 to the 1983 to the 1984 databases respectively (in nominal dollars).

The engine in the F-16 A/B aircraft has benefited from substantial product improvement investments over this time period. This has had an important effect on all of the estimates of lifecycle costs and, indeed, on the total costs incurred by the Air Force to support the program. One might argue, therefore, that these cost estimates are atypical in the sense that they tend to be driven inordinately by engine reliability problems. Nonetheless, we do not know how to improve them without much more extensive research than was undertaken here. Changes in item characteristics due to reliability modifications contribute substantially to churn; therefore, the dollar amount of churn is likely to be lower, other things equal, for a weapon system whose initial reliability is greater. This logic provides reinforcement for strategies designed to enhance design reliability.

The use of the average value of depot repair costs of \$1,175.1 million seems more reasonable because of the consistency of the estimates from year to year.

In conclusion, it is difficult to guess how our estimates of the dollar amount of churn and lifecycle depot repair and condemnation costs for the F-16 A/B might differ from those made for a different weapon system. Perhaps it is an experiment worth replicating on several other weapon systems to get a better sense of the size of churn's contribution to

lifecycle costs of recoverable POS. Clearly, such an analysis could enhance the Air Force's ability to project investment requirements for recoverable spares in future years. It would also provide a better basis for understanding the potential dollar value of reliability improvements in hardware design.

Appendix C

THE EFFECTS OF IMPROVED RELIABILITY ON DEPLOYMENT REQUIREMENTS

In examining the effects of improved reliability on the amount of air-delivered support items (including personnel, spares, and equipment) needed to support a bare-base deployment of a 24-PAA F-16 A/B squadron, we used the equipment list in the "Wing Mobility Materiel List" for the 388th Tactical Fighter Wing at Hill Air Force Base in November 1983 [7]. Information on personnel was obtained from the Air Force Manpower and Personnel Readiness Team.[10] Because such equipment and personnel lists are continually being revised, our results are representative only; however, we believe the major conclusions reached would be the same unless radical changes in deployed equipment were made.

TYPES OF EQUIPMENT AND PERSONNEL DEPLOYED

Reference 1 defines the equipment and personnel to be deployed by means of Unit Type Code (UTC). The items in each UTC are broken down by Deployment Echelon (DEPECH), which defines the purpose of each group of equipment and people. The UTCs and deployment echelons we have considered are shown in Table C.1.

The equipment in the UTC lists allow an independent squadron of 24 F-16s to deploy and operate for a 30-day period, making 2.8 sorties a day per aircraft for the first seven days and 1.1 sorties per day per aircraft thereafter. It also includes the equipment necessary to provide an intermediate maintenance capability after 30 days, and to allow for handling munitions.

EQUIPMENT THAT NEED NOT BE DEPLOYED BY AIRLIFT

The air delivered equipment covered by these UTCs does not represent all of the tonnage that must be delivered to mount an effective operation. Major items such as fuel, armament, housing, and food are excluded because they often will be available locally or from sites much closer to the deployment area than the CONUS and thus need not be delivered by air from the CONUS. Such items actually weigh far more than the support equipment items (see Table C.2), but their closer location would probably allow them to be delivered in time by truck, train, or ship.

Table C.1

DEPLOYMENT OF 24 F-16S

UTC	DEPECH	Purpose	Equipment Weight (tons)	Personnel (excluding pilots)
3FKAA	E1	En route support	5.8	383
	E2	En route support	7.6	
	E3	En route support	5.2	
	S1	Support for 7 days operation at 1.1 sortie rate	70.0	
		Increment to raise sortie rate to 2.8 in the first 7 days	69.3	
	T2	Increment to maintain sortie rate of 1.1 from day 8 to 30	42.6	
HGHAB	M1	Munition support	137.4	66
HFAGA	T3	Intermediate maintenance facility available after 30 days	82.8	113
Total			420.7	562

Table C.2

WEIGHT OF SUPPORT MATERIAL
NOT INCLUDED IN UTCs

Item	Weight (tons) ^a
Fuel	16,641
Bombs	2,346
Housing	519
Food	18

^aF-16s are loaded with 2 AIM-9Js, 2 Mk 84s, 1 ALQ-119-12 ECM Pod, 157 lb of ammo of which half is expended on each mission, and two 370 gal fuel tanks. Fuel load is 34,318 lb of which 90 percent is expended. Combat radius = 486 n. mi.

Housing is Harvest Eagle equipment. Data are obtained from the 4449th Mobility Support Squadron at Holloman AFB.

Food is estimated as 2 lb/man/day.

AIR-DELIVERED SUPPORT EQUIPMENT

From the "Wing Mobility Material List" we obtained a listing of the support items that must be deployed by air. It shows approximately 150 different types of equipment, in addition to hand tools, small parts, and war reserve spares kits (WRSK). The heaviest individual item (an aircraft towing tractor) weighs slightly over 11,000 lb. The heaviest items have been arranged in descending order of total aggregate weight (number of items $\times$ individual weight) and are shown in Table C.3 and Fig. C.1.

The weight of the items shown (591,619 lb or 296 tons) amounts to about 70 percent of the total 421 tons of support material deployed.

DEPLOYED PERSONNEL

A total of 562 support and maintenance people are deployed. Based on the data obtained from the Air Force Manpower and Personnel Readiness Team, we have broken these down into groups associated with various types of work. The results are shown in Table C.4.

POTENTIAL REDUCTIONS DUE TO IMPROVED RELIABILITY

Improvements in aircraft reliability might be expected to allow reductions in the amount of equipment and personnel that must be deployed to support a specified flying schedule. For example, fewer spare parts may be required, and thus the amount of WRSK could be reduced. Likewise, if the avionics become more reliable, the number of generators needed to supply power to the aircraft during avionics system checkout might be reduced.

However, there are limitations on these potential savings. Much of the deployed equipment is not affected by reliability. For example, as long as the sortie rate is kept constant, the number of bomb jammers and ammunition carts will be unchanged, and more tractors and loaders might be needed if reliability is improved.

In addition, the possible reduction in equipment may be limited when only a few items of a particular type are deployed. For example, the CI test station is used for checking and repairing inertial and computer components, items whose reliability might be expected to improve in the future. Typically, two CI test stations are deployed together to guarantee the availability of at least one stand at all times; therefore, it may not be possible to reduce the number of stations deployed even if component reliability is improved.

Table C.3

DEPLOYED SUPPORT AND MAINTENANCE ITEMS

Item	Number	Total Weight (lb)
Ammo Trailers	28	103,160
Bomb Jammers	20	80,760
Ammo Tractors	7	75,460
Aircraft Tow Tractors	8	42,470
Generators	14	40,375
Spare Engines & Components	5	29,177
WSK	—	26,426
Light Carts	12	24,480
Hydraulic Test Stands (MJ-2)	3	15,360
Air Conditioners (C-10)	11	13,420
Truck	1	12,500
Hand Tools	—	11,187
Gas Carts, Cylinders (LOX,N2,O2)	6	10,260
Specialized Testers	4	9,921
Compressors & Vacuum Pumps	10	9,320
Ammo Loaders (Unloaded)	6	9,120
Aircraft Engine Trailers	12	8,880
Storage Cabinets	12	8,320
Maintenance Stands	15	7,440
TER, Launchers, Pylons, Missile Trailers	—	6,900
Weapons (Rifles)	600	6,780
Cranes	2	5,470
Material Handling Equipment	18	5,415
Maintenance Bays	4	5,000
Furniture	17	4,883
Chock Assemblies	8	4,760
CRT Consoles	2	4,300
Test Station (Processor/Pneumatic)	2	4,225
Test Station (Computer/Inertial)	2	4,160
Aircraft Towbars	5	2,500
Total		592,429

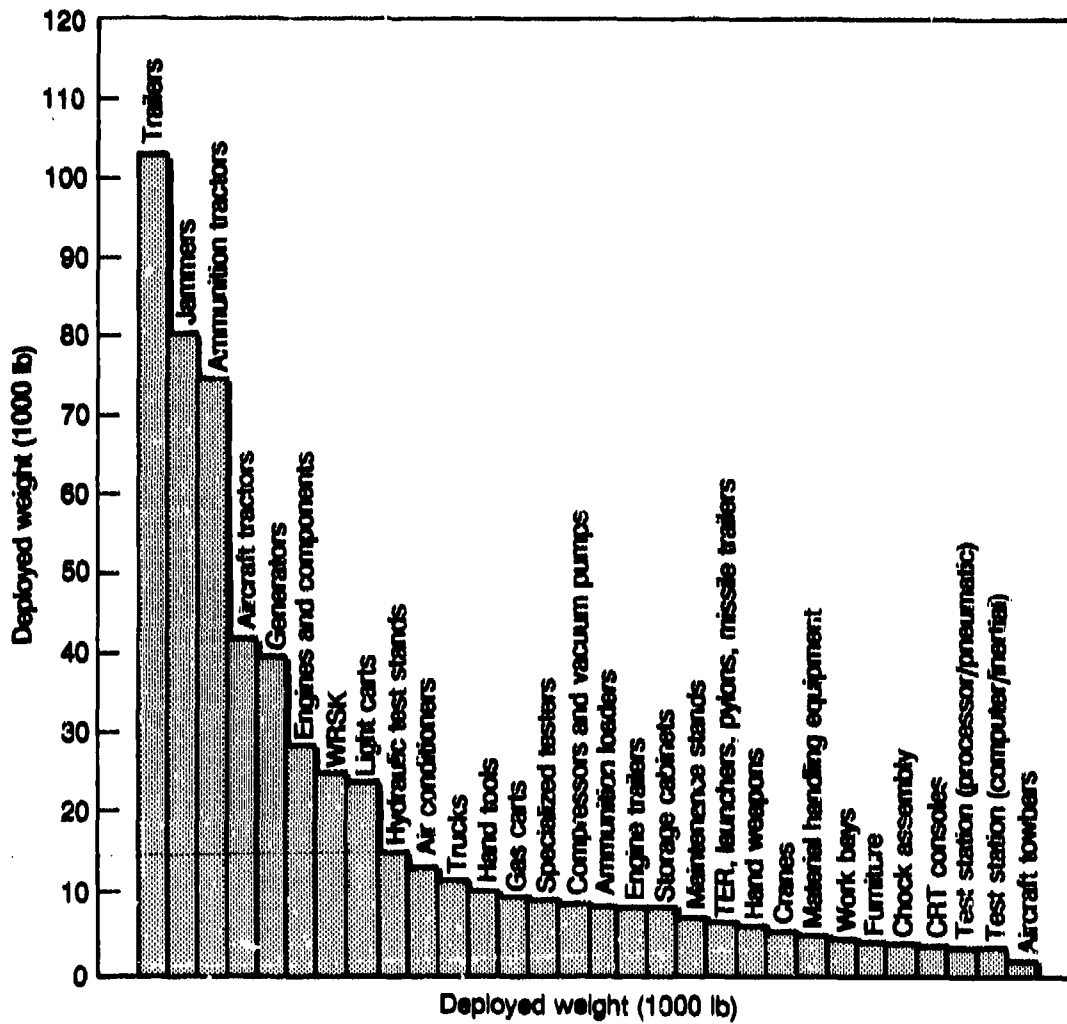


Fig. C.1—Deployed support items

Table C.4

DEPLOYED PERSONNEL

Type of Work ^a	3FKAA				HGHAB	HFAGA			Total
	CRS	AGS	EMS	DCM	EMS	CRS	EMS	DCM	
Engine		16		1		32	4		53
Avionics	11	34		1		24		1	71
Airframe	20	23	1			11	1		56
Supervisory		12	4	69	3	5			93
Armament		66	8	2	63		7		146
Flight Line	78	1	4				14		97
Other	6	4	22				14		46
Total									562

^aCRS = Component Repair Squadron.

AGS = Aircraft Generation Squadron.

EMS = Equipment Maintenance Squadron.

DCM = Deputy Commander for Maintenance.

Finally there are locational problems. Generators are currently assigned at the rate of one to every two aircraft and are located so that cables can be run promptly to either of the two aircraft they serve. Even if an increase in aircraft reliability were to make the use of fewer generators possible in an overall sense, it might not be possible to reduce the number of generators without causing a delay in their availability.

METHOD OF DETERMINING SAVINGS IN SUPPORT EQUIPMENT

To investigate the effect of changes in aircraft reliability and in sortie rate on the amount of equipment required during a deployment, we took several steps:

First, we made a preliminary estimate of the potential savings in deployment weight due to improved reliability by separating the deployed equipment into four groups: (a) equipment related to the number of personnel deployed; (b) equipment related to the number of aircraft deployed and their sortie rate; (c) equipment directly related to the reliability of the aircraft; and (d) all remaining items that did not fit any of the other groups. The results are shown in Fig. C.2. About 35 percent of the deployed weight is associated with aircraft reliability. Obviously, not all of this can be saved, even if reliability is improved substantially. For example, although the number of electrical generators is somewhat related to reliability, ground power is also used for other activities. To determine how equipment usage would actually vary with aircraft reliability, it was necessary to examine the support equipment in further detail.

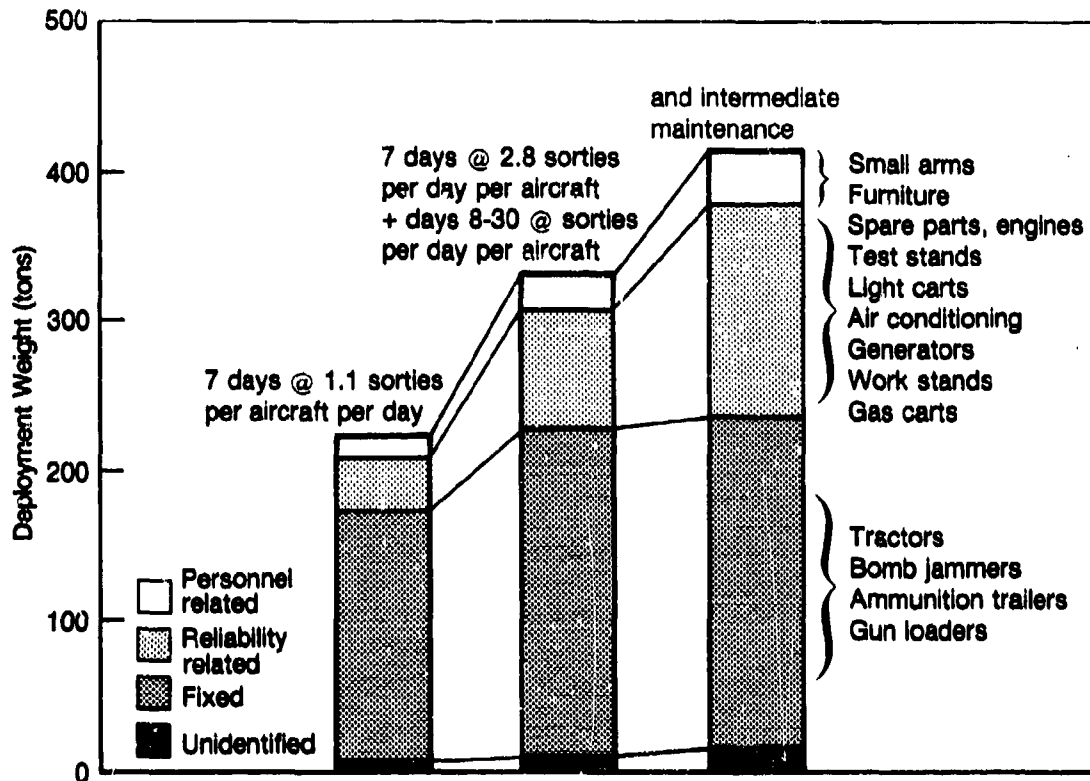


Fig. C.2—F-16 deployment support

USING TSAR TO MODEL THE POTENTIAL SAVINGS

To do this, we used the TSAR model. Although TSAR models the peacetime, steady state operation of an airbase, we believe that following a rapid deployment, peacetime conditions would be approached once the munitions and munition support were brought in and the base was organized.

Given data on the breakdown rates and repair times for various components, together with the equipment required to repair them, TSAR steps through a seven-day period in three minute intervals, keeping track of the time each piece of equipment is in use and the numbers of each type of equipment in use at any one time. The flow of each aircraft, part, piece of support equipment, and maintenance technician is followed through the repair and maintenance cycle. At each branch point in the cycle (where there is a choice of events, such as a spare part is or is not needed, test equipment is or is not available), a random

choice, weighted with the appropriate probabilities, is made. Thus, if a component has a 20 percent probability of breaking during the mission, and has a quantity of one per aircraft, it will be assumed to need repair on 20 percent of the TSAR sorties. (A detailed description of TSAR and the assumptions used in making these runs can be found in Refs. 3 through 5.)

Each TSAR run was made for a combination of reliability and sortie rate. Because of different choices at the branch points, every run produces a different result for the total numbers of each type of support equipment and personnel needed. Each run also defines a cumulative distribution of the fraction of time various pieces of equipment are in use. From these distributions, we determined the numbers of each type of equipment that would allow operations to continue without an equipment shortage for 95 percent of the time. The results of five such distributions were averaged to obtain the maximum numbers of each piece of support equipment needed for the specified sortie rate and reliability.

Sortie rates were varied from approximately one to four sorties per aircraft per day. Reliability was varied by assuming that the time between failures of all aircraft components was increased by a factor of two or four.

Limitations on computer time prevented considering all of the support equipment shown in Table C.3. Instead, we constructed an abbreviated list of items that were most likely to be affected by changes in reliability and sortie rate and that made a large contribution to the weight of the equipment that has to be deployed. The items selected, together with the numbers of each item deployed and their total weight, are given in Table C.5. The items shown are those TSAR estimated were necessary for peacetime operation. Consequently, the list differs slightly from the list in the UTC shown in Table C.3. We believed that this was acceptable because we were using TSAR to calculate the *increment* in weight due to changes in sortie rate and reliability.

The items most likely to be affected by reliability (this includes all items in Table C.5 except ammo trailers) total only 72.3 tons, which is only about 17 percent of the total weight deployed (420.7 tons as shown on Table C.1).

It was not possible to obtain a breakdown by weight of the spare parts making up the WRSK. Because of this, we could not estimate the effect of improvements in reliability and of changes in sortie rate on the weight of the WRSK that needed to be deployed. Although this is a shortcoming, WRSK amounts to only 3 percent of the total deployed weight (see Table C.3). Thus, the omission of changes in WRSK should not cause an error large enough to affect our final conclusions.

Table C.5
SUPPORT ITEMS USED IN TSAR ANALYSIS

Item	Number Deployed	Total Weight (lb)
Computer/inertial test stand	1	4,160
Display and instruments test stand	1	4,690
Processor test stand	1	4,225
Generators	14	42,840
Hydraulic test stand (diesel)	3	15,360
Air compressors	8	6,080
Canopy leak detector	1	2,100
Air conditioners	11	13,420
Hydraulic test stand (electric)	1	5,120
B-1 work stand	3	3,240
C-1 work stand	6	960
B-4 work stand	6	3,240
Nitrogen trailer	1	350
10-ton jack	3	855
LOX cart	2	2,960
Axle jack	3	255
Gun loader	6	9,120
Ammunition trailers	17 ^a	67,220 ^b
Spare engines	5	16,750
Engine trailers	12	8,880
Total		144,605 = 72.3 tons

^aThis is the number of trailers that TSAR estimates are required on a typical air-to-ground mission. An additional 11 trailers are provided in the UTC for short range missions with very heavy armament loads.

^bNot affected by reliability improvement and not included in total.

TSAR does not keep track of the number of spare engines and engine trailers. To find the effect of improved engine reliability on the number of engines and trailers required, we adjusted the number of these items by proportioning them inversely with reliability and rounding up to the next higher integer.

To estimate the effect of varying the sortie rate on the number of needed engines and engine trailers, we examined the number of engines deployed with each deployment echelon and the increment in sortie rate obtained from that echelon. We found that during the first week of operation, one spare engine was allowed for every 150 sorties flown. After the first week, when the sortie rate dropped from 2.8 to 1.1, only about one half as many engines

were allocated per sortie. Presumably this is because the longer time available allows some of the engines removed earlier to be repaired and returned to service. We assumed that the number of engines required was determined by the peak sortie rate in the first week of operations, and that one engine was required for each 150 sorties flown.

Since we averaged only five distributions for each combination of reliability and sortie rate, the resulting plots of equipment weight deployed against sortie rate show some scatter. We have made least squares fits of these points to obtain the final results shown in Fig. C.4 but also have shown the actual data points on this plot to suggest the amount of uncertainty due to the limited number of runs that could be made.

A similar approach, also using TSAR, was taken to evaluate the effect of reliability and expected sortie rate on the number of maintenance personnel that must be deployed with an independent 24-PAA squadron. The results are summarized in Fig. C.4.

The effect of sortie rate and reliability on the weight of equipment and the number of personnel deployed with a squadron of 24 F-16s is shown in Figs. C.5 and C.6 in terms of the net savings achievable through improved reliability. In general the savings are a small fraction of the total deployment effort. Most of these savings occurred when reliability (the mean time between repair) was doubled; further increases in reliability resulted in smaller savings.

CONCLUSION

Higher sortie rates require only small percentage increases in equipment (weight), but larger percentage increases in personnel. With present reliability, raising the sortie rate from 1.5 to 4 requires a 13 percent increase in the weight of support equipment (see Fig. C.3) but a 67 percent increase in the number of support personnel (see Fig. C.4). Doubling the reliability drops these increments to 5 and 55 percent respectively (Figs. C.3 and C.4, respectively).

From these results we conclude that improvements in reliability will have only small effects on deployment requirements.

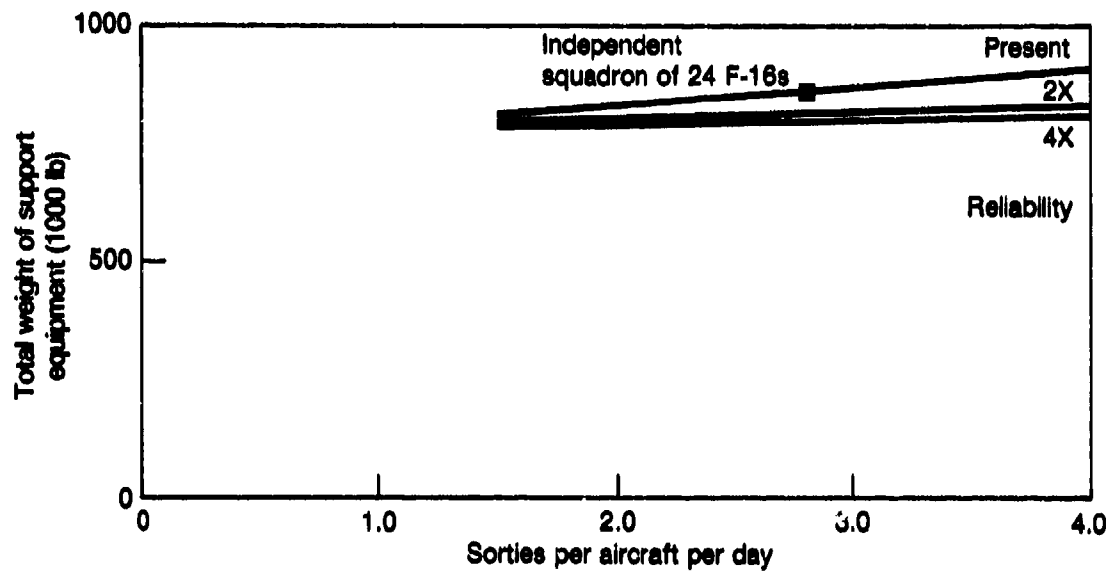


Fig. C.3—Effect of sortie rate and reliability on total weight of support equipment

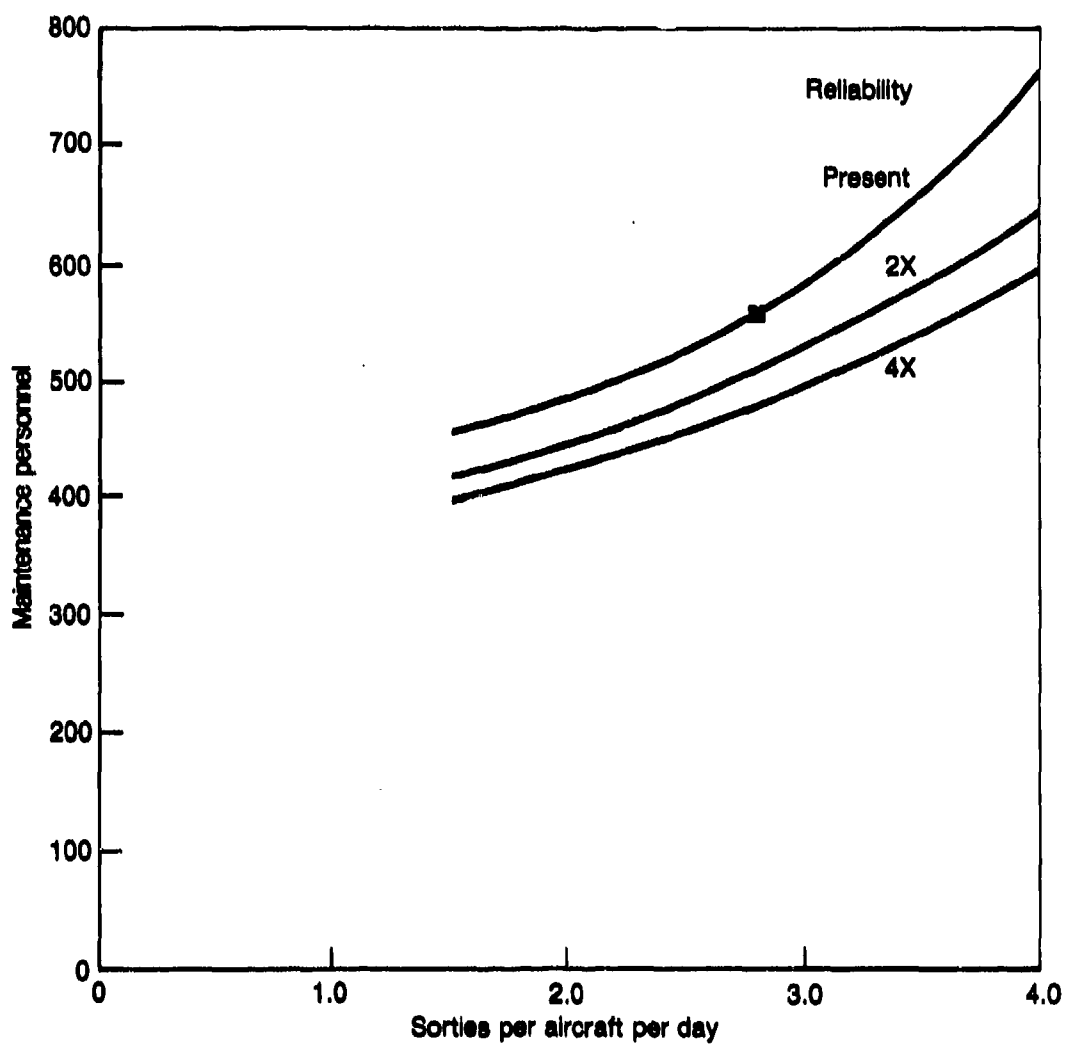


Fig. C.4—Maintenance personnel

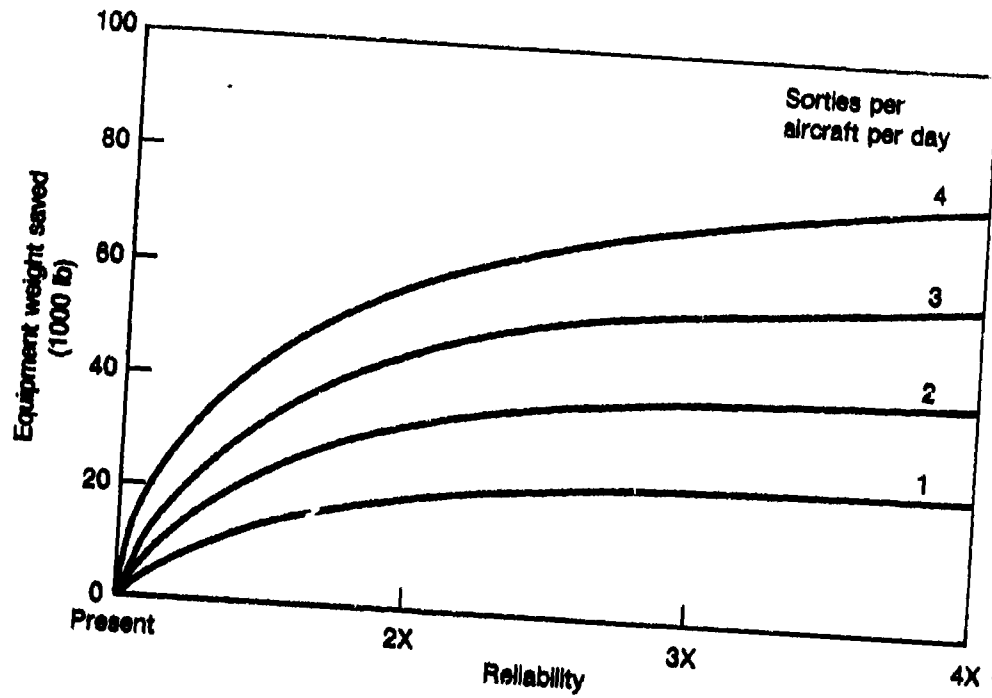


Fig C.5—Savings in deployed equipment weight per squadron

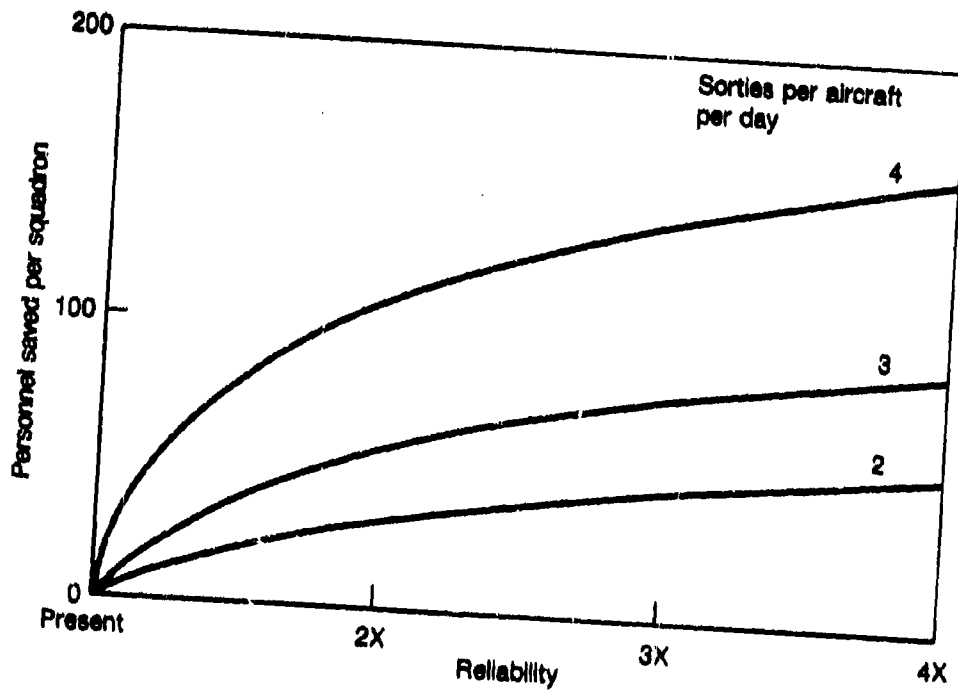


Fig. C.6—Savings in deployed personnel per squadron

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