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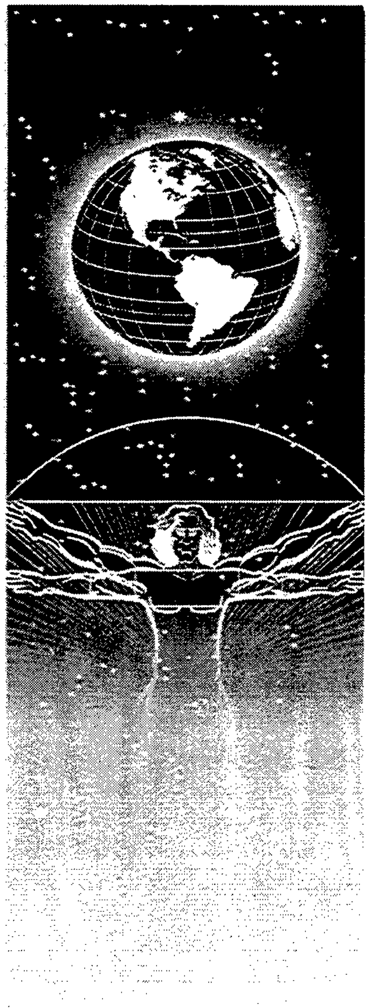

UNITED STATES AIR FORCE RESEARCH LABORATORY

Modular Aircraft Support System (MASS) Concept Validation

David A. Hablanian, et al

Arthur D. Little, Inc.
Acorn Park
Cambridge MA 02140

December 1998

Final Report for the Period December 1997 to July 1998

Human Effectiveness Directorate
Deployment and Sustainment Division
Sustainment Logistics Branch
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This technical report has been reviewed and is approved for publication.

FOR THE COMMANDER

For Lt Col

JAY KIDNEY, Lt Col, USAF, Chief
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13. ABSTRACT *(Maximum 200 words)*

The Modular Aircraft Support System (MASS) program is part of a research effort to improve the reliability, maintainability, operability, and deployability of aerosapce ground equipment (AGE.) The purpose of Delivery Order 0003 was to perform further requirements gathering, conceptual design, and analysis of the six system concepts which were developed in Delivery Order 0002. The results of the analysis were used to perform a downselect to a single system that provides the most promise for the eventual MASS proof-of-concept unit.

The single downselected concept incorporates elements of several of the initial six concepts. The key elelements of the new concept are: 1) diesel prime mover; 2) electrical power distribution between modules; 3) two or three carts; and, 4) no more than four distinct modules per cart. Layoutrdrawings and detailed life-cycle costs projections were developed for the MASS modules, chassis and carts.

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Preface

This report, prepared by staff members of Arthur D. Little, Inc., Acorn Park, Cambridge, Massachusetts, 02140, is the Final Report, Data Item A002, for the Modular Aircraft Support System (MASS) Concept Validation authorized by Delivery Order 0003 under contract F41624-96-D-5002. All work under the contract is performed for the Sustainment Logistics Branch of the Air Force Research Laboratory, Wright-Patterson AFB, OH, as guided and directed by the Program Manager, Matthew Tracy. The report summarizes the effort defined by SOW tasks 3.1 (Additional Requirements Analysis), 3.2 (Initial Preliminary Design), 3.3 (Initial Analysis), 3.4 (Initial Downselect), 3.5 (Preliminary Design), 3.6 (Detailed Analysis), 3.7 (Final Downselect), and 3.8 (Concept Models), and covers the period from December, 1997, through July, 1998.

The key technical personnel at Arthur D. Little, Inc., who participated in this effort and their areas of responsibility are as follows:

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Melissa Crowe	Cooling Modules
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Acknowledgment is also given to the following contributors to the program and to this report:

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K. Isherwood	L. Hegarty (Consultant)
D. Lally	

Executive Summary

The Modular Aircraft Support System (MASS) program is part of an effort to reduce the deployment footprint and increase the supportability of aerospace ground power equipment (AGE). The Air Force currently operates a large and diverse inventory of single-function carts which provide electric power, cooling, hydraulics, pneumatics, or lighting in order to maintain aircraft. The primary objective of the MASS program is to develop a small number of modular ground power carts which use new technologies or innovative packaging to combine the functions mentioned above with less deployment footprint. The secondary objectives of MASS are to lower life-cycle costs and provide higher reliability than current AGE.

Delivery Order 0003, issued in December 1997, under contract F41624-96-D-5003, directed Arthur D. Little, Inc. (ADL) to conduct and document the selection of a final MASS concept (based on the six design concepts explored in Delivery Order 0002) which meets MASS requirements and is suitable for further development.

The final task under Delivery Order 0003 concludes with the preparation and approval of this Final Report. This report describes the selection process and the resulting downselected system concept for support equipment as a candidate solution to the objectives and requirements identified by the MASS Integrated Product Team (IPT) and approved by the Air Force Research Laboratory (AFRL) Program Manager. The scope of this effort has primarily focused on reducing deployed footprint and complying with the flightline support equipment needs of the F-22 and Joint Strike Fighter (JSF) aircraft, and, secondarily, on those of current aircraft, including fighter planes, cargo planes, and helicopters.

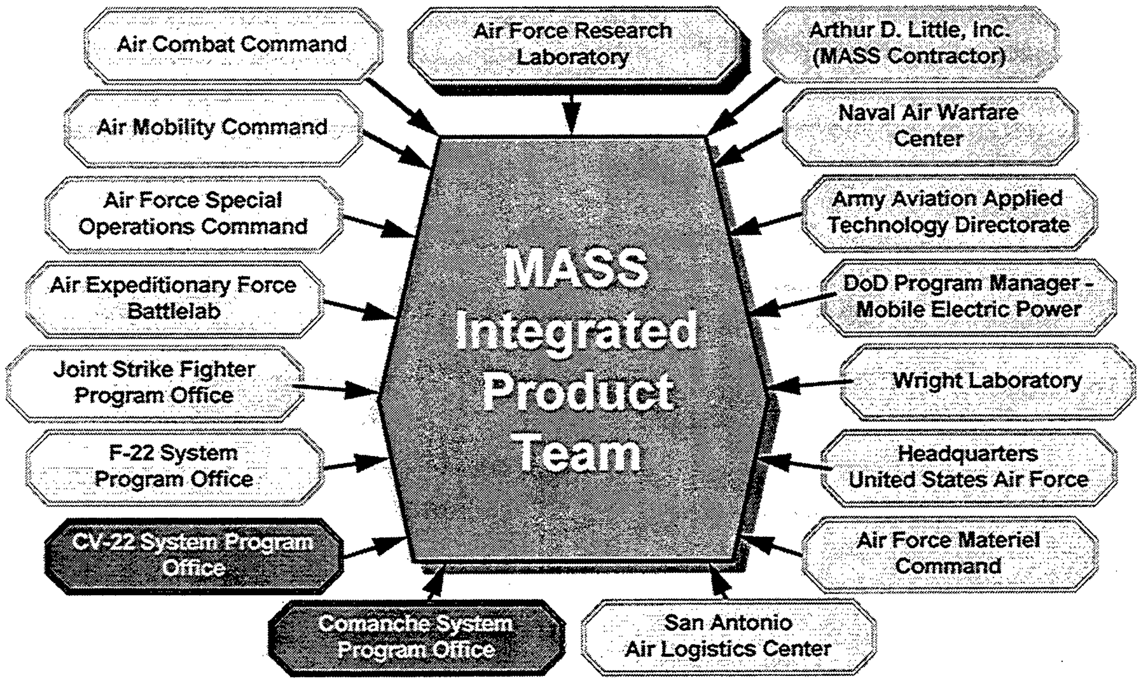
Requirements and Technology Assessment. The requirements for MASS were defined and candidate technologies were assessed in Delivery Order 0002. The results of this task are presented in Sections 2 and 3 of the Delivery Order 0002 Final Report[1].

We followed a Quality Function Deployment (QFD) approach to define the relevant specifications for MASS. The requirements were developed by working with members of the MASS IPT. As shown in Exhibit ES-1, the MASS IPT includes representatives from the major operational commands, supporting commands, acquisition organizations, and other services in order to have direct participation from the user community. Continuous customer input focused the program towards the major user concerns–deployability and affordability–while ensuring that all user requirements are defined and considered.

We followed a tiered approach for the technology assessment:

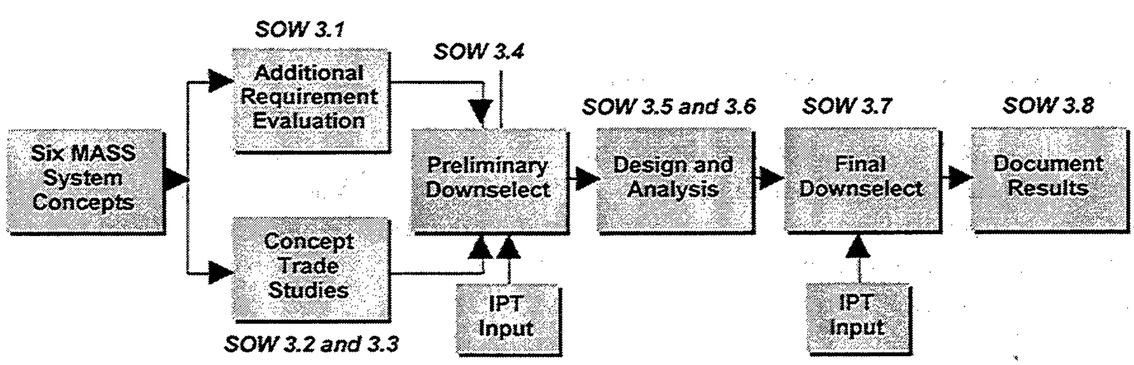
- MASS was segmented by functional subsystem (i.e., electric power, hydraulics, etc.)
- Baseline requirements were defined for each subsystem
- Existing AGE was evaluated
- Potential technologies not currently used in AGE were evaluated
- The most promising technologies for each subsystem were recommended for further development

Exhibit ES-1: Modular Aircraft Support System Integrated Product Team



MASS Concept Validation—Delivery Order 0003. This report fully explores all aspects of Delivery Order 0003, Concept Validation. As shown in Exhibit ES-2, the downselect process started with an additional requirement evaluation (SOW 3.1) and initial design and analysis (SOW 3.2 and 3.3) of six preliminary concepts. As Delivery Order 0003 Concept Development and Evaluation was dependent on Delivery Order 0002 Concept Exploration) design concepts, we have briefly described the concepts within Section 1, which also explains and describes the Delivery Order 0003 downselected choice. Section 2, System Description, provides an overview of the downselected system as well as a subsection on the chassis and each of the modules which make up the system. Section 3 provides System Analysis details. Sections 4 and 5 provide References and Acronyms cited and used in this report.

Exhibit ES-2: Delivery Order 0003 Downselect Process



The result of the IPT downselect session was a single concept that was determined to be the solution that best met the MASS requirements. This selected concept was different from any of the initial six concepts in Delivery Order 0002, although it incorporates elements from several of the initial concepts. We have refined the concept to combine the preferred choices in the following categories as indicated by the IPT. Exhibit ES-3 displays the different choices in the significant design areas. The elements of the design choices preferred by the IPT are shaded. (Please note: The mobility choice is still pending.)

Exhibit ES-3: IPT Preferred Choices

Prime Mover	Diesel	Gas Turbine	Fuel Cell		
Power Distribution between Modules	Mechanical	Electrical			
Number of Carts	1	2	3		
Modules/Cart	1	2	3	4	5
Mobility	Self-powered	Towed			

A comparison of the prime movers indicated that the diesel was the best choice for the MASS technology demonstration primarily because of its relatively low life-cycle cost.

Electrical power distribution between modules was chosen over mechanical for several reasons:

- Electrical power distribution offers more flexibility in module placement than mechanical power distribution
- Mechanical system is difficult and time consuming to set up and teardown
- Spinning driveshafts of mechanical system raise safety concerns
- Mechanical reliability is uncertain due to large quantity of gearboxes, clutches, and universal joints
- Electrical power distribution permits modules to be powered directly from barebase or shipboard power
- Electrical power distribution can accomodate future power plants (such as fuel cells)

Three electrical power generation and distribution system architectures were considered before selecting the preferred choice which employs 3 phase, 60 Hz, 480 Vac COTS generators, motors, control, and protection apparatus. Alternatives based on 400 Hz, 480 Vac or 700 Vdc generation and distribution offered no compelling advantages for MASS. A variation on a 60 Hz system wherein the engine-generator would operate above 1,800 rpm to produce power at a somewhat elevated frequency (e.g., 75 Hz) also was considered in anticipation of the possibility of a small component downsizing to attain cost-effective size and weight savings. These small benefits, however, were outweighed by the penalty of reduced module capacity when operated from shop, barebase, or shipboard power sources. Considerations which led to the ultimate selection of a 60 Hz power generation and distribution system are presented in Section 1.3.3.

An analysis of the effect of the number of carts on deployment and life-cycle cost indicated that a two or three cart approach is preferred. All functions on one cart to meet F-22 requirements (as in the UniCart concept) results in a cart which would be difficult to maneuver on Air Force flightlines. The mobility trade study considered whether the carts should be self-propelled or towed by another vehicle. It was decided that the mobility option would be kept open, since it did not directly affect the cart design and self-powering was a feature that could be added at a later date.

Given that this particular combination of selections did not match exactly with any one design from Delivery Order 0002, the downselect choice necessitated refining and redesigning in order to meet these criteria. In the course of this process, the Avionics Power Converter (APC) was redesigned for mounting on the underside of the cart chassis as an alternative option to top mounting. This orientation allows for several advantages in the design of the system over previous MASS systems:

- APC orientation and mounting allow the option of a four module cart without unfavorably affecting footprint
- A common chassis can be utilized for the various configurations as the other five modules are housed in a common structural frame
- Common size slots greatly simplify chassis design

Up to four modules can be mounted onto a common chassis, depending on the utilities required by the particular aircraft. Three possible configurations of the system are delineated below as examples of the flexibility of the downselected choice:

- A MASS Electric Power/Cooling cart (illustrated in Exhibit ES-4)
- A MASS Hydraulics/Pneumatics/Power cart
- A MASS Dual Hydraulics cart

Exhibit ES-4: Electric Power/Cooling Cart

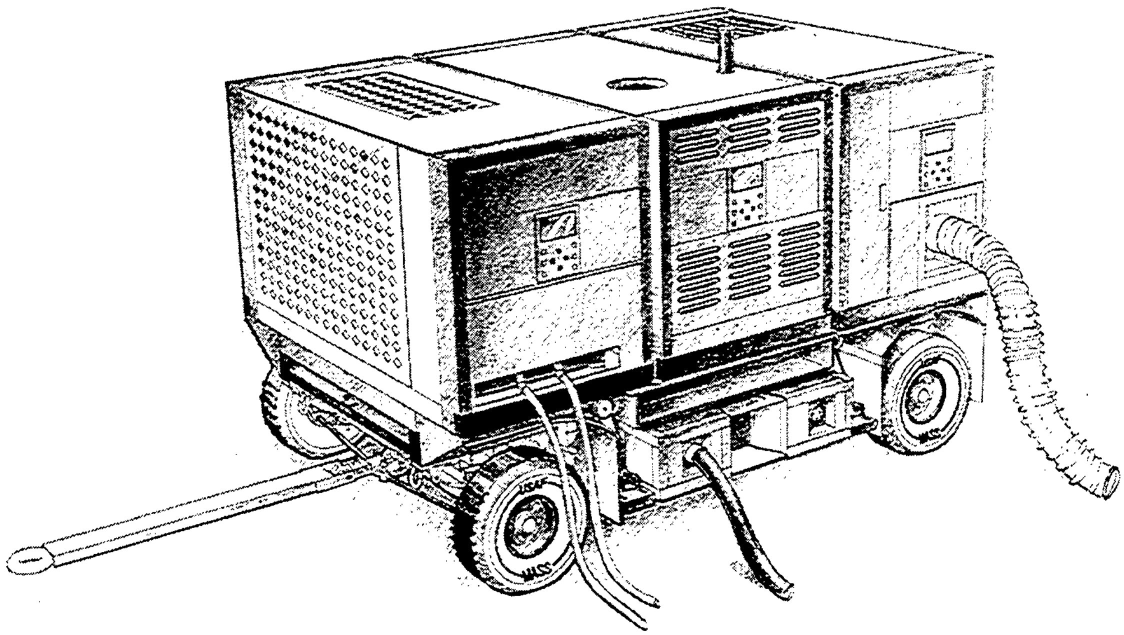


Exhibit ES-5 outlines key characteristics of each of the example carts.

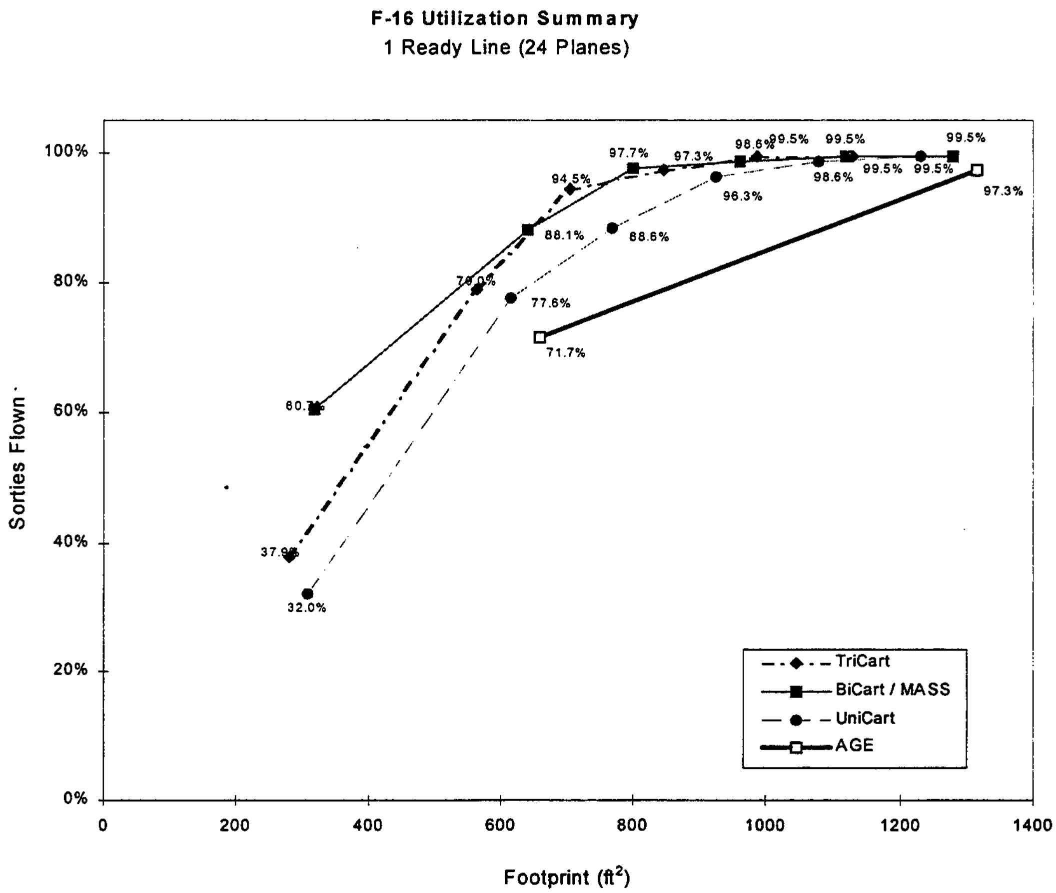
Exhibit ES-5: Cart Summary

	Cart Type		
	Electric Power/Cooling	Hydraulics/Pneumatics	Dual Hydraulics
Dimensions (inches)	126 x 88 x 78	126 x 88 x 78	126 x 88 x 78
Footprint (ft^2)	77	77	77
Volume (ft^3)	500	500	500
Weight (lbs)	9,700	12,100	11,500

A self-contained lighting module can be easily mounted on any cart without special tools and powered by the generator.

Utilization. Preliminary analysis of aircraft utilization was performed for the F-15 and F-16, since maintenance tasks and squadron level quantities of AGE were available as a baseline. A summary of the utilization results for the F-16 are presented in Exhibit ES-6.

Exhibit ES-6: F-16 Utilization Summary (One Ready-Line)



Comparison to Baseline. After the MASS concepts were developed and analyzed, they were compared to the baselines for existing AGE. Two AGE baselines (one based on the A/M 32A-86D diesel generator, another based on the A/M 32A-60A gas turbine generator) were analyzed. The squadron level comparison is shown in Exhibit ES-7.

As shown in Exhibit ES-7 above, the downselected MASS concept has the potential to provide a 40% reduction in footprint and a 20% reduction in life-cycle cost from the average of the AGE baselines (for an equal utilization rate), while increasing reliability.

Exhibit ES-7: Squadron Level Comparison of MASS Concepts with AGE Baseline

Concept	Quantity of Modules/Carts	Weight (lbs)	Footprint (ft^2)	Mean Time Between Failure (Hrs)	Acquisition ($M)	Deployment ($M)	Operation and Maintenance ($M)	Total Life Cycle Cost ($M)
MASS Concept	36	123,000	820	43	3	5	5	13
AGE F-15 Diesel	30	122,000	1,540	36	1	10	4	15
AGE F-15 Gas Turbine	30	65,000	1,310	38	5	8	5	18

Army Comanche Helicopter. In the course of this delivery order, the Comanche System Program Office of the Army (a member of the IPT) expressed interest in our MASS design for the Comanche helicopter. The Army at present is working on a design to accomodate the ground support requirements of the Comanche. The Army AGPU-2000 program emphasizes three particular points which differ from the MASS program's focus: the use of as many aviation parts as possible; the necessity for a rough terrain negotiable chassis; and, a package weight and structural configuration suitable for sling-lift deployment by helicopter. At the request of the Air Force Laboratory Program Manager and the IPT, we provided information and support to their effort based upon our Concept Exploration in Delivery Order 0002. In the course of designing the six systems described in Delivery Order 0002, it was determined that using a MASS specifically designed for satisfying F-22 requirements does not ideally satisfy all services and applications. These requirements in comparison with Army requirements are simply too great, thereby making the USAF F-22 requirement-focused MASS substantially oversized for those applications. At the time of this publication, issues regarding design of a smaller version of MASS to suit Army requirements and our present delivery orders are still pending.

Conclusions and Recommendations. The first priority in creating a MASS system was to reduce deployed footprint while meeting requirements in ground support equipment. **The downselected MASS system concept is estimated to significantly reduce deployed footprint as well as reduce acquisition costs and improve life-cycle costs and maintainability.** Some of the key points which were employed in the design of the system to achieve these results include:

- Loading or unloading modules from the side, rather than the end, of the cart
- Using a "side-by-side" approach in the placement of modules
- Mounting the Avionics Power Converter (APC) module under the cart chassis
- Utilizing a common structural frame for five of the six modules, thereby allowing a common cart chassis to be used
- Downsizing the Diesel Generator from 200 kW to 160 kW

We recommend that the Mass program proceed with Delivery Order 0004 (Brassboard Fabrication) and Delivery Order 0005 (Detailed Design and Analysis).

The purpose of Delivery Order 0004 is to construct a MASS brassboard demonstrator employing several of the key features of the final MASS system concept resulting from Delivery Order 0003 of the MASS contract. This brassboard demonstrator will provide an early assessment of the critical features of the MASS design, reducing the program risk level by evaluating these design concepts during the early stage of the detail design phase. By evaluating these concepts concurrently with the initial detail design effort, the cost and schedule risk due to significant redesign of a module will be reduced. Development and fabrication of the brassboard demonstrator will have the following tasks:

- Design brassboard
- Recommend design to the IPT
- Fabricate brassboard
- Perform checkout testing and evaluation
- Provide test report

The purpose of Delivery Order 0005 is to perform a detailed design of the most promising system concept resulting from Delivery Order 0003 of the MASS contract. This detailed design effort will provide sufficient data, in the form of Computer Aided Design (CAD) generated developmental drawings, from which to fabricate a MASS proof-of-concept system. The detailed design effort will have the following tasks:

- Preliminary design
- Interim design review
- Detailed design
- Detailed design review
- Final report

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1.0 Delivery Order 0003 Downselect

1.1 Introduction

Delivery Order 0003, Concept Validation, continues the Modular Aircraft Support System (MASS) program which is a research effort to improve the reliability, maintainability, operability, and deployability of aerospace ground equipment (AGE). Delivery Order 0003 drew on the concepts explored in Delivery Order 0002 in order to produce the downselect choice for this delivery order.

1.2 Delivery Order 0002 Overview

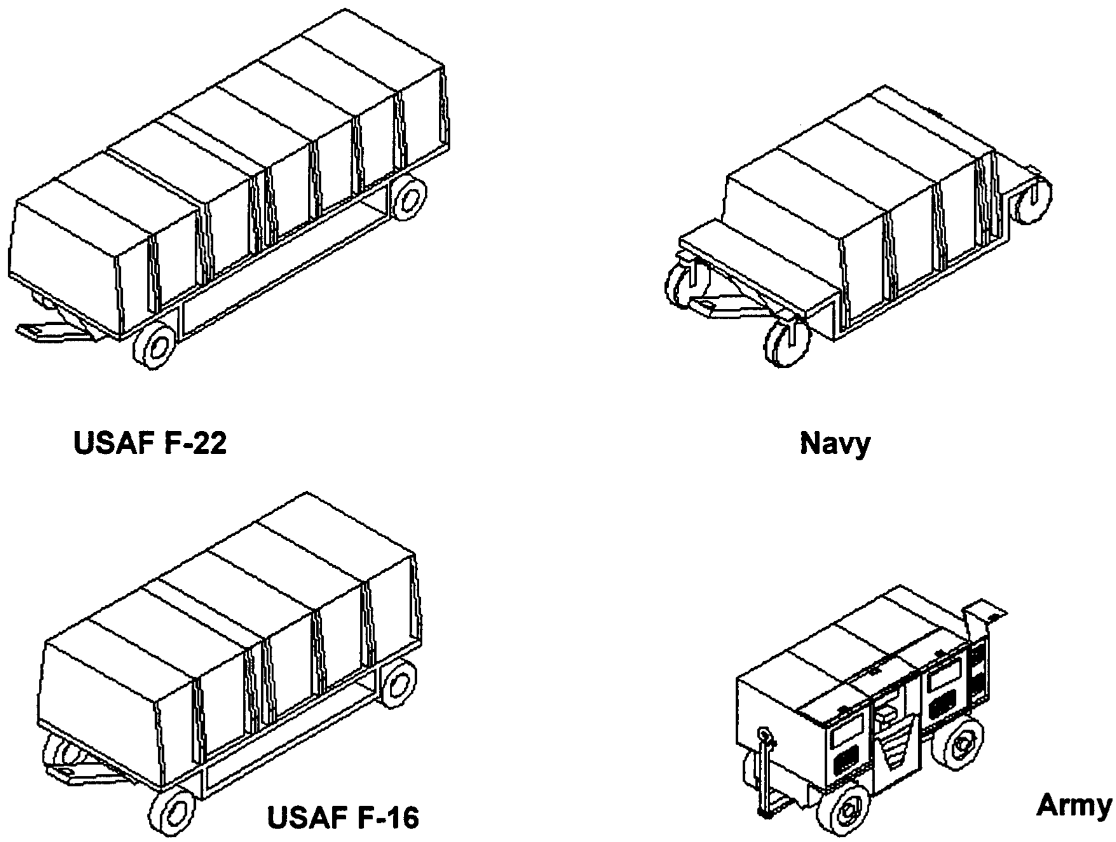
Delivery Order 0002, Concept Exploration, yielded six distinct system concepts using varying combinations of single purpose modules to meet the MASS requirements. As a convenient reference, we have included an overview of the six concepts described in the Delivery Order 0002 Final Report[2]. These concepts are described in Exhibit 1-1.

Exhibit 1-1: Delivery Order 0002 Concepts

Concept Title	Concept Description
Customizable MASS	Family of modules and frames, tailored to specific aircraft
Advanced Mechanical MASS	Mechanically interconnected system with single engine power source
Advanced Electrical MASS	Electrically interconnected system with single fuel cell power source
UniCart	All modules mounted on a single frame
BiCart	All modules mounted on two independent frames
TriCart	All modules mounted on three independent frames

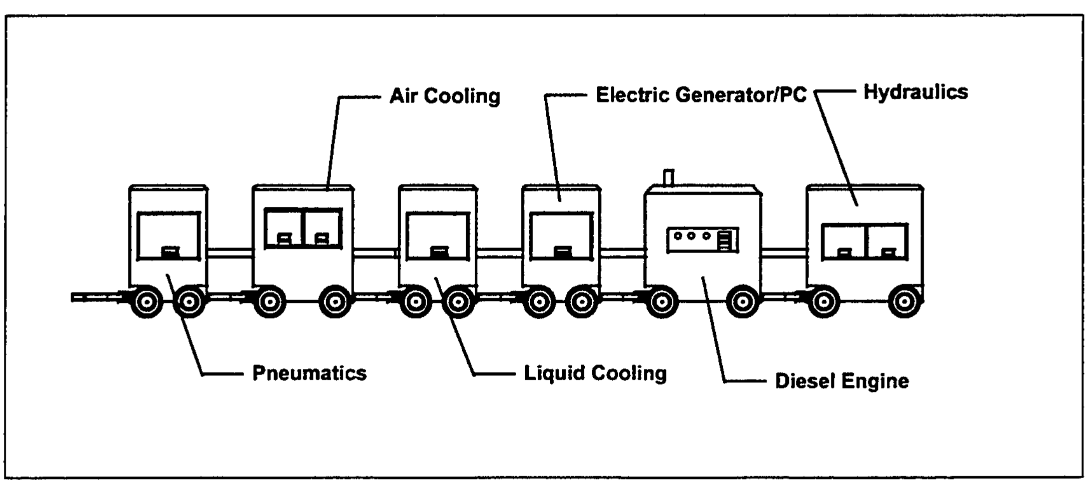
The Customizable MASS concept (Exhibit 1-2) consists of a family of standard modules that can be assembled into a customized system for a specific aircraft.

Exhibit 1-2: Customizable MASS



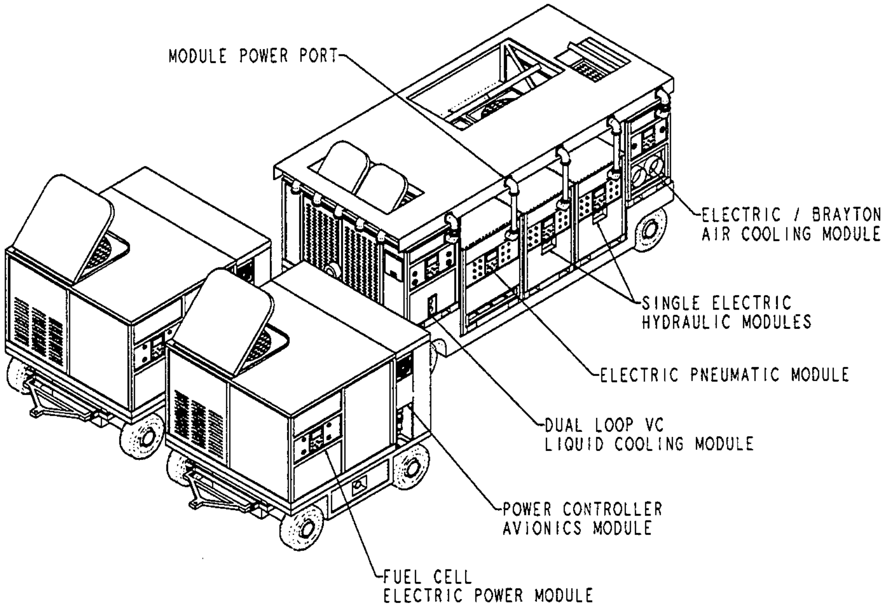
The Advanced Mechanical MASS (Exhibit 1-3) concept consists of a single diesel engine module which provides mechanical power to five freestanding carts.

Exhibit 1-3: Advanced Mechanical MASS



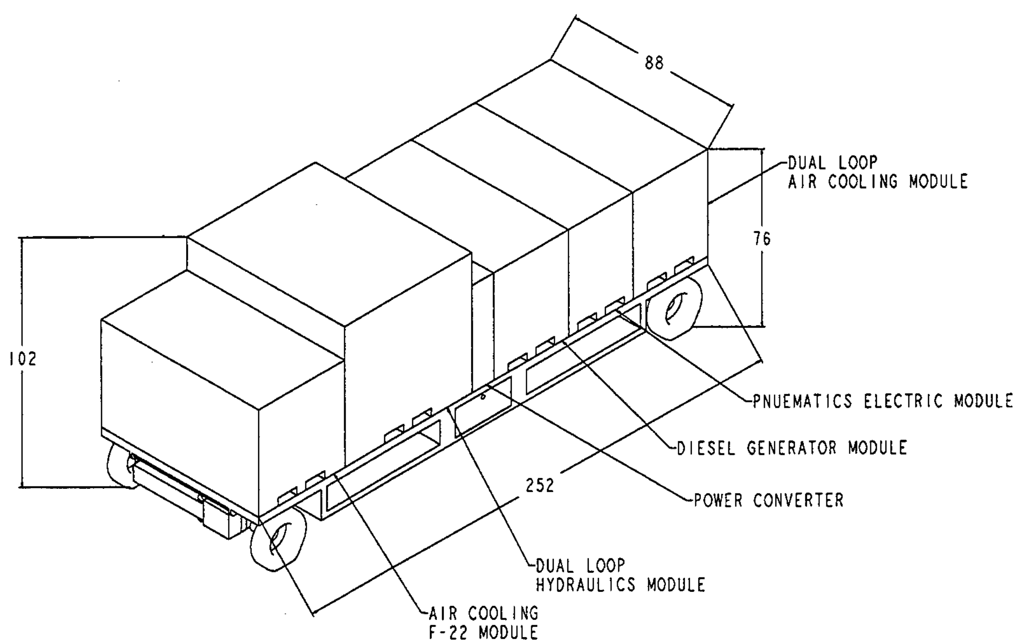
The Advanced Electrical MASS (Exhibit 1-4) consists of two fuel cell powered electrical carts and a service cart that supplies all other functions.

Exhibit 1-4: Advanced Electrical MASS



The UniCart (Exhibit 1-5) has all the functions required to service the F-22 on a single cart.

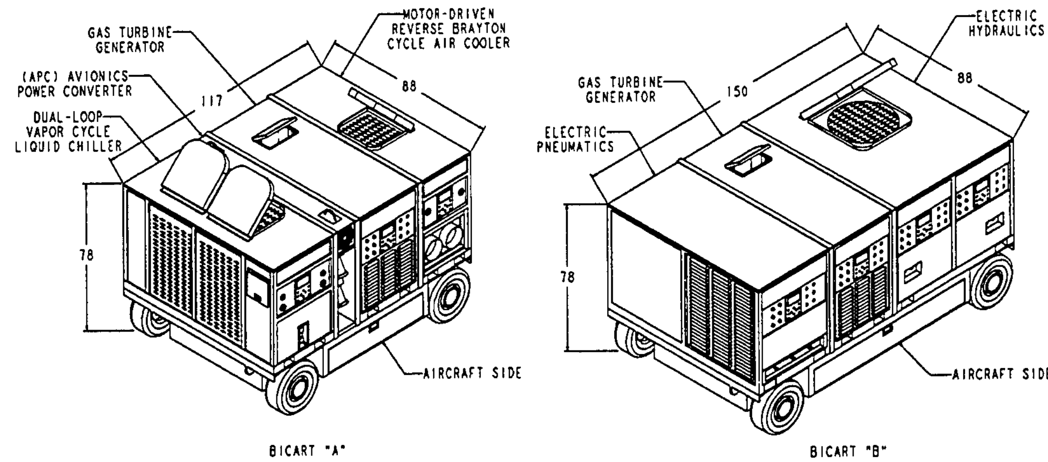
Exhibit 1-5: UniCart



Dimensions in inches.

The BiCart (Exhibit 1-6) concept contains an avionics power/cooling cart and a hydraulics/pneumatics cart.

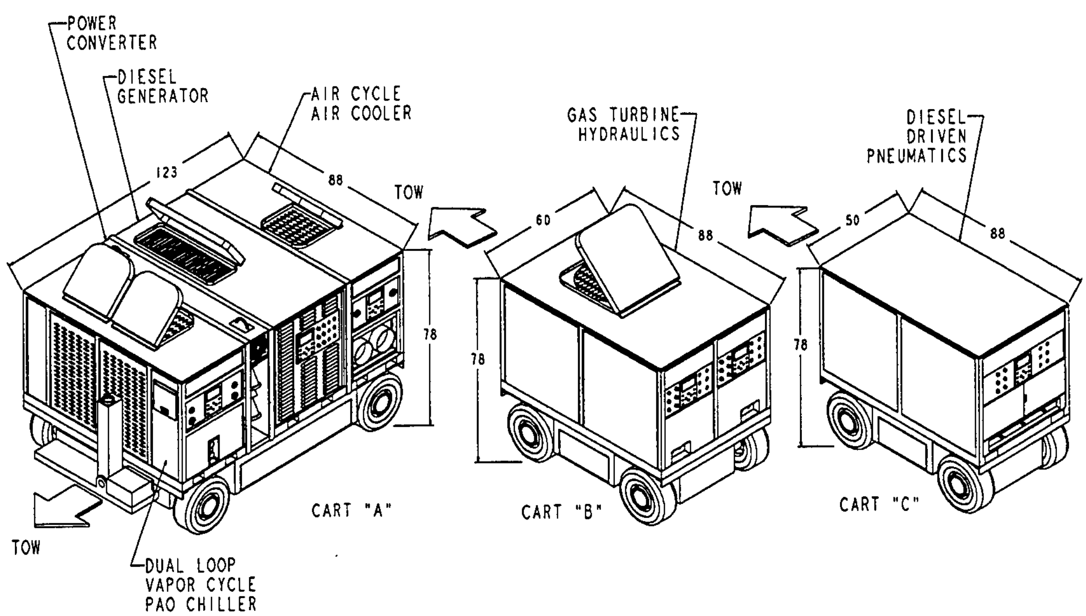
Exhibit 1-6: BiCart



Dimensions in inches.

The TriCart (Exhibit 1-7) concept consists of three carts, each powered by a dedicated engine.

Exhibit 1-7: TriCart



Dimensions in inches.

1.3 Delivery Order 0003 Downselect

1.3.1 MASS Downselect Process Description

The result of the IPT downselect session, while based on the systems and modules explored in Delivery Order 0002, was a single concept that was different from any of the initial six concepts although it employed many features of the six concepts. While analyzing each of the six MASS concepts, a matrix of key characteristics of the six concepts was created (Exhibit 1-8). By selecting the appropriate box in each row of the matrix, one can create any of the six concepts resulting from Delivery Order 0002, as well as several other systems beyond the six concepts.

Exhibit 1-8: MASS Key Characteristic Matrix

Prime Mover	Diesel	Gas Turbine	Fuel Cell		
Power Distribution between Modules	Mechanical	Electrical			
Number of Carts	1	2	3		
Modules/Cart	1	2	3	4	5
Mobility	Self-powered	Towed			

Once this matrix was established, Arthur D. Little, along with the MASS IPT went through a methodical trade study process during which we analyzed, compared, and selected the best candidate in each row of the matrix of Exhibit 1-8. Once the optimum characteristics were determined, the system resulting from this collection of characteristics represented the preferred system design for MASS.

1.3.2 Powerplant Trade Study

The first trade study of the downselect process involved the powerplant technology for MASS. There were three candidate technologies resulting from the technology assessment conducted during Delivery Order 0002: diesel engine, gas turbine, and fuel cell technology.

A trade study was conducted during which the performance capability of each technology was compared in each requirement category. The requirement categories were established early in the MASS program by the IPT during the first several IPT meetings. Each category was also assigned a numerical weighting indicating the relative importance of each category. The requirement category and numerical weightings are indicated in the two left-most columns of Exhibit 1-9. Each technology was then assigned a rating, indicating how well it met the performance goals in each requirement category. The gas turbine, widely employed in AGE, was used as the baseline and therefore had a rank of zero in all categories. If a powerplant technology performed better than the gas turbine in a given category, it received a rank of +1 to +3, depending on the degree to which it exceeded the baseline. Conversely, if it performed worse, it received a -1 to -3 ranking. This process of ranking the technology was conducted interactively with the IPT during IPT Meeting No. 6.

Exhibit 1-9: Powerplant Comparison

Requirement Category	Weighting	Powerplant Type		
		Diesel	Fuel Cell[1]	Gas Turbine
Life-Cycle Cost	14	+2	+1	0
Performance Capability	12	0	-1	0
Deployability	11	-1	-2	0
Supportability	10.5	0	-3	0
Useability	9	+1	+2	0
Documentation	6.5	0	-3	0
Interoperability	4.5	0	-2	0
Operating Envelope	3.5	+1	-2	0
Survivability	1.5	+1	-1	0
Environmental Impact	1.0	+1	+3	0
Weighted Total	**N/A**	**+32**	**-68**	**0**

1 Fuel cell weighting was based on the supposition that applicable fuel cell technology would be production-ready in five years.

The definitions for the requirement categories are described below.

Life-Cycle Cost – Includes a summation of procurement, operation and maintenance, and deployment costs over a defined period of functional equipment life.

Performance Capability – Includes considerations of a technology to meet the stated functional requirements for flowrate, pressure, voltage, current, etc.

Deployability – Includes considerations for the weight, footprint, and volume of the system, as well as requirements for providing a transportable system in all military environments.

Supportability – Includes requirements and considerations for resources needed for a supportable system in all operational scenarios.

Useability – Includes Human System Interface (Human Factors) and safety issues. Human Factors analysis is intended to provide an effective interface for the operator and maintainer and an easy to use system considering personnel issues such as training. Safety analysis includes requirements for identifying and resolving system safety and health hazard issues.

Documentation – Includes requirements for the collection of maintenance data.

Interoperability – Includes requirements for compatibility with all necessary aircraft and aircraft servicing parts.

Operating Envelope – Includes considerations for operation in harsh environments (shock, vibration, noise, EMI).

Survivability – Includes requirements for NBC and battle damage survivability.

Environmental Impact – Includes requirements for ozone depleting substances, hazardous materials, emissions, and generated waste streams.

Once the rankings were completed, the ranking score in a given category was multiplied by the weighting factor for each requirement category. The results were summed to obtain a weighted total for each candidate technology, and the technology with the highest (most positive) score emerged as the preferred technology. As indicated in the weighted total figures of Exhibit 1-9, the diesel powerplant was selected as the preferred powerplant technology for MASS. The most influential factors resulting in its selection were low life-cycle cost and improved useability (lower noise, easier maintenance) which overrode its deployability negatives (higher weight, larger footprint).

1.3.3 Power Distribution Trade Study

A similar trade study was conducted to compare electrical and mechanical means to distribute power between modules. A modular system based on electrical distribution could be powered by an engine driven generator.

A modular system based on electrical distribution could be powered by an engine-driven generator. Electrical power distributed through power cables or busses would energize motor-driven machinery in adjacent cooling, hydraulic, or pneumatic models.

A mechanical power distribution architecture would employ an engine and multi output transmission module which would mechanically couple shaft power to adjacent modules by drive shafts, gears, belts, or other means. The mechanical power would be used directly by adjacent modules to mechanically drive pumps, compressors, generators, or other devices.

Exhibit 1-10 contains the results of a power distribution trade study employing the same methodology described in the previous section. The baseline chosen was mechanical distribution, since the current AGE generally consists of individual single-function carts in which an engine is mechanically coupled to a single piece of equipment.

Exhibit 1-10: Power Distribution Trade Study Results

Requirement Category	Weighting	Power Distribution Method	
		Electrical	Mechanical
Life-Cycle Cost	14	+1	0
Performance Capability	12	-1	0
Deployability	11	+1	0
Supportability	10.5	+1	0
Useability	9	+2	0
Documentation	6.5	0	0
Interoperability	4.5	+2	0
Operating Envelope	3.5	+1	0
Survivability	1.5	+1	0
Environmental Impact	1.0	-1	0
Weighted Total	**N/A**	**+54.5**	**0**

Electrical power distribution between modules was selected over mechanical as the preferred means of power distribution for the following reasons:

- Electrical power distribution offers more user flexibility
- The mechanical system is difficult and time consuming to set up and teardown
- Spinning driveshafts of the mechanical system raise safety concerns
- Mechanical reliability is uncertain due to many gearboxes, clutches, and universal joints
- Electrical power distribution permits modules to be powered directly from barebase or shipboard powerplants
- Electrical power distribution can accommodate future power plants (e.g., fuel cells)

1.3.3.1 Electric Power Architecture Trade Study

Four electrical power distribution architectures were considered before a final selection was made. The alternatives are described briefly below:

60 Hz-AC. We first considered 3 phase, 60 Hz generation, and distribution using COTS 480 Vac generators, motors, control, and protection apparatus with 3 phase, 400 Hz, 200 Vac or 270 Vdc avionics power provided by an electronic power converter. This particular power distribution architecture, while having greater system weight than the other alternatives, has the following advantages:

- Low acquisition and life-cycle cost
- Modules can be directly powered from shop, barebase, or shipboard 60 Hz supplies
- High electrical efficiency minimizes engine power demand and size of engine heat exchangers

- Generator speed requirement reasonably well matched to preferred diesel engine capability
- Leverages wide range of component technologies – especially COTS variable speed motor drives
- Frequency of 400 Hz avionics power is not disturbed by engine-generator speed fluctuations

400 Hz-AC. In this consept we considered 3 phase, 400 Hz generation, and distribution with 480 V generators, motors, control, and protection components – some COTS, others purpose-built- would be used. This particular power distribution architecture has the following advantages:

- 60 to 400 Hz power conversion not required
- Potential to use a smaller, lighter 6,000 rpm generator – but size, weight, and cost of speed increaser gear box between diesel engine and generator would diminish net benefits
- The gear box would permit operation of a diesel engine at its peak power speed – e.g., 2,300 rpm

This particular alternative has the following disadvantages:

- Higher acquisition cost – electrical apparatus costs 3 to 4 times more than for a 60 Hz system
- Higher life-cycle cost due to greater cost of inventory of non-COTS components
- Motor speed not matched to COTS pumps, compressors, fans – speed reducer gear boxes required – high speed aircraft pumps and compressors, if available, cost much more than COTS units
- Motor efficiency is lower due to greater core and windage losses – exacts penalty on size, weight, and cost of generator, gear box, and engine
- High-loss, high-power density 400 Hz motors must be liquid cooled to attain size and weight benefits over 60 Hz alternatives – size, weight, cost, and added complexity of liquid cooling subsystems diminishes anticipated system benefits
- Modules could not be powered from shop, barebase, or shipboard 60 Hz supplies

Advanced DC. An Advanced DC design would employ 3 phase, non-standard frequency AC power generation, AC/DC converter, and DC power distributed at approximately 700 Vdc to COTS 60 Hz motors, each with an associated electronic inverter. This particular alternative offers the following advantages:

- Potential to use a smaller, lighter high frequency permanent magnet generator (PMG)
- PMG could be directly coupled to a diesel engine
- Engine could be operated at its peak power speed

This particular alternative has the following disadvantages:

- Cost and time to develop a suitable PMG beyond MASS program scope
- Higher cost of PMG
- Size, weight, and cost of high frequency AC/DC converter/voltage regulator
- Uncertain availability of 700 Vdc rated circuit breakers and power connectors

- Size, weight, and cost of power inverters to drive COTS AC motors for fixed speed loads
- Modules would not be directly operable from shop, barebase, or shipboard 60 Hz supplies

60+ Hz. We also considered a variation on the preferred 60 Hz power generation and distribution architecture wherein the engine-generator would be operated above 1,800 rpm to achieve an electrical frequency somewhat greater than the standard 60 Hz value (e.g., 75 Hz). This would enable higher engine, generator, and motor power capacity and has the possibility of employing COTS components which would be somewhat smaller and lighter than those required for operation at 60 Hz. Modules would still be operable from 60 Hz shop, barebase, or shipboard supplies but their full capacity would not be available. However, we found that the motor size and weight saving potential would be relatively small and abandoned further consideration of this concept.

After consideration of these architectures (see Exhibit 1-11), the first alternative, which employs 60 Hz power generation and distribution, was chosen because of its many advantages and few disadvantages. This selection of the preferred 60 Hz power generation and distribution system will be incorporated in subsequent MASS delivery orders.

Exhibit 1-11: Power Generation and Distribution System Concept

		Power Generation and Distribution System Concept			
Requirement	**Weighting**	**60 Hz**	**400 Hz**	**DC**	**60+ Hz**
Life-Cycle cost	14	0	-3	-3	+1
Performance	12	0	-1	0	-1
Deployability	11	0	0	0	0
Supportability	10.5	0	-3	-3	0
Useability	9	0	0	0	0
Documentation	6.5	0	-1	-1	0
Interoperability	4.5	0	-2	-2	-1
Operating Envel.	3.5	0	0	0	0
Survivability	1.5	0	0	0	0
Environ. Impact	1.0	0	0	0	0
Weighted Total	**N/A**	**0**	**-101**	**-89**	**-2.5**

1.3.4 Cart Quantity Trade Study

An analysis of the effect of the number of carts on deployment and life-cycle cost was conducted considering a one, two, and three cart system. This evaluation was based on the key requirements of the MASS program: deployability and affordability. Exhibit 1-12 illustrates the comparison between the MASS one, two, and three cart systems with the AGE baselines.

Exhibit 1-12: Cart Quantity Trade Study Results

	MASS One-Cart		MASS Two-Cart		MASS Three-Cart		AGE F-15	Age F-15
Characteristics	Turbine	Diesel	Turbine	Diesel	Turbine	Diesel	Turbine	Diesel
Footprint (ft²)	920	920	820	820	850	850	1,310	1,540
Weight (Lbs)	135,000	173,000	115,000	123,000	135,000	147,000	65,000	122,000
Life Cycle Cost ($)	$21,829,457	$17,919,739	$18,666,147	$13,413,945	$21,449,155	$15,146,511	$17,633,570	$14,709,423
Life Cycle Cost ($M)	22	18	19	13	21	15	18	15
Reliability (MTBF in Hours)	36	39	41	43	31	33	38	36
No. of Systems	6	6	5	5	6	6	1 ToA	1 ToA

The number of systems indicated in Exhibit 1-12 was determined during the aircraft utilization study, which is described in Section 3.4. The number of systems used for each MASS system type, and each AGE baseline, was the quantity required to reach an aircraft utilization rate of 95% or greater.

As shown in Exhibit 1-12, a two or three cart system provides optimum deployability and affordability for the MASS. The footprint of the two systems is 40% less than the average footprint of the existing AGE baseline. This represents a dramatic improvement in deployability. The life-cycle cost of the two cart system is 20% less than the average of the existing AGE baseline, indicating a substantial cost savings. There was not a significant difference in the deployability and affordability between the two and three cart systems. As a result, a MASS can be configured either as a two or three cart system depending on other factors such as maintainability and human factors, with no impact on deployability or affordability.

1.3.5 Mobility Trade Study

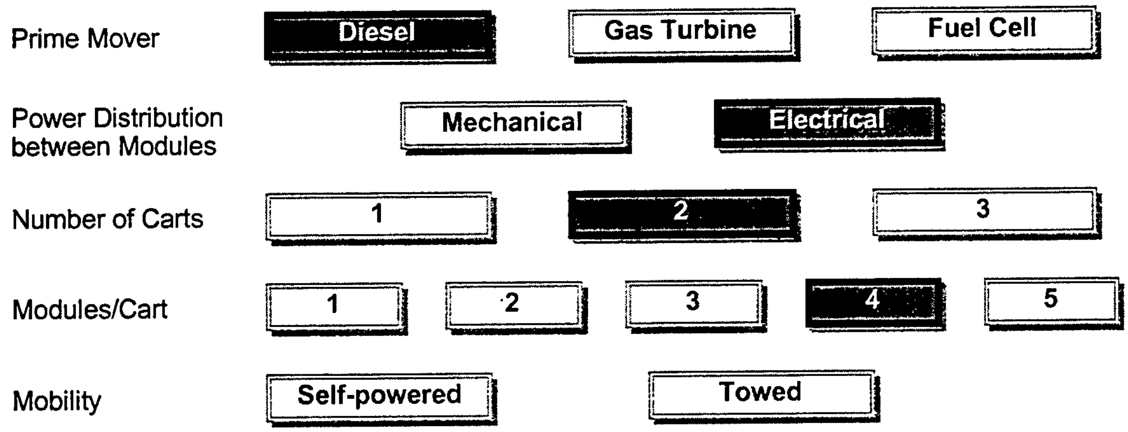
The mobility trade study considered whether the carts should be self-propelled or towed by another vehicle. If the towed method was employed, the carts would have to be maneuvered manually once the carts were dropped off by the tow vehicle. This could present some human factors issues because of the weight of some carts.

The IPT discussed this issue at length. The conclusion of the discussions was split, with some members preferring self-propelled carts because of improved human factors, and some preferring towed carts because of simplicity and reduced cost. It was jointly decided that the mobility option would be kept open, since it did not directly affect the cart design and self-powering was a feature that could be added at a later date.

1.3.6 Concept Resulting From Downselect

Exhibit 1-13 consolidates the results of each trade study. The shaded boxes indicate candidate selected during the trade studies in each category.

Exhibit 1-13: Results of MASS Concept Trade Study



As can be seen in Exhibit 1-13, the conclusion of the trade study represents a MASS concept that does not align exactly with any of the six concepts resulting from Delivery Order 0002, but does include features from many of the six concepts. The selected concept resulting from the trade studies consists of a common cart design and a family of six modules: the Avionics Power Converter, Diesel Generator, Air Cooling, Liquid Cooling, Hydraulics, and Pneumatics modules. The downselected concept has several key characteristics which were based on the trade studies previously mentioned:

- All modules (with the exception of the APC) are of equal size and configured for side-by-side mounting on top of the cart
- The Avionics Power Converter (APC) was reconfigured for mounting below the cart
- Each module is powered electrically from the diesel generator module (or from barebase or shipboard power when available)
- Carts can be customized for a given application by selecting the appropriate modules
- The common chassis can accommodate up to four modules depending on the utilities required by the aircraft.

The MASS concept resulting from the trade studies and downselect process is described in detail in Section 2.0.

1.4 Requirements

In Delivery Order 0003, aircraft operating requirements were refined for the F-15E, F-16, F-18, F-22, and JSF. Aircraft requirements were also determined for the Army's Comanche and Legacy helicopters. These requirements are summarized in Exhibit 1-14 below.

Exhibit 1-14: Requirements Summary

Function	F-15E	F-16	F-18	F-22	JSF	Army[1]
Avionics Power:						
400Hz, 3ph (kVA)	16.5	14	20	-	-	-
270Vdc (kW)	-	-	-	70	90	55[2]
28Vdc (A)	-	-	-	-	-	TBD
Air Cooling:						
Temperature (°F)	50	50	50	50	TBD	40
Flow (lb/min)	71	55	50	42	TBD	55
Total Pressure (psig)	2.3	4.5	3.3	0.8	TBD	1.4
Evap. Load (tons)	17.6	15.7	13.3	9.0	TBD	13.9
Liquid Cooling:						
Temperature (°F)	N/A	N/A	N/A	59;122	TBD	N/A
Flow (gpm)	N/A	N/A	N/A	31	TBD	N/A
Delivery Pressure (psig)	N/A	N/A	N/A	195	TBD	N/A
Differential Press. (psi)	N/A	N/A	N/A	175	TBD	N/A
Total Load (tons)	N/A	N/A	N/A	15.4;31.3	TBD	N/A
Hydraulics:						
Total Flow (gpm)	2@30; 1@13.5	30	40	76	TBD	12
Pressure (psi)	2@3,000; 1@4,500	3,100	5,000	4,000	TBD	3,500
# of Systems	3	2	2	2	TBD	2
High Pressure Air or Nitrogen:						
Flow (scfm)	N/A	15	N/A	15	TBD	-
Pressure (psi)	2,200	3,500	N/A	5,000	TBD	-

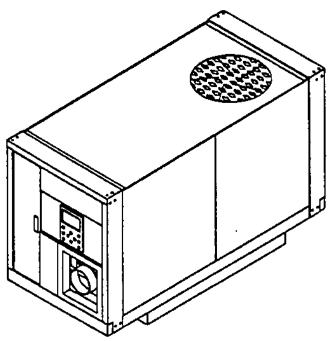
[1] All requirements are for the Comanche Helicopter unless otherwise noted.
[2] Requirement for Apache Longbow.

2.0 System Description

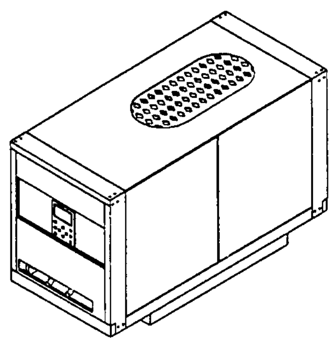
2.1 System Overview

The MASS concept resulting from the downselect performed in Delivery Order 0003 is based on a family of six modules. Layout work was performed for each of the six modules, with the resulting external views shown in Exhibit 2-1.

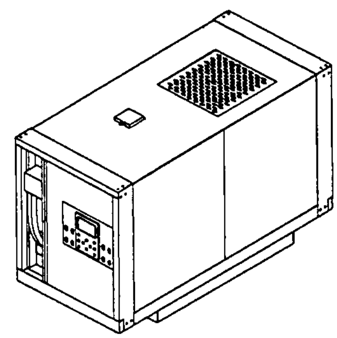
Exhibit 2-1: MASS Modules



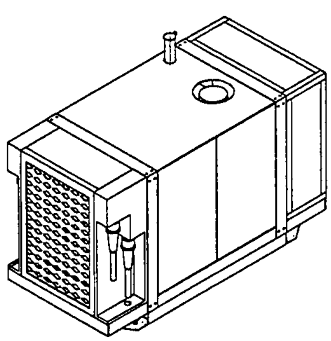
Air Cooling Module



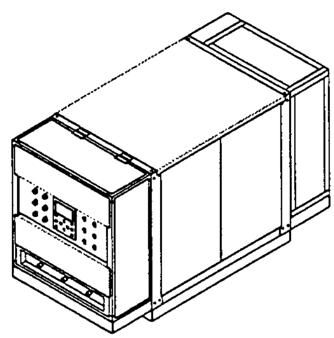
Liquid Cooling Module



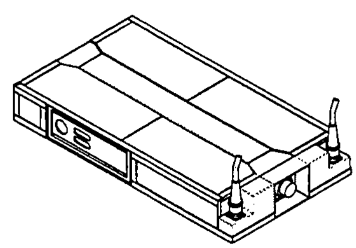
Hydraulics Module



Diesel Generator Module



Pneumatics Module



Avionics Power Converter Module

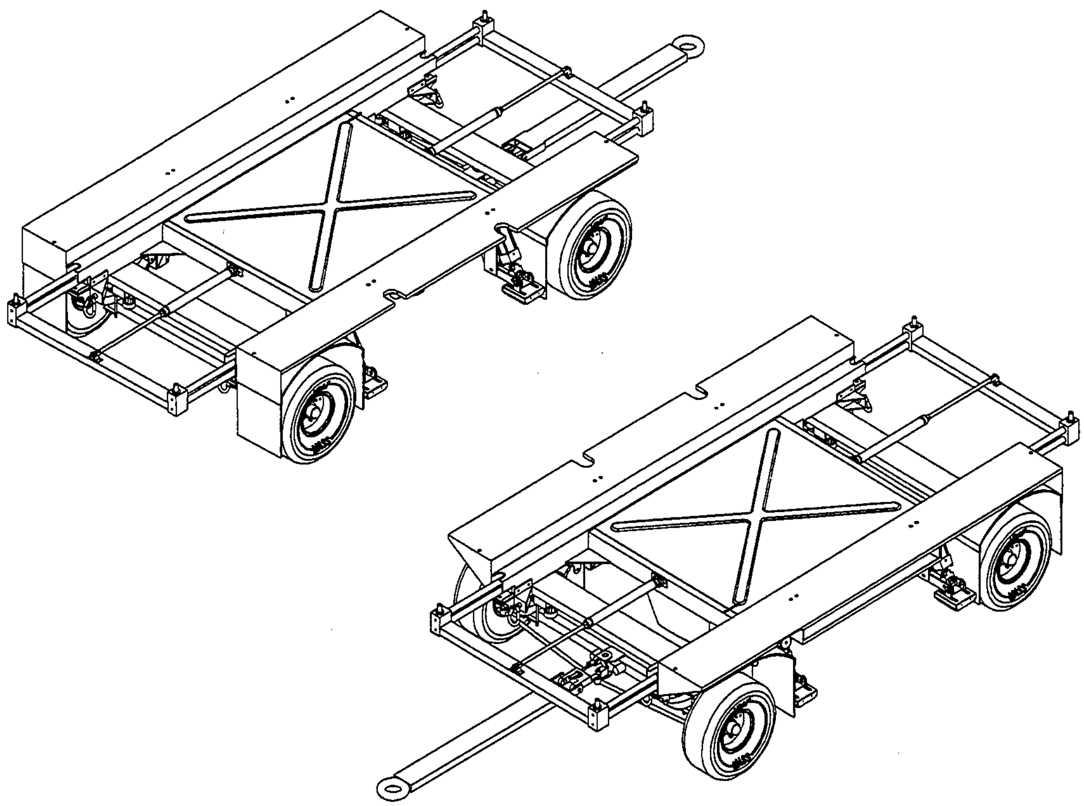
There are several important characteristics that are common to all modules:

- All modules adhere to the general design guidelines described in Section 1.3 of the Delivery Order 0002 Final Report[3].
- All modules (except the APC) are the same size, which provides the benefits of a similar chassis design, easier loading/unloading, and the use of common enclosures and frames
- All modules have control panels and supply and/or return hoses and cables in the side of the cart which faces the aircraft
- Hoses and cables are stored within the modules for which they are used

Further descriptions of the modules, including interior views showing the location of components, beneficial features, and component cost information, are provided in Sections 2.2.1 through 2.2.6 of this report.

Up to four modules can be mounted on a common chassis, depending on the utilities required by the aircraft. Work was performed on the chassis design, with the resulting external view shown in Exhibit 2-2. End Loader and Side Loader versions of the chassis were developed.

Exhibit 2-2: MASS Chassis–End Loader Version



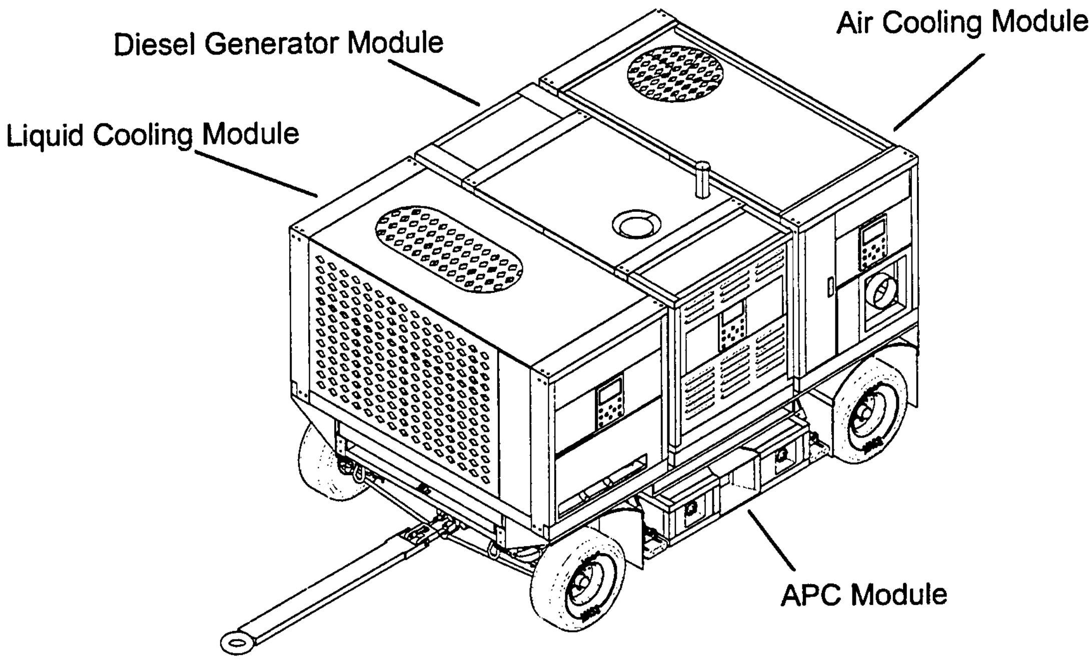
There are several important characteristics of the chassis:

- Up to three of the full size function modules can be mounted on the chassis
- The APC module can be mounted underneath the chassis
- Features to simplify loading/unloading of the modules are provided

Further description of the chassis is provided in Section 2.1.7 of this report.

The flexibility of the MASS concept is exemplified by the different customized carts that can be assembled by using combinations of the six modules and chassis described above. For example, an Electric Power/Cooling Cart (Exhibit 2-3) can be constructed by mounting the Diesel Generator, Air Cooling, Liquid Cooling, and APC modules on the chassis as shown. This particular MASS cart would be used to provide the most commonly used functions (electric power and cooling) for aircraft that require both air and liquid cooling.

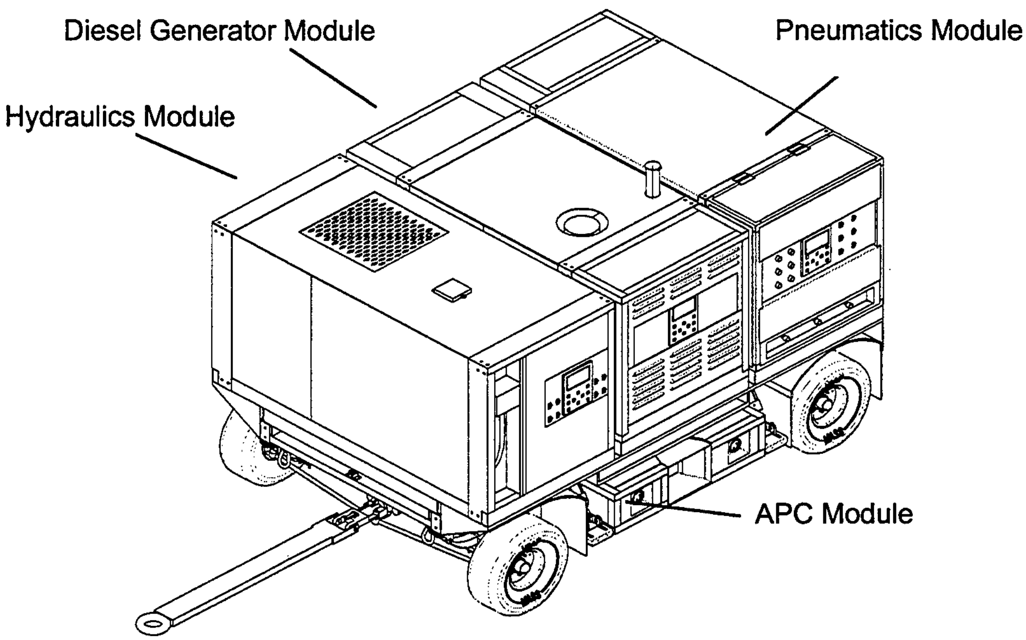
Exhibit 2-3: MASS Electric Power/Cooling Cart



Another potential combination of modules (not shown) includes a Power/Air Cooling Cart, using two Air Cooling modules, a Diesel Generator Module, and the APC.

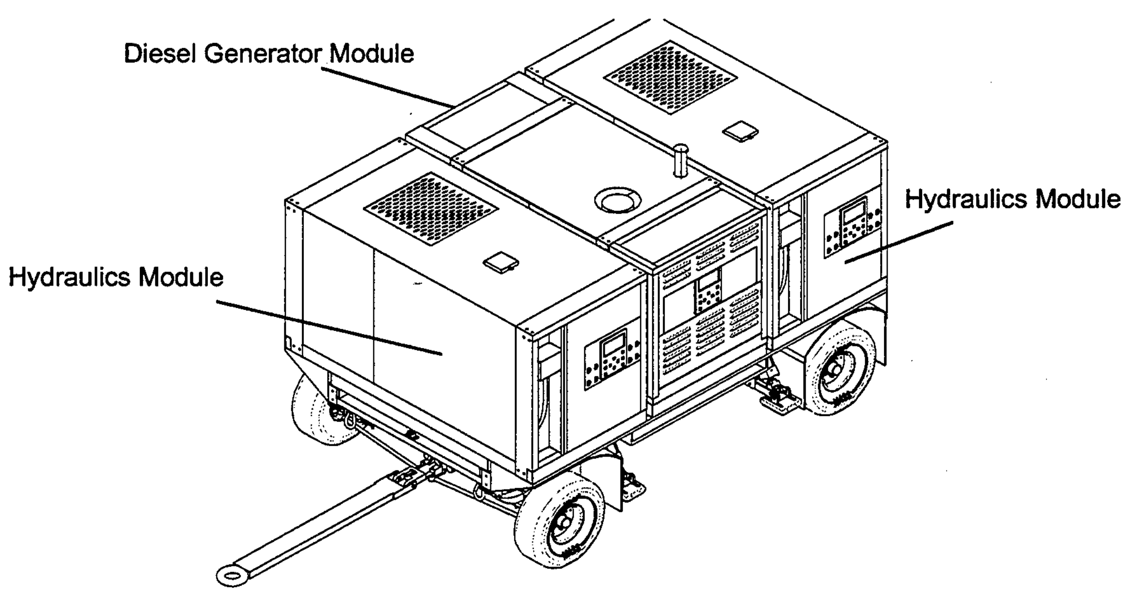
A MASS Hydraulics/Pneumatics/Power Cart can be created by mounting the Diesel Generator, Hydraulics (single loop), Pneumatics, and APC modules on a chassis, as shown in Exhibit 2-4. It should be noted, however, that this cart could not provide all of the functions at full capacity simultaneously.

Exhibit 2-4: Mass Hydraulics/Pneumatics Cart



A MASS Dual Hydraulics Cart can be created by mounting two single Hydraulics Modules and a Diesel Generator Module on a chassis as shown in Exhibit 2-5.

Exhibit 2-5: MASS Dual Hydraulics Cart



Preliminary estimates of the size and weight of the modules and the chassis are shown in Exhibit 2-6. Using these module and chassis estimates, the size and weight of several different cart types was estimated, as shown in Exhibit 2-7. A weight reduction program will be performed in subsequent delivery orders.

Exhibit 2-6: Module Characteristics

Module	Dimension (inches)	Footprint (Square Feet)	Volume (Cubic Feet)	Weight (Lbs)
Diesel Generator	88W 42L 52H	26	111	3,600
Air Cooling	88W 42L 52H	26	111	1,500
Liquid Cooling	88W 42L 52H	26	111	2,200
Hydraulics	88W 42L 52H	26	111	2,700
Pneumatics	88W 42L 52H	26	111	2,300
APC	88W 48L 12H	29	29	1,100
Chassis	88W 126L 32H	77	—	2,400

Exhibit 2-7: Cart Characteristics

	Cart Type		
	Electric Power/Cooling	Hydraulics/Pneumatics	Dual Hydraulics
Dimensions (inches)	126 x 88 x 78	126 x 88 x 78	126 x 88 x 78
Footprint (ft^2)	77	77	77
Volume (ft^3)	500	500	500
Weight (lbs)	10,800	12,100	11,400

Lighting. The lighting module is shown in Exhibit 2-8. Measuring 12 inches high by 16 inches wide by 80 inches deep, and weighing less than 30 lbs (without ballast), it can be easily mounted on the generator module with bayonet and latch mounts. The maintenance crew can also easily remove it for transportation or storage. The lighting module is powered by the diesel generator module.

The lighting module is designed for ease of use. Rotation and tilt of the unit can be accomplished easily and quickly by extending the lower part of the pole and releasing a latch. Assisted by gas springs, the light rotates and tilts up when the end of the pole is pulled. The base can be locked to prevent swaying but remains free to rotate about the pole axis. By means of tensioning wires, the operator can easily tilt the light to the desired position.

Module Loading and Unloading. As previously mentioned, there are two chassis concepts for the replacement, maintenance, and transfer of modules: The end loader and the side loader.

The end loader design uses two hydraulic cylinders and push/pull bars attached to both ends of the chassis and connected to the end modules on a cart. By actuating either or both cylinders, a hydraulic pump is activated which permits movement of the end modules 20 inches from the center module. This space allows for easy access to maintenance panels as well as facilitating module removal using a hoist or derrick (see Exhibit 2-9).

Exhibit 2-8: Lighting Module

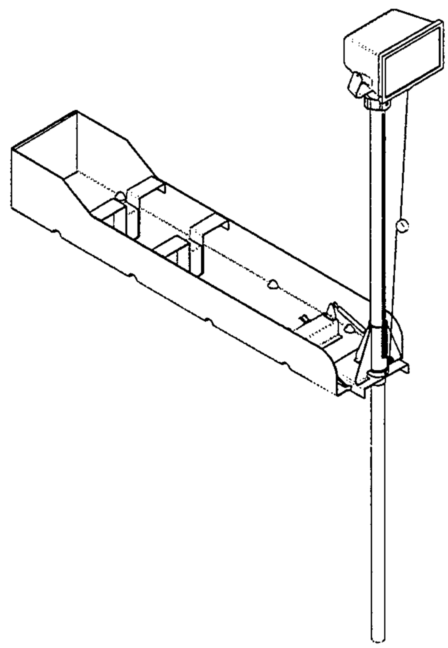
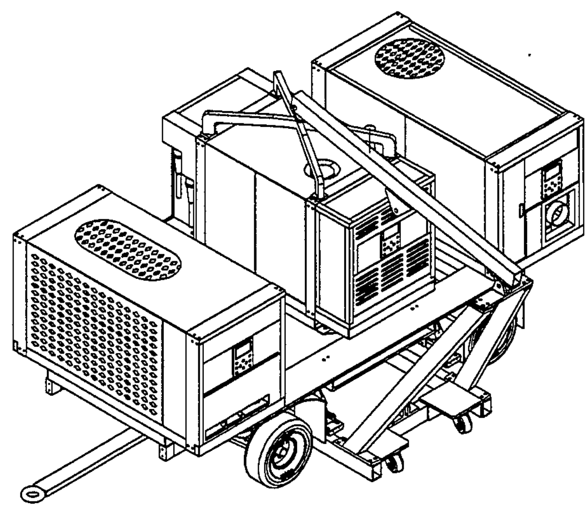
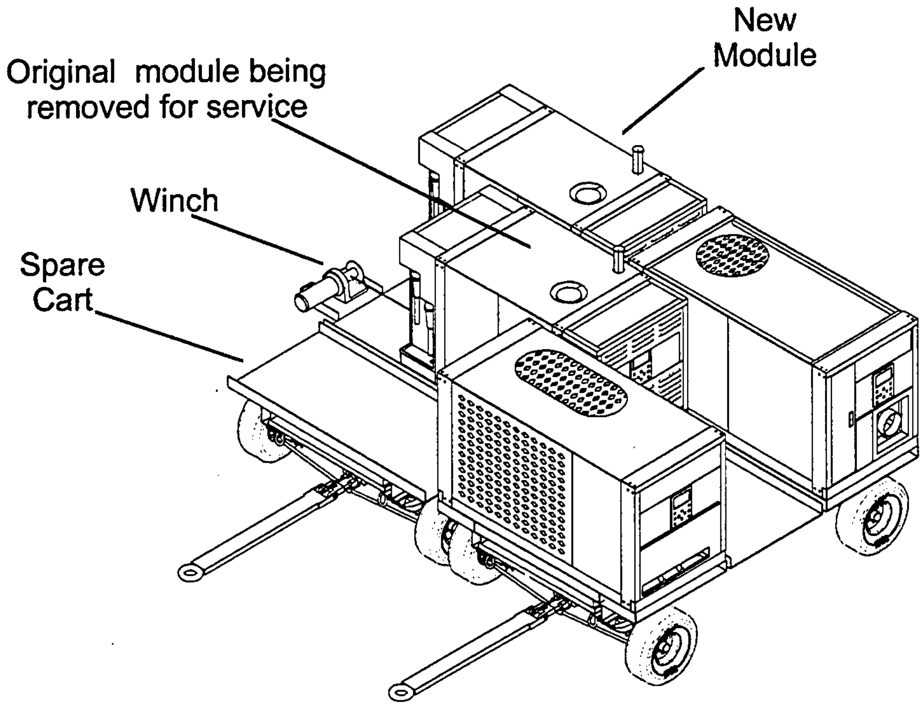


Exhibit 2-9: Module Removal Using a Hoist



The side loader design concept consists of three trays transversely mounted on top of the chassis weldment. When a module requires field replacement, a similar module is installed in another chassis and transported to where the cart with the defective module is located. The spare module cart is positioned behind and parallel to the other cart lining up the empty tray with the defective module to be replaced. A portable hand winch is placed in the empty tray opposite to the defective module. By hooking up the winch cable to the module, the module is then pulled into the maintenance cart (as shown in Exhibit 2-10). The maintenance cart is then moved to align the new spare module into the other cart. The winch is then swapped to the other cart and the same process is repeated to pull the new module into the existing cart. The time required to

Exhibit 2-10: Module Removal Using a Winch



perform the swap is estimated at less than 20 minutes. This side loader design has several advantages including:

- No additional hoists or cranes are required thereby reducing maintenance equipment inventory
- Modules can be replaced in the field thereby reducing repair down-time
- Modules can be partially moved to provide better accessibility for periodic maintenance (Exhibit 2-11)

Module Frames. Module frames, as shown in Exhibits 2-12 and 2-13, are constructed of 2x4 rectangular tubing as the base. The four vertical uprights are made of 13 gage steel. The top cross members are removable for easy maintenance. Underneath the 2x4 frame are two ramps made out of 0.12-inch thick cold rolled steel for loading and unloading the modules.

Module skins are comprised of the following:

1) Top cover
2) Side panels
3) End panels
4) Louvers
5) Hinged access door

Exhibit 2-11: Partial Removal of Center Module

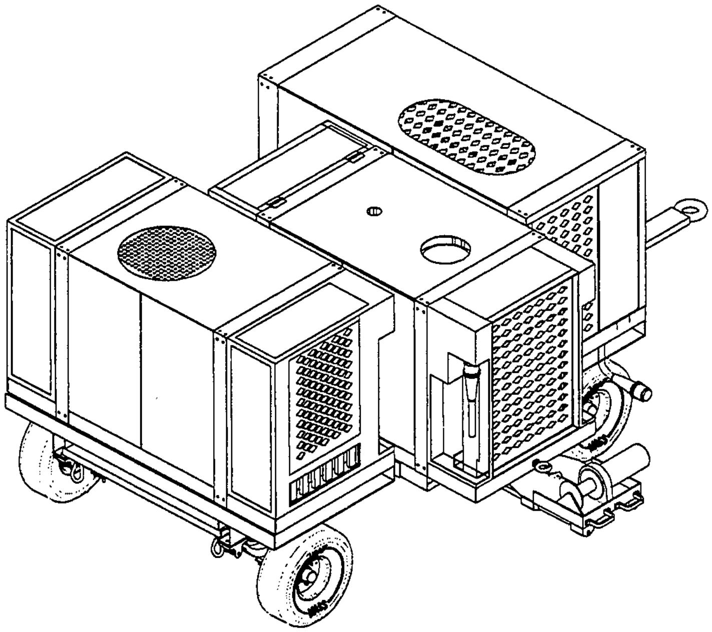


Exhibit 2-12: Module Frame

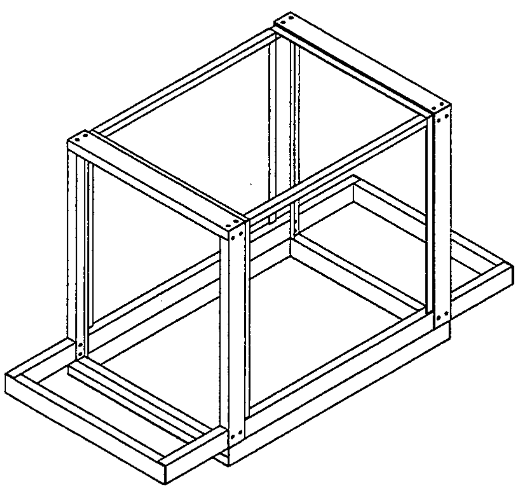
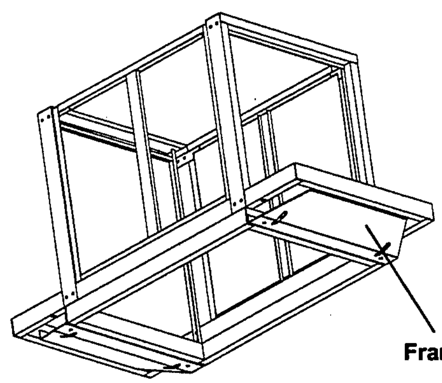


Exhibit 2-13: Module Frame with Ramp



The top cover is fastened by using latches secured to the upright members. Covers and side panels are fastened to the frame with captive screws and have a weather gasket. The hinged access door uses locking latches.

All skins are made of 14 gage aluminum. All modules (with the exeption of the APC) share common frames and panels. (Final materials will be determined with the weight reduction program to be performed in subsequent delivery orders.) The common module frames are slightly smaller than the overall module dimensions to accommodate skins and protruding hardware as well as provide adequate clearance between the modules when placed on the chassis. The basic frame size is 40.5 inches wide by 87 inches long by 51.5 inches high. Modules can be lifted using a hoist or crane by attaching cables to the four eye hooks located on top of the uprights.

2.2 Diesel Generator Module

The MASS Delivery Order 0002 Final Report[4] presented preliminary layouts for potential MASS electric power modules based on three distinct technologies: diesel engines, fuel cells, and gas turbine engines. Estimates of size, weight, maintainability, and cost were prepared for a nominal power capacity of 200 kW. Further work was performed under Delivery Order 0003 to refine the layouts and compare the characteristics of the three power plant technologies.

As a result of IPT meetings #6 and #7, the diesel engine power plant was selected as the preferred choice for the MASS technology demonstrator. The much lower life-cycle cost of a diesel power plant was the salient reason for its preference over a gas turbine alternative. Diesel engine emissions were not a significant factor in the downselect decision as newer designs employing electronically controlled fuel injection will meet stringent California Air Resources Board (CARB) Tier II requirements. A fuel cell power plant was viewed as highly advantageous in some respects but it was ultimately decided that a system of suitable power rating would not be available in a timely fashion for the MASS technology demonstration.

During Delivery Order 0003, cart power requirements were reassessed and it was determined that the previous nominal rating of 200 kW could be downsized to 160 kW. Lower cart power demand permitted use of a more compact engine and generator and avoided the unconventional side mounted radiator used in the previous diesel generator module design.

Current Package Design. The new 160 kW design depicted in Exhibit 2-14 offers important advantages relative to the previous design:

- Conventional engine fan-cooled radiator is less costly and easier to maintain
- Lower weight: 3,600 lbs vs. previous 5,500 lbs
- Lower component cost: $32,000 vs. previous $50,000

Internal Construction. The principal components of the diesel generator module are identified in Exhibit 2-15. Key components and most other components used in the module layout are commercial off-the-shelf (COTS) items widely used in industry. Using COTS components offers the advantage of high quality and performance at a relatively low cost.

Exhibit 2-14: Diesel Module—External View

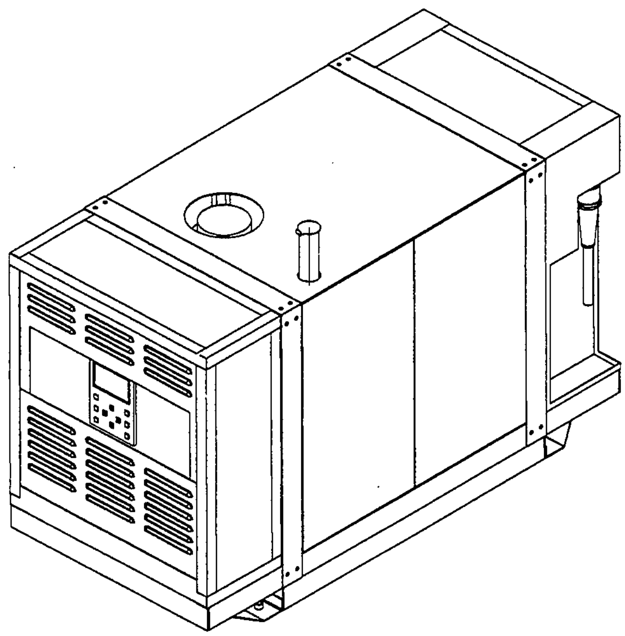
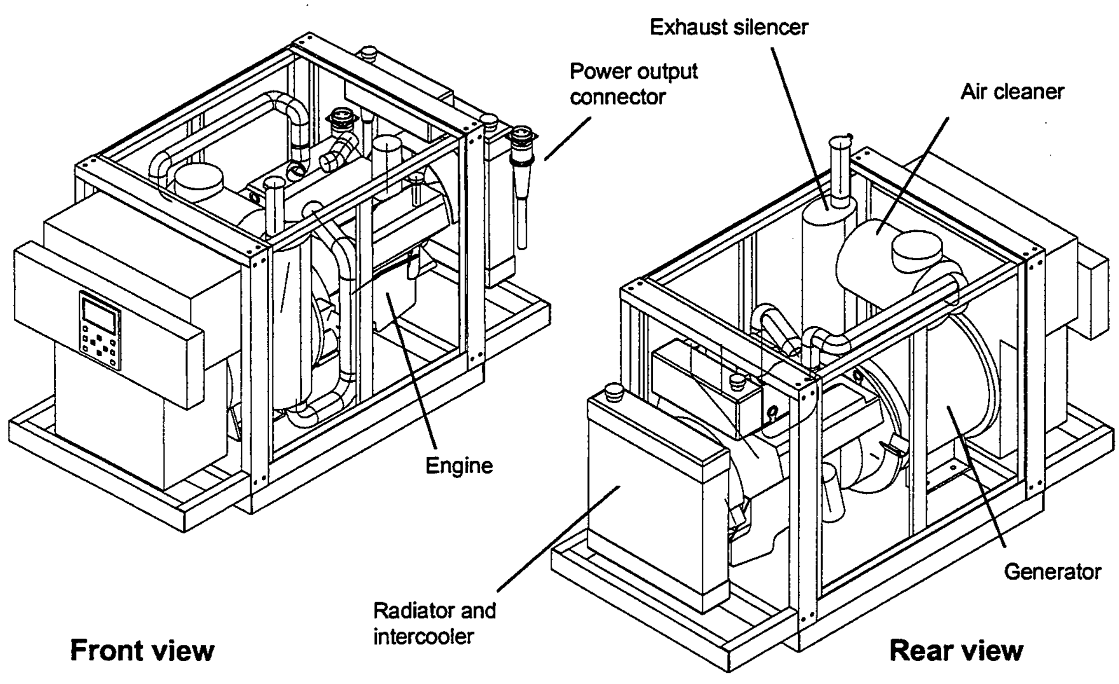


Exhibit 2-15: Diesel Generator Module Front and Rear—Internal View



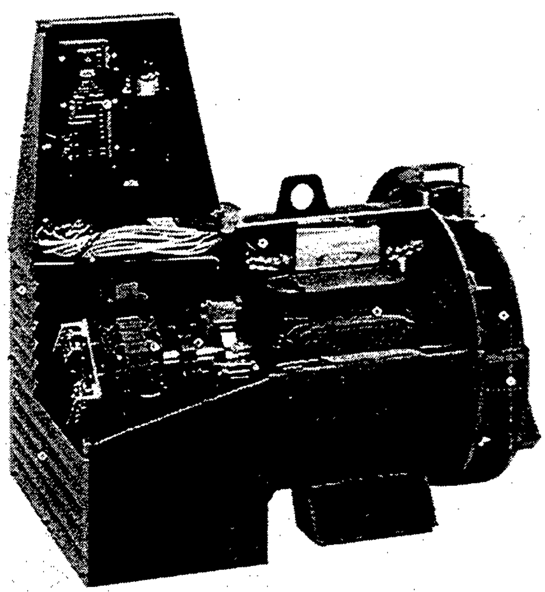
Key Components. An International Navistar T444E V-8 diesel engine coupled to a Marathon Electric MagnaMax 60 Hz synchronous generator depicted in Exhibit 2-16 were identified as a very good fit to MASS requirements. The generator frame is fastened to the engine bell housing and the flex disk coupling is bolted to the flywheel according to standard practice. After an exhaustive search of diesel engines, the Navistar unit was selected for the following reasons:

- Emissions are below California Air Resources Board (CARB) Tier II limits
- Short V-8 block fits within 88-inch module length with conventional radiator and fan
- Power rating matches generator requirement
- No power derating up to 10,000 feet and at least up to 130°F
- Relatively low weight
- Electronic controls can be interfaced with module control and display panel

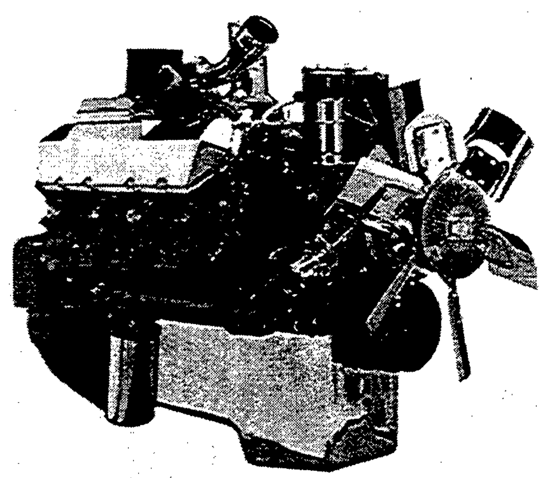
The Marathon generator was selected for the following reasons:

- Electronic voltage regulator provides control flexibility
- Permanent magnet exciter generator provides more reliable fault clearing current
- Convenience of control cabinet package and wiring for module integration

Exhibit 2-16: Generator and Diesel Engine



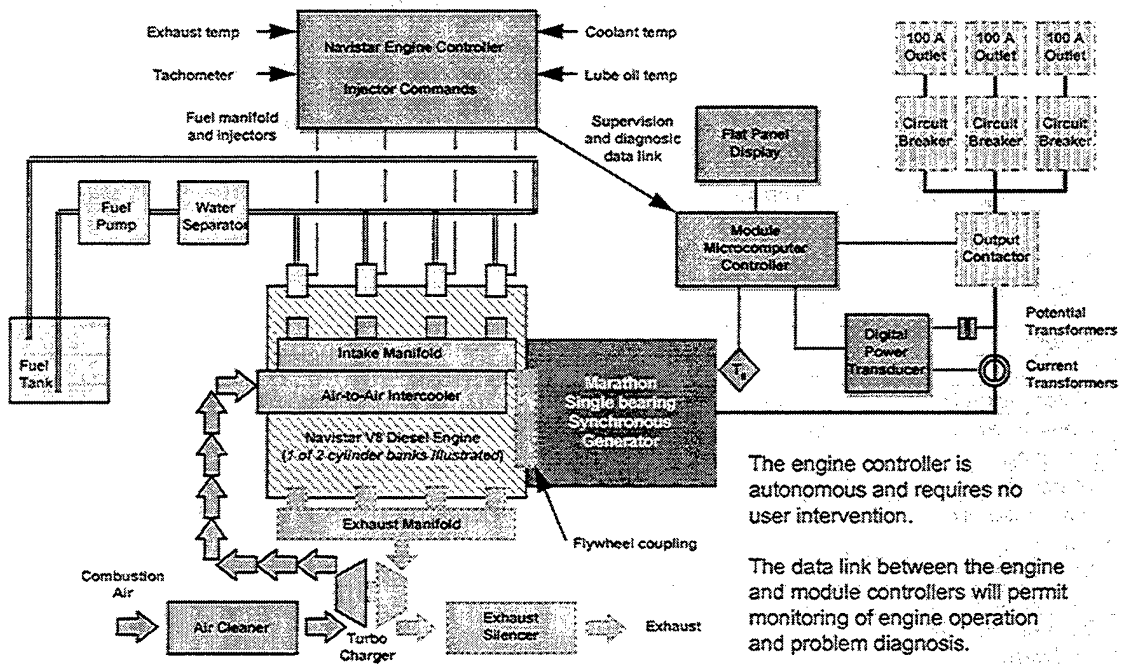
Marathon Generator



Navistar Engine

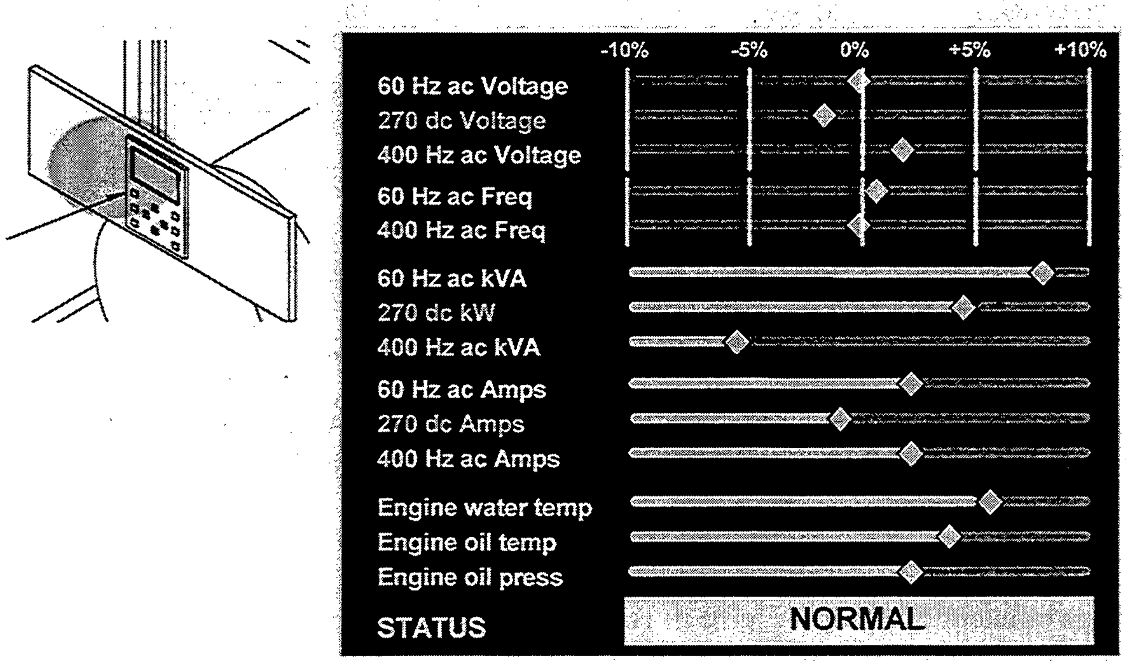
Engine and Module Control Systems. The engine controller and its sensors will be supervised by the module controller and display panel as shown in the system block diagram of Exhibit 2-17.

Exhibit 2-17: Diesel Generator Module Control System Block Diagram



Supervision and Diagnostic Display Panel. Engine and generator control systems will be supervised from a flat panel display. An illustrative display screen is shown in Exhibit 2-18. Available high brightness, active matrix, liquid crystal displays (LCDs), or developmental field emission displays (FEDs) are under evaluation.

Exhibit 2-18: Illustrative Flat Panel Display Screen



Weight and Cost of Principal Components. The quantity, weight, and cost of key components for the diesel generator module have been identified and are listed in Exhibit 2-19.

Exhibit 2-19: Weight and Cost of Key Diesel Generator Module Components

Component	Vendor[1]	Qty	Est. Unit Weight (Lbs)	Est. Unit Cost ($)	Qty x Unit Weight (Lbs)	Qty x Unit Cost ($)
Diesel Engine	Navistar	1	930	8,000	930	8,000
Alternator/Voltage Regulator	tbd	1	20	300	20	300
Starter motor	tbd	1	20	300	20	300
Battery	tbd	2	60	100	120	200
Generator	Marathon	1	1,370	7,440	1,370	7,440
Water jacket Hx	Modine	1	55	500	55	500
Water jacket Hx plumbing	tbd	1	20	100	20	100
Intercooler Hx	Modine	1	50	500	50	500
Intercooler Hx plumbing	tbd	4	50	500	50	500
Air cleaner	tbd	1	50	500	50	500
Exhaust Silencer	tbd	1	50	500	50	500
Oil filter relocation hardware	tbd	2	20	200	40	400
Main Circuit Breaker	GE	1	10	1,400	10	1,400
400A IEC Contactor	GE	1	30	3,020	30	3,020
I, V, & P sensor module	Second/Wind	1	5	1,410	5	1,410
Crankcase oil level sensor	tbd	1	3	100	3	100
Fuel tank level sensor	tbd	1	3	100	3	100
Temperature sensors	Omega	6	0	50	1.5	300
Computer/display unit	tbd	1	20	3,000	20	3,000
I/O interface	IOTech	1	5	700	5	700
Electrical equip. cabinet	tbd	1	50	350	50	350
Structural frame	tbd	1	440	720	440	720
Module enclosure panels	tbd	1	200	700	200	700
100 A, 5 wire receptables	tbd	3	5	100	15	300
Misc. Plumbing	tbd	1	30	300	30	300
Misc. Electrical	tbd	1	30	500	30	500
Misc. Hardware	tbd	1	30	200	30	200
Totals					3,647 lbs	$32,340

[1] Some vendor selections are illustrative and alternative suppliers may be used.

Next Steps. Brassboard demonstration and detail design of the MASS diesel generator module under program Delivery Orders 0004 (Technology Demonstration) and 0005 (Design) will be accomplished with the following steps:

- Selection of remaining components
- Design of interface between engine and module microcontrollers
- Design of power protection and control circuitry
- Development of firmware for module controller

- Preparation of package fabrication drawings
- Procurement of brassboard components
- Assembly, testing, and adjustment of the brassboard demonstration unit

Key components such as the generator and engine will be reused in a Technology Demonstrator version of the diesel generator module which will incorporate lessons-learned from the brassboard model. The Technology Demonstrator will be fabricated and evaluated under future MASS program Delivery Orders.

2.3 Avionics Power Converter (APC) Module

The Avionics Power Converter (APC) module will be powered by the 60 Hz diesel generator module. It provides up to 70 kW at 270 Vdc and 35 kVA at 200 Vac, 400 Hz. The preliminary design developed during the Delivery Order 0002 phase of the MASS program was configured for vertical mounting between other cart modules. During Delivery Order 0003, a new APC configuration was designed to accommodate horizontal installation beneath a cart. Refinements were made to the internal packaging design and a commercial off-the-shelf (COTS) power electronic building block (PEBB) was selected to replace the custom configuration previously considered.

External Configuration. The new APC design depicted in Exhibit 2-20 is configured for horizontal mounting beneath a cart.

Power Electronic Building Blocks (PEBBs). A commercial off-the-shelf (COTS) power electronic building block (PEBB) depicted in Exhibit 2-21 was identified. It will replace the previous custom PEBB design concept selected during Delivery Order 0002. Employing a COTS PEBB will avoid significant development time and cost, thereby reducing the module manufacturing cost. Groups of three PEBBs, controlled by a Digital Signal Processor (DSP), will convert 480 V, 3 ϕ, 60 Hz AC power to 270 Vdc power and 200 V, 3 ϕ, 400 Hz AC power.

Exhibit 2-20: Avionics Power Converter (APC) Module—Exterior View

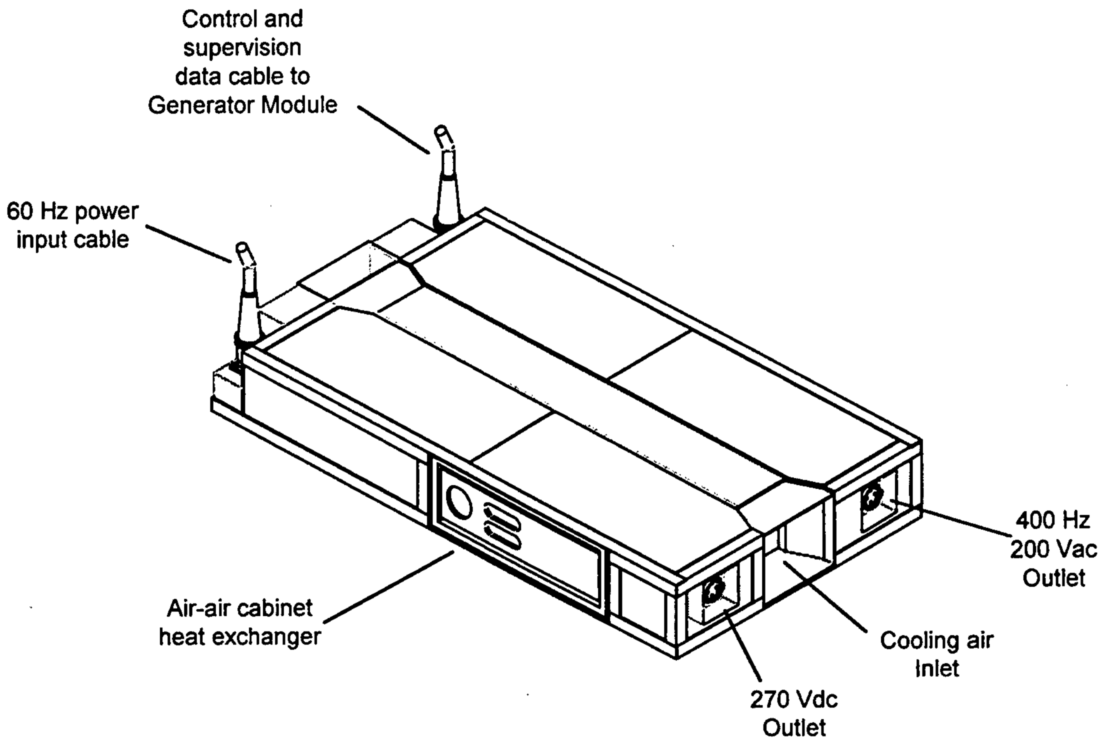
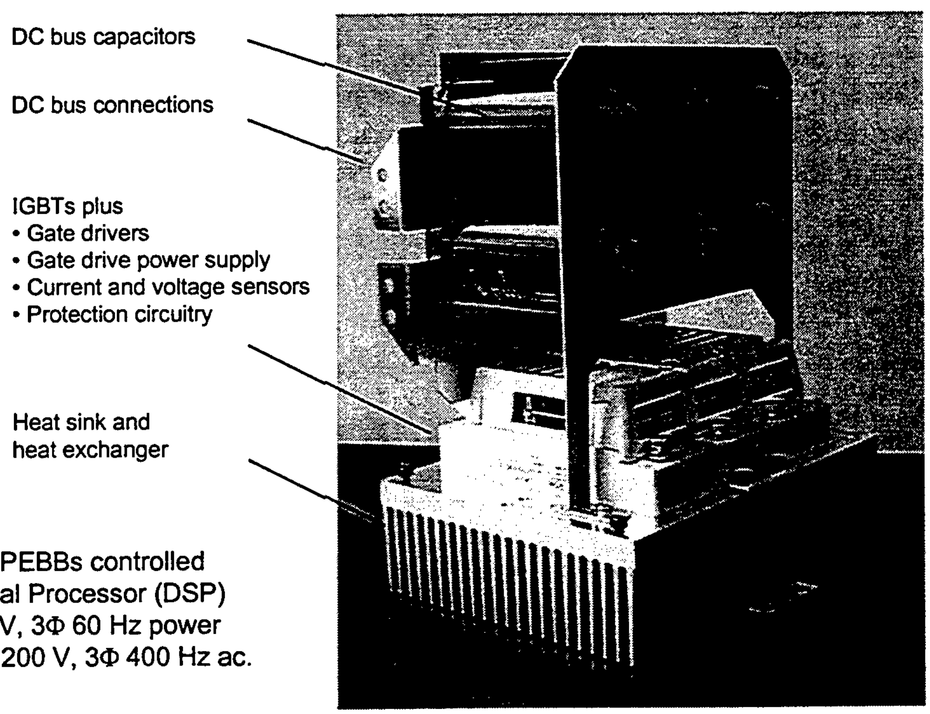


Exhibit 2-21: Commercial Off-the-Shelf Power Electronics Building Block



Groups of three PEBBs controlled by a Digital Signal Processor (DSP) will convert 480 V, 3Φ 60 Hz power to 270 V dc and 200 V, 3Φ 400 Hz ac.

Internal APC Construction. Six PEBBs will be mounted on a central cooling duct with their heat sink fins positioned in a fan induced air stream as shown in Exhibit 2-22.

System Diagram. The system diagram presented in Exhibit 2-23 depicts the proposed power electronic circuitry to be incorporated in the APC. One group of three PEBBs will implement a controlled current rectifier to convert 60 Hz generator power to a DC bus voltage of approximately 700 Vdc with relatively low harmonic current burden on the generator. A step-down DC-DC converter fed by the DC bus will supply DC avionics power at 270 Vdc. Another group of three PEBBs will form an inverter to convert DC bus power to 400 Hz avionics power.

Exhibit 2-22: Internal Construction of Avionics Power Converter Module

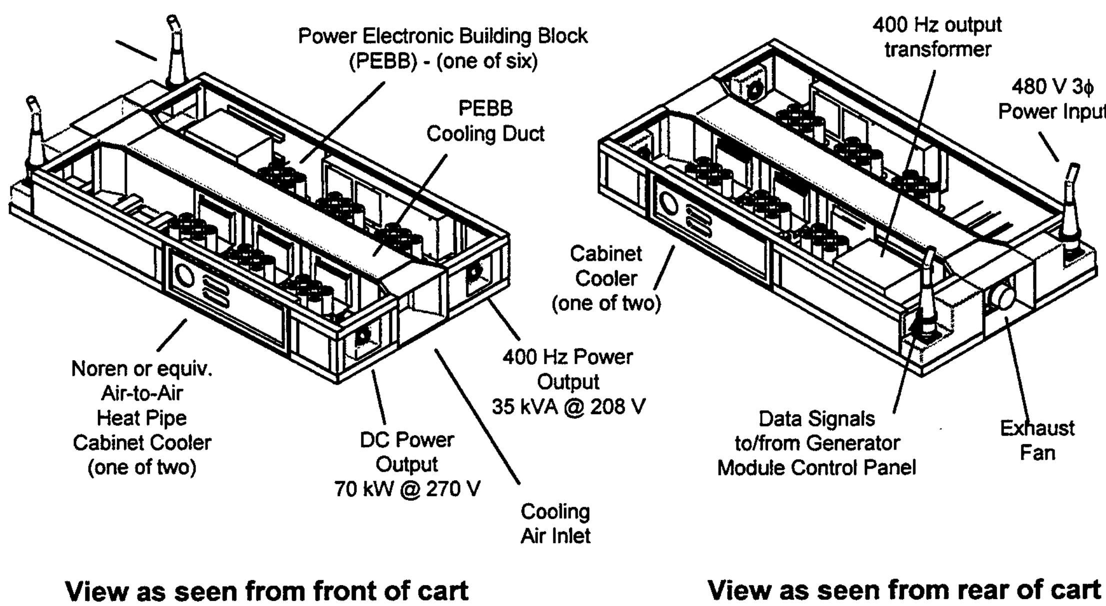
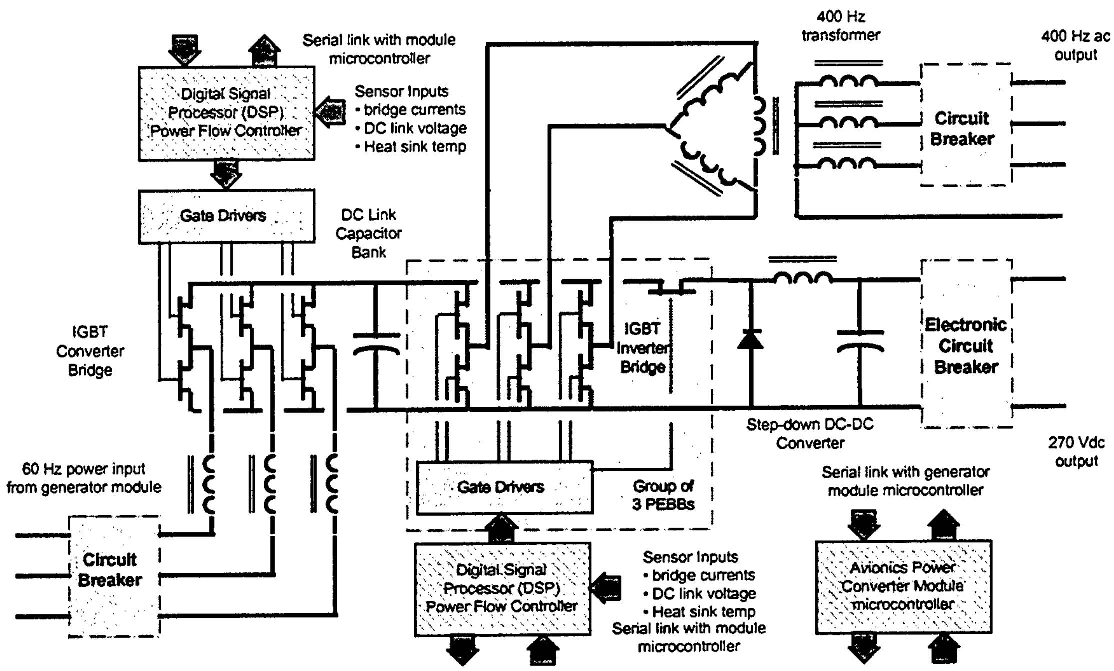


Exhibit 2-23: Avionics Power Converter System Diagram



Weight and Cost of Principal Components. The quantity, weight, and cost of key components have been identified and are listed in Exhibit 2-24.

Exhibit 2-24: Weight and Cost of Key APC Module Components

Component	Vendor[1]	Major Components	Qty	Est. Unit Weight (Lbs)	Est. Unit Cost ($)	Qty x Unit Weight (Lbs)	Qty x Unit Cost ($)
Power	Semikron	2 leg, 400A, 1,200 V IGBT bridge	3	10	600	30	1,800
Electric	Semikron	DC link capacity assemblies	3	10	600	30	1,800
Blk (PEBB)	tbd	DSP controller board	1	0.5	400	0.5	400
		Total PEBB 3 phase bridge				**60.5**	**4,000**
APC		PEBB 3 phase assembly	2	61	4,000	121	8,000
	NWL Transformer	33kVA, 400 Hz iso xfmr	1	180	5,300	180	5,300
	tbd	Input line inductors	3	20	200	60	600
	Octagon	Host microcontroller board	1	1	500	0.5	500
	Amphenol	100 A power inlet	1	5	100	5	100
	tbd	300 A DC power outlet	1	10	300	10	300
	J&B Aviation	70kW, 270 Vdc cable assembly	1	100	1,800	100	1,800
	J&B Aviation	30kVA, 400 Hz cable assembly	1	50	1,000	50	1,000
	Noren	Heat pipe cabinet cooler	2	20	600	40	1,200
	Rotron	Vaneaxial fans	1	50	3,000	50	3,000
	tbd	Cabinet and internal duct+frame	1	250	1,750	350	800
	tbd	Miscellaneous components		100	1,950	100	1,950
		Total APC				**1,067 lbs**	**$24,550**

[1] Some vendor selections are illustrative and alternative suppliers may be used.

Next Steps. Brassboard demonstration and detail design of the MASS APC module under program Delivery Orders 0004 and 0005 will be accomplished with the following steps:

- Assessment of 270 Vdc power protection and control requirements for ground support
- Performance of thermal analyses to assure acceptable component temperatures
- Performance of circuit analyses to test proposed PEBB control policies
- Implementation of adjustments as indicated by thermal and circuit analysis results
- Writing and testing of PEBB control DSP firmware
- Preparation of package fabrication drawings
- Procurement of package and electronic components
- Assembly and testing

It is expected that key components such as the power electronic building blocks and modules of control firmware will be reused in a Technology Demonstrator version of the APC module which will incorporate lessons-learned from the brassboard model. The Technology Demonstrator will be fabricated and evaluated under future MASS program Delivery Orders.

2.4 Air Cooling Module

Air cooling is used during on-ground servicing of aircraft to cool avionics and other electronic equipment. Legacy aircraft use air cooling for all avionics and require delivery pressure in the 3 to 5 psig range. The F-22 will require air cooling only for the cockpit electronic controls and displays, and requires air at 0.5 to 1 psig (liquid cooling is used for frame-mounted avionics).

The air flow, temperature, and pressure requirements vary significantly among different aircraft. Previous air cooling system design work was based on the F-15C requirements. The design called for 90 lb/min of air delivered at 45 °F at a 3 psig delivery pressure. Further work has focused on the F-22 requirements. The current design calls for 45 lb/min of air delivered at 50 °F and 0.7 psig. This change in focus has resulted in a reduction in size of the air cooler.

The air cooling module design conditions are compared with the requirements of different aircraft in the table below (Exhibit 2-25). The air cooling module will supply from 50% to 100% of the required cooling for the listed aircraft at the design ambient conditions. At less extreme ambient conditions, the system will deliver a greater percentage of the required cooling capacity.

Exhibit 2-25: Air Cooling Requirements and Capabilities

	Aircraft Requirements		Air Cooling Module Design Capability	
Aircraft	Air Flow (lb/min)	Delivery Temperature (°F)	Percent of Required Airflow	Percent of Required Cooling[1]
F-15E	71	50	63%	63%
F-15C	86	50	52%	52%
F-16	55	50	81%	81%
F-117A	60	70	75%	100%
F-18	50	50	90%	90%

[1] Assuming average temperature of cooling air leaving aircraft is 115 °F.

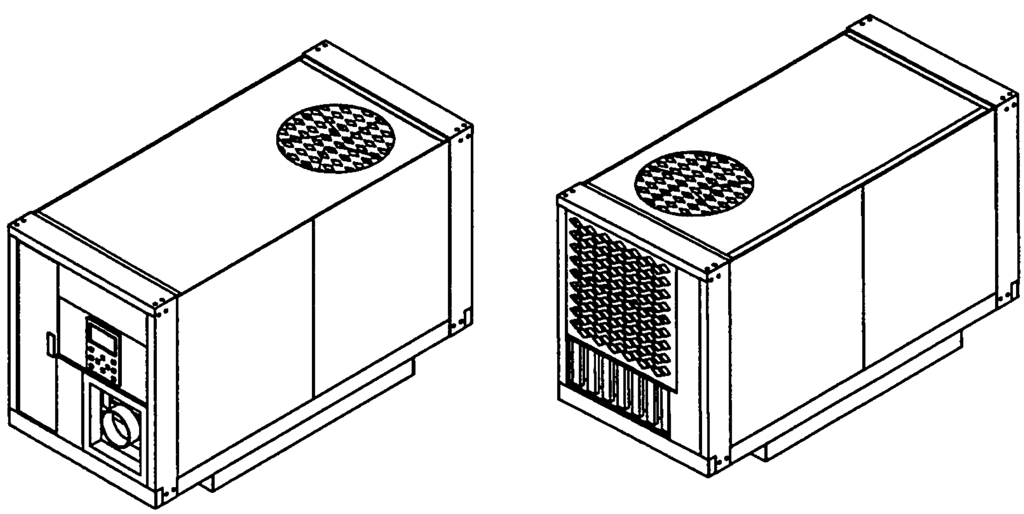
Changes in the design approach as compared with modules described in the MASS Delivery Order 0002 Final Report[5] are as follows:

- Reduction of air cooling capacity to match the lower air cooling load of the F-22 and the decision to use parallel flow type heat exchangers has lessened the importance of reducing condenser face area. Hence, the high condensing temperature possible with the dual-loop refrigerant system is no longer worth the added system complexity.
- System packaging using standard 42-inch width modules means that: (1) the smaller size of the motorized air cycle design does not contribute to a smaller footprint for the overall system; (2) high-speed refrigerant compressors manufactured by Fairchild or United Technologies Corporation do not result in a system size reduction; (3) a 14,000 rpm blower has an acceptable size; and, (4) the use of more conventional hardware results in a system cost reduction.

The primary air cooling design uses a conventional HFC-134a vapor compression refrigeration system. Investigation of motorized air cycle cooling has been ongoing. This option is more expensive and although there is a benefit in reduced weight, the more significant potential benefit of reduced footprint is not achieved due to the 42-inch standard module width.

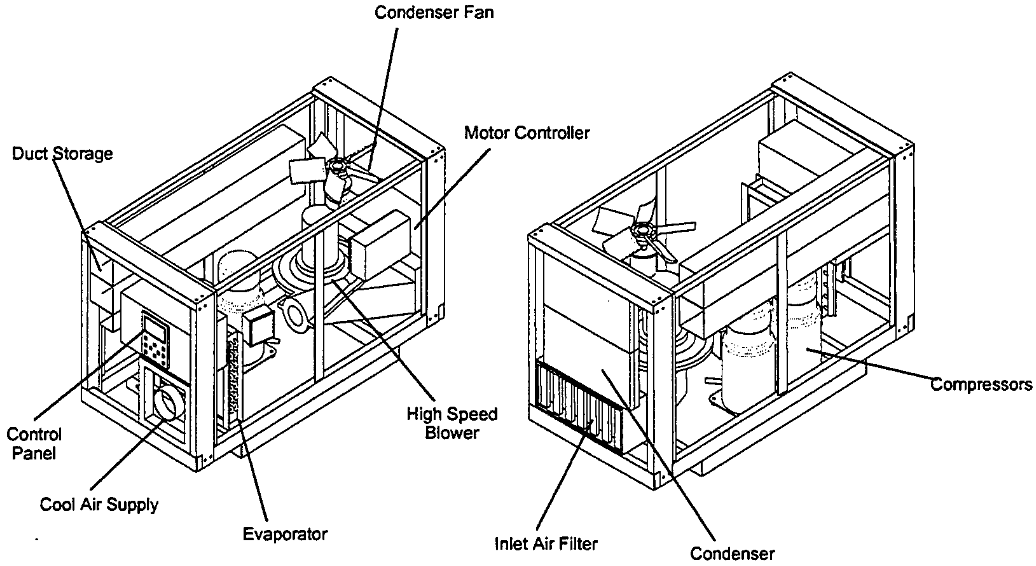
Current Design. The Air Cooling Module is illustrated in Exhibit 2-26. Internal views of the module are shown in Exhibit 2-27. A schematic of the refrigeration system is shown in Exhibit 2-28.

Exhibit 2-26: Air Cooling Module–External View



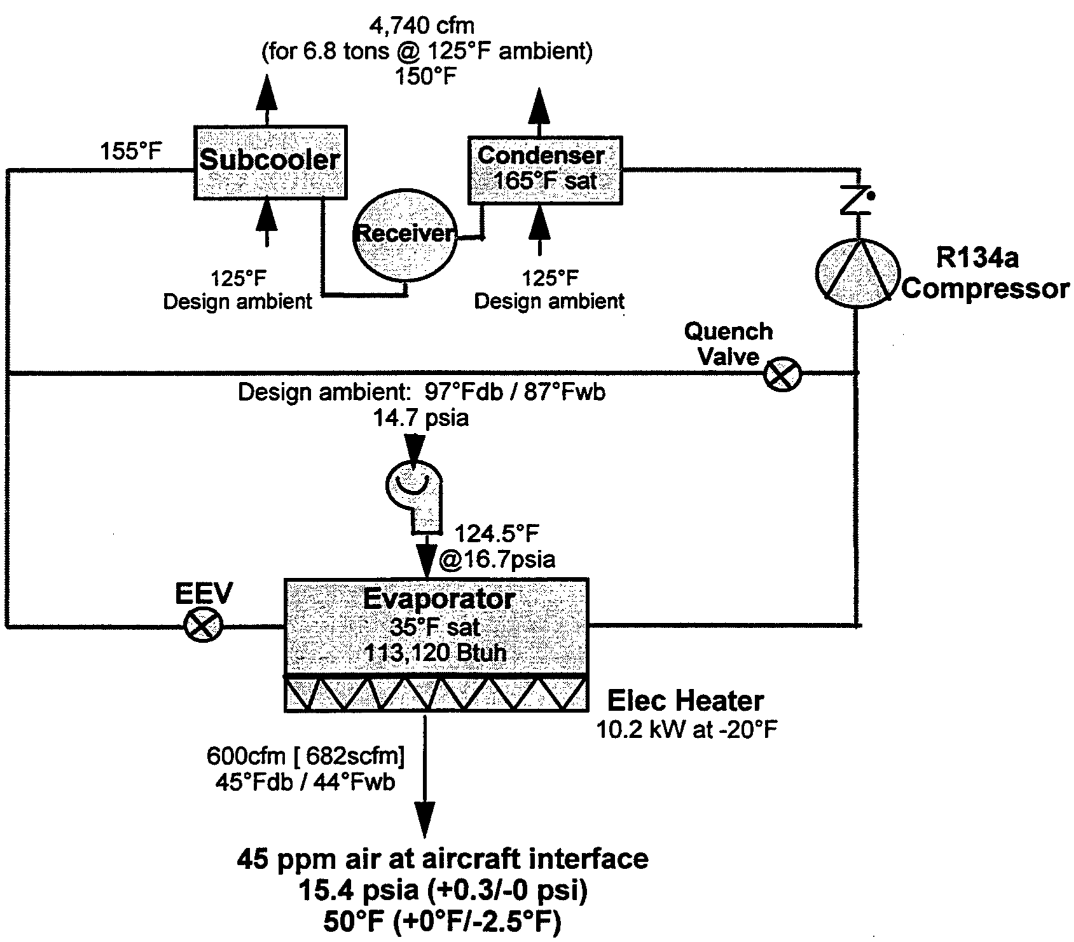
Front View **Rear View**

Exhibit 2-27: Air Cooling Module–Internal View



Front View **Rear View**

Exhibit 2-28: Air Cooling Module Refrigeration Schematic



Key features of the design include:

- Design condition air delivery of 45 lb/min at 50 °F and 0.7 psig (static pressure)
- Blower designed with higher pressure capability for servicing older aircraft such as the F-15 and F-16
- HFC-134a refrigerant operating with a 165 °F condensing temperature
- Refrigerant Compressors: Parallel scroll compressors (see discussion below for other options under consideration)
- Electronic expansion valve
- Condenser and Liquid Subcoolers: Parallel Flow (PF) type heat exchangers
- High-Pressure Blower: High-Speed (14,000 rpm) single-stage centrifugal driven directly by a high-speed permanent magnet motor through a variable-speed controller
- 6-inch diameter supply duct with on-board storage

Key benefits of the design approach are:

- Low cost
- Conventional cooling technology
- COTS components used for the refrigerant compressor(s), evaporator, condenser fan
- Other major components are well-proven if not COTS: PF condensers, high-pressure blower
- The lower load (due to F-22-oriented design) and PF condenser allows placement of the condenser on the 42-inch side of the module. Hence the module position is not critical and can be placed on either end of a MASS cart.

The cost of the major components of the air cooling module are tabulated in Exhibit 2-29 below.

Exhibit 2-29: Air Cooling Module Component Cost

F-22 Air Cooling, Vapor Compression					
Component	Qty	Est. Unit Weight (Lbs)	Est. Unit Cost ($)	Total Weight (Lbs)	Total Cost ($)
R-134a Compressor	2	227	950	454	1,900
Condenser	5	8	164	40	820
Evaporator	1	13	325	13	325
Blower	1	140	8,000	140	8,000
Condenser Fan/Motor	1	30	180	30	180
Air Filter and Housing	1	30	50	30	50
Misc Electrical	1	55	1,000	55	1,000
Ductwork	1	40	250	40	250
Piping	1	80	250	80	250
Refrigeration Components	1	30	500	30	500
Control Computer	1	10	3,000	10	3,000
I/O Board	1	5	1,100	5	1,100
Auxiliary Control Hardware	1	10	300	10	300
Frame and Housing	1	551	2,179	551	2,179
Refrigerant	5	1	5	5	25
Totals				**1,493 lbs**	**$19,879**

Refrigerant Compressors. The major options under consideration for refrigerant compressors are listed in Exhibit 2-30 below. The Bitzer VSK hermetic screw compressor is a compact option, but it requires operation with 70 Hz power with a variable-speed drive in order to provide adequate capacity for the air cooler. The Bitzer 6-cylinder recip compressor listed in the exhibit has adequate capacity for both the air cooling and liquid cooling modules. It has a moderate price and relatively compact size, but is fairly heavy. This compressor may also require use of a suction accumulator to reduce risk of liquid slugs entering the compressor; this issue is being explored with Bitzer. The use of two parallel scroll compressors is the least expensive option, but adds challenges in packaging.

Exhibit 2-30: Refrigerant Compressor Options

Compressor	Size LxWxH (inches)	Weight (lbs)	Delivery Order 0004 Cost	Production Cost	Meets Capacity Req'ment: Air	Meets Capacity Req'ment: Liq
Bitzer VSK Hermetic Screw	36x12x12	330	$4,840	$3,870	N	N
Bitzer VSK w/VSD	Compressor 36x12x12 VSD 9x9x20	Comp 330 VSD 50 Total 380	Comp $4,840 VSD $2,000 Total $7,000	Comp $3,870 VSD $1,500 Total $5,500	Y	N
Bitzer 6-Cylinder Recip	21x18x17	510	$4,190	$3,265	Y	Y
Trane Scroll	12x12x26 each	227 each	$950 each	$950 each	Y[1]	Y[1]

[1] Two compressors required to meet capacity requirement.

High-Pressure Blowers. Exhibit 2-31 displays the five options which have been under consideration for the high-pressure blower for the air cooling module. The first four options are based on two blower options and two motor options. The blower options are:

- The compressor section of an Elliott turbocharger
- The wheel and housing of the Invincible Air Systems blower used in Engineered Air Systems versions of the C-5 and MA-3 AGE cooling carts.

The motor options, which both require the use of a motor controller, are:

- A 400 Hz induction motor
- A custom-designed high-speed permanent magnet brushless DC motor (PMM).

The fifth option, use of a Paxton centrifugal blower, would allow direct use of 60 Hz power or the use of a variable speed drive for tighter control. Clearly, the Paxton blower makes the most sense for the near-term Delivery Order 0004 Brassboard. The pressure capability of the standard Paxton blower falls slightly short of the F-15 requirements. Paxton is investigating modifications to their system to satisfy all aircraft requirements. If Paxton can increase the range of their blower then both Paxton and the PMM/Invincible option could be candidates for production.

Another possibility, however, would be to incorporate a PM motor with the Paxton blower, which would have size similar to the PMM/Elliott option, probably at a more competitive cost.

Motorized Air-Cycle Module. Discussion with both Normalair Garrett, LTD, of England and TAT of Israel have been ongoing to determine the possibilities of developing a competitive air-cycle air cooler. The benefits and disadvantages of air-cycle cooling for this application are tabulated in Exhibit 2-32 below.

Exhibit 2-31: Blower Options

Motor/Blower	Size	Weight (lbs)	DO4 Cost ($1000)	Production Cost ($1000)
400 Hz/Invincible	24" Dia x 29"	325	$50	N/A[1]
400 Hz/Elliott	14" Dia x 26"	280	$40	N/A[1]
PMM/Invincible	24" Dia x 18"	136	$53	$8
PMM/Elliott	14" Dia x 14"	90	$54	~$20
60 Hz/Paxton	27" x 22" x 17"	300	$10	$9[2]

[1] Options with the Induction motor make footprint too large for MASS.
[2] Provided Paxton can expand capabilities to meet all aircraft.

Exhibit 2-32: Air-Cycle Air Cooling Advantages and Disadvantages

Advantages	Disadvantages
Lower weight (~750 lbs less)	Greater cost (~$70,000 acquisition cost for air-cycle components alone)
Smaller footprint (7 ft^2 less)	Greater power requirement
No refrigerant required	Potential spare part stocking requirement for motorized compressor, the most expensive system component
Potentially less maintenance cost	

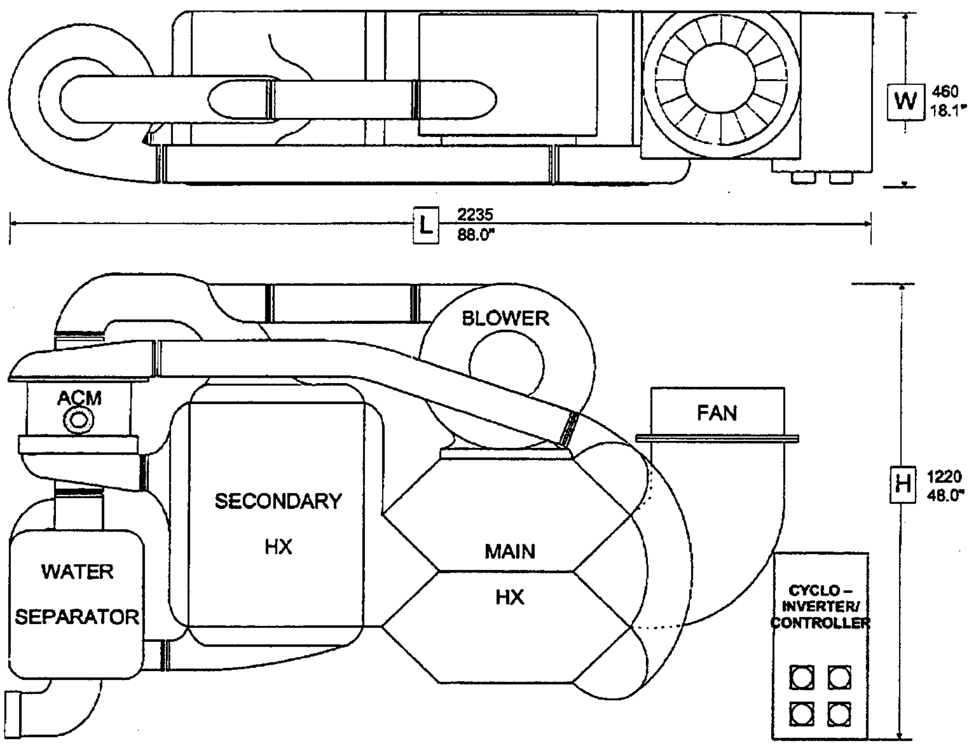
The layout of an air-cycle cooling system proposed by TAT is shown in Exhibit 2-33 below. The indicated system layout does not include air hose storage, a blower motor controller, a fan motor controller, the module frame and skin, and a main intake air filter.

Next Steps. Detail design of the air cooling module will proceed as planned in Delivery Order 0005. A brassboard demonstration of the air handling system is planned as part of Delivery Order 0004. The following key steps still have to be addressed:

- Finalization of the refrigerant compressor selection
- Finalization blower/motor selection for Brassboard demonstrator
- Refinement of overall system design

Exhibit 2-33: TAT Air-Cycle Cooling System Characteristics

Size (L x H x W) not including hose storage	88" x 48" x 18"
Weight (major components)	<600 lbs
Estimated Power Requirement	~40 kW
Preliminary production cost estimate (major components)	$70,000



2.5 Liquid Cooling

Liquid cooling is used during on-ground servicing of aircraft to cool frame-mounted avionics for the F-22 (liquid cooling is also anticipated for the JSF). Liquid cooling uses Polyalfaolefin (PAO) coolant in a module which must be able to meet both a high-temperature and a low-temperature cooling requirement. In both cases, the PAO flow rate is 31 gpm, with a delivery pressure of 195 psig min/210 psig max. For low temperature operation, the system must deliver 54 kW of cooling at 59 °F coolant delivery temperature. For high temperature, the required load is 110 kW at 122 °F delivery temperature. (Please note that these requirements are not intended to be met simultaneously.)

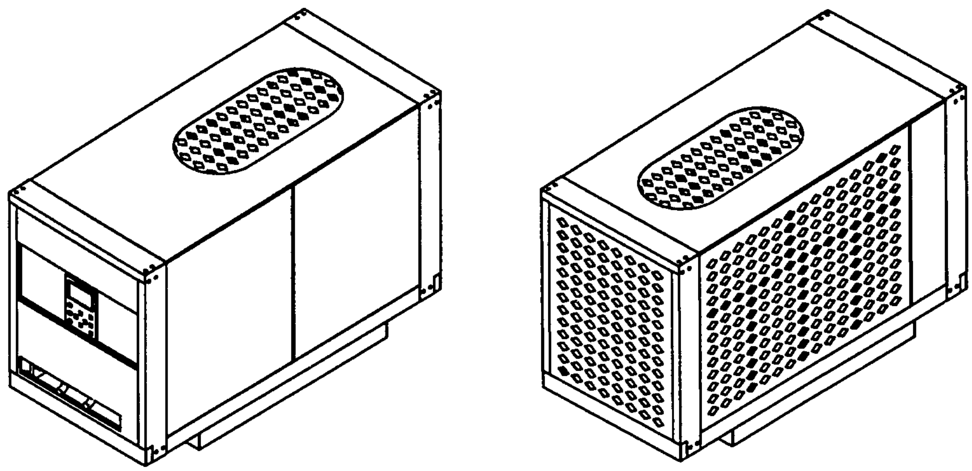
Changes in the design approach as compared with modules described in the MASS Delivery Order 0002 Concept Exploration Final Report[6] are as follows:

- Parallel Flow-type condensers will be used to reduce condenser size
- Module width changed to standard 42 inches

- Internal hose storage with a motor-driven hose reel
- Fluid precooling with ambient air

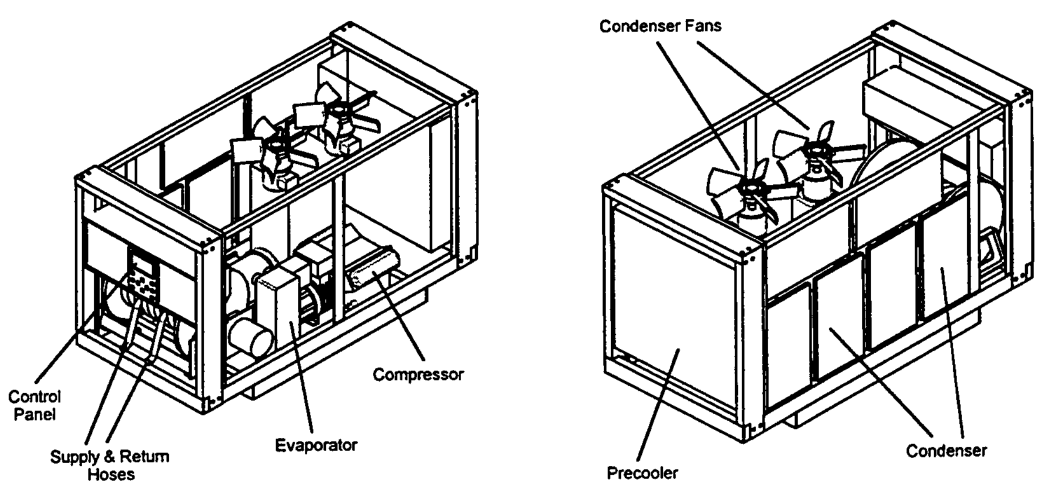
Current Design. The Liquid Cooling Module is illustrated in Exhibit 2-34. Internal views of the module are shown in Exhibit 2-35. A schematic of the refrigeration and PAO piping systems is shown in Exhibit 2-36. (Please note that the current design of the liquid cooling module necessitates placement in an end or outside position on the MASS chassis.)

Exhibit 2-34: Liquid Cooling Module–External View



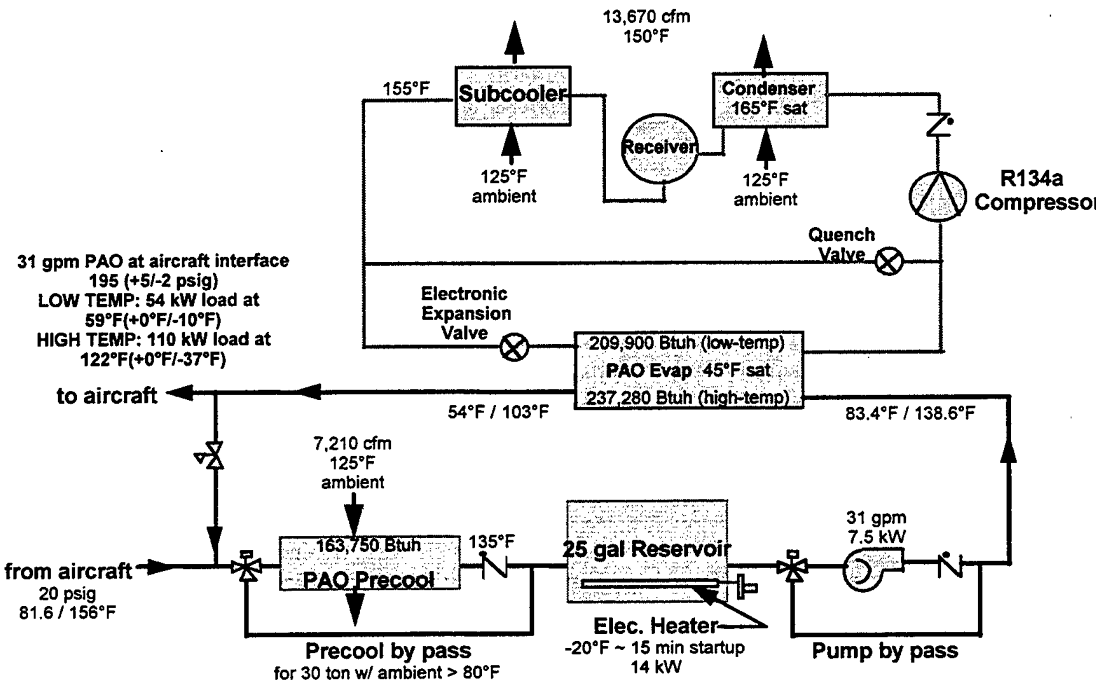
Front View **Rear View**

Exhibit 2-35: Liquid Cooling Module–Internal View



Front View **Rear View**

Exhibit 2-36: Refrigeration and PAO Piping Systems Schematic



Key features of the design include:

- HFC-134a refrigerant operating with a 165 °F condensing temperature
- Refrigerant Compressors: Bitzer 6-cylinder reciprocating (see discussion in compressor section above for other options under consideration)
- Electronic expansion valve
- Condenser and Liquid Subcoolers: Parallel Flow heat exchangers
- Ambient precooling of PAO used to reduce refrigerant system load
- Self-priming external gear PAO pump
- 25-gallon PAO reservoir
- On-board internal liquid hose storage

Key benefits of the design approach are:

- Conventional cooling technology
- COTS components used for the refrigerant compressor(s), evaporator, ambient precooler, condenser fan, PAO pump
- Low cost

The cost of the major components of the liquid cooling module are tabulated in Exhibit 2-37 below.

Exhibit 2-37: Liquid Cooling Module Component Cost

PAO Cooling					
Component	Qty	Est. Unit Weight (Lbs)	Est. Unit Cost	Total Weight	Total Cost
R-134a Compressor	1	510	$ 3,265	510	$ 3,265
Condenser	10	8	$ 164	80	$ 1,640
Evaporator	1	100	$ 1,800	100	$ 1,800
Pump	1	200	$ 1,800	200	$ 1,800
Condenser Fan/Motor	2	30	$ 180	60	$ 360
Fluid Reservoir	1	85	$ 1,000	85	$ 1,000
Fluid Filter	1	20	$ 200	20	$ 200
Misc Electrical	1	80	$ 1,500	80	$ 1,500
Piping	1	200	$ 600	200	$ 600
Refrigeration Components	1	30	$ 500	30	$ 500
"Hydraulic" Components	1	50	$ 1,500	50	$ 1,500
Control Computer	1	10	$ 3,000	10	$ 3,000
I/O Board	1	5	$ 1,100	5	$ 1,100
Auxiliary Control Hardware	1	10	$ 300	10	$ 300
Frame and Housing	1	551	$ 2,179	551	$ 2,179
Refrigerant	5	1	$ 5	5	$ 25
PAO	180	1	$ 2	180	$ 360
Totals				**2,176 lbs**	**$21,129**

Next Steps. Detail design of the liquid cooling module will proceed as planned in Delivery Order 0005. A brassboard demonstration of the liquid cooling module will be fabricated as part of Delivery Order 0004. The following key steps still have to be addressed:

- Finalization of the refrigerant compressor selection
- Confirmation of PAO system requirements
- Refinement of overall system design

2.6 Hydraulics

Extensive industry research on various pump technologies was performed with the intent of reducing cart weight and footprint without sacrificing performance. Due to the high pressure and relatively high flow requirements along with the need for pressure compensation over a varied output flow, the axial-piston pump emerged as the leading choice.

Components were sized and preliminary layouts were constructed to determine minimum footprint needed for various hydraulic modules. The Delivery Order 0002 Final Report[7] presented preliminary layouts for dual system hydraulic carts driven by four methods: diesel, turbine, shaft, and electric power. A single system electric driven module was also presented for integration into the Customizable and Advanced Electrical system concepts. Module cost, weight, and maintainability were estimated.

The hybrid system concept selected from IPT #6 and #7 input has driven the need to incorporate the single system, electric driven concept. Past and current module components have been sized for the following conditions:

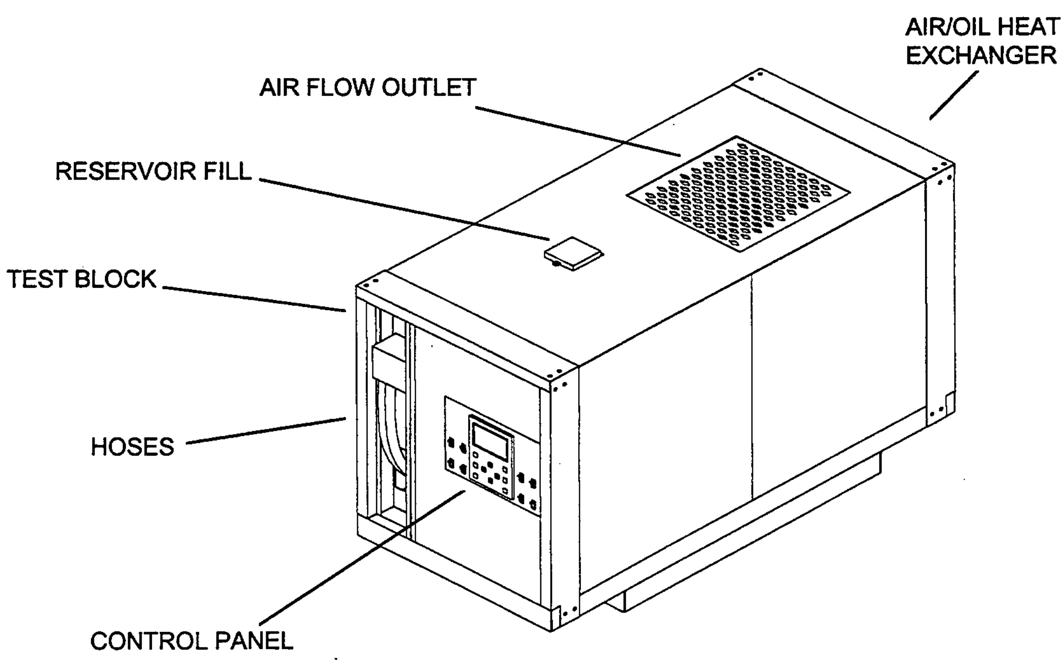
- 38 gpm @ 4,000 psi
- Maximum flow: 60 gpm
- Maximum pressure: 5,000 psi
- Fluid compatibility: MIL-H-5606, MIL-H-6083, MIL-H-46170, MIL-H-83282, MIL-H-87257

These requirements are derived from IPT input and the HTS-2/3 D/E Purchase Description from SA-ALC/LDKSH, Kelly AFB[8]. This draft procurement dictates the design of dual and triple system hydraulic ground support equipment for the entire Air Force fleet (A-10, RF-4C, F-15 A-E, F-16, F-22 fighters; C-130, C-141 cargo aircraft; T-37, T-38 trainers; KC-135, KC-10 aerial refuel aircraft; and, B1-B, B2 bombers). The stated conditions represent the requirements for a single system version of the dual system cart detailed in the procurement.

Current Package Design. The selected system concept utilizes two single system hydraulic modules located in the outer positions of the chassis, driven by either the diesel driven generator or hangar/repair shop power. The single system hydraulics module (see Exhibit 2-38) offers a number of advantages compared to the dual system module:

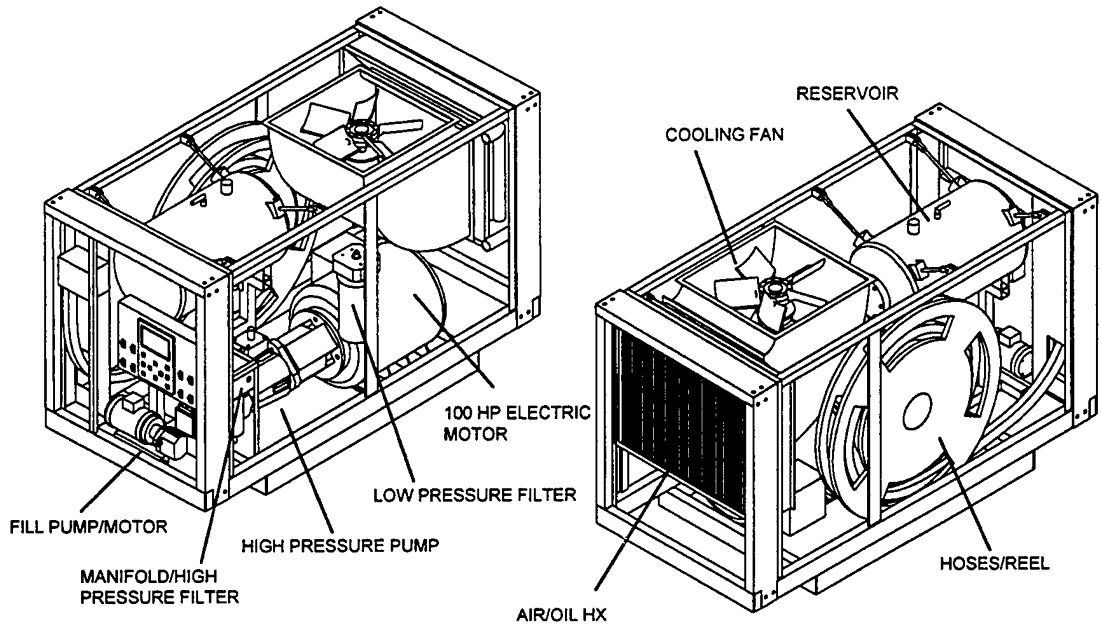
- Increased maintainability compared to previous designs due to relaxed component density
- Decreased module size and weight
- Increased system customization due to common chassis sizes

Exhibit 2-38: Hydraulic Module–External View



Internal Construction. Exhibit 2-39 displays the major components for the hydraulic module.

Exhibit 2-39: Hydraulic Module–Internal View



An electric driven hose reel, manufactured by Hannay Reels, is integrated within the unit to provide efficient hose deployment and compact storage. The model depicted within the figure is a representative example, as the actual design is currently in development. Possible disadvantages for the inclusion of reels within the module include electric motor failure and hydraulic oil leakage. Greater pressure drops will also occur due to the additional piping and rotating couplings within the high-pressure supply line.

The cooling system is ducted from the air/oil heat exchanger through the top of the module to protect the components from sand and precipitation.

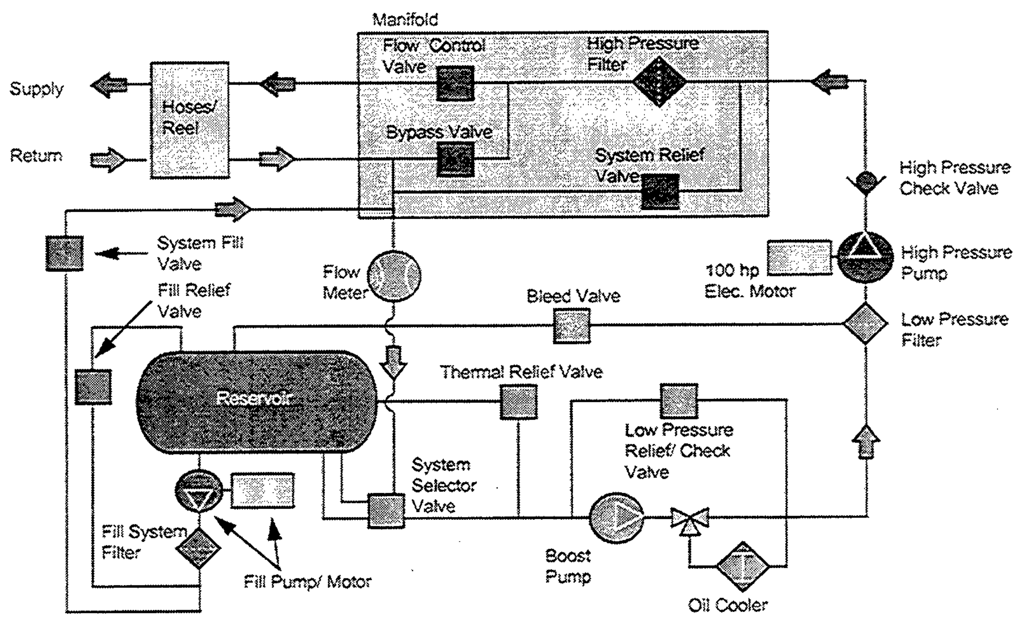
Electric actuated poppet cartridge valves mounted within the manifold offer a number of control and design advantages:

- The manifold can be mounted away from the control panel in a more accessible area by eliminating the manually operated cartridge valves. Replacing and servicing valves and filters within the AGE hydraulic carts present extremely labor intensive tasks due to their compact location.
- The high-pressure relief valve can be automatically set from the control panel for various aircraft loops, eliminating the need to ramp up the system to find and adjust the proper setting.
- Improper bypass valve use can be eliminated by programming the controls to operate exclusively in open or shut states. Poppet valves will fail if left partly open in a high pressure/high flow condition.

System Block Diagram. Exhibit 2-40 presents the operational flow diagram for the hydraulic system. The hydraulic system is designed for three functions: service using aircraft reservoir, service using cart reservoir, and system filling.

The system selector valve enables the operator to select either the aircraft or cart reservoirs. The boost pump, integrated with the high-pressure pump and driven off the 100 hp electric motor, draws fluid from the selected reservoir. The low-pressure fluid flows through the return hose, system manifold, and flow meter. Fluid circulates through a cross flow, air-oil heat exchanger to remove heat added to the system from pump inefficiency and frictional losses. Captured air is exhausted from the system from the top of the low-pressure filter to the reservoir by actuating the bleed valve. The boost flow then enters the high-pressure, variable displacement, pressure compensated axial piston pump. Outlet pressure level is governed by the compensator control on the pump and the system relief valve. The volume control valve on the pump and the flow control valve in the manifold dictate system output flow. The bypass valve allows direction back to the system.

Exhibit 2-40: Hydraulic Module Block Diagram



Weight and Cost of Principal Components. The quantity, weight, and cost of the major components of the single loop system are presented in Exhibit 2-41.

Exhibit 2-41: Weight and Cost of Key Components

Component	Vendor[1]	Qty	Est. Unit Weight (lbs)	Est. Unit Cost ($)	Qty x Unit Weight (lbs)	Qty x Unit Cost ($)
Axial Piston Pump	Denison	1	190	6,400	190	6,400
Electric Motor	Lincoln	1	980	4,390	980	4,390
Reservoir	tbd (cart mfr)	1	180	300	180	300
Low-Pressure Filter	Parker	1	4	180	4	180
High-Pressure Filter	Parker	1	80	850	80	850
Fill Pump	Rexroth	1	10	300	10	300
Fill Pump Motor	Rexroth	1	40	310	40	310
Air/Oil Heat Exchanger	S.R. Coil	1	120	350	120	350
Impeller	Continental	1	10	80	10	80
Fan Motor	Reuland	1	60	620	60	620
Vane Boost Pump	Denison	1	60	1,470	60	1,470
Pump-Motor Adapter	Vescor	1	20	260	20	$260
Pump-Motor Coupling	Vescor	1	20	250	20	$250
Hose Reel	Hannay	1	130	1,910	130	1,910
Hoses	Aeroquip	1	110	1,160	110	1,160
Manifold	Almo	1	10	200	10	200
Manifolding Valve	Vickers	1	1	1,000	1	1,000
Flow Control Valve	Vickers	1	2	1,000	2	1,000
Bypass Valve	Vickers	1	2	1,000	2	1,000
High-Pressure Relief Valve	Vickers	1	4	1,000	4	1,000
High-Pressure Check Valve	Rexroth	1	2	50	2	50
System Selector Valve	Parker	1	4	1,000	4	1,000
Thermal Relief Valve	Rexroth	1	4	400	4	400
Boost Check/Relief Valve	Rexroth	1	10	540	10	540
Remaining Valves	tbd	1	9	630	9	630
Controls - Sensors	tbd	1	40	4,000	40	4,000
Controls - Wiring + Misc. Electrical	tbd	1	90	2,760	90	2,760
Controls - Computer	tbd	1	10	2,900	10	2,900
Structure/Frame + Misc. Hardware, Plumbing	tbd (cart mfr)	1	540	3,250	540	3,250
Totals					**2,740 lbs**	**$38,600**

[1] Some vendor selections are illustrative and alternative suppliers may be used.

Next Steps. Design completion of the single system hydraulic system concept requires the following steps:

- Resolution of manifolding capability issue. The need to combine the supply and return flows between two individual modules will be investigated and incorporated within the system if required.

- Selection of remaining components
- Addition of piping
- Determination of hose reel feasibility
- Structural analysis

2.7 Pneumatics

The pneumatic requirements for the MASS program were determined to be most efficiently met by nitrogen producing hollow fiber membranes integrated with a four-stage air compressor. This technology enables the system to utilize a single module to meet three functions (low-pressure compressed air, high-pressure compressed air, and high-pressure compressed nitrogen).

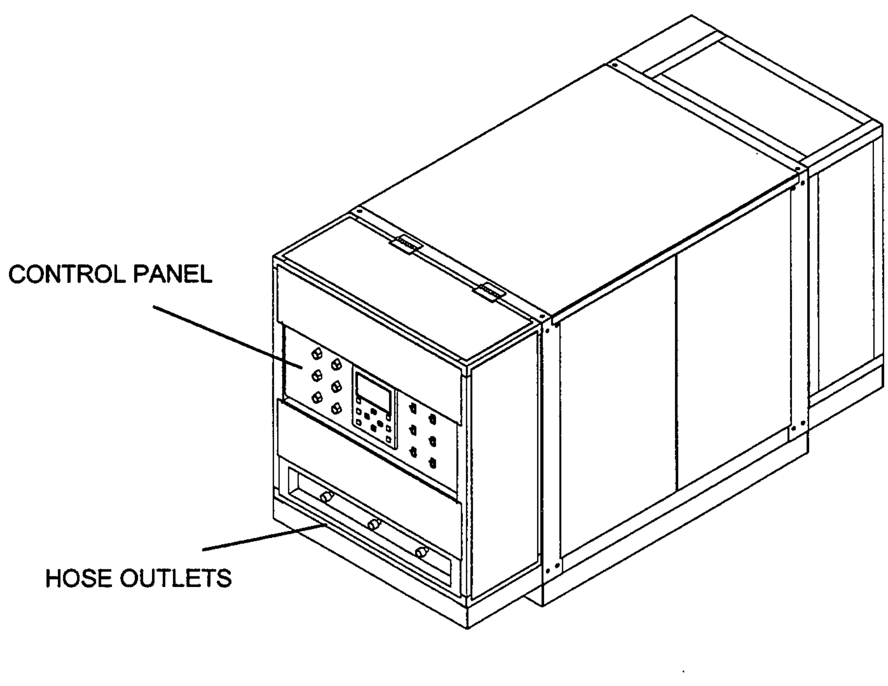
The requirements for the Delivery Order 0003 MASS pneumatic module, driven by the F-22, are as follows:

- 15 scfm, 200 psi compressed air
- 15 scfm, 5000 psi compressed air; 119 scf storage
- 15 scfm, 5000 psi, 95.5% pure compressed nitrogen; 435 scf storage

Preliminary layouts were designed to estimate required envelope. Module cost, weight, and maintainability were estimated.

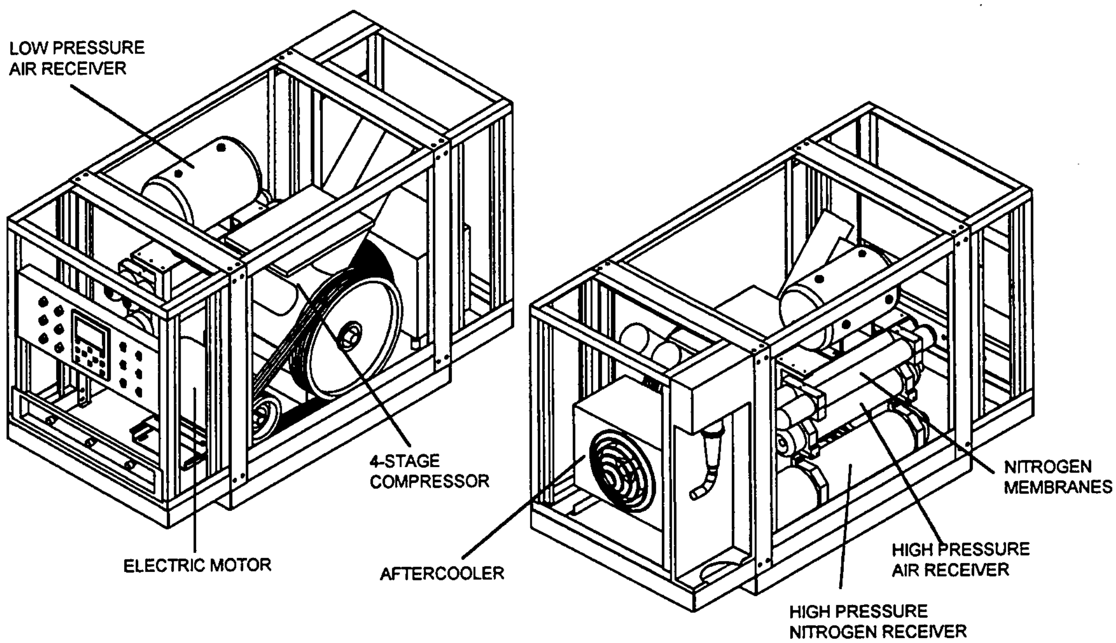
Current Package Design. The pneumatic module, presented in Exhibit 2-42, is capable of being mounted on either side of the diesel generator module on the system chassis. The module utilizes the same frame design as the other ground support functions, with supply hoses accessible from the front control panel.

Exhibit 2-42: Pneumatic Module—External View



Internal Construction. Exhibit 2-43 displays the major components for the pneumatic module. The belt-driven, oil free compressor shown (manufactured by RIX Industries), was selected due to its ability to tap off the second stage to meet the low-pressure shop air requirement. A number of manufacturers can meet the requirements in the envelope provided.

Exhibit 2-43: Pneumatic Module—Internal View



System Block Diagram. The operational flow diagram for the pneumatic system is presented in Exhibit 2-44. The first two stages compress the ambient air to 200-250 psig. The aftercooler drops the process stream temperature to within 20 °F of ambient. After passing through a centrifugal moisture separator, removing 99% of droplets of at least 10 microns in size, the air stream then passes through dual low-pressure filters. The low-pressure shop air source can be tapped at this point, with the remaining air flowing through the system to keep the final stages of the compressor primed. A three-way valve directs the flow to the high-pressure side of the system, either bypassing the nitrogen membranes to produce combustible air, or routing through the membranes to produce the desired purity. The third and fourth stages increase the nitrogen/air to 5,000 psig.

Weight and Cost of Principal Components. The quantity, weight, and costs for the major components of the system are presented in Exhibit 2-45.

Exhibit 2-44: Pneumatic Module Block Diagram

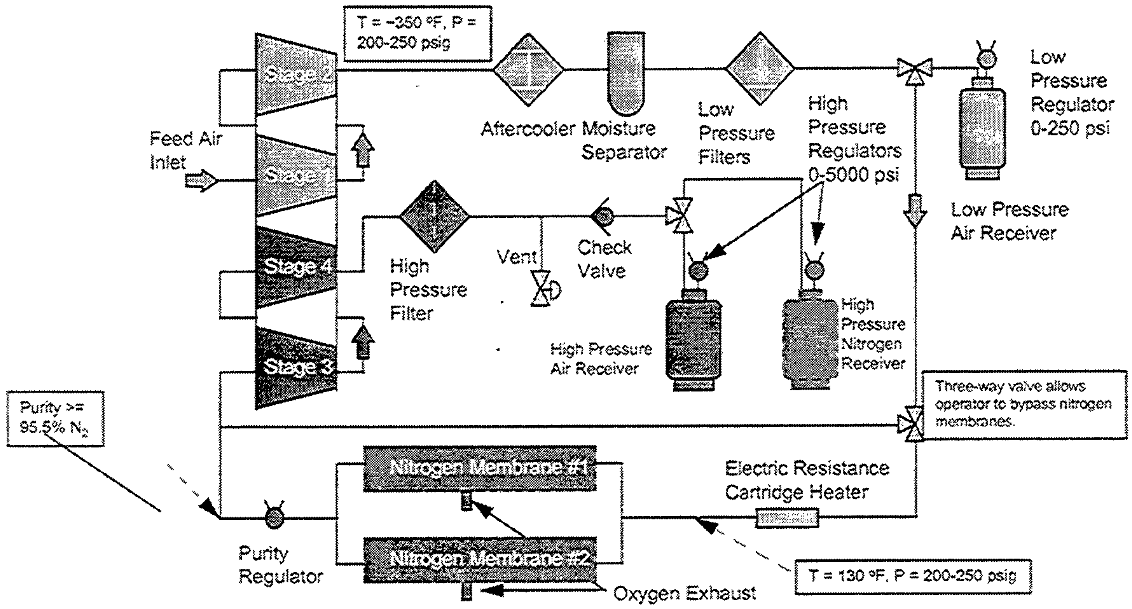


Exhibit 2-45: Weight and Cost of Key Components

Component	Vendor[1]	Qty	Est. Unit Weight (lbs)	Est. Unit Cost ($)	Qty x Unit Weight (lbs)	Qty x Unit Cost ($)
4-Stage Reciprocating Compressor	RIX	1	700	25,000	700	25,000
Electric Motor	Baldor	1	350	1,780	350	1,780
Nitrogen Membranes	Praxair	2	20	1,650	40	3,300
High Pressure Nitrogen Receiver	Taylor Wharton	1	190	970	190	970
High Pressure Air Receiver	tbd	1	100	800	100	800
Low Pressure Air Receiver	tbd	1	50	160	50	160
Aftercooler	Ultra Air Products	1	70	730	70	730
Moisture Separator	Wright Austin	1	20	180	20	180
Compressor Sheave/Bushing	Browning	1	90	390	90	390
Motor Sheave/Bushing	Browning	1	20	120	20	120
V-belt	Browning	1	3	60	3	60
Low Pressure Filters	Hankison	2	3	70	6	140
High Pressure Filter	Balston	1	1	180	1	180
Cartridge Heater	Omega	1	1	120	1	120
Controls - Sensors	tbd	1	50	3,350	50	3,350
Controls - Wiring + Misc. Electric	tbd	1	80	1,680	80	1,680
Structure/Frame + Misc. Hardware, Plumbing	tbd (cart mfr)	1	500	3,000	500	3,000
Totals					**2,270 lbs**	**$42,000**

[1] Some vendor selections are illustrative and alternative suppliers may be used.

Next Steps. The remaining steps before the brassboard stage include:

- Development of layouts for competing nitrogen/compressor technologies to select ideal manufacturer
- Selection of remaining components (valves, pipe fittings, etc.)
- Investigation of useful life-span for competing nitrogen membranes
- Addition of piping; completion of design
- Structural analysis

2.8 Cart Chassis

Each chassis (Exhibit 2-46) is designed to accomodate up to three modules and one APC module. The chassis is comprised of a suspension/steering section, a weldment which supports the modules, and a diesel fuel tank (Exhibit 2-47). Chassis characteristics are displayed in Exhibit 2-48.

Exhibit 2-46: Chassis—End Loader

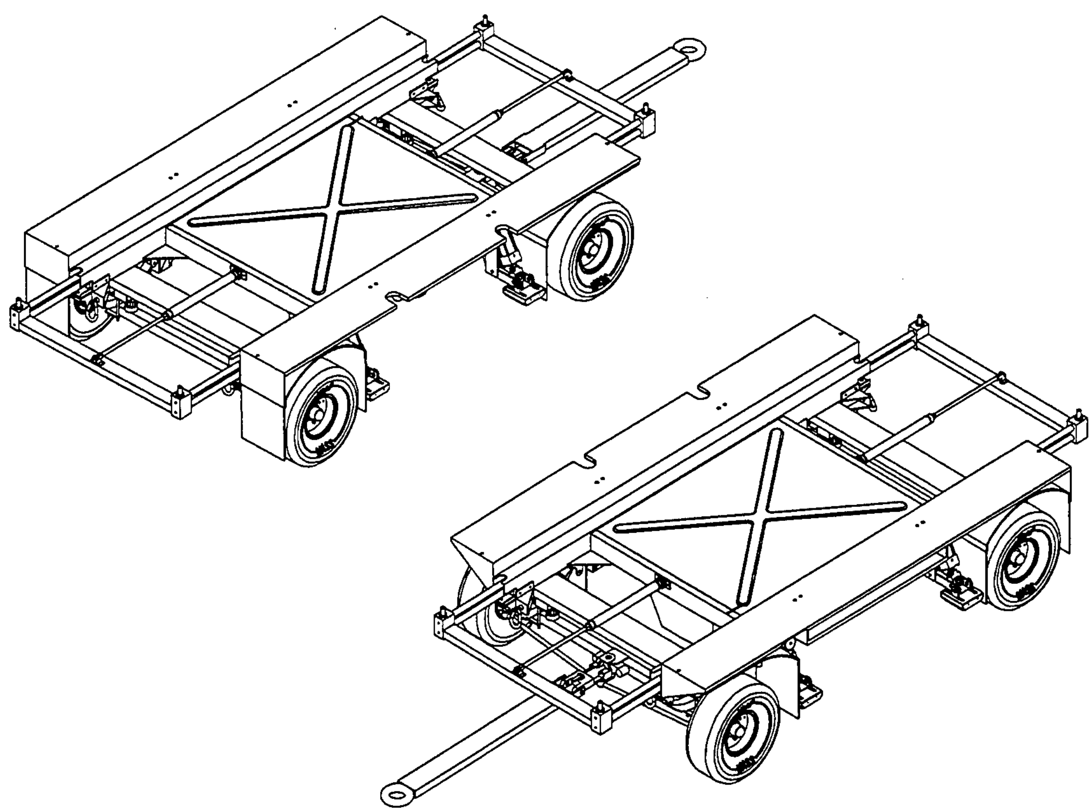


Exhibit 2-47: Chassis Major Components

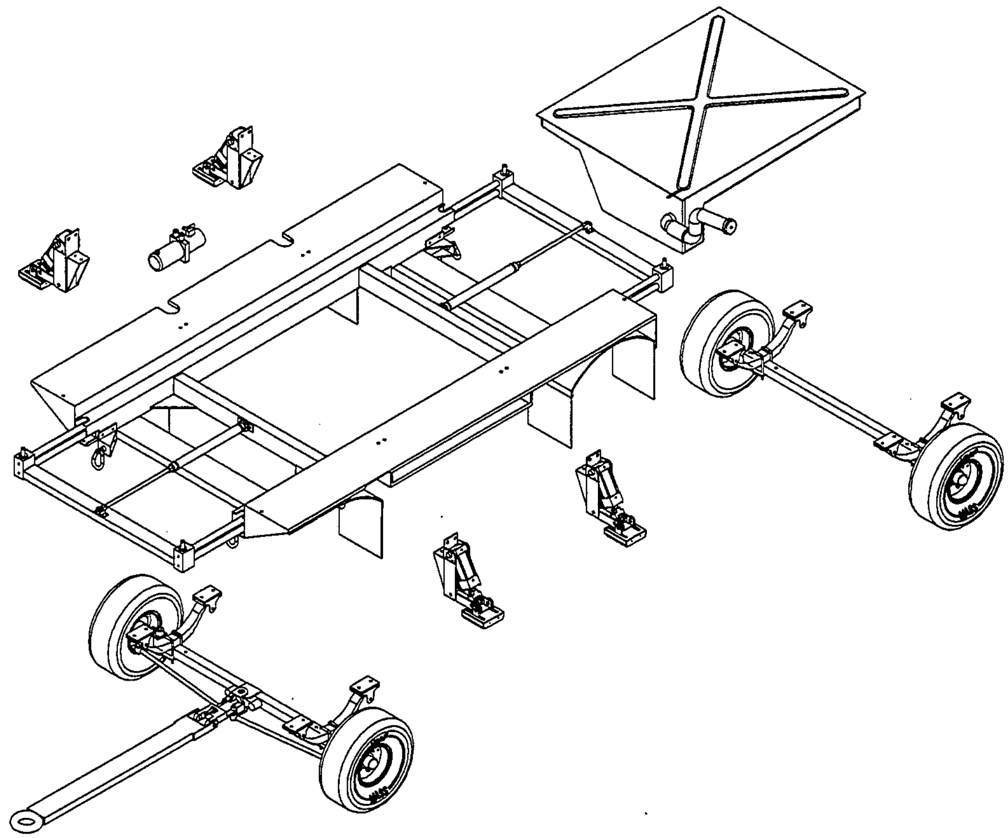


Exhibit 2-48: Chassis Characteristics

Suspension	Four leaf springs, two wheels per axle, a steering mechanism, and a tow bar
Axle	Rated for a load of up to 6,500 lbs per axle; can support twice the static load without damage or permanent deformation
Tires	12 ply mil rated 95 psig; rear axle is equipped with a hand brake
Turning angle of the front axle	$\pm$ 35 degrees; lunette-style two bar
Axle hubs	Sealed, tapered roller bearings

The weldment is comprised of two hollow steel, rectangular beams with a cross section of 4 x 6 inches. There are two transverse members bridging the longitudinal beams to prevent twist. Two additional beams are welded to the bottom of the longitudinal beams to prevent parallellograming on the chassis. All members are made of high-grade steel and are welded to military specifications.

There are two concepts for loading and unloading the modules and also for maintenance which affects the upper weldment. The first method (the end loader) uses two hydraulic cylinders built into the weldment and a pulling bar to separate the modules. The alternative side loader design uses three trays attached to the upper weldment.

Both designs use four leveling or stabilizer feet to support the cart during a module transfer operation. These levelers can be either mechanical or hydraulically operated. Modules are secured to the chassis by using clamps or 3/4 inch bolts (four per module).

3.0 System Analysis

3.1 Introduction

A key task in Delivery Order 0003 was to analyze the improvement over conventional single-function AGE carts that can be provided by MASS system level concepts and individual function modules. Key comparison metrics include:

- Reliability - expressed as mean time between critical failures (MTBF)
- Acquisition Cost - initial cost to procure equipment and place it into service
- Deployability - assessed in terms of deployment footprint and weight and the resulting number of transport aircraft sorties to deploy AGE or MASS equipment at the squadron level
- Operation - defined as consumables (primarily fuel) and personnel
- Maintainability - expressed as annual time and money required to maintain and repair the equipment, based on scheduled maintenance tasks (preventive maintenance), and likely repair tasks (corrective maintenance), given design characteristics such as reliability and accessibility for maintenance and repair tasks
- Life-Cycle Cost - net present value of the projected life time costs to acquire, operate, deploy, maintain, and repair the equipment
- Aircraft Utilization Rates - based on the quantity/availability of AGE or MASS equipment

A squadron level analysis of the AGE and MASS systems has been performed covering these areas (Exhibit 3-1). In the subsections that follow, the analysis methodology is outlined and results are reported. The results are preliminary, with system evaluation in respect to all of these metrics continuing into Delivery Orders 0004 (Brassboard Fabrication) and 0005 (Detailed Design and Analysis).

MASS Modules were packaged together to create the various system concepts as defined in Delivery Order 0002. Six MASS system concepts and two AGE aircraft scenarios (F-15 Diesel and F-15 Gas Turbine) were analyzed for their total life-cycle costs. At the squadron level, the MASS downselected concept is estimated to provide the following distinct advantages:

- 40% reduction in footprint
- 15% increase in reliability
- 20% reduction in total life cycle cost (when compared to the average of the AGE aircraft scenarios)

Details of the methodology and module level analysis results are presented in the subsections that follow.

Future analysis work is expected to focus on the following five issues:

- Definition of realistic deployment scenario regarding distance (miles) and frequency of deployments per year

- Analysis of the reasons for the significant differences between calculated and observed reliability values and determine if factors such as environment, methods of operation, or training issues are causing premature equipment failure; incorporate the findings into the module designs to increase system reliability
- Definition of the anticipated useable life of the modules in years
- Incorporation of maintainability issues into the module level designs
- Update of the acquisition, deployment, operation and maintainability, reliability, and life-cycle cost spreadsheets as the module designs progress

Exhibit 3-1: Squadron Level System Concept Summary

Support Concept	Weight (1,000 Lbs)	Footprint (Ft²)	Mean Time Between Failure (Hrs)	Acquisition ($M)	Deployment($M)[1]	Operation & Maintenance ($M)[2]	Total Life Cycle Cost ($M)	Total Net Present Value ($M)[3]
MASS Selected Concept	123	820	43	3	5	5	13	12
AGE Diesel F-15	122	1,540	36	1	10	4	15	14
AGE Gas Turbine F-15	65	1,310	38	5	8	5	18	17
MASS Advanced Mechanical	134	1,040	34	4	6	6	16	15
MASS Advanced Electrical	239	2,340	37	10	14	8	32	30
MASS UniCart	173	920	39	5	6	8	18	17
MASS BiCart	115	820	41	7	5	7	19	18
MASS TriCart	147	850	33	4	5	6	15	14

[1] Assumes 4 footprint based deployments/year for 30 years on a C-17 transport
[2] Assumes a 30 year functional life
[3] Assumes a 5% Interest Rate

3.2 Reliability

This section summarizes the reliability analyses that were undertaken during Delivery Order 0003 of the MASS program. The focus in the context of early system design was on high-level analyses to support comparative reliability assessments of alternative concepts. As development progresses, the analyses will be updated to account for additional design details. These enhancements are likely to substantially alter the early concept evaluation activities.

3.2.1 Approach

System reliability estimates were developed by combining estimates for individual components into module estimates and then combining the appropriate module types and quantities to create a system using standard methods for reliability assessment. All components are treated on the basis of the "mid-life" period of their life-cycle, with constant failure rates over time. "Infant mortality" and "wear-out" were thus not considered in this analysis. The underlying assumption is that the useful "mid-life" period is long in comparison with the other periods, so the bulk of the product life is well approximated. Such constant failure rate assumptions are commonly used in military reliability assessments. Under this constant failure rate assumption, it follows that the failure rates of individual components may be added to produce an estimate of the system failure rate and that the mean time between failures (MTBF) is the reciprocal of the failure rate. It also follows that the probability of operation during a given time period may be expressed by an exponential distribution.

Listings of the major components of the MASS modules and the AGE carts were developed with the support of the module engineers responsible for the individual concepts. A significant issue for the reliability comparisons arose from the relative maturity of the AGE technology. Since AGE is an existing and well-known system, relatively detailed and accurate listings of all AGE components were possible, while the MASS could be specified only at a level of less detail. It was therefore necessary, in an attempt to develop a fair comparison between MASS and AGE, to abstract the AGE listings to a similar level of detail to that at which the MASS was specified. Although such an approach tends to overestimate the reliability of the AGE system, it permitted a better comparison with the MASS module concepts in their present state of development. As the MASS development continues, more refined component listings will be feasible and, thus, it will be possible to compare the MASS and AGE predictions with greater meaning. This refinement of the MASS component list is also likely to lower the predicted reliability of the MASS components due to the inclusion of a longer (i.e. more detailed) listing of components, each with an associated failure rate estimate.

The component failure rate estimates were developed from available data sources, primarily the Non-Electronic Parts Reliability Database (NPRD) which is maintained by the part of the Air Force Research Laboratory formerly known as Rome Laboratory and Rome Air Development Center (RADC). NPRD is a standard failure rate reference source frequently used in military and commercial reliability assessments. In developing these estimates, two versions of NPRD (NPRD-91[9] and NPRD-95[10]) were used, with NPRD-95 as the primary data source for the MASS.

As the MASS system would be developed using newer technologies than those used in the AGE system, a set of "Technology Adjustment Factors" were developed and used to adjust the tabulated failure rates. These factors are shown in Exhibit 3-2.

3.2.2 Summary of Results

Exhibit 3-3 summarizes the resulting estimates, formatted to facilitate comparison between MASS and AGE at the module/cart level. System level MTBF values are presented at the squadron quantity level in Exhibit 3-1. As discussed above, these estimates represent a comparison between the current MASS concepts and the existing AGE carts abstracted to a similar level of detail based on failure rates from standard reference sources. The estimates shown are of similar magnitude with an improvement projected for the MASS modules. Although MTBF values will decline as additional components are added to the preliminary designs, the current results suggest that the MASS modules will exhibit slightly higher reliability than the corresponding AGE carts. Additional reliability benefits are expected from the MASS system due to the integration of the modules into carts which are more capable than current AGE carts. This can potentially mean fewer modules are required for a given function. This integration benefit has not been analyzed during this initial evaluation, but will be further examined in future delivery orders of the MASS program.

Exhibit 3-2: Technology Adjustment Factors

Level of Technical Improvement	Assumed Reduction in Failure Rate	Assumed Failure Rate Multiplier	Definition
None	0	1.0	Substantially identical technology for AGE and MASS
Minimal	10 - 20%	0.8	Similar technology for AGE and MASS with incremental improvements
Significant	20%-50%	0.5	Substantial technological advancement between AGE and MASS expected to improve equipment reliability significantly
Major	Greater than 50%	0.1	Radical technical improvements expected to result in dramatically improved equipment reliability

Exhibit 3-3: Estimated Mean Time Between Failure (MTBF) Values for MASS and Comparable AGE

MASS		AGE	
Module	**MTBF (Hrs)**	**Cart**	**MTBF (Hrs)**
Diesel Generator	2,500	Diesel Generator	600
Gas Turbine Generator	1,800	Gas Turbine Generator	500
Fuel Cell Generator	3,300	N/A	N/A
Motor-Driven Brayton Cycle Air Cooling	10,200	Air-Cycle Cooling	2,500
Air Cooling (Single Loop)	1,500	Air-Cycle Cooling	2,500
Liquid Cooling (PAO)	1,000	N/A	N/A
Single Electric Powered Hydraulics	1,900	Hydraulic Test Stand	900
Dual Electric Powered Hydraulics	1,300	Hydraulic Test Stand	900
Shaft-Driven Hydraulics	2,800	Hydraulic Test Stand	900
Diesel Powered Hydraulics	1,900	Hydraulic Test Stand	900
Electric Powered Pneumatics	3,700	High Pressure Air Compressor Low Pressure Air Compressor Liquid Nitrogen Nitrogen Cylinder	1,100 2,100 3,700 5,600
Diesel Powered Pneumatics	2,500	High Pressure Air Compressor Low Pressure Air Compressor Liquid Nitrogen Nitrogen Cylinder	1,100 2,100 3,700 5,600
Shaft-Driven Pneumatics	3,700	High Pressure Air Compressor Low Pressure Air Compressor Liquid Nitrogen Nitrogen Cylinder	1,100 2,100 3,700 5,600
Avionics Power Converter	3,300	N/A	N/A
Lights	17,100	Flood Light Cart	1,400

In interpreting these estimates, it should be noted that the MTBF estimates refer to *operating hours*; periods of storage and transport are not reflected in the estimates, but will be evaluated in future work.

To provide a rough calibration against realistic field data, operational AGE reliability data was examined to develop a rough estimate of the actual MTBF values of the AGE equipment. Based on this information, it was estimated that the AGE was performing at a factor of about 30 worse than predicted. The reasons for this variance are unknown but it is theorized that environmental conditions, methods of operation, and training issues are probable causes.

3.3 Life-Cycle Cost Analysis

Analytical work on life-cycle cost (LCC) estimation has included setting up the model and interlinking summary spreadsheets, establishing the framework of operational assumptions, and inputting data for calculating life-cycle costs. LCC estimation will address:

- Acquisition costs
- Deployment costs (including footprint and weight based) over the life-cycle
- Operational costs: consumables (primarily fuel) and personnel
- Maintenance costs: both preventive and corrective

Four LCC computer software models have been reviewed to determine their potential to support the MASS modeling and simulation effort:

- Automated Cost Estimating and Integrated Tools (ACE-IT)
- Cost Analysis Strategy Assessment (CASA)
- Parametric Review of Information for Cost and Evaluation (PRICE)
- Standardization Evaluation Program (STEP)

ACE-IT was selected as the primary LCC Model for MASS because it is a fully validated model and is currently accepted as the industry standard for LCC Models. CASA is not fully validated and therefore was not selected. PRICE (an Acquisition Model) and STEP (an Operation and Supportability Model) together form a third LCC Model, PRICE/STEP. PRICE/STEP are old models which are not commonly used in industry or DoD and therefore were not selected.

After completing several simulation runs with the ACE-IT LCC Model it became apparent that the output format of ACE-IT did not allow for convenient evaluation of MASS at the module level. This was considered essential because evaluations were required at the module level (e.g., diesel generator module vs. gas turbine generator module) to provide support and downselection rationale at the concept level. New summary spreadsheets were then developed based on the ACE-IT LCC Model which would allow direct comparisons at the module level.

Exhibit 3-4 details the life-cycle costs (acquisition, deployment, operation and maintenance, total LCC, and net present value) for the MASS modules and AGE carts based on four deployments per year with a 30-year module/cart life expectancy.

Exhibit 3-4: MASS Module/AGE Cart Life Cycle Costs

MASS Module	Acquisition $	Deployment[1]$	O&M $	Total LCC $
Diesel Generator	73,000	173,000	158,000	404,000
Gas Turbine Generator	438,000	173,000	318,000	929,000
Fuel Cell Generator	329,000	173,000	168,000	670,000
Motor Driven Reverse Brayton Cycle AC	224,000	166,000	72,000	462,000
Single Loop Vapor Comp AC	65,000	166,000	93,000	325,000
Electric Powered Hydraulics (Dual)	149,000	173,000	268,000	590,000
Diesel Powered Hydraulics	164,000	173,000	296,000	633,000
Shaft Driven Hydraulics	144,000	170,000	131,000	444,000
Electric Powered Hydraulics (Single)	87,000	170,000	174,000	430,000
Electric Pneumatics, HP+LP Air, N_2	91,000	166,000	82,000	340,000
Diesel Pneumatics, HP+LP Air, N_2	100,000	166,000	201,000	468,000
Shaft Driven Pneumatics, HP+LP Air, N_2	93,000	166,000	83,000	343,000
Single Loop Vapor Cycle Liquid PAO Chiller	46,000	166,000	161,000	373,000
Avionics Power Converter	60,000	57,000	18,000	134,000
Light	4,000	31,000	3,000	38,000
Chassis	15,000	467,000	32,000	515,000
AGE Cart				
Diesel Generator #A/M 32A-86	39,000	339,000	219,000	597,000
Gas Turbine Generator #A/M 32A-60A	526,000	265,000	342,000	1,133,000
Air Cycle Cooling #A/M 32C-10D	25,000	327,000	52,000	404,000
Air Cooling #MA-3	28,000	420,000	127,000	575,000
Hydraulic Test Stand #TTU-228E	114,000	384,000	481,000	979,000
High Pressure Air Compressor #MC-1A	21,000	239,000	85,000	345,000
Low Pressure Air Compressor #MC-2A	7,000	207,000	44,000	259,000
Liquid Nitrogen #LN-02	27,000	330,000	103,000	460,000
Nitrogen Cylinder #NG-02	8,000	280,000	22,000	310,000
Liquid Cooling #Trielectron PAO	125,000	444,000	259,000	828,000
270 VDC Converter #EPC70-270	48,000	127,000	22,000	197,000
Flood Light Cart #NF-2D	13,000	297,000	107,000	417,000

[1] Assumes 4 Footprint Based deployments/year for 30 years on a C-17 transport

[2] Assumes a 30 year functional life

[3] Assumes a 5% Interest Rate

The MASS modules were then packaged together to create system concepts. Their squadron quantity level total life-cycle costs were summarized in Exhibit 3-1. At the squadron level (24 aircraft per squadron), the MASS downselected concept is estimated to provide:

- 40% reduction in footprint
- 15% increase in reliability
- 20% reduction in total life-cycle cost when compared to the average of the AGE aircraft scenarios

Details of the methodology and module-level analysis results are presented in the subsections that follow.

3.3.1 Acquisition Cost

Exhibit 3-5 displays the acquisition cost for the existing AGE carts and the projected costs for the MASS modules. The data presented in this exhibit is not yet finalized and will be updated as modules are refined and further detailed.

Acquisition costs for the AGE carts were derived from data provided by the Air Combat Command at Langley AFB, VA, including the year in which a particular AGE cart was last procured and its unit cost value (e.g., Diesel Generator cart was last procured in 1985 at a unit cost of $29,162). An inflation adjustment factor obtained from the Air Force Cost Agency was then applied to the unit cost to bring the procurement cost value up to 1997 dollars (e.g., inflation adjustment factor from 1985 to 1997 = 0.748, $29,162/0.748 = $38,987 rounded to $39,000 as seen for the AGE Diesel Generator in Exhibit 3-4).

The MASS cost estimate was prepared by contacting vendors and obtaining price quotations for all major components of each module. In addition, estimates were made for miscellaneous items such as plumbing, electrical, and mechanical hardware. The numerous column headings and their values presented in Exhibit 3-5 were generated by the ACE-IT LCC Model and are typical for equipment such as MASS and AGE. As a check, the MASS and AGE Diesel Generator costs were normalized to a dollars-per-kW value. The 150kW MASS Diesel Generator Module equates to $490/kW while the 70kW AGE Diesel Generator equates to $557/kW. This check confirms that the MASS acquisition costs are within reason and are acceptable for this level of life-cycle cost development. It should be understood that the MASS modules have greater output (higher pressure, flow, kW, etc.) when compared to the AGE carts and the specific cost (defined as the cost/unit output) is lower for MASS than AGE even though the MASS acquisition costs are higher.

3.3.2 Deployment Cost

Module and cart deployment costs were generated based on footprint and weight. Aircraft cost per mile values were obtained from the Air Force Cost Agency for the C-141, C-5, and C-17 transports. It is assumed that the transport aircraft is fully utilized (i.e., maximum footprint or weight capacity is utilized) and that a representative deployment is from the 366th Wing (Mountain Home AFB) to Cairo West which is a total distance of 6,100 miles.

Since the available transport floorspace will be consumed before the cargo weight limit is exceeded, the critical parameter for this type of equipment is footprint not weight. Exhibit 3-6 displays the footprint-based deployment costs for each MASS module and AGE cart. The deployment savings associated with the MASS modules are significant with the result being a reduction in the MASS life-cycle cost.

Exhibit 3-5: Module Acquisition Costs

MASS Module	Piece Part $[1]	Fabrication & Testing $[2]	Delivery $[3]	Engineering Change Orders (= 0.02 x Piece Part $)[4]	Training $ (= 0.011 x Piece Part $)[4]	System Engineering /Program Mgmt (= 0.26 x Piece Part $)[4]	Data (= 0.085 x Piece Part $)[4]	Initial Spares/Repair Parts (= 0.133 x Piece Part $)[4]	Fee (= 5%, applied to ECO, Training, SE/PM, and Data)	G&A (= 10%, applied to ECO, Training, SE/PM, and Data)	Material Handling Overhead (= 1.5%, applied to Piece Part $, and IS/RP)	Plant Wide Overhead (= 110%, applied to ECO, SE/PM, and Data)	Contractor Training Overhead (= 90%, applied to Training Costs)
Diesel Generator	$32,340	$8,000	$1,010	$647	$356	$8,408	$2,749	$4,301	$608	$1,216	$550	$12,985	$320
Gas Turbine Generator	$214,860	$8,500	$850	$4,297	$2,363	$55,864	$18,263	$28,576	$4,039	$8,079	$3,652	$86,266	$2,127
Fuel Cell Generator	$158,360	$12,000	$870	$3,167	$1,742	$41,174	$13,461	$21,062	$2,977	$5,954	$2,691	$63,582	$1,568
Motor Driven Reverse Brayton Cycle AC	$107,360	$9,000	$500	$2,147	$1,181	$27,914	$9,126	$14,279	$2,018	$4,037	$1,825	$43,105	$1,063
Single Loop Vapor Comp AC	$19,879	$10,000	$500	$398	$219	$5,169	$1,690	$2,644	$374	$747	$338	$7,981	$197
Electric Powered Hydraulics (Dual)	$67,303	$13,500	$970	$1,346	$740	$17,499	$5,721	$8,951	$1,265	$2,531	$1,144	$27,022	$666
Diesel Powered Hydraulics	$74,523	$14,500	$780	$1,490	$820	$19,376	$6,334	$9,912	$1,401	$2,802	$1,267	$29,921	$738
Shaft Driven Hydraulics	$65,946	$11,500	$940	$1,319	$725	$17,146	$5,605	$8,771	$1,240	$2,480	$1,121	$26,477	$653
Electric Powered Hydraulics (Single)	$38,600	$9,000	$760	$772	$425	$10,036	$3,281	$5,134	$726	$1,451	$656	$15,498	$382
Electric Pneumatics, HP+LP Air, N_2	$42,000	$6,500	$620	$840	$462	$10,920	$3,570	$5,586	$790	$1,579	$714	$16,863	$416
Diesel Pneumatics, HP+LP Air, N_2	$46,501	$7,000	$720	$930	$512	$12,090	$3,953	$6,185	$874	$1,748	$790	$18,670	$460
Shaft Driven Pneumatics, HP+LP Air, N_2	$43,705	$5,500	$580	$874	$481	$11,363	$3,715	$5,813	$822	$1,643	$743	$17,548	$433
Single Loop Vapor Cycle Liquid PAO Chiller	$21,129	$10,500	$410	$423	$232	$5,494	$1,796	$2,810	$397	$794	$359	$8,483	$209
Avionics Power Converter	$24,550	$10,500	$240	$491	$270	$6,383	$2,087	$3,265	$462	$923	$417	$9,857	$243
Light	$1,500	$500	$60	$30	$17	$390	$128	$200	$28	$56	$25	$602	$15
Chassis	$5,300	$4,200	$600	$106	$58	$1,378	$451	$705	$100	$199	$90	$2,128	$52
AGE Cart													
Diesel Generator													
Gas Turbine Generator													
Air Cycle Cooling													
Air Cooling MA-3													
Hydraulic Test Stand													
High Pressure Air Compressor													
Low Pressure Air Compressor													
Liquid Nitrogen													
Nitrogen Cylinder													
Liquid Cooling													
270 VDC Converter													
Flood Light Cart													

[1] Costs obtained from vendors quotes

[2] Estimated by Module Designers, assumes $50/hour (based on rate from Tobyhanna Depot for similar kind of work).

[3] Assumed delivery from Los Angeles to San Antonio, based on item weight

[4] Factor obtained from Air Force Cost Center

[5] Acquisition Cost $ = Sum of all Columns

The output capacities of the MASS modules (pressure, flow, kW, etc.) are often significantly greater than the AGE carts so the specific weight (defined as the weight/unit output) is significantly lower for MASS. Exhibit 3-7 displays the weight-based deployment costs and illustrates minimal savings due to the moderate weight reductions associated with MASS and the transport aircraft cost structure which is driven by footprint (not weight) for equipment of this footprint-to-weight ratio.

3.3.3 Operation and Maintenance Cost

The operation and maintenance costs are composed of manpower, operating cost (primarily fuel), preventive maintenance, and corrective maintenance.

Manpower costs for AGE were obtained from the Air Force Manpower Standard (AFMS 23FI) which provides the hours required/month for inspection and repair at the cart level. MASS module manpower requirements were then calculated based on the reliability ratio between equivalent MASS modul33es and AGE carts.

Operating costs were defined based on fuel consumption with 4% added for oil and lubrication-related costs.

Exhibit 3-6: Footprint-Based Module Single Deployment Costs

		Transport Cost/Mile					Deployment Cost $[6]		
MASS Module	Footprint (ft^2)	C-141 Aircraft Cost/Mile[1]	C-5 Aircraft Cost/Mile[2]	C-17 Aircraft Cost/Mile[3]	Systems Management $[4]	Military Personnel $[5]	C-141 Deployment Cost[6]	C-5 Deployment Cost[6]	C-17 Deployment Cost[6]
Diesel Generator	26	$0.29	$0.27	$0.21	$80	$106	$1,900	$1,800	$1,400
Gas Turbine Generator	26	$0.29	$0.27	$0.21	$80	$106	$1,900	$1,800	$1,400
Fuel Cell Generator	26	$0.29	$0.27	$0.21	$80	$106	$1,900	$1,800	$1,400
Motor Driven Reverse Brayton Cycle AC	26	$0.29	$0.27	$0.21	$80	$53	$1,900	$1,800	$1,400
Single Loop Vapor Comp AC	26	$0.29	$0.27	$0.21	$80	$53	$1,900	$1,800	$1,400
Electric Powered Hydraulics (Dual)	26	$0.29	$0.27	$0.21	$80	$106	$1,900	$1,800	$1,400
Diesel Powered Hydraulics	26	$0.29	$0.27	$0.21	$80	$106	$1,900	$1,800	$1,400
Shaft Driven Hydraulics	26	$0.29	$0.27	$0.21	$80	$80	$1,900	$1,800	$1,400
Electric Powered Hydraulics (Single)	26	$0.29	$0.27	$0.21	$80	$80	$1,900	$1,800	$1,400
Electric Pneumatics, HP+LP Air, N_2	26	$0.29	$0.27	$0.21	$80	$53	$1,900	$1,800	$1,400
Diesel Pneumatics, HP+LP Air, N_2	26	$0.29	$0.27	$0.21	$80	$53	$1,900	$1,800	$1,400
Shaft Driven Pneumatics, HP+LP Air, N_2	26	$0.29	$0.27	$0.21	$80	$53	$1,900	$1,800	$1,400
Single Loop Vapor Cycle Liquid PAO Chill	26	$0.29	$0.27	$0.21	$80	$53	$1,900	$1,800	$1,400
Avionics Power Converter	7	$0.08	$0.08	$0.06	$80	$35	$600	$600	$500
Light	3	$0.03	$0.03	$0.02	$80	$35	$300	$300	$300
Chassis	77	$0.86	$0.80	$0.62	$80	$53	$5,400	$5,000	$3,900
AGE Cart									
Diesel Generator	54	$0.61	$0.56	$0.43	$80	$106	$3,900	$3,600	$2,800
Gas Turbine Generator	42	$0.47	$0.43	$0.34	$80	$80	$3,000	$2,800	$2,200
Air Cycle Cooling	53	$0.59	$0.55	$0.42	$80	$53	$3,800	$3,500	$2,700
Air Cooling MA-3	69	$0.71	$0.55	$0.55	$80	$53	$4,500	$3,500	$3,500
Hydraulic Test Stand	61	$0.68	$0.63	$0.49	$80	$142	$4,400	$4,100	$3,200
High Pressure Air Compressor	38	$0.43	$0.39	$0.30	$80	$53	$2,700	$2,500	$2,000
Low Pressure Air Compressor	33	$0.37	$0.34	$0.26	$80	$35	$2,400	$2,200	$1,700
Liquid Nitrogen	53	$0.59	$0.55	$0.42	$80	$80	$3,800	$3,500	$2,700
Nitrogen Cylinder	45	$0.50	$0.46	$0.36	$80	$53	$3,200	$3,000	$2,300
Liquid Cooling	73	$0.75	$0.58	$0.58	$80	$53	$4,700	$3,700	$3,700
270 VDC Converter	19	$0.15	$0.00	$0.15	$80	$53	$1,100	$100	$1,100
Flood Light Cart	48	$0.54	$0.50	$0.38	$80	$53	$3,400	$3,200	$2,500

1 Assumes fully utilized aircraft @ $0.0112/mile/$ft^2$ (calculated from Dwight Pavek 10-14-97 fax) in FY 96 $$

2 Assumes fully utilized aircraft @ $0.0103/mile/$ft^2$ (calculated from Dwight Pavek 10-14-97 fax) in FY 96 $$

3 Assumes fully utilized aircraft @ $0.0080/mile/$ft^2$ (calculated from Dwight Pavek 10-14-97 fax) in FY 96 $$

4 Assumes $80 fixed cost for paperwork/distribution

5 Based on weight, assumes enlisted personnel at $17.70/hour x # of hours

6 Assumes a single deployment of the 366th Wing to Cairo West (6,100 miles)

Exhibit 3-7: Weight Based Module Single Deployment Costs

		Transport Cost/Mile						Deployment Cost $[7]			
MASS Module	Weight (Pounds)	C-141 Aircraft Cost/Mile[1]	C-5 Aircraft Cost/Mile[2]	C-17 Aircraft Cost/Mile[3]	Shipboard Cost/Mile[4]	Systems Management $[5]	Military Personnel $[6]	C-141 Deployment Cost[7]	C-5 Deployment Cost[7]	C-17 Deployment Cost[7]	Shipboard Deployment Cost[7,8]
Diesel Generator	3,650	$0.82	$0.68	$0.75	$0.01	$80	$106	$5,200	$4,300	$4,700	$700
Gas Turbine Generator	2,650	$0.60	$0.49	$0.54	$0.00	$80	$106	$3,800	$3,200	$3,500	$700
Fuel Cell Generator	4,980	$1.13	$0.93	$1.02	$0.01	$80	$106	$7,100	$5,800	$6,400	$700
Motor Driven Reverse Brayton Cycle AC	2,380	$0.54	$0.44	$0.49	$0.00	$80	$53	$3,400	$2,800	$3,100	$700
Single Loop Vapor Comp AC	1,490	$0.34	$0.28	$0.31	$0.00	$80	$53	$2,200	$1,800	$2,000	$600
Electric Powered Hydraulics (Dual)	4,690	$1.06	$0.87	$0.96	$0.01	$80	$106	$6,600	$5,500	$6,000	$700
Diesel Powered Hydraulics	4,860	$1.10	$0.90	$0.99	$0.01	$80	$106	$6,900	$5,700	$6,300	$700
Shaft Driven Hydraulics	3,120	$0.71	$0.58	$0.64	$0.01	$80	$80	$4,500	$3,700	$4,100	$700
Electric Powered Hydraulics (Single)	2,740	$0.62	$0.51	$0.56	$0.01	$80	$80	$3,900	$3,300	$3,600	$700
Electric Pneumatics, HP+LP Air, N_2	2,270	$0.51	$0.42	$0.46	$0.00	$80	$53	$3,300	$2,700	$3,000	$700
Diesel Pneumatics, HP+LP Air, N_2	2,560	$0.58	$0.48	$0.52	$0.00	$80	$53	$3,700	$3,000	$3,300	$700
Shaft Driven Pneumatics, HP+LP Air, N_2	1,960	$0.44	$0.36	$0.40	$0.00	$80	$53	$2,800	$2,400	$2,600	$700
Single Loop Vapor Cycle Liquid PAO Chil	2,180	$0.49	$0.40	$0.44	$0.00	$80	$53	$3,100	$2,600	$2,800	$700
Avionics Power Converter	1,070	$0.24	$0.20	$0.22	$0.00	$80	$35	$1,600	$1,300	$1,400	$600
Light	100	$0.02	$0.02	$0.02	$0.00	$80	$35	$300	$200	$200	$600
Chassis	2,400	$0.54	$0.45	$0.49	$0.00	$80	$53	$3,400	$2,900	$3,100	$700
AGE Cart											
Diesel Generator	5,600	$1.27	$1.04	$1.15	$0.01	$80	$106	$7,900	$6,500	$7,200	$700
Gas Turbine Generator	3,100	$0.70	$0.58	$0.63	$0.01	$80	$80	$4,400	$3,700	$4,000	$700
Air Cycle Cooling	1,400	$0.32	$0.26	$0.29	$0.00	$80	$53	$2,100	$1,700	$1,900	$600
Air Cooling MA-3	6,000	$1.36	$1.12	$1.23	$0.01	$80	$53	$8,400	$6,900	$7,600	$700
Hydraulic Test Stand	7,800	$1.76	$1.45	$1.60	$0.01	$80	$142	$11,000	$9,100	$10,000	$800
High Pressure Air Compressor	2,000	$0.45	$0.37	$0.41	$0.00	$80	$53	$2,900	$2,400	$2,600	$700
Low Pressure Air Compressor	800	$0.18	$0.15	$0.16	$0.00	$80	$35	$1,200	$1,000	$1,100	$600
Liquid Nitrogen	3,400	$0.77	$0.63	$0.70	$0.01	$80	$80	$4,800	$4,000	$4,400	$700
Nitrogen Cylinder	1,500	$0.34	$0.28	$0.31	$0.00	$80	$53	$2,200	$1,800	$2,000	$700
Liquid Cooling	6,500	$1.47	$1.21	$1.33	$0.01	$80	$53	$9,100	$7,500	$8,200	$700
270 VDC Converter	1,240	$0.28	$0.23	$0.25	$0.00	$80	$53	$1,800	$1,500	$1,700	$600
Flood Light Cart	2,300	$0.52	$0.43	$0.47	$0.00	$80	$53	$3,300	$2,700	$3,000	$700

[1] Assumes fully utilized aircraft @ $0.452/cargo ton/mile (from Dwight Pavek 10-14-97 fax) in FY 96 $$

[2] Assumes fully utilized aircraft @ $0.372/cargo ton/mile (from Dwight Pavek 10-14-97 fax) in FY 96 $$

[3] Assumes fully utilized aircraft @ $0.409/cargo ton/mile (from Dwight Pavek 10-14-97 fax) in FY 96 $$

[4] Assumes fully utilized ship @ $0.0037 average/cargo ton/mile (from Dwight Pavek 10-14-97 fax) in FY 96 $$

[5] Assumes $80 fixed cost for paperwork/distribution

[6] Based on weight, assumes enlisted personnel at $17.70/hour x # of hours

[7] Assumes a single deployment of the 366th Wing to Cairo West (6,100 miles)

[8] Assumes a 200 mile round trip truck delivery from Air Force Base to Shipping Terminal to Air Force Base (= $500 total)

Preventive and corrective maintenance costs are each comprised of parts and waste disposal costs. The parts and quantities associated with preventive maintenance (PM) were itemized from the equipment manufacturers recommended maintenance intervals (e.g., filter changes, coolant changes, etc.). Part costs were then obtained from the manufacturers and averaged to an annual basis. The parts associated with corrective maintenance (CM) were generated based on component reliability (light bulbs, batteries, etc.) and were also averaged to an annual basis. Waste disposal costs for both PM and CM activities were quantified and costed based on current Massachusetts regulatory laws. Each state has different hazardous waste regulatory laws with

Massachusetts and California being two of the most progressive. It is assumed that all states will eventually regulate the wastes which are currently regulated by Massachusetts law.

Exhibit 3-8 displays the annual Operation and Maintenance costs associated with each MASS module and AGE cart.

Exhibit 3-8: Annual Module Operation & Maintenance Costs

			Operating Cost		Preventive Maintenance			Corrective Maintenance			
MASS Module	MASS/AGE Mechanic Hours/Module or Cart[1]	MASS/AGE Mechanic Cost per Module/Cart $[2]	Fuel Consumption (gallons/hour)	Fuel, Oil, & Lubricant Cost $[3]	Maintenance Parts $[4]	Waste Disposal $[5]	Preventive Maintenance Cost $[6]	Maintenance Parts $[7]	Waste Disposal $[8]	Corrective Maintenance Cost $[9]	Operation & Maintenance Cost $[10]
Diesel Generator	80	1,300	18	$3,400	$140	$30	$170	$290	$8	$300	$5,300
Gas Turbine Generator	70	1,200	34	$6,500	$360	$20	$380	$2,470	$6	$2,470	$10,600
Fuel Cell Generator	60	1,100	17	$3,300	$200	$20	$220	$990	$6	$990	$5,600
Motor Driven Reverse Brayton Cycle AC	120	2,200	0	$0	$30	$0	$30	$220	$0	$220	$2,400
Single Loop Vapor Comp AC	150	2,600	0	$0	$50	$0	$50	$330	$0	$330	$3,000
Electric Powered Hydraulics (Dual)	390	6,900	0	$0	$720	$150	$870	$1,110	$44	$1,150	$8,900
Diesel Powered Hydraulics	270	4,800	18	$3,400	$650	$100	$750	$850	$29	$880	$9,900
Shaft Driven Hydraulics	190	3,300	0	$0	$430	$80	$510	$510	$24	$540	$4,400
Electric Powered Hydraulics (Single)	280	4,900	0	$0	$360	$70	$430	$460	$22	$480	$5,800
Electric Pneumatics, HP+LP Air, N_2	130	2,400	0	$0	$120	$10	$130	$240	$2	$240	$2,700
Diesel Pneumatics, HP+LP Air, N_2	140	2,500	19	$3,600	$180	$20	$200	$410	$5	$410	$6,700
Shaft Driven Pneumatics, HP+LP Air, N_2	130	2,400	0	$0	$140	$10	$150	$250	$3	$250	$2,800
Single Loop Vapor Cycle Liquid PAO Chil	220	4,000	0	$0	$750	$140	$890	$530	$43	$580	$5,400
Avionics Power Converter	10	200	0	$0	$190	$0	$190	$180	$0	$180	$600
Light	10	100	0	$0	$0	$0	$0	$0	$0	$0	$100
Chassis	50	800	0	$0	$120	$0	$120	$150	$1	$150	$1,100
AGE Cart											
Diesel Generator	300	5,300	6	$1,100	$180	$30	$210	$610	$9	$620	$7,300
Gas Turbine Generator	230	4,000	11	$2,100	$450	$20	$470	$4,810	$7	$4,820	$11,400
Air Cycle Cooling	90	1,600	0	$0	$40	$0	$40	$100	$0	$100	$1,700
Air Cooling MA-3	220	3,900	0	$0	$60	$0	$60	$230	$0	$230	$4,200
Hydraulic Test Stand	610	10,900	15	$2,800	$810	$120	$930	$1,330	$37	$1,370	$16,000
High Pressure Air Compressor	120	2,100	2	$400	$110	$10	$120	$190	$3	$190	$2,800
Low Pressure Air Compressor	70	1,200	1	$200	$90	$10	$100	$30	$3	$40	$1,500
Liquid Nitrogen	180	3,300	0	$0	$80	$0	$80	$70	$0	$70	$3,400
Nitrogen Cylinder	40	700	0	$0	$10	$0	$10	$10	$0	$10	$700
Liquid Cooling	340	5,900	0	$0	$900	$170	$1,070	$1,570	$51	$1,630	$8,600
270 VDC Converter	20	300	0	$0	$230	$0	$230	$180	$0	$180	$700
Flood Light Cart	170	2,900	1	$200	$210	$20	$230	$190	$5	$190	$3,600

[1] AGE hours taken from the Air Force Manpower Standard (AFMS 23FI) dated 15 April 1996 (for Inspection & Repair), MASS hours are reliability based

[2] Based on Mechanic hours/year/Module or Cart x $17.70/hour

[3] Based on 200 operating hours per year x fuel consumption/hr x $0.91/gallon fuel cost, plus 4% for oil and lubrication cost.

[4] Determined by module designers for MASS, AGE values are multiplied by technology adjustment factor

[5] Quantities were calculated by module designers, cost was supplied by R. Morrill (ADL) for MA.

[6] Equals Maintenance Parts $ + Waste Disposal $

[7] Based on piece parts acquisition cost and reliability evaluation

[8] Assumed cost was 0.3 x Preventive Maintenance Waste Disposal $

[9] Equals Maintenance Parts $ + Waste Disposal $

[10] Equals MASS/AGE Mechanic Annual Cost $ + Fuel, Oil, & Lubricant Cost $ + Annual Preventive Maintenance Cost $ + Annual Corrective Maintenance Cost $

3.4 Utilization

3.4.1 Description of Work

Using the utilization simulation program described in the D0002 report, further simulations were conducted to change the squadron size and to include F-15 data. At the request of the IPT, the squadron size was increased from 16 to 24 planes (without iincreasing the amount of AGE per squadron). In the simulations, the squadron consists of a 24 plane ready line. F-15 task list data was obtained by Modern Technologies Corporation from the CAMS database.

3.4.2 Simulation

All concepts were analyzed using:

- F-16 and F-15 Task list data
- War-time scenario (2 hours in Air/6 hours on Land)
- One ready line of 24 planes
- 2, 4, 5, 6, 7, or 8 Complete MASS systems

Two AGE cases were analyzed in comparison to MASS: One standard Table of Allowance (less lighting), and one with half the standard Table of Allowance (TOA) as shown in Exhibit 3-9.

Exhibit 3-9: AGE Table of Allowances Used in Simulation

Table of Allow ances used in Simulation		
AGE Cart	Quantity (1 TOA)	Quantity (1/2 TOA)
Gas Turbine Generator #A/M 32A-60A	8	4
Air Cycle Cooling #A/M 32C-10D	8	4
Hyrdraulic Test Stand #TTU-228E	2	1
High Pressure Air Compressor #MC-1A	2	1
Low Pressure Air Compressor #MC-2A	8	4
Nitrogen Cyclinder #NG-02	2	1

3.4.3 Simulation Results

The analysis results of the UniCart, BiCart, TriCart, and AGE systems are shown in Exhibits 3-10 and 3-11. The results show that as the numbers of systems increases, the sortie rate increases until it reaches an asymptote as the sortie rate approaches 100%. To achieve the same utilization (sortie rate) of the existing AGE TOA, various quantities of MASS systems are required. The comparison of these various quantities is shown in Exhibit 3-12. The Bicart concept requires five complete systems to achieve at sortie rate of 90.4% for F-15 and 97.7% for F-16 simulations. The Tricart concept requires six complete systems to achieve at sortie rate of 96.4% for F-15 and 97.3% for F-16 simulations. The Unicart concept requires six complete systems to achieve a sortie rate of 90.4% for F-15 and seven complete systems to achieve a sortie rate of 97.7% for F-16 simulations.

Exhibit 3-10: F-15 Utilization Summary

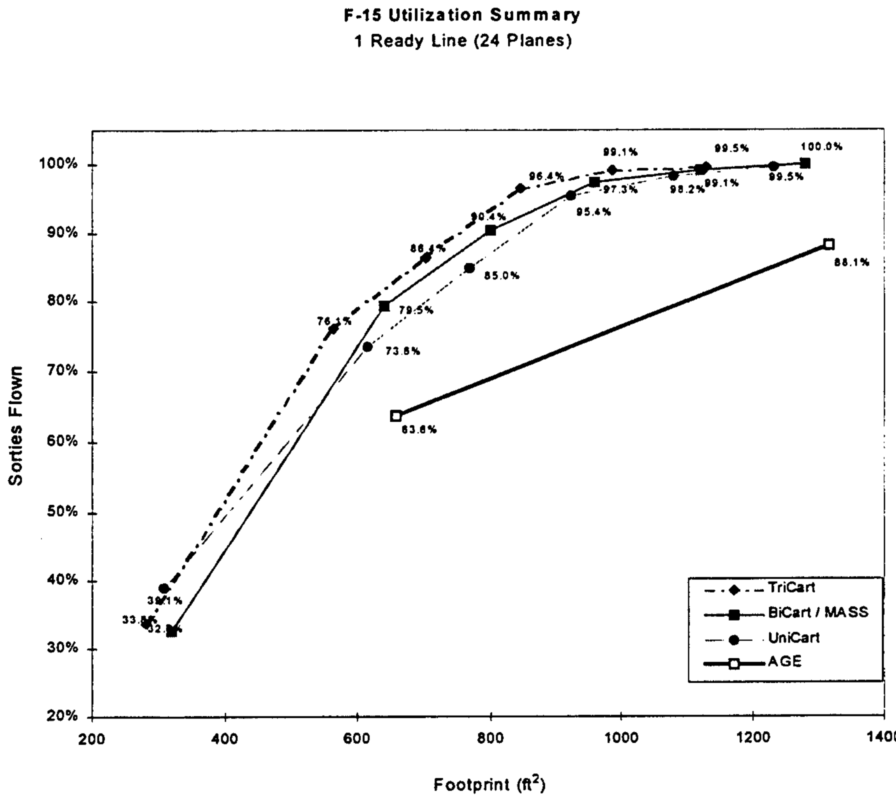


Exhibit 3-11: F-16 Utilization Summary

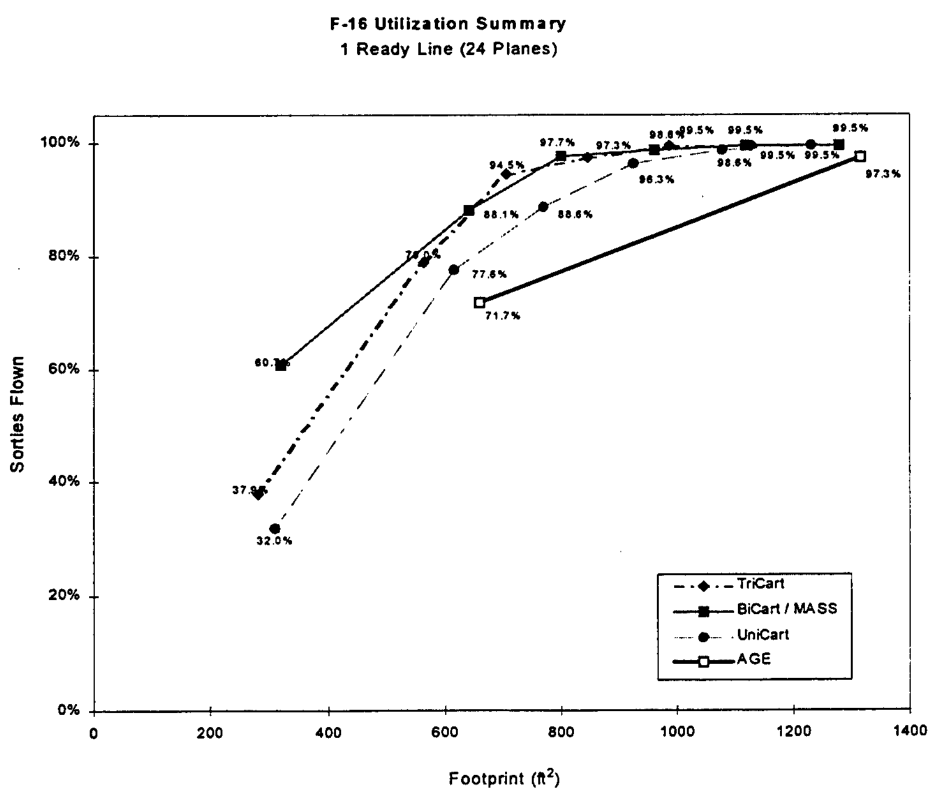
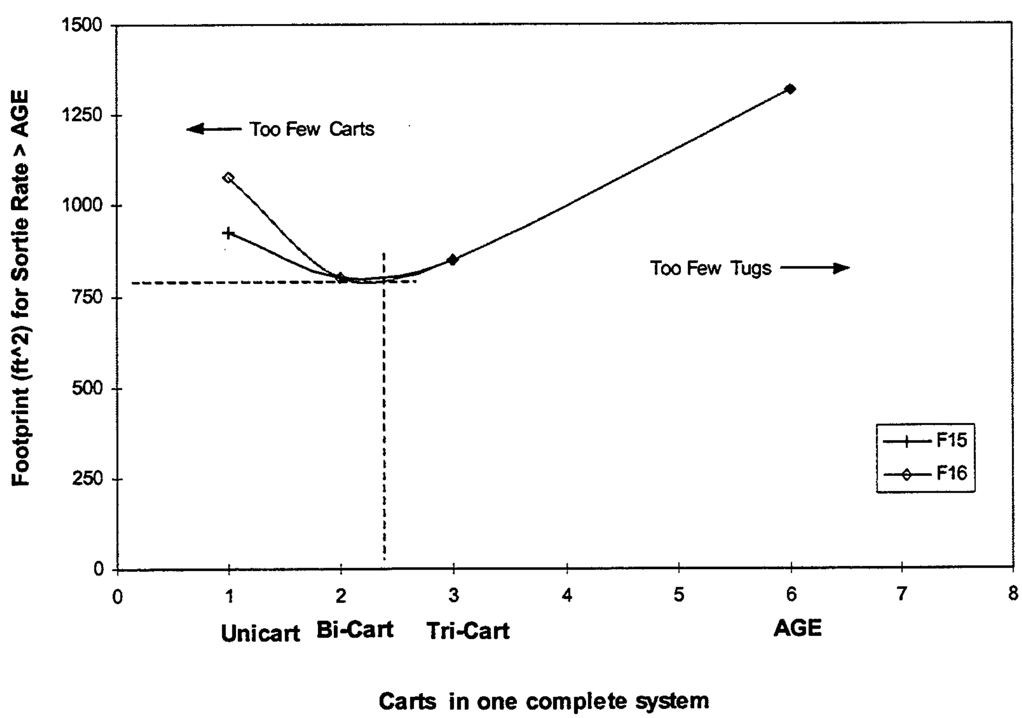


Exhibit 3-12: System Comparison

	F-15 One Readyline 24 Planes			F-16 One Ready Line 24 Planes		
System	# of Systems	Sortie Rate	Footprint ft^2	# of Systems	Sortie Rate	Footprint ft^2
AGE	1 TOA	87.0%	1316	1 TOA	97.3%	1316
Bicart	5	90.4%	800	5	97.7%	800
Tricart	6	96.4%	846	6	97.3%	846
Unicart	6	95.4%	924	7	98.6%	1078

The resulting data was plotted to compare the required footprint of the systems against the number of carts in a system. As shown in Exhibit 3-13, the required footprint for the Unicart system (one cart per system) is between 925 and 1075 ft^2. As the number of carts per system increases, the footprint requirement decreases. For the BiCart and TriCart systems, the required footprint drops to the 800 to 850 ft^2 range. Further increases in cart per system numbers, however, increases footprint until the existing AGE footprint is reached. This indicates that there is an optimum value of carts in a system to meet the necessary number of carts to service all aircraft as well as not exceed the number of tugs available. From these simulations the value that meets these requirements is around 2.5. Therefore a modified bicart or tricart system is the optimum system for MASS.

Exhibit 3-13: Equivalent Sortie Rate Footprint vs. Number of Carts in System



3.4.4 Simulation Program Modification

The simulation program used was designed to compare various MASS concepts based on a variable chassis size (i.e., slots per frame). To analyze concepts developed at ADL, the program was modified to meet the necessary requirements of each concept. Although all of the concepts included the chassis which houses a varying number of modules, the correlation between MASS concepts and the slots per frame variable did not work well because of the interdependence of the modules. Each concept, therefore, necessitated a unique setup requiring modification of several input files. The "frames" were populated with the required modules and the aircraft task list was modified to produce the required module dependencies. For example, if a concept had one chassis and five systems were analyzed, only five frames were populated with modules; similarly, a two chassis concept would have ten populated. The results from these analyses produced a good "A vs. B vs. C" comparison of the different concepts with the same number of 'systems'. This program as written would not allow the user to determine the optimum mix of frames for the multi-frame concepts. To determine the best ratio of A to B chassis in a two frame concept, a new program would need to be created that included a concise task list for all aircraft to be serviced.

4.0 References

[1] Arthur D. Little, Inc. *Modular Aircraft Support System (MASS), Concept Exploration Final Report to Wright-Patterson Air Force Base.* Second Edition. Cambridge, MA: March 11, 1998.

[2] Arthur D. Little, Inc. *Modular Aircraft Support System (MASS), Concept Exploration Final Report to Wright-Patterson Air Force Base.* Second Edition. Cambridge, MA: March 11, 1998.

[3] Arthur D. Little, Inc. *Modular Aircraft Support System (MASS), Concept Exploration Final Report to Wright-Patterson Air Force Base.* Second Edition. Cambridge, MA: March 11, 1998.

[4] Arthur D. Little, Inc. *Modular Aircraft Support System (MASS), Concept Exploration Final Report to Wright-Patterson Air Force Base.* Second Edition. Cambridge, MA: March 11, 1998.

[5] Arthur D. Little, Inc. *Modular Aircraft Support System (MASS), Concept Exploration Final Report to Wright-Patterson Air Force Base.* Second Edition. Cambridge, MA: March 11, 1998.

[6] Arthur D. Little, Inc. *Modular Aircraft Support System (MASS), Concept Exploration Final Report to Wright-Patterson Air Force Base.* Second Edition. Cambridge, MA: March 11, 1998.

[7] Arthur D. Little, Inc. *Modular Aircraft Support System (MASS), Concept Exploration Final Report to Wright-Patterson Air Force Base.* Second Edition. Cambridge, MA: March 11, 1998.

[8] Department of the Air Force. *Pre-proposal conference minutes for the hydraulic test stands, triple system (diesel and electric) and dual system (diesel and electric) [NTS-2/3 D/E], draft solicitation F41608-98-R-13005.* Memorandum for prospective bidders, Pre-proposal Conference, March 27, 1998, Kelly Air Force Base, San Antonio, Texas.

[9] *Nonelectronic Parts Reliability Data - 1991.* Prepared by Denson, Chandler, Crowell, Wanner, for Reliability Analysis Center. Rome, NY: May, 1991.

[10] *Nonelectronic Parts Reliability Data - 1995.* Prepared by Denson, Chandler, Crowell, Clark, Jaworski, for Reliability Analysis Center. Rome, NY: July, 1995.

[11] Arthur D. Little, Inc. *Modular Aircraft Support System (MASS), Concept Exploration Final Report to Wright-Patterson Air Force Base.* Second Edition. Cambridge, MA: March 11, 1998.

5.0 Acronyms/Abbreviations

°F	Degrees Fahrenheit, temperature measurement
AC	Air conditioning: Alternating Current
ACE-IT	Automated Cost Estimating and Integrated Tools
ADL	Arthur D. Little, Inc.
AFB	Air Force Base
AGE	Aerospace Ground Equipment
AGPU	Aviation Ground Power Unit
APC	Avionics Power Converter
CAMS	Computer Aided Maintenance Scheduling
CARB	California Air Resource Board
CASA	Cost Analysis Strategy Assessment
CFM	Cubic feet/minute
CM	Corrective Maintenance
COTS	Commercial off-the-shelf
DoD	Department of Defense
DB	Dry bulb, relative humidity measurement
DC	Direct Current
DSP	Digital Signal Processor
EEV	Electronic Expansion Valve
FED	Field Emission Display
$ft/ft^2/ft^3$	Foot(feet)/squared/cubed
gpm	Gallon per minute, flow measurement, liquid
Hz	Hertz, frequency measurement
IPT	Integrated Product Team
JSF	Joint Strike Fighter aircraft
kVA	Kilovolt-amperes
kW	Kilowatt
lbs	Pounds(s)
LCC	Life-Cycle Cost
LCD	Liquid Crystal Display
MASS	Modular Aircraft Support System
MTBF	Mean Time Between Failures
MTC	Modern Technologies Corporation
N/A	Not applicable
NPV	Net Present Value
NPRD	Non-Electric Parts Reliability Database
PAO	Polyalphaolefin, Heat Transfer Fluid
PEBB	Power Electronic Building Blocks
PF	Parallel-Flow
PM	Preventive Maintenance

ppm	Parts per million
psia	Pounds per square inch absolute; pressure scale
psig	Pounds per square inch gage; pressure scale
QFD	Quality Function Deployment
rpm	Revolutions per minute
scf	Standard cubic feet
scfm	Standard cubic feet per minute, flow measurement, gas
SOW	Statement of Work
TBD	To be determined/defined
TOA	Table of Allowances
USA	United States Army
USAF	United States Air Force
USN	United States Navy
VAC	Volts, Alternating Current
VDC	Volts, Direct Current
WB	Wet bulb, relative humidity measurement