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# UNITED STATES AIR FORCE RESEARCH LABORATORY

## Modular Aircraft Support System (MASS) Proof-of-Concept Demonstrator Field Demonstration


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Acorn Park
Cambridge, MA 02140


October 2001

Final Report for the Period October 2000 to October 2001

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FOR THE COMMANDER

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The Modular Aircraft Support System (MASS) program is part of an effort to reduce the deployment footprint and increase the supportability of aerospace ground equipment (AGE). The MASS program was initiated by the United States Air Force Research Laboratory (AFRL). The contract directed Arthur D. Little, Inc. (ADL) to develop and evaluate concepts, and design, fabricate and test five MASS modules (and a chassis) in order to demonstrate the key features of the MASS design. The MASS Cart met all performance requirements during laboratory testing at ADL. The MASS program concluded with the successful demonstration of the MASS Cart at Edwards AFB, CA, using actual aircraft (F-15, F-16, B-52). This report, the Final Report for the field demonstration (Delivery Order 0012), also summarizes the other Delivery Orders involving the MASS cart.

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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, CDRL A001, for the Modular Aircraft Support System (MASS) Proof-of-Concept Demonstrator Field Demonstration authorized by Delivery Order 0012 under contract F41624-96-D-5002/0012. All work under the MASS contract is performed for the Air Force Research Laboratory, Wright-Patterson AFB, OH, as guided and directed by the MASS Program Monitors, Matthew Tracy (December 1996 – March 2001), Captain David Sanford (April – July 2001), and Igors Skriblis (August – October 2001).

The key technical personnel who participated in this effort and their areas of responsibility are as follows:

| | | |
|---|---|---|
| Michael Bryant | Arthur D. Little, Inc. | Component Procurement and Testing |
| Nelson Carbonell | Arthur D. Little, Inc. | Chassis and Module Frames |
| Allan Chertok | Magnecon | Avionics Power Converter and Diesel Generator Modules |
| David Hablanian | Arthur D. Little, Inc. | DO12 Program Manager |
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| William Murphy | Arthur D. Little, Inc. | Air and Liquid Cooling Modules |

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## EXECUTIVE SUMMARY

The United States Air Force (USAF) has embarked on a large effort to change its strategic capabilities. Global political and defense budgetary changes have radically altered USAF requirements and capabilities. In the past decade, the Pentagon eliminated more than 30 of the 50 bases the USAF operated overseas and over one-third of its personnel. At the same time, a fourfold increase in "temporary" deployments to hot spots and in support of humanitarian emergencies has taxed the capabilities of the USAF. To help alleviate the effect on resources and deal with the increase in missions, the USAF is implementing the Expeditionary Aerospace Forces (EAF) concept. Major General Donald Cook, Director for Expeditionary Aerospace Force Implementation, has stated, "We will be in deployment mode – expeditionary if you will – from now on." He is also quoted as saying, "Therefore we need to be very mobile, we need to be expeditionary, we need to be responsive to provide the national command authority with that air capability that all the [theater commanders in chief require." [1]

Aerospace ground equipment (AGE) is the single largest part of an aviation deployment package (not including fuel or ammunition). The electrical generator, air conditioning, hydraulic, pneumatic, and lighting carts to support a squadron of F-16 aircraft take up over 25% of the total airlift required. This does not include the spares, tools, technical orders, or personnel required to maintain this equipment. Any effort to meet the requirements of the EAF concept requires a drastic downsizing in the AGE deployment footprint. In this report, we discuss how the USAF and its contractor, Arthur D. Little, used the system-of-systems approach to research and develop an advanced AGE concept. This concept can support legacy and future weapon systems and reduce the deployment footprint and the life-cycle costs for a squadron or suite of equipment.

### Approach [2]

Typically, the USAF uses two types of organizations to procure AGE. The first organization is responsible for defining, developing, and procuring equipment to meet the needs of multiple aircraft (common AGE). This organization looks at particular utility requirements (e.g., electrical power) across multiple aircraft to determine the best potential solution based on the acquisition cost to the USAF. The result is a steady stream of single-function carts with very few multi-function carts interspersed. The second organization is responsible for determining the equipment needs for a specific weapon system across all the utilities. This organization typically looks for common AGE solutions prior to defining, developing and procuring equipment that meets only their weapon system requirements (peculiar AGE). For recent weapon systems (e.g., F-15 and F-16) common AGE options have met most of their needs. However, for those requirements that compel peculiar AGE, the organization typically looks for the most cost-effective solution, which usually results in additional single-function carts.

As an outside organization, the Air Force Research Laboratory (AFRL) was free to explore outside the box of the typical AGE acquisition organizations. AFRL took a macro-level view of the situation and realized that many of the current and upcoming issues facing the AGE community could be resolved through a system-of-systems approach to the AGE suite. This approach allowed AFRL to combine the best aspects of common AGE and peculiar AGE procurements. The result was the definition of the Modular Aircraft Support System (MASS) concept. This report describes the MASS concept at the system level and how the AFRL and Arthur D. Little determined which technologies could be used cost effectively to overcome issues raised by the modular system-of-systems result.

Arthur D. Little's review of the current AGE suite quickly pointed to areas where new and emerging technologies could be brought to bear to solve a myriad of issues (e.g., environmental pollution, life-cycle costs, and deployment footprint). It also showed that there were multiple common subsystems across the carts that were minimally standardized. However, implementing the changes was not simple. Exhibit ES-1 indicates the quantity of equipment required to support an F-16 aircraft during maintenance. Depending on the utility and performance of each cart, they can weigh anywhere from less than ½ to over three tons. The power requirements ranged from less than 30 to more than 250 horsepower. Obviously, subsystems that performed the same type of function may be radically different with such a wide range of requirements.

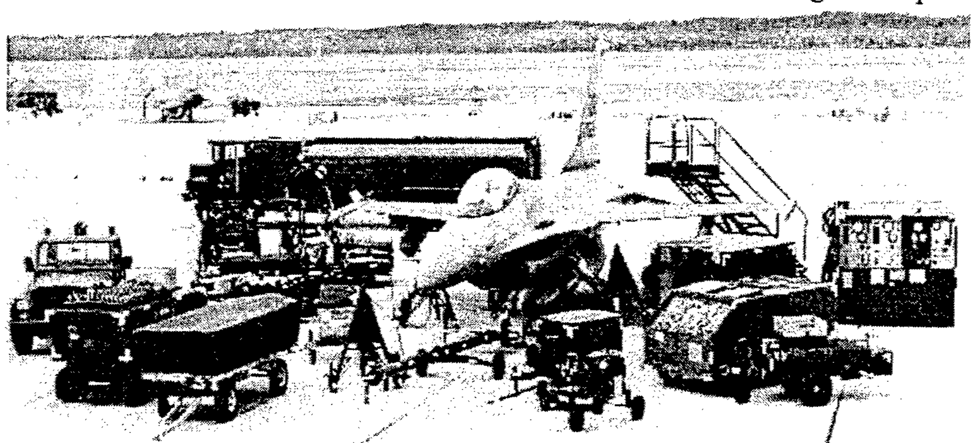


**Exhibit ES-1: Current AGE suite required to support an F-16 aircraft**

At this point, we brainstormed multiple solutions. This brainstorming took place as part of an integrated product team (IPT) meeting. The MASS Integrated Product Team (IPT) included representatives from the organizations shown in Exhibit ES-2.

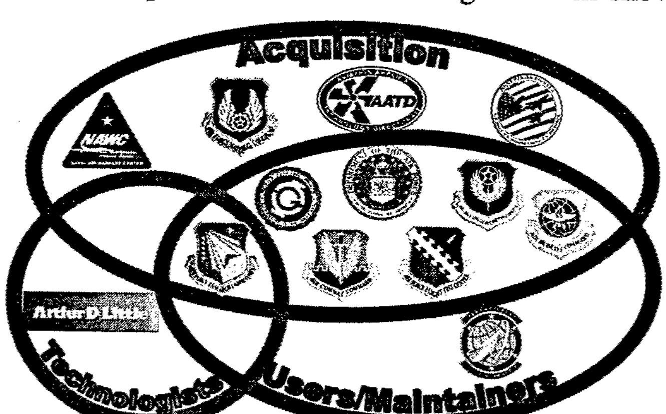



**Exhibit ES-2: MASS Integrated Product Team Organizations (IPT)**

The use of the IPT was crucial in every major step of the program since it ensured that all major parties affected by any new option would verify its acceptability.[3] Each solution was analyzed based on its ability to meet the program and system goals and requirements.[4] However, one of the driving requirements not directly listed was a need for operational flexibility similar to that available from separate carts. The result was that the first analysis iteration quickly eliminated all concepts that did not include a system-of-systems approach. The second iteration analysis directly led to a concept that maximizes AGE subsystem commonality as well as commonality across weapon systems (see Exhibit ES-3).

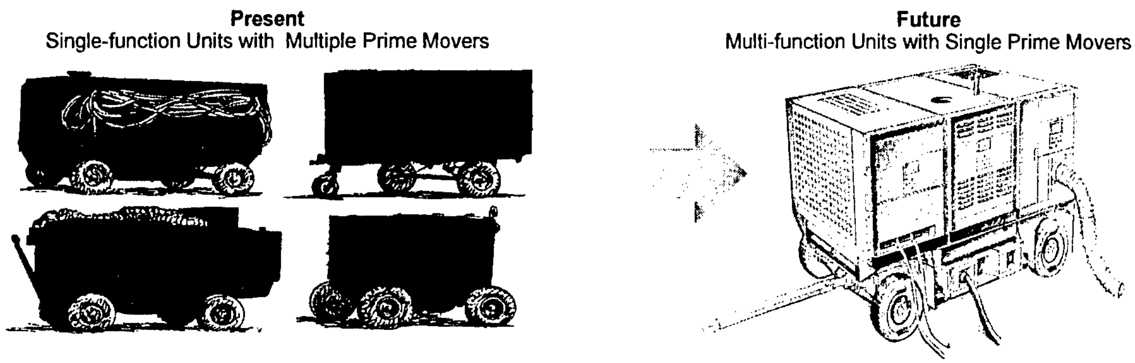



**Exhibit ES-3: A primary goal of MASS is to employ modularity to reduce deployment footprint**

The final concept is shown in Exhibit ES-4.[5] The concept uses a single chassis and a common set of module frames, skins, and electronic control panels to help maximize the subsystem commonality. The center module currently includes a diesel engine generator set to provide power to all the other modules. However, the modular nature of the system allows the replacement of the diesel engine generator set by any electrical energy source (e.g., turbine engine and generator set, fuel cells, or hangar power). The five remaining modules include a pneumatic power system providing high and low pressure air as well as a nitrogen generation and pressurization system, a hydraulic power system, an air conditioning system, a liquid cooling system, and an avionics power converter (which provides both alternating and direct current). This final module is the only module with a different frame size. It resides under the chassis and between the wheels as can be seen in Exhibit ES-4.

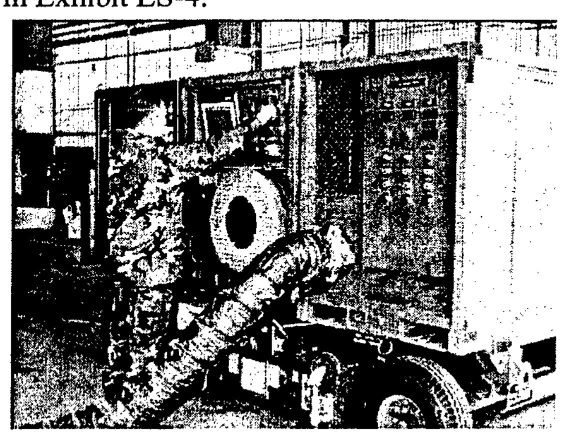


**Exhibit ES-4: MASS Cart**

**MASS Requirements**

The top-level MASS requirements, which were determined in DO2 and DO3, are shown in Exhibit ES-5. The MASS requirements were developed to meet the needs of both future aircraft as well as legacy aircraft (e.g., F-15, F-16).

| Function | Continuous Capability |
|---|---|
| Hydraulics | • 2 x 38 gpm @ 4,000 psi |
| Low Pressure Air | • 15 scfm @ 200 psi |
| High Pressure Nitrogen | • 15 scfm @ 5,000 psi |
| Air Cooling | • 42 lbs/min @ 50 °F, 0.7 psig<br>• 48 lbs/min @ 50 °F, 3.9 psig |
| Liquid Cooling | • 31 gpm of PAO @195 psig / 175 psid<br>• 15.4 tons @ 59 °F (+0 / -10 °F) / 122 °F (+0 / -37 °F) |
| Avionics Power | • 270 Vdc – 70 kW<br>• 115 Vac (line-to-neutral), 400 Hz, 3-phase 33 kVA |

**Exhibit ES-5: MASS Requirements**

**MASS Delivery Orders**

Arthur D. Little's work under the MASS contract included analyzing potential technologies, gathering and analyzing requirements, holding IPT meetings, and evaluation of system concepts. The system concepts were developed in DO2 and evaluated in DO3. Key aspects of the concept were demonstrated in a Brassboard Demonstrator under DO4. The detailed design of the most promising MASS concepts was performed during DO5, resulting in a set of engineering drawings of sufficient detail to fabricate a Proof-of-Concept system. A majority of the parts and components necessary to build the Proof-of-Concept Demonstrator were acquired under DO8.

DO10 directed Arthur D. Little, Inc. (ADL) to construct a MASS demonstrator for use in laboratory and field demonstrations to the operational community and industry. Using the results of previous MASS contract Delivery Orders (i.e., engineering drawings, MASS Brassboard Demonstrator, other procured parts, and analyses results), a MASS Proof-of-Concept Demonstrator was fabricated. This unit was laboratory tested individually and as a system at ADL's Cambridge, MA facility to confirm key concepts and requirements needed to support field demonstration.

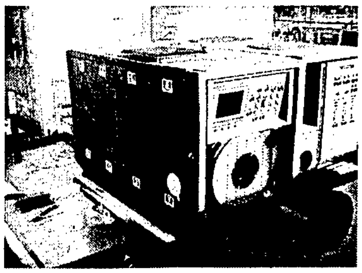
**Module Fabrication and Testing**

This report describes the fabrication and test results for the following MASS modules:

- Diesel Generator Module (DGM)
- Avionics Power Converter (APC)
- Liquid Cooling Module (LCM)
- Air Cooling Module (ACM)
- Pneumatics Module (PNM)

**Diesel Generator Module (DGM)**

A summary of the MASS DGM is shown in Exhibit ES-6 below.

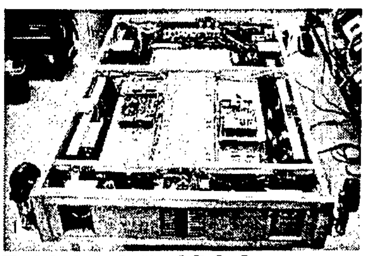


- Size: 86"W x 42"L x 52"
- Weight: 4,200 lbs
- Input: Logistics Fuels (JP-8)
- Output: 135 kW of 480 V 3-phase 60 Hz power
- Meets CARB Tier II emission limits

**Exhibit ES-6: DGM Summary**

**Avionics Power Converter Module (APC)**

A summary of the MASS APC is shown in Exhibit ES-7 below.

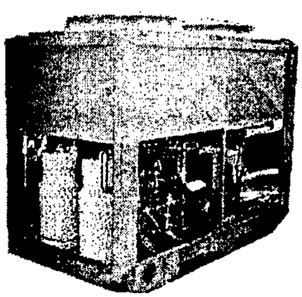


- Size: 86"W x 52"L x 12"
- Weight: 1,200 lbs
- Input: 480 V 3-phase 60 Hz power
- Output: 70 kW of 270 Vdc, or 35 kVA 120/208 V 3-phase 400 Hz

**Exhibit ES-7: APC Summary**

**Liquid Cooling Module (LCM)**

A summary of the MASS LCM is shown in Exhibit ES-8 below.

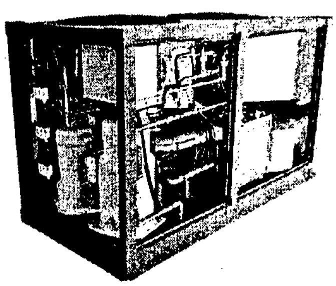


- Size: 86"W x 42"L x 70"
- Weight: 2,600 lbs
- Input: 480 V 3-phase 60 Hz power
- Output: 31 gpm of PAO @ 195 psig
  15.4 tons @ 59 °F (+0 / -10 °F) or 31.3 tons @ 122 °F (+0 / -37 °F)

**Exhibit ES-8: LCM Summary**

**Air Cooling Module (ACM)**

A summary of the MASS ACM is shown in Exhibit ES-9 below.



- Size: 86"W x 42"L x 52"H
- Weight: 1,600 lbs
- Input: 480 V 3-phase 60 Hz power
- Output: 42 lbs/min @ 50 °F, 0.7 psig or 48 lbs/min @ 50 °F, 3.9 psig

**Exhibit ES-9: ACM Summary**

**Pneumatics Module (PNM)**

A summary of the MASS PNM is shown in Exhibit ES-10 below.

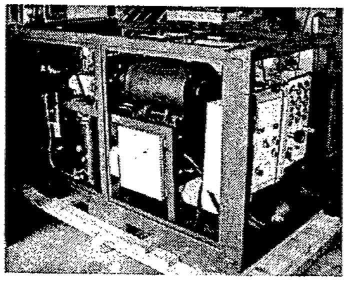


Exhibit ES-10: PNM Summary

- Size: 86"W x 42"L x 52"H
- Weight: 2,200 lbs
- Input: 480 V 3-phase 60 Hz power
- Output:
  - 15 scfm, 400 psi compressed air (regulated); or
  - 15 scfm, 5,000 psi, 95.5% pure compressed nitrogen, 435 scf storage

All of the MASS modules met the MASS requirements shown previously in Exhibit ES-5. The MASS cart was subsequently shipped to Edwards AFB, CA, for field demonstrations with actual aircraft (F-15, F-16, B-52).

**Conclusions and Recommendations**

The MASS concept was successfully demonstrated at Edwards AFB, CA, in February 2001. Our recommendations for future of the MASS Program are as follows:

***MASS Cart Recommendations***

- Further testing at Warner-Robins AFB
  - Additional aircraft testing maintenance
  - Operability/human factors
  - Transport
  - Safety
  - Maintainability
- Use results of testing to update design
- Investigate a gas turbine module to further reduce footprint and weight
- Limited field testing at several selected air bases
- If successful, proceed with an EMD phase
- Continue involvement of MASS IPT

## Table of Contents


**Executive Summary** ..... **iv**

**1.0 Delivery Order Summaries** ..... **1**
- 1.1 DO1 ..... 1
- 1.2 DO2 ..... 2
- 1.3 DO3 ..... 3
- 1.4 DO4 ..... 4
- 1.5 DO5 ..... 5
- 1.6 DO8 ..... 6
- 1.7 DO10 ..... 6

**2. MASS Design Summary** ..... **7**
- 2.1 System Description ..... 7
- 2.2 Diesel Generator Module (DGM) ..... 13
- 2.3 Liquid Cooling Module (LCM) ..... 14
- 2.4 Air Cooling Module (ACM) ..... 15
- 2.5 Avionics Power Converter Module (APC) ..... 16
- 2.6 Hydraulics Module ..... 16
- 2.7 Pneumatics Module (PNM) ..... 17
- 2.8 Chassis ..... 18

**3. MASS Fabrication Effort** ..... **19**
- 3.1 ADL Fabricated Modules ..... 19
- 3.2 Subcontracted Modules ..... 24

**4. Test Program** ..... **26**
- 4.1 Testing at ADL ..... 26
- 4.2 Field Testing ..... 45
- 4.3 Test Conclusions ..... 51

**5. Conclusions and Recommendations** ..... **53**
- 5.1 Program Recommendations ..... 53
- 5.2 Design Improvements ..... 53

**6. References** ..... **56**

## List of Exhibits


| | | |
|---|---|---|
| ES-1 | Current AGE suite required to support an F-16 aircraft | v |
| ES-2 | MASS Integrated Product Team Organizations (IPT) | v |
| ES-3 | A primary goal of MASS is to employ modularity to reduce deployment footprint | vi |
| ES-4 | MASS Cart | vi |
| ES-5 | MASS Requirements | vii |
| ES-6 | DGM Summary | viii |
| ES-7 | APC Summary | viii |
| ES-8 | LCM Summary | viii |
| ES-9 | ACM Summary | viii |
| ES-10 | PNM Summary | ix |
| Exhibit 1-1 | MASS Program Schedule | 1 |
| Exhibit 1-2 | MASS DO2 Subtasks | 2 |
| Exhibit 1-3 | MASS DO2 Concepts | 3 |
| Exhibit 1-4 | MASS DO3 Downselect Process | 3 |
| Exhibit 1-5 | MASS Brassboard Demonstrator | 4 |
| Exhibit 1-6 | MASS DO5 Modules | 5 |
| Exhibit 1-7 | Module Design Updates Overview | 6 |
| Exhibit 2-1 | MASS Configurations | 7 |
| Exhibit 2-2 | Artist's Rendering of MASS | 8 |
| Exhibit 2-3 | Avionics Power Converter Subsystems | 10 |
| Exhibit 2-4 | MASS Requirements | 10 |
| Exhibit 2-5 | AGE Baseline vs. MASS Comparisons | 12 |
| Exhibit 2-6 | Diesel Generator Module (DGM) | 13 |
| Exhibit 2-7 | DGM Virtual Instruments Display | 13 |
| Exhibit 2-8 | LCM (Full front view) and LCM (Full back view) | 14 |
| Exhibit 2-9 | ACM (Full view) and ACM (No Covers) | 15 |
| Exhibit 2-10 | Aircraft Air Cooling Requirements | 15 |
| Exhibit 2-11 | APC Module | 16 |
| Exhibit 2-12 | Exterior View of Hydraulics Module | 17 |
| Exhibit 2-13 | Pneumatics Module | 18 |
| Exhibit 2-14 | MASS Chassis | 18 |
| Exhibit 3-1 | DGM | 20 |
| Exhibit 3-2 | LCM | 21 |
| Exhibit 3-3 | ACM | 21 |
| Exhibit 3-4 | Principal Components and Assembly of the APC Demonstrator | 23 |
| Exhibit 3-5 | Completed APC Demonstrator (without skins) | 23 |
| Exhibit 3-6 | Pneumatics Module | 24 |
| Exhibit 3-7 | MASS Chassis | 25 |
| Exhibit 4-1 | Maximum Module Power Requirements | 26 |
| Exhibit 4-2 | 270 Vdc output mode steady-state test data – 262 Vdc no load set point | 27 |
| Exhibit 4-3 | 270 Vdc mode output voltage disturbance due to 70kW load step | 28 |
| Exhibit 4-4 | 270 Vdc mode output voltage disturbance due to 70kW load rejection | 29 |

## List of Exhibits (continued)


Exhibit 4-5 400 Hz ac output mode steady-state test data ........ 30
Exhibit 4-6 Estimated 400 Hz ac mode APC losses ........ 31
Exhibit 4-7 400 Hz ac output voltage waveform at 75% load ........ 31
Exhibit 4-8 400 Hz ac output voltage disturbance on application of 75% rated load step ........ 32
Exhibit 4-9 400 Hz ac output voltage disturbance on application of 75% rated load rejection ........ 33
Exhibit 4-10 400 Hz ac output mode short term overload test data ........ 34
Exhibit 4-11 APC temperature rise data for 270 Vdc operation at 75% rated load ........ 34
Exhibit 4-12 Low Temperature Mode – Capacity ........ 36
Exhibit 4-13 PAO Supply Temperature – Low Temperature Mode ........ 36
Exhibit 4-14 Low Temperature Mode Testing – PAO Temperatures ........ 37
Exhibit 4-15 Precooler Testing – Capacity ........ 37
Exhibit 4-16 Precooler Testing – PAO Temperatures ........ 38
Exhibit 4-17 High Temperature Mode – Capacity ........ 38
Exhibit 4-18 High Temperature Mode – PAO Supply Temperature ........ 39
Exhibit 4-19 Blower Performance Results ........ 39
Exhibit 4-20 Low Pressure Capacity ........ 40
Exhibit 4-21 High Pressure Capacity ........ 41
Exhibit 4-22 High Pressure Control ........ 42
Exhibit 4-23 Low Pressure Control ........ 42
Exhibit 4-24 PNM Test Results ........ 43
Exhibit 4-25 Fuel Sensor Vdc Output ........ 44
Exhibit 4-26 Function Module Power Demands ........ 44
Exhibit 4-27 MASS Power Demands for Two Illustrative Configurations ........ 45
Exhibit 4-28 Airframes and Modules Tested ........ 45
Exhibit 4-29 MASS Demonstrator Positioned for Testing with a B-52 ........ 46
Exhibit 4-30 MASS Demonstrator Positioned for Testing with an F-15 ........ 47
Exhibit 4-31 F-15C Transformer Rectifier unit Inrush Current – 100 A/div, 4 ms/div ........ 49
Exhibit 4-32 F-16C Transformer Rectifier unit Inrush Current – 100 A/div, 4 ms/div ........ 49
Exhibit 4-33 MASS Demonstrator Positioned for Testing with an F-15 ........ 50

## 1.0 DELIVERY ORDER SUMMARIES

### 1.1 Delivery Order 0001 (DO1)

Delivery Order 0001 consisted of the tasks necessary to manage the MASS program from program kickoff through the end of the program. These tasks included:

- Perform administrative and financial management functions
- Host and participate in meetings
- Facilitate electronic data transfer between IPT members
- Manage cost, schedule, and performance of all subcontractors
- Apply Integrated Process/Product Development (IP/PD) methodologies

The meetings held included an overall program kickoff meeting, as well as kickoff and wrap-up meetings for each delivery order. Key technical staff attended an IP/PD training session early in the program to refresh the team on the basic principles of IP/PD, and we attended the USAF Affordability Transition Conference. There were eleven IPT meetings held throughout the program.

We attended five industry day meetings over the course of the program. We attended the GSE Exposition three times, during which we displayed the MASS system concept, including hardware when available. We also attended the $AS^3$ Show (April 1999) and AEF Battlelab Industry Day (March 1998).

Monthly program and cost status reports (59 total) were submitted throughout the program, and bi-weekly program management teleconferences were held (76 total). We also maintained a MASS website to allow access to the latest schedule and documents by the IPT.

The MASS Program Schedule (Exhibit 1-1) includes the field testing of a proof-of-concept demonstrator.

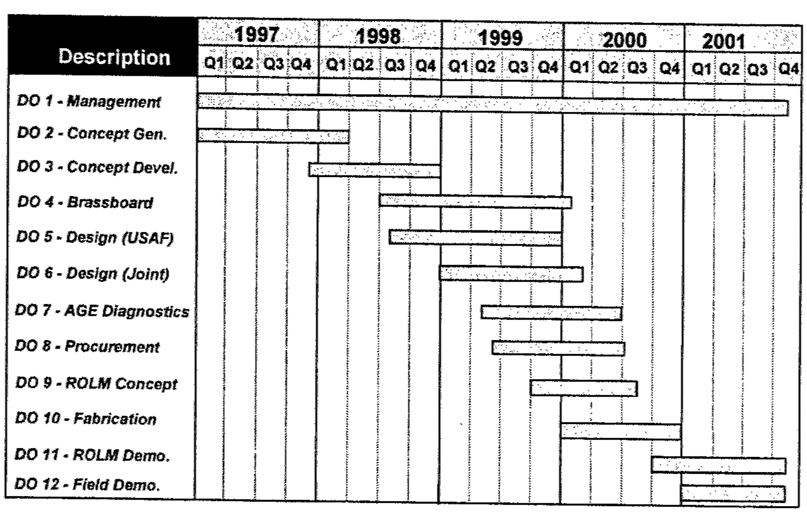



**Exhibit 1-1: MASS Program Schedule**

## 1.2 Delivery Order 0002 (DO2)

Delivery Order 0002, entitled "Concept Generation", consisted of several subtasks leading to the selection of six concepts with which to proceed to the next phase of the development program. Exhibit 1-2 outlines these subtasks in the form of a flowchart. After prior research related to the program was reviewed, two parallel tasks were conducted. These tasks were the generation of a set of requirements, based on input from the user community, and research into new technologies that were applicable to MASS. Once these parallel tasks were completed, the new technologies were then compared to the requirements in the technology trade studies in order to determine which technologies were suitable for inclusion into MASS. The investigation into the requirements, technologies and trade studies was completed during May 1997, and the results documented in the MASS Interim Report.[6]

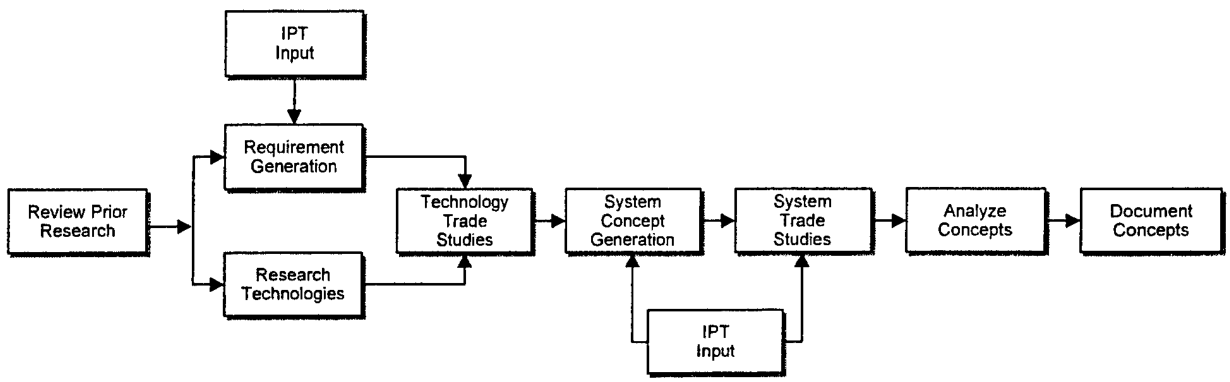



**Exhibit 1-2: MASS DO2 Subtasks**

The subsequent subtasks in MASS DO2 consisted of the generation of system concepts, comparison of those concepts to the MASS requirements to determine their suitability, selection of the six most attractive system concepts, and the analysis and documentation of the six final concepts (see Exhibit 1-3) for exploration in subsequent Delivery Orders. Input from the MASS IPT was solicited throughout the program to provide input to the MASS program from the users and maintainers of AGE from the Air Force, Army, and Navy. The DO concluded with the submittal of the Final Report.[7]

| [illegible] | Concept Title | Design Description |
|---|---|---|
| 1 | Customizable MASS | Family of modules and frames, tailored to specific aircraft |
| 2 | Advanced Mechanical MASS | Mechanically interconnected system with single engine power source |
| 3 | Advanced Electrical MASS | Electrically interconnected system with single fuel cell power source |
| 4 | UniCart | All modules mounted on a single frame |
| 5 | BiCart | All modules mounted on two independent frames |
| 6 | TriCart | All modules mounted on three independent frames |

**Exhibit 1-3: MASS DO2 Concepts**

## 1.3 Delivery Order 0003 (DO3)

Delivery Order 0003, issued in December 1997, directed 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 DO3 concluded with the preparation and approval of the Final Report.[8] The report described 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 (see Exhibit 1-4). The scope of this effort 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.

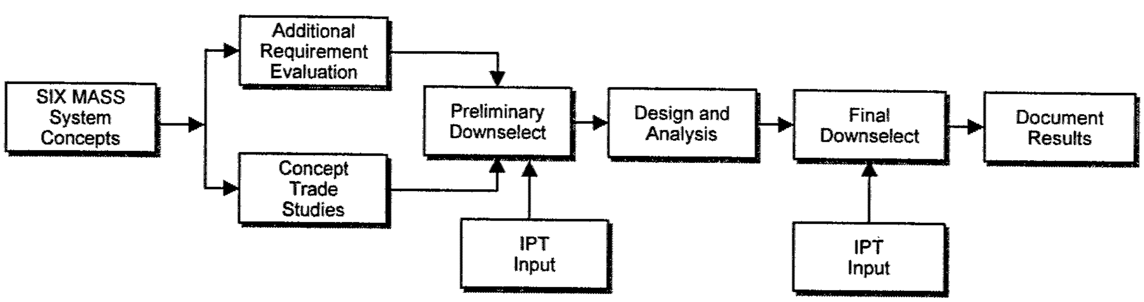



**Exhibit 1-4: MASS DO3 Downselect Process**

## 1.4 Delivery Order 0004 (DO4)

The purpose of Delivery Order 0004 was to construct a MASS brassboard demonstrator employing several of the key features of the final MASS system concept resulting from DO3 of the MASS contract. This brassboard demonstrator provided 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 was significantly reduced. Development and fabrication of the brassboard demonstrator consisted of the following tasks:

- Design brassboard
- Recommend design to the IPT
- Fabricate brassboard
- Perform checkout testing and evaluation
- Submit final report[9]

The following modules were developed:

- Diesel Generator
- Avionics Power Converter (DC only)
- Liquid Cooler
- Air Cooler (air side only)
- Chassis

A photo of the Diesel Generator and Chassis is shown in Exhibit 1-5.

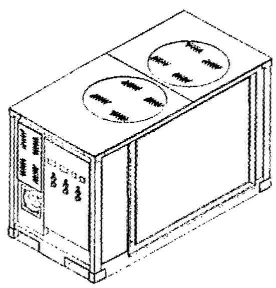
**Exhibit 1-5: MASS Brassboard Demonstrator**

## 1.5 Delivery Order 0005 (DO5)

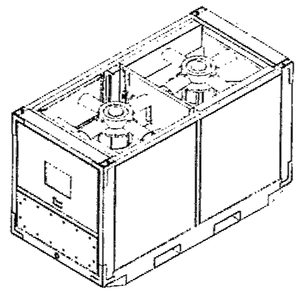
The purpose of Delivery Order 0005 was to perform a detailed design of the most promising system concept resulting from Delivery Order 0003 of the MASS contract. This detailed design effort provided sufficient data, in the form of Computer Aided Design (CAD) generated developmental drawings, from which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

- Preliminary design
- Interim design review
- Detailed design
- Detailed design reviews
- Submit Final report[10]

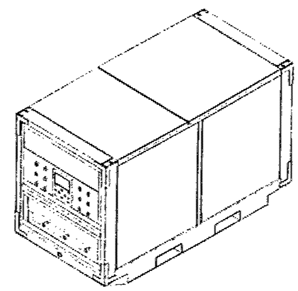
Developmental drawings were created for the following modules (see Exhibit 1-6):



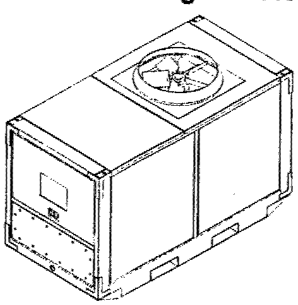
**Air Cooling Module**



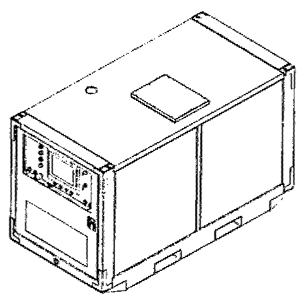
**Liquid Cooling Module**



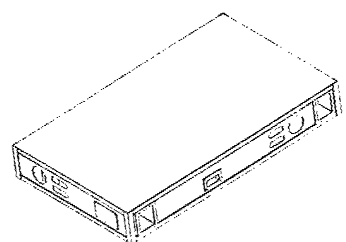
**Pneumatics Module**



**Hydraulics Module**
**(large capacity)**



**Diesel Generator Module**
**(large capacity)**



**Avionics Power Converter Module**

**Exhibit 1-6: MASS DO5 Modules**

## 1.6 Delivery Order 0008 (DO8)

The key task of Delivery Order 0008 was to identify and procure the majority of the components necessary to fabricate the proof-of-concept system during DO10.

DO8 Design Updates were made as a result of the DO4 testing and feedback received from the MASS IPT. The significant updates are summarized by module in Exhibit 1-7 below.

| Module | Design Update |
|---|---|
| Diesel Generator | • Specified modifications to engine control governor parameters<br>• Installed higher capacity fuel pump and tungsten carbide fuel injectors<br>• Designed modifications to integrate the air cleaner and muffler within the module<br>• Specified upgrades to the electrical cabinet and flat panel display |
| Avionics Power Converter | • Specified and procured 400 Hz ac components<br>• Determined supervision of output and status using Virtual Instruments display<br>• Modified packaging |
| Liquid Cooling | • Specified modifications to pump<br>• Specified higher capacity evaporator and condensers<br>• Added sub-cooler |
| Air Cooling | • Completed interface details for high-speed blower<br>• Finalized electrical and control schematics<br>• Designed brackets/supports |

**Exhibit 1-7: Module Design Updates Overview**

During the downselection process of the IPT #6 meeting, the diesel engine primemover incorporated in the current MASS design was chosen over a gas turbine alternative in order to achieve a more affordable product. However, during the IPT #8 meeting, ADL was subsequently asked to revisit other MASS solutions to determine attainable lower bounds on footprint and weight if cost was not a constraint. The ensuing investigation identified that using a gas turbine engine and air cycle cooling technology would significantly reduce the weight and size of a typical MASS cart.

At the direction of AFRL, the hydraulics module was not fabricated during the proof-of-concept segment of the MASS program. Instead, a hydraulic study was performed by visiting selected USAF bases to further quantify pressure and flow requirements for various aircraft. The DO8 concluded with a Final Report.[11]

## 1.7 Delivery Order 0010 (DO10)

Delivery Order 0010, issued in February 2000, directed ADL to construct a MASS demonstrator for use in laboratory and field demonstrations to the operational community and industry. Using the results of previous MASS Delivery Orders, (i.e. engineering drawings, MASS Brassboard Demonstrator, other procured parts, and analyses results), a MASS Proof-of-Concept Demonstrator was fabricated. This unit was laboratory tested sufficiently to confirm key concepts and requirements needed to support field demonstration. DO10 concluded with the submittal of the Final Report.[12]

## 2.0 MASS Design Summary

### 2.1 System Description

The MASS concept is based on a family of modules, from which one can select to create custom support cart configurations tailored to specific aircraft (see Exhibit 2-1).

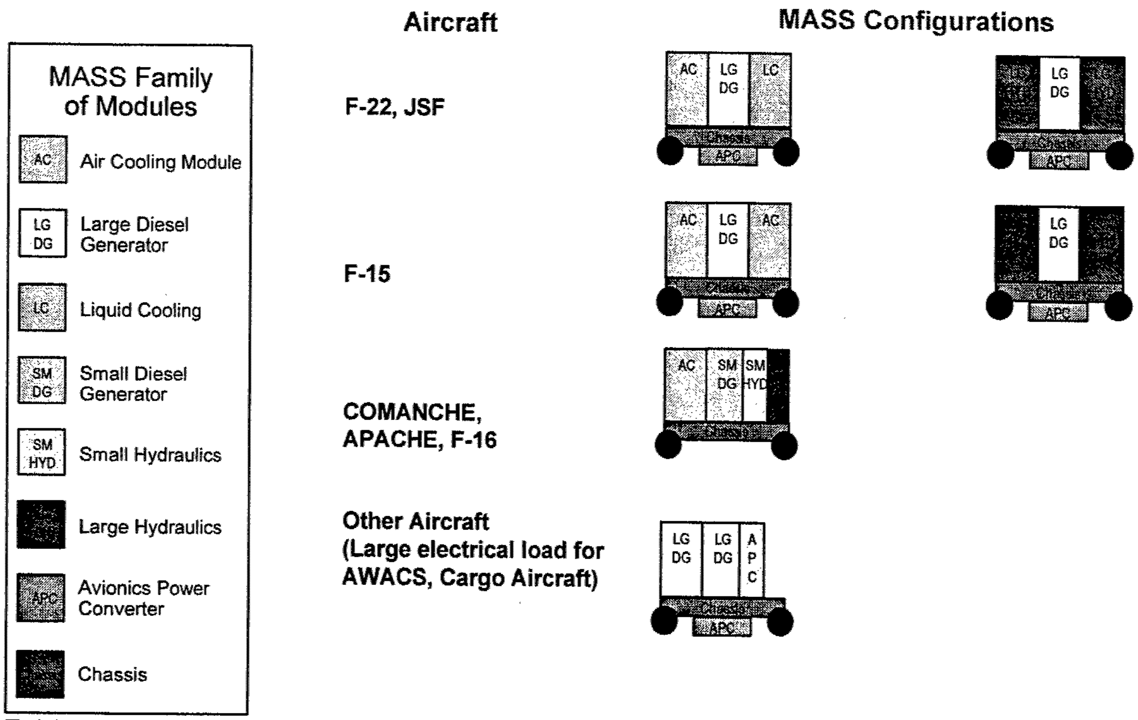



**Exhibit 2-1: MASS Configurations**

The concept uses a single chassis and a common set of module frames, skins, and electronic control panels to help maximize the subsystem commonality. The center module currently includes a diesel engine generator set to provide power to all the other modules. However, the modular nature of the system allows the replacement of the diesel engine generator set by any electrical energy source (e.g., turbine engine and generator set, fuel cells, or hangar power). The five remaining modules include a pneumatic power system providing high and low pressure air as well as a nitrogen generation and pressurization system, a hydraulic power system, an air conditioning system, a liquid cooling system, and an avionics power converter (which provides both alternating and direct current. This final module is the only module with a different frame size. It resides under the chassis and between the wheels. An artist's rendering of this final concept is shown in Exhibit 2-2.

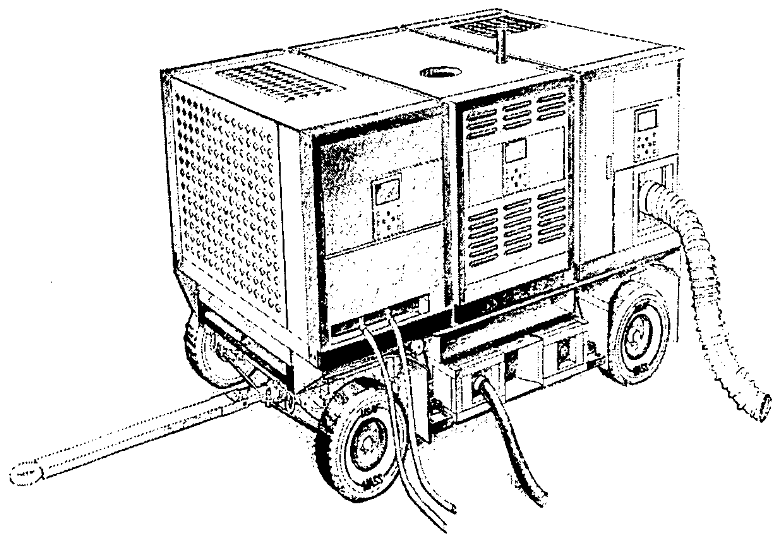


**Exhibit 2-2: Artist's Rendering of MASS**

### *2.1.1 Modular Concept*

A "system-of-systems" approach directly led to modularity in the MASS at two distinct levels. The first level is the utility level. This provides for the ability to easily reconfigure cars as necessary to meet any multi-functional combination. This maintains the flexibility that was crucial to supporting flight operations without hampering LCC or deployment footprint. Both levels also improve the maintainability and upgradability of MASS subsystems as needed to reduce downtime and life-cycle costs of MASS. The second level is the module or subsystem level. This is the basic building block that allows multiple parts that would typically be unique to each piece of common or peculiar AGE to be reused across multiple modules across all weapon systems.

#### 2.1.1.1 Modular Utility

At the utility level, the MASS is made up of seven basic parts. These are the chassis, generator module, hydraulic module, liquid cooling module, air cooling module, pneumatic module, and the avionics power converter module. There are additional options such as lighting that can be added on an as-needed basis. The artist's rendering of the final MASS system (shown earlier in Exhibit 2-2) has one each of the generator, air-cooling, liquid cooling, and avionics power converter modules. This setup allows for an easy division of effort across the acquisition, maintenance, and operational requirements.

Utility modularity combines the best aspects of separate cart procurements with fewer procurement actions. For years, the support equipment acquisition organizations have been moving to reduce the proliferation of equipment. However, unique weapon system requirements and single function cars have defined the limits that could be met. A modular system is a major step in redefining that limit since specialized carts are built from common modules. Individual modules can be purchased from the experts in each utility area. This ensures that the best capabilities are brought to bear on the specific problems associated with electrical, hydraulic, or pneumatic attributes. The use of only one or two manufacturers for a module permits a reduction in the number of diverse systems being repaired and parts being stockpiled. This also can increase the volume of systems purchased under a smaller number of contracts leading to a direct reduction in both government and contractor non-recurring costs and taking advantage of the economy of scale.

As mentioned above, fewer manufacturers and system designs results in reduced numbers of engines, generators, etc. Using the current common AGE approach on the modules should also lead to a commonality of parts across modules. These two approaches lead to multiple cost and time savings. These include a reduction in the amount and types of training each maintainer must receive, the number of technical orders that must be maintained, and the proliferation in spare parts that are required to maintain the equipment. As a result, the maintainers can spend more time performing maintenance and becoming experts on the smaller number of AGE versus the jack-of-all-trades approach required for a diversity of AGE types and design approaches.

Finally, the operational aspects of this approach can provide multiple benefits, both in life- cycle costs (LCC) and operational flexibility. For costs, the use of highly common modules as part of a suite versus separate systems leads to savings in chassis and module frames (e.g., wheel and tire assemblies and skins) and subassemblies (e.g., common engine, motors, and controls). For usage, common controls and multi-function carts allow users to start and monitor one engine versus many and easily understand the layout of each control panel due to their similarity. Finally, common modules across legacy and future weapon systems operated in an EAF provide maximum capability with minimum spares and deployment footprint.

#### 2.1.1.2 Module Subsystems

As described above, substantial benefits can be gained through the modularization of the MASS system, allowing carts to be customized to meet the needs of specific aircraft and improving maintenance by allowing modules to be removed and replaced quickly and with minimal impact on the system. Modularization can also be applied at the module level, in effect creating "modules within modules." While this lower level of modularization is not designed to allow customization of the output of a module, it can substantially improve maintenance by allowing subassemblies to be isolated and replaced should a failure occur.

An example of this modularity can be seen in the Avionics Power Converter (APC), a module that converts electrical power from the 60 Hz generated by the generator module to the 400 Hz ac and 270 Vdc power required by the aircraft. This module is composed of several sub-modules, as shown in Exhibit 2-3. One example of a sub module within the APC is the Power Electronic Building Block (PEBB), the basic electrical power conversion device used to convert the electrical power from 60 Hz to both 400 Hz ac and 270 Vdc. There are six of these modules in the APC. Another example is the heat-pipe heat exchanger used to cool the power electronics. There are two of these modules in the APC.

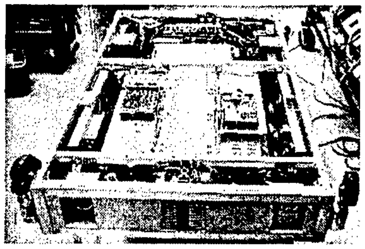


**Exhibit 2-3: Avionics Power Converter Subsystems**

There are several advantages to the modular design of the APC:

- Failed components can be isolated and replaced rapidly
- As manufacturers upgrade and improve components, these components can be integrated more easily
- Out-of-production components can be more easily replaced by newly produced components

This level of modularization was adopted in the design of MASS modules to proved these benefits whenever possible.

### *2.1.2 MASS Requirements*

The top-level MASS system requirements are shown in Exhibit 2-4. The MASS requirements were developed to meet the requirements of both future aircraft as well as legacy aircraft (e.g., F-15, F-16). This set of requirements was developed after determining the worst-case requirements in each performance category, for each of the aircraft under consideration, and then selecting the overall maximum in each category. The positive side of this approach is that it guarantees that the MASS cart will be able to meet the requirements of any aircraft under any condition. The negative side is that the resulting system is oversized for operating conditions less extreme than the worst cases.

| Function | Continuous Capability |
|---|---|
| Hydraulics | • 2 x 38 gpm @ 4,000 psi |
| Low Pressure Air | • 15 scfm @ 200 psi |
| High Pressure Nitrogen | • 15 scfm @ 5,000 psi |
| Air Cooling | • 42 lbs/min @ 50 °F, 0.7 psig<br>• 48 lbs/min @ 50 °F, 3.9 psig |
| Liquid Cooling | • 31 gpm of PAO @ 195 psig / 175 psid<br>• 15.4 tons @ 59 °F (+0 / -10 °F) / 122 °F (+0 / -37 °F) |
| Avionics Power | • 270 Vdc – 70 kW<br>• 115 Vac (line-to-neutral), 400 Hz, 3-phase 33 kVA |

**Exhibit 2-4: MASS Requirements**

### *2.1.3 Comparison with AGE*

#### 2.1.3.1 Existing AGE And Other AGE Development Efforts

Legacy aircraft such as the F-15 and F-16 are currently supported by a turbine engine generator set, three different pneumatic carts, an air conditioning cart, a hydraulic cart, and a light cart (for lighting and electric hand tool power). Initiatives are underway to condense this package to one turbine engine generator and air conditioning cart, one pneumatic cart, a hydraulic cart and a light cart. However, this AGE system configuration includes four different engines of two different types (i.e., turbine and diesel); four chassis with different tires, skin panels, and other components; and some dated technology that all lead to higher maintenance costs.

Future aircraft requirements are still in the definition stage. For our analysis, we selected a diesel engine generator set, combined air/liquid cooling cart, hydraulic cart, and two types of pneumatic carts. This solution, while generic in nature, is based on various future aircraft studies and plans. The future aircraft analysis has a vastly reduced initial footprint due to anticipated maintenance operations changes and improved aircraft reliability. However, it still requires five different engines and chassis sets. Four of the five carts could be based on existing AGE used by other weapon systems (i.e., common AGE) while one cart would need to be peculiar to future aircraft.

The system-of-systems approach undertaken by the MASS program has led to a single suite of modules with one chassis, one engine in the generator module, one hydraulic module, one pneumatic module, one air conditioning module, one liquid cooling module, one avionics power converter, and optional close-area lighting. The reduction in the number and types of parts and maintenance tasks directly leads to reduced operational costs while the decreased deployment footprint results in reduced deployment time and costs.

#### 2.1.3.2 Improved Deployment Footprint and Costs

The overriding goals of the MASS program are to reduce the deployment footprint and LCC of AGE. The footprint, weight, and LCC estimates have been tracked throughout the program to ensure that these goals are being met. In order to have a basis of comparison, four squadron-level suites of AGE were used as baselines to calculate the relative performance of MASS:

- An AGE suite currently in inventory, based on diesel engine technology
- An AGE suite currently in inventory, based on gas turbine technology
- A new suite of AGE based on the Combined Generator and Air Cooling (CGAC) cart
- A new suite of AGE based on carts planned to support future aircraft requirements.

MASS projections were compared to these four baselines to determine the gains in deployment footprint and LCC. The results of the comparison are presented in Exhibit 2-5. These comparisons are based on operational model results (using an internally developed model, other analyses, and a set of assumptions. As a consequence, we feel the results are optimistic but acceptable.

| | | AGE Baselines | | | MASS | | |
|---|---|---|---|---|---|---|---|
| Aircraft | AGE Type | Footprint ($ft^2$) | Weight (lbs) | LCC ($K) | Footprint ($ft^2$) | Weight (lbs) | LCC ($K) |
| F-15 | Diesel | 2,300 | 182,700 | 23,200 | 1,130 | 162,000 | 20,300 |
| F-15 | Turbine | 1,970 | 97,500 | 28,000 | 1,130 | 162,000 | 20,300 |
| F-15 | CGAC | 1,620 | 112,600 | 30,300 | 1,130 | 162,000 | 20,300 |
| F-16 | Diesel | 2,300 | 182,700 | 23,200 | 750 | 115,500 | 14,400 |
| F-16 | Turbine | 1,970 | 97,500 | 28,000 | 750 | 115,500 | 14,400 |
| F-16 | CGAC | 1,620 | 112,600 | 30,300 | 750 | 115,500 | 14,400 |
| Future | Diesel | 240 | 24,600 | 4,200 | 225 | 31,700 | 4,000 |

**Exhibit 2-5: AGE Baseline vs. MASS Comparisons**

As can be seen from the table, MASS has the potential to create a deployable footprint substantially less than the baselines. The footprint savings range from 6% to 67% with an average of 51%. The weight is an issue since the future aircraft baseline and the turbine engines in the gas turbine and CGAC baselines provide savings in this area. The MASS weights range from an increase of 66% to a decrease of 37% with an average of a 7% increase. Since the current equipment for legacy aircraft typically reaches a volume limit ("cubes out" before a weight limit ("weighs out"), this may not be an issue. Continuing studies with more refined models are taking place to determine if any issues arise from this situation. The result of the increased weight on a future aircraft deployment package is unknown. Mandatory airlift requirements associated with all future aircraft may have serious implications on the acceptability of MASS. The LCC of MASS ranges from a 52% decrease (CGAC for F-16) to a 12% decrease. The average LCC is a 35% savings over existing equipment.

While the comparisons shown in Exhibit 2-5 show favorable results for the F-15 and F-16 aircraft, the future aircraft comparison is not as favorable. Additional analyses show the potential for a more favorable result. The above comparisons assume a full suite of future aircraft AGE versus a full suite of MASS. Another option is a combination of a single MASS consisting of a generator module, liquid cooling module, air cooling module, and avionics power converter module to replace the engine generator saet and combined air/liquid cooling cart. The hydraulic cart and pneumatic carts are used instead of MASS modules. This increases potential commonality across legacy and future aircraft. The footprint is reduced an additional 30 square feet resulting in a 19% savings over the future aircraft baseline. The weight decreases dramatically to 22,500 pounds, for a 9% savings over the future aircraft baseline.

### 2.1.3.3 Conclusion

The application of the system-of-systems approach to the USAF AGE situation has resulted in a dramatic conceptual change. The conclusion from the baseline comparison analysis shows that MASS has the potential to provide a major benefit in deployment, providing a significant reduction in the number of cargo aircraft needed to move the AGE during a deployment. This benefit is of even greater importance now that the USAF has implemented the EAF concept, making rapid deployment essential. An added benefit is that this improvement can be accomplished while reducing life-cycle costs. Finally, commonality across legacy and future aircraft is increased.

## 2.2 Diesel Generator Module (DGM)

The Diesel Generator Module (DGM) provides 60 Hz power to operate the MASS modules when hangar power is not available. The DGM (as seen in Exhibit 2-6) is a modular assembly containing a diesel engine driving a 60 Hz synchronous generator at 1,800 rpm. The engine employs an electro-hydraulic fuel injection system that is controlled by an electronic Engine Control Module (ECM), which also communicates diagnostic data to the virtual instruments flat panel display (VI Display). The frame of the generator is bolted to the engine bell housing and power is directly transmitted through a flex disc coupling. This sub-assembly is mounted to the module frame with rubber vibration isolators. The controls for the module are contained in an electrical cabinet with the high brightness VI Display computer for monitoring and displaying operational data (see Exhibit 2-7). The module is provided with JP-8 fuel from the chassis-mounted fuel tank. Fuel tank capacity is 80 gallons, which provides for an eight-hour run-time at full load.

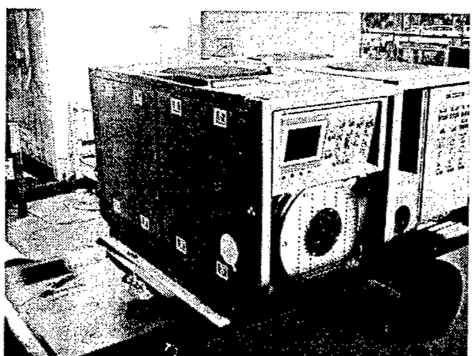


**Exhibit 2-6: Diesel Generator Module (DGM)**

The DGM Demonstrator control panel features a daylight-readable virtual instruments display (VI Display), which replaces conventional gauges, meters, and indicators. The VI Display also demonstrates the ability of this system to support more than one module – in this case both the DGM and the APC located beneath it.


**Exhibit 2-7: DGM Virtual Instruments Display**

Diesel Generator Module Specifications

| | |
|---|---|
| Size | 86"Wx42"Lx52"H |
| Weight | 4,200 lbs. |
| Input | Logistics Fuel (JP-8) |
| Output | 135 kW of 480 V 3-phase 60 Hz power |
| Other | Meets CARB Tier II emissions limits |

### 2.3 Liquid Cooling Module (LCM)

The MASS liquid cooling Module (see Exhibit 2-8) provides cooling to an aircraft Environmental Control system (ECS) by means of a heat transfer fluid, polyalphaolefin (PAO). The module is designed to meet the liquid cooling requirements of the F-22 aircraft, which calls for operations in either Forward mode (delivering PAO with 54 kW of cooling) or Aft mode (delivering PAO with 110 kW of cooling).

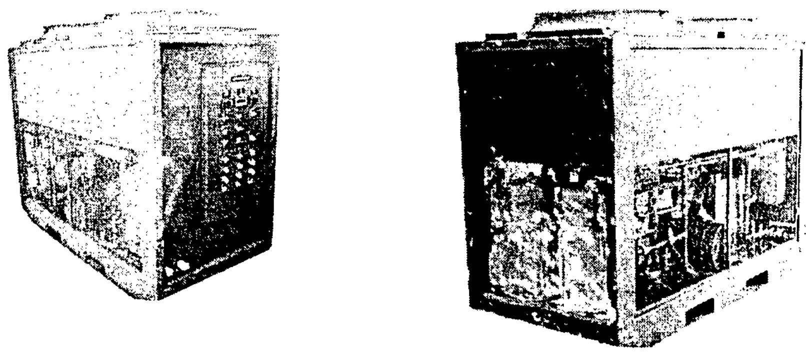


**Exhibit 2-8: LCM (full front view) and LCM (full back view)**

The Liquid Cooling Module (LCM) requires 460 V, 3-phase, 60 Hz input power. The cooling system is divided into two subsystems, a liquid-to-air pre-cooler and a standard vapor compression refrigeration system based on R134a. Two compressors are used in parallel, but with a common condenser, reservoir, expansion valve, and evaporator. Each compressor is controlled individually by the switches on the front panel, giving the operator flexibility to operate one or both compressors.

Depending on the operational mode and the ambient conditions, a portion of the cooling load can be removed by using the pre-cooler to remove heat to the ambient air by the use of fans only. The remaining cooling load, if any, is removed by the refrigeration system. The PAO flow rat and delivery temperature is operator selectable from the control panel of the module.

Liquid Cooling Module Specifications

| | |
|---|---|
| Size | 86"Wx42"Lx70"H |
| Weight | 2,600 lbs. |
| Input | 480 V, 3-phase, 60 Hz electrical power |
| Output | Flow: 31 gpm of PAO @ 129 psig<br>Cooling: 15.4 tons @ 59 °F (+0 / -10 °F)<br>Or 31.3 tons @ 122 °F (+0 / -37 °F) |

## 2.4 Air Cooling Module (ACM)

The MASS Air Cooling Module (ACM) (see Exhibit 2-9) provides conditioned cooling air to an aircraft Environmental Control System (ECS) through a single high pressure supply hose. The module is designed to meet the air cooling requirements of the aircraft shown in Exhibit 2-10, with one exception. The F-15 requirement, due to the high airflow rate, is intended to be satisfied using two air cooling modules operating in parallel. A single air cooling module can satisfy part load requirements of the F-15.

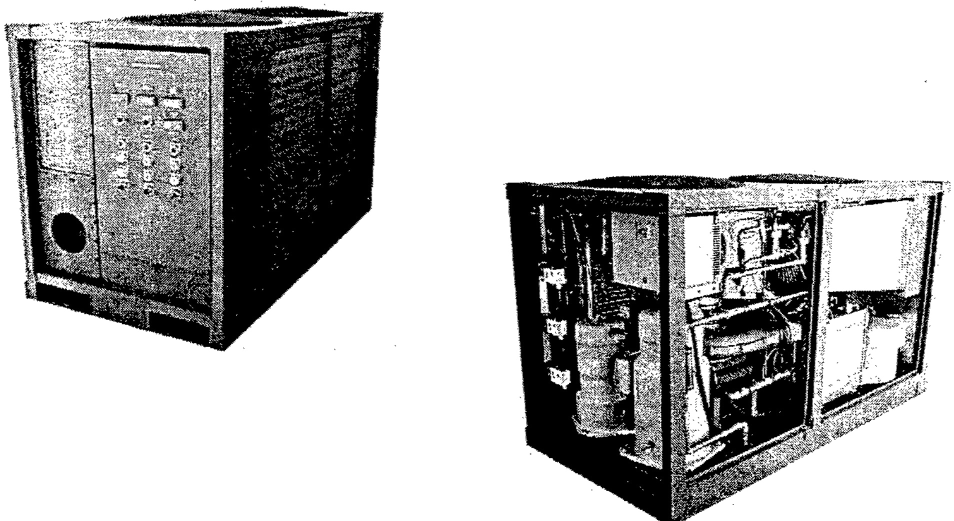


**Exhibit 2-9: ACM (Full view) and ACM (No Covers)**

| Aircraft | Air Flow (lbs/min) | Delivery Temperature (°F) | Delivery Pressure (psig) |
|---|---|---|---|
| Companche RAH-66 | 55 | 41 | 1.4 |
| Apache AH-64A | 34 | 42 | Negligible |
| F-22 | 34 | 40 | 0.5 |
| | 42 | 50 | 0.7 |
| | 52 | 60 | 1.0 |
| F-16 | 48 | 50 | 3.9 |
| F-15 | 90 | 50 | 3 |
| F-18 | 50 | 50 | 3.3 |

**Exhibit 2-10: Aircraft Air Cooling Requirements**

The Air Cooling Module (ACM) requires 460 V, 3-phase, 60 Hz of input power. The ACM conditions ambient air and delivers it to an aircraft at a required airflow rate and temperature. The cooling of the air is accomplished using two essentially independent refrigeration systems. The two systems share a common condenser. A high-speed centrifugal blower moves air through the system.

**Air Cooling Module Specifications**

| | |
|---|---|
| **Size** | 86"Wx42"Lx52"H |
| **Weight** | 1,600 lbs. |
| **Input** | 480V, 3-phase, 60 Hz electrical power |
| **Output** | 42 lbs/min @ 50 °F, 0.7 psig<br>or 48 lbs/min @ 50 °F, 3.9 psig |

## 2.5 Avionics Power Conditioner (APC)

The APC module (see Exhibit 2-11) delivers avionics power in one of two switch selectable formats – 3-phase, 400 Hz 200 V (line-to-line) for legacy aircraft or 270 Vdc for the F-22 and Comanche. For flightline operation, the APC can be powered by the MASS Diesel Generator Module (DGM) which supplies 3-phase, 60 Hz 480 V power. Alternatively, the APC can be powered by utility or barebase power for hangar maintenance operations.

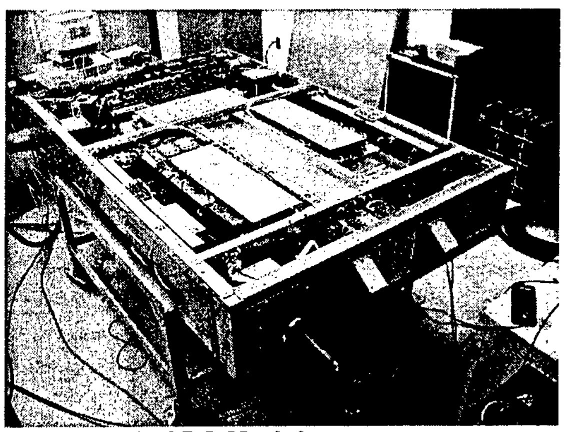


**Exhibit 2-11: APC Module**

APC power conversion operations are implemented with six commercial off-the-shelf (COTS) power electronic building blocks (PEBBs). The PEBBs employ insulated gate bipolar transistor (IGBT) switching devices rated at 1,200 Vdc/900 A. Each PEBB includes DC link capacitors, IGBT gate drivers, gate driver power supplies, protection circuits and wideband DC-coupled current sensors.

**Avionics Power Module Specifications**

| | |
|---|---|
| **Size** | 52"Wx84"Lx13"H |
| **Weight** | 1,200 lbs. |
| **Input** | 480 V, 3-phase, 60 Hz electrical power |
| **Output** | 33 kVA of 120/208 V, 3-phase, 400 Hz continuous electrical power<br>*or:* 70 kW of 270 Vdc continuous electrical power |
| **Other** | Ducted forced air and heatpipe air-to-air heat exchangers |

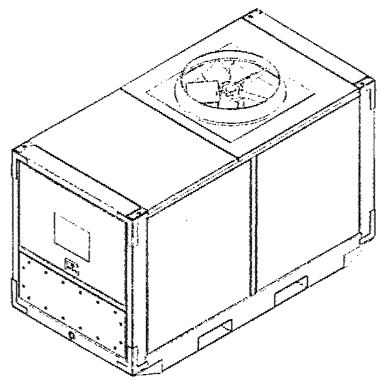
## 2.6 Hydraulics Module

The MASS Hydraulics Module was designed to meet the following requirements:

Hydraulics Module Specification

| | |
|---|---|
| **Size** | 86" W x 42" L x 52" H |
| **Weight** | 2,300 lbs. |
| **Input** | 480 V, 3-Phase, 60 Hz electric power |
| **Output** | 40 gpm at 4,000 psig hydraulic fluid |

The Hydraulics Module was packaged in the standard MASS module frame. An exterior view of the Hydraulics module is shown in Exhibit 2-12.



**Front View**

**Exhibit 2-12: Exterior View of Hydraulics Module**

A MASS dual hydraulics cart would have the same flow and pressure output as the AGE hydraulics cart. While the MASS hydraulics cart has the potential to provide a significant improvement in flexibility and maintainability by virtue of the modular concept, the size and weight are projected to be larger than the corresponding AGE cart.

In order to determine if a significant reduction in size can be achieved for the MASS hydraulic module, a hydraulic study was performed under DO8 as opposed to building the module. The result of the hydraulic study was that the actual flow and pressure required for legacy aircraft during typical maintenance operations as significantly less than the MASS requirement. Therefore, the flow and pressure requirements for the Notional Future Aircraft (NFA) will influence the potential for weight reduction.

## 2.7 Pneumatics Module (PNM)

Fabrication of the Pneumatics Module (see Exhibit 2-13) was subcontracted to Pacific Consolidated Industries (PCI) located in Santa Ana, CA. The PNM leverages the same technologies (membrane separation, feed air and booster compressors, carbon absorber filters) used in PCI's Self-Generating Nitrogen System Cart, presently being supplied to the U.S. Air Force. The module was fully tested by PCI prior to shipping and met all performance requirements.

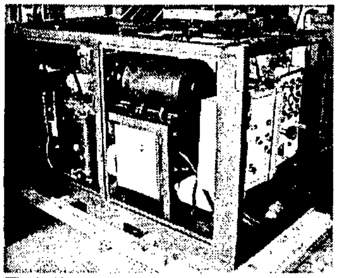


Exhibit 2-13: Pneumatics Module

**Pneumatics Module Specifications**

| | |
|---|---|
| **Size** | 86"Wx42"Lx52"H |
| **Weight** | 2,200 lbs. |
| **Input** | 480V, 3-phase, 60 Hz electrical power |
| **Output** | 15 scfm, 400 psi compressed air (regulated)<br>or 15 scfm, 5,000 psi, 95.5% pure compressed nitrogen, 435 scf storage |

## 2.8 Chassis

The steerable chassis (see Exhibit 2-14) is rated at 6,000 pounds per axle and 12,000 pounds total, with a design factor of safety of 2.0. The overall chassis dimensions are 130 inches long by 86 inches wide by 29 inches high. The chassis construction is made of two main 4 inch by 6 inch by ¼ inch thick tubular steel beams. Two end plates and two cross-connected beams for torsional rigidity tie the beams together. The suspension is made of four leaf springs attached to the frame and four tires sized for the rated load.

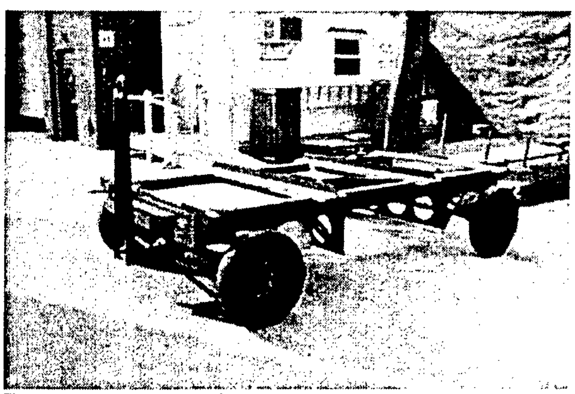


Exhibit 2-14: MASS Chassis

A fuel tank is integrated into the chassis to provide fuel for the DGM when wall power is not available. The tank is constructed of 316 stainless steel and has a capacity of 80 gallons, which provides for an eight hour run time at full-load. The fuel tank is vented to atmosphere to prevent over pressurization when the ambient temperature rises and prevents the tank walls from collapsing inwards when fuel is being consumed. A pair of dry-break quick-disconnect hoses supplies fuel to and recovers excess fuel from the diesel generator module.

## 3.0 MASS FABRICATION EFFORT

Fabrication activities occurred in Delivery Orders 4, 8, and 10. New components for the modules (DGM, LCM, ACM, APC, PNM) and the chassis were ordered as necessary. A significant number of components that were procured in previous delivery orders were reused in the DO12 Proof-of-Concept Demonstration. After the ordered components were received, the modules were fabricated using the MASS developmental drawings as a guideline. This section provides summary information regarding the components that were procured, and the fabricated modules and chassis.

### 3.1 ADL Fabricated Modules

Arthur D. Little, Inc, fabricated the DGM, LCM, ACM, and APC.

#### *3.1.1 Diesel Generator Module (DGM)*

The DGM was fabricated using components that were procured mainly under DO4 and DO8. Final design improvements were completed as follows:

- Higher engine power at stable generator speed
- Greater ease of manufacture and maintenance of the electrical cabinet
- Better labeling of the control switches
- Better visibility of the virtual instruments display screen
- Easier insertion of the power plugs into the receptacles on the electrical cabinet
- Integration of the exhaust silencer and the intake air cleaner within the DGM envelope

In addition, other improvements to the DGM were identified, designed and fabricated under DO10 as listed below:

- Re-located the filters for oil, coolant, and fuel so that they are accessible from the control end of the module
- Installed an engine oil drain valve and an oil level sight glass that are accessible from the control end of the module
- Installed a service fitting for the engine coolant system that is accessible from the control end of the module
- Installed latches for the side panels
- Added ventilation grilles to one top panel
- Upgraded the mounting of the coolant tank
- Extended the oil filler tube so that it is accessible from the top of the module
- Installed an electrical connector at the rear end of the module to allow the engine to be jump-started using an external battery

The DGM is shown in Exhibit 3-1.

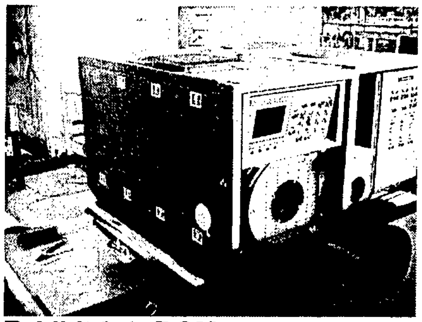


**Exhibit 3-1: DGM**

### *3.1.2 Liquid Cooling Module (LCM)*
The Brassboard configuration of the LCM was modified using components that were procured mainly under DO4 and DO8 as follows:

- The frame was modified to accommodate the horizontal orientation of the heat exchangers.
- The PAO reservoir was modified to accommodate a level sensor and the fill port location was changed.
- A new electrical box was fabricated to incorporate electronic controls and user-friendly front panel

In addition, other improvements to the LCM were identified, designed and fabricated under DO10 as listed below:

- The Rotan pump internal cooling circuit and magnetic coupling were modified to accommodate the higher PAO operating temperatures.
- Higher efficiency fan blades were used on the condenser to improve airflow and avoid stall.
- The controls were modified to reflect improvements.
- Ventilation grilles were added to the sides of the module.
- A thermocouple instrumentation array was added for diagnosing performance.

The LCM is shown in Exhibit 3-2.

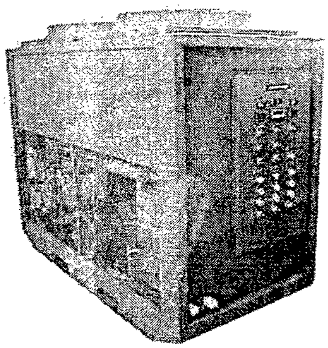
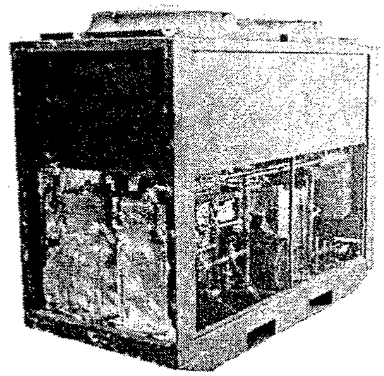



Exhibit 3-2: LCM

### *3.1.3 Air Cooling Module (ACM)*

The Air Cooling Module design was developed under MASS Delivery Order 0006, *Design for Joint Service Use*. Procurement of the Air Cooling module components was split between DO8 and DO10. The module (as seen in Exhibit 3-3) is comprised of many commercial-off-the-shelf items as well as custom fabricated components. The majority of the DO10 effort was in the fabrication of the custom components and the assembly of the components in the frame. Significant efforts were concentrated in the following areas:

- Machining and fabrication of the aluminum high-pressure duct assembly and the associated high-pressure duct work
- Layout and assembly of both the high- and low-pressure refrigeration systems
- Electrical assembly of the main electrical box and control panel
- Fabrication of all structural supports in compliance with limited space requirements
- Troubleshooting and testing complex control strategy

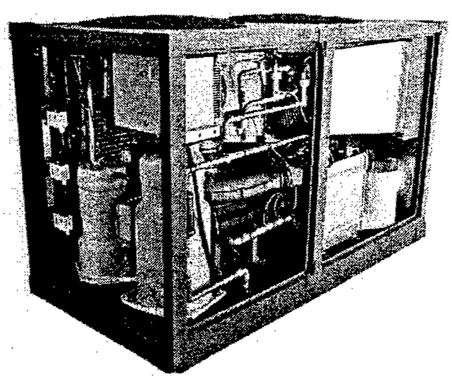
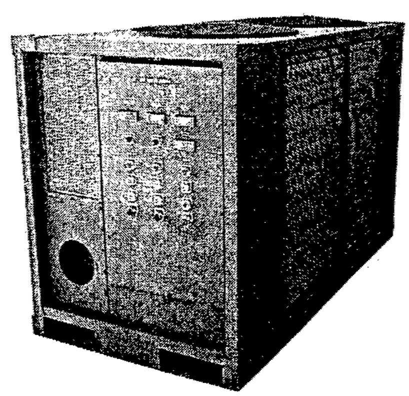



Exhibit 3-3: ACM

### 3.1.4 Avionics Power Converter Module (APC)

Most of the components used in the DO4 and DO8 Brassboard APC were reused in the DO10 Demonstrator module. These included three rectifier and two output Power Electronic Building Blocks (PEBBs), 270 Vdc mode power components, and the cabinet weldment. New components procured and fabricated under DO10 were principally those to implement the 400 Hz output mode and Controlled Current Rectifier (CCR) feature not provided in the Brassboard. The principal additional components included the following:

- Third output PEBB to implement the 400 Hz inverter
- 400 Hz mode transformer
- 400 Hz mode filter inductors and capacitors
- 400 Hz mode output contactor
- 400 Hz ac aircraft ground power cable
- 270 Vdc / 400 Hz ac mode transfer contactor
- Commercial Off-the-Shelf (COTS) Digital Signal Processor (DSP) units for 400 Hz mode and CCR operation
- Custom control circuit boards and components to interface DSP units to sensors and PEBBs
- COTS Modular Signal Conditioners (MSCs) to transmit supervision data to the DGM display

In addition, the DO4 APC chassis and cabinet weldment was modified to incorporate the following features for the DO10 Demonstrator module:

- Top covers with drip-proof seals
- Pivoting casters to facilitate installation and removal of APC from the MASS chassis
- Additional bottom skin panels and internal bracing to enhance cabinet stiffness
- Mounting provisions for 400 Hz mode components
- Recessed mountings for 60 Hz inlet and 400 Hz ac and 270 Vdc outlets
- Recessed mounting for APC supervision and control cable link to the DGM panel

Fabrication of the APC demonstrator as depicted in Exhibits 3-4 and 3-5 encompassed the following tasks:

- Modification of the DO4 Brassboard cabinet weldment
- Fabrication of control circuit boards
- Assembly and preliminary testing of control circuit boards (2)
- Mounting of components in the cabinet weldment
- Wiring of components and subassemblies

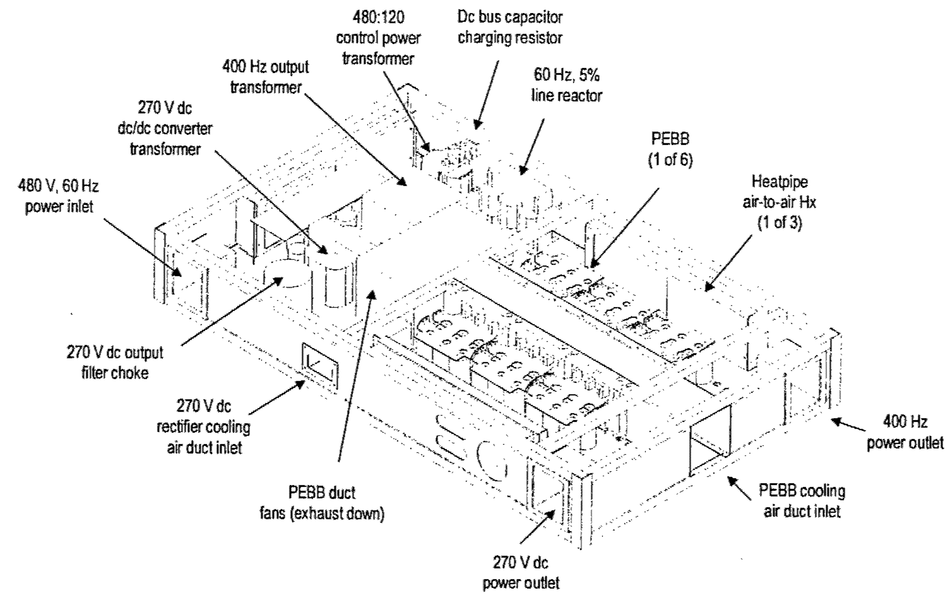



**Exhibit 3-4: Principal Components and Assembly of the APC Demonstrator**

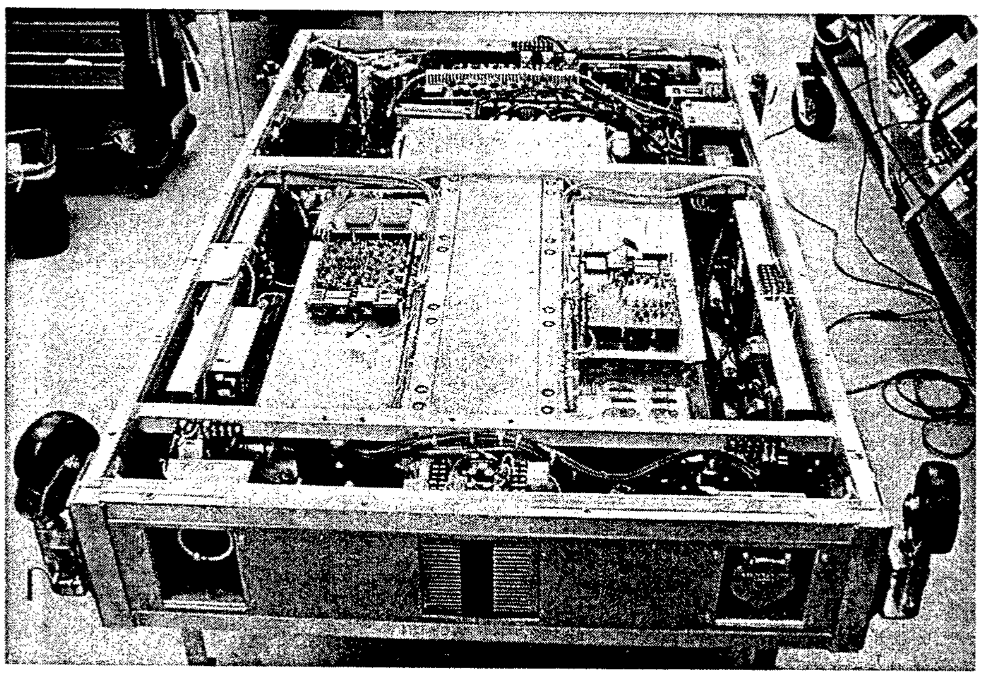


**Exhibit 3-5: Completed APC Demonstrator (without skins)**

## 3.2 Subcontracted Modules

The Pneumatic module and chassis were procured from vendors based on designs and requirements generated by Arthur D. Little, Inc.

### *3.2.1 Pneumatics Module (PNM)*

Fabrication of the pneumatics module was subcontracted to Pacific Consolidated Industries (PCI) located in Santa Ana, CA. PCI was previously awarded a contract by the US Air Force to fabricate the Self Generating Nitrogen Service Cart (SGNSC) and therefore was a logical source to fabricate the PNM (see Exhibit 3-6).

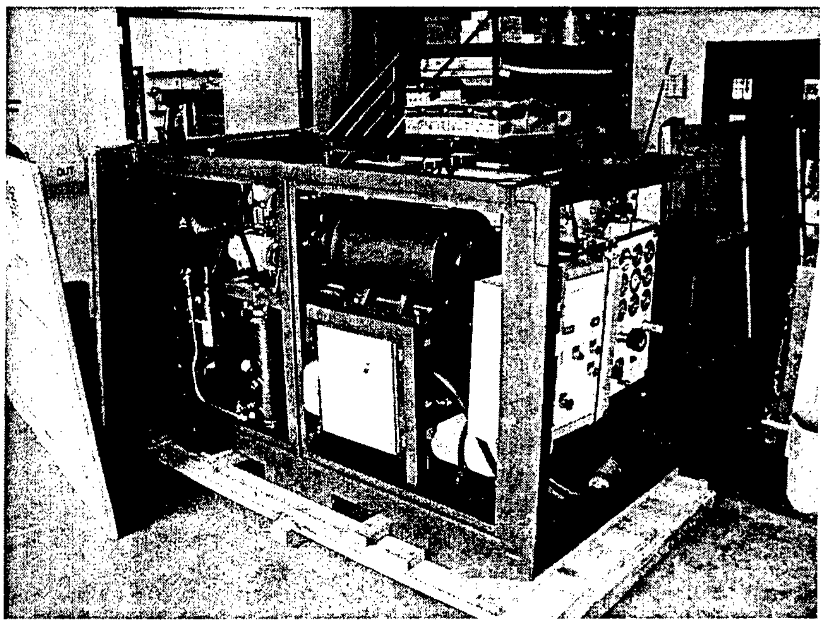


**Exhibit 3-6: Pneumatics Module**

The major components of the PNM include the following:

- Electric motor
- Speed reducer
- Hydraulic pump
- Feed air compressor
- Nitrogen separation membranes
- Booster compressor
- Heat exchangers
- High-pressure storage cylinders

The module was fully tested by PCI (and witnessed by Arthur D. Little personnel) prior to shipping and met all performance requirements. The module arrived at Arthur D. Little, Inc. with significant structural damage and was returned to PCI for damage evaluation and repair. Once the module was fully repaired, PCI again completed an operation and performance test and the module again met all performance requirements.

### *3.2.2 Chassis*

The steerable chassis (see Exhibit 3-7) is rated at 6,000 pounds per axle and 12,000 pounds total, with a design safety factor of 2.0. The overall chassis dimensions are 130 inches long by 86 inches wide by 29 inches high. The chassis construction is made of two main 4 inch by 6 inch by ¼ inch thick tubular steel beams. Two end plates and two cross-connected beams for torsional rigidity tie the beams together. The suspension is made of four leaf springs attached to the frame and four tires sized for the rated load.

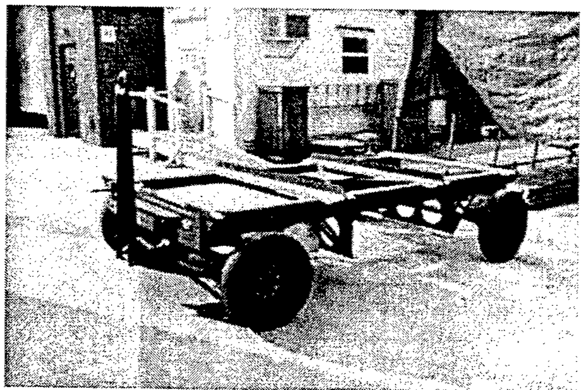


**Exhibit 3-7: MASS Chassis**

A fuel tank is integrated into the chassis to provide fuel for the DGM. The tank is constructed of 316 stainless steel and has a capacity of 80 gallons, which provides for an eight hour run time at full-load. The fuel tank is vented to atmosphere to prevent over pressurization when the ambient temperature rises and prevents the tank walls from collapsing inwards when fuel is being consumed. A pair of dry-break quick-disconnect hoses supplies fuel to and recovers excess fuel from the DGM.

## 4.0 TEST PROGRAM

The modules were tested at Arthur D. Little's Cambridge, MA facility using utility power to verify that their individual performance met the design criteria. The modules were then mounted on the chassis and tested using power generated by the DGM to verify that system performance met the design criteria. The tests were performed according to the "MASS Proof-of-Concept Demonstrator Laboratory Test Plan," Second Edition, dated September 26, 2000.[13]

Once the system testing was successfully completed the chassis and all of the modules were shipped to Edwards AFB for field demonstrations.

### 4.1 Testing at ADL

#### *4.1.1 Diesel Generator Module (DGM)*

The first testing activity during March 2000 for the DGM under DO10 was to verify module performance after Navistar personnel completed software modifications to the engine's electronic control module (ECM). ADL engineers, assisted by two engineers from Navistar, tested the DGM. Test results showed stable frequency, voltage, and current output up to 135 kW. When a 100 kW load was instantaneously applied, engine speed dropped by 19% and steadily climbed back to 1,800 rpm within 7 seconds without overshoot. Load shedding characteristics at 100 kW were also impressive as the engine speed would increase by 5.5% and recover to 1,800 rpm within 3 seconds. A 100 kW load or unload condition exceeds any individual maximum module potential as seen in Exhibit 4-1.

| Module | Maximum Power Required (kW) |
|---|---|
| ACM | 25 |
| LCM | 34 |
| PNM | 32 |
| APC | 75 (e.g., Future Aircraft), 36 (Legacy) |

**Exhibit 4-1: Maximum Module Power requirements**

The second phase of testing during December 2000 was conducted with the purpose of ensuring that the module performance was unchanged after modifications had been made to the new electrical control cabinet. Test results at 25, 50, and 75 kW were very similar to those collected during first phase testing. The DGM supported a maximum steady-state load of 133 kW comparable to the 135 kW value observed in the first phase test.

### 4.1.2 Avionics Power Converter Module (APC)

**270 Vdc output mode testing and results**

This aspect of APC operation had been comprehensively tested during the DO4 Brassboard program and the test findings are substantially identical with those reported in the DO4 Final Report. The only significant change indicated by the Brassboard testing results was the need to add a minimum "ballast" load to assure voltage regulation stability when an external step load is applied from a zero load condition or when there is a step unloading to a zero load condition. An internal switched 2.7 kW ballast load was installed in the Demonstrator with control provisions to disconnect it when an external load was present so as to minimize unnecessary dissipation within the APC. However, during testing it was found that noise generated by Space Vector Pulse Width Modulation (SVPWM) high voltage switching interfered with operation of the sensitive external load detection circuit. Subsequent testing indicated that only half of the planned ballast loading (1.35 kW) was sufficient to achieve voltage regulation stability. This level of dissipation on a continuous basis was deemed acceptable for the Demonstrator and it was decided to connect only half of the originally planned ballast load on a fixed basis.

As previously found during Brassboard testing, the COTS ASIC controller chip used for 270 Vdc output PEBB control provides excellent steady state and transient voltage regulation. Exhibit 4-2 reports the very small variation in output voltage for steady state loadings from 0 to 100% of nominal 70 kW capacity. These deviations are well within the limits of MIL-STD 704E. For these tests the output voltage was adjusted for 260 Vdc (3% below 270 Vdc) at no load to accommodate the lower unregulated dc link voltage provided by the uncontrolled rectifier. Had a 3% lower resistance load bank setting been available, it would have been possible to achieve the 70 kW output power requirement.

| Load bank step | Input line voltage | Output voltage | Output current | Output power |
|---|---|---|---|---|
| % rated | $V_{rms}$ L-L | $V_{dc}$ | $A_{dc}$ | kW |
| 0 | 484.6 | 260.2 | 0 | 0 |
| 20 | 484.3 | 260.2 | 50.1 | 13.0 |
| 40 | 483.5 | 260.3 | 100.4 | 26.1 |
| 60 | 483.0 | 260.6 | 150.4 | 39.2 |
| 80 | 482.7 | 261.6 | 200.5 | 52.3 |
| 100 | 485.8 | 261.2 | 245.2 | 64.1 |

**Exhibit 4-2: 270 Vdc output mode steady-state test data – 262 Vdc no load set point**

The oscillogram presented in Exhibit 4-3 reports output voltage disturbance for a 64 kW load application. The deviations are well within limits defined by figure 10 of MIL-STD 704E. Note that the difference in steady state no load and full load voltage would be much smaller than indicated if the controlled current rectifier were operational and maintained a higher internal dc link voltage.

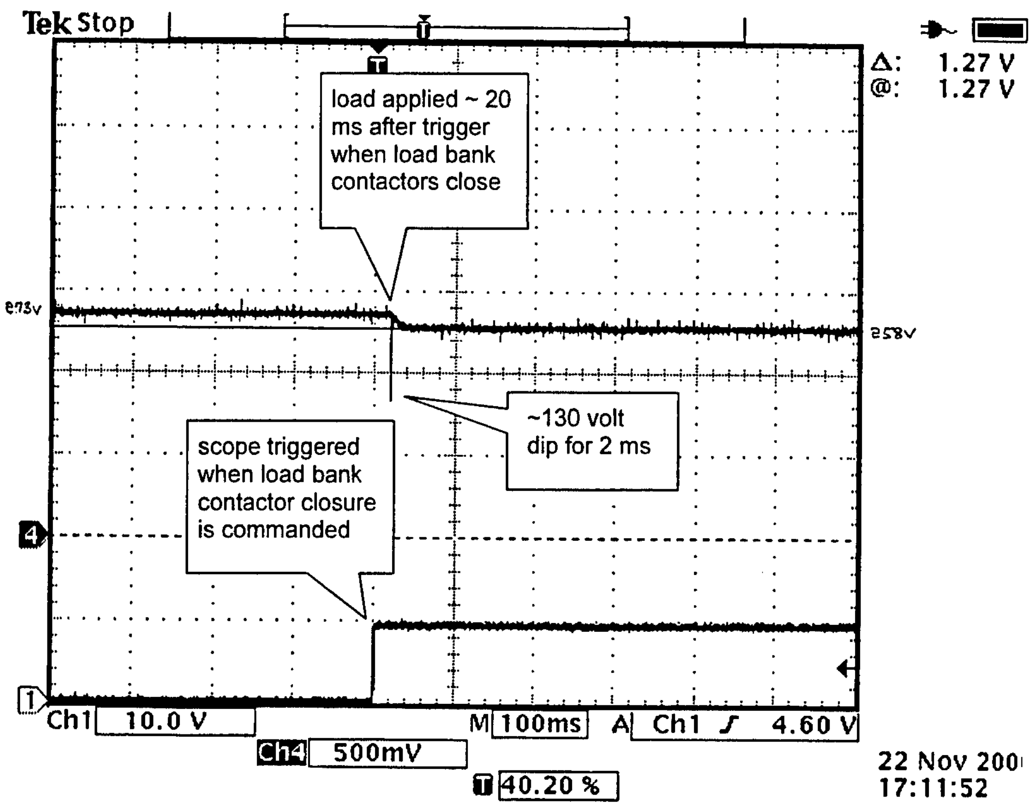



**Exhibit 4-3: 270 Vdc mode output voltage disturbance due to 70 kW load step**

The oscillogram presented in Exhibit 4-4 reports output voltage disturbance for a 64 kW load rejection. The deviations are well within limits defined by figure 10 of MIL-STD 704E. Note again that the difference in steady state no load and full load voltage would be much smaller than indicated if the controlled current rectifier were operational and maintained a higher internal dc link voltage.

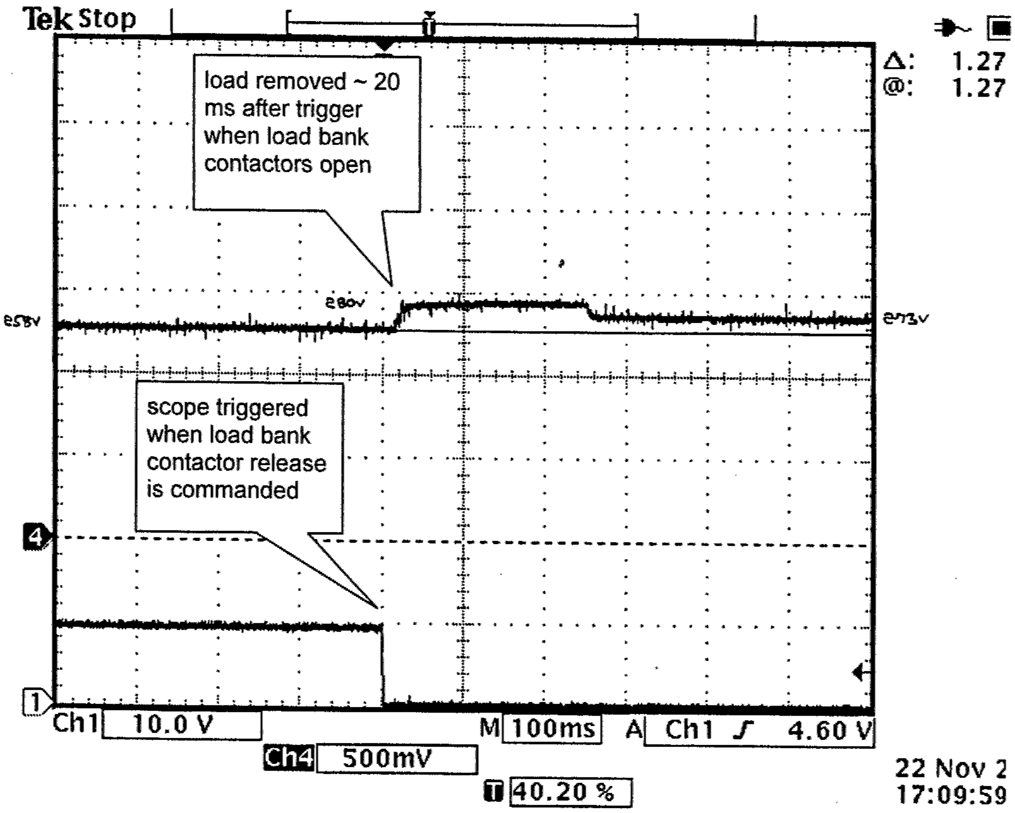



**Exhibit 4-4: 270 Vdc mode output voltage disturbance due to 70 kW load rejection**

**400 Hz output mode testing and results**

Testing of this new APC feature was initially conducted with reduced input voltage power to safely identify problems with minimal risk of damage to components. The principal problems were associated with the voltage feedback input to the output DSP and were readily corrected.

The need for ballast loading to assure stable voltage regulator operation under no load conditions was anticipated and provisions made for installation of a switched 1.6 kW internal ballast load. As in the case of the 270 Vdc mode, it was determined that a smaller ballast load was sufficient – in this case only 0.85 kW. Again it was decided to avoid problems with noise disturbance of the external load detection circuit and this relatively small ballast load was permanently connected across the 400 Hz ac output. The external load detector circuitry on the output control circuit board was left in place but is not active.

With this small ballast load there was too little damping to contain the transient voltage at the 400 Hz transformer primary at the start up of inverter switching. The consequential high PEBB transient current caused the PEBB protective overcurrent detectors to shutdown their switching operation and this in turn triggered other APC protective circuits to trip and disconnect the incoming power. This difficulty was overcome by adding a soft start feature to the output DSP code which ramps up the output voltage over an interval of approximately 1.5 seconds and thus avoids the startup trip.

The intensity of acoustic noise developed by magneto restriction of the 400 Hz output transformer core when operated at full voltage was unexpected. Consultation with the vendor confirmed that factory tests had been conducted at full voltage and that a very high level of noise had been observed. The vendor advised that high power density 400 Hz transformers of this type typically produce a very high noise level due to high core flux loading. The Demonstrator transformer is louder than a production unit might be because it was intentionally fabricated without bonding of the split core faces or varnish impregnation of the core to enable rebuilding if necessary.

After correcting these initial start-up problems, the 400 Hz ac output mode of the Demonstrator was tested at various power levels within its 32.5 kVA continuous output rating. The custom load bank designed and fabricated for laboratory testing of both 270 Vdc and 400 Hz ac modes was used for these tests as it provided for convenient remote switching of load steps and a trigger signal for recording load step transients. Tests for five minute and five second overloading at design ratings of 50 and 65 kW respectively were conducted with an Avtron "suitcase" loadbank unit provided as Government Furnished Equipment (GFE). Actual five minute and five second overloads achieved were 54 and 74 kW.

The results of continuous load tests are presented in Exhibit 4-5 and demonstrate the high degree of load voltage regulation achieved by the DSP algorithm. Voltage regulation could be improved further by adding an integral term to the regulation algorithm, which presently incorporates only proportional control.

| Load Bank Nominal | Input Line Voltage | Input Line Current | Input Apparent Power | Input Real Power | Output Voltage | Output Current | Output Power | Effi-ciency | Input Power Factor |
|---|---|---|---|---|---|---|---|---|---|
| % rated | $V_{rms}$ L-L | $A_{rms}$ | kVA | kW | $V_{ac}$ | $A_{ac}$ | kW | % | % |
| 0 | 483.5 | 4.2 | 3.5 | 2.5 | 200 | 0 | 0 | 0 | 71.4 |
| 10 | 483.0 | 8.3 | 6.9 | 5.2 | 201 | 8.4 | 2.9 | 56.3 | 75.4 |
| 25 | 482.7 | 15.9 | 13.3 | 10.2 | 202 | 23.0 | 8.1 | 79.2 | 76.7 |
| 50 | 482.3 | 25.7 | 21.5 | 18.0 | 201 | 45.3 | 15.8 | 87.5 | 83.7 |
| 75 | 481.9 | 40.2 | 33.6 | 25.7 | 199 | 67.3 | 23.2 | 90.2 | 76.5 |
| 100 | 481.3 | 52.8 | 44.0 | 36.2 | 197 | 96.4 | 32.9 | 90.8 | 82.3 |

**Exhibit 4-5: 400 Hz ac output mode steady-state test data**

Losses at full load equal 36.2 – 32.9 = 3.3 kW made up of the components estimated in Exhibit 4-6.

| Loss Component | Estimated Loss (W) |
|---|---|
| Fans | 200 |
| PEBB dc link capacitor bleeder resistors | 250 |
| Contactors, relays, 24 Vdc supply | 200 |
| 400 Hz output transformer copper and iron | 300 |
| PWM filter inductor and capacitor | 100 |
| Fixed ballast load | 850 |
| PEBB conduction and switching | 1,400 |
| *TOTAL* | ***3,300*** |

**Exhibit 4-6: Estimated 400 Hz ac mode APC losses**

Exhibit 4-7 shows the 400 Hz ac waveform and Fast Fourier Transform (FFT) harmonic analysis at an illustrative 75% load, which exhibits a very low degree of distortion relative to an ideal sinusoid. The FFT indicates very small components at the 2nd and 4th harmonics. The 5th (at 2,000 Hz) is the largest harmonic visible in this analysis and has an amplitude that is approximately within the fundamental of Figure 3 referenced by Table I of MIL-STD 704E, which permits a maximum distortion of 3.16 Vrms relative at 2,000 Hz or 2.8% when normalized to an allowable distortion voltage to a base of 115 Vrms.

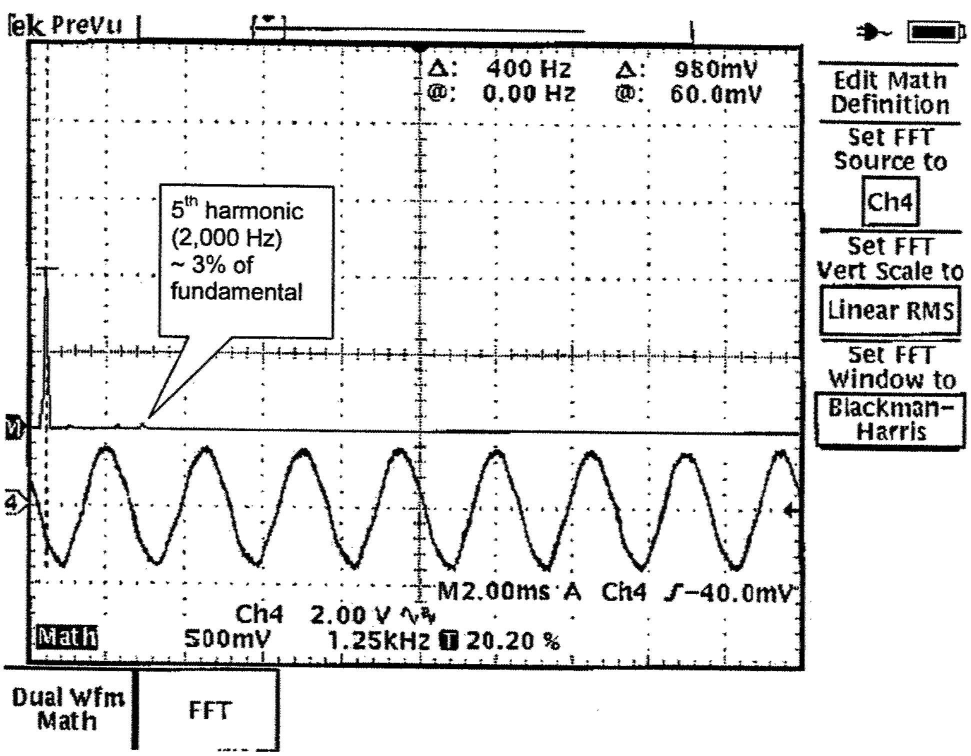



**Exhibit 4-7: 400 Hz ac output voltage waveform at 75% load**

The oscillogram presented in Exhibit 4-8 reports the output voltage disturbance for a step application of a 75% rated load (24 kW resistive). The brief, sub-cycle transient deviation is well within the limits defined by Table I and Figure 4 of MIL-STD 704E.

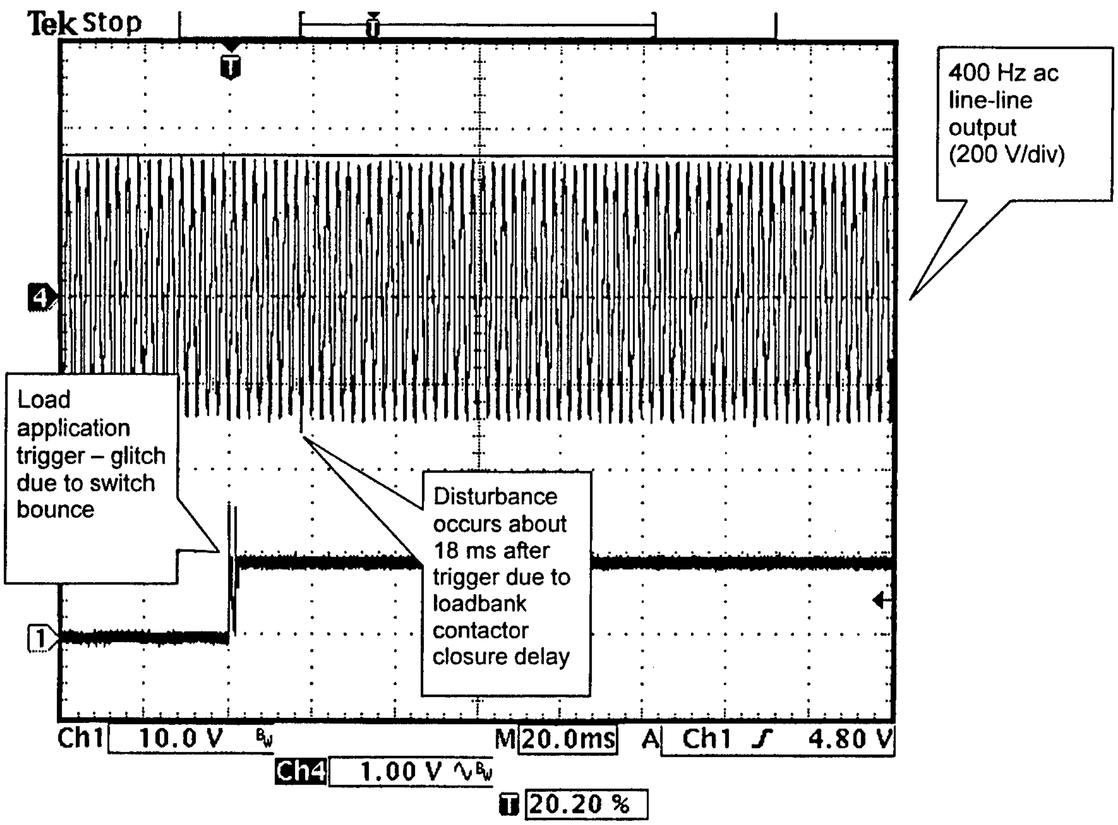



**Exhibit 4-8: 400 Hz ac output voltage disturbance on application of 75% rated load step**

The oscillogram presented in Exhibit 4-9 depicts the observed output voltage disturbance for a step dump of 75% rated load (24 kW resistive). While this load dump transient disturbance has a longer duration (approximately 20 ms) than that observed for a step load application it is also well within the limits defined by Table I and Figure 4 of MIL-STD 704E.

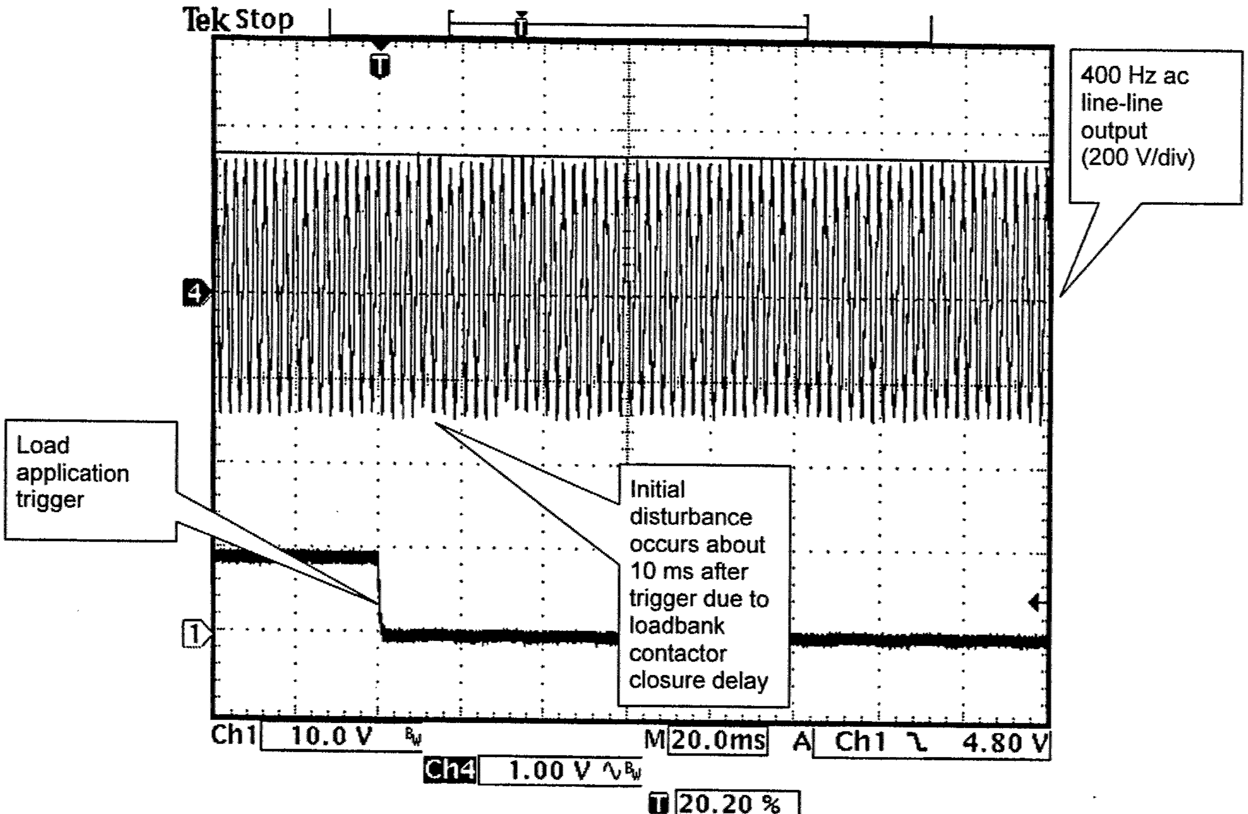



**Exhibit 4-9: 400 Hz ac output voltage disturbance due to 75% rated load rejection**

Exhibit 4-10 reports the results of five minute and five second overload load tests at nominal 55 and 75 kW respectively and indicates that the APC was able to maintain output voltage at these power levels. Waveform quality was not compromised relative to that observed under normal load conditions. The principal limitation on sustained operation at these power levels is dissipation in the 400 Hz output transformer which was sized for a 32.5 kVA rating to meet the largest continuous demand requirement (C-17A transport) of the MASS program as indicated in the aircraft power requirements summary by Computer Sciences Corporation (CSC), provided to ADL at the start of the MASS program.

| Load Bank Setting KW | Output Voltage $V_{trms}$ | Output Current $A_{trms}$ | Output Power kW |
|---|---|---|---|
| 55 | 197 | 159 | 54.3 |
| 75 | 197 | 217 | 74.0 |

**Exhibit 4-10: 400 Hz ac output mode short term overload test data**

**Thermal Management Evaluation**

This test was run for approximately 1.5 hours, which was sufficient to determine temperature rise trends. Temperature rises were computed using relevant internal or external ambient temperatures as reference bases.

The results shown in Exhibit 4-11 indicate that the PEBB heat sink rise has stabilized at approximately 27 °C which is in very good agreement with the 29 °C value projected by a previously conducted computational fluid dynamics analysis. Front internal air temperature rise near the control and digital signal processor circuit boards settled out at approximately 10 °C which is in agreement with the performance expected of the heatpipe air-air heat exchangers under the thermal loading in this portion of the cabinet.

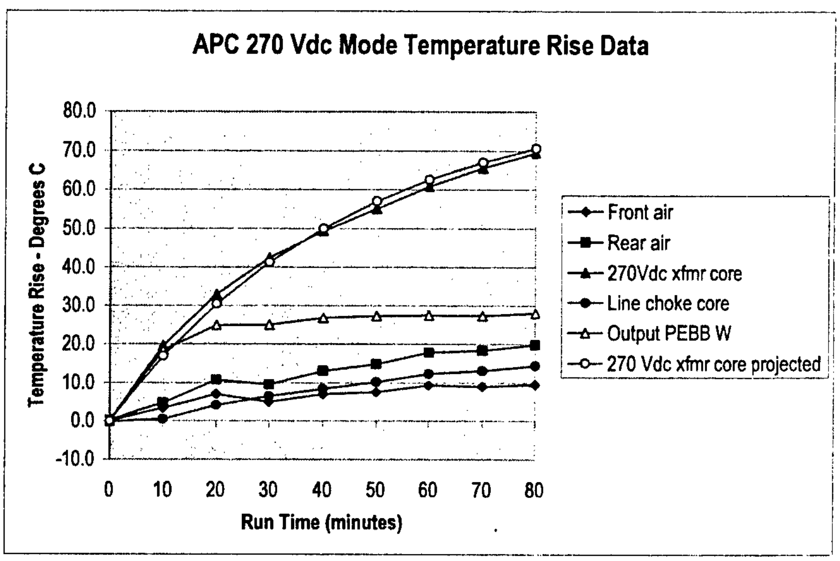



**Exhibit 4-11: APC temperature rise data for 270 Vdc operation at 75% rated load**

Rear internal air temperature rise did not stabilize during the test period because it is driven by 270 Vdc output transformer temperature rise that also is still increasing. However, it appears that rear air temperature rise will stabilize at approximately 25 °C – about 10 °C higher than desired to avoid degradation of power capacitor lifetime under worst-case external ambient conditions (55 °C = 131 °F).

At a 75% test power level the 270 Vdc output transformer core rise is projected to settle at 85 °C – substantially less than the transformer's design rise of 115 °C at 100% rated power.

### *4.1.3 Liquid Cooling Module (LCM)*

Testing of the LCM was completed in two stages. The testing in early October 2000 addressed the Forward cooling (low temperature/low cooling capacity) mode. The testing in early November 2000 addressed the Aft cooling (high temperature/ high cooling capacity) mode. In addition to the issues of measurements of cooling capacity, the temperature control capability of the LCM was also verified.

#### Forward cooling mode/ low temperature-low capacity testing

The results of the capacity testing for the Forward cooling mode of operation are shown in Exhibit 4-12. The capacity ranges from 140-225 kBtu/hr with a mean value of 15.4 tons of refrigeration. The PAO delivery temperature (see Exhibit 4-13) is 55 °F, well below the maximum 59 °F temperature requirement. The detailed temperatures for PAO supply and return are presented in Exhibit 4-14. The time period for the temperature fluctuations is approximately 30 minutes and verifies that the automatic cycling operation of the expansion, de-superheating, and hot gas bypass valves is satisfactory.

In addition to the Forward cooling mode tests, the Precooler capacity without refrigeration system was measured. The capacity results are presented in Exhibit 4-15. The Pre-cooler alone will be able to provide on the order of 75 kBtu/hr of cooling. Depending on the load requirement and the ambient temperature this may well be sufficient to meet the overall cooling demand. The temperature data is shown in Exhibit 4-16. This is a high efficiency mode of operation as the only energy expended is condenser fans and PAO pump.

#### Aft cooling mode/ high temperature-high capacity testing

The results of the capacity testing for the Aft cooling mode of operation are depicted in Exhibit 4-17. The LCM delivers approximately 380 kBtu/hr or 31.6 tons of cooling capacity. The PAO delivery temperature is presented in Exhibit 4-18, with PAO temperature running at approximately 100 °F, well below the 122 °F limit.

The results of the LCM testing verify that the cooling capacity and temperature requirements for the Module have been met.

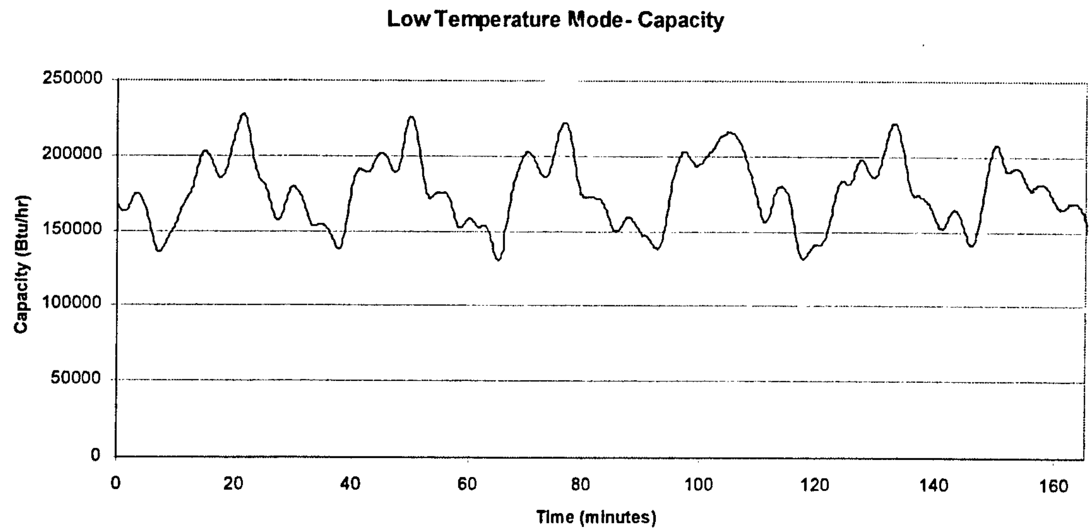



**Exhibit 4-12: Low Temperature Mode – Capacity**

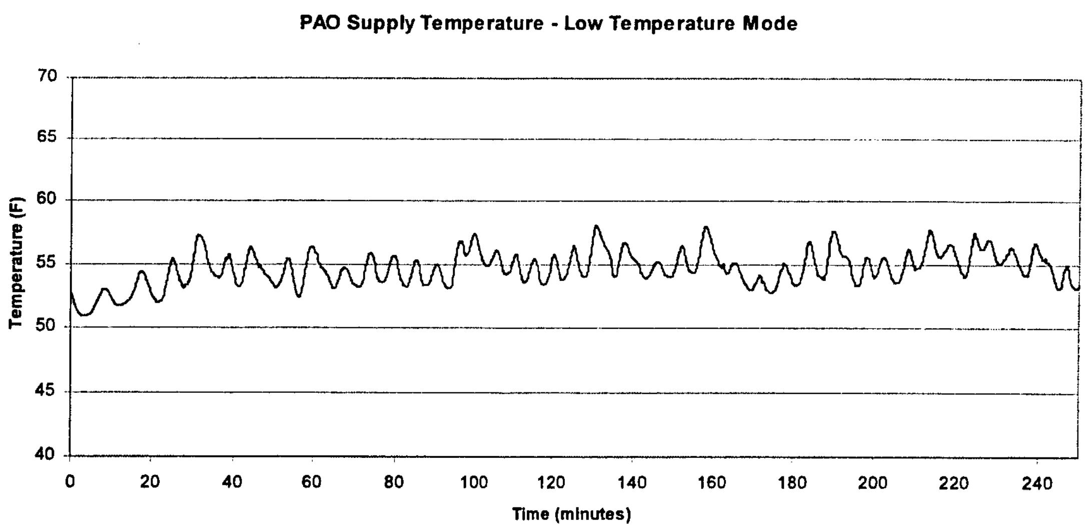



**Exhibit 4-13: PAO Supply Temperature – Low Temperature Mode**

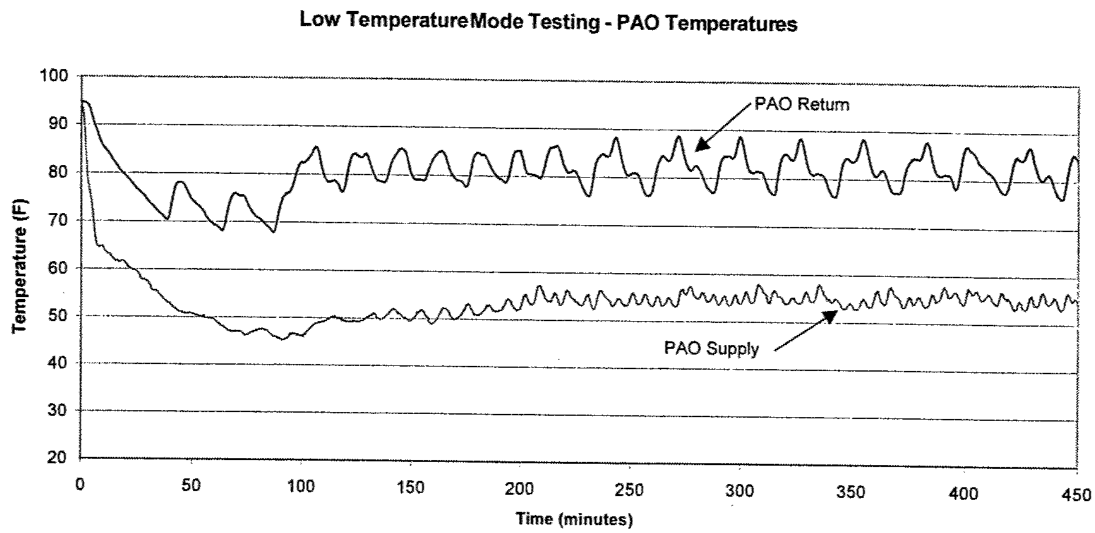



**Exhibit 4-14: Low Temperature Mode Testing – PAO Temperatures**

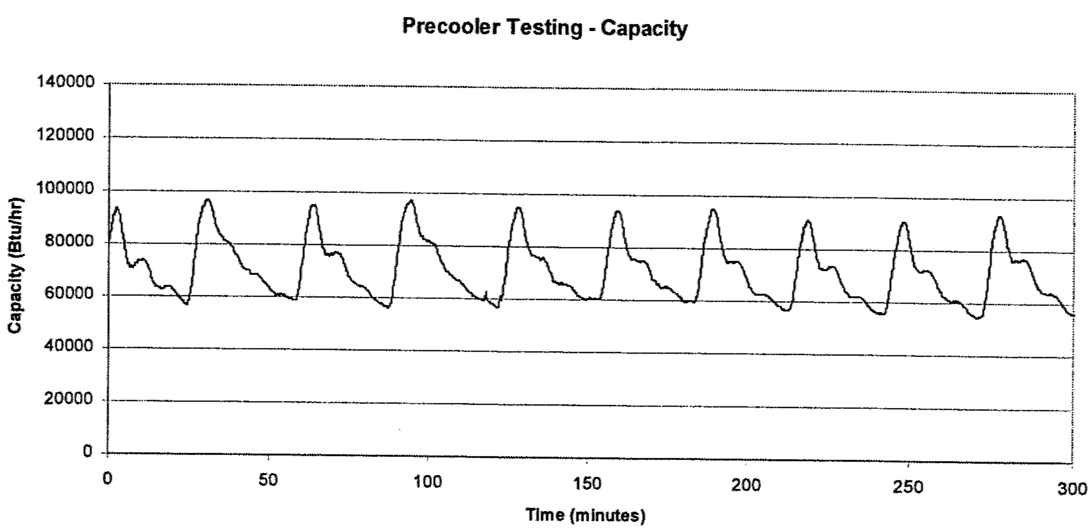



**Exhibit 4-15: Precooler Testing – Capacity**

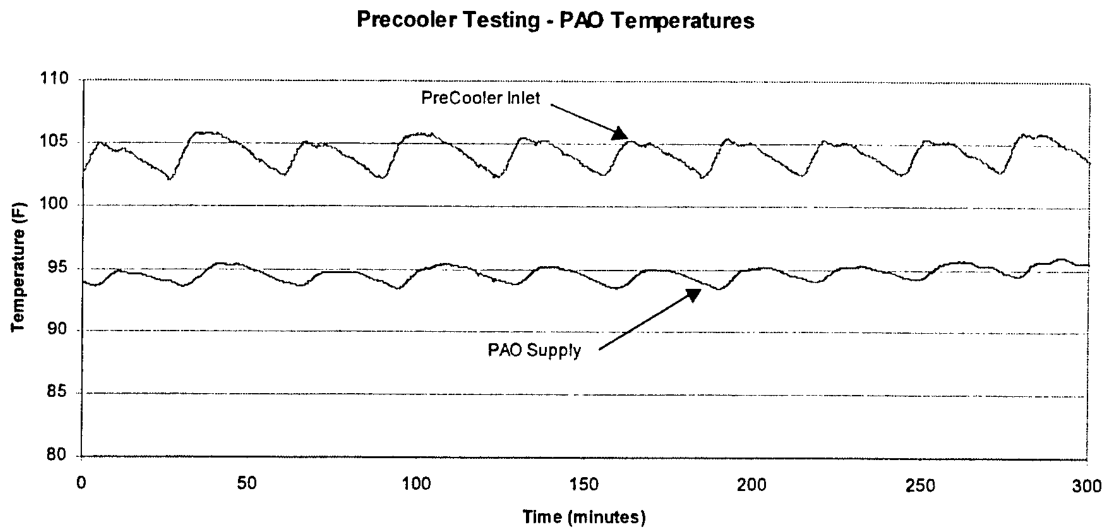



**Exhibit 4-16: Precooler Testing – PAO Temperatures**

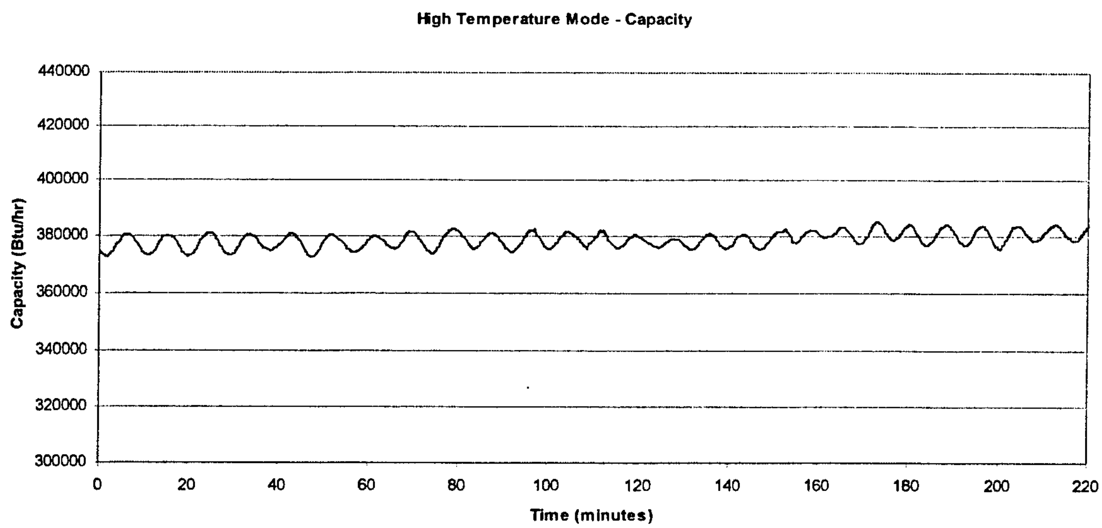



**Exhibit 4-17: High Temperature Mode – Capacity**

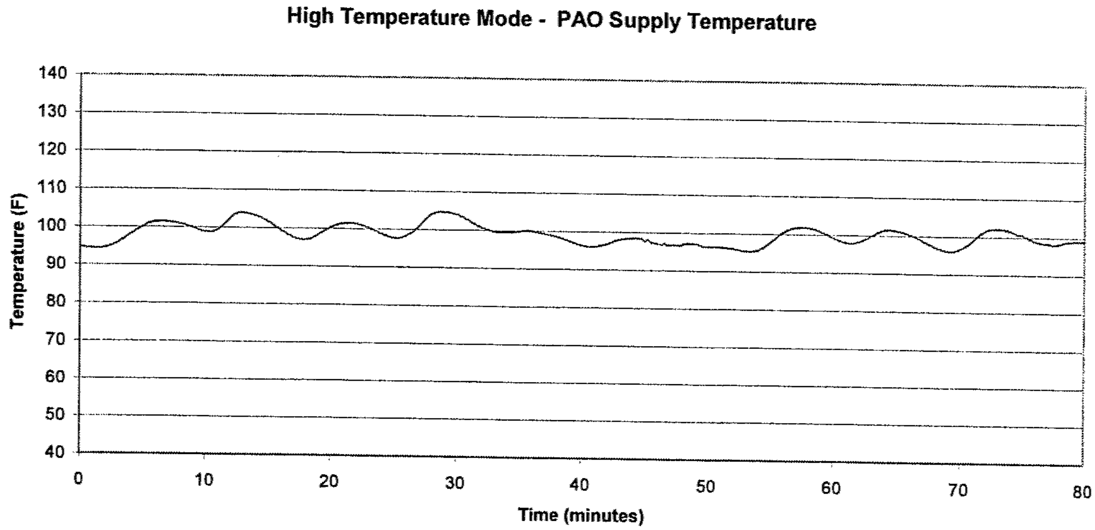



**Exhibit 4-18: High Temperature Mode – PAO Supply Temperature**

### *4.1.4 Air Cooling Module (ACM)*

Operational testing of the Air Cooling Module was completed in two stages. First, the performance of the various subsystems was verified, then the system as whole. The air handling system, both refrigeration systems, and the control system performed as expected. Adjustment of both thermal expansion valves was necessary to improve system capacity output. Both hot gas control valves also required adjustment for improved control.

The air handling system, consisting of the high-speed centrifugal blower, ductwork, and mass flow meter, was tested first. Confidence in the performance of the airflow system is critical to the successful adjustment of the refrigeration systems. Resistors to limit the rotational speed of the blower were added to the control panel at the request of Invincible Airflow Systems to minimize risk of damage to the blower. The performance of the blower was verified at an ambient temperature of 70 °F. The results are shown in Exhibit 4-19.

| Blower Setting (% speed) | Estimated Blower rpm | Airflow Rate (lbs/min) | Delivery Pressure (psig) |
|---|---|---|---|
| 5 | 2,350 | -- | 0.0 |
| 25 | 5,700 | 35 | 0.4 |
| 50 | 9,900 | 52 | 1.0 |
| 75 | 14,100 | 68 | 3.0 |

**Exhibit 4-19: Blower Performance Results**

During testing of the air handling system a discrepancy in the mass flow meter output was noticed. It was determined that high frequency electrical noise generated from the blower drive interfered with the mass flow meter display, resulting in inaccurate displays. The problem was resolved by adding noise reduction capacitors to the signal wires. A more robust measurement device will be recommended on any future versions of the ACM.

The ACM was designed to meet the aircraft cooling requirements at two extreme ambient conditions, warm/humid 97DB/87WB, and hot/dry 125DB/75WB. These two extremes presented some difficulty for our testing facility. The designed latent cooling capacity of the module is significant, enough to overpower our conventional industrial humidification system. Performance of the two refrigeration systems was measured at less than required humidity. Enough data was gathered and analyzed to feel confident that the system will meet the high humidity requirement.

The Air Cooling Module is comprised of two virtually independent refrigeration systems, the low-pressure and high-pressure systems. The distinction in pressure refers to the cooling air (as opposed to refrigerant pressure). The following exhibits show the test results for each system individually. Each refrigeration system's cooling capacity was measured as well as temperature control performance.

The refrigeration capacity test results were as expected. The low-pressure system capacity is shown in Exhibit 4-20. This system has the capability for a higher cooling capacity with the presence of higher humidity. The limitations of our test facility resulted in a lower full-load evaporator temperature than would exist in the true warm/humid environment.

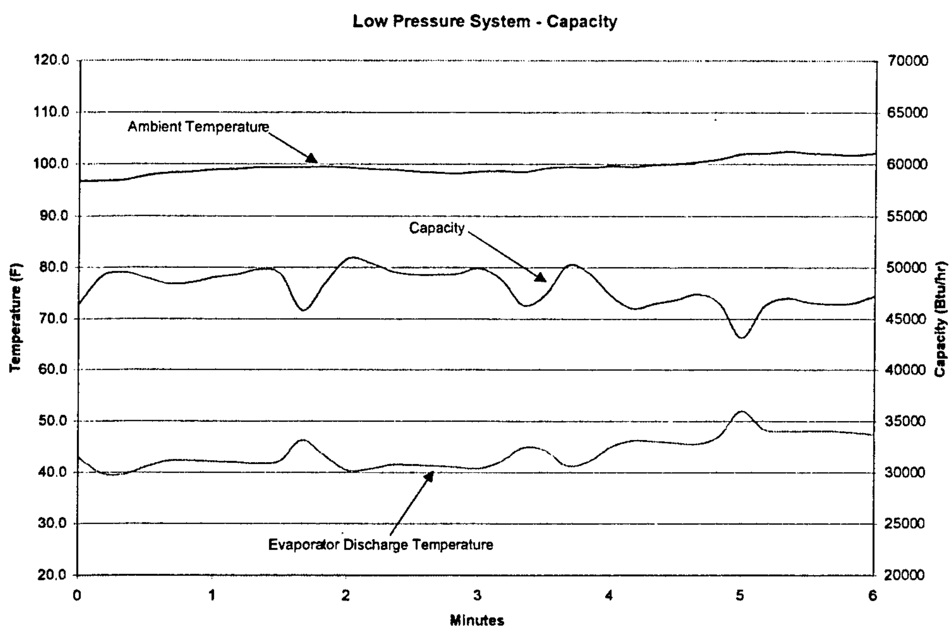



**Exhibit 4-20: Low Pressure Capacity**

The high-pressure system capacity, shown in Exhibit 4-21, was encouraging; proving that our high-pressure duct design provides good airflow distribution across the coil. The high-pressure control system also performed well as shown Exhibit 4-22. The activity of the hot gas control valve is evident by the cycling condensing temperature of both systems. The low temperature system control is shown in Exhibit 4-23. The fluctuations of this temperature are of less importance than the actual module discharge temperature, as the high-pressure control dampens them before leaving the module.

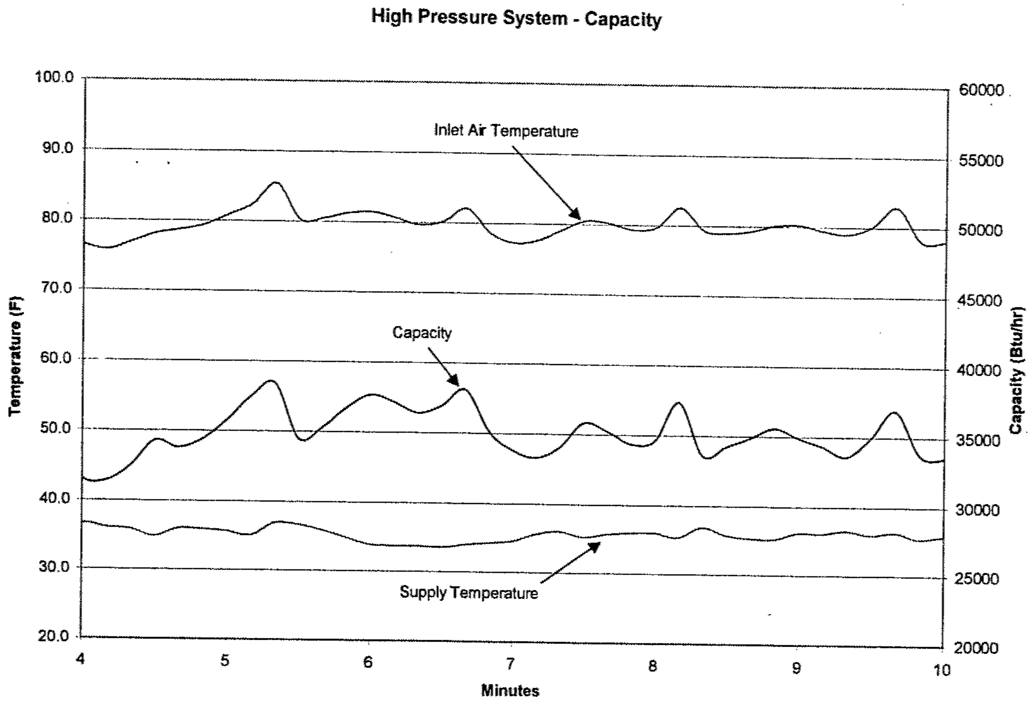



**Exhibit 4-21: High Pressure Capacity**

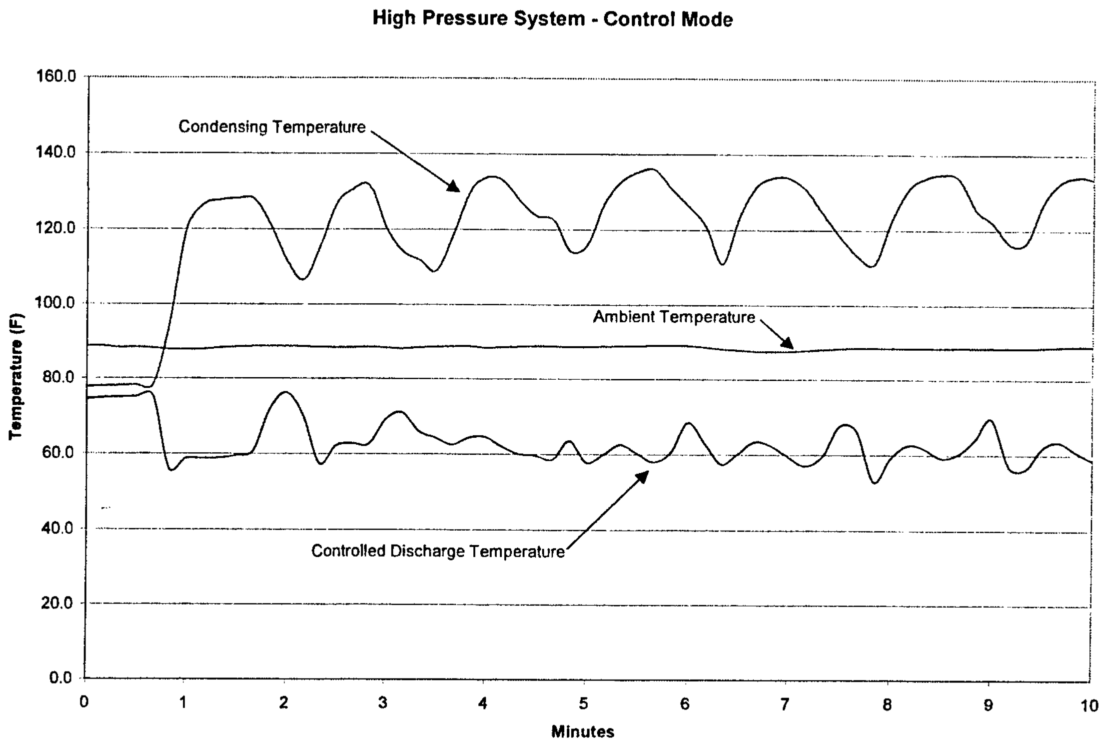



**Exhibit 4-22: High Pressure Control**

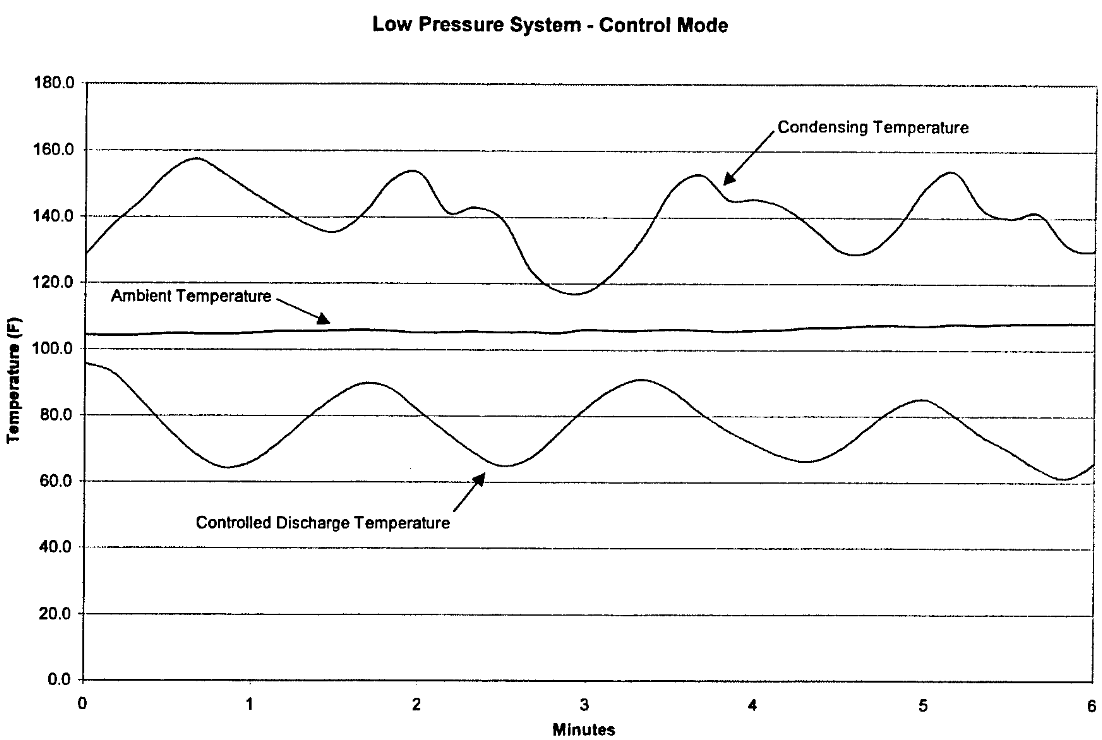



**Exhibit 4-23: Low Pressure Control**

It should be noted that testing was performed with the condenser fans operating at 2/3 of their rated speed. This insures some margin in the system performance at higher ambient temperatures.

### *4.1.5 Pneumatics Module (PNM)*

The pneumatics module underwent operational and performance testing at PCI's Santa Ana, CA facility prior to shipping and met all performance requirements. Exhibit 4-24 details the module performance requirements and the measured performance.

| Tested Parameter | Requirement | Measured Performance |
|---|---|---|
| Time to 95.5% $N_2$ purity | 15 minutes | 1 minute 30 seconds |
| Time to begin filling high pressure cylinder | 30 minutes | 21 minutes 15 seconds |
| Time to fill cylinder to 5,500 psig | 35 minutes | 28 minutes 15 seconds |
| $N_2$ flowrate | 15.0 scfm | 16.55 scfm |

**Exhibit 4-24: PNM Test Results**

Once the high-pressure cylinder reached 5,500 psig, pressure was manually released (to simulate nitrogen usage) at a 5-10 scfm rate. Nitrogen release continued and the low-pressure switch automatically activated the booster pump when cylinder pressure dropped to 5,150 psig. Nitrogen purity varied between 95.7% and 95.9% during booster pump operation (when the cylinder was being re-charged). Once the cylinder pressure reached 5,550 psig the high-pressure switch automatically turned the booster pump off.
The module operated in this nitrogen release mode for three hours to ensure that all system controls functioned properly.

### *4.1.6 Chassis*

The chassis related tests included measurements of module induced chassis deflection and calibration of the fuel tank level sensor.

#### Chassis Deflection

The chassis can accommodate up to 6,000 pounds per axle, (12,000 pounds total) with a 2.0 design factor of safety. The chassis height (without mounted modules or fuel) is 28.5 inches from the module mounting surface (the high-density polyethylene slides) to ground level with tires inflated to 95 psig. Total chassis deflection with the DGM, LCM, ACM, and a full tank of fuel is 2.5 inches. Ground clearance at this fully loaded condition is 6.0 inches. Tire and leaf spring compression was calculated during chassis design and determined to contribute equally to the total deflection value. This was confirmed after fabrication.

#### Fuel Tank Level Sensor

The chassis mounted fuel tank capacity is listed at 80 US gallons but the tank's height-based cross section varies due to tank geometry. The fuel tank mounted fuel sensor functions by sending a DC voltage output to the DGM mounted VI Display. The DC voltage output varies according to fuel height as seen in Exhibit 4-25.

| Depth of Fuel (inches) | Fuel Volume (gallons) | Fuel Sensor Output (volts) |
|---|---|---|
| 0.00 | 0.00 | 0.000 |
| 0.50 | 0.77 | 0.000 |
| 1.00 | 1.54 | 0.195 |
| 1.50 | 2.31 | 0.403 |
| 2.00 | 3.66 | 0.600 |
| 2.50 | 5.02 | 0.814 |
| 3.00 | 6.37 | 1.026 |
| 3.50 | 8.30 | 1.243 |
| 4.00 | 10.23 | 1.439 |
| 4.50 | 12.16 | 1.660 |
| 5.00 | 14.67 | 1.847 |
| 5.50 | 17.19 | 2.061 |
| 6.00 | 19.70 | 2.258 |
| 6.50 | 22.78 | 2.470 |
| 7.00 | 25.86 | 2.655 |
| 7.50 | 28.94 | 2.866 |
| 8.00 | 32.02 | 3.062 |
| 8.50 | 36.13 | 3.284 |
| 9.00 | 40.23 | 3.486 |
| 9.50 | 44.34 | 3.693 |
| 10.00 | 48.66 | 3.896 |
| 10.50 | 52.98 | 4.084 |
| 11.00 | 57.31 | 4.300 |
| 11.50 | 61.63 | 4.480 |
| 12.00 | 65.87 | 4.700 |
| 12.50 | 70.11 | 4.890 |
| 13.00 | 74.36 | 5.090 |
| 13.50 | 77.97 | 5.280 |
| 13.82 | 81.57 | 5.421 |

**Exhibit 4-25: Fuel Sensor Vdc Output**

The fuel tank volume was calculated in vertical increments of 0.50 inches over the entire tank height (as seen in Exhibit 4-25). An algorithm was then written for the VI Display computer to convert the fuel sensor Vdc output into the volume of fuel remaining in the tank.

### *4.1.7 System*

A system test was completed where the DGM provided electrical power to the APC, LCM, and ACM. DGM power capacity was sized to meet the projected demands of function modules for prospective MASS configurations determined by the IPT. Data gathered during DO10 confirmed that this objective had been met. Worst-case demands of function modules are presented in Exhibit 4-26.

| Function Module | Power Demand (kW) |
|---|---|
| ACM – Air Cooling Module | 25 |
| LCM – Liquid Cooling Module | 34 |
| APC – Avionics Power Converter Module | 36 – 400 Hz ac mode |
| APC – Avionics Power Converter Module | 75 – 270 Vdc mode |
| PNM – Pneumatics Module | 32 |

**Exhibit 4-26: Function Module Power Demands**

Exhibit 4-27 illustrates MASS power demands relative to DGM capacity for two illustrative configurations.

| Cart Configuration | Module Suite | Maximum Module Demands (kW) | Suite Total (kW) |
|---|---|---|---|
| **Legacy Aircraft** | | | |
| | ACM | 25 | |
| | APC | 36 | **93** |
| | PNM | 32 | |
| | | | |
| **Future Aircraft** | ACM | 25 | |
| | LCM | 34 | |
| | APC | 75 | **134** |
| | | | |

**Exhibit 4-27: MASS Power Demands for Two Illustrative Configurations**

The measured DGM output capacity, determined by engine capability, is 135 kW and will support the larger of the two configurations illustrated in Exhibit 4-27.

## 4.2 Field Testing

MASS Field Testing was completed successfully at Edwards AFB using actual aircraft, including the F-15, F-16, and B-52. These field tests proved the viability of the MASS modular concept and demonstrated key performance requirements. In addition, we received positive feedback on the following specific MASS features:

- Easy to use controls
- Much improved display in comparison with current AGE
- Improved and ease of DGM maintenance procedures

Exhibit 4-28 provides the list of modules and aircraft tested.

| Airframe | Module | | | |
|---|---|---|---|---|
| | DGM | APC | ACM | PNM |
| B-52 | √ | √ | | √ |
| F-15E | √ | -60 | √ | |
| F-16 | √ | √ | | |
| F-15A | √ | √ | √ | |

**Exhibit 4-28: Airframes and Modules Tested**

### *4.2.1 B-52 Field Testing*

Initial field testing of the MASS demonstrator was conducted with a B-52 aircraft. Preliminary discussions with B-52 maintainers determined that the cooling air inlet was beyond the reach of available flexible ducts and that an adapter to accommodate its large diameter (approximately 12 inches) was not available. Hence tests would focus on operation of the DGM and demonstrating delivery of 400 Hz electrical power from the APC and high-pressure nitrogen from the PNM.

The MASS demonstrator was towed to the flight line, positioned along side the aircraft as shown in Exhibit 4-29. The DGM was warmed up at idle speed (700 rpm) and then brought to operating speed (1,800 rpm). Observers remarked favorably on the readability of the virtual instruments display (VID). DGM noise level was modest in comparison to other ground power carts of lesser power capacity (e.g., -60 or –86) and it was observed that a one-on-one conversation could be conducted while standing in close proximity to the unit.

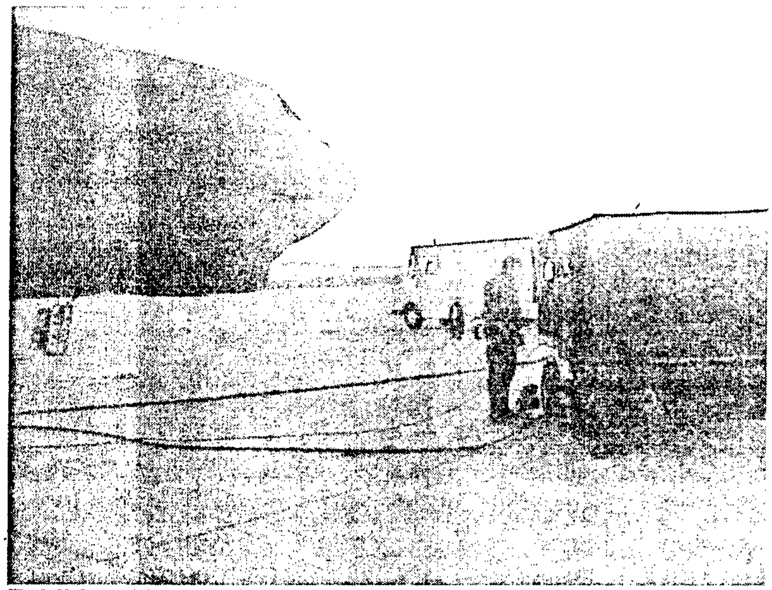


**Exhibit 4-29: MASS Demonstrator Positioned for Testing with a B-52**

The 400 Hz ground power cable was connected to the aircraft and the APC was energized by the DGM without difficulty. The aircraft maintainer in the cockpit was given a visual signal to activate transfer to external power but no transfer occurred after several attempts. It was concluded that the problem likely was due to an incompatibility with management of the E and F pin control signal lines of the ground power connection to the aircraft. The test was concluded and a visit was made to the B-52 operations office where electrical schematic diagrams of the ground power circuit were examined. From this examination it was determined that the B-52 requires the ground power cart to energize the E pin with a nominal DC voltage of 28 V in order to enable power transfer.

As a work-around a 28 Vdc battery pack was promptly assembled from locally available COTS components and interfaced to the APC to enable E pin powering. With this modification a second test was conducted with successful delivery of approximately 10 kVA of 400 Hz power to the B-52 aircraft. Simultaneously with this operation of the APC a successful demonstration of the PNM was conducted using high pressure nitrogen to inflate the main landing gear struts. Plans were made for a third test, which would enable additional electrical loads to demonstrate the operation of the APC at higher power output. However, other maintenance priorities on the available aircraft necessitated cancellation of this demonstration.

### 4.2.2 F-15E Field Testing

Meetings with representatives of F-15 operations were conducted in preparation for testing with this aircraft series. It was determined that an adjustment of APC E and F pin management would be required and the necessary changes were implemented.

It was also determined during these preliminary meetings that a minimum cooling air flow rate of 85 ppm would be required from the ACM to extinguish the aircraft ECS warning indicator. This requirement had not previously been communicated to ADL and it had been expected that satisfactory operation of the ECS was based only on observation of an air temperature limit. The ACM was designed under DO6 to meet joint USAF and USA requirements, which did not require flows up to 85 ppm. Nonetheless it was expected that 85 ppm flow might be within the capabilities of the permanent magnet motor powered blower incorporated in the ACM – either as it was then configured or with a simple modification of its electronic motor drive to permit a small increase in blower speed.

The MASS demonstrator was towed to an F-15E hangar and readily positioned just outside the door as shown in Exhibit 4-30. Thus located, MASS engine exhaust and noise in the hangar were minimized while power cable and cooling air hoses were in reach of their respective aircraft inlets. Difficulty was encountered in activating APC operation from the DGM, which may have been due to a temperature sensitive APC control system component (a non-MIL integrated circuit).

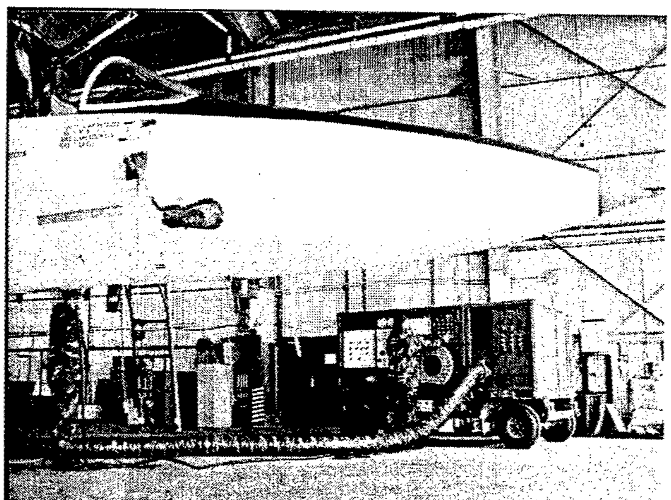


**Exhibit 4-30: MASS Demonstrator Positioned for Testing with an F-15**

To enable testing of the ACM without delay it was decided to use a –60 cart to power the aircraft. After applying –60 ground power the ACM was started and the blower speed was raised to its maximum value at which point the ECS warning light was extinguished. As the requirement for 85 ppm had not been anticipated by the DO6 joint USAF-USA requirements the ACM flow meter display range had a maximum value of 65 ppm. Hence, the flow meter digital display was "pegged" at this value and it was not possible to determine the actual flow rate attained or the margin against the 85 ppm requirement which was available. The ECS warning indicator was maintained in a safe state while maintainers conducted a comprehensive suite of aircraft tests over a period of approximately 30 minutes. At the conclusion of this test sequence air flow unexpectedly declined and an attempt to restart the ACM blower motor was unsuccessful. It was later determined that the permanent magnet brushless motor windings had faulted to the frame. The motor, which was a developmental model, was subsequently replaced by the blower supplier with insulation system improvements developed for a production design. Notwithstanding this post-test problem there was great satisfaction in the favorable results of this demonstration of MASS ACM capability.

#### *4.2.3 F-16DG Field Testing*

Meetings with representatives of F-16 operations were conducted in preparation for testing with this aircraft series. Efforts made to contact an F-16 SPO or Lockheed Martin electrical systems specialist to verify E and F pin management requirements for this aircraft were unsuccessful. However, it was observed that –60 and –86 ground power carts with the same E and F pin control mode were used for both F-15 and F-16 aircraft. Hence it was concluded that E and F pin modifications implemented in the APC to conform with verified requirements for the F-15 would serve for the F-16.

The MASS demonstrator was towed to the F-16 ramp and positioned next to the F-16C test aircraft. Prior to testing with the aircraft the DGM was warmed up and the APC activated without difficulty. Maintainers were favorably impressed by the visibility of the VID under the bright sunlight conditions at that time. Maintainers who normally use a –60 ground power cart for F-16 testing also appreciated the relatively quiet operation of the DGM.

After connecting the APC cable to the aircraft ground power inlet the cockpit maintainer was given a visual signal to enable external powering. The APC tripped coincident with the maintainer's action to transfer power. Interrogation of the APC alarm indications revealed that the trip was due to an overcurrent condition observed by the Power Electronic Building Blocks (PEBBs) of the 400 Hz inverter output stage. The alarm condition was cleared and a second attempt was made with the same result. In each case the maintainer reported that no confirmation of transfer was indicated. Further testing was concluded and the MASS demonstrator was returned to the AGE shop for evaluation.

The possibility was considered that high frequency pulse width modulation (PWM) noise imposed on the APC 400 Hz power output waveform might have caused the aircraft External Power Monitor (EPM) to register an out of limit frequency thus inhibiting power transfer. Additional PWM noise suppression measures were installed in the APC and plans were made for a second test with the F-16C. However, maintainers by that time had determined that some AC emergency bus circuit breakers were found tripped on the test aircraft and that a Programmable Display Generator (PDG) had failed. The aircraft had been restored to service by replacement of the PDG.

Prior to further APC testing with aircraft an intensive investigation of possible causes of this failure was conducted. Ultimately it was concluded that certain aspects of the high inrush current demand of the aircraft Transformer Rectifier Units (TRU's) had caused the

APC to trip and that interruption of this high current had produced a transient voltage exceeding the MIL-STD-704A allowable of 255 $V_{peak}$. It was also considered that the reactance of this transient load might have caused a resonance condition with reactive components in the APC output filter circuit causing its output voltage to exceed the MIL-STD-704A limit.

Measurements of inrush current made on F-15C and F-16C aircraft confirmed the expected high values. Moreover, it was observed that the waveforms – especially that for the F-16C – were highly asymmetric in the sense that initial positive and negative portions of the current waveform are not equal. The consequence of this asymmetry is that a transient dc offset current component is drawn which has the potential to saturate the core of the APC 400 Hz output transformer. Illustrative F-15C and F-16C transformer rectifier unit inrush current waveforms are presented in Exhibits 4-31 and 4-32 respectively. Note that in both cases the current is the total drawn by the pair of TRUs provided in each aircraft.

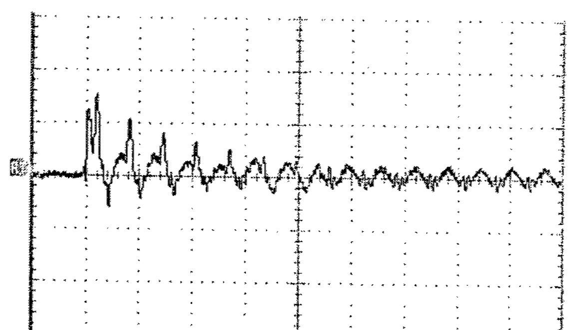


**Exhibit 4-31: F-15C Transformer Rectifier Unit Inrush Current – 100 A/div, 4 ms/div**

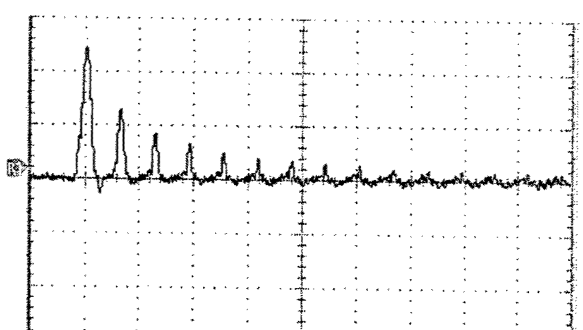


**Exhibit 4-32: F-16C Transformer Rectifier Unit Inrush Current – 100 A/div, 4 ms/div**

It is of interest to note that the lower rated F-16C TRU pair draws a substantially larger and more asymmetric inrush current than the pair of F-15C TRUs. The greater peak current of the F-16C is approximately 250 $A_{peak}$ and is within the short-term overcurrent capacity of the APC for moderate power factor (PF) loads (e.g., PF = 70%).

Prior to commencing further aircraft tests the APC was fitted with an Inrush Current Limiter (IRCL) unit to suppress PEBB tripping and possible consequent overvoltage transients due to interruption of high current levels. Additionally a Transient Voltage Surge Suppression (TVSS) unit was provided to limit any transient overvoltage.

The effectiveness of these protective measures was evaluated by various tests conducted with a –8 loadbank to simulate, as closely as possible, inductive reactive loading conditions representative of the aircraft at the instant of external power connection. Transient disturbance of APC 400 Hz output voltage (line-neutral) was observed coincident with connection of various loads up to 50 kVA and power factor in the range of 24 to 100%. The greatest transient voltage was noted for interruption of a 40 kVA load at 24% power factor. Tests with higher 60 kVA loads at 45% and 32% power factor initiated APC output voltage irregularity and immediate tripping due to a PEBB overcurrent condition suggesting the possibility of a resonant condition. Other tests were conducted to observe output voltage transients coincident with simulated PEBB trips and all were contained within the MIL-STD-704A allowable limit. For all cases peak transient voltage was contained within MIL-STD-704A 255 $V_{peak}$. At the conclusion of these tests conducted in the AGE shop it was decided that further aircraft tests could continue with reasonable assurance that overvoltage damage would be avoided.

#### *4.2.4 F-15A*

Meetings with representatives of F-15 operations were conducted in preparation for further testing with this aircraft series. An F-15A aircraft and maintainer support were provided. The MASS demonstrator was towed to the F-15A hangar and positioned just outside the door in cable and hose reach of the aircraft as shown in Exhibit 4-33.

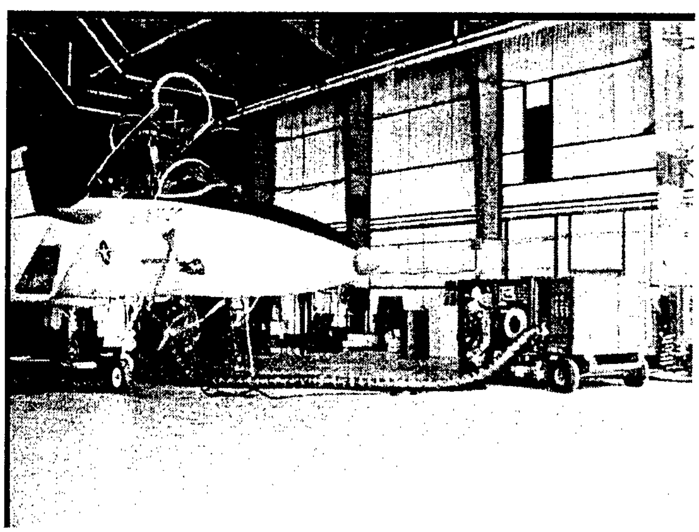


**Exhibit 4-33: MASS Demonstrator Positioned for Testing with an F-15**

After warming up the DGM and APC the 400 Hz AC power cable was connected to the aircraft inlet. The maintainer was signaled to enable external power input to the aircraft and coincident with this action the APC tripped on an overcurrent condition. However, immediate tests and observations by the maintainers confirmed that no circuit breakers had tripped and no electrical damage had been incurred. Moreover, the transient voltage captured when the APC tripped was within the MIL-STD-704A limit. Surmising that the highly reactive low power factor TRU transient load was more severe than that simulated by the –8 loadbank tests previously conducted at the AGE shop it was decided to see if improving the load power factor would overcome this barrier to APC operation. This test mode was readily implemented by connecting a 20 kW resistive load "suitcase" loadbank in parallel with the aircraft. With this 20 kW resistive load in place no difficulty was encountered in powering the aircraft and the maintainers successfully conducted a variety of electrical system checks. Loading was incrementally increased by activating landing lights, position lights, cockpit lights, instrumentation, navigation avionics and radar in the standby mode. The maximum aircraft electrical load was approximately 5 kVA which is the maximum demand reported for the F-15B by the Computer Sciences Corporation (CSC) reference document *Acsumreq* which served as the basis for MASS design requirements. The total APC loading presented by the aircraft and the loadbank was 5 + 20 = 25 kVA.

### 4.3 Test Conclusions

The principal thrust of the MASS program and the field test in particular was to demonstrate that the requisite capabilities could be packaged in modules of acceptable size and to assess the functionality of a *proof-of-concept* multi-function ground support unit. Lessons-learned from the MASS field test were as follows:

- The basic MASS concept was successfully demonstrated
- All of the modules met their performance requirements
- AGE maintainers were satisfied with the serviceability of the equipment
- No difficulty was found in towing and positioning the unit near aircraft
- Aircraft maintainers found it easy to operate the equipment
- Low DGM noise was a plus
- High visibility of the VID was a plus
- Manually moving the MASS unit (by personnel) was difficult due to its weight
- Night time visibility of panel controls was inadequate
- Visibility of LED displays used on certain modules was inadequate in bright sunlight

The APC had been successfully tested in the ADL laboratory using available resistive loads to 70 kVA on the 400 AC output. As the peak fighter aircraft loading reported by the CSC reference document was approximately 40 kVA the successful support of a 70 kVA load provided confidence that these aircraft loads could be accommodated. However, it is apparent from the field tests and investigations that TRU inrush loading presents challenges not anticipated by the specifications provided by the CSC reference document. Modifications of the APC 400 Hz inverter, which would avoid the TRU loading difficulty encountered, have been identified and could be readily implemented. Moreover, there is no doubt that a solid-state inverter can reliably support aircraft loads as these are in widespread use for commercial aviation. The APC is unique in that it integrates both 400 Hz ac and 270 Vdc capabilities in a single compact module demonstrating advanced power electronic technology such as DSP controlled PEBBs.

Difficulties encountered with E and F pin circuit management were easily corrected once the requirements were clarified through on-site contacts with more detailed knowledge of aircraft electrical systems and the opportunity to closely examine aircraft and ground power cart TO documents.

Electrical and mechanical difficulties encountered during testing of the DGM, PNM, and ACM were of relatively minor significance and for the most part were corrected on-site. Those that were not resolved (e.g., inoperability of the DGM engine alternator and automatic operation of the engine glow plug relay) did not interfere with conduct of the aircraft tests.

## 5.0 CONCLUSIONS AND RECOMMENDATIONS

### 5.1 Program Recommendations

The MASS concept was successfully demonstrated at Edwards AFB, CA, in February 2001.

Recommendations for further MASS research and development are as follows:

***MASS Cart Recommendations***

- Further testing at Warner-Robins AFB
  - Additional aircraft testing maintenance
  - Operability/human factors
  - Transport
  - Safety
  - Maintainability
- Use results of testing to update design
- Investigate a gas turbine module to further reduce footprint and weight
- Limited field testing at several selected air bases
- If successful, proceed with an EMD phase
- Continue involvement of MASS IPT

### 5.2 Design Improvements

Aircraft maintenance requirements need to be accurately defined by conducting field measurements. The resulting data would then allow for optimal design refinements and provide modules with the smallest footprint and lightest weight to efficiently support maintenance activities.

Lessons-learned from the field test experience suggest a host of design improvements which would enhance the utility of the MASS concept.

#### *5.2.1 Weight Reduction*

During the MASS demonstrator development the IPT advocated that affordability and use of low cost COTS industrial and commercial components was of greater importance to program success than weight reduction – especially as experience indicates that transport payloads "cube out" before they "weigh out". Moreover, module requirements were principally determined by the greater requirements of the F-22 aircraft. While these are still valid considerations the field tests revealed that manual maneuverability of the equipment is important. Several weight reduction possibilities include the following:

- Replace the diesel engine generator with a gas turbine generator unit of suitable capacity
- Retain the robust, affordable and highly capable diesel engine but use a permanent magnet generator – generator weight would be greatly reduced and DGM power output increased

- In either of the above cases it would might be desirable to use high voltage dc power distribution to the function modules thus avoiding the need for converting the output of these unconventional generators to standard 480 Vac format. The size, weight and cost of the APC could also be reduced because the ac to dc conversion stage would be eliminated.
- Refine module capacity and functionality requirements (e.g., perhaps lower capability modules for legacy aircraft and others for more demanding newer aircraft)

### 5.2.2 DGM

Recommended DGM improvements prompted by field test experience include the following:

- Use of permanent magnet generator as noted above
- Reconfigure the VID to use a hardware platform and software operating system which enables "instant ON" and avoids need for a hard drive
- Power the VID from the engine battery so engine status can be monitored during startup
- Correct unresolved problem with operation of engine alternator
- Correct unresolved problem with automatic operation of the glow plug relay
- Further refine the electrical cabinet packaging to improve maintenance accessibility
- Reconfigure suspension of the air cleaner and exhaust system components to allow easier removal of the module top cover for maintenance access

### 5.2.3 APC

Improvement recommendations for the APC are as follows:

- Incorporate E and F pin management changes to accommodate all supported aircraft
- Add fast acting overvoltage monitor and trip as well as transient suppressors
- Adjust inverter output filter to avoid potential resonance with low power factor TRU loads and/or add active means to damp transient oscillations – lab test with TRUs to verify
- Reassess maximum power requirements and adjust capacity accordingly
- Reassess need for 400 Hz ac and 270 Vdc dual mode capability and adjust accordingly
- Reassess demonstrator under-chassis configuration and repackage as desired

### 5.2.4 ACM

ACM improvements suggested by the field test results include the following:

- Improved motor winding over-temperature protection
- Increase range of flow meter display
- Replace LED instrument displays with back lit LCD or other devices to provide suitable visibility under night and bright daylight conditions
- Add panel lighting for controls

### 5.2.5 LCM

The LCM was not used in the field testing, as none of the aircraft that were used required liquid cooling.

### 5.2.6 PNM

Recommended PNM improvements are as follows:

- Add phase sequence relay to protect pump against reverse rotation due to power phasing error
- Add soft starter for motor to avoid heavy transient load and consequent voltage dip
- Add panel lighting for controls and gauges

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