RESEARCH AND DEVELOPMENT DIVISION

MECHANICAL TECHNOLOGY INC

2

MTI 86TR25

ELECTRONICS CONTROLS ASSESSMENT FOR THE PATRIOT AIR CONDITIONER SYSTEM

Prepared for:
POTOMAC RESEARCH INC.
Under Ft. Belvoir R&D Center

Contract No. DAAK70-84-D-0082
Task Order 0018
14 March 1986

Revised: 28 April 1986

MECHANICAL TECHNOLOGY INCORPORATED
968 Albany-Shaker Road
Latham, New York 12110

MTI 86TR25

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Task Order 1.0 Final Report

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Potomac Research Inc.
Under Ft. Belvoir R&D Center
Alexandria, Virginia

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MECHANICAL TECHNOLOGY INCORPORATED

R&D DIVISION - APPLIED RESEARCH OPERATION

968 Albany-Shaker Road
Latham, New York 12110

Electronics Controls Assessment
For The PATRIOT Air Conditioner System

March 14, 1986

Revised: 28 April 1986

TASK ORDER 1.0 FINAL REPORT

MTI Document No. 86TR25

Prepared For

POTOMAC RESEARCH INC.
Under Ft. Belvoir R&D Center
Contract No. DAAK70-84-D-0082
Task Order 0018

by: Herbert Short
Jeffrey Asher
Robert Johnson
Alan Offt
Howard Clark (Consultant)

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The HVAC Electronic Controller Development Program currently consists of eight specific tasks. Task Order 1.0, the Final Report which is contained in this communication, consisted of researching, assessing and evaluating potential electronic controller candidates which satisfied a Controller Specification generated for the US Army 18K BTUH Split-Package HVAC Units. Follow-On Tasks 2 through 8, which culminate in the delivery of an electronically-modified unit for a Troop Demonstration in Panama, and of a second unit for more rigorous performance evaluation at Ft. Belvoir, are described. A summary of Task Order 1.0 accomplishments forms the basis for this report.

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TASK ORDER 1.0 FINAL REPORT

(Contract No. DAAK70-84-D-0082, Task Order 0018)

SUMMARY

During the summer of 1985, Mechanical Technology Inc. (MTI) was approached by the Ft. Belvoir R&D Center to do an assessment of current, commercially available product offerings for their potential application to electronic controls in Army Air Conditioner Systems. This assessment used criteria which included: cost (initial and life cycle), efficiency, weight, size and reliability/availability/maintainability. A presentation was given September 18, 1985 at Ft. Belvoir at which time the following conclusions were made:

- Major technological advances in microprocessors and power semiconductors make a reliable, cost-effective controller a feasible alternative to current methods of air conditioner control.

- Further evaluation and development is needed in the areas of ambient temperature considerations, sensitivity to line voltage regulation, EMI/RFI reduction, improvements in compressor design and efficiency, 400 Hertz capability, and military versus commercial electronic equipment.

- A payback of two to four years is possible based on the significant increase in efficiencies (up to 40%) as well as improved reliability and logistics support.

On the basis of this work, it was recommended that follow-on activities be initiated to fully explore and quantify the new electronic controller technology. This follow-on activity would include the performance evaluation of a domestic and/or foreign controller systems for incorporation in the Army Air Conditioner System(s). On the basis of these evaluations, a prototype controller system which utilized the components and technology having the best impact and least risk for future TEC systems, would be designed, assembled and evaluated.

As a result of this assessment, MTI was awarded a contract through Potomac Research Incorporated (PRI) for continued investigation, evaluation, and development of a suitable electronic controller to interface with an 18000 BTUH

Split-Package Air Conditioning Unit. The Scope of Work now consists of eight separate tasks, culminating in the "Troop Demonstration" of one unit at The Panama Environmental Test Center in July, 1986, and a second unit at the Ft. Belvoir R&D Center, tentatively in August, 1986. This Final Report summarizes the first task included in this overall Statement of Work.

PREFACE

Task Order 1.0 has, as its primary objectives, the following:

1. Develop appropriate milestones and establish schedules for the performance of follow-on tasks 2-8.

2. Perform an assessment of available off-the-shelf electronic controllers in the 1Hp-5Hp range with operating requirements and capabilities commensurate with the demands of the Split-Package Air Conditioner System.

3. Procure and evaluate, via simulated operating conditions, each selected controller using one of the furnished air conditioners as a test bed.

4. Initiate electrical and thermodynamic analyses of the air conditioner and electronic controller for the purpose of defining their requirements and optimizing their combined operation.

5. Become familiar with the Army Split-Package Air Conditioner through actual disassembly of the unit and review of furnished technical and operating manuals and available schematics.

The above activities have been begun and each, due to their nature, will be continued in future tasks.

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TASK ORDER 1.0 - HIGHLIGHTS

Since initiating Task Order 1.0 in November, 1985, there have been activities focused on interfacing a commercially-available, variable capacity, electronic controller for use in a government-furnished air-conditioning system. The "Statement of Work and Services" accompanying the Potomac Research Incorporated (PRI) Purchase Order No. 01875 is given as Appendix A. A detailed summary of the various Purchase Order commitments is provided in the body of this report; applicable Sections of Appendix A will be addressed on an individual paragraph basis.

A synopsis of the significant highlights occurring during the three month duration of this contract are provided below:

- 11/18/85 -
  Task Order 1.0 authorization received.

- 11/21/85 -
  Meeting at Ft. Belvoir; objectives included the development and scheduling of follow-on contract milestones, and laying the groundwork for the creation of a Controller Specification; discussions were held on controller capabilities as they pertained to the Army's Split-Package and Compact Air Conditioner models.

- 12/03/85 -
  Received two 18000 BTUH Split-Package Air Conditioning Systems from the government; began dismantling one unit for familiarization purposes.

- 12/11/85 -
  Meeting at Ft. Belvoir; objectives were to provide a Monthly Progress Report, make plans with respect to the Task Order 1.0 contract through PRI's T&M Contract with Ft. Belvoir, and to develop a mutually agreeable work scope for future tasks funded through Value Systems Engineering's (VSE) T&M contract with Ft. Belvoir. Conclusions were to:

  1. Ship one modified GFE Split-Package Air Conditioner to Panama for environmental testing on or about July 15, 1986.

2. Ship a second GFE unit to Ft. Belvoir for rigorous performance evaluation in mid-summer, 1986.

3. Perform a thermodynamic analysis in cooperation with VSE (Sherfy).

- 12/12/85 -

  Joint trip to Zycron (Paul Landino, West Haven, CT); objectives were to discuss Zycron's advances in the development of variable voltage/variable frequency (VV/VF) fractional and low horsepower motor controllers and their adaptability to Army air conditioner systems.

- 12/19/85 -

  Established HVAC Bench Test area at MTI.

- 1/02/86 -

  Received two 18000 BTUH Horizontal Compact Air Conditioners from the government. These were transferred to our warehouse for use in anticipated follow-on tasks.

- 1/03/86 -

  Meeting at MTI, objectives were to review the Controller Specification, discuss preliminary results of an electrical analysis performed by H. Clark (MTI), and compare the advantages/disadvantages of "reduced-voltage" and VV/VF soft-start motor controllers; a demonstration of a Zycron 5Hp controller was provided. Some of the conclusions reached were:

  1. To eliminate the temperature sensor at the condenser and use a damper to regulate the airflow of the condenser fan by providing head pressure control at low ambient temperatures.

  2. To operate and remain above 50% rated speed of the compressor.

  3. To seriously consider employing a low-resistance rotor for the compressor drive motor.

- 1/07/86 -

  Joint trip to Welco (Cincinnati, Ohio); objectives were to obtain a cost quotation for specially modified air conditioner compressors for the TECS Troop Demo Units, and to determine if Welco could provide documentation for their previous work as a supplier of militarized compressors to KECO in the early 1980's. Welco's response was to provide quotations for both the modified Carlyle compressor and the associated operation and technical manual.

- 1/07/86 -

  Joint trip to KECO Industries (Florence, KY) to detail the Army's overall program objectives so that KECO could provide VSE with a cost quotation for the delivery of two soft-start air conditioners for the summer, 1986 Panama Troop Demo. Keco's method of mounting and integrating their controller and their method of starting under overcurrent conditions were discussed.

- 1/17/86 -

  Received two Zycron SPUD 500 5Hp motor controllers for bench testing. Requested and received an extension of the Task Order 1.0 contract from 1/17/86 to 2/21/86.

- 1/20/86 - 1/30/86 -

  Dismantled the compressor from TECS-18 Unit Serial No. N310W. Permission was obtained from Ft. Belvoir to operate the compressor with air instead of freon, using a 1500 psi cylindrical accumulator as a reservoir. Because of the poor compression ratio achieved during a test using one of the Zycron units, it was decided that the second TECS-18 Unit, S/N N302, could be used as the test bed. MTI Maintenance Technicians, following Operation Manual guidelines, placed a charge on the unit. Following minor wiring interconnections, the unit has been used successfully for obtaining preliminary test data on the Zycron and Lovejoy controllers.

• 1/19/86 - 1/22/86 -

J. Asher att .ided an ASHRAE meeting in San Francisco to develop first hand knowledge of the state-of-the-art in air conditioner compressor technclogy, electronic controls and analysis (See Appendix B).

• 2/05/86 - 2/06/86 -

Meeting at MTI; objectives were to finalize the Controller Specification and discuss the criteria being followed for controller selection and purchasing. Conclusions were to:

1. Issue the final draft of the Controller Specification (see Appendix C).

2. Perform no-load and locked rotor tests on the dismantled compressor motor; directions for disassembly were to be provided by Ft. Belvoir.

3. Create an "environmental chamber" out of the designated HVAC Lab area, using recommendations supplied by Ft. Belvoir.

4. Focus our attention specifically on the 400 Hertz complication and select controller manufacturers willing to address both 50/60 Hz and 400 Hz operation at 208VAC, 3-phase.

5. Restate Program Goals and clarify the roles of all participants.

• 2/10/86 - 2/21/86 -

Continued bench tests on the Zycron and Lovejoy 5 Hp PWM controllers (Test results are included in this report as Appendix F); began design of the environmental chamber.

• 2/25/86 -

Submitted final Monthly Progress Report for Task Order 1.0

TASK ORDER 1.0 - MAJOR ACCOMPLISHMENTS

The major accomplishments of Task Order 1.0 can best be addressed and described by referring to Purchase Order No. 01875 and its accompanying Statement of Work and Services for this task. This document has been included in this report as Appendix A, primarily for paragraph referral. To provide a status for these various commitments, paragraphs 3, 5, 6, 7 and 8 are hereby given individual attention.

- Paragraphs 3.a. and 5 - "Soft Start/Variable Speed Controller Selection"

  A preliminary market survey was taken of several manufacturers of variable speed controllers with the requisite that cost, unit size, efficiency, reliability, component availability and complexity be given due consideration, in that order. Although the generated listing is not comprehensive, Appendix D does provide sufficient guidelines for further investigation into twelve likely controller candidates. As of this writing, only the Zycron SPUD500 and the Lovejoy VSD-S units have undergone some degree of bench testing. Therefore, categories for judging controller efficiency and reliability are not included in Appendix D. The method of ranking each of the twelve selected controllers as to cost and size qualifications was accomplished by assigning reasonable weight factors according to the following table:

WEIGHT FACTOR	COST (Per Unit Price Range)	SIZE (Volumetric Range)
1	Under $1000	Under 700 in^3
3	$1000 to $1500	700-1000 in^3
5	$1501 to $2000	1001-2000 in^3
7	$2001 to $3000	2001-4000 in^3
9	Over $3000	Over 4000 in^3

TABLE 1: CONTROLLER COST AND SIZE WEIGHT FACTORS

As to the remaining categories of "Drive Technique", "Serviceability" and "Complexity/Modularization", the following weight factors and considerations were given:

Drive Technique - Studies have shown that severe harmonic content due to input power conditioning methods can reduce controller, and motor, efficiency as well as disrupt signal communication and data analysis. From this standpoint, a controller which alleviates harmonic content in the output waveform to an acceptable level, is the most desirable. A controller which uses power transistors and a soft-start pulse width modulation technique has been determined to generate the least amount of electro-magnetic interference (EMI). One using Gate Turn-Off (GTO) services would produce more, and so on, to those using SCR's, which generate the most. Weight factors were assigned accordingly, as shown in the Appendix D table.

Serviceability - Consideration here was given to a manufacturer's ability to service his controller quickly, with domestic parts and labor, rather than depend on complete card (or unit) removal and shipment overseas for repair or replacement. Weight factors 1 and 3 were assigned accordingly.

Complexity/Modularization - Weight Factor assignments for this category were given according to a product bulletin's or to a salesperson's description of the compactness of the unit. No controllers were found to be as simply arranged as the Zycron unit, although the Contraves, Mitsubishi and Graham models came close. On the other hand, the circuitry sophistication of the Lovejoy and Parametric models made their rearrangement (demodularization, if you will) most difficult. On this basis, Zycron was given a "1" while the Lovejoy and Parametric units were assigned "5"s. The others fell somewhere between these two estimates and were each given a "3".

The resulting scores were tabulated and the twelve cntrollers under consideration were placed in order of lowest-to-highest score, lowest being the most likely candidate based on these categories.

When questioned as to their ability to accept either 50/60 or 400 Hertz, 208 VAC, 3-phase input power, the majority of the manufacturers contacted stated that:

1. No attempts had been made to test at 400 Hz and, therefore, they would not commit themselves without sufficient payback (orders); or

2. They were uncertain, but would be willing to investigate if a copy of the Controller Specification were sent to them.

Only Parametrics (due to a power supply design which incorporates off-line regulation), stated that their devices would handle an input frequency of 400 Hz, as well as the standard 50/60 Hz.

For this reason, Parametrics became an immediate contender for selection as one of the controllers to be evaluated at MTI. However, as indicated by its ranking in Appendix D, Parametrics also had several disadvantages: large size, highly sophisticated electronics, and relatively high cost. Moreover, a six-week quote for delivery of one unit for base comparisons with the Zycron unit would have created an unacceptable delay in the program; only six weeks remained in Task Order 1.0 at the time.

As an alternate approach, a decision was made to acquire a Lovejoy VSD-S model instead. From a review of the categories in Appendix D, it can be seen that the Lovejoy unit is in many respects comparable to the Parametrics drive, with the possible exception of not being readily adaptible to 400 Hz power input. A distinct advantage was a three-week delivery. In addition, since the Lovejoy uses GTO's to produce a sine-encoded PWM waveform, it provided a means of comparing a distinctly different technique with the 6-width voltage approach used by Zycron. Lovejoy also offered a 5-year warranty which gave credibility to both its reliability and serviceability. A working demonstration of the unit at MTI convinced us that the Lovejoy controller should be purchased, and evaluated in conjunction with on-going bench tests of the Zycron units. Consequently, a purchase order was released in January and the unit was received in early February, allowing MTI a more suitable time frame in which to complete some preliminary comparison tests.

There remain several other controller manufacturers under consideration; however, for the following reasons, each was sublimated to a much lower priority and not listed in Appendix D.

Allen-Bradley's SMC-3, Fincor's 4150/4155, and the Square-D units employ undesirable SCR drives. General Electric and Westinghouse models were expensive and appeared to be Americanized versions of Japanese controllers, such as Toshiba. The Sabina Type 9550, a West German product, was both expensive (over $2500) and bulky (about 5000 in^3), and, at the 5 Hp level, was not offered at 3-phase voltages lower than 460 VAC. The Eaton Series-E, Rondo RMC TWK-s Series, Boston Gear models, B&B LA5 series, and the Emerson Accuspede 200 series, although smaller and less costly, were also subject to this last constraint. The TB Woods and Sons AFC-2005 unit was extremely large (6600 in^3) and required an excessive amount of cooling space.

As a side note, it appears that American suppliers of adjustable frequency drives generally manufacture their own units for horsepower ratings above 10 Hp, while inclining to import units from Japan, West Germany or Denmark for ratings of 7 Hp and below. This complicates a market survey somewhat since a product such as Toshiba could be carried under General Electric's nameplate. Serviceability then becomes a questionable market advantage in spite of the reputation of the distributor.

- Paragraph 3.b. - "Critical Milestone Development"

  A PERT chart has been constructed which effectively outlines the Scope of Work, associated task funding, and scheduling necessary to ensure meeting a Troop Demonstration by July 15, 1986 with the PATRIOT 18,000 BTUH Air Conditioner. This PERT chart, included in this report as Appendix E, assumed continuity between Task Orders 1.0 and 2.0. A postponement in the awarding of a follow-on contract for Tasks 2-8 has necessarily delayed the two Program Goals identified on this PERT chart: (1) the Troop Demo in Panama, and (2) the testing of the Ft. Belvoir unit.

- Paragraph 3.c. - "Thermodynamic Cycle Analysis"

  After a preliminary investigation of the benefits of performing a thermodynamic cycle analysis, an agreement was reached between MTI and T. Sgroi, BRDEC, to suspend further analyses. This is a result of the complexity involved and questionable usefulness to the success of the program.

Initial investigations into the suitability of the high resistance-type rotor used in the Welco-modified Carlyle compressors, were performed by Howard Clark, a consultant to MTI. His findings indicated that the efficiency of this style rotor was approximately 59%, while that of a normal resistance rotor is generally 80%. (Mr. Clark's analysis was based on information provided by Ft. Belvoir. His repoıt is included in Appendix G). In order to simulate soft-starting of the compressor and limit in-rush currents, the standard low resistance windings had been sacrificed. To better quantify what these losses are, and establish an efficiency rating, locked-rotcr and no-load tests of the compressor are required. The results will be used by Mr. Clark to complete his equivalent circuit analysis of the motor. Permission was obtained from Ft. Belvoir to open the air-contaminated compressor; subsequent tests on the rotor are scheduled for Task 3.0.

As it is desirable to retain as much of the TECS-18 machinery as possible, so that an eventual one-on-one comparison can be made in Panama and at Ft. Belvoir with a competitive KECO unit, replacement of the Welco compressor is not likely. This electrical analysis, however, will not be treated as insignificant, since the outcome will be used to optimize controller operation.

- <u>Paragraph 3.d. - "Research and Evaluation of Soft Start/Variable Capacity Controls"</u>

The intent of the subparagraph is being addressed, though on a more generalized basis. Efforts have been expended in Task Order 1.0 to determine, through the market survey mentioned earlier, what controllers are commercially available which can accept 208VAC, 3 phase, 50/60Hz power at the 1-5 horsepower levels, and then eliminate from this field those controller manufacturers whose products are not suitable for 400 Hz applications. This is an on-going activity and will continue well into follow-on Tasks 2.0 and 3.0. MTI intends to utilize a Controller Specification, completed in Task Order 1.0, and the assistance of its Purchasing Department, in researching both domestic and foreign prospects further.

Any evaluation of these controllers has been performed on a very limited basis thus far. Although several bench tests (usually associated with temperature effects), have been conducted on the Zycron and Lovejoy units, more rigorous tests are pending the construction of the environmental chamber and the installation of instrumentation such as thermocouple grids, pressure sensors, air flow monitors, and vibration sensors. Appendix F summarizes the major results of bench tests performed thus far. Appendix G contains graphs, calculations and related correspondence which substantiate comments made in Appendix F.

- Paragraphs 3.e. and 6 - "Government Approval for Controller Purchases"

Rather than devote time and expense in researching and evaluating reduced voltage starters not capable of 400 Hz input compatibility, a decision was made midway through Task Order 1.0 to eliminate them from further consideration. Efforts were then focused on procuring 400 Hz input compatible controllers using either 6-step, pulse width modulation, or some combination of both techniques. However, an immediate selection of such a unit was not possible for the reasons mentioned in the previous discussion on Paragraphs 3.a and 5 commitments. As available time to perform any meaningful bench-testing was quickly being used up in this search effort, a decision was made in January to purchase the Lovejoy controller on the basis of delivery time and similarity to the Parametric Parajust "GX" model.

- Paragraphs 7 and 8 - "Work, Services and Deliverables"

The attitude of flexibility which governed the conduct of Task Order 1.0 permitted a certain amount of compromise in reaching a mutual definition of program objectives. It also prevented a serious, in-depth evaluation of commercially-available controllers from beginning on schedule. Now that a direction has been provided for pre-operational market evaluation, the task of bench testing should be much easier since the number of potential suppliers can be reduced drastically.

MTI considers the "work and services" referred to in Paragraph 7 to be complete as far as Task Order 1.0 funding would allow; the Follow-On Activity of Tasks 2.0 and 4.0 will essentially complete the entire controller research, procurement and evaluation testing efforts. Consequently, this Final Report shall constitute the "deliverables" requested by Paragraph 8.

CONCLUSIONS/RECOMMENDATIONS

Task Order 1.0 placed major importance on determining the availability of, and operationally evaluating the performance of, a 5 Hp controller capable of functioning satisfactorily at 208 VA, 3-phase, 400 Hertz as well as 50/60 Hertz. Much of the scheduled three-month work period was expended researching numerous manufacturers as to this one capability. With the one exception mentioned (Parametrics), all contacted suppliers hesitated to guarantee 400 Hz operation without first performing their own in-house evaluations. Many inferred additional costs would be incurred due to the resulting engineering and mechanical design changes necessitated by this criterion.

It is evident that before any decision can be made regarding a final candidate (or candidates), additional surveys using the Controller Specification as a guideline should be made. It is imperative that controller size and reliability be given top consideration prior to requesting that a particular vendor initiate his own research and development effort in an attempt to make his controller operational at both frequency ranges. Although, on the basis of the findings tabulated in Appendix D, such a decision is currently possible, it is still premature. Following the receipt of all vendor responses to a Request for Quotation solicited by MTI's Purchasing Department, narrowing the selection to one or more promising candidates will be much easier. More factors would be considered and a choice could be better justified. As mentioned earlier, this is an on-going function being performed by MTI via its Purchasing Department's capabilities.

The PERT Chart of Appendix E outlines the scope of work necessary to reach the two Program Goals for air conditioner deliveries. MTI considers this plan to be workable for attaining both of these goals provided delays of future Task Orders are minimal.

MTI considers this program to be a challenging but achievable goal to incorporate recent advancements in the development of solid-state power technology into existing, energy-inefficient air conditioning units. The flurry of engineering activity being performed on a world-wide basis indicates the wisdom of the Army in seeking to employ this new technology.

REFERENCES

1. US Army Technical Manual TM 5-4120-359-14, "Split Package Air Conditioner 18/30 KBTU/HR-KECO Model F18H4-2".

2. Preliminary Draft Equipment Publication - Operator, Organizational, Direct Support and General Support Maintenance Manual for 18,000 BTU/H Total Environment Control System (TECS-18), August 1975.

3. "Analytic And Experimental Techniques For Evaluating Compressor Performance Losses", John J. Jacobs, Carlyle Compressor Co., Syracuse, NY.

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7. "Saving Energy With AC Drives", Ben H. Carlisle, Machine Design, February 1980.

8. "Solid State Motor Control Gives Smooth Starting", David J. Bak, Design News, April 1981.

9. "The Effect Of Voltage Waveshape On The Performance Of A 3-Phase Induction Motor", G.C. Jain, IEEE Paper 64-96, February 1964.

10. "Plate, Schematic Diagram (For 18,000 BTUH Split Pack Air Conditioner)", Dwg. 13221E9102.

11. "Plate, Wiring Diagram (For 18,000 BTUH Split Pack Air Conditioner)", Dwg. 13221E9103.

APPENDIX A

PURCHASE ORDER

NO. 01875

POTOMAC RESEARCH, INCORPORATED
6121 LINCOLNIA ROAD
ALEXANDRIA, VA 22312

TO: Mechanical Technology, Inc.
968 Albany-Shaker Road
Latham, NY 12110

Attn: Dr. Asher

SHIP TO:

COST CODE 1060-18

DATE	SHIP VIA	TAX EXEMPT: YES ☐ NO ☐ TAX EXEMPT. NO.	DATE REQUIRED	TERMS	ACCOUNT NO.
11-14-85			ASAP		

☐ PLEASE SIGN AND RETURN ACKNOWLEDGEMENT COPY ☐ ACKNOWLEDGEMENT COPY NOT REQUIRED	PRIORITY	CONTRACT NO.	REQUISITIONER
			R. Nailor

ITEM NO.	QTY	STOCK NO.	DESCRIPTION	UNIT PRICE	TOTAL
	1		As Subcontractor, supply service, personnel, materials and supplies IAW DAAK70-84-D-0082, TO 0018. SOW attached. Begin work 18 Nov. 1985		$73,929 00

DELIVERY PROMISED: FOB:

SPECIAL INSTRUCTIONS:

☐ Required ☐ Not Required — "A Certificate of Compliance (C of C) is required for this order. The C of C must state QA inspection/test data verifying compliance is available for review and/or verification. The C of C must be signed by a responsible individual, and must state the title or position of that individual."

RECEIVING HOURS 9:00AM-3:00PM MONDAY-FRIDAY
INSIDE DELIVERY REQUIRED
ABOVE ORDER NO. MUST APPEAR ON ALL PAPERS AND PACKAGES RELATIVE TO THIS ORDER
TERMS & CONDITIONS ON REVERSE SIDE ARE PART OF THIS ORDER.

John S Pixley
(Signature)
☐ PURCHASING AGENT ☐ BUYER ☐ CONTRACT ADMINISTRATOR

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STATEMENT OF WORK AND SERVICES

1. The Contractor shall supply service, personnel, materials, and supplies for engineering programs to provide documentation in support of the PATRIOT Air Conditioner used with the PATRIOT Missile System Ground Support Equipment.

2. Specifically, the Contractor shall perform research and evaluation of domestic/Japanese sources of soft start/variable speed controls for the PATRIOT 18,000 BTUH Air Conditioner and recommend to the PATRIOT Development Project Office the most promising soft start/variable speed controls. Suggested sources are:

   Parajust
   Reliance
   Hampton
   Westinghouse
   Mitsubishi
   Louis Allis
   Toshiba
   Zychon
   General Electric
   Square D
   Ramsey

3. The conduct of this Task Order will require the Contractor to:

   a. Select soft start/variable speed controls in accordance with the following criteria: cost, size/efficiency, reliability, component availability and complexity. The primary criteria for making this selection will be cost and size/efficiency for an acceptable military version.

   b. Critical milestones will be developed within 30 days following award of Task Order to ensure meeting a Troop Demonstration by July 15, 1986 with the PATRIOT 18,000 BTUH Air Conditioner using solid state environmental controls.

c. Thermodynamic cycle analysis will be performed from which electronic controls tradeoffs will be made. This includes the control and operation of the condenser and evaporator fan motors. Efficiency projections will be made based on projected duty cycles supplied by the Government.

d. Perform research and evaluation for the soft start/variable capacity controls of the PATRIOT environmental control units (ECU). The function of these controllers is to convert 208 VAC, 3 Phase, 50/60 or 400 Hz electric power to variable frequency and voltage sources to power the compressor, condenser fan and/or evaporator fan of the ECU and with ambient temperature considerations of 120°F to -25°F. The nominal output of the convertors will be 208 VAC, 3 Phase, 60 Hz. Frequency and voltage may be varied to facilitate a soft start capability for the various motor loads. These electrical power controllers shall be applicable to the following electric motor:

Power Input: 208 V, 3 Phase, 50/60 Hz.

Compressor . . . . . 4200 Watts
Condenser Fan . . . . 700 Watts
Evaporator Fan . . . 600 Watts

e. With Government approval, two (2) samples from each acceptable vendor will be purchased for later evaluation.

4. Prepare monthly and final Technical Reports and milestone chart in accordance with DI-S-4057 to provide the developed data as required in paragraph 3 above (Section C, paragraph F.5).

5. Provide the Government an Evaluation Report with recommendations for selection of vendors based upon the criteria in paragraph 3 (Section C, paragraph F.7).

6. The Contractor shall purchase two sets of controls from Government selected domestic and/or Japanese vendors (Section C, paragraph H.1). Government Furnished Equipment will include: three 18,000 BTUH Air Conditioners and will be supplied within 15 days after award of contract.

7. The work and services shall be performed in accordance with Section C, paragraphs F.5, 7, and H.1.

8. Deliverables shall be in accordance with Section F.2, CLIN 002, Data ELINs AOOM, AOOU, and AOOW as set forth on the attached Exhibit A, DD 1423, Contract Data Requirements List.

9. Mr. Robert Brantly (664-5871) shall perform the duties of Contracting Officer's Representative, and Mr. Tom Sgroi (664-6031) shall serve as technical advisor for this Task Order.

10. The Task Order completion date is 60 days after award.

CONTRACT DATA REQUIREMENTS LIST

ATCH NR ______ TO EXHIBIT ______

TO CONTRACT/PR DAAK70-84-D-0082

CATEGORY ______

SYSTEM/ITEM PATRIOT

CONTRACTOR Potomac Research, Inc

1. Sequence Number	2. Title or Description of Data / 3. Subtitle	4. Authority (Data Item Number)	5. Contract Reference	6. Technical Office	7. DD250 Req	8. App Code	9. Input to IAC	10. Frequency	11. As of Date	12. Date of 1st Submission	13. Date of Subsequent Subm/Event ID	14. Distribution and Addressees (Addressee – Regular Copies/Repro Copies)	15. Total
AOOM	Performance and Cost Reports	DI-F-1208A W/Addend. 3/13/84		STRBE-EPAT	LT			Mthly	0	Blk 16	See 16	STRBE-EPAT 1/0; STRBE-PRA 1/0; STRBE-EM 1/0	
AOOU	Scientific and Technical Reports / Final Report	DI-S-4057		STRBE-EPAT	LT	A		One/R	See 16	Blk 16	Blk 16	STRBE-EPAT 1/1; STRBE-EM 3/0; DTIC 12/0; STRBE-WC 2/0	18/1
AOOW	Evaluation Reports	DI-E-1907		STRBE-EPAT	LT	A		One/R	See 16	Blk 16	Blk 16	STRBE-EPAT 1/1; STRBE-EM 1/0; STRBE-TQ 1/0	3/1

16. REMARKS (AOOM): Provide NLT 10 days after end of month.

16. REMARKS (AOOU): Interim report due 30 DAT. 5 days for Gov't review. Final submittal due NLT 10 days prior to completion of task order.

16. REMARKS (AOOW): Draft due 40 DAT. 5 days for Gov't review. Final submittal due 60 DAT.

16. REMARKS:

PREPARED BY: THOMAS J. SCHOL, Project Engineer

DATE: 31 OCT 85

APPROVED BY: T.W. O'CONNOR, Ch Env Cont Division

DATE: 1 Nov 85

DD FORM 1 JAN 73 1423 — SUPERSEDES EDITION OF 1 JUN 69, WHICH WILL BE USED UNTIL EXHAUSTED.

PAGE 1 OF 1 PAGES

APPENDIX B

TRIP REPORT

American Society of Heating Refrigeration and Air Conditioning Engineers (ASHRAE) Winter Meeting

San Francisco, CA - January 19-22, 1986

MTI ATTENDEE: J. Asher (Author)

OBJECTIVE:

To develop first-hand knowledge of the state-of-the-art in air conditioner compressor technology, electronic controls and analysis.

SUMMARY:

The Japanese continue to advance the state-of-the-art with new hardware and software. Domestic vendors do it with mirrors and promises. It is tragic that this industry is destined to disappear despite the obvious signs of technological progress by the Japanese. The Japanese are not even hiding their developments, yet the major USA vendors' are responding with actions at a snail's pace.

Generally the meeting was worthwhile - the exposition was enormous and extremely important to develop first-hand impressions. The technical sessions were poor in developing a coherent picture of where the technology is going (except for the Japanese perspective). As I have seen at other Conferences, universities remain the major force for technological advances, but are not really plugged into the industry's commercial thrusts. The result is a poor use of the new technology.

ITEMS OF INTEREST:

The most important paper in the Technical Sessions was by H. Itoh, Manager of Development Engineering - Toshiba. I met with him at his booth and we discussed his work in greater detail, but in very broken English. H. Itoh's paper concerned the use of a pulse motor driven expansion valve and its inherent advantages. As an introduction, Itoh put the earlier Japanese advances in perspective. (It was almost like it was Toshiba's turn to present the progress of the entire Japanese HVAC industry).

Itoh indicated that the pulse motor driven expansion valve is the natural result of the Japanese thrust for full microprocessor control of the air conditioning cycle. It began with a variable speed fan motor control in 1978 and was extended to the compressor motor in 1982. Now in 1984 (not 1985!) the expansion valve was the next target. Such an advance leads to: 1) improved EER; 2) no need for compressor injection cooling; 3) a defrost time which can be shortened by 50%; 4) increased performance reliability and 5) reduction in manufacturing costs. As a footnote, the inverter controlled compressor for domestic Japanese heat pumps has increased from 20K units in '82 to 150K in '83 to 350K in '84 and 800K in '85. In '85 the total delivered units for Japanese heat pumps was 1,250K - more than a full third being inverter controlled.

Back to this novel expansion valve. While the paper is attached, several other items not mentioned in the paper were divulged. The valve costs 1000 yen ($5) while the control unit costs 2000 yen ($10). Toshiba is already manufacturing 50 to 100,000 a year for Japanese use. A unit by ALCO appears to have a similar function.)

By use of this valve (2 watts consumption when on) the EER can be improved to 10. A 10% efficiency increase was mentioned. The valve is operated by sensing the discharge temperature from the evaporator. As a result, the temperature entering the compressor can be limited to less than 120°C. Defrosting can occur in 3 rather than 6 minutes. Toshiba is looking "at other effective applications" for the valve in the future. These applications will likely include supermarket and domestic refrigeration units. The maximum flow for these valves is 80 kilogram per hour, but a 5HP unit generating 400 kg/hour is now a reality as well. Speed from full close to full open is 7.2 seconds. Hunting is prevented by altering the time constant automatically by the microprocessor.

The other paper of note involved shutdown transients. It was coauthored by Vic Goldschmidt (Purdue) one of my Syracuse University buddies who has made quite a name for himself in this area. Transients at shutdown do decrease system efficiencies - but this everyone knows. The efficiency "damage" is done after a 40 second time period; longer shutdown periods do not have a further degradation on efficiency. Running the condenser fan for 2 to 10 seconds after compressor shutdown will result in better overall efficiencies. The model they developed along with the experiment was elegant in its simplicity. Goldschmidt's expertise may be useful in the future.

Another paper which deals with the effect of cycling was presented by Murlroy. Unfortunately, this paper was presented on Wednesday at the time I was leaving. I found its written conclusions confusing and will attempt to get clarification in the future. They appear to confirm Murphy's thesis, but the variables are larger in number.

Most interesting by its total absence were papers detailing work with variable speed controls or rotary compressors. The Japanese reported on their recent compressor control activities in the summer of 1985. It appears from the technical sessions and exhibits that the USA suppliers have little to offer.

Now to the exhibits. They were extensive with over 600 filling up the entire Moscone Center. Highlights included:

- Toshiba - An extensive number of rotary compressors for air conditioner/heat pump use were shown. These included:
  - Model PH170X2-3LU: 17,580 BTU/hr., 60 Hz operation
  - Model PH250X3-3LU: 24,700 BTU/hr., 60 Hz operation
  - Also 5950 and 11,400 BTU/hr.

  The heat pumps and air conditioners all had rotary compressors but none of the USA models were inverter controlled.

- While software vendors were in evidence, none focused on the refrigeration cycle design. The best software available for this need can be obtained from a Mr. Van Baxter of Oak Ridge National Labs. (Action: Asher to call to obtain source code.)

- Mitsubishi had an extensive exhibit of electronic controllers as well as heat pumps/air conditioners. I was impressed by the Model K controller in terms of its compactness. No literature was available for the heat pumps/air conditoners. One of the Mitsubishi personnel indicated that only Japanese systems have variable speed, but all have rotary compresors except their 4 ton unit. The reason he gave was that the Japanese are proving the technology domestically before foreign distribution. (I do not believe this). Currently, all USA units are thermostat units which cycle the compressor on and off.

- Rotorex Compressor - Rotaries have been the only type of compressor they manufacture. Unfortunately, Rotorex has not qualified their compressor for the miliary - "too costly". They did show a variable speed heat pump unit which uses an electrically commutating DC motor. The cost is very high - $600 per motor and control - and the market is captured by G.E. Friedrich of Utica, New York, is trying to commercialize this concept, but are two years away according to a Rotorex engineer. The main problem is cost - selling a variable speed one-ton system for the price of a conventional two-ton unit. They will never make it if they are tied to G.E. pricing and sourcing.

- Copeland Compressor - *A major disappointment.* They had a prototype scroll compressor in operation, but they admitted it was one year away from introduction. The variable speed system was not in operation and was amateurishly and sloppily presented - it was a conventional Zycron unit painted black. The backdrop (marketing) was impressive in stating their use of electronic controls, but the technology was not at hand. Their literature was full of promises for the future!

- Tecumseh - They are a major vendor for rotaries. Their Model RN 30 Frame have sizes from 15,300 through 24,250 BTU/hr with EER's between 10.8 to 11.0. They indicated by words the capability for inverter speed control but showed no hardware). The booth was (under) manned by personnel who enjoyed the good old boys rather than meeting new customers (me). There was minimal literature - not very impressive.

- Ranco Industries - Lee McCollough (V.P. - Sales) was there in a large booth. They had their 5 HP electronics control unit on show along with a sophisticated system to show people the advantages of variable speed. The variable speed unit has changed significantly from the one we saw in July. Lee indicated that they did hybridize the circuits although such could not be seen. Nonetheless, the two logic boards are now one. A huge capacitor ate up much of the space. The assembly was sloppy. Lee said product introduction would occur in July. They are still looking at $150 for a 5 HP unit in production levels of 100,000 per year.

- Sanyo - Again an impressive assortment of air conditioners and heat pumps. All had rotary compressors, but none of the USA units had inverters. Again only in Japan. The salesman said this was caused by too low an EER for USA use plus they have difficulty with UL approval. Bull!

- Emerson - Pure mirrors! They had an impressive display of words and mock-ups. When one talks with the engineer they admit without reluctance that the mock-ups are for show so that Emerson can indicate a progressive image. They indicated variable speed control but have done nothing substantial. No literature was available.

- Parametrics - Another disappointment. Their variable speed unit was operational, but the 5 HP unit is mammoth. No literature and very tight lipped. Clearly, they rushed this to the show.

- Bristol - An excellent display with lots of personnel to talk with. Unfortunately, their rotary is still "on the drawing board". I think they will be too late to survive.

- Graham and Ramsey - Impressive units in terms of specs and size. Unfortunately neither is capable of 400 Hz service.

- Keco, Welco, Zycron - No booth nor did I see their familiar faces. The focus of this show was nonmilitary and they evidently felt their presence would not be cost-justified.

If I were to guess, the USA vendor's marketing strategy, it is to ensure sales long term in the larger, centrally controlled systems. Digital Direct Control

(DDC) was discussed widely in the technical sessions and at the Exposition. Technology advances and marketing seem to focus on this arena rather than the residential units. I expect in a short time the Japanese will take this market by default (like the VCR, automobile, . . .).

JAA/dml
1/24/86

APPENDIX C

SPECIFICATION
(Purchase Description)
FOR VARIABLE SPEED AC MOTOR CONTROLLER TO RESIDE IN A TOTAL ENVIRONMENTAL CONTROL SYSTEM

December 20, 1985

(Revision 1 - January 7, 1986)

(Revision 2 - February 7, 1986)

MTI Project Number 0450-30039

Mechanical Technology Incorporated
Applied Research Operation
968 Albany-Shaker Road
Latham, New York 12110

1.0 SCOPE

The following is a request for quotation and specification that establishes the design, performance, test, and acceptance requirements for the motor controllers to be installed in a military air conditioner/heater (herein referred to as the Total Environmental Control System (TECS)).

2.0 REQUIREMENTS

2.1 Item Description

The Total Environmental Control System (TECS) is an air conditioning (18,000 BTUH) and heating (30,000 BTUH) unit that provides variable capacity cooling through the use of a variable speed motor controller for the compressor and is capable of operating from 208V, 3-phase AC power at frequencies of 50, 60 or 400 Hz. The TECS consists of a compressor with equalizing valve, condenser coil, condenser fan, evaporator coil, evaporator fan, heater and electronic controls as shown in Figure 1.

2.1.1 Description of Electronic Controls

The electronic controls of the TECS system shall consist of: (1) a variable speed motor controller for the compressor (herein referred to as the compressor controller), (2) an acceleration/deceleration motor controller (herein referred to as the fan controller), for "on" and "off" operation of the condenser and evaporator fan motors, (3) a heater controller to control the power to the resistance heaters (18,000 BTUH variable and 12,000 BTUH fixed) and (4) a logic section for the control of the motor controllers. The motor controllers and the logic section are shown in the block diagram in Figure 2.

To reiterate, the electronic controls consist of the three (3) above mentioned controllers and one (1) logic section. However, this Request for Quotation shall pertain to only the compressor controller and fan controller.

2.2 Input Power Characteristics

The input power will be balanced 208 Volts, 3-Phase AC power at 50, 60 or 400 Hz frequency. The voltage level can vary from -5% to +10%. The motor controllers must be capable of operating from frequencies of 47.5 - 63 Hz

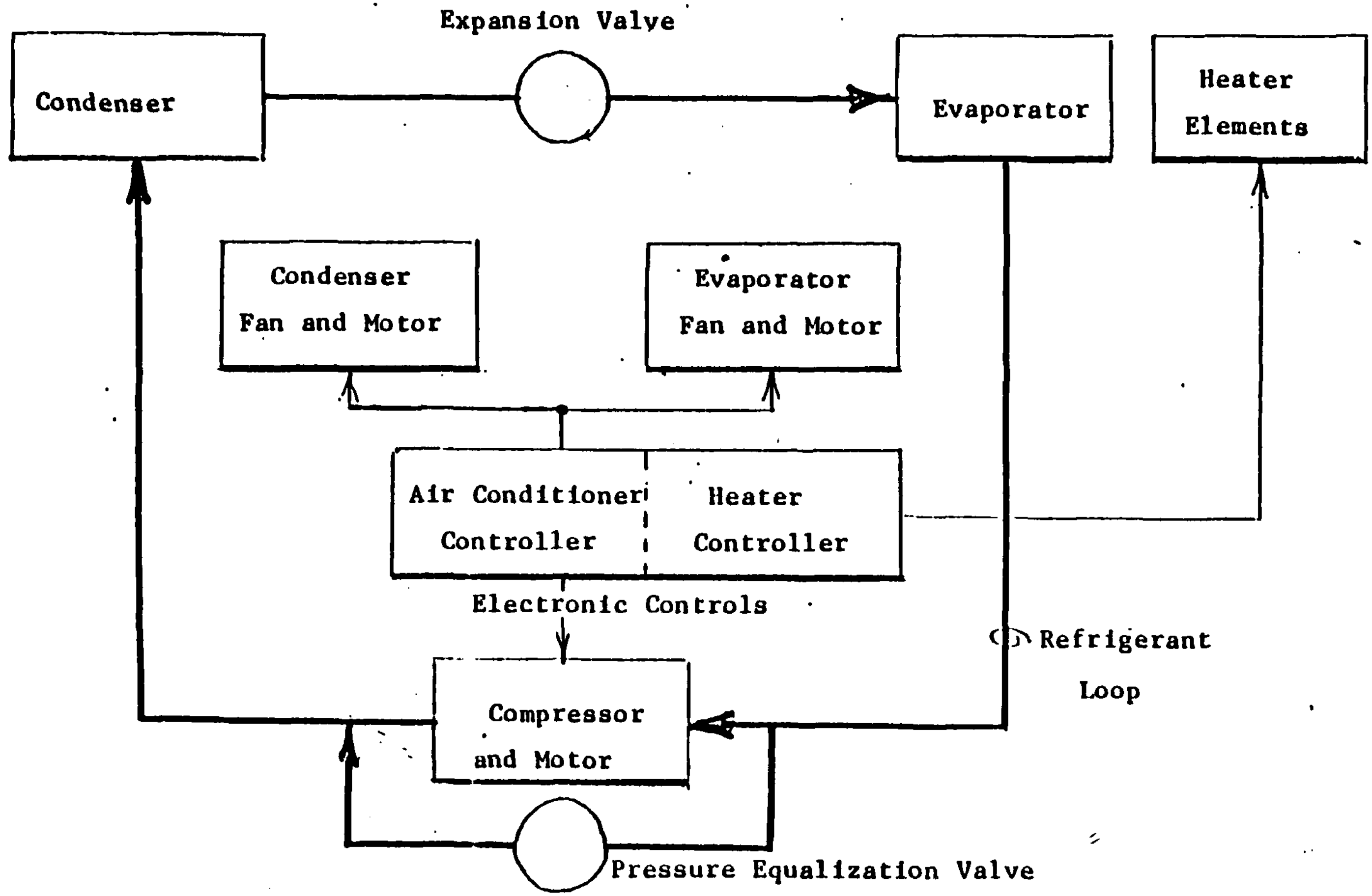


FIGURE 1 - SIMPLIFIED TECS BLOCK DIAGRAM

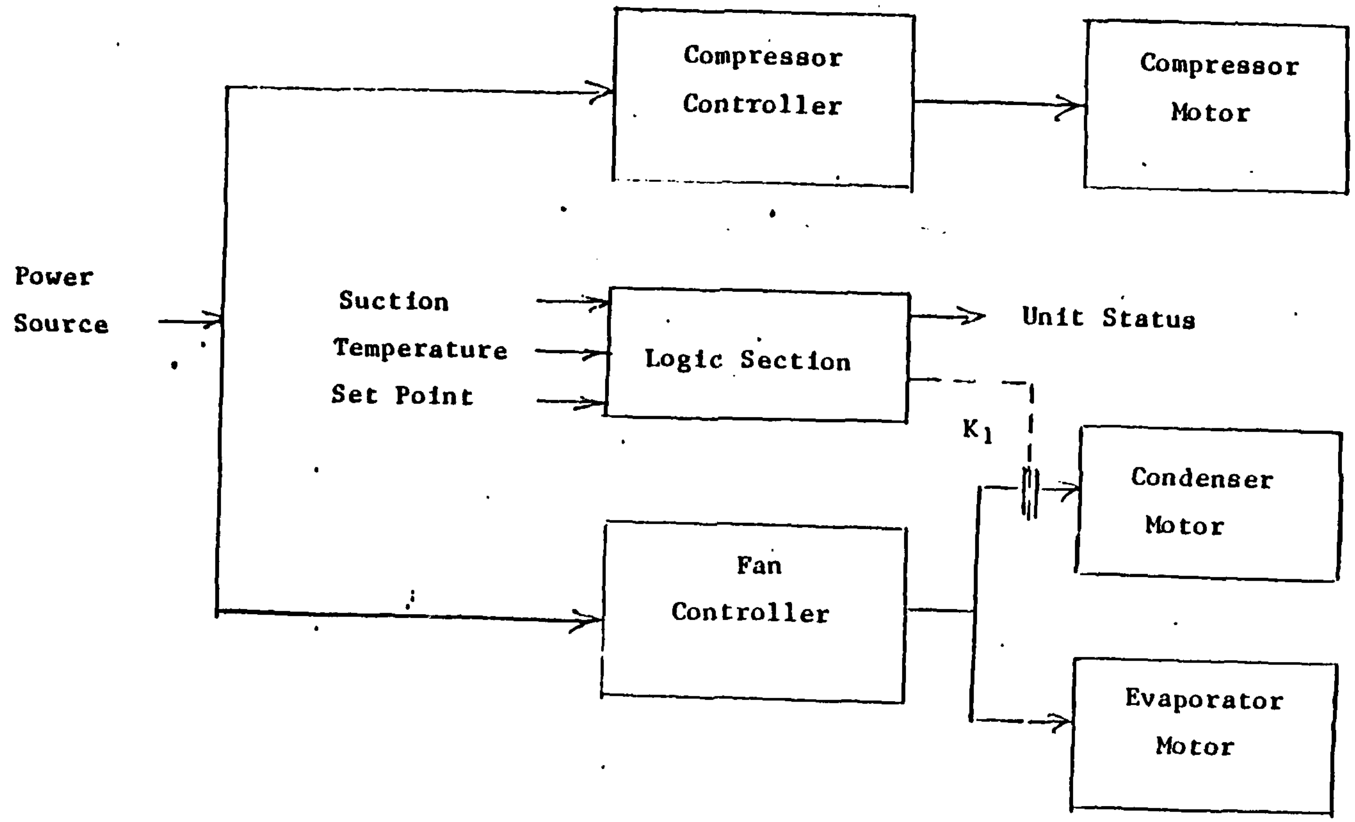


FIGURE 2 - ELECTRONICS CONTROLS BLOCK DIAGRAM

and 380 - 420 Hz. Input voltage leads will be attached to the controller with three, number TBD sized screws capable of carrying 50 amperes. All input phases shall be plainly marked. The controller shall be grounded to the source through a fourth wire, also connected to the controller's input terminals. Under normal operation, no controller current shall flow through this ground wire. Current flow greater than 0.5 amperes in this wire shall indicate a ground fault condition. All terminals to the motor(s) shall be isolated from this ground wire.

2.3 Motor Characteristics

2.3.1 Motor Load Characteristics

The load on the compressor controller unit will consist of one 208V, 3-phase, 50/60 Hz, 5 HP AC induction motor driving the reciprocating compressor. The loads on the fan controller will consist of two, 208V, 3-phase, 50/60 Hz, AC induction motors of 0.5 HP and 1.0 HP size (for a total of 1.5 HP) driving the evaporator and condenser centrifugal fans, respectively. The 5 HP motor requires 14 amperes of continuous controller current. The condenser fan motor requires 1.4 amperes, while the evaporator fan motor requires 1.1 amperes, continuous controller capability. Screw terminals capable of carrying 150% of the above rated currents shall be provided for terminating leads to the motors. All phases shall be plainly marked "A", "B" and "C".

2.3.2 Motor Speed Control

The speed of the motors shall be commanded by a 0 to 10VDC analog voltage. The source impedance shall be less than 10 ohms. Zero (0) voltage shall command the controller's minimum speed and 10 volts shall command the controller's maximum. This command voltage shall be supplied to the controller through two wires, both isolated from the controller's ground. One motor start and one motor stop command shall be provided. These commands shall be implemented with a contact closure on the start switch to signal a start condition and a contact open on the stop switch for stop. The two events will not occur simultaneously.

2.4 Output Power Characteristics

The motor controllers shall have the following characteristics:

2.4.1 Frequency Variation

2.4.1.1 Range

The controller shall be variable through a maximum of one Hertz increments between 10 and 60 Hz. Linearity between output frequency and commanded frequency shall be 2% of maximum frequency over the full range.

2.4.1.2 Resolution

Resolution throughout the frequency range shall be at least 1.0 Hz.

2.4.1.3 Acceleration/Deceleration

The time for acceleration and deceleration must be adjustable between 5 and 20 seconds. Dynamic breaking is not required.

2.4.1.4 Direction

The motors will turn in only one direction. Therefore, no electronic or mechanical reverse is required.

2.4.2 Output Voltage

2.4.2.1 Shape

The output voltage shall be a simulated sine wave on all phases with the capability to vary amplitude. Because of electromagnetic and radio frequency interference restrictions, no SCR devices can be tolerated in the output stages. Harmonic content in the current waveform causes additional losses in induction motors. Therefore, the technique which produces the least amount of harmonic current losses, which is the most cost effective, is desirable.

2.4.2.2 Variation with Speed

Output voltage to the motors shall vary from 10 to 208 Volts AC as dictated by a programmable Volts/Hz curve. The slope of the Volts/Hz curve must be able to be user set in a range from 3.2 to 4.0 Volts/Hz. A user-adjustable "boost" feature, limiting the minimum voltage to the motors at low speeds is necessary.

2.4.3 Input Controls

2.4.3.1 Speed of Motors

The frequency of the controllers' output shall be controlled externally by a DC voltage between 0 and 10 volts to be provided by the Logic Section as shown in Figure 3. Zero volts will correspond to minimum speed and 10 volts to maximum speed. Minimum and maximum frequencies will be 10 to 60 Hz, respectively.

2.4.3.2 Start/Stop

One switch closure to each variable speed motor controller will command that controller to start the compressor and fan motors. Another set of switch contacts will command the controller to stop the motor(s). When commanded to start, each controller will automatically accelerate the motor(s) at a previously set internal rate to the command speed. The command speed will be determined by the Logic Section. When commanded to stop, the controller will remove power to the motor (dynamic braking is not required). Self protection against damage caused by regeneration is required.

2.5 Motor Controller Protection and Features

2.5.1 Overcurrent Protection

Current levels beyond that which would damage the controller shall cause the drive to shut down immediately and keep it off-line until the stop command is sent. The current limit status line (and indicator) shall be activated when the condition exists.

2.5.2 Current Limiting

The drive shall sense current in all phases and have an internal current limit adjustable between at least 100% and 125% of full load current. If output current in any phase exceeds this limit for more than 15 seconds, the drive shall shut itself down and remain off-line until a stop (Reset) command is sent.

2.5.3 Overvoltage/Undervoltage

The controller shall automatically shutdown when the input voltage exceeds 250 Volts RMS. It shall also automatically shutdown if the input voltage is below 198 Volts RMS. The undervoltage/overvoltage status line and indicator shall be active under this condition. The

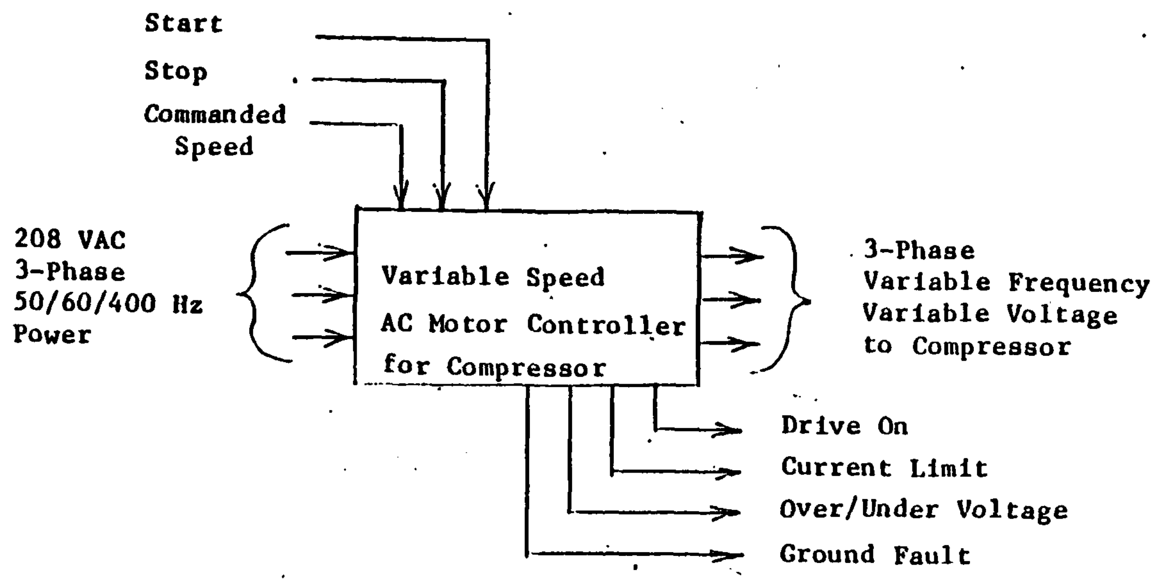


FIGURE 3 - COMPRESSOR MOTOR CONTROLLER INTERFACE

controller shall be supplied with an undervoltage and overvoltage protection manual reset.

2.5.4 Ground Currents

The controllers' output will be shut down if more than .05 amperes flow in the ground wire from the source. The ground fault status line (and indicator if available) shall become active if this condition exists.

2.5.5 Phase Rotation

The phase sequence of the controller connected to the motors shall be "A-B-C" such that the motors operate in the correct direction (A-B-C).

2.5.6 Fault Status

Motor controller status shall consist of at least four signals: drive on, overcurrent, current limit and overvoltage/undervoltage. Each output shall consist of two wires from open collector outputs. These outputs should be capable of withstanding 35 volts (with the correct polarity) and 20mA continuously. No wires shall be connected to any other. With a nominal 5-Volt supply connected (correctly) across each set of wires, a current greater than 10mA shall indicate a positive condition (i.e. drive on, current limited) while less than 10mA shall indicate a negative condition. Status indicators may also be supplied.

All signals entering and leaving the controllers shall be connected to appropriately-sized terminal blocks.

2.6 Technical Approach

It is requested that the two following technical approaches to the design of the motor controllers be bid on separately. A decision to "No-Bid" should be so stated.

2.6.1 Two Separate Controllers

Each controller shall consist of one converter, and one inverter. One controller will control the compressor and the other controller will control the two fan motors. A logic section will interface with the two controllers to operate the TECS air conditioner. This logic section will provide the functions of the air conditioner and interface between the sensors and the compressor controller. It will also provide fault location indication to be displayed on the front of the air conditioner. The logic section will be designed and engineered by Mechanical Technology Incorporated (MTI).

2.6.2 Two Inverters and One Converter

This approach will provide one converter to provide DC power to two inverters. One inverter will be for the compressor motor and the other inverter will be for the condenser fan motor and the evaporator fan motor. The logic section will interface with the converter and two inverters to operate the TECS air conditioner. This logic section will provide the functions of the air conditioner and interface between the sensors and the compressor inverter. It will also provide fault location indication to be displayed on the front of the air conditioner. The logic section will be designed and engineered by Mechanical Technology Incorporated (MTI).

2.7 Environmental Conditions

2.7.1 Operation

All controllers shall be capable of operating over an ambient temperature range of 0°F to +120°F with the respective relative humidity levels as described in Attachment 1.

2.7.2 Storage

All controllers shall be capable of storage over an ambient temperature range of 0°F to +160°F with the respective humidity levels as described in Attachment 1.

2.8 Troubleshooting

The front panel which houses the logic section will indicate where a fault is located. The electronic module where a fault is indicated will be removable for replacement. The converter, inverters and the controllers shall have test points to enhance finding a fault. To easily correct a fault, electronic boards shall be removable for replacement.

2.9 Reliability

The controller, converters and inverters shall be capable of operating continuously over the full temperature range for 12 months. Mean Time to Repair, once parts and qualified personnel are available, shall be less than 4 hours.

2.10 Physical Characteristics

Both controllers must fit within the three volumes shown in Figures 4, 5 and 6. The volume shown in Figure 4 is mounted near the 5 HP load while the volumes in Figures 5 and 6 are near the 1.5 HP load and source of input voltage. No division of function for each volume is specified. All volumes lie with their largest area horizontal. Approximately TBD cubic feet per minute air flow is available over the top of the one volume located near the 5 HP load.

2.11 Design and Construction

2.11.1 Material, Processing and Workmanship

Parts, methods of fabrication, assembly and test shall conform to accepted commercial practice. Use of dissimilar metals in construction is not permitted.

2.11.2 Product Marking

The controller shall contain the manufacturer's name, model number and serial number along with labels on all controls and adjustments. The labels may be on the panel or printed circuit board as long as they are visible during adjustment or normal use.

2.11.3 Interchangeability

All units of the same rated load shall be interchangeable after internal adjustments have been made for these same sets of operating conditions.

2.12 Safety

The controller shall be serviced by only qualified personnel. However, reasonable care must be taken to protect service personnel from lethal voltages by recessing, covering and/or labeling areas of danger.

2.13 Documentation

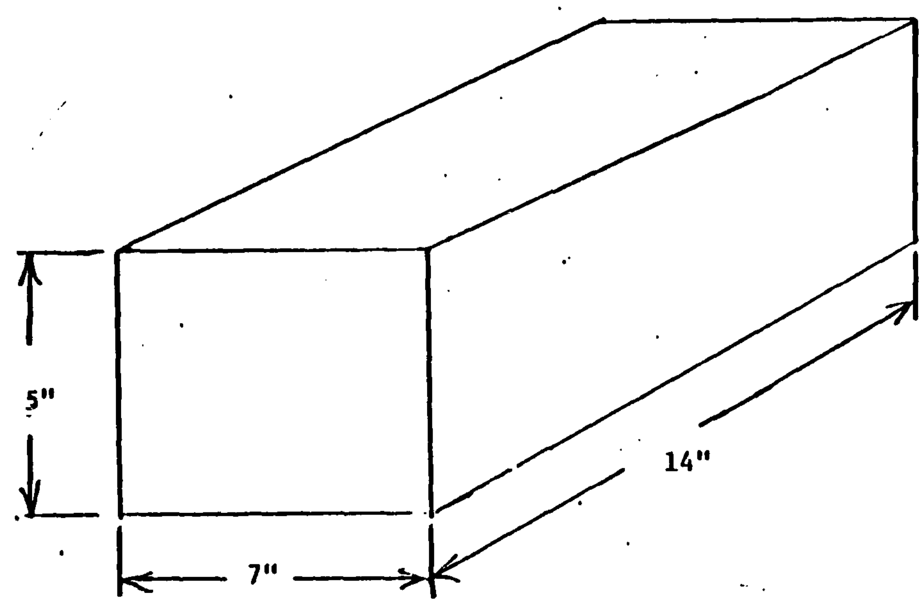


FIGURE 4 - VOLUME NEAR 5 HP COMPRESSOR MOTOR

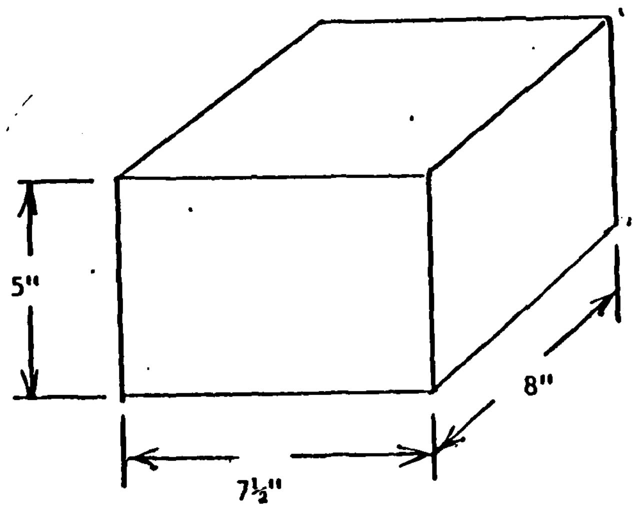


FIGURE 5 – VOLUME NEAR 2 HP FAN MOTORS

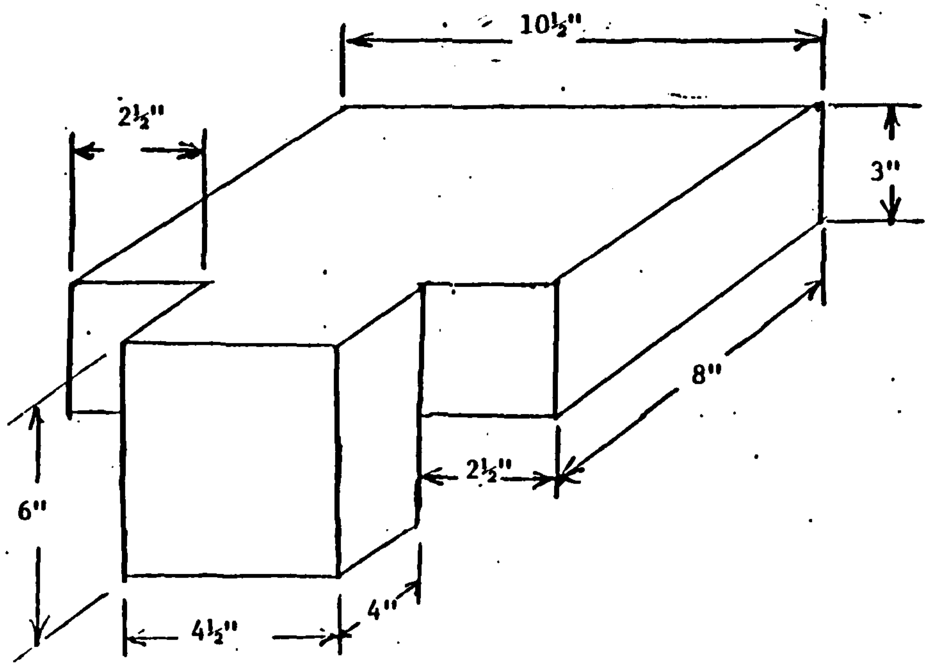


FIGURE 6 – SECOND VOLUME NEAR FAN MOTORS

An operations and maintenance manual shall be supplied with each controller so that qualified personnel will be able to identify normal system behavior and service and troubleshoot the controllers. The manual shall include as a minimum:

1. General Description of System

2. Theory of Operation

3. Major Specifications

4. Operating Instructions for Start-Up, Normal Operation and Shut-down

5. Warnings, Cautions, Safety Notes

6. Routine Functions such as Fuse/Circuit Breaker Replacement/Reset, Cleaning Precautions, and Such

7. Description of Simple Malfunction Systems

8. Simplified Electircal Diagrams

9. List of Major Components

This manual shall show voltages and/or waveforms at all test joints so that board level diagnostics may be performed by an electrical technician.

3.0 ACCEPTANCE TESTS

Each controller will be connected to their appropriate motor(s) and run for 40 hours at varying loads and temperatures. All controls and reaction to fault conditions shall be tested. The unit will be accepted if no failures occur during this period.

4.0 DELIVERY

Both controllers will be shipped to Mechanical Technology Incorporated (MTI) as its Latham, New York location.

ATTACHMENT 1

ENVIRONMENTAL CONDITONS
(Temperature Vs. Humidity)

OPERATIONAL CONDITIONS		STORAGE CONDITIONS	
Temperature (°F)	Relative Humidity (%)	Temperature (°F)	Relative Humidity (%)
120	3	160	14
115	3	155	15
110	4	150	18
105	59	145	21
100	69	135	24
95	77	125	31
90	85	120	34
85	86		
80	100		
75	100		

APPENDIX D

MANUFACTURER MODEL	COST/UNIT $	VOLUMETRIC SIZE, IN	[illegible]VE [illegible]NI[illegible] PWM-PWR TRANS = 1 PWM-GTO = 3 6-STEP = 5	[illegible]VIC[illegible]LIT[illegible] DOMESTIC = 1 FOREIGN/ DOMESTIC = 3	CO[illegible]XIT[illegible]DUL[illegible]ATI[illegible] SIMPLE CONSTRUCTION = 1 AVERAGE = 3 OVER-SOPHISTICATION = 5	TOTAL SCORE
Zycron SPUD 500	$ 800 (1)	664 (1)	5	1	1	9
Contraves CIMR-3.7B	$ 714 (1)	784 (3)	1	3	3	11
Mitsubishi FR-F2-3700-U	$1453 (3)	566 (1)	1	3	3	11
Graham 1520	$1383 (3)	1000 (3)	1	1	3	11
Reliance GP1000	$1450 (3)	917 (3)	1	3	3	13
VEE-ARC PWM 7000-5	$1324 (3)	2000 (5)	1	1	3	13
Toshiba 2055B	$1280 (3)	1225 (5)	1	3	3	15
Louis Allis Lancer	$2106 (7)	1140 (5)	1	1	3	17
Lovejoy VSD-S-8018	$1800 (5)	1232 (5)	3	1	5	19
Parametrics Parajust GX	$1673 (5)	2040 (7)	3	1	5	21
Ramsey XL5-57	$1900 (5)	4851 (9)	5	3	3	25
Hampton VLT 1040CN	$2151 (7)	2542 (7)	5	3	3	25

NOTES: 1. Figures in ( )s represent weight factor in specific category. Best Total Score = 5

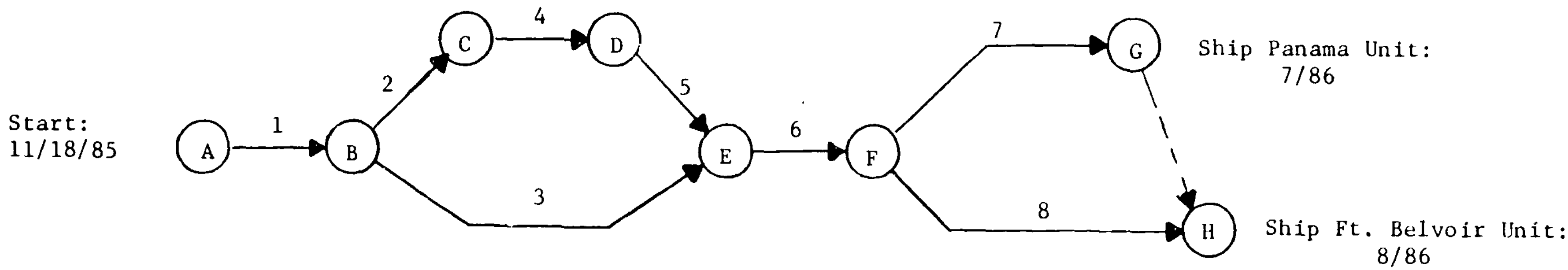
2. Other manufacturers still under consideration, but given lower priority are: General Electric, Rondo, Westinghouse, Square D, Allen-Bradley, Fincor, Emerson, Eaton, Boston Gear, Sabina, Siemens, and B&B

RANKING OF TWELVE ELECTRONIC CONTROLLERS

APPENDIX D

APPENDIX E

APPENDIX E - PERT CHART FOR HVAC ELECTRONIC CONTROLLER DEVELOPMENT PROGRAM



TASK 1.0	(A-B)	Familiarization; ECU Tests
TASK 2.0	(B-C)	Additional ECU Tests
TASK 3.0	(B-E)	Electrical/Thermo-Analyses
TASK 4.0	(C-D)	Demonstration of External ECU
TASK 5.0	(D-E)	Design of Integral ECU
TASK 6.0	(E-F)	Fabricate/Debug Integral ECU
TASK 7.0	(F-G)	Rigorous Test of Panama Unit
TASK 8.0	(F-H)	Fabricate/Debug Ft. Belvoir Unit

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MECHANICAL TECHNOLOGY INCORPORATED
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APPENDIX F

APPENDIX F

Preliminary Test Results (R. Johnson, Author)

In order to perform baseline comparison tests on the controllers chosen for evaluation, a suitable laboratory area equipped with a source of 3-phase power and monitoring instruments was set up at MTI. The location does not permit ready access to outside air; however, this disadvantage can be circumvented with a properly designed environmental chamber. Initial tests using one of the 18000 BTUH Split-Package Air Conditioners, S/N N302, proved that heat generation and containment would not be a problem for the 120°F Temperature Tests. The air conditioner is located inside an 1800 cubic foot interior room. An ambient air temperature of 106°F was reached after six hours of operation at 300 psi head pressure, due mostly to the exhaust heat from the condenser and compressor. Simple ventilation and duct work routing techniques should furnish the amount of heat required and provide a means of temperature regulation as well.

Laboratory Test Set-Up

Three-phase, 220 VAC power was fed into the HVAC Laboratory Area to a 20-ampere disconnect. A ganged, 3-phase autotransformer using a motorized drive was used to adjust the value of the voltage to *208 VAC ± 2 VAC*. This method of voltage regulation will be used whenever Section D.2 (Figure F-1) tests are conducted.

A combination Controller Power On/Off and 0-10 VDC speed analog circuit was designed and constructed at MTI to facilitate bench-testing the controllers. Wiring connections were easily accessible. Electrical diagrams for the TECS-18 air conditioner package (Reference 10 and 11) were consulted when the three-phase power connections to the compressor motor were made. Power for the condenser and evaporator fan motors was supplied directly from the output of the autotransformer.

The following Table F-1 is a list of the instrumentation and equipment used in gathering operational data on the Zycron SPUD 500 and Lovejoy VSD-S/8018 PWM controllers.

Figure F-1 is an outline of the performance evaluation tests MTI considers necessary to adequately qualify each controller as to its ability to drive the compressor unit in the 18000 BTUH Air Conditioner noted above.

TABLE F-1: HVAC LABORATORY EQUIPMENT INVENTORY

INSTRUMENT/EQUIPMENT	MODEL	SERIAL NUMBER	Calibration Date
1. Oscilloscope	Tektronix 7623A	MTI 4643	2/23/85
- Current Probe Amplifier	Tektronix AM503	MTI 20204	2/23/85
- Digital Multimeter	Tektronix DM501A		
- Dual Power Supply	Tektronix PS503A	TM503 MTI 20212	Operational Check 1/27/86
- Function Generator	Tektronix FG502		
- Current Probe	Tektronix P6303		
2. Temperature Indicator Type K	Fluke 2175A	MTI 10191	
3. Analog Ammeter, Clamp-On	Amprobe	---------	--------
4. Isolation Transformer	Stancor GIS-1000	MTI 10991	--------
5. DVM	Beckman 3020	MTI 20973	10/1/85
6. Pressure Gauges			
- US Gauge	0-600 psi	---------	Factory set
- Lenz	0-600 psi	---------	Factory set
7. Three-Phase Variac	General Radio, 25 Amperes	---------	--------
8. 5Hp, 208VAC Induction Motor, 3-Phase	Baldor Electric	S-S546967	--------
9. Oven, Hi-Low Heat Cycle	----------------	MTI 2188	--------
10. Regulated DC Power Supply	Lambda LH130 0-120VDC, 0-0.5A	MTI 1395	--------

FIGURE F-1: HVAC ELECTRONIC CONTROLLER PERFORMANCE EVALUATION TESTS

A. Performance Tests

1. Determine V/Hz Ratio

   a. Resolution of input voltage vs. frequency output

   b. Adjustment range (if adjustable)

2. Efficiency

3. Temperature rise above ambient (dependence on load requirements)

B. Power Tests

1. Automatic Trip Characteristics

   a. Over current

   b. Short circuit

   c. External, shorted phases, ground fault sensitivity

2. Temperature Test (run at 120°F test)

   a. Full load capacity

   b. V/Hz stability

   c. Heat bake effect on industrial controllers

   d. Frequency drift

3. Endurance Test

   a. Run at full load at temperature for "X" amount of time

4. Locked Rotor Tests Using Disassembled Compressor

5. No Load, or Lightly Loaded, operation

6. 400 Hertz Operation (derating, other considerations)

C. Features Testing

1. To be determined by Drive

2. Assess desirability of standard features/options

D. Analysis of Controller Performance

1. Perform calculations to determine 150°F ambient (stress) characteristics

   a. Determine how conservatively the controller is designed for:

      (1) Temperature

      (2) Power ratings

2. Determine max stress which may be applied (overvoltage limitations, max temperature range, full load/no load transients)

3. EMI/RFI Testing (to be performed at Ft. Belvoir)

Discussion of Test Procedures and Test Results

As of this point in the overall program, only certain sections of Figure F-1 have been performed for the Zycron and Lovejoy controllers. Results of these tests are listed in Table F-2 for side-by-side comparison. Figures F-5, F-6 and F-7 are schematic illustrations and block diagrams of the circuits used to obtain some of this information.

Parameters Tested or Compared

The parameters which were evaluated on each controller were:

- Volts per Hertz (V/Hz)
- Efficiency
- Voltage drop across power devices (heat sink)
- Temperature rise
- Low voltage operation
- Voltage boost adjust
- Current limit adjustment
- Resolution of control voltage vs. frequency
- Current waveform
- Drift with temperature
- Acceleration and deceleration adjustment

The procedures used in the evaluation of each of these parameters are as follows:

- Volts/Hertz Procedure -

  The ratio of volts per Hertz (V/Hz) is not a directly measurable parameter of the controllers and must be calculated from generated data. With the V/Hz potentiometer fully counterclockwise, the control voltage was varied from 1 volt dc to 10 volts dc. The output frequency and the ac voltage was measured, recorded in Test Booklets, and plotted on appropriate graph paper. A multimeter was used to measure the low voltage (at low frequency) across the compressor motor and an oscilloscope was used to determine the frequency. Straight-line approximations were then used to establish the range of V/Hz for each controller. Figures G-1 and G-2 in Appendix G graphically illustrate the results of these tests for the Zycron and Lovejoy controllers, respectively.

• Efficiency Procedure -

The efficiency of the drives is difficult to measure with the equipment at hand. The controllers each have a 95% manufacturer's efficiency rating to begin with; to be able to measure small variations in efficiency, one must measure within 1% of all contributing parameters. The waveshapes which are produced by the controllers decrease the accuracy of the meters. Instead, calculations were made using the efficiency equation (F-1). The total losses were derived by measuring the temperature rises of each of the controller heat sinks. The input power was calculated using directly-measured values of voltage (V) and current (I):

$$\text{Efficiency (\%)} = \frac{\sqrt{3}\ VI - \text{Total Losses}}{\sqrt{3}\ VI} \times 100 \qquad \text{(F-1)}$$

For the Zycron controller:

The measured temperature rise in the Zycron unit was approximately 40°C, with a current of 9 Amps at 208VAC, 3-phase. Zycron used an AAVID 61580 heat sink about 12 inches long with thermal dissipation of 1.4°C/Watt/3 in., which for this application provides a temperature rise of 0.35°C/Watt. With a 40°C temperature rise above ambient, this equates to 40°C/.35°C/Watt or 114.3 Watts. The total power supplied to the unit is $\sqrt{3}(9)(208)$, or 3242 Watts. Using equation (F-1), the Efficiency for the Zycron becomes:

$$\text{Efficiency (\%)} = \frac{3242 - 114.3}{3242} \times 100 = 96.4\%$$

If we compare the total losses to the power dissipated in the transistor, with the following assumptions:

1. Saturation Voltage = 1 Volt

2. Ideal rise and fall times

3. Three transistors are conducting at any one time

4. No base drive current (i.e., current gain of the transistors is infinite),

then the transistor losses become (9A) (1V) (3 transistors), or 27 Watts total. The bridge rectifier losses are similarly (9A)(1.2V) (3 transistors), or 32.4 Watts. Together these semiconductor losses account for 59.4 Watts, or approximately 59.4/114.3, or 52% of the losses being dissipated by the 61580 heat sink.

For the Lovejoy controller:
The efficiency of the Lovejoy unit must be obtained in a very indirect manner, mainly because the heat sink it uses is not a standard product of any of the major heat sink manufacturers. Using the AAVID 61580 specifications as a base, the following assumptions were made:

1. Area of sink is 2X that of the Zycron.

2. Use of a fan provides an additional factor of 2.

Therefore, the temperature rise above ambient in the Lovejoy heat sink is ($.35^\circ$C/Watt) (1/2)(1/2) = $.0875^\circ$C/Watt. For a measured rise above ambient of 7°C, the power dissipated by the heat sink becomes 7°C/$.0875^\circ$C/Watt = 80 Watts.

Again, at 9 Amps of running current, and using equation (F-1), the efficiency becomes:

$$\text{Efficiency (\%)} = \frac{3242 - 80}{3242} \times 100 = 97.5\%$$

Assuming a saturation voltage of 2 volts, the losses from the power devices are (2)(9)(3 devices) = 54 Watts. If we assume that a bridge rectifier similar to the Zycron's is used, with a bridge rectifier loss of 32 Watts, then the total semiconductor losses become 86 Watts. This value is in agreement with the predicted losses using the temperature rise method.

TABLE F-2: SUMMARY OF PARAMETER COMPARISONS

PARAMETER	LOVEJOY	ZYCRON
Size	14.2" x 11.0" x 8.3"	12.5" x 8.5" x 6.25
Weight	25.3 lbs	15 lbs
Max. Specified Temp	50 deg. C	50 deg. C
Efficiency, Full Load	95%	95%
Power Device	Gate Turn-Off	Transistor
Saturation Voltage Across Device	2 Volts	1 Volt
Heat Sink Temp. Rise at 9 Arms	App. 7 deg. C	App. 25 deg. C
Waveform	PWM Sine wave	PWM 6-Step
Voltage Boost	2:1, Freq. Dependent	2:1, Freq. dependent
Current Limit	125% Full Load	125% Full Load
Frequency Resolution	< 1 Hz	< 1 Hz
Volts/Hertz Ratio	.8 - 5.6	2.9 - 4.4
Under voltage operation	185 volts	198 volts
Hz drift/temp over 20-40 deg. C Range	< 2%	< 2%
Max. temp. tested	150 deg. F	150 deg. F

- Temperature Rise Procedure -

Temperature rise is a constant °C/Watt increase above a given ambient temperature. The temperature rise for each controller was measured on the warmest part of the device's heat sink, while supplying between 8 and 9 amperes (approximately 75% full load capability) to the compressor test bed. An estimate of the temperature rise for the Zycron unit was determined for full load current using heat dissipation specifications of 310 Watts at 2.0 Volts Collector-Emitter saturation for the power transistors (Zycron uses Westinghouse KD22450510 Dual Darlington transistor devices). The estimate, approximately 26.3°C, is low compared to an extrapolated value of 38.7°C (the calculations used in determining these figures are provided in Figure G-3). The reason for this difference is that the commutating current through the transistors and the power dissipated in the diode bridge were not taken into consideration, nor were rise and fall times taken into account. An estimate of the temperature rise for the Lovejoy unit was not done because the heat sink is nonstandard, and no data is available to MTI.

- Low Voltage Operation Procedure -

The 3-phase input voltage to the motor controller undergoing testing was decreased with the ganged-autotransformer to approximately 188 volts (-10% of nominal 208VAC). Effects on compressor performance, current levels and temperature changes were negligible. Both controllers started and accelerated properly under partial load (75% full load) with input voltages as low as 198 VRMS, which satisfied the requirements of paragraphs 2.2 and 2.5.3 of the Controller Specification. Below this level, the Zycron Unit would shut down on undervoltage fault, while the Lovejoy continued to operate to as low as 185 VRMS before submitting to an undervoltage trip.

- Voltage Boost Procedure -

The Voltage Boost characteristic for each controller was measured by lowering the output frequency and measuring the output voltage at this point. With frequency constant, the Voltage Boost potentiometer was then rotated and a new voltage measured. The Voltage Boost then becomes a ratio of fully counterclockwise to full clockwise values of voltage/frequency, particularly for the Lovejoy unit. The Zycron drive uses a switching technique which does not give a smooth transition between the maximum and minimum voltage levels. At a given operating frequency, both controllers provided a 1.5:1 voltage level to drive the compressor. For example, at 10 Hertz, 50 Volts instead of 35 Volts was delivered to the compressor, assuming a nominal 3.5 Volts/Hertz ratio.

- Resolution of DC Control Voltage Input vs. Frequency Output Procedure - The effect small changes in the magnitude of the dc control signal being input had on the operating frequency, was difficult to determine with the equipment available. However, the resolution was less than 1 Hertz, which is adequate for this application.

- Current Waveform and Drift With Temperature Procedure -
Photographs were taken of the output current waveform from each controller as it was subjected to similar operating conditions. These waveforms are shown in Figures F-2 and F-3 for the Zycron and Lovejoy units, respectively. Current magnitudes were 8-9 Amperes-rms at a motor speed of 3600 RPM (60 Hz). The distortion in the sinusoidal waveforms reflect the differences in the 6-width PWM approach used by Zycron and the sine-encoded PWM offered by Lovejoy. The rich harmonic content of the waveform shown in Figure F-2 would tend to produce more EMI than the more sinusoidal envelope of Figure F-3. The analytical discussions in several technical articles (References 3, 6,7 and 9, for example) point out this disadvantage in addition to as much as 5-15% increased motor heating losses and less productive torque. Figure F-4 is included to show the more pronounced distortion occurring in the Zycron unit as the motor speed is reduced.

The drift due to temperature was determined by placing each controller inside an unheated oven-type enclosure and letting the controller's dissipation heat the inside. By monitoring frequency variation, the drift was thus calculated using the data listed in Figure G-4. The drift was found to be less than 2% over a 70-140°F operating range.

- Acceleration and Deceleration Times - Measurement Procedure -
The acceleration and deceleration times were measured using a stop watch. The length of time required to reach maximum (or minimum) operating

frequency at approximately 70% full load conditions was measured as the input control signal was increased (or decreased) rapidly. Acceleration and deceleration times were each 20 seconds maximum for the Lovejoy controller, and 18.5 and 17.3 seconds, respectively for the Zycron controller. These values satisfied the Controller Specification requirements of 5-20 seconds for both times.

GENERAL OBSERVATIONS

- Zycron SPUD 500 -

The Zycron controller is a compact unit which uses power transistors to pulse width modulate the voltage supplied to a motor load. The current waveform produced at 60 Hz is similar to that of a standard 6-step generator (refer to Figure F-2). Zycron uses a 68705 microcontroller for drive signals, logic and miscellaneous functions. All components installed in the SPUD 500 unit are commercially available from electronic parts manufacturers. Zycron does not use any isolation techniques between the power sections and the logic sections, a design which is apparently not followed by other manufacturers; Zycron uses transistors to drive transistors directly rather than employing optical or magnetic isolation. The main disadvantage of direct coupling is that the possibility for failure to occur is greatly increased because the Logic Section is not isolated from the Power Electronics. Should the the high voltage DC bus be applied to the Logic Section, the logic components would not survive.

The control boards are supported by nylon stand-offs and are not bolted or rigidly held together. The commutation capacitor was mounted adjacent to the heat sink; relocation should be considered so that overheating of the capacitor does not occur.

Operationally, the Zycron controller was not able to restart the compressor under a partial load of about 300 psi head pressure (Ref. 1, Table 4-4 lists the maximum head or discharge pressure for this air conditioner as 370-410 psig). The 6-step waveform may be the cause for this problem.

The unit will fit snugly into the available vacated volumes in the TECS-18 units with little modification or circuit rearrangement.

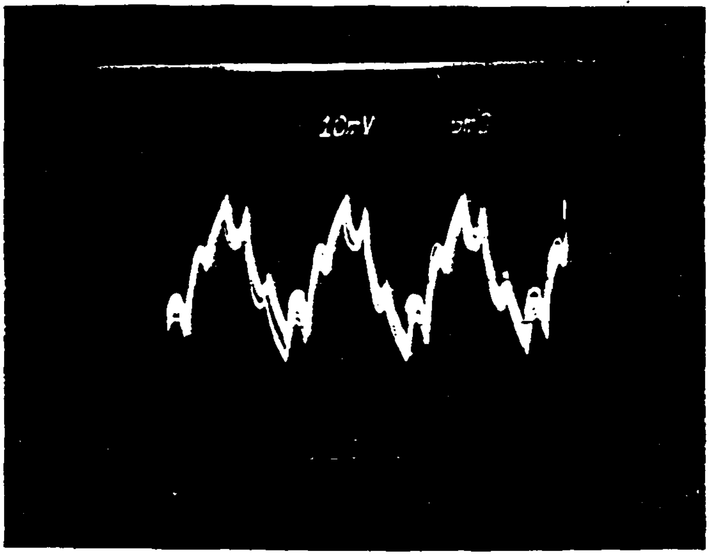


FIGURE F-2:

Zycron
SPUD 500

Output Current Waveform

9 Arms @ 66 Hz

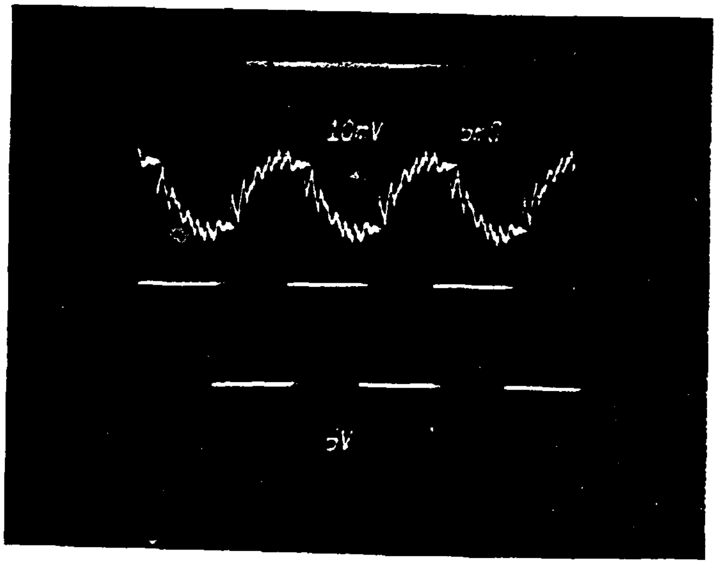


FIGURE F-3:

Lovejoy
VSD-s

Output Current Waveform

8 Arms @ 60 Hz

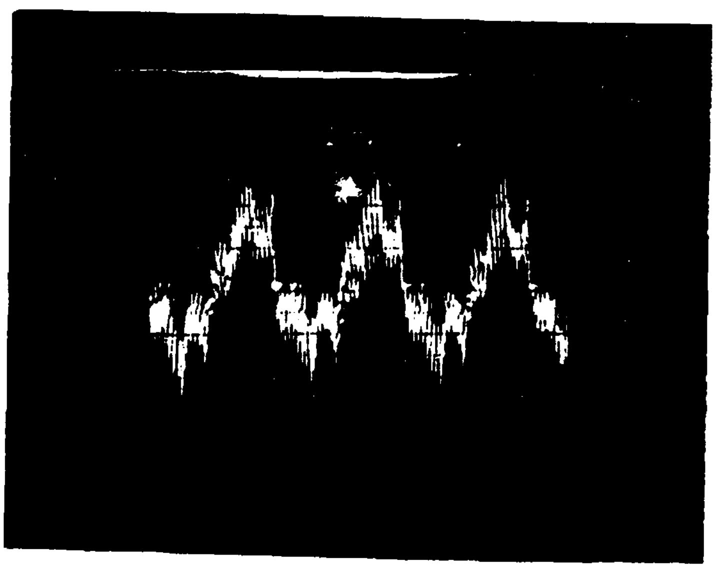


FIGURE F-4:

Zycron
SPUD 500

Output Current Waveform

9 Arms @ 33 Hz

• Lovejoy VSD-S/8018 -

The Lovejoy controller is physically much larger and more robust than the Zycron unit. It employs gate turn-off (GTO) semiconductors for power control. Each power device has its own isolated power supply. The current waveform produced (at 60 Hz) is a simulated sine wave (see Figure F-3).

The control and signal electronics are comprised of custom-designed devices, which are hybrids and custom chips in a 48-pin package available only from Lovejoy.

The unit uses a cast aluminum heat sink with a dc fan for forced-convection cooling. The printed circuit boards are supported on metal brackets and bolted to the chassis.

The controller produces an audible noise at low operating frequencies; the noise disappears as the speed is increased.

Due to its sophistication and complexity, and hence its physical dimensions, it will be difficult to fit the Lovejoy controller into the TECS-18 unit without a significant amount of component rearrangement.

DIRECT COMPARISON OF ZYCRON AND LOVEJOY CONTROLLERS - CONCLUSIONS

Both drives performed up to, and often exceeded, their individual specifications. They represented the wide differences in PWM techniques being implemented by the adjustable speed controller industry. Zycron uses standard, off-the-shelf components, a unique method of encoding drive signals, and tends to push the specifications of the Westinghouse power transistors, although remaining below the devices' allowable operating limits of 50 Amperes continuous collector current, at 2.0 volts collector-emitter saturation voltage and 125°C junction temperature. On the other hand, Lovejoy uses a more conservative approach, specifying and designing their own components and maintaining low temperature rise well within safe limits. It also employs a more rugged method of chassis construction.

Both drives, too, are aimed at the heavy industrial environment and, therefore, their design emphasis is more on reliability than compactness. The question of

400 Hz operation is not a concern for them, and neither would guarantee operation at this frequency, at this time. This, of course, is a drawback for this application.

From the standpoint of overall performance, the nod would have to go to the Lovejoy unit. It ran cooler, started the compressor with less surge current than the Zycron, and at 75% full load, would not trip out after a start command. This ability supports the theory that the starting torque is higher for a sine-encoded sine wave PWM than a 6-step PWM. It is also possible that a malfunctioning equalization valve, partially or fully closed, may have contributed to this trip condition.

The Zycron drive also exhibited nuisance tripping during start-up (no real fault present or evident in the system) if the control signal changed faster than 2 Hz/sec; this problem can perhaps be remedied by limiting the control electronics frequency. The Zycron trips under this condition because it measures the regenerative current, whereas the Lovejoy does not. At the moment, it is impossible to tell if this feature is a detriment or enhancement.

On receipt of a Stop command, the Zycron coasts to a halt; the Lovejoy unit has a built-in feature which controls the rate of coast down. This feature, if desirable, can be added to the Zycron unit in the electronic controller circuit.

The fact that the Lovejoy unit uses only hybrid and custom-designed integrated circuits is a disadvantage, as parts availability may be difficult and second sourceing impossible. The Zycron unit uses standard parts which are mostly second sourced.

The baseline Lovejoy model is too large to permit easy installation into any or all of the vacated space in the TECS-18 air conditioner. The Zycron unit should fit with some modifications, such as component rearrangement for better temperature distribution, and more rugged support structure. Before a component rearrangement can be made, certain characteristics should be improved:

1. Current waveform should be perceptibly closer to being a true sine wave.

2. Temperature rise should be decreased by improving the design of the heat sink or by providing more efficient means of convection cooling.

3. Drive chassis and component supports should be ruggedized.

As to the important question of 50/60 Hz and 400 Hz operation, there is a good possibility that the Zycron controller, for example, can be modified by replacing its control transformer (which has two, center-tapped outputs) with a transformer rated for 50-400 Hz operation. The likelihood of such a device being marketed is good; for example, Torotel Products manufactures a PC mount power transformer, step-up and step-down in a variety of combinations, with operation usable from 60Hz to above 400 Hz. In the worst case, a control transformer meeting 400 Hz requirements could be custom wound.

In conjunction with the transformer, an off-line voltage regulator or AC/DC converter would be used to provide the proper dc bias voltages for the microprocessor, logic section, and peripheral displays. Power General manufactures devices such as their Model 326 or Model 325 which operate from a 180-260 VAC, 45-450 Hertz power source, with operating temperature in excess of 150°F; the unit is encapsulated in a 4" x 2 3/4" x 1 3/8" PC-mountable package and costs approximately $120.00. Consideration will be given to the feasibility of combining the off-line regulators used by Zycron, with the unit used by MTI for the necessary dc bias voltages. This would require a larger package and additional internal wiring for interconnections; however, space constraints may dictate such a modification.

As three-phase, 400 Hz power is presently not available at MTI, testing for 400 Hz compatibility would have to be performed on a single-phase basis using an audio power amplifier. Measurements of device voltages and currents, temperature rises and waveshapes would indicate whether or not the modifications would yield satisfactory performance with 400 Hz, 3-phase, 208 VAC power.

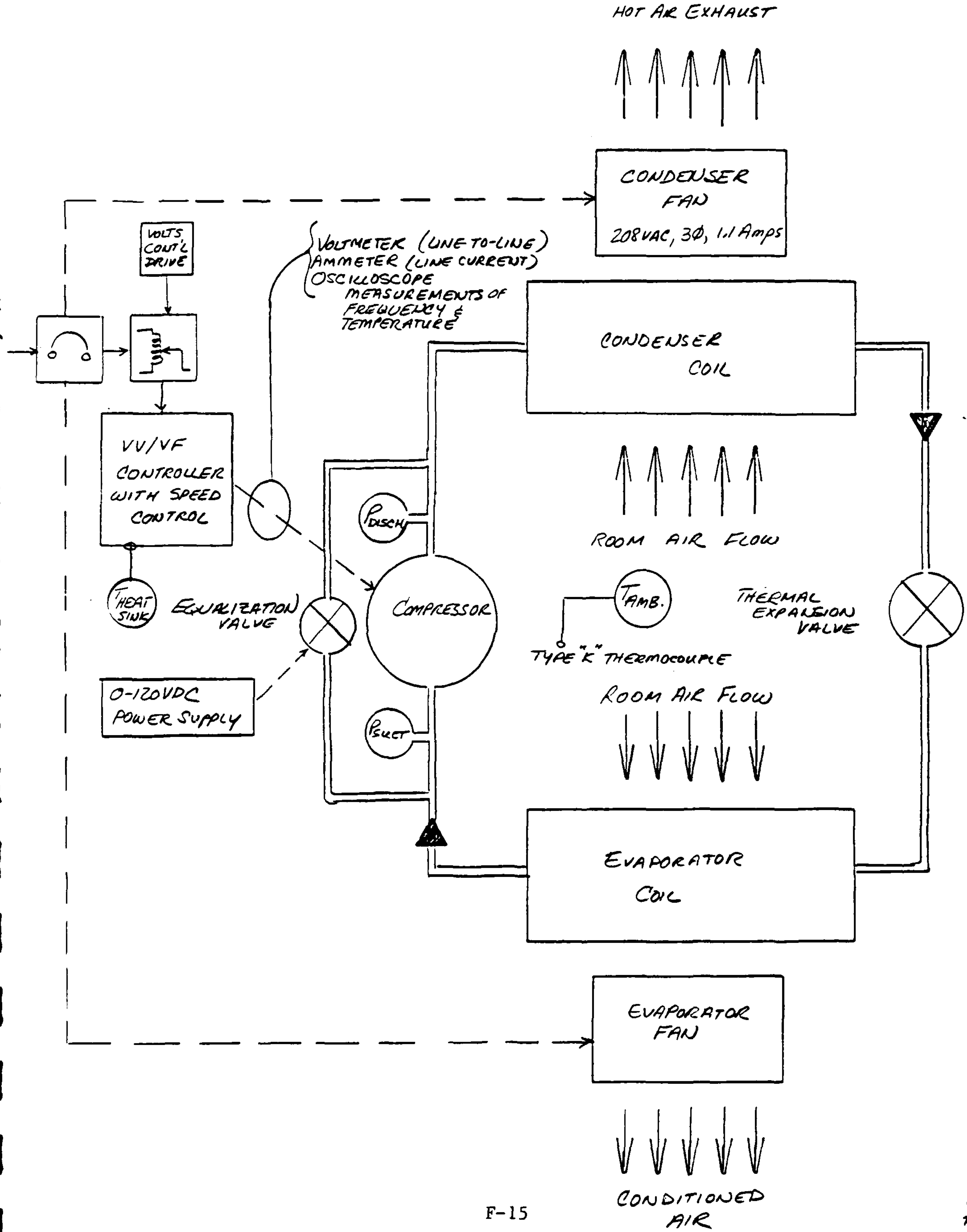
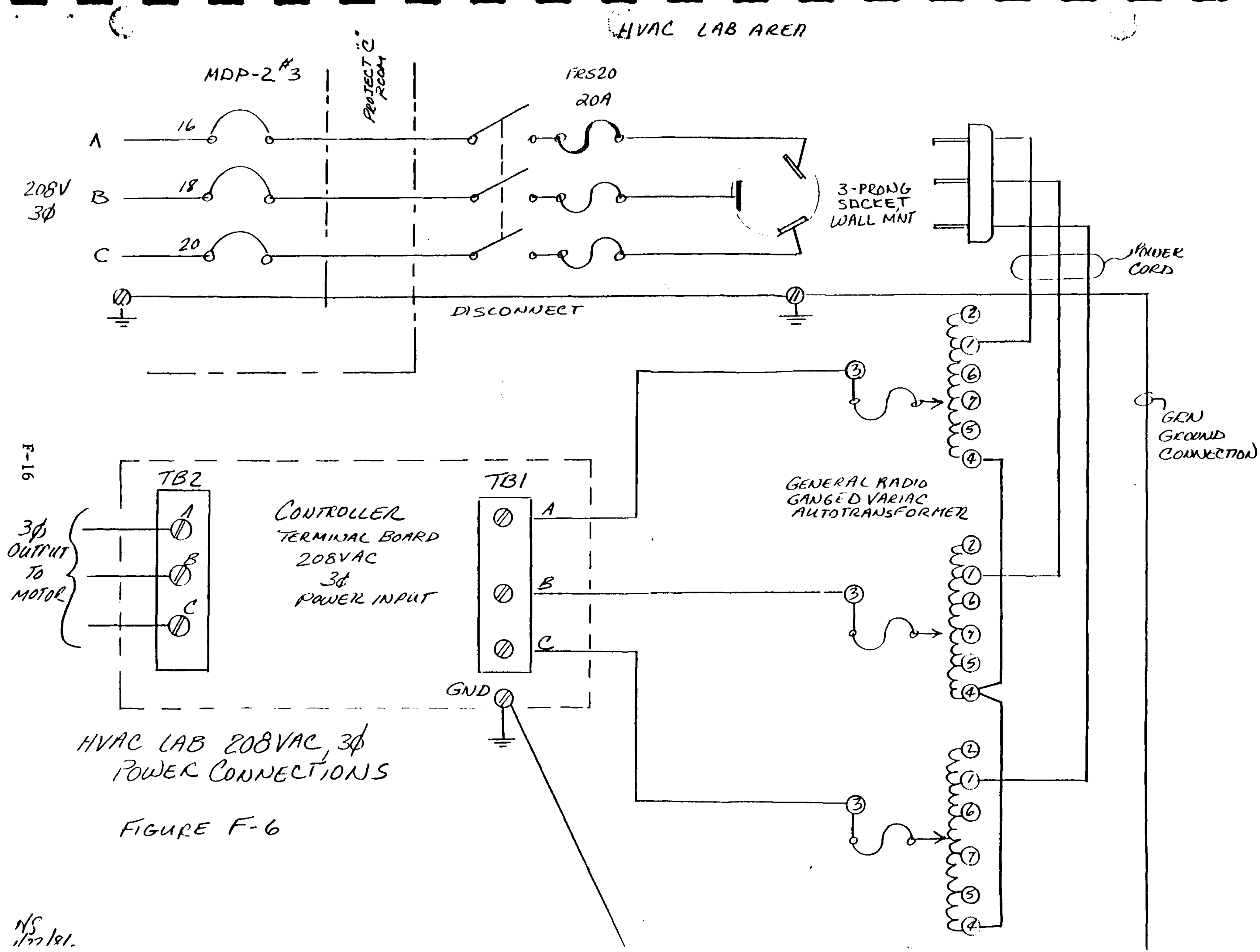


FIGURE F-5: SIMPLIFIED SPLIT-PACKAGE A/C (TECS) BLOCK DIAGRAM FOR CONTROLLER BENCH TESTS



HVAC LAB 208VAC, 3Ø POWER CONNECTIONS

FIGURE F-6

NOTES:

* ZYCRON CONTROL TB1-6 TO THERMAL OVERLOAD SWITCH (TOS) ON MOTOR. RETURN FROM TOS TO TEST BOX TB1-8.

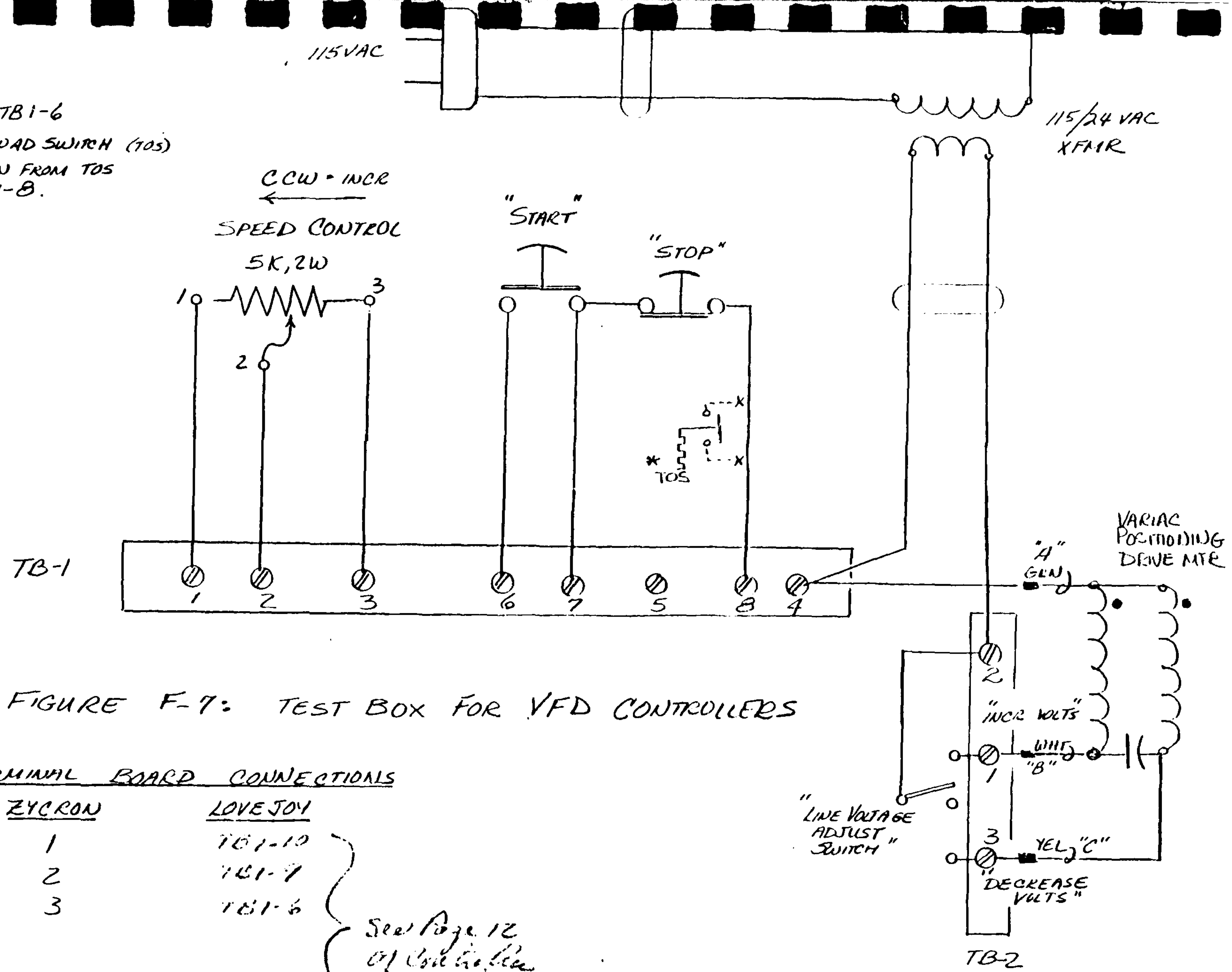


FIGURE F-7: TEST BOX FOR VFD CONTROLLERS

TERMINAL BOARD CONNECTIONS

TEST BOX	ZYCRON	LOVEJOY
1	1	TB1-10
2	2	TB1-7
3	3	TB1-6
4		
5		
6	4	TB1-3
7	5	TB1-5
8	6*	TB1-1

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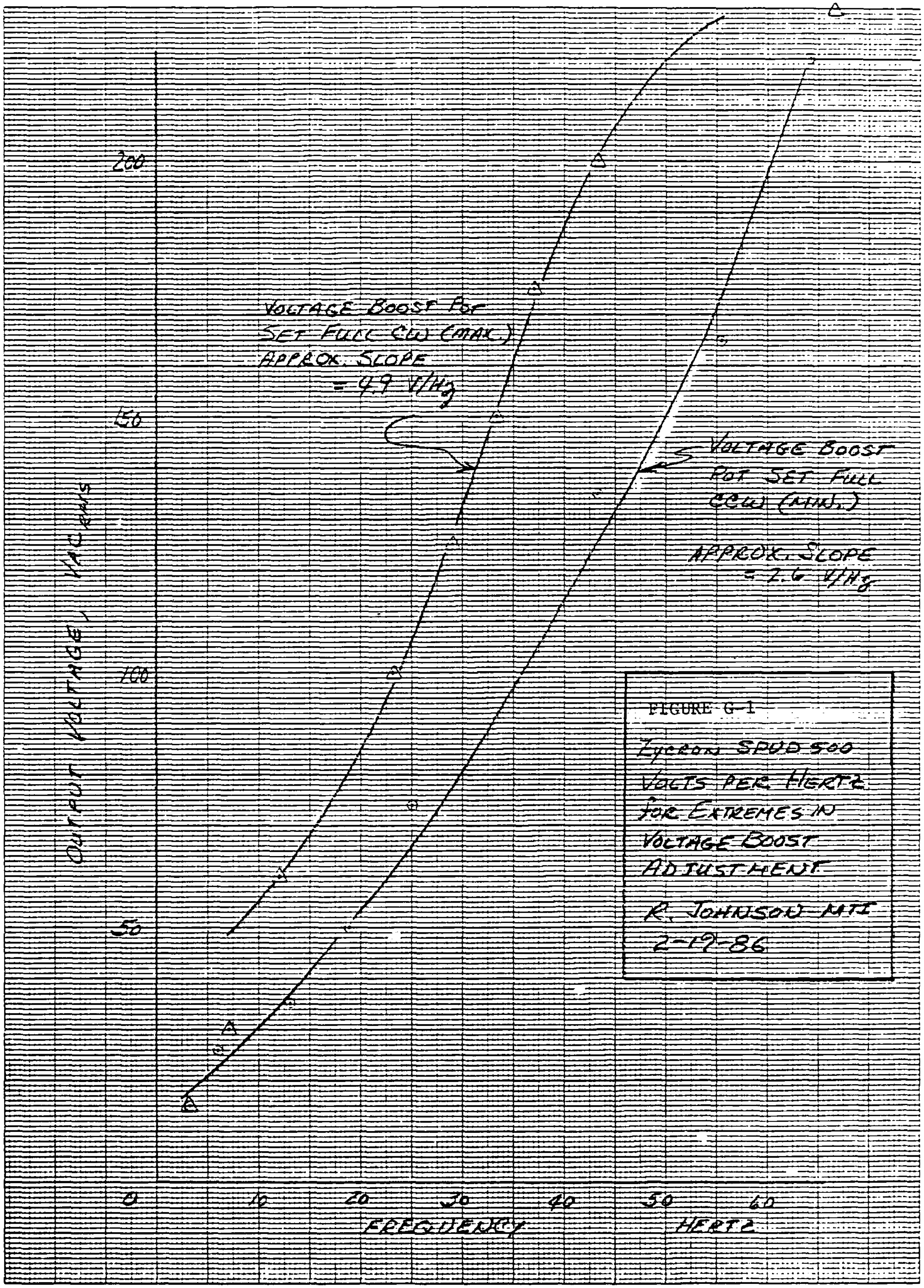
APPENDIX G


200
150
100
50
0
10
20
30
40
50
60
OUTPUT VOLTAGE, VAC RMS
FREQUENCY HERTZ
VOLTAGE BOOST POT SET FULL CW (MAX.) APPROX. SLOPE = 4.9 V/Hz
VOLTAGE BOOST POT SET FULL CCW (MIN.)
APPROX. SLOPE = 2.6 V/Hz
FIGURE G-1
Zycron SPUD 500
Volts per Hertz for Extremes in Voltage Boost Adjustment
R. JOHNSON MTI
2-19-86

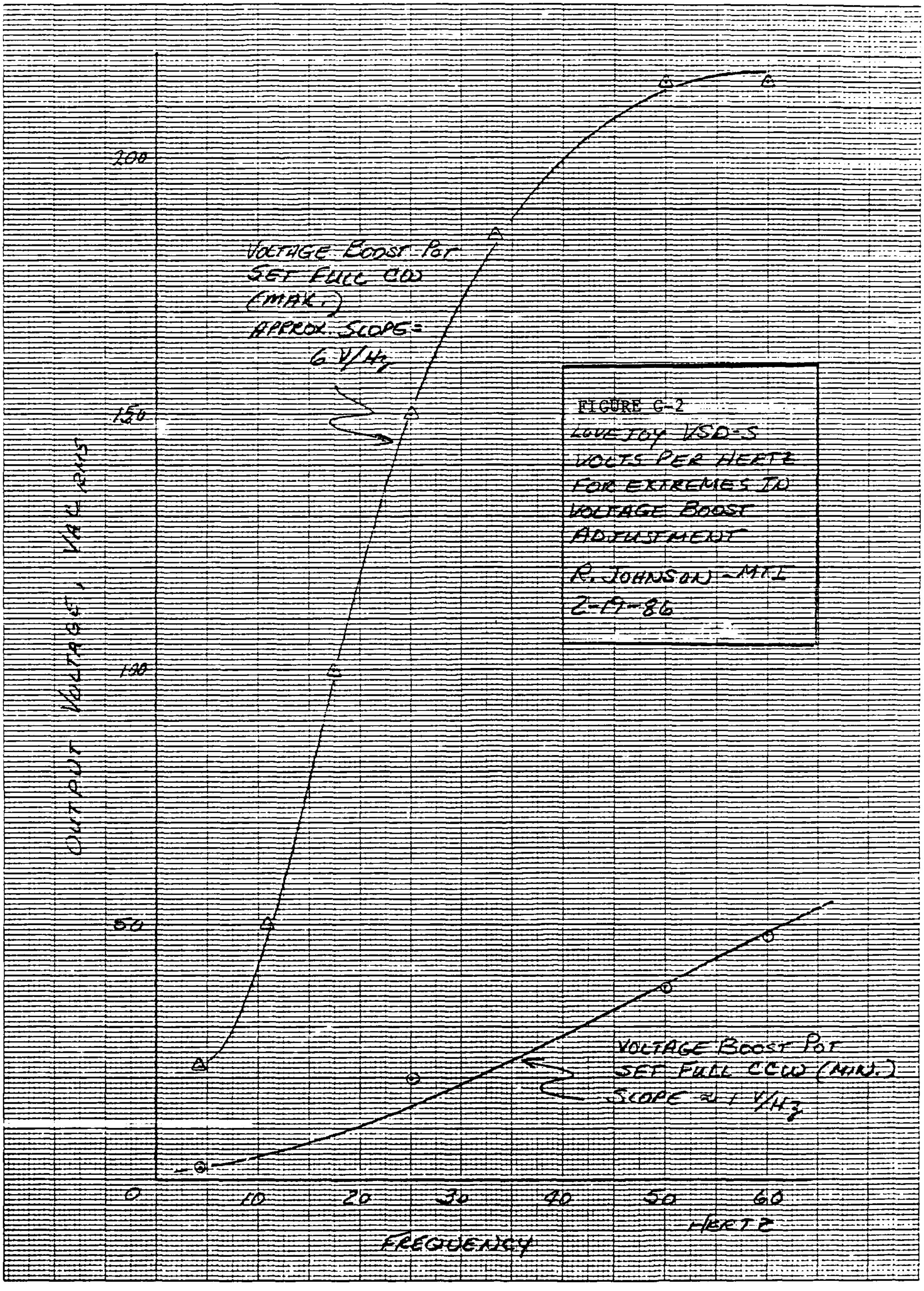


FIGURE G-2
LOVEJOY VSD-S
VOLTS PER HERTZ
FOR EXTREMES IN
VOLTAGE BOOST
ADJUSTMENT
R. JOHNSON - MTI
2-19-86

FIGURE G-3: CALCULATIONS USED TO DETERMINE TEMPERATURE RISE IN ZYCRON UNIT AT FULL LOAD OPERATION

ZYCRON POWER DRIVE: WESTINGHOUSE 2N505 DARLINGTON:

450 VOLTS @ 50 Amps

$V_{CE}(SAT) = 2.0VAC$ @ 12A

$h_{fe} \approx 100$ @ 12A

POWER DISSIPATED @ $I_{FL} = 12.5A = (12.5)(2.0) = 25$ WATTS

IF ALL 3 TRANSISTORS CONDUCT SIMULTANEOUSLY,

P_T = TOTAL POWER DISSIPATED = $3 \times 25 = 75$ WATTS

AAVID 61520 SPEC: $1.4°C/WATT/3\text{ in} = K$

FOR 12" LENGTH, $K' = (1.4)(3)(\frac{1}{12}) = .35\ °C/WATT$

$$\Delta T = K' P_T = \left(\frac{.35°C}{WATT}\right)(75\text{ WATTS}) = 26.3°C$$

ASSUME LINEAR RELATIONSHIP BETWEEN ΔT AND I:

$P = VI \qquad V = \frac{P}{\Delta T} = (\text{CONSTANT})$, where the ΔT term is a direct function of I:

AT 68% FULL LOAD,

$$V = \frac{68\%}{26.3°C}$$

At 100% Full load,

$$V = \frac{100\%}{T°_{fL}}$$

$$T°_{full\ load} = \frac{100}{68}(26.3) = 38.7°C$$

Controller	Chassis Temperature °F	Frequency msecs	Frequency Hertz
Cycron	72	16.3	61.3
	86	16.7	59.9
	106	16.6	60.2
	122	16.7	59.9
	140	16.5	60.6
			Average = 60.4 Hz
Lovejoy	74	16.4	61.0
	88	16.6	60.2
	103	16.7	59.9
	120	16.7	59.9
	139	16.6	60.2
			Average = 60.2 Hz

KJ 2/19/76

Figure G-4: DATA USED TO DETERMINE FREQUENCY DRIFT DUE TO TEMPERATURE

Mr. Herbert Short
Mechanical Technology Inc.
968 Albany-Shaker Road
Latham N.Y. 12110

Dear Herb:

I was requested to analyze the motor used in the TECS compressor. In order to develop an equivalent circuit of the motor a load test is needed. The data obtained in such a test gives:

- RPM
- Torque
- Line Voltage
- Line Current
- Watts Input

Data was supplied by Ft. Belvoir which appears to give the needed information. The sheet is hand written on a printed form which apparently came from Western Gear. The Test Report No is 1026-97. Other sheets of the same printed form clipped together were dated 4-10-73 and 4-11-73 although the sheet labeled "Compressor Motor" was not dated. Other sheets in the same pack are apparently those for a 0.3 HP. and a .75 HP. motor which agree with the ratings for the fan motors. In a meeting with Tom Sgroi and Don Fetterman it was questioned whether or not this data applied to the compressor motor in the TECS units supplied to MTI. Another report No. 119301 Page 2 and labeled in hand writting "60 line power" gives Watts input of 3380 and Line Current of 10.4 Amperes agrees with the Western Gear Data Sheet. As a result of the question I requested that the above listed data required to develop a motor equivalent circuit be obtained at at least one operating point on the compressor motor in the TECS unit be obtained to confirm whether or not the Western Gear data applies to this motor. This has not yet been done as it is planned for the next task. Having no other alternative the analysis was done on the Western Gear data.

It was found that the standard induction motor equivalent circuit with fixed coefficients would not match the data over the speed torque range. In order to make a match to 1% or better it was necessary to include an extra loss element in the rotor which contributed to loss but not to torque. This requirement is common with high resistance rotor construction. The equivalent circuit and efficiency figures are given for four levels of horsepower and are shown in Fig. 1. When operating the TECS at 60 Hz a line current of approximately 11 Amperes was found. This means that the motor is developing approximately 3 Hp. at an efficiency of about 59%. With a rotor resistance of normal value the efficiency would be about 80%

It is planned to operate the TECS on a variable speed motor drive having pulse width modulated six step output. When running at less than full speed (i.e. 60 Hz) pulse width modulation is used to reduce the applied voltage so as to maintain constant Volts/Hertz. When running at full speed the pulse width modulation dissapears and the applied voltage has the six step waveform. The exact pattern of the pulse width modulation is not known so that a harmonic analysis of the waveform at lower values of input voltage cannot be made.

Figure 2(a) shows the motor performance with 208 Volts 60 Hz applied and giving an output of 4.64 Hp. at 3250 RPM. When 208 Volts is applied to the motor control unit the line to line switched voltage is less due to drop in the rectifier bridge and the switching transistors. This drop is assumed to be 6.0 Volts. This gives a line to line switched voltage of 288.2 Volts. Two phases are connected in parallel with the third phase in series for 60 degrees when one of the paralled phases is switched to be in parallel with the above third phase. Fig.2(b) shows the resulting phase voltage having a peak value of 192.1 Volts. A harmonic analysis of this waveform as given in Fig. 3 shows that the peak of the fundamental is .954958 of the peak value. The rms. value of the phase voltage is then 129.6 and the rms. value of the line to line voltage is 194.6 Volts. As shown in the tabulation of motor performance at this voltage and 3250 RPM is 4.06 Hp. This reduction in motor output due to reduced line voltage is the principal effect of the six step motor drive system. If the higher output obtained on full voltage sine wave input is desired the motor speed must be reduced (higher slip) and the line current increased. This causes a substantial reduction in motor efficiency.

Another cause of reduction in motor efficiency when using a six step motor drive are losses caused by harmonics in the voltage supply. A harmonic analysis of the six step waveform is given in Fig. 3. A first approximation of loss analysis is to apply each of the harmonic voltages (for the fifth harmonic, .19238 x 194.6 = 34.73 Volts) to the motor equivalent circuit at an input frequency of 300 Hz and a running speed of 3250. The resultant loss calculated is approximately 40 watts for the fifth harmonic. Likewise 25 watts is obtained for the seventh. All other harmonic losses are very small. Thus only about 1.25% additional loss is caused by the harmonics. On the other hand raising the slip enough to get back to the power output obtained on the 208 Volt input will require approximately 14% additional line current and will result in 255 Watts additional loss when operating at 4.6 hp. This is a 4.3% loss as compared to the 1.25% loss caused by the harmonics.

The reduced line voltage on the six step supply also reduces the motor starting torque available and may caused the motor to fail to start under load when it would sucessfully do so when operating on the 208 Volt supply.

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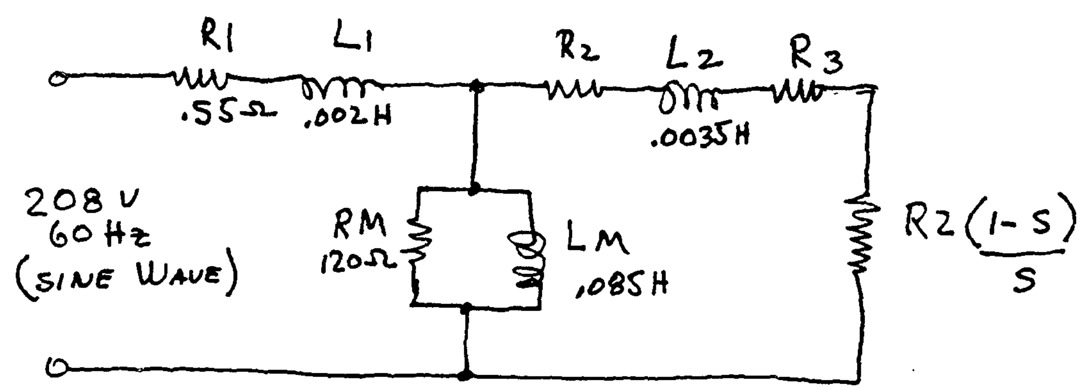
April 24, 1986

TECS 4½ H.P. Motor



INDUCTION MOTOR
EQUIVALENT CIRCUIT

HP	RPM	EFF%	R1	L1	RM	LM	R2	L2	R3	R2(1-S)/S
.56	3540	37.2	.55	.002	120	.085	.5	.0035	23.0	29.5
2.18	3450	55.2	.55	.002	120	.085	.43	.0035	4.8	9.89
3.09	3390	59.2	.55	.022	120	.085	.457	.0035	2.9	7.38
4.64	3250	58.3	.55	.002	120	.085	.457	.0035	1.55	4.24

Note: R3 contributes to loss but not to torque.

FIG 1.

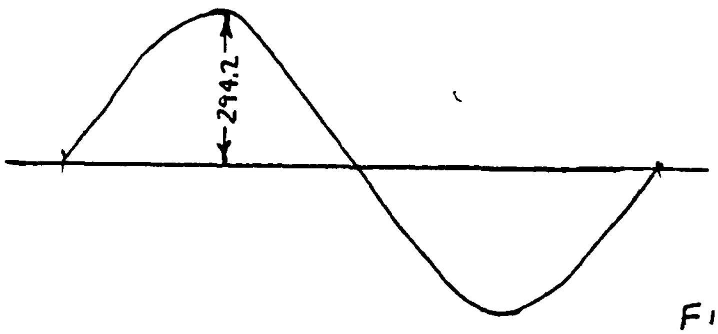
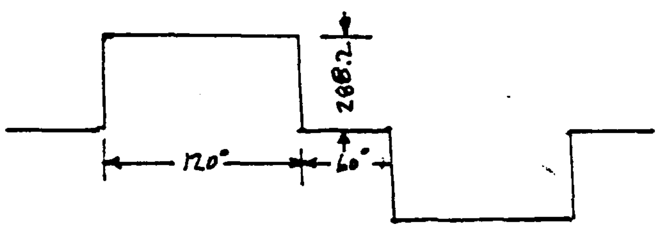


Fig 2 (a)

208V rms. 60 Hz

```
50 R1=.55:RM=120:R2=.457
60 L1=2.000001E-03:LM=.085:L2=3.500001E-03
70 VT=208:HZ=60
83 RPM=3250
```

TORQUE	RPM	ILINE	EFF	PIN	POUT	HP
89.97377	3250	18.28063	.5839773	5927.197	3461.349	4.639878



Line to Line Voltage

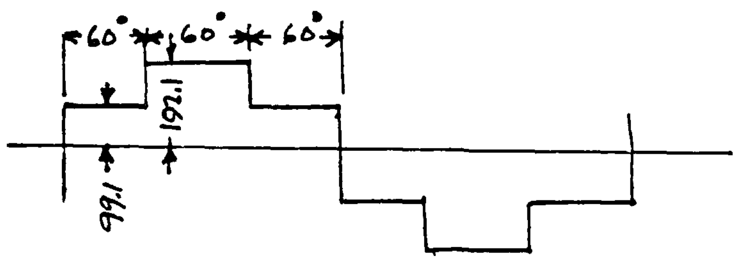


Fig 2(b)

Phase Voltage

RMS line to line = $(192.1 + 99.1) \times .95496 \times \frac{1}{\sqrt{2}} = 194.6V$

```
50 R1=.55:RM=120:R2=.457
60 L1=2.000001E-03:LM=.085:L2=3.500001E-03
70 VT=194.6:HZ=60
83 RPM=3250
```

TORQUE	RPM	ILINE	EFF	PIN	POUT	HP
78.75443	3250	17.10294	.5839775	5188.101	3029.734	4.061306

HARMONIC ANALYSIS

```
FUNDAMENTAL =  .954958    DEGREES= .7499239
2ND HARMONIC=  3.380885E-06   DEGREES= 55.20382
3RD HARMONIC=  1.642628E-06   DEGREES=-15.19871
4TH HARMONIC=  4.356937E-04   DEGREES= 89.99298
5TH HARMONIC=  .1911236   DFGrEES= 3.749957
7TH HARMONIC=  .1923838   DEGREES= 45
9TH HARMONIC=  5.510487E-07   DEGREES=-46.14586
11TH HARMONIC= 8.711342E-02  DEGREES= 8.24977
13TH HARMONIC= .073811 DEGREES= 9.74982
```

FIG 3.