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ARROWs MODEL EVALUATION

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OPERATIONS ANALYSIS DEPARTMENT

NAVY FLEET MATERIAL SUPPORT OFFICE
Mechanicsburg, Pennsylvania 17055

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Report 166

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PROJECT NUMBER
N9324-B11-4135

REPORT 166

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ABSTRACT

The Aviation Readiness Requirements Oriented to Weapon Replaceable Assemblies (ARROWs) model was specifically designed for Readiness Based Sparing (RBS) of aircraft. This report examines various approaches to predicting availability of aircraft that are provided by the model and compares requirement quantities computed by the Availability Centered Inventory Model (ACIM) for the SH60B and the Multi-Item Multi-Echelon (MIMF) model for the F14A to those computed by ARROWs for high cost, mission essential, organizational level removables when using the same assumptions. We recommend that ARROWs be established as the RBS model for aircraft and that analysis of availability predictions be continued to enhance the credibility of these projections so that the ultimate goal of sparing to availability can be achieved.

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EXECUTIVE SUMMARY

1. Background. We were tasked to develop a Readiness Based Sparing (RBS) model specifically designed to compute consumer level requirements. Development of this model, known as the Aviation Readiness Requirements Oriented to Weapon Replaceable Assemblies (ARROWs), began with a data analysis and background research. Concurrent with this effort, the Retail Inventory Model for Aviation (RIMAIR) was developed to comply with Department of Defense and Chief of Naval Operations supply policy. While RIMAIR is not a RBS model, we demonstrated it's ability to produce results comparable to other RBS models when minimizing the average customer waiting time of high cost, mission essential, organizational level removables for a specified cost objective. For sparing to availability, ARROWs was developed to offer a variety of assumptions for predicting availability based on downtime generated by organizational level removables. The assumptions can be categorized into historical and analytical approaches to predicting availability. The historical approach uses information from past maintenance actions for organizational level removables to determine the impact of these items on aircraft availability, while the analytical approach is purely mathematical. These different approaches allow the model to adapt to the changes in the data base that occur during the life cycle of an aircraft and take advantage of additional information as operational experience accumulates. The RIMAIR computations are also available in ARROWs for application to lower indenture Shop Replaceable Assemblies (SRAs) and consumable piece parts.

2. Objective. To examine availability projections and requirement quantities computed by the ARROWs model for high cost, mission essential, organizational level removables.

3. Approach. Real world observations based on standard ASO stockage were compared to model predictions. A Center for Naval Analyses (CNA) simulation of aircraft operations was conducted to provide a basis of comparison for RBS stockage techniques. Requirement quantities computed by the Availability Centered Inventory Model (ACIM) for the SH60B and the Multi-Item Multi-Echelon (MIME) model for the F14A were compared to those computed by ARROWs using comparable assumptions. Data for the SH60B were provided by CACI. Data for the F14A were provided by CNA and CACI.

4. Findings.

a. Benchmark. Availability projections for the requirements computed by the Navy Aviation Supply Office (ASO) for the 1986 USS ENTERPRISE deployment were developed using the ARROWs model and a CNA simulation. These projections were compared to historical availability for high cost, mission essential F14A items, as provided by CACI from Naval Aviation Logistics Data Analysis (NALDA) data. The Fleet-wide average Full Mission Capable (FMC) rate, based on NALDA, was 70%. The ARROWs historical approach predicted 61% while the analytical approach predicted just 21%. The CNA simulation produced 65% FMC. The cause of the differences between predicted availability and real world observations is not known and requires further study.

b. SH60B. Both ARROWs and ACIM project a cost of $4.8M to achieve the 84% FMC goal used for sparing. The requirement quantities are the same for 99% of the candidates for stockage. The predicted FMC rate generated by the ARROWs historical and analytical approaches were 84% and 73%, respectively. The CNA simulation predicted 79% FMC.

c. F14A. ARROWs projects a cost of $47.7M to obtain 42.6% FMC (using the MIME analytic approach), while MIME projects $47.8M to obtain about 42% FMC

according to CNA. The CNA simulation predicted 62% for this same inventory, while the historical approach predicted 79% FMC. The requirement quantities are the same for 94% of the items stocked by both models. MIME stocked 40 zero demand items not stocked by ARROWs because of an assumed attrition rate of one unit every 400,000 flying hours for such items. Using impact factors in the availability optimization increased the projected FMC rate only one percentage point.

5. Recommendations. We recommend that the Navy:

a. Establish ARROWs as the RBS model for aircraft.

b. Use ARROWs in lieu of ACIM when support of the SH60B transitions to ASO.

c. Reevaluate the use of subsystem average impact factors on the SH60B when a sufficient historical data base is accumulated to allow use of item specific values.

d. Use ARROWs in lieu of MIME in any future at sea tests of RBS.

e. Conduct an analysis of predicted versus real world availability using data from the 1986 USS ENTERPRISE deployment.

I. INTRODUCTION

Operational Availability (A_o) is the primary measure of material readiness for Navy weapon systems and equipment. Some systems and equipments require the application of readiness based sparing techniques to achieve the A_o objectives specified by their Chief of Naval Operations (CNO) sponsor. Specific guidance on the use of readiness based sparing is provided in reference 1 of APPENDIX A. In short, it must be approved by CNO on a case by case basis and is limited to the computation of consumer level requirements. In the past, the Availability Centered Inventory Model (ACIM) has been used for Naval Sea Systems Command (NAVSEASYSCOM) systems and equipment. Application of ACIM to Naval Air Systems Command (NAVAIRSYSCOM) systems has been limited to the SH60B. This aircraft only requires spares to support organizational level maintenance at the consumer level and hence is similar to NAVSEASYSCOM systems. Application to other aircraft requiring spares to support organization and intermediate maintenance has not been validated.

The need for a readiness based sparing model specifically designed for aircraft resulted in a FMSO tasking to develop the Aviation Readiness Requirements Oriented to Weapon Replaceable Assemblies (ARROWs) model. The model is designed to compute consumer level requirements; i.e., Aviation Consolidated Allowance List (AVCAL) quantities. Development of ARROWs began with a data analysis and background research. The results of the data analysis were provided in reference 2 of APPENDIX A. These results indicated the theoretical distribution best suited for representing the repair and resupply pipelines depends on the assumptions made in computing aircraft availability. In particular, availability computations that consider cannibalization require a more precise

distribution. The required precision is provided by forecasting the variance of the pipeline distribution. Other approaches to computing availability only require forecasting a mean. Availability computations were found to be sensitive to forecasting inaccuracies for a small number of critical items. However, correction of these inaccuracies had little effect on the optimality of the rest of the inventory. Thus, there is no need to constantly reoptimize to maintain an optimal inventory.

The results of the background research were provided in reference 3 to APPENDIX A. The background research examined existing models and delineated the technical framework on which ARROWs would be built. Specifically, the assumptions made in computing availability allow use of a steady-state Poisson distribution to model the repair and resupply pipelines. The Poisson distribution requires only a forecasted mean which is readily available from existing data elements. Redundancy is not considered; i.e., stockage is computed to keep all components within an aircraft operational. The optimization considers essentiality so that each item's impact on an aircraft's mission(s) is considered in making trade-offs between items. Multiple indenture levels within an aircraft are addressed in such a way as to provide flexibility in the treatment of lower indenture parts used by intermediate maintenance in the repair of organizational level removables. Lower indentured Shop Replaceable Assemblies (SRAs) may be spared along with organizational level removables to an availability goal, to support an Awaiting Parts (AWP) time specified for a higher level assembly on which they are installed or with any of the computational procedures available in Retail Invertory Model for Aviation (RIMAIR) which is discussed below.

Concurrent with the ARROWs data analysis and background research, we developed RIMAIR to eliminate the dichotomy between the material availability (fill rate) goals and stockage criteria promulgated in OPNAVINST 4441.12A. We designed RIMAIR to comply with DOD instructions 4140.45, 4140.46 and 4140.47. RIMAIR computes consumer level requirements that consist of an operating level, repair cycle level, order and ship time level, resupply delay time level, endurance level and safety level. The model is parameterized and offers alternative range and depth criteria as discussed in reference 4 of APPENDIX A. Range selection may be based on item removal rates or the depth computation; i.e., items not computing to a positive depth are excluded from the range. The depth criteria determines the safety level. This may be based on a fixed protection against stockout or optimizing to a fill rate, Average Customer Wait Time (ACWT) or cost goal. We added the ACWT optimization to RIMAIR to comply with OPNAVINST 4441.12B subsequent to reference 4 of APPENDIX A. We released RIMAIR to the Navy Aviation Supply Office (ASO) in August 1983 for use with the TECH-EX AVCAL system and in June 1985 for use with the FMSO designed Uniform Inventory Control Program (UICP) AVCAL system. RIMAIR is included as part of the ARROWs model for application to lower indentured SRAs and consumable piece parts.

Concurrent with our efforts, CNO tasked the Center for Naval Analyses (CNA) to evaluate aviation allowance policies and produce recommendations for improving the support provided by the AVCAL. Known as the Aviation Parts Allowance Policy Study (reference 5 of APPENDIX A), the analysis recommended an at sea test of RBS. CNO endorsed the test which was conducted during the 198[illegible] cruise of the USS ENTERPRISE. Stockage requirements for high cost, mission essential, F14 organizational level removables (Weapons Replaceable Assemblies (WRAs) and high cost consumables) were computed using CNA's

Multi-Item Multi-Echelon (MIME) model. The remainder of the AVCAL was produced using standard ASO techniques. The final results of the test are not yet available. Preliminary results, however, appear to be favorable. ACIM, MIME, RIMAIR, and ARROWs can all be used to spare to a readiness goal. We demonstrated (in references 6 and 7 of APPENDIX A) that the RIMAIR ACWT optimization can produce stockage requirements comparable to those produced by MIME. The model produced the same requirement quantity for nine out of every 10 candidates when run to a cost goal. This means the optimization routines are making very similar stockage decisions even though they have different objective functions. RIMAIR minimizes the expected backorders for the candidates. The ACWT that results can be used to manually compute availability. MIME maximizes availability directly using different assumptions. Although the stockage decisions are very similar, the predicted availability is different because of the difference in assumptions. Thus, RIMAIR will not produce results comparable to MIME when sparing to an availability goal.

RIMAIR, however, was not designed to be a RBS model. That function belongs to ARROWs which, while minimizing organizational level removable's expected backorders, offers a variety of assumptions regarding availability. These can be categorized into historical and analytical approaches. The historical approach takes advantage of information on how past organizational maintenance actions affected availability. The analytical approach is that used by CNA's MIME model. The impact of organizational level removables on aircraft availability is implied in the calculations.

The remainder of this report examines availability predictions produced by the ARROWs model and compares ARROWs requirement quantities to those generated by ACIM and MIME. An overview of ARROWs is provided in APPENDIX B and a

discussion of the various methods for predicting availability may be found in APPENDIX C. The mathematical background for the ARROWs computations is contained in APPENDIX D. ARROWs/MIME and ARROWs/ACIM comparisons are contained in the main body of the report.

II. APPROACH

The criteria used to evaluate ARROWs and the data upon which the evaluation was based are discussed below.

A. EVALUATION CRITERIA. The evaluation of ARROWs ability to spare to availability has two purposes: (1) establish the credibility of the availability projections, and (2) establish the credibility of the stockage requirements computed for high cost, mission essential, organizational level removables. Organizational level removables have a direct impact on availability and the high cost, mission essential items account for the bulk of the cost to support an aircraft. For example, the cost of the high cost, mission essential F14A items included in the MIME test was $47.5M. Initial implementation of RBS will only address this type of item. Requirements for lower indenture SRAs and piece parts will be examined in the future.

The credibility of ARROWs availability projections is best determined by comparing ARROWs predictions to real world observations. A real world observation of RBS is being provided by the MIME test, which is not yet completed. The results of that test should provide a basis for evaluating predictions produced by RBS techniques. Real world observations based on standard ASO stockage are readily available and are discussed in the BENCHMARK RESULTS

part of Section III, FINDINGS. In addition to real world observation, the ARROWs predictions were compared to results produced by a simulation model designed by CNA to evaluate the effects of spare part stockage on the readiness of aircraft. This simulation model is described in reference 5 of APPENDIX A.

Because ARROWs offers a variety of assumptions regarding availability, it is capable of producing a variety of stockage requirements when sparing to availability. To establish the credibility of these requirements, they were compared to those computed by other models with compatible assumptions. The only model currently used to spare an aircraft to availability is ACIM. A comparison between ARROWs and ACIM requirements is provided in the SH60B RESULTS part of Section III, FINDINGS. The MIME requirements computed for the at sea test of RBS were not determined by an availability goal. Rather, the cost of the standard ASO stockage requirements was ascertained and MIME was used with this cost as a goal. MIME did produce an availability projection for this funding level which was compared to that produced by ARROWs for the same cost using compatible assumptions. Similar projections would indicate both models produce comparable cost when sparing to availability and thus permit a comparison of the requirements produced by the cost goal. This comparison is provided in the F14A RESULTS part of Section III, FINDINGS.

B. <u>DATA</u>. Data were obtained for two aircraft, the SH60B and the F14A. The SH60B was selected because ASO is to assume responsibility for computing stockage requirements and requested a comparison between RIMAIR/ARROWs and ACIM. The F14A was selected because it was used in the MIME test on the USS ENTERPRISE. Data sources for the two aircraft are discussed below.

1. SH60B DATA. Candidate item data were provided by CACI. Included were 405 high cost, mission essential items which previously had requirements computed by ACIM. Item data provided by CACI included part number, Best Replacement Factor (BRF), population and unit price. Essentiality was not provided so all items were assigned an Item Mission Essentiality Code (IMEC) of five and availability was in terms of an FMC rate. Each item was assumed to have an average resupply time of 12 days to be consistent with ACIM. Average impact factors were computed for three distinct "subsystems", avionics, airframe and engine. Impact factors translate predicted item downtime into aircraft downtime. Their use in predicting availability with the historical approach is discussed in APPENDIX C. The ratio of the number of subsystem failures to the total number of item failures within the subsystem produced values of .67 for avionics items, .92 for airframe items and .22 for engine items. An aircraft mean calendar time between failure of 36.6 hours and mean time to repair of .9 hours were used to be consistent with ACIM.

2. F14A DATA. Candidate item data were provided by CNA. The data were for the 701 high cost organizational level removables used in the MIME test on the USS ENTERPRISE. The data included stock number, Maintenance Replacement Factor (MRF), Rotatable Pool Factor (RPF), Turn Around Time (TAT), population, unit price and aircraft flying hour program. Population and flying hour program data were for the F14A and any other aircraft to which common items had application. Data for common items were summarized across all applications to obtain total pipelines for the deckload. CNA provided their own essentiality coding. Items were identified as rendering the aircraft either Not Mission Capable (NMC) or Partially Mission Capable (PMC) upon failure. There were 635 NMC items which were assigned an IMEC of 5 and 66 PMC items assigned an

IMFC of 4. An average resupply time of 90 days and a mean time to repair of three hours were assumed to be consistent with the MIME test.

Impact factors based on Naval Aviation Logistics Data Analysis (NALDA) data were provided by CACI. The impact factors were computed for Work Unit Codes (WUCs) within the aircraft with at least 50 hours of downtime between October 1983 and March 1985, the time period over which the overlap of all maintenance actions for the F14 was observed. Separate Mission Capable (MC) and FMC factors were included. The MC impact factors were based on maintenance actions that rendered the aircraft NMC. These were used for NMC (IMEC 5) items. The FMC impact factors were based on maintenance actions that rendered it Not Fully Mission Capable (NFMC). These were used for FMC (IMEC 4) items. The WUC factors were cross-referenced to stock number with the result that 58% of the candidates had item specific values. The remainder of the candidates used values averaged across all WUCs.

III. FINDINGS

The data obtained for the evaluation were for the SH60B and F14A. The findings for these two aircraft are presented below. A separate BENCHMARK RESULTS section addresses predicted availability versus real world observation for the standard ASO stockage policy.

A. BENCHMARK RESULTS. TABLE I compares real world historical availability to model predictions computed using requirements computed by ASO for the 1986 USS ENTERPRISE deployment. Historical availability based on just the high cost, mission essential F14A items included in the MIME test was provided by CACI. NALDA data from October 1983 to March 1985 were used to determine the percent

time these items were up. The Fleet-wide average FMC rate for these items was 70%. The value for a carrier would typically be 10-15 percentage points higher than the Fleet average. The FMC rate predicted by ARROWs using the historical approach with item specific impact factors and a 45 day average resupply time was 61%. A full fledged CNA simulation of aircraft operations predicts 65% FMC with a 45 day resupply time. The pure analytical prediction produced an FMC rate of just 21%.

TABLE I

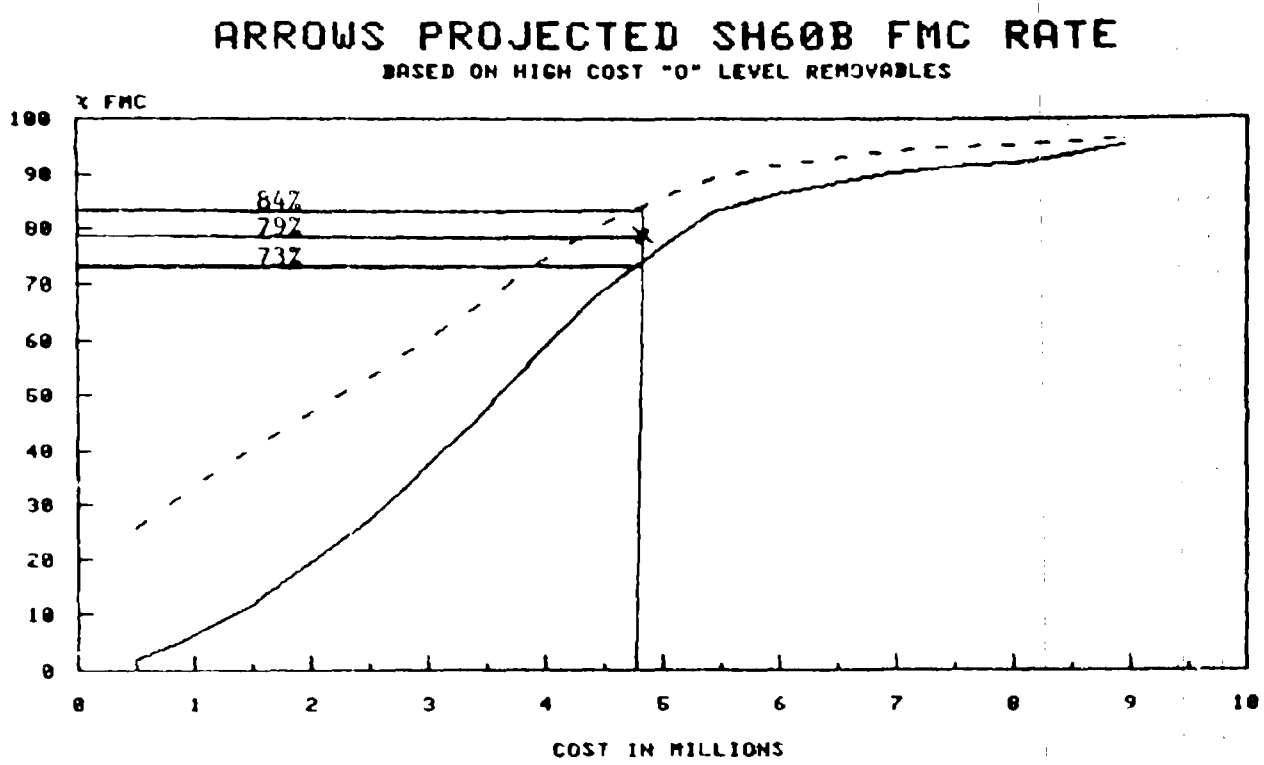
AVAILABILITY OF HIGH COST MISSION ESSENTIAL
F14A ORGANIZATIONAL LEVEL REMOVABLES
BASED ON STANDARD ASO STOCKAGE

	FMC
Real World Observation	70%
CNA Simulation of Aircraft Operations	65%
ARROWs Historical Approach Prediction	61%
ARROWs Analytical Approach Prediction	21%

In comparing the rates, note that the real world observation and CNA simulation allow for cannibalization. The ARROWs historical approach uses impact factors that can be influenced by cannibalization. However, the NALDA data from which the impact factors were derived showed very few cannibalization hours. There was little difference between impact factors computed with and without these cannibalization hours. The 61% FMC rate includes the cannibalization hours but would not change if those hours were deleted. The cause of the difference between the real world observation and the predictions produced by the CNA simulation and ARROWs is not known and requires further research.

While further research may be required to fine tune the historical approach, it appears to be promising, particularly in comparison to the analytical approach which is very conservative.

B. SH60B RESULTS. FIGURE 1 shows cost versus FMC rate based on requirements computed by ARROWs for the SH60B. FMC rate is predicted using both the historical and analytical approaches. The FMC rate produced by a CNA simulation of SH60B operations is also shown. This is the availability predicted for the third month of wartime operations. The curve produced with the historical approach is the same as would be produced by ACIM. This is verified by noting that both ARROWs and ACIM project a cost of $4.8M to achieve the 84% FMC goal used for sparing. Also, the requirement quantities produced by both models at this point are almost identical as shown in TABLE II. The requirement quantities differed for only four of the 405 items. ARROWs stocked an avionics item not stocked by ACIM and one additional unit of two airframe items. ACIM stocked one engine item not stocked by ARROWs.



- - - - - Historical Approach

———— Analytical Approach

X CNA Simulation

FIGURE 1

TABLE II

ARROWS VERSUS ACIM SH60B REQUIREMENTS

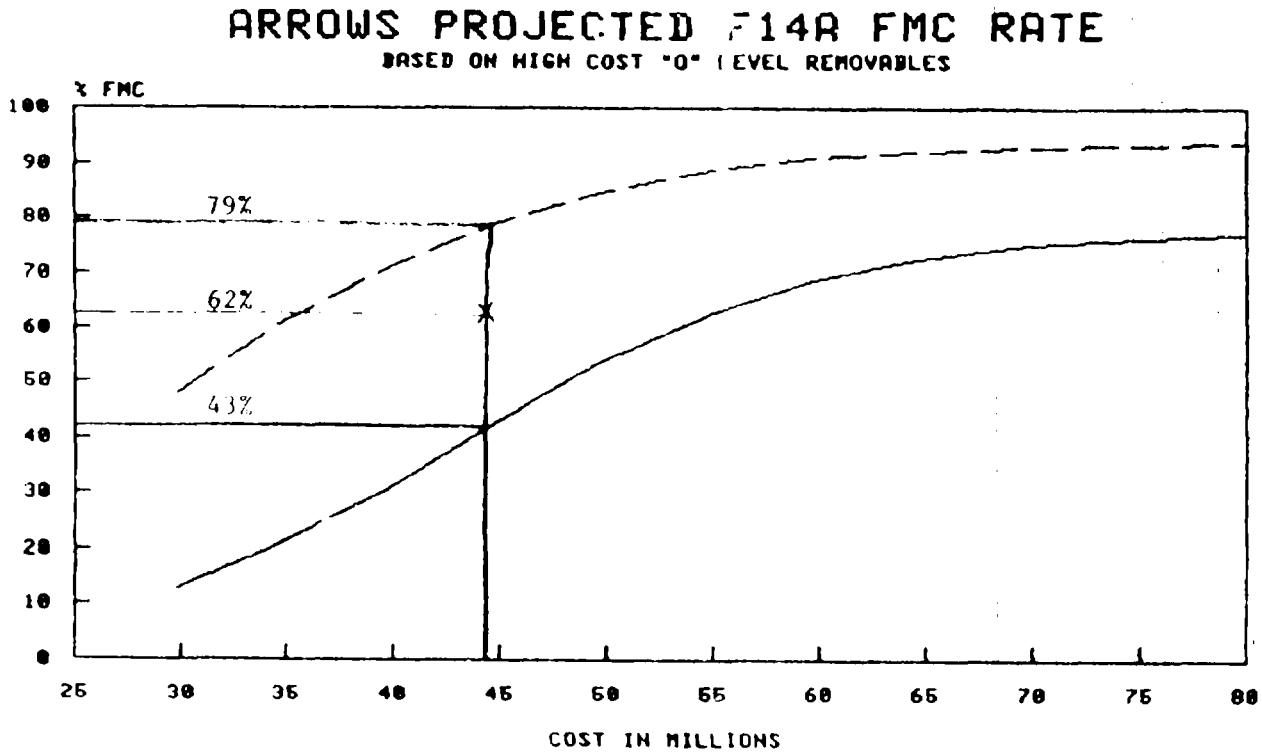
TOTAL ARROWs COST = $4.8M TOTAL ACIM COST = $4.8M

	AVIONICS	AIRFRAME	ENGINE	TOTAL
Candidates	124	263	18	405
Stocked by ARROWs and ACIM	97	223	10	330
ARROWs = ACIM	97	221	10	328
ARROWs = ACIM + 1	0	2	0	2
ARROWs = ACIM - 1	0	0	0	0
Stocked by ARROWs Only	1	0	0	1
Stocked by ACIM Only	0	0	1	1

The curve produced with the analytical approach is lower than the historic curve but the difference diminishes as cost increases. Use of this curve to spare to the 84% goal would have increased cost several hundred thousand dollars. The FMC rate predicted by the CNA simulator lies half way between the historical and analytical approaches.

C. F14A RESULTS. FIGUREs 2 and 3 show cost versus availability based on requirements computed by ARROWs for the F14A. FMC and MC rates are predicted using both the historical and analytical approaches. The FMC and MC rates predicted by a CNA simulation of F14A operations are also shown. These values are for the third month of wartime operations. The curves produced with the analytical approach are the same as would be produced by MIMF. This is verified by noting that according to CNA, MIME predicts about 42% FMC for the inventory

built for the USS ENTERPRISE. ARROWs predicts 42.6% FMC for an inventory built to the same cost goal. The cost goal used to generate the inventories was $47.5M. The MIME requirements cost $47.8M. ARROWs cost was $47.7M. This cost is for items pecular to the F14A as well as items common to other aircraft. ARROWs prorates the cost of common items. The cost shown in FIGUREs 2 and 3 is the cost of F14A peculiars plus a prorated share of the common item cost. The cost to produce 42.6% FMC on the F14A was $44.6M. The other $3.1M is a share of the F14A common items regarded as supporting the other aircraft in the deckload.

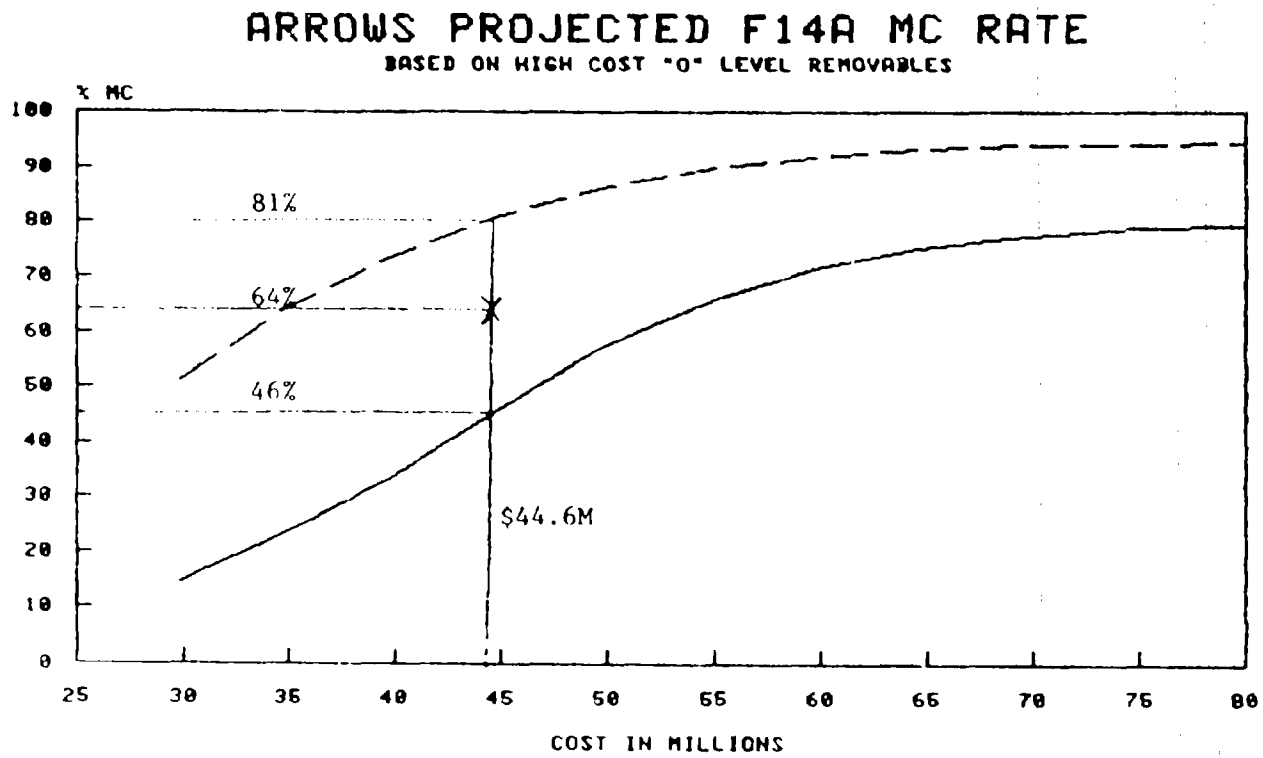


- - - - - Historical Approach

——— Analytical Approach

X CNA Simulation

FIGURE 2



- - - - - Historical Approach

——— Analytical Approach

X CNA Simulation

FIGURE 3

The requirement quantities produced by ARROWs and MIME are very similar as shown in TABLE III. ARROWs stocks all but 40 of the items stocked by MIME. These 40 items all had zero MRFs and RPFs. However, CNA used an attrition rate of .00025 for the MIME computations. This equates to using one unit every 400,000 flying hours. ARROWs was run using the zero rates which makes stockage of these items impossible. There were no items stocked by ARROWs that were not stocked by MIME. The requirements for the items stocked by both models were the same 94% of the time.

TABLE III

ARROWS VERSUS MIME F14A REQUIREMENTS

TOTAL ARROWs COST = $47.7M TOTAL MIME COST = $47.8M

	AVIONICS	AIRFRAME	ENGINE	TOTAL
Candidates	142	522	31	701
Stocked by ARROWs and MIME	140	450	28	624
ARROWs = MIME	115	435	28	584
ARROWs > MIME	21	7	0	28
ARROWs = MIME + 1	16	5	0	21
ARROWS < MIME	4	8	0	12
ARROWs = MIME - 1	4	8	0	12
Stocked by MIME Only	0	37	3	40
Zero Removal Items	0	37	3	40

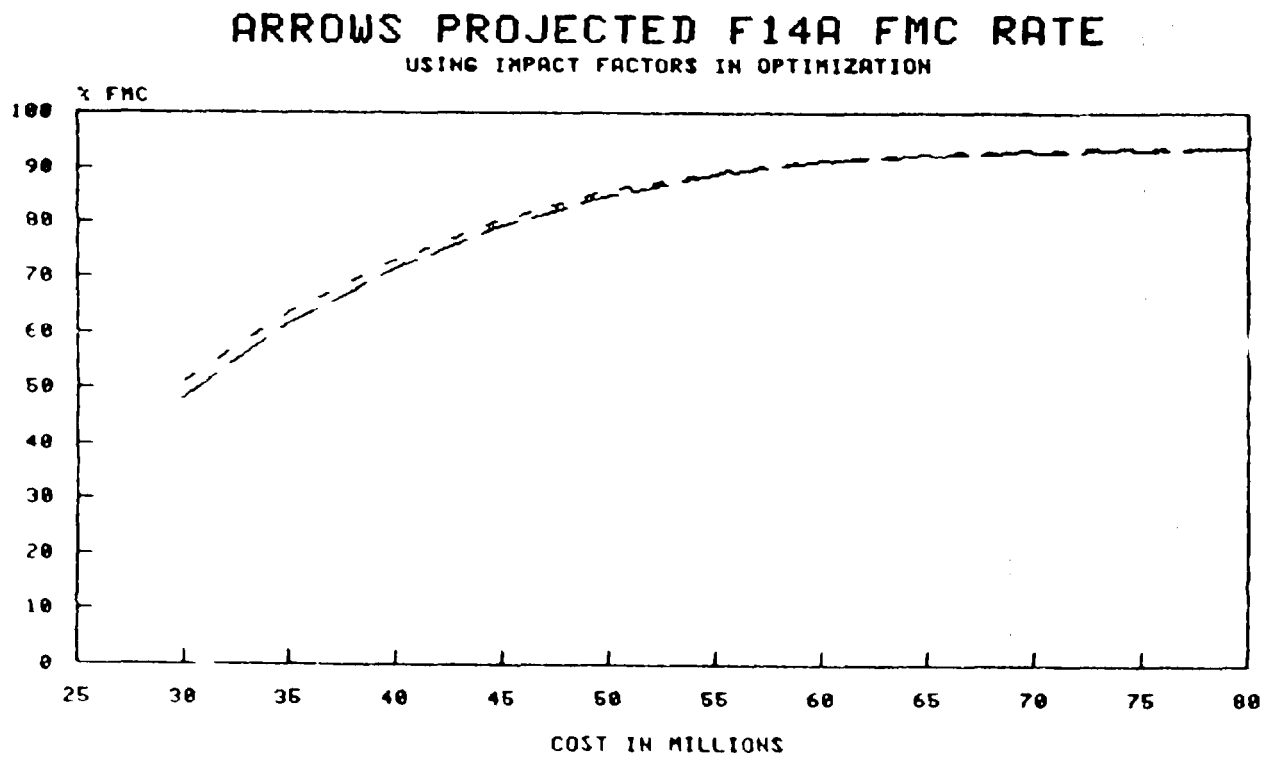
Note: Six items could not be identified as avionics, airframe or engine.

The contrast between the historical and analytical approaches is greater for the F14A than it was for the SH60B. This can be at least partially attributed to the impact factors. The SH60B used subsystem averages which reflected less overlap of item downtimes for avionics and airframe items than their F14A item specific counterparts. If the F14A had been spared to an availability goal, the analytical approach would have generated a cost much greater than the historical approach, if the goal could be reached at all. The maximum value with the analytical approach was 78% FMC. The results of the CNA simulation were about halfway between the historical and analytical approaches just as with the SH60B.

The CNA simulated FMC rate of 62% is less than that produced using ASO quantities (65%) because the ARROWs quantities were evaluated assuming a 90 day resupply time, while the ASO quantities were evaluated assuming a 45 day resupply time. Decreasing the assumed resupply time from 90 to 45 days increases the simulated FMC rate for the ARROWs quantities to 68% which would mean a three percentage point gain over current ASO quantities for the same cost. Note that the CNA simulation considers cannibalization and, as discussed in the BENCHMARK RESULTS part of Section III, ARROWs historical predictions were not affected by cannibalization hours. The reason the ARROWs historical prediction exceeded the CNA simulation results is not known.

There is little difference between the FMC and MC curves. This is because the PMC items identified by CNA had little impact on availability. Only about 9% of the total projected aircraft downtime was PMC time. This is as would be expected from the data since about 9% of the candidates were PMC items. Until good IMEC coding is available, MC projections will be of little use.

FIGURE 4 shows the results of using impact factors in the availability optimization. The stockage decisions are based on selecting the item with the greatest reduction in aircraft downtime instead of item downtime. Thus items with a greater impact on aircraft availability are weighted more heavily. This is intuitively appealing but the results show there is little overall improvement in predicted availability for a given cost. The maximum increase in predicted FMC rate was three percentage points. At the cost goal used for the MIME test, the increase was about one percentage point. The inventory generated is different. This can be seen in TABLE IV where the new requirements are compared to the ME requirements and show many more differences than those computed without using the impact factors in the optimization. Only 77% of the requirements for items stocked by both models were the same. A greater improvement may have resulted if item specific values were available for more of the items (42% used the aircraft average).



- - - - - Historical Approach using Impact Factors in Optimization

——— Historical Approach without using Impact Factors in Optimization

FIGURE 4

TABLE IV

ARROWS VERSUS MIME F14A REQUIREMENTS
USING IMPACT FACTORS IN OPTIMIZATION

TOTAL ARROWs COST = $47.7M TOTAL MIME COST = $47.8M

	AVIONICS	AIRFRAME	ENGINE	TOTAL
Candidates	142	522	31	701
Stocked by ARROWs and MIME	136	449	28	619
ARROWs = MIME	83	369	22	479
ARROWs > MIME	28	44	5	77
ARROWs = MIME + 1	21	42	4	67
ARROWS < MIME	25	36	1	63
ARROWs = MIME - 1	23	35	1	60
Stocked by MIME Only	4	38	3	45
Zero Removal Items	0	37	3	40

Note: Six items could not be identified as avionics, airframe or engine.

IV. SUMMARY

We developed ARROWs to serve as the RBS model for computing AVCAL requirements. It offers flexibility in projecting availability using different assumptions. It may be applied to all the aircraft at a site because it considers commonality. Different computations can be applied to different types of items. For example, high cost, mission essential, organizational level removables can be spared to achieve an availability goal while low cost, non-mission essential items can be spared to achieve an average customer wait time objective. Lower indenture SRAs can be spared to maximize availability along

with the organizational level removables or to support awaiting parts times specified for individual WRAs. Consumable piece parts can be spared to an average customer waiting time or fill rate objective or just to achieve a specified level of projection against stockout. The requirements for individual items can be constrained. Thus minimums can be input for items stocked in the past that experienced some demand to reduce inventory churn. Maximums can be input for items with weight or cube limitations. ARROWs is a consumer level stockage model. (However, it can be used in conjunction with other models that address higher echelons of supply to perform pseudo multi-echelon analysis).

We examined ARROWs application to high cost, mission essential, organizational level removables. These items account for most of the cost to support an aircraft. Availability predictions for these items varied considerably when the assumptions were varied. The ARROWs historical approach predicts much higher availability than the purely analytical approach because of greater overlap of item downtimes. The CNA simulations predicted higher availability than either approach when used to evaluate the standard ASO stockage; but all predictions were less than the real world observation. When evaluating inventories generated by the ARROWs availability optimization, the CNA simulation predicted availability halfway in between the analytic and historical approach predictions.

The CNA simulation considers cannibalization. The ARROWs historical approach uses impact factors that can be influenced by cannibalization hours; however, this was not the case with the data used in this study. The cause of the differences between the predicted availability and real world observation, as well as between the CNA simulation and ARROWs predictions, is not known. Further research is required to refine the predictions.

The historical approach appears to be very promising. Further analysis of the predictions should be conducted using data from the 1986 USS ENTERPRISE deployment. With a sound historical data base, the historical approach should produce the most realistic prediction possible without resorting to a more complex simulation of flight operations. Without a good historical data base, average impact factors must be estimated. Those should still provide a more practical tool for sparing to availability than the purely analytical approach which is very conservative and costly.

Application of ARROWs to the SH60B showed it can produce results almost identical to ACIM. The cost to achieve the availability goal of 84% FMC was $4.8M for both models. The requirement quantities generated by the two models were the same for 99% of the candidate items. Application of ARROWs to the F14A showed it can produce results very similar to MIME. In optimizing to a cost goal of $47.5M, ARROWs cost $47.7M and predicted an FMC rate at 42.6% with MIME's analytical approach and MIME cost $47.8M and predicted about 42% according to CNA. The requirements generated by the two models were the same for 94% of the items stocked by both. MIME stocked 40 zero demand items because CNA assumed a minimum MRF value of .00025 for these items, whereas ARROWs did not consider these items for stockage.

Using impact factors to influence stockage decisions increases predicted availability up to three percentage points. At the cost goal used for the MIME test, the increase was about one percentage point in the FMC rate. Only 58% of the candidates had item specific impact factors. Aircraft averages were used for the rest. Obtaining item specific values for more items may result in a greater predicted improvement. However, the stockage decisions are more sensitive to inaccuracies in the impact factors than the availability predictions where errors may cancel. Impact factors are dynamic and will

change over time so that stocking items with the greatest impact on aircraft downtime in the past does not guarantee an increase in availability in the future. A better way must be found to evaluate any predicted improvement before use of impact factors in stockage decisions can be recommended.

V. RECOMMENDATIONS

We recommend the following:

- Establish ARROWs as the RBS model for aircraft. It is specifically designed to operate at ASO where AVCALs are built and includes the capabilities of other models such as ACIM and MIME.
- Use ARROWs in lieu of ACIM when support of the SH60B transitions to ASO. This will save the cost of bringing ACIM in-house at ASO.
- Reevaluate the use of subsystem average impact factors on the SH60B when a sufficient historical data base is accumulated to allow use of item specific values. This should allow for a better availability prediction.
- Use ARROWs in lieu of MIME in any future at sea tests of RBS. ARROWs can be run at ASO on the ASO data base. This would afford ASO the opportunity to gain operational experience in generating RBS requirements as part of a test.
- Conduct an analysis of predicted versus real world availability using data from the 1986 USS ENTERPRISE deployment. This will provide insight into the cause of the discrepancy between predicted and real world availability.

APPENDIX A: REFERENCES

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3. ALRAND Working Memorandum 471.
4. Operations Analysis Report 155.
5. CNS 1180, Aviation Parts Allowance Policy Study Report of August 1984.
6. FMSO presentation to CNO (OP-41) of 22 May 1985.
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8. RIMAIR Users Manual, FMSO Document No. UM-D59.
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APPENDIX B: ARROWs OVERVIEW

Aviation Readiness Requirements Oriented to Weapon Replaceable Assemblies (ARROWs) is designed to be a Readiness Based Sparing (RBS) model that offers flexibility in both predicting availability and in applying different stockage objectives to different subsets of items within an aircraft. At a minimum, the high cost, mission essential, organizational level removables can be spared to an availability objective as in the MIME at sea test. ARROWs can be applied to one or all the aircraft in a deckload since it considers the commonality of parts between different aircraft. The aircraft in a deckload can be optimized one at a time to either a cost or availability goal. The model determines the stockage requirements required to achieve the goal specified for the first aircraft optimized. Stockage decisions for items common to the next aircraft optimized begin where the first aircraft left off. The third aircraft picks up where the second left off and so on. The cost and benefit of increasing stockage of a common item are prorated to reflect the aircraft being optimized.

Low cost or nonmission essential organizational level removables can also be spared to availability, if desired, or can be processed using the Retail Inventory Model for Aviation (RIMAIR) procedures. The RIMAIR model is included as part of the ARROWs software package. The RIMAIR Average Customer Wait Time (ACWT) optimization provides a stockage objective closely related to availability. Its application to the low cost items eliminates trade-offs between high cost items with scrubbed data and low cost items whose shear number prohibits effective data scrubbing. Even when optimized separately, however, the impact of these items on availability is computed. The user has access to availability based solely on the high cost items that were spared to availability, or all items.

Lower indentured Shop Replaceable Assemblies (SRAs) and piece parts may be treated in a variety of ways. The SRAs may be spared directly to availability if the user believes the integrity of the SRA data is high enough to permit trade-offs between the SRAs and higher cost Weapons Replaceable Assemblies (WRAs). Where SRA data integrity is questionable, they can be spared indirectly to availability. Awaiting Parts (AWP) times may be specified for the WRAs. These AWP times are then used in the availability optimization to compute the WRA requirements. They also drive the requirements computations for the SRAs within a given WRA. The SRAs are optimized to achieve the specified AWP time. Although the AWP optimization does not involve trade-offs between WRA and SRA stockage, the resulting mix is at least coherent; i.e., the AWP time upon which the WRA calculations are based is supported by the SRA stockage.

Sparing SRAs either directly with the availability optimization or indirectly with the AWP optimization requires the input of an indenture structure to identify the parts hierarchy. The integrity of the indenture structure is critical and it is validated for completeness. If an adequate indenture structure is not available, the RIMAIR ACWT optimization may be applied to the SRAs. This is similar to the AWP optimization except that trade-offs are made between all the SRAs at a site as opposed to just those installed on a particular WRA. This means the AWP times used in the WRA computations may be over or under supported by the SRA computations.

Piece part requirements may be computed using any of the RIMAIR procedures described in reference 8 of APPENDIX A. When piece parts are identified within an indenture structure, the results of the RIMAIR computations are used in the availability and AWP optimizations. This means the expected backorders

for the piece parts are considered when computing the average time a repairable assembly spends awaiting parts when it fails. Piece parts may also be considered without regard to any indenture structure, although their effect on the repairables will not be computed.

All the optimizations available within ARROWs compute requirements between specified minimum and maximum quantities. These quantities are fixed in the RIMAIR fill rate and ACWT optimizations. The minimum equals the mean war repair and resupply pipelines plus an endurance delta plus an operating level minus one rounded to the nearest integer. The maximum equals the smallest quantity that provides 99% protection against stockout based on the mean war repair and resupply pipelines and endurance delta. The constraints are variable in the AWP and availability optimizations. The user specifies minimum and maximum protection against stockout. These protection levels generate quantities based on the mean war repair and resupply pipelines and endurance delta. The protection levels may be varied by Cognizance Symbol (Cog) code and Item Mission Essentiality Code (IMEC) within aircraft. The above constraints may be overridden for an individual item. A minimum or maximum may be input on the items candidate record. The option also exists to specify the requirement for an item. This absolute constraint sets both the minimum and maximum equal to the specified value.

Constraints can have a significant impact on the results as shown in reference 7 of APPENDIX A. How they are used is a matter of policy. They have the potential, though, to solve some practical problems. Minimum constraints can help reduce inventory churn that results from changes in stockage requirements from one deployment to the next. An item stocked on the previous deployment that experienced some usage can have its stockage on the

next deployment assured with a minimum constraint of one. Similarly, items that have built up higher than average demand based levels at a particular Unit Identification Code (UIC) may have these levels perpetuated into the future by setting the minimum constraint equal to the Requisition Objective (RO). The maximum constraint can be used to assure specific item requirements do not exceed weight or cube limitations. The absolute constraint can be applied when an aircraft must be reoptimized because of a configuration change. Stockage requirements for items not affected by the change can be fixed if they have already been agreed upon at an Aviation Consolidated Allowance List (AVCAL) conference.

We designed the ARROWs software package to function in an on-line interactive environment. A technical description of the approach taken in developing the software may be found in reference 9 of APPENDIX A. Briefly, batch procedures for validation, computations and statistics generation are initiated from a user menu. Parameter entry, error correction and the review of interim statistics are also menu driven but are accomplished on-line. Tasks must be performed in a specified order. Parameters must be entered first, then the candidate data are validated. RIMAIR computations precede the AWP optimization which is followed by the availability optimization. When multiple aircraft are being optimized to availability, they may be processed in any order. However, the first aircraft will establish requirements for common items that act as minimum constraints on subsequent aircraft. Common items on the last aircraft will begin the optimization with stockage levels reflecting decisions made for the other aircraft. The final cost of all but the last aircraft can increase somewhat because of decisions made on subsequent aircraft.

When all aircraft have been processed, final cost and availability statistics are produced for each aircraft. Total cost and supply performance statistics for the UIC are also provided. The total UIC cost is stratified to show Peacetime Operating Stock (POS) and war reserve dollars as well as costs associated with the operating level, repair and resupply pipelines, endurance delta and safety level. The supply performance measures are fill rate and Average Customer Wait Time (ACWT).

APPENDIX C: AVAILABILITY PROJECTIONS

ARROWs projects availability in terms of Mission Capable (MC) and Fully Mission Capable (FMC) rates. An aircraft is considered MC if all the organizational level removables with an IMEC of 5 are functioning. An FMC aircraft is one with all IMEC 3, 4 and 5 items functioning. If accurate IMECs are not available, setting each organizational level removable's IMEC equal to 5 will produce a FMC rate only.

Projecting availability starts with the computation of expected backorders for organizational level removables. A backorder is a demand for material that must be satisfied by expeditious repair or direct turnover requisitioning. This happens when the number of units being repaired (repair pipeline) or on order from the supply system (resupply pipeline) exceeds the stockage requirement. The computation of backorders therefore requires the mean repair and resupply pipelines, an assumption about the distribution of the number of units in the pipelines at a random point in time and the stockage requirement. The mean repair and resupply pipelines equal the rate at which an item fails and is repaired times the time it takes to repair it, plus the rate at which it fails and is attrited times the time it takes to requisition it from the supply system. A Poisson distribution is used to determine the probability that the number of units in the pipeline exceeds the stockage requirement; i.e., that there are one, two, three or more backorders. An item's expected backorders is obtained by multiplying these probabilities by the associated number of backorders and accumulating over all possible values.

Expected backorders divided by an item's removal rate yields the average supply delay per removal. This combined with the time it takes maintenance to remove and replace the item is the total item downtime. Multiple item removals can be generated by an aircraft failure. How the item downtimes overlap determines how long the aircraft is down.

ARROWs offers two approaches to determining the overlap of downtimes for organizational level removables. The first approach uses historical information. Past maintenance actions are examined to determine overlapping item downtimes. Time during which an item has sole impact is combined with a percentage of the time its impact is shared with other items. The result is the aircraft downtime associated with an item which is less than or equal to the total item downtime. The percentage of total item downtime that is aircraft downtime is called an impact factor. A more detailed explanation of impact factors is provided in reference 10 of APPENDIX A. Impact factors are used within the model to project the amount of aircraft downtime that will be generated by the candidates for stockage. This is done by multiplying the total projected item downtime per removal times the removal rate times the impact factor for each item and accumulating. The projected aircraft downtime is used to compute aircraft availability as discussed in APPENDIX D.

Impact factors based on past maintenance actions will not be available for new aircraft which lack a historical data base. In this case, an average impact factor must be used. One approach is to assume that when an aircraft fails it is down for the average time it takes to remove and replace an item plus the average supply delay time to obtain a replacement; i.e., the average total item downtime. Divide this aircraft downtime equally among the

average number of items used per aircraft failure. Then the average impact factor is one divided by the average number of items used per failure because that is the percent of the average total item downtime that the aircraft is down for each item. This approach assumes that all item downtimes are completed in the average total downtime for one item so that there is a high degree of overlap between the items used per failure. The value assumed for the number of items per failure determines how much shared downtime is being generated overall. For example, a value of 1.1 results in an average impact factor of .9 which reflects little shared downtime. A value of four produces an average impact factor of .25 indicating a high degree of shared downtime. This approach may be refined by stratifying the average impact factors by functional areas within the aircraft.

The second approach to determining the overlap of item downtimes is purely analytical. The organizational level removables are considered to be statistically independent. Aircraft availability is computed as the product of the availabilities of individual items as discussed in APPENDIX D. The overlap of item downtimes is determined by the mix of item availabilities. For example, if two items are each available 90% of the time, then the combination is available 81% of the time. Each is down 10% of the time of which one percentage point is shared downtime. The combination is down 19% of the time of which one percentage point is shared downtime. As the number of items increase, the amount of shared downtime will increase. However, the item availabilities must also increase if the availability of the combination is to remain constant. Increasing item availabilities decreases shared downtime. The net effect is a slight increase in shared downtime. For example, if a combination of 1,000 items is down 10% of the time, about three percentage points will be shared downtime.

The purely analytical approach allows for some shared downtime but the amount is small resulting in low availability. The main use of the analytical approach is to establish minimal levels of availability when the historical approach cannot be applied for lack of data. When sparing to an availability goal, its use will increase cost and must be carefully controlled.

APPENDIX D: MATHEMATICAL BACKGROUND

1. Predicting Availability. The formulas used to compute predicted availability are presented below. A brief explanation of each one is provided. Rigorous derivations may be found in references 2 and 11 of APPENDIX A.

a. Historical Approach. This approach uses impact factors to determine the percent of item downtime that is aircraft downtime. The number of hours of item downtime generated when an item is removed from an aircraft is determined as follows:

$$IDT_i = (RRT_i + EBO_i/R_i)$$

where

IDT_i = number of hours of item i downtime per removal

RRT_i = number of hours to remove and replace item i

EBO_i = expected backorders for item i on aircraft

R_i = number removals per hour for item i on aircraft

The total number of hours of aircraft downtime generated by item removals in a month is found by multiplying each item's downtime by its impact factor and accumulating across items as follows:

$$ADT = \sum_{i=1}^{N} (720 * R_i * IDT_i * IF_i)$$

where

ADT = number of hours aircraft downtime per month

IF_i = impact factor for item i

N = number of items affecting aircraft

720 = number of hours per month

If N represents all NMC items, then ADT is the number of NMC hours per month. If N is the number of NMC and FMC items, then ADT is the number of NFMC hours per month. Thus computation of a MC or FMC rate is determined by the set of items over which the predicted hours of downtime is summed. Computation of the MC or FMC rate is accomplished by dividing the downtime by the total number of hours in a month, and subtracting from 1.00. After substitution and reduction, this yields the following formula for aircraft availability known as type 1A in ARROWs:

$$A(1A) = 1 - \frac{\sum_{i=1}^{N} (RRT_i * R_i * IF_i + EBO_i * IF_i)}{\text{Number of Aircraft}}$$

The A(1A) formula considers the aircraft to be down only as a result of item removals. The reliability of the aircraft is a function of the total projected item removals. The maintainability is reflected in the remove and replace times specified for each item. A more general expression which can be

used to allow aircraft failures that do not result in the removal of any item is uptime divided by uptime plus downtime. This formula for aircraft availability known as type 1B in ARROWs is:

$$A(1B) = \frac{MCTBF}{MCTBF + MTTR + MLDT * \%\ FAILURES\ REQUIRING\ PARTS}$$

where

MCTBF = number of hours of calendar time between failures that render aircraft NMC for MC rate, or NFMC for FMC rate

MTTR = number of hours of maintenance time to restore failed aircraft to an operative condition given any items needed to complete repair are available

MLDT = number of hours of supply time to obtain items when required to complete repair

% FAILURES REQUIRING PARTS = percentage of aircraft failures which require maintenance to obtain items from supply

MCTBF, MTTR and % FAILURES REQUIRING PARTS are all input to ARROWs as parameters. The MCTBF and MTTR explicitly specify the reliability and maintainability of an aircraft. If the MCTBF reflects aircraft failures not requiring maintenance to obtain items from supply, the % FAILURES REQUIRING PARTS should have a value less than 1.00. MTTR should reflect the overall average maintenance time required to remove and replace an item or otherwise repair the aircraft. MLDT is computed as follows:

$$MLDT = \frac{\sum_{i=1}^{N} EBO * IF}{\sum_{i=1}^{N} R_i}$$

Without the use of impact factors, MLDT is the average number of hours of backorders time associated with each removal of an average item. When impact factors are used, an adjustment must be made so that the MLDT is the average number of hours of aircraft supply downtime associated with each failure of the aircraft. The adjustment consists of multiplying the MLDT by the ratio of the sum of item removal rates to the aircraft failure rate. This can be done by entering a % FAILURES REQUIRING PARTS that has been adjusted with this ratio.

b. Analytical Approach. This approach is the same as that in the Multi-Item Multi-Echelon (MIME) model. It assumes that all items are statistically independent and that the aircraft availability is the probability that all the items are operational at a random point in time. The probability that an item is operational is computed using a variation of the uptime over uptime plus downtime approach for the individual item. The formula used in ARROWs known as availability type 2 is:

$$A(2) = \prod_{i=1}^{N} \left(\frac{1}{1 + ANU}\right)$$

where

ANU = average number of nonoperational units at a random point in time

The nonoperational units consist of those being removed and replaced by maintenance and those backordered by supply. This is computed as follows:

$$ANU = (RRT_i * R_i + EBO_i)/\# \text{ Aircraft}$$

If a positive MTTR parameter is specified, it is used as RRT_i for all items. If not, the values used in computing availability type 1A are used.

2. Availability Optimization. The availability optimization is multi-indentured and allows trade-offs between SRAs and WRAs in maximizing availability predicted with the historical approach. As used in this study, the optimization only considered trade-offs between organizational level removables; i.e., the multi-indentured capabilities were not utilized and are not described here. A brief summary of how the model computed requirements for organizational level removables is presented below.

Maximizing availability predicted with the historical approach is accomplished by minimizing the total number of backorders for organizational level removables. Backorder reductions for stock increases starting at the minimum and stopping at the maximum quantities for an item are computed using a total mean wartime pipeline. This pipeline consists of repair and resupply segments. The repair segment includes an AWP time portion that considers the impact of lower indentured SRA and consumable piece part stockage. The resupply pipeline segment considers the impact of stockage at higher echelons of supply. Backorder reductions are weighted by the items essentiality. If impact factors are used in the optimization, the essentiality weighted backorder reduction is multiplied by the item's FMC impact factor.

The essentiality weighted backorder reductions are divided by the item's cost to determine the ranking of each potential stockage level of an item. All potential stockage levels for all items are sorted by this ranking. The resulting list of item stock levels is used to construct a cost versus availability curve for the aircraft. The curve starts at the inventory consisting of minimum quantity for all items. Successive backorder reductions result in increased availability for an increase in cost. The final point of the curve is for the inventory consisting of the maximum quantity for all items. Any point on the curve may be selected. The ranking of the last unit of stockage associated with the selected point is used to select the requirement quantity for each item. This is done by comparing the ranking of each potential stockage level for each item to the ranking associated with the selected point. The stockage level with the smallest ranking which is greater than or equal to the selected ranking is the requirement quantity for each item.

3. Backorders for Common Items. The computation of expected backorders for items common to multiple aircraft is based on the total pipeline of the item at the site. Computations that require backorders associated with a particular aircraft are accomplished by prorating the total backorders. The proration is based on the pipelines for the individual aircraft. The backorders associated with a particular aircraft are computed by multiplying the total site backorders by the ratio of the aircraft pipeline to the total site pipeline.

Security Classification

DOCUMENT CONTROL DATA - R & D

Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author)

Navy Fleet Material Support Office
Operations Analysis Department (93)
Mechanicsburg, PA 17055-0787

2a. REPORT SECURITY CLASSIFICATION

Unclassified

2b. GROUP

3. REPORT TITLE

ARROWs Model Evaluation

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)

5. AUTHOR(S) (First name, middle initial, last name)

Frank C. Strauch

6. REPORT DATE

7a. TOTAL NO. OF PAGES: 47

7b. NO. OF REFS: 12

8a. CONTRACT OR GRANT NO.

b. PROJECT NO. N9324-B11

c.

d.

9a. ORIGINATOR'S REPORT NUMBER(S)

166

9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)

10. DISTRIBUTION STATEMENT

Distribution of this document is unlimited.

11. SUPPLEMENTARY NOTES

12. SPONSORING MILITARY ACTIVITY

13. ABSTRACT

The Aviation Readiness Requirements Oriented to Weapon Replaceable Assemblies (ARROWs) model was specifically designed for Readiness Based Sparing (RBS) of aircraft. This report examines various approaches to predicting availability of aircraft that are provided by the model and compares requirement quantities computed by the Availability Centered Inventory Model (ACIM) model for the SH60B and the Multi-Item Multi-Echelon (MIME) model for the F14A to those computed by ARROWs for high cost, mission essential, organizational level removables when using the same assumptions. We recommend that ARROWs be established as the RBS model for aircraft and that analysis of availability predictions be continued to enhance the credibility of these projections so that the ultimate goal of sparing to availability can be achieved.

DD FORM 1 NOV 65 1473 (PAGE 1)

S/N 0101-807-6801

Security Classification

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