A Study of Fuel Pump Performance Testing and its Implications on Product Acceptability

by

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ABSTRACT

In this study, gage capability testing was conducted on the fuel pump, performance test equipment in the Engineering Test Laboratories and the Fuel Pump Production Facilities. A sequence of tests was designed to identify the sources of and quantify the measurement error while measuring the performance of two types of electric fuel pumps under numerous conditions. Some of these conditions included multiple technicians, Lab location, test fluid type, operating point, and many "noise" variables. For each of the pump types, the results from the Lab and respective Plant were analyzed and compared using statistical analyses.

An integral part of the fuel pump, performance testing at the Labs and the Plants is the test fluid. Both use different test fluids for their testing, and the test procedures and equipment are different. As a result, an additional investigation was conducted to determine a test fluid correlation and its impact on the pump acceptance criteria such as production test limits and design specifications (independent of test location, procedure, and equipment). Lastly, the effects of the different test fluids and their properties on fuel pump performance were studied.

One of the most important conclusions from these studies was that there was an interaction between test process variance (gage repeatability and reproducibility of measurements) and the pump variance. Therefore, the pump acceptance criteria have to accommodate both sources of variability in the fuel pump performance measurements. The effects of these sources of variability could be minimized by: minimizing the differences between the test equipment in the Labs and Plants, verifying the instrumentation calibration procedures, and minimizing manufacturing variability through robust design. If these steps are not addressed, many costs, such as scrap costs and warranty costs, could result.

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PREFACE

The presentation of this thesis investigation in the subsequent chapters serves as one of the requirements for completing the Leaders for Manufacturing (LFM) Program at the Massachusetts Institute of Technology. Combined with the research efforts I have undertaken upon the assignment of this project, this paper is also the culmination of the LFM internship experience. The diversified and applied curriculum of the LFM Program and previous employment experience at the Ford Motor Company, Truck Operations have served as invaluable instruments to these ends.

Since this thesis project employed the use of much experimental design and statistical analysis techniques as well as the fundamentals of fluid mechanics and dc motor principles, previous coursework and consultation with my M.I.T. advisors were very beneficial. Preliminary research was conducted both at M.I.T. and at Ford to become more familiar with the thesis topic and fuel pumps, their performance, and the fuel pump performance test equipment. It also became important to ascertain and study any previous work in the area of gage repeatability and reproducibility studies of the fuel pump performance test equipment and test fluid/equipment correlation. With the enduring and patient assistance of so many engineers and production personnel at the Electrical and Fuel Handling Division (EFHD) as well as people from the Scientific Research Labs, Central Labs, and Automotive Components Group Staff, I was able to design numerous tests and have them run to determine the measurement error of the fuel pump performance test equipment and the test fluid correlation at the Engineering Test Laboratories and the Component Production Facilities.

Consequently, I would like to take this opportunity to express my appreciation to all the technicians and engineers in the Engineering Test Laboratories and the Test Systems, Current Model Fuel Pump, Advanced Fuel Pump, and the European Fuel Pump Engineering Activities at EFHD. Their experience and knowledge of the fuel pumps and performance test equipment has been immensely helpful. Without their support, the project would not have been contained within the time frame allotted. Their follow-up on the thesis project was pivotal as I resumed academic work at M.I.T. during the 1993

Spring term. Furthermore, I would like to thank the Engineering Services Manager, Mr. Bruce Park, for providing me with the opportunity to work in his department and to interact with so many great people. His advice and consultation were influential in directing the scope of the thesis project. I would also like to thank the Fuel Pump Engineering Manager, Mr. John Pearn, for putting me in contact with all the "right" people at both Components Production Facilities and providing an overwhelming amount of support and influence in getting the thesis project testing implemented at all the test sites. Lastly, I would like to extend much thanks to my direct supervisors, Mr. Mike Schmenk and Mr. Jeff Riedel, in the Test Systems Engineering Section for being such "great guys". Their enthusiastic support, commitment, and openness to the conclusions and recommendations that resulted from this project have made this internship experience great.

To extend my appreciation further, there was also much outside help and support from other organizations within the Ford Motor Company. These included Mr. E. Schanerberger from the Fuels and Lubricants Section of the Scientific Research Staff and Mr. A. Reaume from the Organic Chemistry Lab of Central Lab Services. Mr. Reaume conducted much of the fluid property testing. It was from these two activities that much was learned about the test fluids and how to control them as variables and test them for correlation in impact on the fuel pump performance. The test fluids were a very integral part of all the experimentation that was conducted throughout this thesis project.

Next, an extra-special thanks is extended to Mr. Curtis Yates of the Current Model Fuel Pump Engineering Section. Without his support, patience, enthusiasm and continued tracking of the thesis project and testing, the project would not have been completed. His knowledge and experience about the gerotor pumps, performance test procedures, and electrical engineering helped me to design the performance test experiments and organize a test plan. In addition, Mr. Ferenc Prager and Mr. Rick Pilkiewicz of the Engineering Test Laboratories at the Alba and ETC Labs, respectively, were outstanding implementers. They took the many test procedures that I developed and all the drums of gasoline and infinite amount of fuel pumps that I sent them and produced the results. Perhaps, one day I will be able to formally thank Mr. Prager by a visit to the Ford-Alba Plant in Hungary.

In summary, I would also like to express my gratitude to my advisors at M.I.T. as they were very influential in directing my efforts as well as providing me with objective insight on how to design my testing, what to study, and how to analyze the data. Specifically, I would like to thank Professor John Lienhard of the Mechanical Engineering Department for not only visiting the internship site but for providing me with a better understanding of the principles behind positive displacement pumps and dynamic, regenerative pumps. In addition, his review of how fluid properties and fluid mechanic principles are applied to fuel pumps was very insightful and provides the basis for Chapter 5 of this thesis paper. I have appreciated his time and willingness to set up meetings with me to discuss some of the trends in the results of the testing. I would be honored to work for him in the future and admire his expertise.

Without anymore delay, I would like to extend my thanks to Professor Roy Welsch of the Sloan School of Management at M.I.T. Without our numerous statistical consultations on ANOVAs, inverse regression analyses, balanced and crossed experimental design, my data analysis would have been overwhelming. I am certain I would have been buried beneath the 10,000+ pieces of data that resulted from all the testing. His insight and statistical expertise have convinced me of the importance and power of the use of applied statistics in decision making. Chapters 3 and 4 of this thesis paper reflect this insight and expertise.

As a whole, Ford Motor Company has been very influential in my decision to pursue a career in mechanical engineering as well as my participation in the Leaders for Manufacturing Program at M.I.T.. My internship experience at the Electrical and Fuel Handling Division has been outstanding, all due to the employees. Combined with the academic experience of the Leaders for Manufacturing Program, my perspective and understanding of the automobile industry has broadened. This is one of the key advantages of the internship experience. I also wish to acknowledge the Leaders for Manufacturing Program for all its support and valuable resources that it offered me and will continue to offer me in the future.

My pages here are limited, but to everyone involved with this project, from the day it was begun until the last signature on this document: **A BIG THANKS!!!!**

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF FIGURES (Continued)

LIST OF TABLES

LIST OF TABLES (Continued)

Chapter 1: Introduction

1.1 BACKGROUND AND UNDERLYING MOTIVATION

The Ford Motor Company, Electrical and Fuel Handling Division (EFHD) is responsible for supplying the Car and Truck Divisions of North America with two types of fuel pumps, the gerotor and turbine type. Since 1985, the gerotor type pumps have been produced by EFHD at the Rawsonville (Michigan) Plant under a licensing agreement with an external supplier. This supplier's design, both of pump and manufacturing process, was adopted. The turbine type fuel pumps were produced solely by suppliers for Ford's North American Automotive Operations as well as its European Operations or Ford of Europe. Recently, however, a new production facility has been built in Hungary to accommodate a joint licensing agreement that Ford-EFHD has entered into with one of these suppliers. This allowed Ford-EFHD to purchase the pump design from this supplier and manufacture and sell in Europe.

Currently each type of pump goes through 100% inspection or test at the Component Production Facilities where it must meet production, performance specification limits created for a test solvent. These limits were established by EFHD. Then, samples of the production population go through a series of production validation tests (performance) at the Engineering Test Laboratories in accordance with the Ford Engineering Specifications (ES). If the pumps pass the tests in the Labs, they are proven for production and shipment to the customers. Frequent quality control is performed at the Plants with in-plant checks and samples taken and sent back to the Labs for continued verification.

Based on the above discussion, there are several underlying motivations for completing this thesis project, they are as follows:

- External suppliers of the gerotor pump possess more "liberal" end-of-line fuel pump, performance specifications (especially for outlet flow at fixed voltage and pressure).
- The recent ramp up and launch of turbine pump production at the Hungary Alba Plant and the start of the licensing agreement with another external supplier.
- The expiration and non-renewal of the gerotor pump licensing agreement with the external supplier.
- The Ford Engineering Specifications for the fuel pumps and their impact on Lab testing and Plant testing (gasoline versus solvent).

- The design, production process re-design, and launch of the new modular fuel pump at the Rawsonville Plant by the end of the decade.

1.2 PROBLEM IDENTIFICATION

In order to address the underlying motivations, the following studies were conducted during this thesis project:

- A gage capability (repeatability and reproducibility) study, analysis, and comparison of the fuel pump, performance test equipment (pump performance measurements) at the Engineering Test Laboratories and respective Components Plants in Michigan and Hungary,

- A gage capability (repeatability and reproducibility) study, analysis, and comparison of the fuel pump, performance test equipment (pump performance measurements) at the Engineering Test Laboratories in Michigan and Hungary and,

- A test fluid correlation, analysis, and potential modification of the production, performance specification limits for outlet flow and current draw on the production test equipment.

1.3 OBJECTIVES

There were many objectives of this thesis project as input was received from many engineering activities within the Electrical and Fuel Handling Division. All the experimental designs and the forms of data analysis were selected to accomplish these objectives. The objectives are as follows:

- To quantify the measurement error of the performance test equipment in the Engineering Test Laboratories and the respective Components Plants.

- To develop a test methodology and statistical analysis procedure that would result in an ongoing, universal engineering specification to correlate fuel pump performance testing capability across different laboratory and production facilities.

- To identify the most significant contributors to measurement error/measurement variability of the fuel pump performance test equipment.

- To determine the effect of various test fluids and their properties on fuel pump performance and develop empirical relationships that would compensate for fuel pump performance under different conditions.

- To modify the fuel pump production specification limits for outlet flow and current draw.

- To determine the impact of all of the above on production yields, scrap costs saved, and product acceptability. (This analysis will be part of a separate EFHD-internal report).

1.4 OVERVIEW OF PROBLEM SOLVING APPROACH

A vast amount of testing was designed to address the objectives of this thesis project, and the resulting test strategy organized this testing by location, Michigan and Hungary. These two strategies are shown in Figures 1.4a and 1.4b. Performance tests were conducted on a limited sample size of each of the fuel pump types to quantify the capability of the performance test equipment in both the Labs and the Plants. A test fluid correlation was also conducted at the Engineering Test Laboratories using a larger sample size of each of the pump types. This resulted in the following criterion: if the correlation is significant, the performance specification limits (for flow and current draw) on the production test equipment in each of the Plants can be modified. If this is met, then a trial production run is recommended to verify that the pumps will continue to pass the production performance tests and the Engineering Specification tests (at the Labs).

TEST PHASE	DESCRIPTION
PRE-PHASE II	Two-Station Performance Test Stand Gage Capability Comparison w/Rawsonville Production Testers
PHASE I/RI	ETC/Alba Fuel Lab Two-Station Performance Test Stand Gage Capability Comparison
PHASE II	Test Fluid Correlation on Two-Station Performance Stand with Alba Production Pumps (built 12/92) for Comparison with Alba Lab Fluid Correlation
PHASE II	Test Fluid Correlation on Two-Station Performance Stand with Rawsonville Production Pumps (built in 1992)
PHASE I/RII	ETC/Alba Fuel Lab Two-Station Performance Test Stand Gage Capability Comparison
PHASE III	Verification of Test Fluid Correlation at Rawsonville on Selected EOL Pump Tester/Fixture and ETC Fuel Lab

Figure 1.4a: Electronics Technical Center (ETC) Fuel Lab and the Rawsonville Components Plant

TEST PHASE	DESCRIPTION
PRE-PHASE II	Two-Station Performance Test Stand Gage Capability Comparison w/Alba Production Testers
PHASE I/RI	ETC/Alba Fuel Lab Two-Station Performance Test Stand Gage Capability Comparison
PHASE II	Test Fluid Correlation on Two-Station Performance Stand with Alba Production Pumps (built 12/92) for Comparison with ETC Lab Fluid Correlation
PHASE I/RII	ETC/Alba Fuel Lab Two-Station Performance Test Stand Gage Capability Comparison
PHASE III	Verification of Test Fluid Correlation at Alba Plant on Selected EOL Pump Tester/Fixture and Lab

Figure 1.4b: Hungary Fuel Lab and Components Plant

The first part of this project began September, 1992 and consisted of project definition, investigative research, and test methodology development. An extensive interviewing process of personnel from the Engineering Services Department, Plant/Production, Quality Control/QC Lab, Fuel Pump Engineering, laboratory technicians, and Ford Scientific Research took place. Sixty percent of the time was spent at the Electronics Technical Center, Fuel Laboratory and the remaining 40% spent at the Rawsonville Plant. An extensive literature search on fuel systems, fuel pumps, and fuels was also conducted. While at M.I.T. during January through June, 1993, the majority of the above testing was completed by Ford (in Hungary and Dearborn, MI). Also during that time, numerous meetings with the M.I.T. faculty advisors took place.

Returning to Ford at the beginning of June, 1993, an extensive data compilation and analysis was conducted, and many meetings with Fuel Pump Engineering and Engineering Services Department personnel and corporate statisticians resulted. By the end of the summer, an executive summary of conclusions and recommendations was prepared for Ford-EFHD. This thesis paper is an elaborated version of that executive summary and a comprehensive compilation of all the preliminary investigationsthat went into designing the test phases, the test methodologies, statistical analyses, and fluid property investigation.

1.5 THESIS ORGANIZATION

This thesis paper is organized into five chapters. Chapter 2 provides a summary of the conclusions and recommendations that resulted from the extensive data analysis. Chapter 3 discusses the considerations that went into designing the experiments including test location, test equipment, factor identification, test methodology, and assumptions. In addition, fuel pump sampling techniques are addressed. Chapter 4 offers a comprehensive review of the data analysis and statistical tools applied to the test results. It also discusses these results. Lastly, Chapter 5 looks at the test fluids more closely and identifies the effects of temperature on the test fluid properties and the effects of the test fluid properties on fuel pump performance by applying fluid mechanics/turbomachinery principles. It also provides an overview of positive displacement versus dynamic, regenerative fuel pumps and their impact on a vehicle if they do not perform as designed.

Chapter 2: Conclusions and Recommendations

2.1 OVERVIEW

In pursuit of the thesis project objectives that were described in Chapter 1, much experimentation was conducted at the Electronics Technical Center Lab (ETC Lab), the Alba Fuel Lab (in Hungary), and the respective fuel pump Production Facilities located in Rawsonville, Michigan (Rawsonville Plant) and in Hungary (Alba Plant). Two types of fuel pumps were used for test, the gerotor type and the turbine type, both of which are electric pumps. However, the gerotors are manufactured and tested both at Rawsonville and the ETC Lab. The turbines are manufactured and tested at both the Alba Plant and Lab and can be tested at the ETC Lab. It should be mentioned here that the fuel pump performance test practices of Ford's external suppliers were not included in this thesis project. Nonetheless, they were looked at as tools to understand how EFHD has designed its Engineering Test Specifications as it has licensed both the gerotor and turbine pump designs from these suppliers. The differences that exist between the performance testing by the suppliers and performance testing by EFHD include the test fluid type and the hardware and software features of the test equipment.

Numerous performance tests were conducted on each of the fuel pump types at each of the above locations over a series of test phases: Phase I, Pre-Phase II, and Phase II. The performance test equipment was held constant between both Labs since it has identical hardware and software features. However, the test equipment in the Plants was similar to the Labs because of the types of measurements but different because of the different pump types it can test. These test phases will be described in detail in the Chapter 3. The performance tests included flow, current draw and speed at a fixed operating voltage and back-pressure, both of which are set by the vehicle application requirements (see Chapter 5). During some test phases, it was also necessary to break in the pumps in order to seat the brushes on the commutator surface before actual performance tests were run and to ensure the flow was stabilized. Some of the most important variables that were controlled and/or varied included test fluid type, fluid properties (such as kinematic viscosity), test fluid stability (evaporation or volatility over time), temperature, technician, contamination of fluids and pumps, filtration of test fluids, calibration fluctuations in instrumentation, pump-to-pump variability, and test site.

The majority of the tests were designed to run gage repeatability and reproducibility studies on the fuel pump performance test equipment in both the Labs and the Production Facilities under methods prescribed by the Measurement Systems Analysis Manual. These methods were adapted and modified to accommodate the dynamic nature of the fuel pump and the test equipment. Analysis of variance techniques were then used to analyze the data and estimate the components of variance attributed to technician, fuel pump, test equipment, and the interaction between the technician and pump while all other variables were held fixed or considered noise and controlled. Furthermore, for some of the results of the test phases, it was necessary to run regression analyses to determine the test fluid correlation. Lastly, to study the effects of the test fluid properties on fuel pump performance, many fluid properties were measured at Ford's Central Labs throughout the course of the test fluid correlation. These measurements were analyzed according to methods prescribed by most fluid mechanics books but adapted to fuel pumps and fuels. These statistical analysis procedures and the fluid mechanics principles applied will be discussed in Chapters 4 and 5.

The following sections discuss the most significant conclusions that were determined by reviewing the results of all the test phases. Conclusions are also provided from the test fluid analysis. Lastly, the recommendations are proposed. They suggest future action plans to further verify and confirm the conclusions. With the implementation of some of these recommendations, the potential exists to improve fuel pump production yields (or increase the amount of good pumps that pass), reduce scrap costs, reduce warranty costs (or reduce the amount of bad pumps that pass), and to modify the fuel pump acceptance criteria (Engineering Specifications and production specifications) to accommodate the test process variance and pump variance. A cost/benefit analysis of implementing some of the these recommendations has been provided to EFHD as an internal report, and it will be further investigated there.

2.2 CONCLUSIONS FROM TESTING

2.2.1 HIGHLIGHTS FROM PHASE I, PRE-PHASE II, AND PHASE II TEST RESULTS

In this section, the conclusions that were determined from the results of all the tests (Phase I to Phase II) are briefly described. For a complete description of these conclusions and a summary of the data they were derived from, see APPENDIX A:

1) The influence of the technician, operator, or robotic arm (of Rawsonville test stands) on the performance measurements is negligible regardless of test condition and location. There is no interaction between the technician and the pump.

2) The test fluid temperature is not a primary source of pump flow variance under the current testing conditions in the Labs and the Plants. This is due to small Δ's in fluid viscosities over the measured temperature ranges for each of the pump types. The temperature ranges were narrow.

3) The test fluid is not a primary source of variability in the measurements between the Lab and the Plant for the gerotor pumps. This was determined by a one-to-one correlation from a regression model of the flow averages, over various gerotor models and in each of the test fluids. This observation can also be shown from the Phase I and Pre-Phase II test results .

4) The test fluid type is a source of variability in the measurements between the Labs and the Plant for the turbine pumps. The driving force of this variability is the viscosity of the test fluids (the viscosity of M99 is three times that of gasoline).

5) On average, the production stands at Rawsonville and Alba possess less $6\sigma_{R\&R}$ variability* for the flow and current measurements than the two-station stands at the ETC/Alba Labs.

6) The within-part variation cannot be isolated from the instability of the performance test equipment, and this is reflected in the $6\sigma_{repeatability}$ estimates; the complete system is dynamic, and the pump and test stand interact.

7) Standard gage repeatability and reproducibility procedures cannot be directly applied to the fuel pump performance test equipment; the R&R of the test equipment should be measured independently of the pump. However, this is unrealistic and not representative of the production test process.

8) For the gerotor pumps, the most accurate fluid correlation can be determined by testing numerous gerotor models at a fixed voltage and pressure to obtain a large flow and current distribution.

9) For the turbine pumps, an average performance curve at a fixed voltage and varying pressures is required for a more accurate correlation and prediction of the fuel pump performance in the solvent given the performance (Engineering Specifications) in gasoline.

10) The production specifications can be expanded for flow at 13.2V for the gerotor pumps and flow at 8.0V/13.2V for the turbine pumps; potential exists to reduce scrap and increase yields for both pump types. The regression models for current draw in each of the fluids are not very insightful, and the specifications do not need to be changed for each of the pump types.

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* R&R indicates repeatability and reproducibility.

11) On average, the current $6\sigma_{R\&R}$ estimate is larger from the measurements resulting from the test equipment in the ETC Lab than from those in the Alba Lab. This estimate is also larger than that which resulted from the measurements taken at the Rawsonville Plant. Another observation is that this estimate is larger for the gerotor pumps than for the turbine pumps. (over all voltages and test fluids)

12) The speed measurements taken from the equipment in the Labs possess large $6\sigma_{R\&R}$ estimates independent of pump type, test fluid, and voltage.

13) A large difference between the performance measurements taken at the ETC Lab and Rawsonville exists when testing in the solvent (gerotors).

2.2.2 HIGHLIGHTS FROM THE TEST FLUID PROPERTY MEASUREMENTS

Control of the test fluids was a very significant part of all the testing. Temperature was measured during every run, test fluids were purged and replaced frequently, and the two-station performance test equipment was cleaned before each set of tests and when the test fluids were changed. Filter socks were also attached to the pumps.

In addition, during testing at the ETC and Alba Labs, test fluid specimens were collected and sent to the Organic Chemistry Unit of Central Labs for analysis. Even in Hungary, fluid specimens were collected and sent to a Lab. The fluid properties that were measured included Reid vapor pressure, specific gravity, and kinematic viscosity. These property measurements were collected for the following reasons: 1) to determine the amount of change in viscosity with change in temperature from one run to the next and from one pump to the next for a given test fluid, 2) to determine the impact on fuel pump flow, power input, and pumping head when testing in various types of fluids (by applying pump similarity relationships), and 3) to determine the underlying or root cause of the fuel pump performance differences between the Lab and Plant sites (is test fluid type a primary root cause?). See Chapter 5 for a complete analysis. In addition to the conclusions drawn from the results of Phase I, Pre-Phase II, and Phase II testing, the following observations were made:

1) The average estimated viscosity of the test fluids at the average fluid temperature reached during testing is:

ESE-M4C50-D:	0.5465 mm^2/s @ T_{avg} = 25.05°C
ESF-M99C82-A Solvent:	1.6101 mm^2/s @ T_{avg} = 22.47°C
EUROSUPER95:	0.6665 mm^2/s @ T_{avg} = 20.00°C

2) When performance testing all the gerotor pump models at 13.2V, the viscosity of the test fluids indicate a small rate of change over the fluid temperature from one run to the next:

ESE-M4C50-D: <0.5% change in viscosity for a 1°C change in temperature over all the gerotor models tested. *Note here that this test fluid was dumped after every other run, and (10) pumps of (4) gerotor models were run.*
ESF-M99C82-A Solvent: <3% change in viscosity for a 1°C change in temperature over all the gerotor models tested. *Note here that the test fluid was dumped after every other (10) runs, so the fluid could have heated up.*

3) When performance testing the turbine pumps at 8.0V and 13.2V, the viscosity of the test fluids indicate a small rate of change over the fluid temperature from one run to the next:

ESE-M4C50-D: <0.5% change in viscosity for a 1°C change in temperature over (46) turbine pumps. *Note here that this test fluid was dumped after every other run.*
ESF-M99C82-A: <3% change in viscosity for a 1°C change in temperature over (46) turbine pumps. *Note here that the test fluid was dumped after every other (10) runs, so the fluid could have heated up.*
EUROSUPER95: <1% change in viscosity for a 1°C change in temperature over (46) turbine pumps. *Note here that this test fluid was dumped after every other run.*

4) As shown by the pump similarity rules applied to the gerotor models (with constant geometry), the impact of the specific gravities of the test fluids on pump flow, power, and pumping head is small. The pump flow and input horse power increase by only 3% when tested in ESE-M4C50-D versus ESF-M99C82-A solvent. Consequently, this supports the test fluid correlation results. Pumping head increases by only 5% when testing in the gasoline versus the solvent.

5) As shown by the pump similarity rules applied to the turbine pumps (constant geometry), the specific gravities of the test fluids have the following effects:

13.2V/310 kPa and 8.0V/(200 and 250 kPa)

	ESE-M4C50-D vs Solvent	Solvent vs EUROSUPER95	ESE-M4C50-D vs EUROSUPER95
FLOW	3% higher in 50-D	2% lower in M99	0.7% lower in 50-D
PUMPING HEAD	5% higher in 50-D	4% lower in M99	1% lower in 50-D
INPUT POWER	3% higher in 50-D	2% lower in M99	0.7% lower in 50-D

6) Flow past the gerotor gear and the turbine impeller blades is highly turbulent. This turbulence is increased or decreased depending on the viscosity of the fluid. The more viscous the fluid, the less turbulent is the flow and the (smoother) lower the flow. However, since both type of pumps tested during this project exhibited highly turbulent flow, the small changes in viscosity per change in temperature for each of the test fluids caused very small changes in pump outlet flow. (Chapter 5)

2.3 RECOMMENDATIONS AND RATIONALE

The test phases were very broad in scale and scope, and they point to actions that should be taken to ensure that the integrity of the pump design and that pump quality are maintained. One action that could be taken is to "build" in the test process variation and pump manufacturing variability into the fuel pump acceptance criteria, such as the production specification limits and the Engineering

Specifications. In addition, periodic "checks" should be performed on the performance test equipment in both the Labs and the Plants to check their repeatability and reproducibility not only under the obvious conditions of process changes or pump design changes but as part of the preventative maintenance schedules currently in place. Frequency, of these checks could run in parallel with the PM schedule or half of the frequency of the PM schedule.

Although most of the conclusions pointed to the complexity involved in separating the dynamics of the performance equipment from the dynamics of the fuel pumps, quality control, production, and the engineering activities should work together to develop a standardized test procedure that meets all their requirements. Furthermore, the Test Systems Engineering activity responsible for test Lab performance equipment should communicate with the Fuel Pump Engineering activity responsible for the production performance test equipment. Participation by the Test Systems activity in the monthly Fuel Pump QOS meetings is one such example. For this author, participation in the meetings was important to understand the interaction between all the elements of fuel pump engineering (responsibility for production test equipment, design and release of pumps, etc.) and production. Lab testing is also a very important element of fuel pump engineering.

Another possibility is the creation of a QOS meeting for fuel pump testing including both Lab and production testing. Specifically, QFD methods could be applied to understand both activities' requirements. The test equipment at both sites possess similar features in terms of tests, but have very different requirements. However, both sites are complementary to each other; the fuel pumps have to pass performance tests in the Plant before they are sent to the Labs for verification testing prescribed by the Engineering Specifications. To minimize the potential for too frequent capability comparisons between the Lab and production facilities which could be costly and interfere with scheduled production, hardware and software requirements could be commonized as is feasible and practical and still meet the requirements of both test sites.

The test procedures detailed in this paper are merely suggestions or places in which to start thinking about these actions. It should also be kept in mind that these "checks" or actions may imply additional costs, labor, and time, but their objectives are to guarantee the integrity and quality of the pump design and upstream manufacturing processes and to guarantee the customer a product that performs to his specifications and requirements.

Lastly, considering the numerous conclusions that have resulted from this study, more immediate and specific actions have been identified. These could potentially impact and increase fuel pump production yields and thereby reduce associated retest and scrap costs. These actions are recommended below:

- **INVESTIGATE CURRENT AND SPEED MEASUREMENT/CALIBRATION PROCEDURES ON THE TWO-STATION PERFORMANCE TEST STAND.**

Before the true differences between the Rawsonville/ETC Lab and Alba Plant/Lab can be identified and quantified, the current and speed measurement and calibration procedures of the two-station test stand need to be modified so that they can become more repeatable and independent of each other. As an example, pump speed could not be correlated in the test fluids, and the $6\sigma_{R\&R}$, on average, was very large for all the fuel pumps. This could also prove or disprove whether the two-station stand is more repeatable than the plant production test stands.

- **INVESTIGATE PRESSURE CONTROL DIFFERENCES/SIMILARITIES BETWEEN THE ETC FUEL LAB TWO-STATION TEST STAND AND THE RAWSONVILLE PRODUCTION TEST STANDS.**

The pressure regulator, pressure control method, and pressure transducer location differences/similarities between the ETC Lab-two-station test stand and Rawsonville production test stands should be thoroughly investigated, both from a hardware and software standpoint in order to explain the large differences in average flow and current at 13.2V/310 kPa. The production specification limits should not be modified without resolving the differences between the test sites.

- **COMPARE THE CALIBRATION PROCEDURE OF THE TWO-STATION STAND TO THE CALIBRATION PROCEDURE OF THE PRODUCTION TEST STANDS.**

Another potential cause of the gerotor pump performance differences between the test sites could be the calibration procedures of the two-station test stand and the Rawsonville production test stands. A comparison of these procedures could also add more significance to the conclusion that the average

$6\sigma_{R\&R}$ estimates for the production test stand performance measurements are "better" than the Fuel Lab two-station stand estimates.

- **INVESTIGATE THE METHOD OF OUTLET SEALING PERFORMED BY THE ALBA PRODUCTION TEST FIXTURES/HOW AND WHERE FLOW/PRESSURE IS MEASURED.**

One of the most probable causes of the flow (at 13.2V) measurement variation in the M99-solvent between the Alba production test stands and the two-station stand at both the Alba and ETC Labs could be the way the plant fixtures seal the turbine pump outlet. This might not be repeatable from pump-to-pump and fixture to fixture. Centerlines of pump outlet and seal may not coincide, and this could also be affected by the way the operator seats the pump in the test pocket. In combination, more flow losses could result regardless of the fact that the same fluid and pumps were tested at both the Plant and Lab.

- **REPLACE THE POSITIVE DISPLACEMENT FLOW METER THAT IS CURRENTLY USED ON THE TWO-STATION PERFORMANCE STANDS.**

Depending on the needs and requirements of the particular test sites, a flow meter should be selected. Speed (cycle-time) and accuracy are important considerations for plant usage. If the upstream manufacturing processes, as well as the pump design are optimally robust, repeatability could be compromised for speed and low cost. It could also be argued that 100% end-of-the line testing would no longer be necessary thereby eliminating test time from the cycle-time. The test process could then be used as a "check". For lab usage, important considerations could be sampling rates/times as well as high accuracy and insensitivity to test fluids and pressure differentials. Since lab testing is required to verify the production process as well as satisfying the corporate customer/vehicle requirements and launching new products, perhaps it is justified to invest in a flow meter with "tight" specifications.

- **MODIFY AND VERIFY THE RAWSONVILLE PRODUCTION TEST SPECIFICATIONS AT 13.2V FOR ALL THE GEROTOR PUMP MODELS AFTER QUANTIFYING THE AVERAGE FLOW AND CURRENT DIFFERENCES BETWEEN TEST EQUIPMENT AT THE RAWSONVILLE PLANT AND ETC LAB.**

Since it has been concluded that the test fluid types used in the plant and lab environment do not account for the differences between the pump performance measurements obtained in these places and that there is a one-to-one fluid correlation, the Rawsonville production specification for flow at 13.2V/310 kPa could be modified or set to the same values as designated by the Engineering Specifications (see Table

2.3a). However, the current draw limits at 13.2V/310 kPa should not be modified, as there is not much of a gain. The best way to determine or modify these limits could be through on-line process tests.

The flow limit should be modified only if the differences between the test sites/equipment are quantified and minimized. It should also be adjusted up or down (from the base Engineering Specification of 60 lph, for example) by some constant offset or Δ_{avg} (determined by the difference). Once this limit is modified on the production test stands, the standard production validation testing as prescribed by the Engineering Test Specifications should be conducted at the Lab to verify that pumps will continue to meet those requirements in gasoline. A large assumption is being made here: time ("green" versus broken-in) is not a significant variable. If the correlation does not hold based on the verification testing, then time is likely to be a variable, and an additional compensating factor should be added to the flow limit: **60 lph + Δ_{avg} + $Time_{factor}$ = new flow spec. in M99**

- **MODIFY THE LOW VOLTAGE FLOW, PRODUCTION SPECIFICATION LIMIT FOR THE TURBINE PUMPS AT THE ALBA PLANT.**

Referring to Table 2.3b, there are few alternatives here that could be taken depending on the level of conservatism employed. The limit could be changed to a minimal flow of 25 lph at 8.0V/250 kPa for each of the test stands. In addition, since the erratic behavior of the pump at this operating point interacts with the inaccuracy of the flow meter at such a low region of its operating curve, it is suggested that a new flow meter be investigated. If not a viable option, the possibility of increasing the measurement sample time of the flow meter should be investigated. This could average out the variability of the flow measurements at 8.0V/250 kPa. Having a measuring device error or variance larger than the accepted production or process variability at 8.0V/250 kPa makes it impossible to effectively and successfully modify this low flow limit.

Another, perhaps less viable option, would be to change the Engineering Specification to 8.0V/200 kPa, leave the production limit at 8.0V/200 kPa, and drop the minimal flow or threshold to 15 lph. The flow meter should still be investigated for its accuracy and sampling rate when measuring the flow on a turbine pump at this operating point.

Lastly, the limit could be left at 8.0V/200 kPa on the production floor, but change the threshold to greater than 15 lph. This is contingent on investigating and maybe modifying the sampling rate of the flow meter or purchasing a more accurate flow meter.

With all these alternatives or options, there are two large assumptions, which also apply to the gerotor pumps: 1) the turbine pump design is robust and possesses minimal manufacturing variability and 2) the production and Lab performance test process and respective equipment generates repeatable and reproducible measurements.

- **CREATE ENGINEERING SPECIFICATIONS FOR FUEL PUMP PERFORMANCE TESTING IN M99-SOLVENT.**

Since the M99 solvent is an integral part of the fuel pump, production test process, the pumps must pass performance tests at the plant in this solvent before they are shipped to the customer, and plant testing has significant implications of the production validation testing at the Labs (in gasoline), it is recommended that additional Engineering Specifications (ESs) for fuel pump performance in M99 be created and proposed to EFHD's customers. Based on the gerotor performance test results, these Specifications could result in: **ES in M99 = 60 lph +** Δ_{avg} **+** Time_{factor} (as an example for the flow specification). The current draw ESs in M99 could be generated from process testing on the floor. However, most of the previous recommendations would have to be implemented before this recommendation could be applied at a high confidence level. As always, the two large assumptions that are being made here are: 1) the pump design is robust and possesses minimal manufacturing variability and 2) the production and Lab performance test process and respective equipment generate repeatable and reproducible measurements. Nonetheless, these ESs in M99 could become a standard for any performance testing in the Plants just as they are a standard in the Labs in gasoline.

Response	Pump Type	MODEL	R-sqd	ES Spec. in Gas	Equivalent in M99	Current Production Specs.	New Production Specs.
FLOW **13.2V/100/110/270/310 kPa**	45 lph 60 lph 95 lph 125 lph	Ym99 = 0.924*Xgas + 7.556	99.50%	45 lph 60 lph 95 lph 125 lph ($\mu - 3\sigma$)	49.12 lph 62.93 lph 95.30 lph 123.01 lph	60 lph 77 lph 112 lph 140 lph ($\mu - 3\sigma$)*	49.12 lph 62.93 lph 95.30 lph 123.01 lph
CURRENT **13.2V/100/110/270/310 kPa**	45 lph 60 lph 95 lph 125 lph	Ym99 = 0.964*Xgas - 0.114	97.42%	3.0 amps 6.0 amps 8.5 amps 10.5 amps ($\mu + 3\sigma$)	2.779 amps 5.672 amps 8.083 amps 10.011 amps	0.34 - 3.0 amps** 2.66 - 5.5 amps 4.75 - 7.5 amps 4.5 - 9.25 amps ($\mu - 3\sigma$)*	0.34 - 2.78 amps 2.66 - 5.67 amps 4.75 - 8.08 amps 4.5 - 10.01 amps
SPEED **13.2V/100/110/270/310 kPa**	45 lph 60 lph 95 lph 125 lph	Ym99 = 0.922*Xgas + 133.865	98.12%	N/A N/A N/A N/A	N/A N/A N/A N/A	N/A N/A N/A N/A	N/A N/A N/A N/A
FLOW **13.2V/310 kPa**	45 lph 60 lph 95 lph 125 lph	Ym99 = 0.910*Xgas + 10.081	99.07%	45 lph 60 lph 95 lph 125 lph ($\mu - 3\sigma$)	51.05 lph 64.70 lph 96.57 lph 123.88 lph	60 lph 77 lph 112 lph 140 lph	51.05 lph 64.70 lph 96.57 lph 123.88 lph
CURRENT **13.2V/310 kPa**	45 lph 60 lph 95 lph 125 lph	Ym99 = 0.995*Xgas - 0.318	91.71%	3.0 amps 6.0 amps 8.5 amps 10.5 amps ($\mu + 3\sigma$)	2.669 amps 6.153 amps 8.144 amps 10.135 amps	0.34 - 3.0 amps** 2.66 - 5.5 amps 4.75 - 7.5 amps 4.5 - 9.25 amps ($\mu - 3\sigma$)*	0.34 - 2.67 amps 2.66 - 6.15 amps 4.75 - 8.14 amps 4.5 - 10.13 amps
SPEED **13.2V/310 kPa**	45 lph 60 lph 95 lph 125 lph	Ym99 = 0.873*Xgas + 522.386	98.17%	N/A N/A N/A N/A	N/A N/A N/A N/A	N/A N/A N/A N/A	N/A N/A N/A N/A
FLOW **10.0V/100/110/270/310 kPa**	45 lph 60 lph 95 lph 125 lph	Ym99 = 0.892*Xgas + 13.298	96.90%	7.5 lph 7.5 lph 7.5 lph 7.5 lph	19.988 lph	N/A N/A N/A N/A	N/A N/A N/A N/A

Average M99C82-A Temp: 23.55 C
Average ESE-M4C50-D Temp: 22.41 C

* Based on previous correlation study.
** Lower values determined from CIMM system.
** Upper values determined from previous correlation.

Table 2.3a: Phase II: Test Fluid Correlation with Various Gerotor Models

MEASURED M99 VALUE	CONFIDENCE LIMIT IN GAS	NEW PRODUCTION SPEC. IN M99-SOLVENT
Smallest Lab Flow Value measured in M99 @13.2V/310 kPa based on curve correlations. = 72.95 lph	Lower Confidence Limit @ 99.75% or $X_{new} - 1.152\sigma$ = 72.085 lph in gas	New Spec in M99 @13.2V/310 kPa based on regression model: $Y_{M99} = 5.246 + 0.869(72.085)$ **> 67.87 lph**
Largest Lab Current Value measured in M99 @13.2V/310 kPa based on curve correlations. = 5.82 amps	Upper Confidence Limit @ 99.75% or $X_{new} + 1.152\sigma$ = 5.877 amps in gas	New Spec in M99 @13.2V/310 kPa based on regression model: $Y_{M99} = 0.401 + 0.951(5.877)$ **< 5.989 amps**

Table 2.3b: Estimated Turbine Pump Production Specification Limits @ 13.2V/310 kPa Based on Inverse Regression

MEASURED M99 VALUE	CONFIDENCE LIMIT IN GAS	NEW PRODUCTION SPEC. IN M99-SOLVENT	
Largest Lab Flow Value measured in M99 @8.0V/250 kPa based on curve correlations. = 20.51 lph	Upper Confidence Limit @ 99.75% or $X_{new} + 1.152\sigma$ = 21.37 lph in gas	New Spec in M99 @8.0V/250 kPa based on regression model: $Y_{M99} = 6.991 + 0.836(21.37)$ **> 24.86 lph**	Conservative
Smallest Lab Flow Value measured in M99 @8.0V/200 kPa based on curve correlations. = 19.14 lph	Lower Confidence Limit @ 99.75% or $X_{new} - 1.152\sigma$ = 9.321 lph in gas	New Spec in M99 @8.0V/200 kPa based on regression model: $Y_{M99} = 6.991 + 0.836(9.321)$ **> 14.79 lph**	Moderately Conservative
Largest Lab Flow Value measured in M99 @8.0V/200 kPa based on curve correlations. = 36.43 lph	Upper Confidence Limit @ 99.75% or $X_{new} + 1.152\sigma$ = 40.39 lph in gas	New Spec in M99 @8.0V/200 kPa based on regression model: $Y_{M99} = 6.991 + 0.836(40.39)$ **> 40.77 lph**	Highly Conservative

Table 2.3b (Continued): Estimated Turbine Pump Production Specification Limits @ 8.0V/200 or 250 kPa Based on Inverse Regression

Response	MODEL	R-sqd	ES Spec. in Gas	Equivalent in M99	Current Production Specs.	Recommended New Limits
FLOW CURVE **8.0V/(25,50,75,100,125,175,200,250 kPa)**	Ym99 = 0.836*Xgas + 6.991	96.03%	10 lph **(8.0V/250)** ($\mu - 3\sigma$)	15.351 lph	28 - 60 lph ($\mu - 3\sigma$)*	15.351 lph ($\mu - 3\sigma$)
CURRENT CURVE **8.0V/(25,50,75,100,125,175,200,250 kPa)**	Ym99 = 0.898*Xgas + 0.451	95.89%	N/A	N/A	N/A	N/A
FLOW CURVE **13.2V/(25,88,163,238,310,388,463,538 kPa)**	Ym99 = 0.869*Xgas + 5.246	98.86%	60 - 100 lph mean = 80 lph ($\mu - 3\sigma$)	74.766 lph (@ 80 lph)	78 - 130 lph ($\mu - 3\sigma$)	74.766 lph ($\mu - 3\sigma$)
CURRENT CURVE **13.2V/(25,88,163,238,310,388,463,538 kPa)**	Ym99 = 0.951*Xgas + 0.401	98.05%	6.5 amps ($\mu + 3\sigma$)	6.581 amps	4.5 - 6.5 amps	4.5 - 6.58 amps

Average M99 temperature @ 8.0V: 24.54 C
Average M99 temperature @ 13.2V: 24.83 C
Average 50-D temperature @ 8.0V: 23.26 C
Average 50-D temperature @ 13.2V: 23.43 C

* Based on production stand correlation in M99 at 8.0V/200 kPa to the Lab in gasoline at 8.0V/250 kPa.

Table 2.3b (Continued): Estimated Turbine Pump Production Specification Limits Based on "Standard" Regression

Chapter 3: Testing Methodology

3.1 OVERVIEW

Some of the most significant decisions that had to be made before conducting any fuel pump testing during this thesis project were the type of fuel pumps to test, the number of pumps, and the amount and type of fuel pump tests. Many statisticians from Ford, the M.I.T. advisors, and the EFHD fuel pump production and engineering personnel were consulted with frequently to assist in the design of the experiments. In addition, many statistical techniques were reviewed during the decision making process. The probability and statistics theory that was employed in the up front planning is discussed in this chapter.

The underlying determinants of the scale and scope of the fuel pump testing were time and the availability of the fuel pump, performance test equipment at both the Engineering Test Laboratories (ETC and Alba) and the respective Components Plants. Logistics became an emerging challenge primarily because a substantial portion of testing took place at the Alba Lab and Plant in Hungary. Facilitation of the testing was conducted via telephone, fax, and electronic mail during the six hour time differential. Communication was also a significant challenge as two different sets of test procedures had to be designed and explained, one for the facilities in the United States and another for the facilities in Hungary. Nonetheless, the procedures were kept as identical as possible. Lastly, the transportation of test fluids from the United States to Hungary via an ocean freighter was a significant time sink and challenge even though the fluids were purchased internally from Ford. Long lead times before any of the testing could start at the Alba facilities had to be allowed to ensure that the fuels and the pumps arrived in tact. For most tests, the pumps were tested at the ETC Lab and Rawsonville Plant first and then were sent to Hungary for further tests.

Working with the above constraints, there were only two predetermined test parameters. These included the test location and the fuel pump performance test equipment. Many other variables had to be identified and will be described below. All of these variables were either held constant, allowed to vary by selecting factor levels, or left as noise. The appropriate action was selected depending on the objectives of each particular test phase.

In this chapter, the preliminary investigation and actual test phases that were conducted during this thesis project, along with key assumptions, will be presented. The test methods employed during these test phases are only a few of the many methods that could be applied. They were deemed to be efficient and containable within the test sites and time available. An underlying objective was identified: to test the pumps in an environment that closely matched their testing in the Components Plants and their actual usage conditions in the field. With the exception of one test phase, a gage repeatability and reproducibility (R&R) capability study was the primary test method adapted to the fuel pumps, the fuel pump performance tests, and the Lab and Plant test equipment. The gage R&R method and limitations that were identified (how they were addressed with the assumptions made) will also be explained in this chapter.

3.2 TEST LOCATION

3.2.1 ENGINEERING TEST LABORATORIES: Electronics Technical Center and Alba Fuel Laboratories

These Laboratories contain different types of fuel pump performance test equipment and durability test stands. The performance test stands include the two-station performance test stand, seven-station performance test stand, and the hot fuel performance test stand. This equipment can accommodate two types of fuel pumps, the gerotor and the turbine type. The pumps undergo a series of testing (comprised of performance and durability at these Labs) which is designated in the Ford Engineering Specifications based on the vehicle, car or truck, applications. These tests include design validation, production validation, and in-process testing. The testing that takes place at the ETC Lab is typically of the design and production validation nature. In-process testing occurs when the Plants randomly select pumps off the line (after they have passed the production performance tests and the Quality Control Lab tests for performance) and sends them to the Lab where they undergo a complete cycle of tests based in gasoline.

Although a significant amount of tests are prescribed by the Engineering Specifications, the primary tests of interest for this thesis project were the fuel pump performance tests which can be run on any of the Lab equipment. When performance testing is conducted, the pump performance characteristics that are measured are current draw, outlet flow, and pump motor speed at a fixed pressure and voltage. The pumps have to meet a minimum flow and maximum current draw requirement in order to pass the tests/meet the Engineering Specifications.

The Alba Fuel Laboratory in Hungary has comparable fuel pump performance and durability test equipment that was developed, engineered, and implemented by the Test Systems Engineering Section of the Engineering Services Department (EFHD). The Lab has just recently come on line and is capable of testing the turbine type fuel pumps. It is part of the Ford of Hungary Alba Plant. Comparably, these pumps undergo a series of production validation and in-process testing. However, the design validation for the turbine pumps takes place at the ETC Lab since most of the design engineers are at the Rawsonville Plant. Lastly, the performance limits vary from the gerotor pumps, but the performance test procedures are identical.

3.2.2 COMPONENT PRODUCTION FACILITIES, Rawsonville, Michigan Plant and Ford of Hungary Alba Plant

There are currently six models of the gerotor type fuel pump which are produced at the Rawsonville Plant. They are identified by their minimum (μ-3σ) outlet flow rating (in liters per hour) in gasoline based on the Engineering Specifications and include the 45 lph, 60 lph, 88 lph, 95 lph, and 125 lph models. They are nearly identical with the exceptions of gerotor thickness, wear plate thickness, and the amount of windings in the electric motor. They are produced over two production shifts per day. Depending on the demand, only certain fuel pump models are run each day or week. Production is not mixed, because not only are some of the pump components different depending on the model, but the end-of-line fuel pump, production test stands can only accommodate one model at a time.

There is one fuel pump line which separates into two branches at the end. On each branch, there are two fuel pump, production test stands, one on either side of it. As a result, there are a total of four test stands that test the fuel pumps after final assembly. Each test stand has three fixtures which can test three fuel pumps simultaneously. The pumps are fed into the fixtures by robot arms, and all of the test stands are automatic and computer controlled. The line operator just has to type in the part number every time a different pump model is scheduled for production.

The Alba Plant is a new facility and has been in operation for less than four years. It was built in Eastern Europe or Hungary for numerous strategic reasons. It has been producing the single-stage, turbine type fuel pump for less than two years under a joint-licensing agreement with an external supplier for Ford of Europe. It currently produces pumps during one shift per day.

Similar to the Rawsonville Plant, each pump goes through inspection testing via the end-of-line, fuel pump production test stands. There are five test stands located at the end of the line each equipped with two fixtures that hold the pumps during test. Unlike the Rawsonville Plant, operators at the end of the line actually load and unload the pumps and operate the test stands. In other words, the stands are semi-automatic.

3.3 FUEL PUMP PERFORMANCE TEST EQUIPMENT

3.3.1 TWO-STATION PERFORMANCE TEST STAND (ETC and Alba Lab)

This test stand is located at both the ETC and Alba Fuel Labs and is identical in design, features, and function. It is capable of running performance tests with test fluids (i.e., gasoline) at ambient or elevated temperatures. It will test two pumps at a time and generate complete performance curves of flow, current, and speed or single and multi-point performance measurements at fixed voltages and pressures. This test stand was selected because it has recently been implemented in Hungary and will be used (with additional stands) at the new fuel laboratory that is currently under construction at the Rawsonville Plant. Lastly, some of the other fuel pump performance test stands have become obsolete, and some will currently undergo software and hardware changes to accommodate relocation to Rawsonville and equivalency to the hot fuel test stand hardware and software.

3.3.2 FUEL PUMP PRODUCTION TEST STANDS AND FIXTURES (Rawsonville and Alba Plant)

As mentioned previously, there are four fuel pump, production test stands at the Rawsonville Plant, and all were used in this thesis study. Each test stand fixture performs a series of tests on a fuel pump for a specific period of time, then the pump is removed, and the next one is loaded. These test times vary slightly by fuel pump model. These times can be changed by modifying the actual production tests.

Depending on the fuel pump model running on the line for the day or shift, the production specifications will vary. If a pump is rejected in any of the fixtures for any particular test, it is collected and retested. The pump will then go through the whole test sequence again. Sometimes the pumps do not pass the first time due to mechanical problems or break-in effects.

Although the pump models are identified by their lower μ-3σ outlet flow in gasoline based on the Engineering Specifications in the Lab after 30 minutes of break-in, the production specification limits have been established for the production test stands in a test fluid solvent (M99-solvent). The two sets of limits are not identical, and certain tests that are performed in the plant are not performed in the Lab. Currently, the expected difference between the performance measurements at the Plant and the ETC Lab has been thought due to the gerotor performance differences in the different test fluids. Consequently, correlation tests had been performed to establish an offset that could be applied to the prescribed Engineering Specifications and would result in adequate and conservative fuel pump, production specification limits. It is these specifications that have been used at the Rawsonville Plant for the past three to four years. However, it should also be mentioned that the production specifications for some of the other production tests are determined based on the test process itself.

At the Alba Plant and Lab, the production test situation is somewhat similar to that of the Rawsonville Plant. Since both the Lab and the Plant are so new, there were many process studies and verifications completed before the pumps were launched to satisfy Ford of Europe, the customer of the turbine pumps. Based on fluid correlation studies between the Alba Lab performance test equipment in gasoline and the production equipment in the Plant, the current production limits were established.

It has already been proven that the turbine pumps behave differently in the test solvent in the Plant than when performance tested in gasoline in the Lab due to viscosity effects. Here, the difference between the Lab and the Plant is the fuel.

3.4 FACTORS

There were many factors that were identified, more than could be feasibly and efficiently included in the tests. Careful screening and selection were required before any of the test phases could be implemented. As mentioned previously, the factors were either held constant, varied at different levels, or left as noise depending on the objectives of the test phase. These factors and their levels will be described below as well as rationale for their state (constant, variable, or noise):

Test Location (As described above.)

Test location was held as a constant for each test phase. It was the fuel pump performance results by test location that were compared for the gage R&R studies.

Fuel Type

ESE-M4C50-D	Unleaded gasoline used for exhaust and evaporative emission test (Howell Hydrocarbons)
ESF-M99C82-A	Calibration Solvent, Colorless, (Gage Products)
EUROSUPER95	High octane gasoline used at the Alba Lab/supplied by a European Supplier

The test fluids and their properties will be elaborated in much more detail in Chapter 5. At both the Rawsonville and Alba Plants, the M99-solvent is used in the production test stands and the Quality Control Lab and is also purchased from the same supplier The fuel that is used for pump performance testing at the ETC Lab is of a different blend than the fuel used in the Hungary Lab. The unleaded fuels that are used at ETC vary depending on test application and what the engineer specifies. There are also winter and summer grades of these fuels that are used. At the Hungary Lab, the unleaded gasoline is known as Eurosuper95 (95 octane) and is obtained from a local supplier in Europe. However, all these fuels are commercial fuels.

In order to account for the variability that could result in the pump performance measurements due to different types of test fluids and to obtain a more accurate correlation and gage capability comparison of the fuel pump performance test equipment between Labs, and Labs and Plants, all three of the above test fluids were used in this thesis project. In place of the standard or commercial grades of gasolines that are typically used in the Labs, the ESE-M4C50-D gasoline was selected due to its stability in vapor pressures and other properties over time and temperature. This fuel was purchased internally from the Ford Scientific Research, Fuel House and also shipped to the Lab in Hungary. It was used during all phases of testing. The Eurosuper gasoline was only used at the Hungary Lab for the correlation tests due to complexities in international shipping and the complexities involved in synthesizing the blend over in the U.S.. Lastly, the M99-solvent was used for all the testing due to its stability over time and the fact that it was already available in Hungary.

When conducting the gage R&R comparison study between the Labs, the test fluid took on two levels, M99-solvent and the 50-D gasoline. For the test fluid correlation studies, the test fluid took on two levels, M99-solvent and 50-D gasoline at the ETC Lab, and three levels, M99-solvent, 50-D gasoline, and Eurosuper gasoline at the Alba Lab.

Fixturing

Since the gerotor type fuel pumps are tested at the ETC Lab, and turbine pumps are tested at the Alba Lab, the existing fixturing on the two-station performance stand had to be modified. This fixture connects the pump, at its positive and negative terminals, to the test stand. At each of the Labs, an electrical connector that accommodated the type of pump to be tested was used. This fixturing was considered a "noise" factor. However, the gerotor pumps will never be tested at the Alba Lab. The majority of the turbine pumps will be tested at the Alba Lab because they are manufactured at the same facility, but some will be tested at the ETC for design validation.

Break-in and Warm-up of Pumps

Gerotor Pumps

The break-in of the gerotor pump occurs when the brushes seat on the copper commutator surface. According to the Engineering Specifications, the pump should pass flow and current performance characteristics after 30 minutes at a fixed voltage and pressure of 13.2V and 310 kPa respectively. At this point, the μ outlet flow increases, and the σ decreases. The μ current draw decreases, and its σ decreases. In other words, the pumps stabilize.

Previous test results from in-process testing (in gasoline) at the ETC Lab for a large sample of 60 lph gerotor pumps were studied. However, this data could not be compared with pump performance in the M99-solvent for the same period of break-in since the data did not exist, and pumps were only measured "green" in the solvent at the plant. Nonetheless, this data allowed the author to understand the break-in characteristics of the gerotors in gasoline. It was necessary to break the gerotors in before testing them.

For the performance test stand, gage capability test phases, the pumps were selected such that they had already undergone many hours of in-process testing and were considered "stable". All they required was a minimal amount (less than 5 minutes) of warm-up before they were tested. For the fluid correlation test phase, pumps were selected off the line and were "green". However, they were then run for many hours on the durability stands in order to break them in. As a result, pump break-in for the gerotors was considered a significant noise and was controlled.

Turbine Pumps

For the turbine fuel pumps, the break-in characteristics diverge from those of the gerotor pumps. Based on the external supplier's specifications and the current experience of the European Fuel Pump Engineering Section and much of their testing, these pumps only require at most and even less than 30 minutes of run time at 13.2V and 310 kPa.

For the performance test stand, gage capability test phases, "stable" pumps with a significant amount of test time on them were selected for test. They, only required warm-up before testing. On the other hand, for the fluid correlation tests, production level pumps were selected. They required 30 minutes of break-in time. As a result, the break-in of the turbine pumps was not as significant as the gerotors. It was considered a noise and controlled.

Calibration

To account for the potential variability that could be introduced into the fuel pump performance characteristics by the test stand instrumentation due to the noise of calibration drift, the two-station performance test stand at both Labs was calibrated before all test phases. For the production test equipment, only the Alba Plant test stands were calibrated before tests were conducted on them. This was done because of production downtime and availability. The Rawsonville production test equipment was not calibrated before testing due to production constraints and the fact that the current preventative maintenance schedule would have calibrated most of the test stands and fixtures within a relatively short time frame (four weeks at a time) near the testing.

Laboratory Technician or Operator

To determine if there was a significant amount of variability in the performance test results caused by different technicians running the same test equipment at the Labs, technician or operator was considered a variable in which two operators were selected to run the tests. It was believed that the only source of difference between technicians was the way they attached the pumps to the fixtures and how they positioned the pumps in the test stand fuel tank. An attempt to control these two particular noises was made by having the pump placed in the tank in the same position every time at each Lab location.

At the production facilities, the operators were still considered variables, and there were two levels or two operators selected. However the test process is semi-automatic at the Alba Plant and automatic at the Rawsonville Plant. For the Alba Plant, there was more interaction between the operator and the test fixture since he had to put the pump in the test pocket and operate the switches on the machine. Whereas at Rawsonville, there is minimal to no interaction between the end-of-the line operator and the test fixtures. There were still two levels for the operator factor, the test and load side of the dial table. A dial table, for each fixture, held the gerotor pumps before and during test.

Test Fluid Filtration and Purges

As potential sources of noise, test fluid filtration and purge were controlled at the test Labs. It was not feasible or practical to do so at the Production Facilities due to preventative maintenance schedules and potential interference with production. Before each test phase was conducted at the Labs, the test stands were purged and flushed of any old fuel and cleaned out, and the filters were changed. Between test fluid switches, the stand was flushed and purged for almost 30 minutes or more before testing would commence in the next fluid. All these actions served to minimize the potential for contamination of the test fluids and the pumps. In addition, large fluid spills were to be compensated and fluid levels checked. Lastly, the lid on the test equipment was always kept closed to minimize evaporation loss of the fluids and contamination.

Test Fluid Temperature/Tank Fills (Discussed further in Chapter 5)

When the test fluids arrived at Labs, they were stored in a cool environment (refrigerator or outside) so they would not evaporate. Before they were used in the test stands, they were brought to room temperature.

The test fluid temperature was considered a noise and controlled very carefully. In order to keep the test fluid temperature from rising too rapidly, to minimize vapor losses (volatility) in the test fluids, and to reduce the risk of any undue air bubbles or vapor pressure acting on the pump (particularly at the inlet), the fluid temperatures were controlled to room temperature in the Lab test stands. By keeping a conservative and constant fuel tank level of test fluid (depending on how many gallons were filled), the fluid could be prevented from heating up too rapidly. Another reason for controlling the temperatures in the Lab equipment was to try to replicate the test fluid temperatures in the Plant test equipment since the pumps are tested at ambient conditions in the Plants. For both the Labs and the Plants, if the temperature of the test fluid rose too high, testing would be stopped until the temperatures declined. It was also important to control the temperatures of the test fluids to minimize the effects of the temperature changes on the test fluid properties which could affect the pump performance.

All the gasolines used during the test phases were purged more frequently because of their higher volatility and potential to change more rapidly (especially the Eurosuper) than the M99-solvent with changing temperatures. In addition, they could heat up faster during particular test runs in which many measurements were taken; this was to be avoided.

Pump (Variability)

Pump manufacturing variability was a very significant noise factor that was attempted to be minimized or held constant. Part break-in or test time was a consideration for doing this. Sampling strategy also played a role here, and this will be discussed later.

Pump Types

Independent of pump sampling or pump sample size selection for test, there were six gerotor models that could be tested. For the fuel pump, performance test stand capability test phases, the pumps were identified as a factor to be varied. As a result, levels or pump quantities ranging from two to four were tested. For the turbine pumps, two to three pumps or two to three factor levels were tested at a given test location and in different test fluids.

Operating Characteristics of the Performance Test Equipment

Although, the Lab fuel pump, performance test equipment is identical between Lab sites, there were many characteristics of this equipment that were left as noise or not feasible or practical to adjust, vary, or optimize to make the pump performance measurements more robust. This would warrant a separate study. Such characteristics include sampling rates of performance measurements, electronics, hardware (flow meters, pressure regulators), resolution or accuracy of the individual measuring devices, software, and control mechanisms. It was also not feasible to try to modify the production, performance test equipment to match the Lab equipment and vice versa. All test equipment was allowed to operate the way it normally does when it measures the fuel pump, performance characteristics. As a result, there were many "noises" contained within the test systems, but the test equipment was held as a constant.

3.5 TEST DESIGN AND METHODOLOGY

Before any testing was conducted during this thesis project, much preliminary investigation of the Lab, Production facilities, and the operation of the fuel pumps took place. This was done with the assistance of the Fuel Pump Engineering Department, Fuel Pump Production personnel, and the Engineering Systems Department as well as numerous corporate and divisional statisticians and researchers from Scientific Research. Much time was also spent at the Ford Technical Library in Dearborn to obtain SAE papers and related literature on fuel pumps and fuel systems. Time was also spent at the Barker Library at M.I.T. in search of fluid mechanics books, pump handbooks, and other books on turbomachines. Consequently, many experiments were designed and conducted during this thesis project. These experiments were divided into three test phases, Phase I, Pre-Phase II, and Phase II and spanned across four test facilities including the ETC and Alba Engineering Test Laboratories and the Rawsonville and Alba Components Plants. Numerous gerotor models and turbine pumps were selected as the test specimens, and noncommercial test fluids were used. Total test time was four to five months with some additional follow-up tests. These test phases will be described below.

3.5.1 PHASE I: Gage Capability Comparison Between the Alba and ETC Fuel Lab

Background

This test Phase had three primary objectives:

1) To determine the relative amount of variation in the fuel pump performance measurements due to the repeatability and reproducibility (R&R) of the fuel pump, performance test equipment at the Engineering Test Laboratories,
2) To compare the R&R variation across Labs, and
3) To determine which test conditions or factors influence measurement error.

Considering these objectives, the most significant decisions that had to be made were which pumps and how many to test given that the test equipment, the two-station performance stand, was to be used at all times. Although a statistically significant and adequate sample size greater than n=25 is required to capture the underlying "normal" distribution of the production population, there were two large drawbacks to having pump samples of this size.[1] The first drawback was efficiency of test (time and cost considerations). The second drawback was that there is a lot of variability from one pump to the next ranging from as little as a tenth of a lph in flow to larger values. This was observed consistently in fuel pump data that was retrieved from both the Rawsonville Plant and the ETC Lab even after a significant amount of break-in. It was already decided that testing "green" pumps was not acceptable. As a result, in selecting the pumps for test, part variation was attempted to be minimized so that it would not contribute to the R&R variability in the test stand. There were three ways that were investigated to accomplish this:

1) Select $n \leq 3$ gerotor (same model) and turbine pumps, one at low end of the specification limit, one at the mean of specification, and one at the upper end of the specification limit for flow. This will capture some of the inherent variability in the pumps.

2) Select different gerotor type pumps, one at 60 lph, one at 95 lph, and one at 125 lph, all at the lower $\mu - 3\sigma$ limit for flow. This assumes pump models are irrelevant, but distribution is more important.

3) Select $n \leq 3$ gerotor models (same model) and $n \leq 3$ turbine pumps based on their similar performance values for flow or current draw (when comparing one gerotor to another or one turbine to another).

For these possible ways of selecting pumps, a large sample of parts (25 to 50) could be selected from the line and then performing an X-hour durability test on them to break them in and stabilize them.

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[1] Ledolter and Hogg, Applied Statistics for Engineers and Physical Scientists (New York, 1992), 163.

Then a single point performance test could be run on them at 310 kPa and 13.2 volts (flow, current, speed) repeatedly. Lastly, following (1), (2), or (3), the pumps could be selected.

With these above considerations in mind, the pumps were actually selected by looking at the in-process data on a large sample of 60 lph and 95 lph gcv gerotors and choosing four pumps, two 60 lphs and two 95 lph gcv pumps which had similar flow values from their respective in-process test populations. These populations mirror the production population (because the pumps are sampled off the line per week and throughout the year for in-process testing). For the turbine pumps, a similar procedure was followed by looking at previous performance data and selecting two of those pumps tested which had similar performance values for flow.

These pumps all had a significant amount of break-in on them due to the prior in-process or performance testing. The gerotors had more than a 1000 hours on them, and the turbines had more than one hour of test. Again, minimizing pump-to-pump variability was important. The test stand should accommodate the pump regardless of the pump model or the variability of the performance characteristics within that model. Test stand repeatability and reproducibility are what are sought after not pump repeatability. Ideally, it is desirable to separate out the test stand repeatability from the pump repeatability, but in practice, this cannot be done. This will be discussed further in Chapter 4.

The test stand should also accommodate or adapt to whatever the operating parameters the pump is tested at such as 386 kPa versus 310 kPa. This was an underlying reason why two gerotor models were selected in order to subject the test equipment to this noise.

Coupled with the fact that pumps change over time, in combination with other noises such as properties of the test fluids and change or drift in actual test stand calibration, time between tests was an important noise to subject the pumps to. As a result, this test phase was split into two rounds where one group of pumps (a 60 lph, a 95 lph, and a turbine) would start test at the Alba Lab, and an identical group of pumps would be tested simultaneously at the ETC Lab. Once these tests were completed, the pumps were swapped.

Assumptions

While designing this test phase, many assumption were made. They related to the factors that were described in the previous section and to the gage repeatability and reproducibility method that was applied. These assumptions are described below:

- Pumps are "stable" and possess minimal between-part and within-part variability; meaning they are stable over time and perform similarly. This was ensured by the selection of the pumps as described above.

- The properties of the ESF-M99C82-A solvent and the ESE-M4C50-D gasoline are equivalent between Labs. This assumption was made because the M99-solvent was not sent over to Hungary as the 50-D gasoline was. As a result, it was likely it came from a different batch. In addition, the time between tests was considered here. For example, even though the 50-D gasoline was sent to Hungary from the U.S., there was a potential for it to change as it was stored prior to use. It was assumed that this change was small. This potential for change was also minimized with a layer of nitrogen gas filled over the top surface of the fuel in the drum.

- Sample size can be small when conducting a gage R&R as long as there are many replications. Pump-to-pump variability was not desired.

- Fuel Lab shift creates no effect on the performance measurements. This was considered a noise even though the Lab technician was considered a factor. It was possible that he would test over one shift and into the next. The Alba Lab only has one shift.

- Time lag between testing each group of pumps at each Lab does not affect performance measurements as long as the test stand calibration does not drift. Calibration of the two-station stand took place before the beginning of each set of tests at each Lab.

Test Method

It was realized that the two-station performance test stand and the fuel pumps are a dynamic system of interactive hardware and software. Nonetheless, the gage R&R methods prescribed by the A.I.A.G. Manual[2] were adapted. These methods, characterized by the mode of data analysis, will be discussed in the next chapter. However, these methods are most readily applied to measurement systems that are employed in a manufacturing process. A typical application is the measurement system analysis of the gage (or caliper or micrometer) that is used by an inspector or operator to measure a circular rod which is assumed to possess a constant diameter no matter where it is measured. Conducting a gage R&R on a laboratory measurement system was a challenge that was not addressed in this Manual. Its assumptions are that the test specimen does not change over time or is stable, there is no interaction

[2] This is entitled the Measurement Systems Analysis Reference Manual and was created in collaboration with Ford, General Motors, and Chrysler, 1990 under the A.I.A.G..

between the specimen and the test equipment, and the operator or technician can potentially influence the measurements.

In general, assessing the quality of a measurement system means examining the variation of the measurement system and determining the factors that influence the variation.[3] This quality is characterized by its statistical properties, not cost or ease of use. Although, cost and ease of use could be discriminating factors for selection between numerous test systems that possess similar statistical properties. A measurement system possesses many statistical properties, and there are some common to all systems:[4]

1) The measurement system must be in statistical process control, or the variation within it is due to common causes not special causes.
2) The variability of the measurement system is smaller than the production process variability.
3) The variability is small compared to the specification limits.
4) The increments of measure are small relative to the smaller of either process variability or specification limits (< 0.1 of either).

The statistical properties and sources of measurement system variation that are addressed, most of which are tested for in this test phase, include repeatability, reproducibility, accuracy, stability, and linearity. The procedure of testing that assesses these properties is often called the gage repeatability and reproducibility (Gage R&R) procedure.[5] This procedure lends itself well to the production environment, but there are also classical or other procedures from much statistics literature that can be used to assess the measurement system variability and the sources of this variability. Some of these include design of experiments or robust design techniques (Taguchi). Before explaining the procedure that was used during this phase, in contrast with the gage R&R procedure suggested by the A.I.A.G. Manual, it is necessary to define these sources of measurement system variation and address how they apply to this test phase[6]:

Measurement system: the collection of operations, procedures, gages and other equipment, software, and personnel used to assign a number to the characteristic being measured. In the case of this test phase, it is the two-station test stand (hardware and software), Ford Engineering Specifications for pump design criteria and test, the Lab technician, and the fuel pump to be tested.

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3 A.I.A.G., Measurement Systems Analysis Reference Manual, (1990), 3.
4 A.I.A.G., 5.
5 A.I.A.G., 13.
6 A.I.A.G., 14.

Gage accuracy: the difference between the observed average of measurements and the master value (Figure 3.5.1a). In this test Phase, there was no "master" test stand in which master values of fuel pump performance characteristics could be determined. It was assumed that by testing "master" fuel pumps in terms of total test time or their break-in, the accuracy would be implied, and their standard deviations would be within the rated accuracy of the testing instrumentation/devices within the two-station performance stand. However, this assumes an adequate calibration, which does not drift, of these devices.

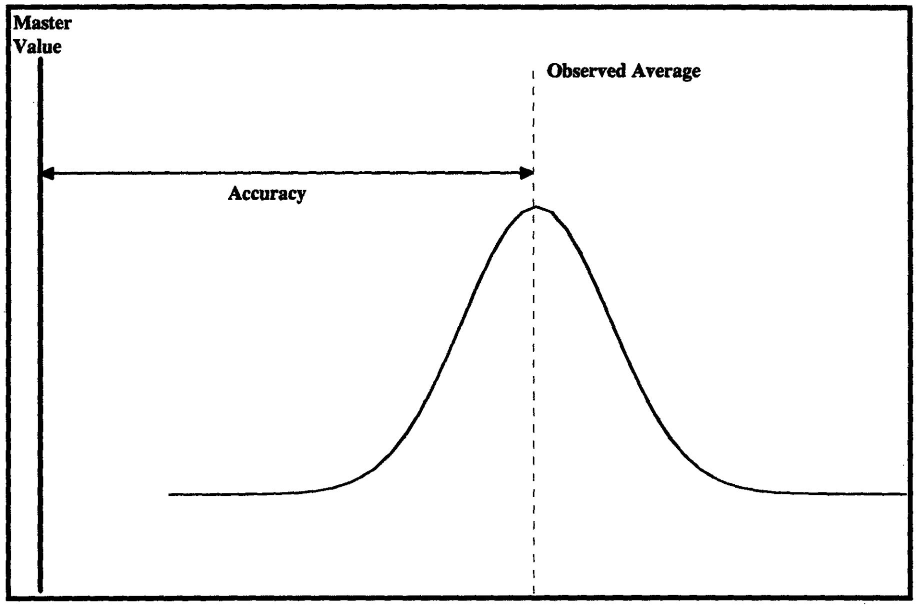


Figure 3.5.1a: Gage Accuracy

Gage repeatability: is the variation in measurements obtained with one gage when used several times by one operator while measuring the identical characteristics on the same parts. As indicated below by Figure 3.5.1b, there were many measurements taken for each pump by a given operator. To minimize the within and between-part variation, only three different fuel pump models were used during this test phase for a total of six pumps. All six were never tested at one time. There was a time lag between the tests at each Lab for each set of three pumps due to Round I and Round II testing.

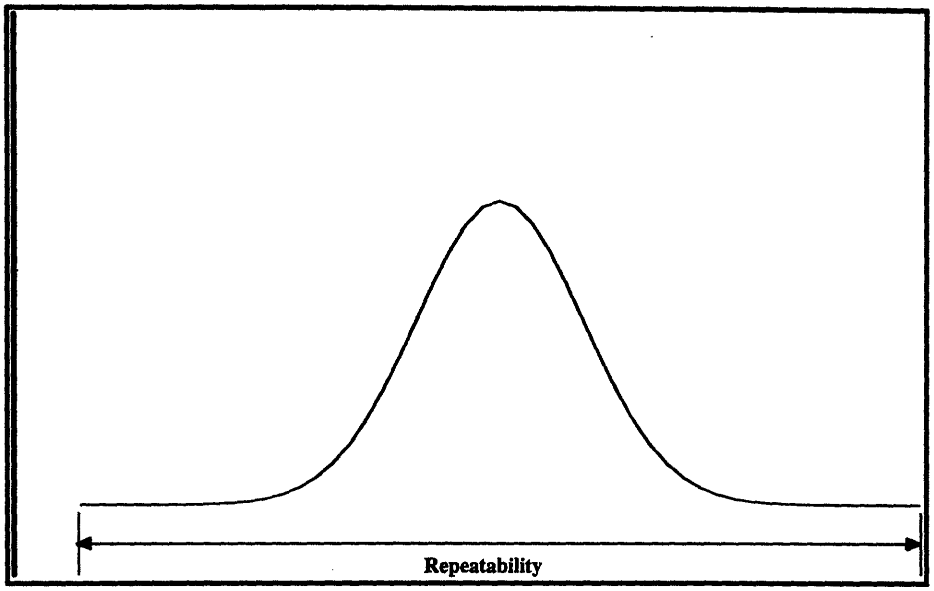


Figure 3.5.1b: Gage Repeatability

Gage reproducibility: is the variation in the average of the measurements made by different operators using the same gage when measuring identical characteristics on the same parts (Figure 3.5.1c). During this test phase, two lab technicians were selected at each Lab site and performed numerous replications of the performance tests on the same pumps. Although the technicians were different at each location, it was anticipated that the technicians would have insignificant impact on the measurements obtained. The test process is semi-automatic.

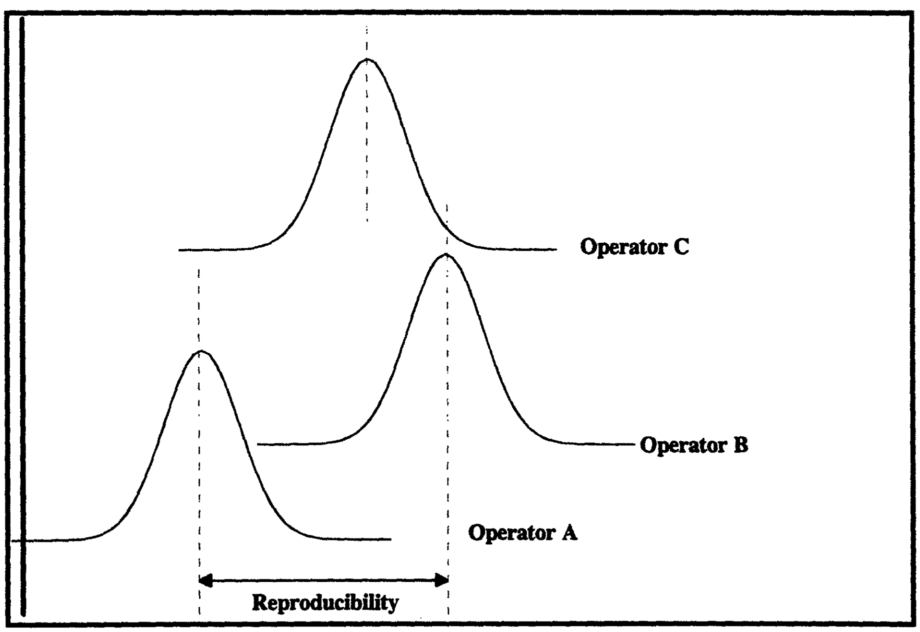


Figure 3.5.1c: Gage Reproducibility

Gage stability: also known as drift, is the total variation in the measurements obtained with a gage on the same parts when measuring a single characteristic over an extended time period. In this test phase, this was addressed in three ways (as a noise): 1) calibration of two-station stand before testing each Round at each Lab, 2) testing over a period of time, Round I and Round II at each Lab, and 3) testing over shifts and test days since the scope of the testing was so large that it could not be completed in one shift or one day. Furthermore, the test equipment is typically control charted for a given "master" or stable fuel pump to determine if it stays within the acceptable calibration limits. This is done everyday before beginning testing.

Gage linearity: is the difference in the accuracy values through the expected operating range of the gage. In this test phase, this was accomplished by testing numerous pump models at their various operating points, fixed voltages and pressures. Are the gage R&R results the same regardless of pump or setting on the two-station stand?

Before running the tests in the Labs, two fundamental aspects had to be guaranteed during this test phase: 1) the experimentation or test procedure designed and conducted most closely simulated the actual test conditions or environment of the Lab sites and 2) the operating characteristics of the pumps as they occur in the field and as prescribed by the Ford Engineering Specifications are tested. If these two do not happen, the optimum or ideal capability of the test equipment and technicians will be assessed not the assessment of the statistical properties of the complete measurement system as it is typically employed.

This test Phase was ultimately designed as a multifactor, balanced design with randomized and repeated runs. However, for the ETC Lab, the repetitions for each pump were not equal for each operator because of the two shifts. There was no blocking of variables. The only factor that was confounded was test location with test equipment and time between Lab tests (Round I and II). The effect of test location on testing could not be determined. This multifactor model consisted of two fixed and random-effects, technician at two levels (A, B) and fuel pump at three levels (60 lph, 95 lph, turbine). Both factors were selected from a much larger population. As indicated previously, all the other factors were controlled or left as noise. The measurements that were taken at these control/noise combinations included multi-point performance tests of outlet flow, current and speed at:

Turbine pumps: 8.0V/200 kPa, 8.0V/250 kPa, and 13.2V/310 kPa (which are control factors)
Gerotor pumps: 7.0V/270 kPa, 10.0V/270 kPa, and 13.2V/310kPa or 386kPa (which are control factors)

As a result, for each location, there were 15 replicates for each pump at three operating points in each test fluid. This resulted in:

$$\frac{15\ \text{runs}}{\text{trial}} \times \frac{3\ \text{pumps}}{\text{run}} \times \frac{3\ \text{operating points}}{\text{pump}} \times \frac{3\ \text{measurements}}{\text{operating points}} \approx \frac{405\ \text{measurements}}{\text{trial}}$$

$$\frac{405\,\text{measurements}}{\text{trial}} \times \frac{2\,\text{trials}}{\text{test fluid}} \times 2\ \text{test fluids} \approx 1620\ \text{measurements}$$

3.5.2 PRE-PHASE II: Gage Capability Comparison between the Alba Fuel Lab and Plant and the ETC Fuel Lab and Rawsonville Plant

Background

The objectives of this test phase are very similar to those of Phase I, but with an added dimension, the plant. They were to determine the relative amount of variation in the fuel pump, performance measurements due to the repeatability and reproducibility of the performance test equipment and to compare this amount across the Lab and the Plant sites. The test equipment used included the two-station performance test stands at the Labs and the fuel pump production test stands at the Plants. The primary motivation for this test phase was Phase II, the test fluid correlation and impact on fuel pump, production specification limits.

Since one of the overall objectives of this thesis project was to address the modification of the fuel pump, production specification limits at the components plants, the production test stand, gage capability had to be verified before any of the limits could be modified and the test fluid correlation verified. This need to conduct a gage R&R on the test stands at the Rawsonville Plant was further verified by control charting the fuel pump flow and current performance characteristics for each test fixture, but for only one fuel pump model, the 60 lph gerotor.

As described in Phase I, a small sample of pumps to be tested was selected from a population that had undergone a significant amount of previous testing, primarily in-process testing. Three of the pumps selected were the 60 lph pumps, and they were tested at the ETC Lab and Rawsonville Plant (plus one additional pump at Rawsonville). The other three pumps selected were the turbine pumps, and they were tested at both Lab sites and the Alba Plant. Many of the same factors identified in Phase I occur in this test phase.

Assumptions

Many assumptions were made before performing this test phase. These are similar to those in

Phase I, and are also a common thread behind gage R&R testing. They are described below:

- Pumps are "stable" and will not change during testing.
- The properties of the ESF-M99C82-A solvent are equivalent at each test site.
- Fluid temperature variation (20°C - 25°C) between Lab and Plant will not cause large changes in the pump properties such as viscosity and therefore, will not significantly affect pump performance.
- Sample size can be small when conducting a gage R&R as long as there are many run replications.

Test Method

The testing consisted of an R&R comparison between the Labs and Plants with an emphasis on whether the test stands or their fixtures are statistically equivalent to each other in terms of repeatability and reproducibility. Although, there are many tests that are performed at the production facilities by each of the test fixtures, the only tests that were focused on as a source of comparison between the Labs and the Plants, were the performance tests, outlet flow and current draw. These tests consisted of:

Gerotors: 13.2V/310 kPa
Turbines: 13.2V/310 kPa and 8.0V/200 kPa (for flow only)

Furthermore, aside from the obvious differences between the hardware, software, and test environment of the test equipment between all the facilities, other factors were searched for (beside fuel) to determine if these were the sources of the differences between the capability of the test equipment. These differences could then be used to make changes to the equipment and even the production specification limits with the possibility of impacting the pump yields.

The test design for the Labs was the same as for Phase I, but there were only two trials for each pump type in the M99-solvent. In addition, the randomization scheme was also modified slightly, and the pumps were tested at the following operating points:

Gerotors: 13.2V/310 kPa and 10.0V/270 kPa
Turbines: 13.2V/310 kPa and 8.0V/200 kPa

This resulted in:

$$\frac{15\ \text{runs}}{\text{trial}} \times \frac{3\ \text{pumps}}{\text{run}} \times \frac{2\ \text{operating points}}{\text{pump}} \times \frac{3\ \text{measurements}}{\text{operating points}} \approx \frac{270\ \text{measurements}}{\text{trial}}$$

$$\frac{270\ \text{measurements}}{\text{trial}} \times \frac{2\,\text{trials}}{\text{pump type}} \times 2\ \text{pump types} \approx 1080\ \text{measurements}$$

For the Rawsonville Plant, a test matrix was set up for each test fixture. The only factors were the 60 lph fuel pump at four levels and the operator which was considered the test and load side of the dial table of each fixture. In addition to the performance tests, all the tests that the test stands perform were recorded. For each fixture and the test or load side, each pump was measured three times for each of the tests. This resulted in a multifactor, balanced design with randomized and repeated runs. Over all the factor level combinations, this resulted in:

$$\frac{8\ \text{runs}}{\text{test fixture}} \times \frac{6\ \text{tests}}{\text{run}} \times \frac{3\ \text{measurements}}{\text{test}} \approx \frac{144\ \text{measurements}}{\text{test fixure}}$$

$$\frac{144\ \text{measurements}}{\text{test fixture}} \times \frac{3\ \text{test fixtures}}{\text{test stand}} \times 4\ \text{test stands} \approx 1728\ \text{measurements}$$

For the Alba Plant, a test matrix was set up for each test fixture where the only factors were the turbine pump at three levels and the operator, two selected from the production floor. Even though the production test stand fixtures measured more than the standard fuel pump performance measurements, only these were measured. They were also used as a point of comparison with the performance measurements from both the ETC and Alba Labs. For each test fixture and operator, the performances tests were run ten times for each pump. This amounted to:

$$\frac{10\ \text{runs}}{\text{test fixture}} \times \frac{3\ \text{tests}}{\text{run}} \times \frac{1\ \text{measurements}}{\text{test}} \approx \frac{30\ \text{measurements}}{\text{test fixure}}$$

$$\frac{30\ \text{measurements}}{\text{test fixture}} \times \frac{2\ \text{test fixtures}}{\text{test stand}} \times \frac{5\ \text{test stands}}{\text{operator}} \times 2\ \text{operators} \approx 600\ \text{measurements}$$

3.5.3 PHASE II: Test Fluid Correlation

Background

This test Phase had three primary objectives:

1) To supplement the current understanding of the effect of different test fluids on the fuel pump performance characteristics such as outlet flow and current draw,

2) To develop a correlation factor(s) between fuel pump flow and current draw in gasoline, which is used at the Labs, and M99-solvent, which is used at the components production facilities with the possibility of modifying the production specification limits, and

3) To determine if the correlation factors in the two fluids are equivalent between the different gerotor fuel models (45 lph, 60 lph, 88 lph, 95 lph, and 125 lph) regardless of their different operating conditions (13.2 V/110 kPa versus 13.2 V/310 kPa versus 13.2V/386 kPa).

Out of all the test phases, this one took the longest time to design. There were numerous sources of complexity which contributed to this time. These included pump break-in characteristics and durability test stand availability, 2) sample size selection and production schedule, and 3) production test stand gage capability. These complexities mainly applied to the gerotor fuel pumps that were selected for test. At the time this test was developed, the turbine pumps were just launched at the Plant in Hungary, and minimal production history was known. Much prove out had already taken place on the pumps, and gage capability studies were performed on all the production test stands. The Lab equipment was also verified and on-line. As a result, 46 production-level turbine pumps were selected for correlation testing at both the ETC and Alba Labs in anticipation that this was a significant sample size, and they did not require the level of break-in of the gerotors.

In the next few paragraphs, the above sources of complexity will be described for the gerotor pumps. It should be noted here that although a substantial amount of preliminary work and investigation took place, a different alternative for gerotor testing was ultimately selected.

Fuel Pump Selection and Sampling Strategy

One of the key criteria for selecting the gerotor pumps for test was that they should be representative of the production population. It was decided, initially, to include only the 60 lph gerotor pumps in the tests under the assumption that the results would hold for all the other gerotor models. As will be seen shortly, this did not work. Nonetheless, a sampling strategy was designed for the 60 lph gerotor fuel pumps:

1) A production test stand (at Rawsonville) was selected from which to sample the 60 lph pumps from. This test stand should be fairly consistent or within control by comparing its three fixtures. X-bar and range charts from plant generated data were analyzed to determine this. Sampling was done from only one fixture off this "best" test stand. However, sampling could have been done from all three fixtures if their means for pump flow and current were equivalent and their standard deviations were "relatively" small.

2) A sample size of the 60 lph gerotor pumps was determined. The intent was to capture a sample that was representative of the entire production population and its underlying (normal) distribution in terms of outlet flow (based on the production specification limits for flow and the test process mean and standard deviation).

3) The sample of the 60 lph pumps were separated into different strata or segments based upon their flow. In other words, the pumps were selected from the test stand fixture such that their flow fell within different regions of their production distribution curve for flow in the M99-solvent.

4) The frequency with which the fuel pumps were sampled from the line was determined by analyzing the SPC data for each production test stand fixture.

Assumptions

- Technician does not significantly influence measurements.
- Turbines are "stable" and will not change during testing.
- Gerotors are "stable" and will not change during testing.
- The properties of the ESF-M99C82-A solvent are equivalent at each Fuel Lab.
- The fluid correlation should be determined at ambient conditions.
- Sample size represents pump production population.
- The R&R of the two-station performance stand is "acceptable" for flow and current draw.

Resulting Test Method

Proceeding along in the direction discussed above, the original plan of just testing the 60 lph gerotors in the ESE-M4C50-D gasoline and ESF-M99C82-A solvent, was changed. Since a large concern was whether or not a correlation factor between performance results in both test fluids would hold over the entire fuel pump population, it was ultimately decided to select four gerotor models for test in each of the test fluids. These included the 45 lph, 60 lph, 95 lph, and 125 lph pumps, and ten of each were tested. The ten 60 lph pumps were selected from the prior sampling that took place. The remaining 30 pumps were just randomly selected from production.

During the correlation tests conducted at the ETC Lab for the gerotor pumps, all the pumps were aggregated together, randomized, and tested in each test fluid. This resulted in 40 runs with each run repeated three times without removing the pump between repetitions. Furthermore, multi-point performance tests of flow, current, and speed were performed in each test fluid at the following:

45 lph pumps:	10.0V/100 kPa, 13.2V/100 kPa, and 13.2V/110 kPa
60 lph, 95 lph, and 125 lph pumps:	10.0V/270 kPa,13.2V/270 kPa, and 13.2V/310 kPa

However, the primary points of interest were the standard operating points of 13.2V/110 kPa for the 45 lph pumps and 13.2V/310 kPa for the remaining gerotors for two reasons: 1) because they are tested at the Plant at those points and 2) because they operate at those parameters in the vehicle. The low voltage performance measurements were included for additional information. Speed is included because it is a common measurement in the Lab. However, the speed measuring apparatus in the test stand was not operating properly or consistently, and was undergoing modification.

Even though there were four types of gerotor models lumped together and tested to determine the test fluid correlation, the fuel pump was not selected as a variable. The only variable was the test fluid. As long as all the pumps were tested at a fixed voltage of 13.2V, their flow and current distributions could be compared in each of the test fluids. The test fluid correlation of pump flow and current draw should hold no matter what gerotor model was tested:

$$\frac{40\ \text{runs}}{\text{test fluid}} \times \frac{3\ \text{replications}}{\text{run}} \times \frac{4\ \text{tests}}{\text{replication}} \times \frac{3\ \text{measurements}}{\text{test}} \approx \frac{1440\ \text{measurements}}{\text{test fluid}}$$

$$\frac{1440\ \text{measurements}}{\text{test fluid}} \times 2\ \text{test fluids} \approx 2880\ \text{measurements}$$

The test scenario for the production turbine pumps was somewhat different than the gerotor pumps. Aside from the 30 minutes of break-in before they were tested, the turbines underwent correlation testing twice, once at the ETC Lab and once at the Alba Lab. The significant difference was that at the Alba Lab, three test fluids were used: the 50-D gasoline, the M99-solvent, and the Eurosuper gasoline. At each Lab, the performance measurements of flow, current, and speed were measured in each of the respective test fluids at the following conditions:

ETC Lab:	8.0V/200 kPa and 250 kPa, 8.5V/250 kPa, 9.0V/250 kPa, and 13.2V/310 kPa
Alba Lab:	8.0V/200 kPa and 250 kPa, 8.5V/200 kPa and 250 kPa, 9.0V/200 kPa and 250 kPa, and 13.2V/310 kPa

This resulted in:

$$\frac{46\ \text{runs}}{\text{test fluid}} \times \frac{5/7\ \text{tests}}{\text{run}} \times \frac{3\ \text{measurements}}{\text{test}} \approx \frac{690/966\ \text{measurements}}{\text{test fluid}}$$

$$\frac{690/966\ \text{measurements}}{\text{test fluid}} \times 2/3\ \text{test fluids} \approx 1380/2898\ \text{measurements}$$

There were two reasons why the low voltages were included: 1) Ford of Europe or the Engineering Specifications call for a minimum flow criteria that has to be met at both the Lab and the Plant, and 2) even though the Engineering Specification is given as 8.0V/250 kPa, the pumps are tested at the Plant at 8.0V/200 kPa.

As one last step, this test phase was rerun for the same turbine pumps on the basis of the results that were obtained (discussed in Chapter 4). The pumps were only retested at the ETC Lab in the 50-D gasoline and the M99-solvent. However, instead of running the multi-point performance tests as given above, a performance curve for flow, current, and speed at each of two fixed voltages, 8.0V and 13.2V, over a fixed pressure range was run. The pressure range for the 8.0V was 25 kPa to 250 kPa, and the pressure range for the 13.2V was 25 kPa to 538 kPa. Since these pumps are unlike the gerotors in that there is only one model, a larger flow and current distribution was obtained and able to be compared in each of the test fluids by running performance curves at a fixed voltage.

Chapter 4: Data Reduction and Analysis

4.1 OVERVIEW OF METHODOLOGIES USED

4.1.1 GAGE REPEATABILITY AND REPRODUCIBILITY

The primary test methodology described for Phase I and Pre-Phase II in Chapter 3 was the gage repeatability and reproducibility (gage R&R) methodology. With this method, there are many techniques in which the data can be organized and analyzed. These include the range method, the average and range method, and the analysis of variance method (ANOVA). One most notable feature of all these methods is that they do not calculate within-part variation in their analyses. Unless there is a way to select the test samples or fuel pumps to eliminate the within-part variation, it will be included within the estimate of measurement variability attributed by the gage repeatability variation.[1] It is important that the total measurement system variation, which can be directly measured by the above three methods, includes not only the measuring device (flow meter or pressure transducer) and other variations as discussed in the last chapter, but it also includes the variation of the parts being measured. This is the within-part variation and between part-variation. The exclusion of the within-part variation from the study should be generally avoided, and the determination of how to handle this component of variation must be based on a rational understanding of the intended use of the part and the purpose of the measurement.[2] For this thesis project, calculating and extracting out the within-part variation was not attempted, because it would not have been representative of the test system. In addition, the methods prescribed by the AIAG manual for determining within-part variation cannot be applied to dynamic test systems and dynamic test specimens.

4.1.2 DESCRIPTION OF ANALYSIS METHODS[3]

Range Method

This method will provide a quick approximation of measurement variability and will only provide an overall picture of the measurement system. It does not decompose this variability into repeatability

[1] A.I.A.G., Measurement Systems Analysis Manual (Troy, MI, 1990), 37.
[2] A.I.A.G..
[3] A.I.A.G..

and reproducibility. Furthermore, it only requires five parts and two operators, who each measure the part once, to run the study. The calculations are shown below in Table 4.1.2.a:

Parts	Measurement: Operator A	Measurement: Operator B	Range (A-B)
1	A_1	B_1	A_1-B_1
2	A_2	B_2	A_2-B_2
3	A_3	B_3	A_3-B_3
4	A_4	B_4	A_4-B_4
5	A_5	B_5	A_5-B_5

Table 4.1.2a: Range Method Calculations

$$\overline{R} = \frac{\sum_{i=1}^{5}(Ai - Bi)}{5}$$

$$G_{R\&R} = (4.33) \times \overline{R}$$

$$\sigma_{process} = USL - LSL$$

$$\%G_{R\&R} = 100 \times \frac{G_{R\&R}}{\sigma_{process}}$$

This method is further described in many SQC books and the Measurement Systems Analysis Manual (AIAG, 1990).

Average and Range Method

This is currently the method of analysis used by the Rawsonville Plant. It is a mathematical method which can determine both the repeatability and reproducibility for a measurement system and break the total variability of the measurement system into these two components. However, it ignores the possible interaction between gage and operator. Nonetheless, it will provide insight into the possible causes of the measurement system error (part variation, within-part variation, operator variation, gage variation, calibration, maintenance, and others). In addition, the number of operators, trials, and parts tested may be varied, but the typical selection, according to Ford standards is shown in Figure 4.1.2a.

As noted in the previous chapter, master parts should be tested during these studies. "Master" implies stable and repeatable parts that will minimize both within-part and between-part variation within

Figure 4.1.2a: Ford Gage R&R Standard

GAGE REPEATABILITY AND REPRODUCIBILITY STUDY

Data Sheet

	1	2	3	4	5	6	7	8	9	10	11	12
Operator	A–				B–				C–			
Sample #	1st Trial	2nd Trial	3rd Trial	Range	1st Trial	2nd Trial	3rd Trial	Range	1st Trial	2nd Trial	3rd Trial	Range
1												
2												
3												
4												
5												
6												
7												
8												
9												
10												
Totals												

Sum $\bar{X}_A$ $\bar{R}_A$

Sum $\bar{X}_B$ $\bar{R}_B$

Sum $\bar{X}_C$ $\bar{R}_C$

$\bar{R}_A$	
$\bar{R}_B$	
$\bar{R}_C$	
Sum	
$\bar{\bar{R}}$	

# Trials	D_4
2	3.27
3	2.58

($\bar{\bar{R}}$) x (D_4) = UCL_R*

(____) x (____) = ____

Max. $\bar{X}$	
Min. $\bar{X}$	
$\bar{X}$ Diff.	

* Limit of individual R's. Circle those that are beyond this limit. Correct R by repeating those readings using the same appraiser and unit as originally used or discard values and reaverage and recompute R and the limiting value. UCL_R

NOTES: ________________________________

Quality Oct 91 1763 (Reverse)

the gage variability (repeatability) component. The standard statistical techniques in terms of randomization and factor selection or control should be taken into account as discussed previously. It should also be noted that with traditional gage R&R studies, the part measurements taken by the operators are "checked" against a standard. In this thesis project, dynamic fuel pumps were tested during the gage R&R studies of Phase I and Pre-Phase II, and there was no real "standard" or best pumps to check against. Every pump is different from the other. In order to minimize within-part and part variation, pumps which had a substantial amount of previous testing on them were tested. Once all the data is taken and recorded on a sheet like that in Figure 4.1.2a, the following calculations can be made (after determining the $\overline{R}$ and $\overline{X}_{diff}$). (All the constants that are used in these calculations and those in Figure 4.1.2a are determined from the number of trials and operators. Tables of them are included in APPENDIX B.)

1) Repeatability or Equipment Variation

$EV = \overline{R} \times K_1$ (K_1 based on number of trials)

2) Reproducibility or Appraiser Variation:

$AV = \overline{X}_{diff} \times K_2$ (K_2 based on number of operators)

3) Repeatability & Reproducibility (R&R):

$$R\&R = \sqrt{(EV)^2 + (AV)^2}$$

4) Part Variation:

$PV = R_p \times K_3$ (K_3 based on number of parts)

$R_p = \overline{X}_{pmax} - \overline{X}_{pmin}$ (These $\overline{X}$ values are computed by summing up the measurements for each part over each operator, averaging them, and then looking for the max and min averages)

5) Total Variation in Measurements

$$TV = \sqrt{(R\&R^2 + PV^2)}$$

Figure 4.1.2b: Components of Variance or Measurement Unit Analysis

In Figure 4.1.2b, these calculations are based on predicting 5.15σ or 99.0% of the area under the normal probability curve. Therefore, these values for each of the components of variance of the total measurement error are magnitudes and provide an indication of where the largest source of variability comes from. In Figures 4.1.2c and 4.1.2d, these calculations have a similar interpretation and are complimentary to each other. Figure 4.1.2c provides, for example, the percent the equipment variation consumes of the total variation, but the summation of these percentages does not equal 100%. The calculations in Figure 4.1.2d are more subjective and are based primarily on the accepted tolerance for the part (assuming the process control limits lie within these tolerances). The key percent of tolerance (P/T) factor is the %R&R, and there are typical criteria or guidelines that indicate whether the measurement system is performing adequately:[4]

Under 10%:	Measurement system performance is acceptable.
10% to 30%:	Measurement system is "probably" acceptable based upon the significance of its application, cost to repair, etc.
Over 30% error:	Measurement system needs improvement, make effort to identify causes, and correct them.

$$\%EV = 100 \times \frac{EV}{TV}$$

$$\%AV = 100 \times \frac{AV}{TV}$$

$$\%R\&R = 100 \times \frac{R\&R}{TV}$$

$$\%PV = 100 \times \frac{PV}{TV}$$

Figure 4.1.2c: % Process Variation for the Components of Variance

[4] A.I.A.G..

$$\%EV = 100 \times \frac{EV}{(USL - LSL)}$$
$$\%AV = 100 \times \frac{AV}{(USL - LSL)}$$
$$\%R\&R = 100 \times \frac{R\&R}{(USL - LSL)}$$
$$\%PV = 100 \times \frac{PV}{(USL - LSL)}$$

Figure 4.1.2d: % of Tolerance for the Components of Variance

ANOVA Method

This is a standard statistical technique and can be used to analyze the measurement error and other sources of variability in the measurements obtained in a gage R&R study. It was the primary method used to analyze the data resulting from the Phase I and Pre-Phase II test phases. With ANOVA, the method of collecting the data is important. Randomization and replication are also necessary to ensure a balanced design or that each operator tests each pumps the same number of times. The method of data collection shown in Figure 4.1.2a is acceptable.

What makes this method of analysis different than the others is the fact that more sources of variability such as interactions between factors can be determined. One such interaction is that between the operator and gage. Another difference is the way the components of variance are estimated. However, it is still possible to perform a measurement unit analysis as well as determine the % process variation, % of tolerance, and % contribution to total variation. In sum, the following steps can be performed when applying the ANOVA as the method of analysis of a gage R&R study. These were applied to Phase I and Pre-Phase II:

1) Design the gage R&R study (see Figure 4.1.2a) including sample and operator size as well as randomization scheme and the amount of runs and repetitions to make.
2) Determine what to measure.
3) Perform necessary calibrations and test equipment preparations.
4) Run gage R&R study.
5) Run ANOVA on the measurements using the factors of fuel pump, operator, and interaction between operator and part. (See APPENDIX C for an ANOVA summary table.)
6) Determine which factors contribute the most to the total variability in the measurements and whether there are any interactions.

7) Calculate the estimates of the variance components.
8) Calculate the sigma spreads of the EV, AV, interaction of part and operator, R&R, and PV.
9) Determine % process variation, % of tolerance, and % contribution to total variation.

$$\text{Repeatability: } \sigma^2_{gage} = MS_{error} \qquad MS_{error} = \text{Mean Square Error}$$

$$\text{Interaction: } \sigma^2_{oxp} = \frac{(MS_{oxp} - MS_{error})}{r} \qquad MS_{oxp} = \text{Mean Square Interaction Operator / Part}$$

$$\text{Operator: } \sigma^2_{o} = \frac{(MS_{o} - MS_{oxp})}{nr} \qquad MS_{o} = \text{Mean Square Operator}$$

$$\text{Part: } \sigma^2_{part} = \frac{(MS_{p} - MS_{oxp})}{kr} \qquad MS_{p} = \text{Mean Square Part}$$

r = runs
k = number of operators
n = number of parts

Figure 4.1.2e: Estimate of Variance Components Based upon ANOVA

If the interaction between the operator and part is significant, the 5.15σ estimates of EV, AV, Interaction, R&R, and PV can be determined. If the interaction is not significant, the MS_{oxp} is replaced by the MS_{pool} (pooled Mean Square) in the above calculations, and the σ^2_{oxp} is eliminated. This indicates an additive model. See Design and Analysis of Experiments Book (Montgomery 1991) for a derivation of the MS_{pool} (pooled Mean Square). There was not enough degrees of freedom to use MS_{pool}, so the MS_{error} was substituted instead. The ANOVA output generated from the Phase I and Pre-Phase II data showed that there was no interaction between the Lab technician and pump or the test and load sides of the production test equipment and the fuel pumps. Therefore, the 5.15σ values can be calculated:

$$
\begin{aligned}
EV &= 5.15\sqrt{MS_{error}} \\
AV &= 5.15\sqrt{\frac{(MS_O - MS_{error})}{nr}} \\
R\&R &= 5.15\sqrt{(EV)^2 + (AV)^2} \\
PV &= 5.15\sqrt{\frac{(MS_P - MS_{error})}{kr}}
\end{aligned}
$$

Figure 4.1.2f: Estimate of 5.15 Sigma Spread based on ANOVA and for an Additive Model

The % process or total variation and the % contribution to total variation were calculated for the Phase I and Pre-Phase II test results. The % of tolerance was only calculated for the Pre-Phase II results, because the process tolerances were known for the particular measurements that were taken on the production test stands. These were calculated as above in Figure 4.1.2d with some modification, because some production limits were single-sided.

$$
\begin{aligned}
\text{Total Variation (TV)} &= \sqrt{R\&R^2 + PV^2} \\
\text{\% of Total Variation} &= 100\frac{5.15\sigma(\text{EV or AV or Interaction or} R\&R \text{ or PV})}{5.15\sigma(TV)} \\
\text{\% Contribution to TV} &= 100 \times \left(\frac{5.15\sigma(\text{EV or AV or Interaction or} R\&R \text{ or PV})}{5.15\sigma(TV)}\right)^2
\end{aligned}
$$

Figure 4.1.2g: %'s based upon Estimates of 5.15σ from ANOVA

4.1.3 TEST FLUID CORRELATION

The analysis technique that was applied to the results from Phase II was regression analysis.[5] This was selected because of the amount of data that was collected and the fact that the underlying test objective was to be able to predict the fuel pump performance in the M99-solvent test fluid given the performance in gasoline. The regression model that was predicted was a simple linear regression model (Figure 4.1.3a) whereby pump flow, current draw, and speed in the solvent were regressed on the same parameters in gasoline. As a result, the only factor that was considered was the test fluid type. All the

[5] A detailed description of regression analysis can be found in many books on regression or introductory statistics books.

other factors were controlled or left as noises and were imposed on each test run via randomization of the runs and measurement replication.

Y_{M99}	$= \beta_0 + \beta_1 X_{GAS} + \varepsilon$
Y_{M99}	= Pump flow, speed, or current measurement at a fixed voltage / pressure in M99 - solvent.
X_{GAS}	= Pump flow, speed, or current measurement at a fixed voltage / pressure in a gasoline.
β_0, β_1	= Coefficients or intercept and slope.
ε	= Error around model.

Figure 4.1.3a: Simple Linear Regression Model

Once the regression was run on the data, the adequacy of the model or fitted line and a check on the normality assumptions of the underlying distribution of all the fuel pumps that were tested were performed. This included the standard checks on the residual values, which are determined by subtracting the predicted values from the actual Lab measurements. See Figures 4.1.3b-c for an example plot of the residual values versus the predicted values and an example normal, probability plot of the residuals. By looking at these plots, it can be determined whether or not the data or measurements need to be transformed into a logarithmic or exponential scale or any other form. Typically the data should be transformed, to stabilize the variance in the model and minimize the dependence of one factor on another, if there are any obvious patterns that show up in the above residual plots.[6]

In summary, the way the correlation tests were designed and the way the resulting measurements were organized for the regression analysis were the most significant aspects of this analysis. These two aspects were also very influential in determining whether or not the fuel pump, production specification limits could be modified and how they could be recomputed.

4.2 STATISTICAL SOFTWARE APPLICATIONS IN THE ANALYSES

All the actual analyses that were conducted for each test phase were implemented by the application of numerous software packages. These were very efficient and minimized the amount

[6] Hogg and Ledolter, Applied Statistics for Engineers and Physical Scientists (1992), 367.

Figure 4.1.3b: Plot of Residual vs Predicted Values
Regression of Flow in M99 on Flow in Gas

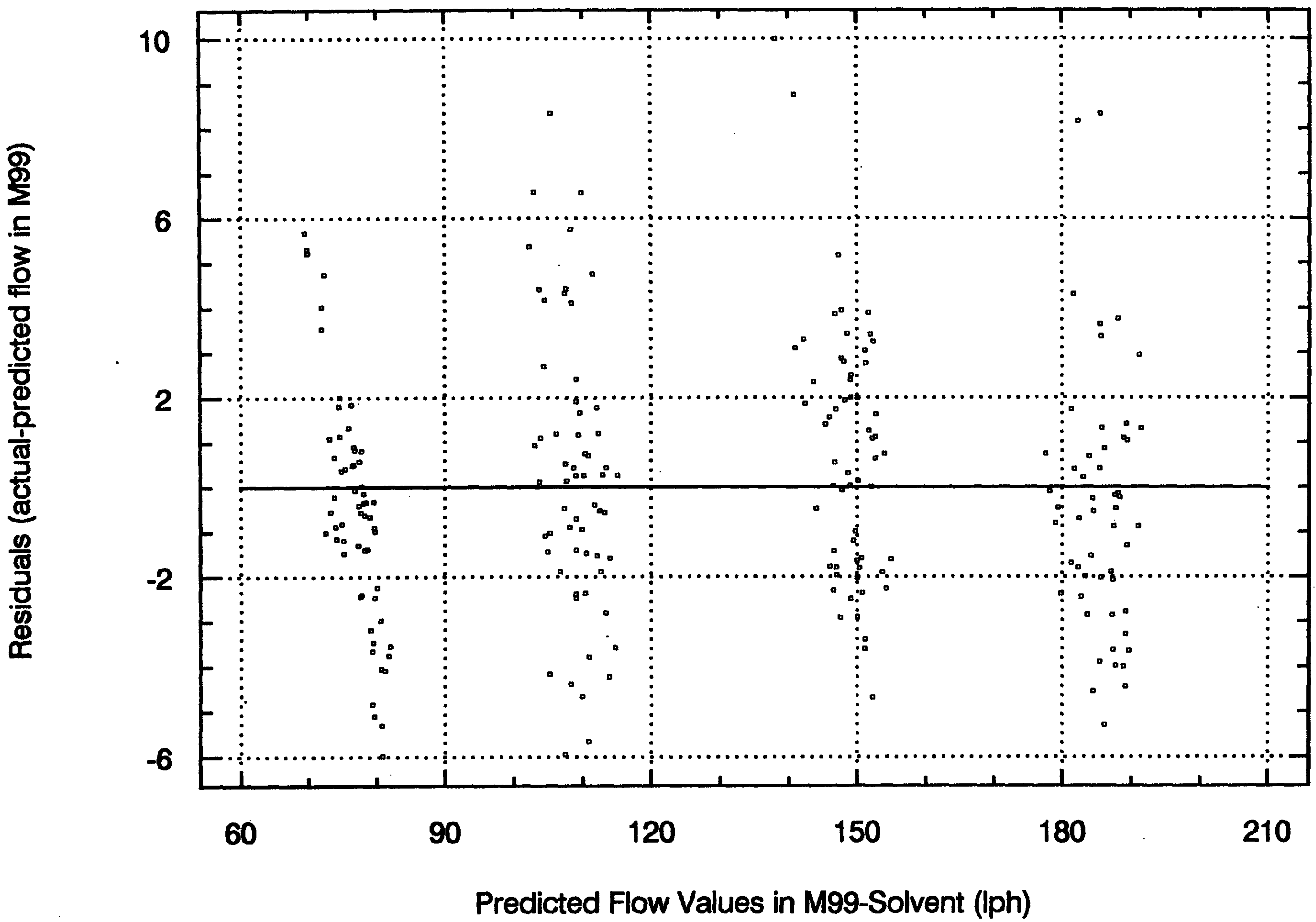
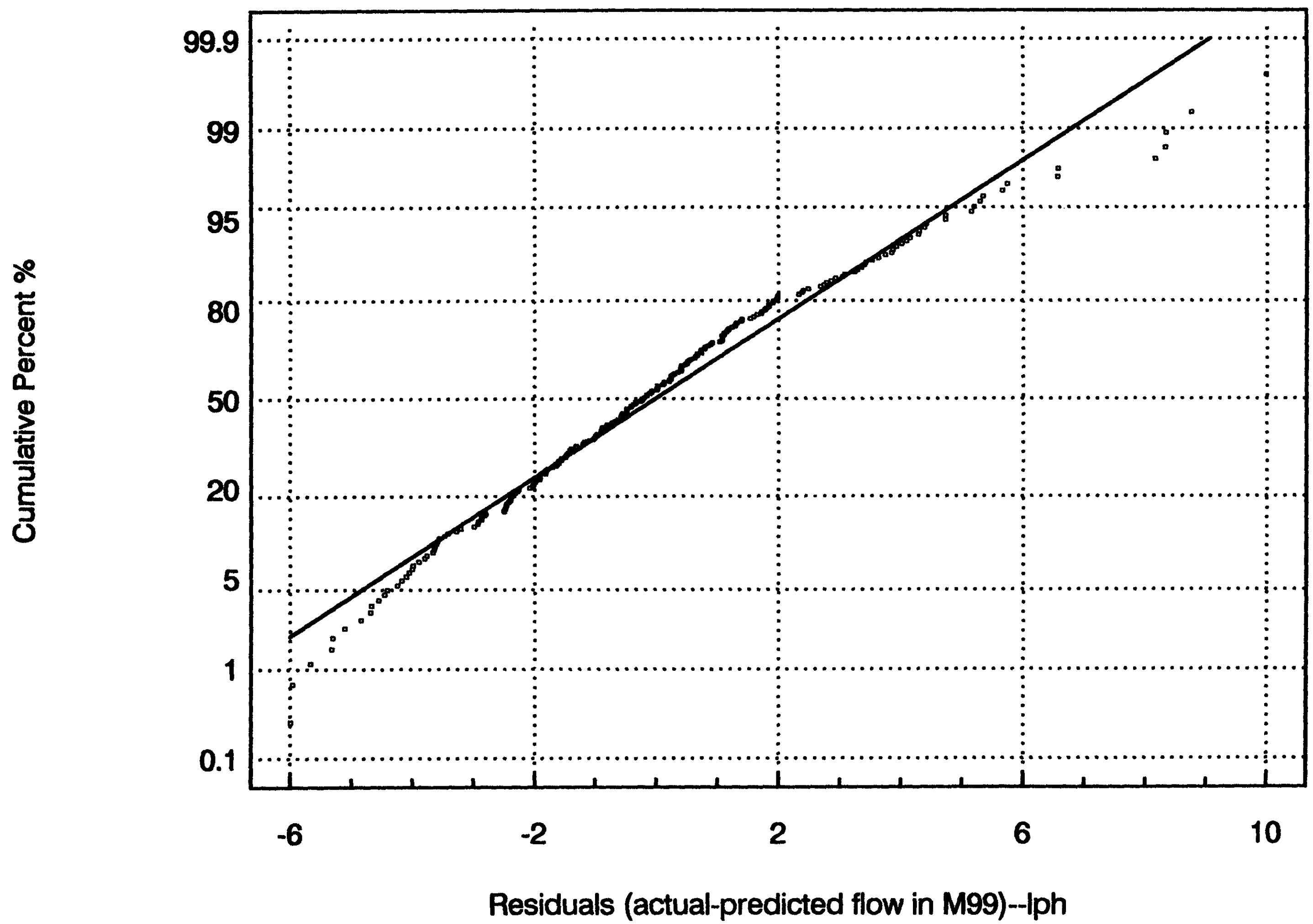


Figure 4.1.3c: Normal Probability Plot of Residuals
Regression of Flow in M99 on Flow in Gas



of analysis time. During this thesis project, the analysis accounted for at least 50% of the total time spent on the project with the other 50% spent on the actual design and running of the tests. The primary (PC/IBM compatible) software packages used were Excel V4.0--spreadsheet program and Statgraphics V6.0, a statistical, DOS-based program. Excel was pivotal in organizing the data from the two-station performance test stand. The raw data from this stand was saved in a .CSV format on a floppy disk which could then be read directly into the Excel program. This eliminated the potential of having to enter the data into Excel manually. Once the data was read into Excel, it was then formatted in a manner that could be read and analyzed by the Statgraphics program. This typically involved column formatting. The file was then saved as .CSV file in Excel and imported into Statgraphics for the application of the ANOVA and regression analyses, as well as, much exploratory data analysis and plotting.

Statgraphics was chosen over the statistical functions of Excel due to the broad range of these functions and the graphics capability that it has. However, it was difficult to determine a way to read the raw data directly from the two-station performance test stand. Statgraphics could not analyze the data in the format that resulted from the stand. Even if the data is entered manually into Statgraphics, it has to be entered in a particular way or the analyses will not be performed. Statgraphics was unforgiving if changes needed to be made to the data once it was entered.

Lastly, some of the output from the analyses that were performed on Statgraphics could be saved in Statgraphics and then exported back to Excel for further analysis or manipulation. This was done by exporting the Statgraphics' file as a .WKS or Lotus123 file and then read into excel as a Lotus123 file. Once in Excel, it could be then saved in a .XLS/.XLC format.

4.3 RAW DATA

As described in Chapter 4, there was a significant amount of data generated from each test phase, typically over 1000 rows in an Excel spreadsheet. As a result, the data files will be located at the Rawsonville, Michigan Plant of the Ford Motor Company, Electrical and Fuel Handling Division. These files are the basis for the ANOVA, regression, and exploratory data analyses that were performed in

Statgraphics. These analyses can be replicated if desired. Lastly, other background analyses (means, standard deviations) and their respective files will be included from each test phase for reference.

4.4 DATA REDUCTION AND ANALYSIS: Phase I

As discussed in section 4.1, the ANOVA method of analysis for the gage repeatability and reproducibility (gage R&R) study conducted during this test phase was the primary method of analysis. However, there were also other analyses that were initially performed on the data to provide insight on which factors had a significant impact on the gage R&R between the Labs, which unforeseen or noise factors entered into the data, and which factors could be eliminated during the ANOVA.

ANOVA of Variance

In this analysis, many more factors and interactions were evaluated here. These factors included test fluid at two levels, M99-solvent and 50-D gasoline, test location at two levels, ETC and Alba Lab, and fuel pump at three levels, 60 lph gerotor, 95 lph (gcv) gerotor, and turbine, and the two-factor interactions between all of these. The time factor of Round I and Round II was not an independent factor and was linked or confounded to each pump at each test site. Operator was also eliminated and considered a noise factor because the same operator could not test the same pumps at each Lab site.

Furthermore, there were two pumps, of each type, tested at each site. Since it was not desired to determine pump-to-pump variance, the variance of the measurements for each pump type was averaged together. These multi-point measurements of flow, current, and speed that were taken for each pump ranged from:

	LOW	MEDIUM	HIGH
60 lph gerotor	7.0V/270 kPa	10.0V/270 kPa	13.2V/310 kPa
95 lph (gcv) pump	7.0V/270 kPa	10.0V/270 kPa	13.2V/386 kPa
Turbine pump	8.0V/200 kPa	8.0V/250 kPa	13.2V/310 kPa

Table 4.4a

The ANOVA was performed on the data shown in Table 4.4b on the next page. The standard deviations are also included. The LOW, MEDIUM, and HIGH measurements were aggregated across the pump levels as shown above. The data was aggregated this way to determine whether or not measuring the pump performance at different operating points made a difference on the overall variability in the results. In other words, can the test stand repeat regardless of what operating points or fixed points it is supposed to measure the pump performance?

The ANOVA showed, at a significance level (90% confidence level) of $\alpha = 0.10$, that the interaction between fuel and pump had the most significant effect on the total variability of the results for the LOW data values for flow and current. However, this could be a combination of potential causes such as the insensitivity of the pumps to low operating points, especially 7.0V/270 kPa for the gerotor models regardless of fuel, the sensitivity of the turbine pumps to test fluids regardless of the operating point at which they are tested, and the gage R&R error that cannot be computed by conducting an ANOVA of variances.

In addition, the MEDIUM and HIGH current data values analyzed by the ANOVA indicated that fuel, pump, and their interaction have the most significant effect on the overall variability in the current draw measurements. This phenomenon was consistent over all the pumps and operating points.

Lastly, the speed variances are included in Table 4.4b only a under a strong suspicion the speed measuring device on the two-station test stand was not working properly. However, nothing out of the ordinary appeared in the ANOVA results from this data.

One other important observation, looking at the overall ANOVA of variance results, was that the turbine pumps contributed the least to the total variability in the results. Please refer to Figure 4.4a for a summary of the ANOVA of variance results by aggregate performance values.

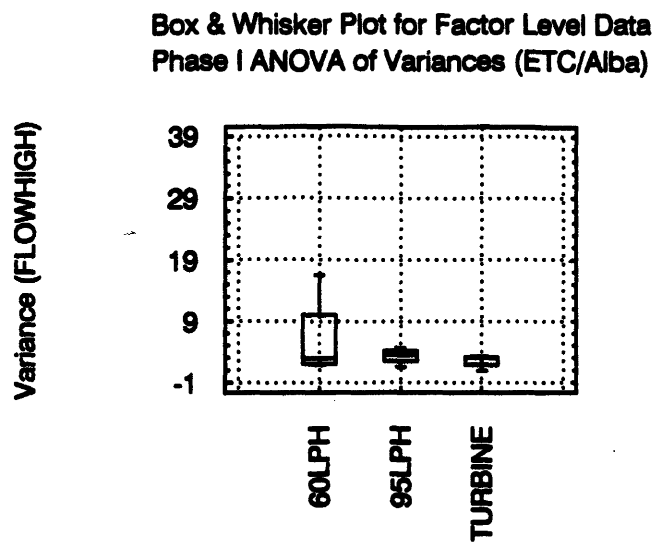
FACTORS			VARIANCES								
FUEL	LOCATION	PUMP* type	AMPLOW (amps)^2	FLOWLOW (lph)^2	SPDLOW (rpm)^2	AMPMED (amps)^2	FLOWMED (lph)^2	SPDMED (rpm)^2	AMPHIGH (amps)^2	FLOWHIGH (lph)^2	SPDHIGH (rpm)^2
GAS	ALBA	60LPH	0.147	16.433	29893.999	0.060	4.619	8961.981	0.063	1.880	3801.752
GAS	ETC	60LPH	0.361	31.185	1232913.185	0.128	10.498	18824.507	0.103	3.682	6111.372
GAS	ALBA	95LPH	0.174	14.073	27506.990	0.044	1.304	2778.110	0.054	3.479	5603.857
GAS	ETC	95LPH	0.086	10.383	22792.742	0.022	4.350	13677.243	0.021	3.519	7942.037
GAS	ALBA	TURBINE	0.001	2.231	3335.967	0.001	2.805	3688.824	0.011	3.145	2838.205
GAS	ETC	TURBINE	0.302	2.073	3397.652	0.002	2.598	3579.250	0.004	3.191	7680.273
M99	ALBA	60LPH	0.005	0.992	2184.269	0.003	9.452	26736.167	0.014	16.507	41965.952
M99	ETC	60LPH	0.010	4.621	7996.994	0.010	1.625	3777.188	0.005	2.193	11747.534
M99	ALBA	95LPH	0.008	1.598	3210.376	0.016	7.146	22991.210	0.031	4.625	11797.319
M99	ETC	95LPH	0.027	1.462	4073.763	0.008	2.184	4037.436	0.007	1.481	3477.486
M99	ALBA	TURBINE	0.001	1.650	2495.390	0.003	10.906	1657.419	0.003	0.874	13948.862
M99	ETC	TURBINE	0.002	6.849	8446.973	0.003	13.538	6790.145	0.004	2.842	126717.883

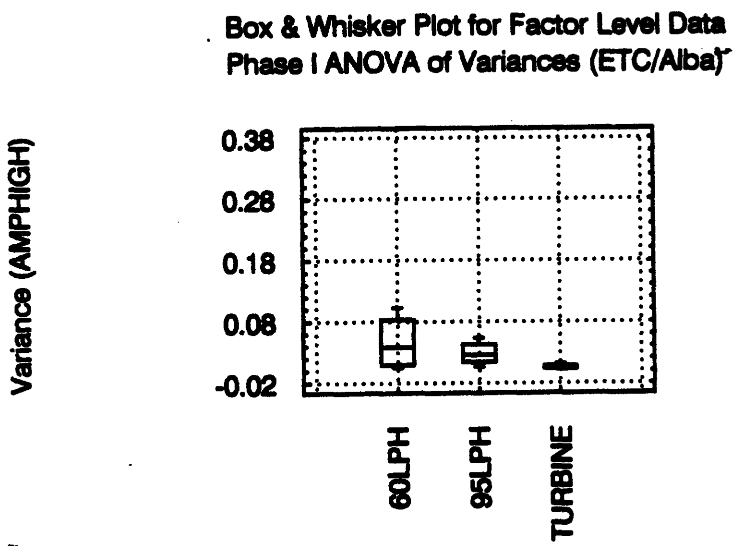
* Represents an average of variances between two pumps of the same kind.

FACTORS			STANDARD DEVIATIONS								
FUEL	LOCATION	PUMP type	AMPLOW (amps)	FLOWLOW (lph)	SPDLOW (rpm)	AMPMED (amps)	FLOWMED (lph)	SPDMED (rpm)	AMPHIGH (amps)	FLOWHIGH (lph)	SPDHIGH (rpm)
GAS	ALBA	60LPH	0.383	4.054	172.899	0.246	2.149	94.668	0.252	1.371	61.658
GAS	ETC	60LPH	0.601	5.584	1110.366	0.358	3.240	137.202	0.322	1.919	78.175
GAS	ALBA	95LPH	0.417	3.751	165.852	0.210	1.142	52.708	0.232	1.865	74.859
GAS	ETC	95LPH	0.293	3.222	150.973	0.148	2.086	116.950	0.145	1.876	89.118
GAS	ALBA	TURBINE	0.024	1.494	57.758	0.030	1.675	60.736	0.106	1.773	53.275
GAS	ETC	TURBINE	0.041	1.440	58.289	0.041	1.612	59.827	0.066	1.786	87.637
M99	ALBA	60LPH	0.069	0.996	46.736	0.056	3.074	163.512	0.117	4.063	204.856
M99	ETC	60LPH	0.100	2.150	89.426	0.100	1.275	61.459	0.071	1.481	108.386
M99	ALBA	95LPH	0.092	1.264	56.660	0.126	2.673	151.629	0.176	2.151	108.615
M99	ETC	95LPH	0.164	1.209	63.826	0.092	1.478	63.541	0.085	1.217	58.970
M99	ALBA	TURBINE	0.031	1.285	49.954	0.056	3.302	40.711	0.051	0.935	118.105
M99	ETC	TURBINE	0.045	2.617	91.907	0.055	3.679	82.402	0.059	1.686	355.975

Table 4.4b: Data Used for ANOVA of Variances from Phase I

Figure 4.4a: Phase I Results Based on ANOVA of Variances





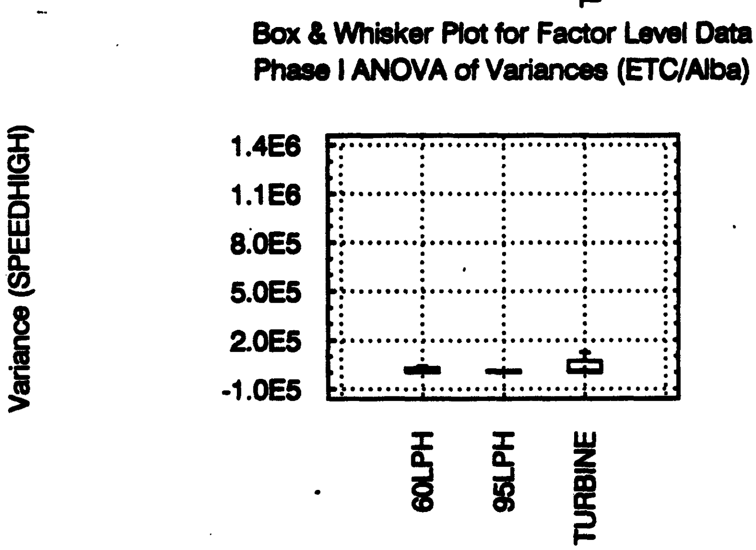
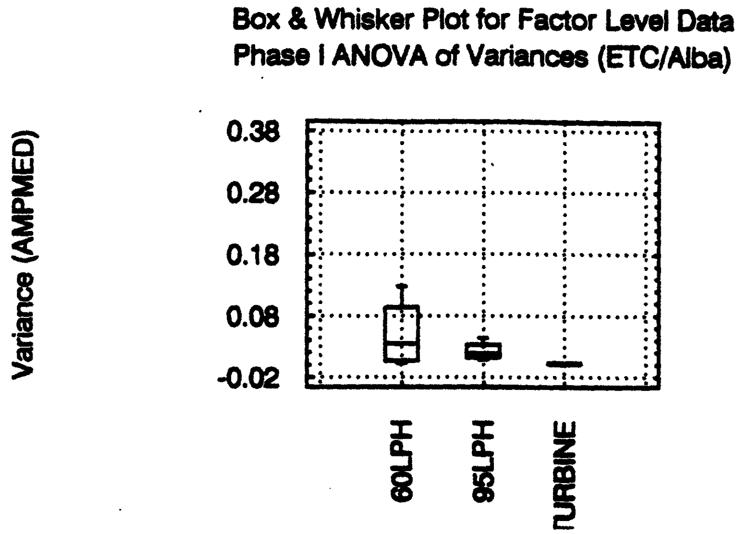
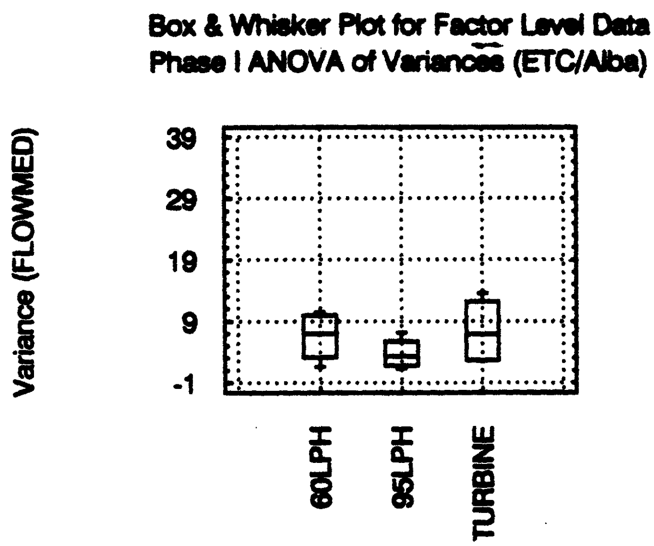


Figure 4.4a: Phase I Results Based on ANOVA of Variances (Continued)





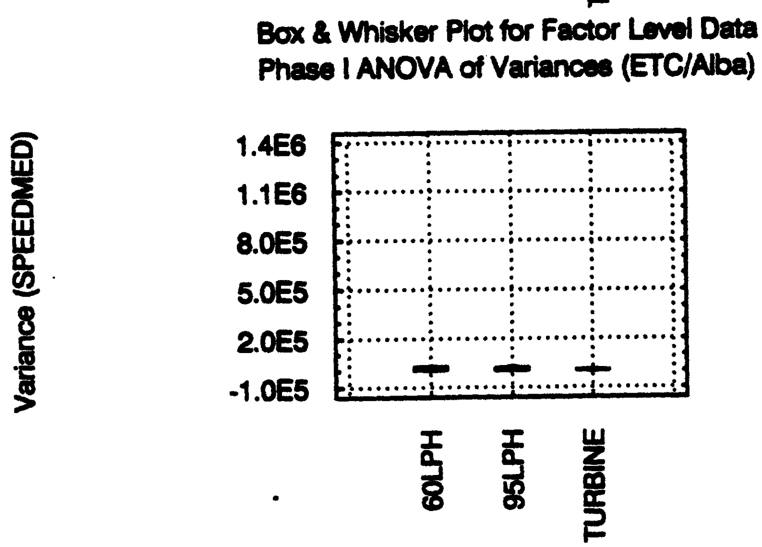
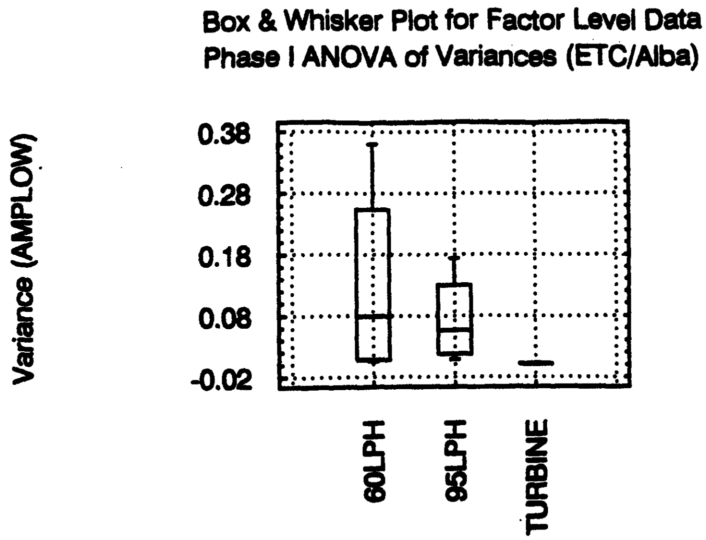
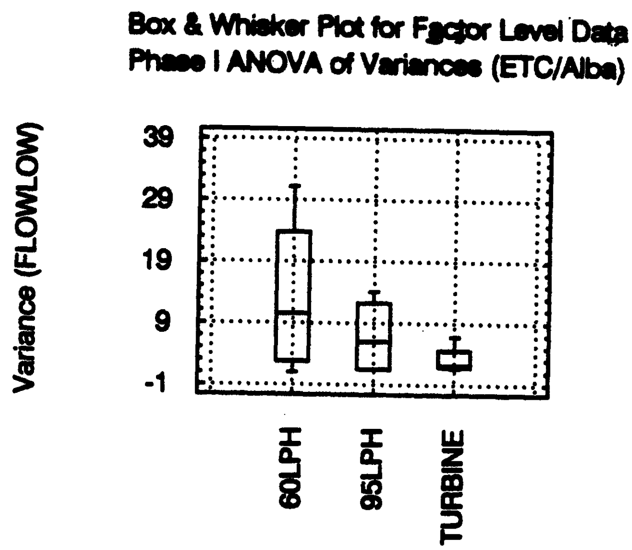
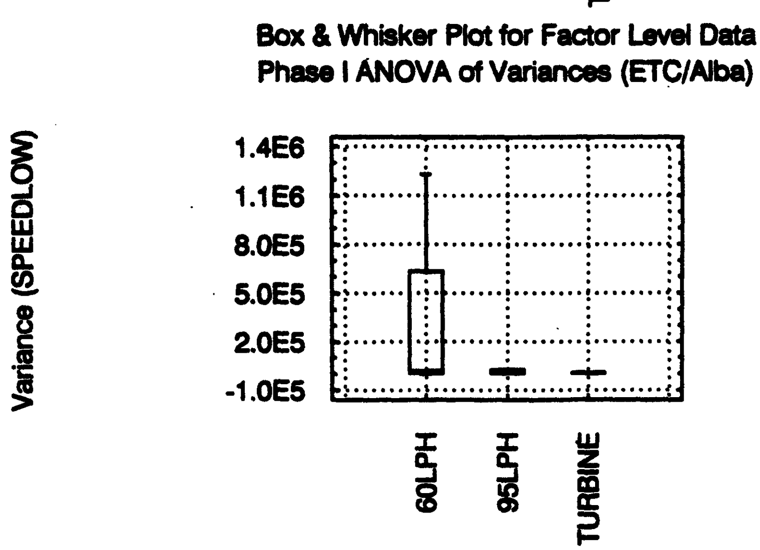


Figure 4.4a: Phase I Results Based on ANOVA of Variances (Continued)







ANOVA of Gage R&R Raw Data

After reviewing the above results for the ANOVA of variance, the next step was to determine the gage R&R variation in the fuel pump performance measurements of flow, current, and speed at a particular fixed voltage and pressure (not aggregated across all pumps). Since the ANOVA of variances revealed that test location factor was not a significant contributor to the overall variability in the measurements, this factor was held constant during this analysis. What resulted was an ANOVA performed on the data resulting from testing at each Lab and then compared between the Labs. However, the results were only compared between Labs for the turbine pumps in both test fluids, M99 and 50-D gas, at 8.0V/200 and 250 kPa and 13.2V/310 kPa. Furthermore, a gage R&R ANOVA analysis was conducted for the two types of gerotor pumps that were tested at the ETC Lab and compared across the different test fluids only for the performance measurements taken at 10.0V/270 kPa and 13.2V/310 or 386 kPa. The 7.0V/270 kPa is a test criterion for gerotors at low temperature-low voltage and was not included because a pump just has to "turn-over".

The operator or technician factor, at two levels (two technicians), also reentered the analysis here, since individual gage R&R analyses were being performed on the measurements from each Lab (over various pump models with test fluid types held as constants). However, due to the two shift structure at the ETC Lab, each operator did not test each pump the same number of times in each fluid. In Hungary, however, there was only one shift, and each of the two operators performed the same amount of tests on the same pumps in each test fluid. It was anticipated that the Lab technician would not significantly influence the fuel pump measurements, because the two-station stand is semi-automatic. All the technician has to do is connect the pump, at its terminals, to the stands, and select the settings. Nonetheless, the operator factor would determine the amount of reproducibility error if included in the analysis. As a result, there were three factors that were included in the gage R&R ANOVA analysis within and between test Labs: 1) fuel pump at two levels (or two of the same pump type replicated numerous times; i.e., 60 lph#1 and 60 lph#2), 2) operator at two levels, A and B, and 3) the interaction between the operator and part. As mentioned in the previous chapter, all the other factors were held constant or treated as noise.

Following the steps (5) through (9) outlined in section 4.1.2, a multifactor ANOVA of the performance data was run on Statgraphics generating results by location, fuel, pump, and operating point, as well as confidence interval plots, box and whisker plots, and factor interaction plots. These along with an inspection of the F-statistic and the significance level provided on the ANOVA output table, determined which factors were the most significant. The confidence level that was used to determine whether the F-statistics were significant was 75% with a significance level of $\alpha = 0.25$ to decrease the risk of falsely concluding that there is no interaction effect.[7]

On average, the operator factor and the interaction effect came out negligible, with most of the error attributed to the gage and the part. Therefore, taking the results from the ANOVA output table and computing the estimates of the variance components attributed to each of the factors as well as the values that are shown in Figures 4.1.2f-g, the following analysis sheet is shown in Figure 4.4b on the following page. This sheet was completed for each pump performance measurement in each test fluid at each Lab. These sheets are, in turn, summarized in APPENDIX D, Tables D1-D10.

The results indicate the total gage R&R error in the measurements is largely contributed to by the repeatability or gage error (EV or equipment variation). These $6\sigma_{repeatability}$ estimates could be inflated because there was no practical way to separate the effects of the within-part variation from the fluctuations or stability of the performance test equipment. Also, any other unknown sources of variability will show up in these estimates. Unless the gage R&R study or test is designed properly and conducted carefully, the probability other sources of variability are picked up is high. However, the cost of testing in terms of time and dollar amount will increase with how carefully the test is designed to make the estimate of $6\sigma_{repeatability}$ as accurate and representative of the test process as possible.

Another observation, is that the $6\sigma_{part}$ or part variation (PV) was large. This could be indicative of the production variation inherent within each pump such that no one pump performs the same as the

[7] A.I.A.G., 67.

IF INTERACTION IS INSIGNIFICANT

ETC FUEL LAB ESE-M4C50-D GAS
(2) 60 LPH (1000 HR PUMPS)

ESTIMATION OF VARIANCE COMPONENTS FOR CURRENT @ 10.0V/270 KPA

GAGE VARIANCE = MSe	0.1166642				
OPERATOR = (MSo - MSe)/n*r	-0.003262	(r) = SAMPLE SIZE	15	MSo =	0.0188164
PART = (MSp - MSe)/k*r	0.0049474	(n) = PUMP FACTOR LEVELS	2	MSp =	0.265086
		(k) = OPERATOR FACTOR LEVEL	2	MSe =	1.17E-01

BASED ON INTERACTION PLOT: THE F-TEST FOR THE INTERACTION EFFECT BTWN PART/OPERATOR IS STATISTICALLY INSIGNIFICANT
THEREFORE, SINCE THE BASIC MEASURE OF SPREAD IS: 3σ **(PLOT OF INTERACTION INDICATES NO INTERACTION)**

EQUIPMENT VARIATION OR REPEATABILITY MEASURE = 3*SQRT(MSe)
1.0246842

OPERATOR VARIANCE OR REPRODUCIBILITY MEASURE = 3*SQRT((MSo-MSe)/n*r)
0

REPEATABILITY & REPRODUCIBILITY = SQRT(EV^2 + OV^2)
1.0246842

PART VARIATION = 3*SQRT((MSp - MSe)/k*r)
0.2110131

CONCLUSIONS

TV = total variation = SQRT(R&R^2+PV^2)
2.0923712

Estimate of Variance		σ	6σ	% Study Variation	% Contribution
Repeatability 0.1166642	(gage)	0.3415614 EV	2.0493685	97.94	95.93
Reproducibility -0.003262	(oper.)	0 OV	0	0.00	0.00
R&R 0.1134026	(sum of rep+repro.)	0.336753 R&R	2.0493685	97.94	95.93
Part 0.0049474	σ2	0.0703377 PV	0.4220263	20.17	4.07

Adapted from AIAG Manual, pgs 66 -71.

Figure 4.4b: ANOVA Sheet

next pump when it is tested. It was attempted to safeguard against this when designing this study by testing well broken-in and "stable" pumps.

4.5 DATA REDUCTION AND ANALYSIS: Pre-Phase II

The analysis that was performed on the data resulting from this test phase was identical to the gage R&R ANOVA analysis that was described above for Phase I. Therefore, a lot of the statistical details will be excluded here. However, there were a few different dimensions to this test phase that warranted some deviation. One difference was that the testing was conducted with only the M99-solvent. Secondly, the gage R&R variation was also determined for the fuel pump production test equipment in the component production facilities. Lastly, the only pumps that were tested included the 60 lph gerotor pumps and the turbine pumps with the same pumps undergoing the gage R&R study in both Labs and the production facilities. As mentioned during the last chapter, the objective of this test phase was to compare the gage R&R results from the production test equipment with the gage R&R results from the test Labs: 1) the gage capability of the Alba Plant versus the Alba Lab and 2) the gage capability of the Rawsonville Plant versus the ETC Lab. The % of tolerances, however, were also calculated from the results from the gage R&R study that took place at the plants, since tolerances or production specification limits existed for the each of the performance tests.

It was not intended for this ANOVA analysis to determine which performance test equipment was better or that the Lab equipment was more capable than the plant equipment. Both test environments have very different needs or requirements. The $6\sigma_{R\&R}$ estimates that were computed were relative measures used to capture the capability of the test stand at a given point in time with pump and Lab technicians/operators representing the population from which they came. As a result, most of the factors were left as noise or allowed to occur as they normally occur (shifts, multiple technicians, test fluid change and filtration) with the exception of the pump and operator factors as discussed above.

ETC and Rawsonville Plant Gage R&R ANOVA

The results from the Lab, two-station test stand gage R&R were run through an ANOVA similar to Phase I. The ANOVA output and components of variance are summarized in APPENDIX E,

Table E1. The interaction between part and operator was negligible. For pump flow and current draw at the 13.2V/310 kPa operating point, the 6σ estimates for reproducibility and part variation were the two largest components of variation. Ideally, for the current draw, the $6\sigma_{R\&R}$ estimate should be less than 0.10 amps. For the speed measurements, large $6\sigma_{R\&R}$ error resulted for the pumps at 13.2V/310 kPa.

Both the AVERAGE and RANGE and ANOVA gage R&R methods of analyses were performed on the data resulting from the gage R&R study on the production test equipment. The operator factor became the test and load side of the dial table for each test fixture (three fixtures per test stand and a total of four test stands). Aside from the analyses of the outlet flow and current draw at 13.2V/310 kPa, analyses were performed on the other measurements taken from each fixture of each test stand. These measurements included dead head pressure, outlet leak, and low voltage (1.5V) current draw. This resulted in 15 ANOVAs and other calculations as prescribed in section 4.1 for each test stand.

For the AVERAGE and RANGE method of analysis, the PV and TV estimates were computed separately. Furthermore, the % of tolerances for each measurement on each fixture was determined. The tolerances used were the USL-LSL for each measurement where the USL and LSL were set by the production test process or engineering designs as necessary. However, there was only one single sided specification, the LSL, for outlet flow. To determine the denominator to use in order to compute the flow $6\sigma_{R\&R}$ P/T, the flow readings were averaged across the test and load side of each fixture and then averaged across all of the fixtures:

$$\overline{\overline{Q}} = \sum_{i=\text{fixture } 1}^{12} \frac{\overline{Q_i}}{12} = 25.31 \text{ lph}$$

$\overline{\overline{Q}}$ = Average outlet flow over all test fixtures.

$\overline{Q_i}$ = Outlet flow averaged over test and load side of each fixture i.

Tolerance $= 2 \cdot \text{LSL} - \overline{\overline{Q}}$

LSL = Outlet flow production specification limit or $\overline{\overline{X}} - 3\sigma$ = 77 lph for 60 lph pumps in M99.

The results from the ANOVA analysis are summarized in APPENDIX E, Table E2. The results from the AVERAGE and RANGE analysis are also summarized in APPENDIX E, Table E3, along with the tolerances for each measurement and P/T calculations.

After reviewing the % or tolerance results, the "best" test stand was test stand #1/fixture A, and the "worst" was test stand #2. Another observation was that the $6\sigma_{R\&R}$ estimates for all the measurement types were not equivalent between fixtures or between test stands. Some explanations for this could include calibration or maintenance of the particular test stand or fixture. Furthermore, the largest $6\sigma_{R\&R}$ was for deadhead pressure, and this was fairly consistent across all the test fixtures. This could suggest two things: 1) that test needs to be investigated or modified or 2) the pumps do not respond the same, over time, to the dead head pressure test. In addition, the P/Ts for outlet flow were not unacceptably large. It was also observed that the outlet flow measurements were dependent on the outlet pressures which should center around 310 kPa. Lastly, the outlet leak measurements and the $6\sigma_{R\&R}$ error depended upon whether or not there were some leaky seals in the test system or other sources of leaks which were difficult to find. This could be controlled by continued and routine maintenance on the test fixtures/stands.

When comparing the gage R&R results from the production test equipment to the gage R&R results from the two-station performance stand at the ETC Lab: the $6\sigma_{R\&R}$ results for outlet flow and current draw were smaller at the Plant than in the Lab, and a large differential in average flow and current was determined. The outlet flow was X lph higher at the Plant under similar test conditions of test solvent and pumps. This relationship was just the reverse for the current draw measurements which were 0.3 of an amp larger in the Lab than in the Plant under the same conditions of pump and fuel.

ETC Lab, Alba Lab, and Alba Plant Gage R&R ANOVA

The results that were analyzed here were based on testing three turbine pumps at each of the three locations during three similar gage R&R studies. The same three pumps were sent to each location and tested, and the gage R&R results for the respective performance test equipment were compared across all locations. For the gage R&R tests that were conducted on the pumps at both Labs, identical ANOVA analyses were performed. However, one pump and all its measurements had to be eliminated from inclusion in further analysis.* The ANOVA results for the Lab data are summarized in APPENDIX F, Tables F1-F2.

Upon inspection of these results, the $6\sigma_{R\&R}$ variation for the flow was similar at both the 8.0V and 13.2V operating points at both Labs. The $6\sigma_{R\&R}$ for current draw, however, was two to three times larger at the Alba Lab. The calibration of the current measuring device was suspected. Lastly, the $6\sigma_{R\&R}$ for the pump speed was the largest at the 13.2V operating point than at the 8.0V operating point, especially at the ETC Lab. If these phenomena occurred consistently across Labs and across operating points, then it could be argued that the measuring device was at fault. With these results, it was difficult to determine if the pumps were at fault, or the specific test equipment was at fault.

As with the analyses performed on the data resulting from the gage R&R tests in the Labs, the ANOVA was also performed on the results from the gage R&R tests conducted at the Alba Plant. Although the production test stands at Alba can perform many of the same measurements as the Rawsonville test stands, the only measurements that were analyzed included the outlet flow at 13.2V and 8.0V and current draw at 13.2V for each test fixture. The P/Ts were also estimated from the ANOVA results since the production specification limits at the Alba Plant were known. Test stand #1/left-hand fixture was identified as the "best" or most capable and could be used for the verification of the test fluid correlation. The ANOVA and components of variance summary are shown in APPENDIX F, Table F3.

For an indication of the behavior of each of the test fixtures when measuring outlet flow at 13.2V and 8.0V and current at 13.2V, see Figures 4.5a-c. In addition, the average $6\sigma_{R\&R}$ across each test stand was similar for the 8.0V outlet flow and ranged from 7 to 10 lph. The average test stand $6\sigma_{R\&R}$ estimates were not consistent for the current measurements at 13.2V; perhaps a calibration issue because not all the fixtures were "bad". Lastly, another observation made when comparing all the flow measurements (8.0V/13.2V) across all the fixtures was the $6\sigma_{R\&R}$ values were larger for the right-hand fixtures than the left-hand fixtures of each test stand. This is anticipated to be a function of the way the gage R&R study was designed where one operator at a time per test stand would randomly test the three pumps between the left-hand and right-hand fixtures. The fixtures were not randomized nor was the

* To be discussed further in section 4.8.

order of the test stands on which the operator tested the pumps. First operator A would run the tests, and then operator B would run the tests on the same test stand, from test stand one through five. This phenomenon could also be caused by the way the operator puts the pump in the test pocket of the test fixture or the way the fixtures seal the pump outlet.

When comparing the gage R&R results from both of the Labs to the results from the Alba Plant, the $6\sigma_{R\&R}$ averages for outlet flow at 8.0V and 13.2V were smaller at the Plant. However, the current draw $6\sigma_{R\&R}$ at 13.2V was smaller at the ETC Lab. At the Alba Lab and Plant, the average $6\sigma_{R\&R}$ for current was two to three times larger. This could be a calibration issue. Also, looking at the average flow and current values for each of the test fixtures at the Plant, the current values at 13.2V were similar to the Alba Lab but deviated significantly from the ETC Lab. For the 13.2V flow values, the Alba Plant fixtures were lower by 5 to 10 lph compared to both Labs. It was anticipated again that the way the pumps are positioned in the test pocket and the way the fixture head seals the outlet of the pump could be the causes. Lastly, the average outlet flow at 8.0V on the production test stand fixtures compared closely to both Labs.

Figure 4.5a: Alba Plant Test Stand
Gage R&R Summary--(2) Master Turbines

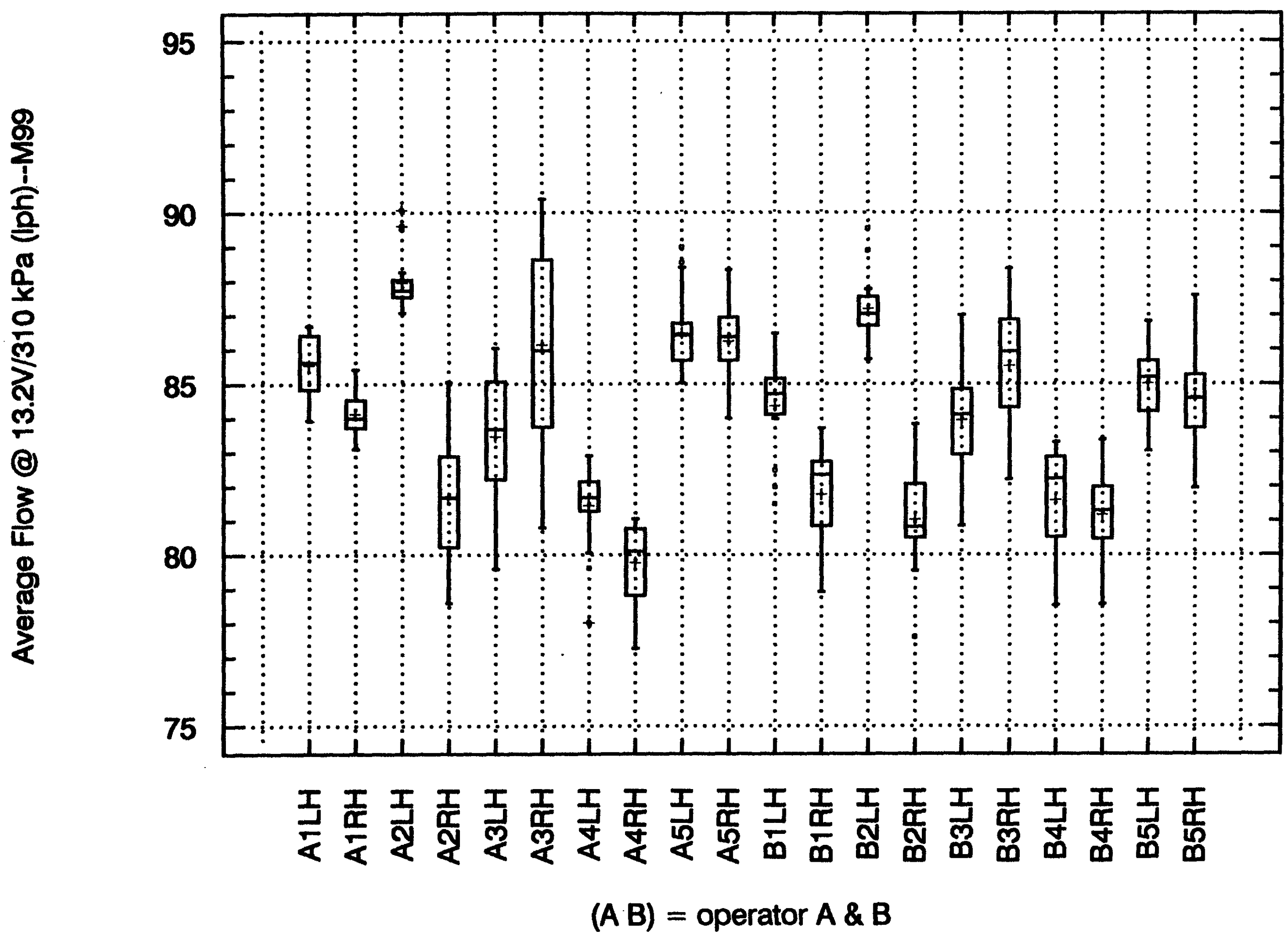


Figure 4.5b: Alba Plant Test Stand
Gage R&R Summary--(2) Master Turbines

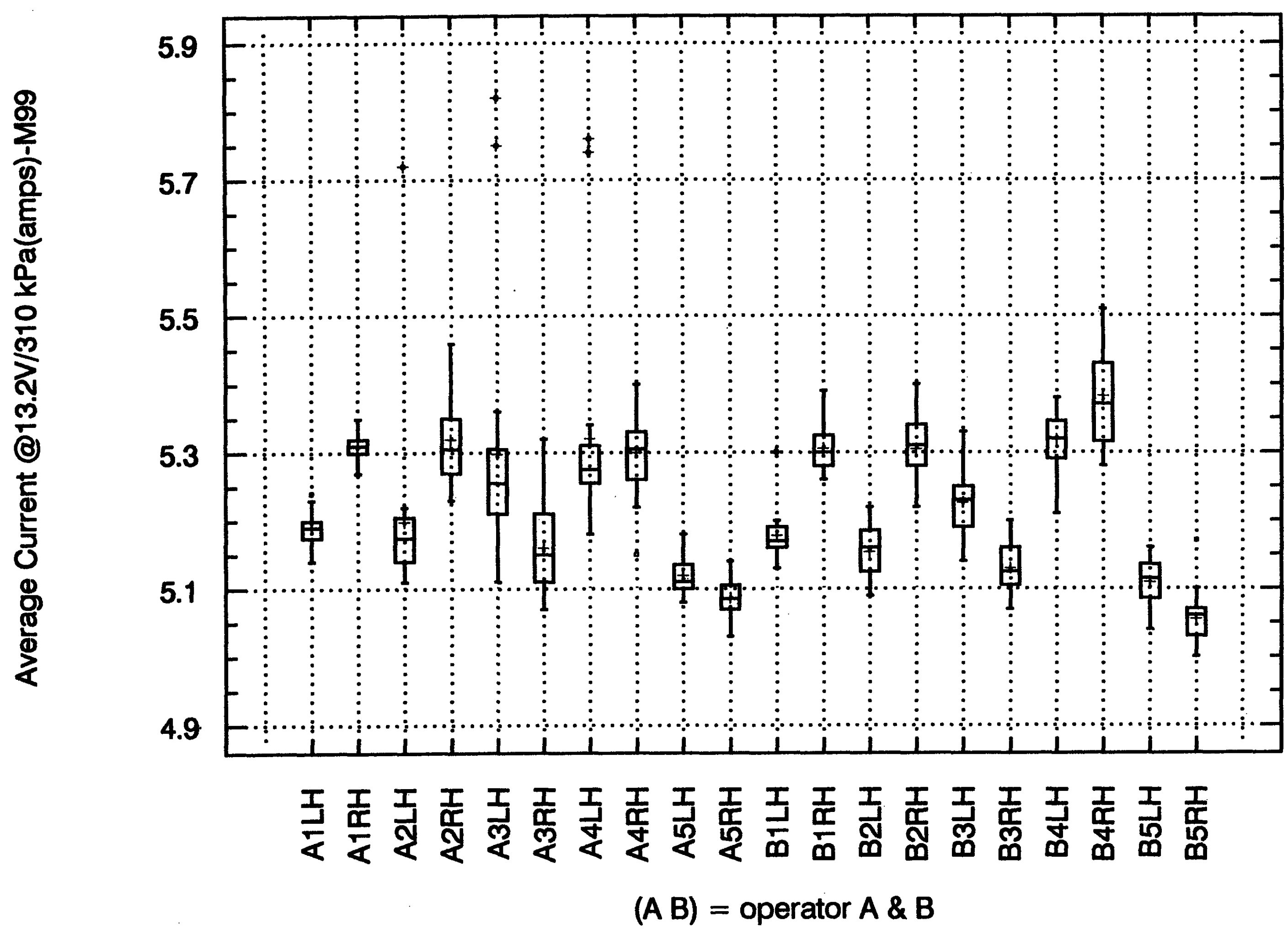
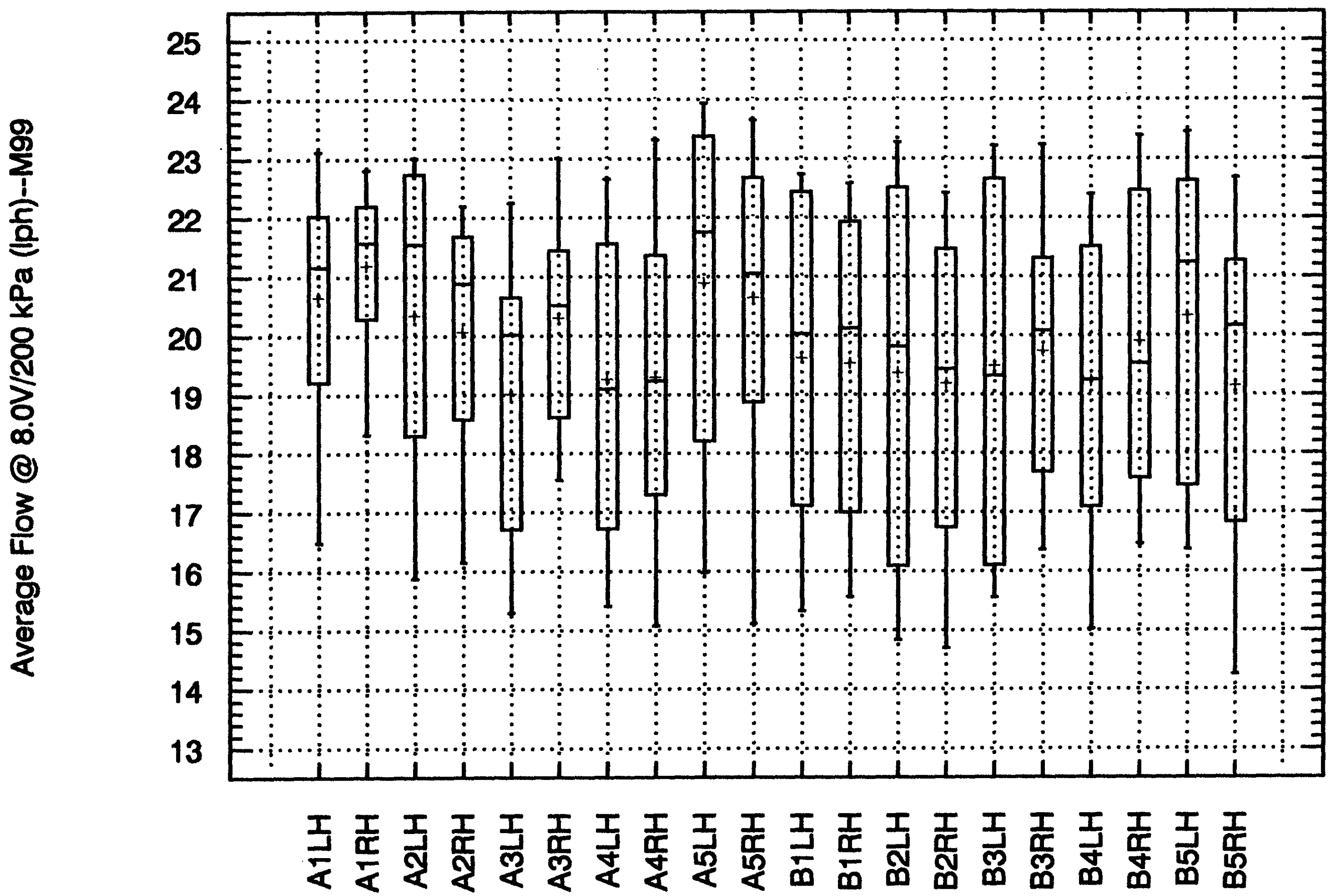


Figure 4.5c: Alba Plant Test Stand
Gage R&R Summary--(2) Master Turbines



(A B) = operator A & B

4.6 DATA REDUCTION AND ANALYSIS: PHASE II

As discussed in Chapter 3, many considerations were taken into account when this test phase was designed in order to "truly" capture the effects of the different test fluids on pump performance and determine the test fluid correlation--a correlation independent of test location, the type of pump, and many other factors that were controlled. The resulting performance data, at various operating points, was carefully manipulated to determine the most "robust" regression model. This regression analysis was performed for both gerotor and turbine pumps in numerous test fluids. These models did not correlate green pump performance in M99-solvent (in the Plants) to performance in gasoline after 30 minutes of test (in the Labs).

Since regression analysis was the primary form of analysis of the performance results, single point data (performance measurements at one voltage and pressure) in M99 was regressed on single point data in gasoline. Then multiple point data (performance measurements at a fixed voltage but numerous pressures) in M99 was regressed on multiple point data in gasoline. For the gerotors, these regression models in the test fluids were based on data that resulted from testing four types of gerotor models at the same voltage and fixed or multiple pressures (rationale, last chapter). However, the turbine pump fluid correlation tests were actually rerun so that, instead, the performance curves at a fixed voltage and numerous pressures could be correlated in the various test fluids.

These above regressions were only one level of regression analyses that were performed on the data. To prove that the resulting, estimated production specification limits would hold at the Plant, an inverse regression was performed on the gerotor data. An inverse regression was also performed on the turbine pump performance data to determine new production limits for flow and current draw.

4.6.1 GEROTOR FUEL PUMP TEST FLUID CORRELATION

Standard linear regression techniques were applied here, and as indicated above, the gerotor pump performance (across four models) in M99-solvent was regressed on its performance in the 50-D gasoline. By looking at Table 4.6.1a, many iterations were completed on individual gerotor models at a given operating point, then aggregated (3) gerotor models at the 13.2V/310 kPa operating point, and lastly all the models aggregated together at a fixed voltage and multiple pressures. The reason for going through all these regression iterations was to show that an inadequate correlation could not be obtained by just correlating one gerotor model at a single operating point.

Performance Measurements	Pump(s) 10/model	#*	R^2 (%)	Correl. Coeff**	Model: $Y_{M99}=\beta_o+\beta_1 X_{GAS}$ (lph or amps or RPM)
Q @ 13.2V/110 kPa	45 lph	30	27.21	0.522	Y_{M99} = 56.03 + 0.260X_{GAS}
Q @ 13.2V/310 kPa	60 lph	30	17.33	0.416	Y_{M99} = 56.75 + 0.472X_{GAS}
Q @ 13.2V/310 kPa	95 lph	30	31.87	0.564	Y_{M99} = 67.07 + 0.537X_{GAS}
Q @ 13.2V/310 kPa	125 lph	27	48.97	0.670	Y_{M99} = 36.03 + 0.772X_{GAS}
i @ 13.2V/110 kPa	45 lph	30	2.53	0.159	Y_{M99} = 1.00 + 0.1652X_{GAS}
i @ 13.2V/310 kPa	60 lph	30	56.54	0.752	Y_{M99} = 1.94 + 0.407X_{GAS}
i @ 13.2V/310 kPa	95 lph	30	1.93	0.139	Y_{M99} = 4.80 + 0.099X_{GAS}
i @ 13.2V/310 kPa	125 lph	27	1.8	0.134	Y_{M99} = 5.99 + 0.135X_{GAS}
N @ 13.2V/110 kPa	45 lph	30	0.45	0.067	Y_{M99} = 3394.96 + 0.066X_{GAS}
N @ 13.2V/310 kPa	60 lph	30	45.93	0.678	Y_{M99} = 946.40 + 0.787X_{GAS}
N @ 13.2V/310 kPa	95 lph	30	22.47	0.474	Y_{M99} = 4052.05 + 0.399X_{GAS}
N @ 13.2V/310 kPa	125 lph	27	34.37	0.586	Y_{M99} = 1513.47 + 0.746X_{GAS}
Q @ 13.2V/310 kPa	60, 95, 125 lph	87	99.07	0.995	Y_{M99} = 10.08 + 0.910X_{GAS}
i @ 13.2V/310 kPa	60, 95, 125 lph	87	91.71	0.958	Y_{M99} = -0.318 + 0.995X_{GAS}
N @ 13.2V/310 kPa	60, 95, 125 lph	87	98.17	0.991	Y_{M99} = 522.39 + 0.873X_{GAS}
Q @ 13.2V/270,310 kPa	60, 95, 125 lph	174	99.11	0.995	Y_{M99} = 9.33 + 0.913X_{GAS}
i @ 13.2V/270,310 kPa	60, 95, 125 lph	174	92.56	0.962	Y_{M99} = -0.281 + 0.993X_{GAS}
N @ 13.2V/270,310 kPa	60, 95, 125 lph	174	98.13	0.991	Y_{M99} = 524.14 + 0.871X_{GAS}
Q @13.2V/100,110,270,310 kPa	**45,60,95,125 lph**	**234**	**99.50**	**0.997**	**Y_{M99} = 7.56 + 0.924X_{GAS}**
i @13.2V/100,110,270,310 kPa	**45,60,95,125 lph**	**234**	**97.42**	**0.987**	**Y_{M99} = -0.114 + 0.964X_{GAS}**
N @13.2V/100,110,270,310 kPa	**45,60,95,125 lph**	**234**	**98.12**	**0.990**	**Y_{M99} = 133.86 + 0.922X_{GAS}**

Table 4.6.1a: Summary of Simple Linear Regressions

Q = flow rate, i = current draw, N = speed--* 3 measurements/pump-- correl. coeff =** $\sqrt{\frac{R^2}{100}}$

The averages for each of the gerotor models in each of the test fluids are included in APPENDIX G, Tables G1-G2. Also shown in APPENDIX G are Figures G1-G3, which are the bolded models in Table 4.6.1a. The impact on the gerotor production specification limits for flow and current draw and how these limits can be modified will be described later.

Gerotor Fuel Pump Fluid Correlation and Inverse Regression Analysis

As a verification of the three bolded regression models in Table 4.6.1a, it was determined whether they could be used to approximate the new production specification limits for flow and current draw at 13.2V. If these new limits could be derived from the models, would they hold over time and not pass pumps that should not pass and reject pumps that should have passed, and could they be applied for all the gerotor models? This verification was conducted by performing an inverse regression analysis on the performance data used to generate the above three models. However, rather than aggregating the gerotor fuel pump models together, this analysis was performed on the performance measurements for each pump model. First, a definition of inverse regression.

Inverse Regression or Inverse Predictions: When a regression model of Y on X is used to make a prediction of the value of X which gives rise to a new observation Y, this is known as inverse prediction.[8] Since the Engineering Specifications in gasoline are known, and the regression models were to be used to predict the flow and current values in M99 given these limits in gasoline, the following steps were performed:

1) The same linear regression as described above was conducted on each gerotor pump model for its flow and current measurements at 13.2V/270 and 310 kPa. However, a total of 9 replicates for each pump model were left out of the regression model for a control check. The results of the regression are as follows:

Performance Measurements	Pump Model	# of Data	R^2 (%)	Correl. Coeff.	$Y_{M99}=\beta_o+\beta_1 X_{GAS}$ (lph or amps) MODEL
Q @ 13.2V/100 and 110 kPa	45 lph	51	30.26	0.550	Y_{M99} = 53.57 + 0.304X_{GAS}
i @ 13.2V/100 and 110 kPa	45 lph	51	4.80	0.219	Y_{M99} = 0.906 + 0.227X_{GAS}
Q @ 13.2V/270 and 310 kPa	60 lph	51	29.33	0.542	Y_{M99} = 47.52 + 0.561X_{GAS}
i @ 13.2V/270 and 310 kPa	60 lph	51	66.43	0.815	Y_{M99} = 1.524 + 0.504X_{GAS}
Q @ 13.2V/270 and 310 kPa	95 lph	51	39.18	0.626	Y_{M99} = 64.52 + 0.556X_{GAS}
i @ 13.2V/270 and 310 kPa	95 lph	51	7.43	0.272	Y_{M99} = 4.009 + 0.218X_{GAS}
Q @ 13.2V/270 and 310 kPa	125 lph	45	52.05	0.721	Y_{M99} = 24.39 + 0.835X_{GAS}
i @ 13.2V/270 and 310 kPa	125 lph	45	9.73	0.312	Y_{M99} = 4.507 + 0.325X_{GAS}

Table 4.6.1b: Summary of Simple Linear Regressions for Inverse Prediction

2) Based upon the Y_{new} values (pump flow and current in M99) that were generated at the ETC Lab for each pump model, the X_{est} (pump flow and current in 50-D gasoline) that gave rise to these estimates can be determined by the following:[9]

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[8] Neter, Wasserman, and Kutner, Applied Linear Regression Models, 2nd Edition, (1989), 173.
[9] Neter, Wasserman, and Kutner, 174.

$$\hat{X}_{est.} = \frac{Y_{new} - \beta_0}{\beta_1} \qquad \beta_1 \neq 0$$

3) The next steps were to calculate the following with the Lab data and data generated from the regression ANOVA:[10]

$$\hat{X}_{est.} \pm t(1 - \frac{\alpha}{2}; n - 2)s(\hat{X}_{est.}) \qquad 1 - \alpha \text{ Confidence Limits for } \hat{X}_{est}$$

$$s^2(\hat{X}_{est.}) = \frac{MSE}{\beta_1^2}[1 + \frac{1}{n} + \frac{(\hat{X}_{est.} - \bar{X})^2}{\sum(X_i - \bar{X})}]$$

t-statistic = 1.164 for all Pumps except 125 lph
t-statistic = 1.166 for 125 lph Pumps
t-statistic = 1.152 for Tubine Pumps
α = 0.25
n = Number of Replicates used in the Model (#)
MSE = Mean Square Error from Regression ANOVA
β_1 = Slope of Regression Model
$\hat{X}_{est.}$ = Determined from Above
X_i = Flow or Current Measurement from Lab in Gasoline
$\bar{X}$ = Average of Flow / Current Measurements from Lab in Gasoline

4) The regression models were then applied to the fuel pump data that was set aside in step (1). These models, in application with the corresponding left out M99 values, were used to predict the X_{est}. Step (3) was then repeated.

Observations: For each pump regression model for outlet flow, the R^2 values were small and gave evidence there was more error in the pump flow measurements than can be attributed to just test fluid type. However, the X_{est}s, as well as the confidence limits, indicated that each pump would continue to pass the gasoline Engineering Specifications in the Lab if the production limits were modified. This appears to support the flow results shown in Table 4.6.1a.

The results for the current draw models for each pump type generated X_{est}s that were within the Engineering Specification in gasoline, but the regression models were inadequate because of very small R^2 values. If the production limits are changed, the model did not show whether or not the pump would continue to pass the Lab tests, especially when looking at the confidence intervals surrounding each X_{est}.

[10] Neter, Wasserman, and Kutner, 175.

This is in direct contrast to the regression model and results that were generated when all the pumps were aggregated together at multiple pressures and fixed voltage (13.2V) as shown in Table 4.6.1a.

Implications for Production Specification Limits at the Rawsonville Plant

Although these test fluid correlations for the gerotor pumps and subsequent regression analyses were performed on data from broken in and acceptably "stable" (500 hours of break-in) pumps, not "green" pumps, new production specification limits can be derived. For outlet flow at 13.2V, the production specification limits can take on the values of the Engineering Specifications in gasoline (refer to Chapter 2). This was determined initially by the aggregate pump correlation and regression and further verified the inverse regression analysis above.

For the current draw at 13.2V, the production limits can take on those proposed in Chapter 2, but the results from the standard and inverse regression analyses were conflicting. More suitable current draw production limits could be determined based on process capability testing or SPC data. Verification testing is required if both the current draw and flow production limits are changed. This testing will be discussed in section 4.7.

4.6.2 TURBINE PUMP FLUID CORRELATION (ETC, ALBA LAB, AND REDO AT ETC LAB)

Similar to the gerotor pumps, simple, linear regression analyses were performed on the performance data resulting from testing at both Lab sites (ETC and Alba) and in each test fluid. However, at the Alba Lab, the pumps were tested in an additional test fluid, Eurosuper95 gasoline. In Tables H1-H3 in APPENDIX H, the means and standard deviations for the all the results (fluids and Labs) are summarized. The regression analyses below in Table 4.6.2a and in Figures H1-H4 in APPENDIX H.

Test Site	Performance Measurements	# of Data	R^2 (%)	Correl Coeff.	$Y_{M99}=\beta_o+\beta_1 X_{GAS}$ or Euro. (lph or amps or RPM) MODEL
ETC LAB	FLOW				
	8.0V/(22,200,250 kPa)	324	96.94	0.984	$Y_{M99} = 4.172 + 0.860X_{GAS}$
	8.0V/(200,250 kPa)	276	76	0.872	$Y_{M99} = 3.24 + 0.909X_{GAS}$
	8.5V/250 kPa	44	34.47	0.587	$Y_{M99} = 9.22 + 0.541X_{GAS}$
	9.0V/250 kPa	44	36.93	0.608	$Y_{M99} = 12.51 + 0.522X_{GAS}$
	13.2V/(200,250,310 kPa)	405	88.52	0.941	$Y_{M99} = 8.88 + 0.843X_{GAS}$
	8.0V/200 kPa	138	26.59	0.516	$Y_{M99} = 8.88 + 0.716X_{GAS}$
	8.0V/250 kPa	138	23.90	0.489	$Y_{M99} = 5.98 + 0.656X_{GAS}$
	13.2V/310 kPa	135	50.79	0.713	$Y_{M99} = 16.28 + 0.765X_{GAS}$
ETC LAB	CURRENT				
	8.0V/(22,200,250 kPa)	324	92.75	0.963	$Y_{M99} = 0.292 + 0.952X_{GAS}$
	8.0V/(200,250 kPa)	276	59.25	0.770	$Y_{M99} = 0.704 + 0.832X_{GAS}$
	8.5V/250 kPa	44	28	0.530	$Y_{M99} = 0.993 + 0.760X_{GAS}$
	9.0V/250 kPa	44	23.10	0.480	$Y_{M99} = 1.170 + 0.718X_{GAS}$
	13.2V/(200,250,310 kPa)	405	71.49	0.845	$Y_{M99} = 0.178 + 1.024X_{GAS}$
	8.0V/200 kPa	138	17.81	0.422	$Y_{M99} = 0.888 + 0.772X_{GAS}$
	8.0V/250 kPa	138	20.81	0.456	$Y_{M99} = 1.173 + 0.703X_{GAS}$
	13.2V/310 kPa	135	31	0.557	$Y_{M99} = 0.022 + 1.053X_{GAS}$
ALBA LAB	FLOW				
	8.0V/(16,200,250 kPa)	108	96.73	0.983	$Y_{M99} = 1.541 + 0.878X_{50D}$
	8.0V/(200,250 kPa)	92	70.14	0.837	$Y_{M99} = 1.76 + 0.865X_{50D}$
	8.5V/(200,250,310 kPa)	138	87.80	0.937	$Y_{M99} = 0.88 + 0.876X_{50D}$
	9.0V/(200,250,310 kPa)	138	88.65	0.941	$Y_{M99} = 1.93 + 0.860X_{50D}$
	13.2V/(200,250,310 kPa)	138	80.90	0.899	$Y_{M99} = 10.27 + 0.830X_{50D}$
	8.0V/200 kPa	46	10.40	0.322	$Y_{M99} = 13.47 + 0.455X_{50D}$
	8.5V/250 kPa	46	11.08	0.332	$Y_{M99} = 11.17 + 0.423X_{50D}$
	9.0V/250 kPa	46	12.90	0.359	$Y_{M99} = 16.46 + 0.414X_{50D}$
	13.2V/310 kPa	46	11.93	0.345	$Y_{M99} = 37.63 + 0.531X_{50D}$
ALBA LAB	FLOW				
	8.0V/(16,200,250 kPa)	108	96.89	0.984	$Y_{M99} = -0.15 + 0.873X_{EURO}$
	8.0V/(200,250 kPa)	92	71.94	0.848	$Y_{M99} = -0.15 + 0.873X_{EURO}$
	8.5V/(200,250,310 kPa)	138	88.91	0.943	$Y_{M99} = -0.605 + 0.893X_{EURO}$
	9.0V/(200,250,310 kPa)	138	89.98	0.948	$Y_{M99} = 0.63 + 0.882X_{EURO}$
	13.2V/(200,250,310 kPa)	138	82.78	0.910	$Y_{M99} = 8.12 + 0.851X_{EURO}$
	8.0V/200 kPa	46	19.87	0.446	$Y_{M99} = 8.02 + 0.612X_{EURO}$
	8.0V/250 kPa	46	11.10	0.333	$Y_{M99} = 5.24 + 0.441X_{EURO}$
	8.5V/250 kPa	46	17.76	0.421	$Y_{M99} = 8.09 + 0.532X_{EURO}$
	9.0V/250 kPa	46	20.73	0.455	$Y_{M99} = 12.70 + 0.522X_{EURO}$
	13.2V/310 kPa	46	10.27	0.320	$Y_{M99} = 42.10 + 0.484X_{EURO}$
ALBA LAB	FLOW				
	8.0V/(16,200,250 kPa)	108	99.28	0.996	$Y_{50D} = -1.79 + 0.991X_{EURO}$
	8.0V/(200,250 kPa)	92	91.76	0.958	$Y_{50D} = -1.05 + 0.954X_{EURO}$
	8.5V/(200,250,310 kPa)	138	97.84	0.989	$Y_{50D} = -1.300 + 1.002X_{EURO}$
	9.0V/(200,250,310 kPa)	138	97.62	0.988	$Y_{50D} = -0.88 + 1.005X_{EURO}$
	13.2V/(200,250,310 kPa)	138	96.87	0.984	$Y_{50D} = 0.42 + 0.998X_{EURO}$

Table 4.6.2a: Summary of Linear Regression on Results from both Labs

Test Site	Performance Measurements	# of Data	R^2 (%)	Correl Coeff.	$Y_{M99}=\beta_o+\beta_1X_{GAS}$ or Euro. (lph or amps or RPM) MODEL
ALBA LAB	CURRENT				
	8.0V/(16,200,250 kPa)	108	92.40	0.961	$Y_{M99} = 0.459 + 0.866X_{50D}$
	8.0V/(200,250 kPa)	92	57.13	0.756	$Y_{M99} = 0.803 + 0.760X_{50D}$
	8.5V/(200,250,310 kPa)	138	82.37	0.907	$Y_{M99} = 0.581 + 0.845X_{50D}$
	9.0V/(200,250,310 kPa)	138	80.11	0.895	$Y_{M99} = 0.686 + 0.828X_{50D}$
	13.2V/(200,250,310 kPa)	138	73.17	0.855	$Y_{M99} = 0.012 + 1.063X_{50D}$
	8.0V/200 kPa	46	13.49	0.367	$Y_{M99} = 1.275 + 0.601X_{50D}$
	8.0V/250 kPa	46	16.80	0.410	$Y_{M99} = 1.424 + 0.582X_{50D}$
	9.0V/250 kPa	46	11.82	0.344	$Y_{M99} = 1.838 + 0.506X_{50D}$
	13.2V/310 kPa	46	47.50	0.690	$Y_{M99} = -0.923 + 1.245X_{50D}$
ALBA LAB	CURRENT				
	8.0V/(16,200,250 kPa)	108	92.44	0.961	$Y_{M99} = 0.330 + 0.908X_{EURO}$
	8.0V/(200,250 kPa)	92	59.31	0.770	$Y_{M99} = 0.733 + 0.785X_{EURO}$
	8.5V/(200,250,310 kPa)	138	85.12	0.923	$Y_{M99} = 0.495 + 0.877X_{EURO}$
	9.0V/(200,250,310 kPa)	138	84.40	0.919	$Y_{M99} = 0.599 + 0.861X_{EURO}$
	13.2V/(200,250,310 kPa)	138	79.72	0.893	$Y_{M99} = -0.104 + 1.090X_{EURO}$
	8.0V/200 kPa	46	32.18	0.567	$Y_{M99} = 0.421 + 0.886X_{EURO}$
	8.0V/250 kPa	46	27.20	0.521	$Y_{M99} = 0.959 + 0.721X_{EURO}$
	8.5V/250 kPa	46	32.23	0.568	$Y_{M99} = 0.816 + 0.783X_{EURO}$
	9.0V/250 kPa	46	26.70	0.517	$Y_{M99} = 0.932 + 0.765X_{EURO}$
	13.2V/310 kPa	46	51.35	0.717	$Y_{M99} = 0.241 + 1.019X_{EURO}$
ALBA LAB	CURRENT				
	8.0V/(16,200,250 kPa)	108	98.53	0.993	$Y_{50D} = -0.126 + 1.041X_{EURO}$
	8.0V/(200,250 kPa)	92	89.97	0.948	$Y_{50D} = 0.138 + 0.960X_{EURO}$
	8.5V/(200,250,310 kPa)	138	97.76	0.989	$Y_{50D} = -0.003 + 1.009X_{EURO}$
	9.0V/(200,250,310 kPa)	138	97.64	0.988	$Y_{50D} = 0.033 + 1.000X_{EURO}$
	13.2V/(200,250,310 kPa)	138	95.75	0.978	$Y_{50D} = 0.192 + 0.961X_{EURO}$

Table 4.6.2a (continued): Summary of Linear Regression on Results from both Labs

The pump speed measurements were not modeled here, because they could not be obtained from the Alba Lab due to instrumentation error. The speed measurements that were determined at the ETC Lab possessed a large amount of gage R&R error as described during Phase I.

Even though the objective of this regression analysis was to determine if the production specification limits could be modified for pump flow (at 8.0V/200 kPa and 13.2V/310 kPa) and current draw (13.2V/310 kPa), more performance measurements were taken at the lower voltage settings. Currently, the flow production specification is not set at 8.0V/250 kPa, which is designated by the Engineering Specification in gasoline. As a result, the fuel pump production specification limit was changed to 8.0V/200 kPa which was determined to correlate with the pump performance in gasoline at

8.0V/250 kPa in the Lab (after 30 minutes of break-in). Therefore, part of this test phase was devoted to investigating whether another low voltage setting could be applied, for outlet flow in the Plant, and still hold in the Lab.

As can be seen from Table 4.6.2a, the regression model is a "better" predictor of pump performance in the M99-solvent when more pressures or "portions" of performance curves are correlated. This is because more "spread" or variation is introduced into the measurements. In addition, the correlation between M99 and Eurosuper and M99 and the 50-D gas on the turbine pumps at the Alba Lab, gave relatively "similar" results. Therefore, the Eurosuper could be a "close" substitute for the 50-D gas even though some of its fluid properties such as viscosity is different. This will be elaborated further in the next chapter.

On the basis of the above results, it was anticipated that a more accurate model, as well as a better correlation, could be obtained if performance curves in a particular fluid at a fixed voltage could be correlated. Since only one type of pump model was involved, this would be better than only correlating portions of performance curves with only two or three pressures. However, since there are many gerotor models, it would have been costly to run correlation tests/performance curves on each gerotor model separately.

Turbine Pump Fluid Correlation Redo at the ETC Lab

Therefore, it was decided to rerun the turbine pump fluid correlation to correlate performance curves. This time, the pumps were only run at the ETC Lab in order to avoid shipping complexities, time delay, as well as the fact that there was a backlog of work at the Alba Lab. Only the 50-D gasoline and the M99-solvent were used because as was seen previously, there was little difference in the Eurosuper versus 50-D models for flow and current draw. The test procedure was nearly identical to the tests that were run previously. However, each of the 46 turbine pumps were run at eight pressures at two fixed voltages, 8.0V and 13.2V. The "new" averages and standard deviations for the 46 pumps at each pressure are shown in Tables I1-I2 in APPENDIX I. The performance curves in each of the two test fluids are plotted in Figures I1-I4 in APPENDIX I. These plots show the average at each pressure and the $\mu \pm 3\sigma$ limits. The regression analysis results are depicted below in Table 4.6.2b and Figures I5-I7 in APPENDIX I.

Performance Measurements (for 46 turbine pumps)	**# of Data**	**R^2 (%)**	**Correl Coeff.**	**Model: $Y_{M99}=\beta_o+\beta_1 X_{50D}$ (lph or amps)**
FLOW 13.2V/(25,88,163,238,310,388,463,538 kPa)	368	98.86	0.994	$Y_{M99} = 5.246 + 0.869X_{50D}$
CURRENT 13.2V/(25,88,163,238,310,388,463,538 kPa)	368	98.05	0.990	$Y_{M99} = 0.401 + 0.951X_{50D}$
FLOW 8.0V/(25,50,75,100,125,150,175,200,250 kPa)	403	96.03	0.980	$Y_{M99} = 6.991 + 0.836X_{50D}$

Table 4.6.2b: Summary of Linear Regression Results from ETC Lab Redo

Inverse Regression and Inverse Predictions on the New Results

Similar to the inverse regression analysis performed on each of the gerotor fuel pump models, this analysis was performed on the new turbine results in each of the test fluids. The regression models shown above were used. No data was left out of the model.

Implications for the Production Specification Limits at the Alba Plant

Although the regression model for flow and current at fixed voltage (13.2V) and a pressure range indicated a high correlation of the these performance characteristics, the turbine pumps behave differently in the M99-solvent due to its larger viscosity. The production limits that are estimated from these models (as shown in Chapter 2 and below) for flow and current at 13.2V could be sufficiently applied to the production test stands. Correlating entire performance curves in the test fluids is a conservative test method when considering one pump model.

MEASURED M99 VALUE	CONFIDENCE LIMIT IN GAS	NEW PRODUCTION SPEC. IN M99-SOLVENT
Smallest Lab Flow Value measured in M99 @13.2V/310 kPa based on curve correlations. = 72.95 lph	Lower Confidence Limit @ 99.75% or $X_{new} - 1.152\sigma$ = 72.085 lph in gas	New Spec in M99 @13.2V/310 kPa based on regression model: $Y_{M99} = 5.246 + 0.869(72.085)$ **> 67.87 lph**
Largest Lab Current Value measured in M99 @13.2V/310 kPa based on curve correlations. = 5.82 amps	Upper Confidence Limit @ 99.75% or $X_{new} + 1.152\sigma$ = 5.877 amps in gas	New Spec in M99 @13.2V/310 kPa based on regression model: $Y_{M99} = 0.401 + 0.951(5.877)$ **< 5.989 amps**

Table 4.6.2c: Estimated Turbine Pump Production Specification Limits @ 13.2V/310 kPa

There is much variability in the low voltage performance measurements (at 8.0V/250 kPa), especially at high pressures. This variability created a "good" correlation model between the test fluids for the turbine pumps. There is some level of uncertainty surrounding the pumps' ability to pass that stringent, low voltage performance test (flow at 8.0V/250 kPa versus 8.0V/200 kPa) on the production line. There are some causes of this uncertainty, barring test fluid effects: 1) turbine pumps can only meet minimum flow requirements (10 lph in gasoline after 30 minutes) at such a large pressure and low voltage due to their inherent design, 2) the flow meters used both in the Labs and the plant are too insensitive to read very low flow values, and 3) the Engineering Specification for the Lab test is too conservative.

In terms of the production specification for flow at the 8.0V/200 kPa setting, unless the Engineering Specification can be modified to 8.0V/200 kPa, there are alternatives for the production specification. These are based on the inverse regression results and a level of conservatism:

MEASURED M99 VALUE	CONFIDENCE LIMIT IN GAS	NEW PRODUCTION SPEC. IN M99-SOLVENT	
Largest Lab Flow Value measured in M99 @8.0V/250 kPa based on curve correlations. = 20.51 lph	Upper Confidence Limit @ 99.75% or $X_{new} + 1.152\sigma$ = 21.37 lph in gas	New Spec in M99 @8.0V/250 kPa based on regression model: $Y_{M99} = 6.991 + 0.836(21.37)$ **> 24.86 lph**	Conservative
Smallest Lab Flow Value measured in M99 @8.0V/200 kPa based on curve correlations. = 19.14 lph	Lower Confidence Limit @ 99.75% or $X_{new} - 1.152\sigma$ = 9.321 lph in gas	New Spec in M99 @8.0V/200 kPa based on regression model: $Y_{M99} = 6.991 + 0.836(9.321)$ **> 14.79 lph**	Moderately Conservative
Largest Lab Flow Value measured in M99 @8.0V/200 kPa based on curve correlations. = 36.43 lph	Upper Confidence Limit @ 99.75% or $X_{new} + 1.152\sigma$ = 40.39 lph in gas	New Spec in M99 @8.0V/200 kPa based on regression model: $Y_{M99} = 6.991 + 0.836(40.39)$ **> 40.77 lph**	Highly Conservative

Table 4.6.2d: Estimated Turbine Pump Production Specification Limits @ 8.0V/200 or 250 kPa

Lastly, for all these alternative production specification limits (at 8.0V and 13.2V) to be applied to the production test stands, there are some preliminary tasks that should be completed. These include:

1) reconciliation of why there are differences, primarily in outlet flow at 13.2V in M99, between the Lab and the Plant; these differences are not as significant as those between the ETC Lab and the Rawsonville Plant and could just be related to calibration or operator involvement in the production test process and

2) investigation of the flow meters used both in the plant and the Lab; these could be the source of the difference as well as the inability to get consistent flow readings when testing the pumps at 8.0V/200 or 250 kPa.

The final step is a verification of these new production specification limits at the plant and in the Lab. A verification procedure or Phase III of this thesis project testing will be described below.

4.7 VERIFICATION TESTING/CONTINGENCY PLANNING FOR MODIFIED PRODUCTION, PERFORMANCE SPECIFICATION LIMITS

Since these correlation tests were run on broken-in pumps which are not representative of production, it is essential the new production specification limits are verified on "green" or production level pumps. This procedure would have originally been the Phase III part of this thesis testing. If these verification tests prove to be ineffective or provide inadequate results (pumps not passing in the Lab after they pass in the Plant), this will probably indicate that the "green" variable is too large a variable to ignore in the testing, and new correlation test methods will have to be devised.

4.8 OTHER CONSIDERATIONS AND THE REJECTION OF OUTLIERS

4.8.1 OUTLIERS AND HOW THEY WERE HANDLED

One general rule was followed in eliminating outliers: unless they could be explained, they were not removed from the data set. This is typically a "safe" rule to follow especially if the objective of taking a series of measurements is to assess or determine the amount of variability that exists. It is also not true that outliers are "errors" (although in some cases the data was recorded incorrectly or test specimens were mixed up).[11] However, in following any particular statistical method (such as Grubb's or Dixon's outlier tests) for identifying the existence of outliers and therefore discarding them, if the purpose of detecting outliers is to check the values, it is their extremeness and the plausibility of simple explanations that should weigh in the decision, and not their statistical significance.[12] The variability that could be obtained in practice could be seriously underestimated.

Applying the above rationale, fuel pump performance measurements which were recorded as negative by the two-station performance test stand, were eliminated from the data before it was analyzed. As indicated previously for the turbine pump Pre-Phase II testing, the data for one of the pumps had to be eliminated. This was because the pump was burning off residue from its brushes while it was tested at the ETC Lab. In some instances, data was eliminated, because the results exhibited a very large deviation from one measurement to the next (i.e., 0.1 lph to 10 lph) even though it could not clearly be identified if it was the two-station performance test stand or the pump itself that caused such large deviations. This was done mainly for some of the turbine pump data at 8.0V/250 kPa and 310 kPa. However, it was strongly anticipated that the pump was the cause, and the results would have been severely skewed if those measurements were left in for the subsequent analysis.

Once the above type of outliers were removed from the data sets, the means and standard deviations were not so large and seemed to compare with historical test results. It should be noted that there are statistical methods in which to identify and discard outliers. Once such method, which was

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[11] Royal Society of Chemistry, "Robust Statistics--How Not to Reject Outliers", Analyst, (December 1989), vol. 114.

[12] Royal Society of Chemistry.

proposed by one of the members of Ford's Scientific Research Staff and adapted from the Analytical Methods Committee of the Royal Society of Chemistry in the United Kingdom, is shown in APPENDIX J. This method could be applied to future performance test results/data from the plant or Lab.

4.8.2 THE TREATMENT OF NORMALITY

Since the outliers tended to skew the underlying distribution of the performance data, and it was assumed that the measurements would follow a normal distribution, removing the outliers made some difference in the shape of the distribution. However, for the data that resulted from the gage capability test phases, this normality assumption was checked as the gage R&R analysis is contingent on the test specimens or pumps coming from a normal distribution and the performance measurements being normally distributed. Numerous, normal probability plots were made of the residuals and as well as frequency histograms of the raw data. Some examples are shown in APPENDIX K. For the regression analysis, the normality assumption was checked upon review of plots of the residuals (see APPENDIX K).

After reviewing some of these probability plots and frequency histograms for the Pre-Phase II and Phase I test results, the data was not truly normally distributed as only a small sample of pumps were tested, and these only represent one small fraction of the entire pump population. The data appeared skewed, bimodal, and in some instances, uniform. This could suggest a few alternatives: 1) run the capability studies on a larger sample size (10 pumps as suggested by the standard gage R&R methods, but this would mean less replicates and probably capture much more of the pump-to-pump variability which could cloud the gage R&R results), 2) transform the performance measurements into a logarithmic or some other mathematical scale, or 3) apply a different method of analyses.

To expand on option (3) a little further, analyses that could be applied to the data include nonparametric regression analysis or nonparametric analysis or variance, both of which are less sensitive to the underlying distribution of the data. These methods can be found in more advanced statistics books and were beyond the scope of the time required to complete this thesis project as programming might have been necessary. However, the results and conclusions assessed from the Pre-Phase II and Phase I data analyses pointed to some observations that were useful in changing the production specification limits for the pumps. They also detected a difference between the average performance measurements generated from the two-station test stand at the ETC Lab and those generated from the Rawsonville production stands. Lastly, these results provided a "relative" comparison of the performance test capability at each of the test locations.

Chapter 5: Fluid Property Effects on Fuel Pump Performance

5.1 OVERVIEW

In this chapter, the most significant factors that were either controlled or varied throughout all of the test phases will be described. These included fuel pump type and test fluid type, and they were pivotal in determining the gage capabilities of the Lab two-station performance test stand and the production performance test equipment, test fluid correlations, and ultimately the production specification limits for pump flow and current draw.

The fuel pump designs which are currently mass produced for automotive applications include the gerotor or positive displacement, regenerative turbine, the two-stage regenerative turbine, and the roller vane type pump.[1] Only the gerotor and single-stage regenerative turbine pumps, which are produced by EFHD, will be discussed here. A brief overview of their operating principles within the vehicle and their impact on the vehicle driveability as their wear-in occurs will also be provided.

In addition, a description of the test fluids used during the testing and the test fluid, property results of the these fluids will be presented. Lastly, the effects of test fluid properties, as related to temperature changes, on fuel pump performance will be discussed. This includes the application of some fluid mechanics and turbomachinery principles (Reynolds number, laminar versus turbulent flow, dimensional analysis, pump similarity rules, pump efficiency and so forth).

5.2 PRODUCTION FUEL PUMPS

The fuel pump applications are primarily driven by the customer requirements. These can be from internal Ford customers such as the Car or Truck Divisions, external customers, or from the end-user. These requirements can range anywhere from quiet sounding vehicle, to startability and driveability in sub-zero temperatures, to smooth, uninterrupted acceleration at wide-open-throttle. The

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[1] Yu, Dequan, "Fuel Pumps--A Brief Technical Overview", EFHD Advanced Fuel Delivery Engineering, (1991).

electric fuel pump must be able to deliver the necessary amount of fuel when and where it is needed and under all conditions, both vehicle and customer use. Under these conditions, a flow rate, pressure, and temperature range of use are determined or influenced by the engine and the battery voltage. Engine demand typically requires a fuel flow of 45 lph to 125 lph and pressure range of 270 kPa to 386 kPa.[2] Typically, the pressure and voltage (pump speed) are fixed to give an outlet flow and current draw (see Figure 5.2a):

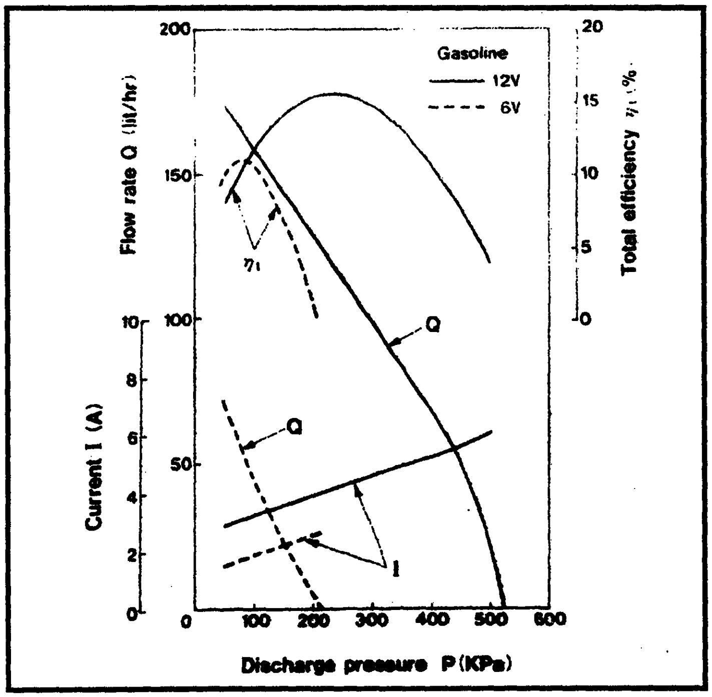

Figure 5.2a: Fuel Pump Operating Point at Fixed Voltage

The pressure is set by the fuel pressure regulator (which is part of the fuel rail). The purpose of this fuel pressure regulator is to maintain a constant fuel pressure drop across the injectors under all engine operating conditions (this is controlled electronically such that an electronic controller regulates the time the valves open and the fuel that enters, at a constant pressure).[3] Because an injector spray tip is exposed to continuous changes in air pressure inside the intake port, this regulator must vary fuel pressure to maintain the same pressure drop across the injector.[4] This fuel pressure regulator consists of

[2] Yu, EFHD, (1991).
[3] General Motors, "AC Spark Plug In-tank Fuel Pump and Fuel Level Sender Application Guide" (1988), 1-4.
[4] General Motors, 1-4.

an air chamber (connected to a source of manifold vacuum), a fuel chamber, a diaphragm and relief valve assembly, and a calibrated regulator spring.[5] The air chamber contains the regulator spring and is separated from the fuel chamber by the diaphragm assembly. The fuel pressure is regulated by the difference between the fuel pump pressure acting on one side of the diaphragm and the variable force of the calibrated spring and opposing manifold vacuum acting on the other side. Fuel pressure varies inversely with manifold vacuum; it is greatest at low vacuum or wide-open-throttle, and is lowest at high vacuum (engine idle). See Figure 5.2b for a diagram of a "basic" fuel supply system and a port fuel injection system.

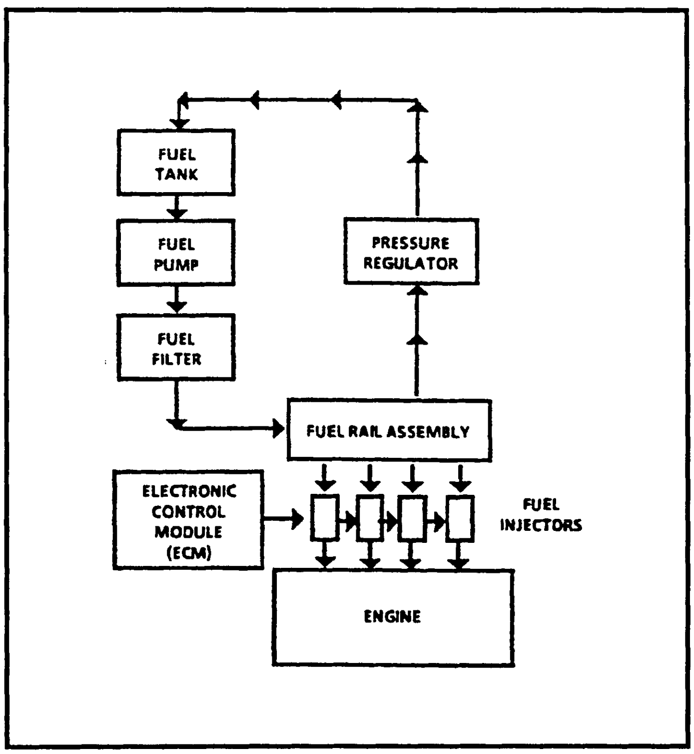

Figure 5.2b: Basic Fuel Delivery System

[5] General Motors, 1-4.

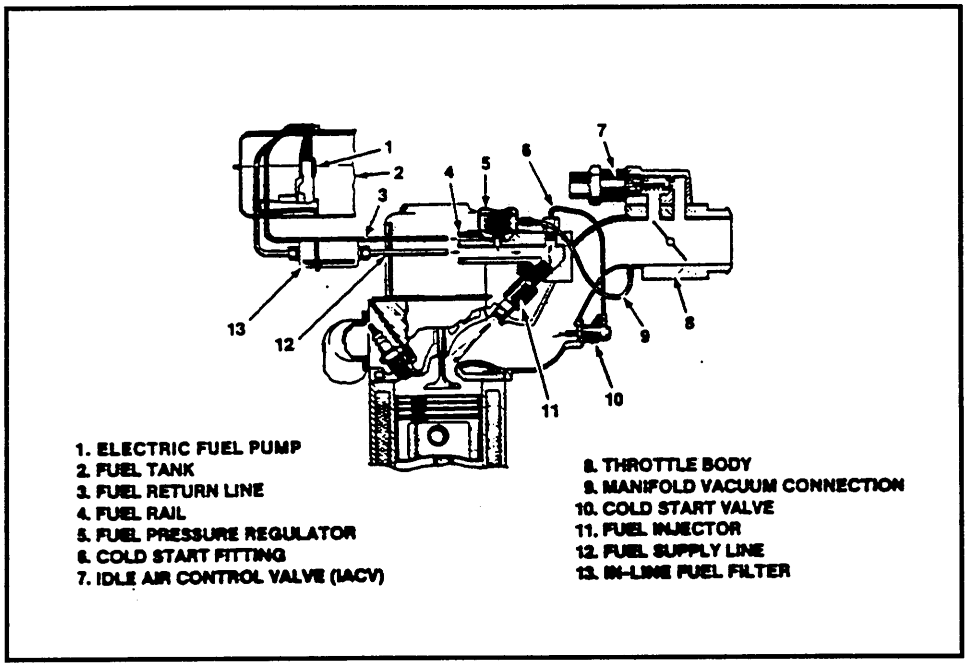

Figure 5.2b (cont.): Port Fuel Injection System

The voltage is set by the battery or the power requirements, one of which is to run the fuel pump once the ignition is turned on. This is fixed at 13.2 volts. One important consideration, here, is that the voltage of the charging system or battery changes with temperature and battery condition. Consequently, in addition to testing the pump operation to its Engineering Specifications for performance and noise, hot and cold weather testing becomes necessary (hot weather testing for vapor lock and cold weather testing for battery turn-over and fuel pump performance). Typically, vehicles can operate in temperatures ranging from -30^{o}C to 65^{o}C.[6]

5.2.1 ELECTRIC FUEL PUMP--COMMON COMPONENTS

Regardless of the type of electric fuel pump that is used in an automobile (gerotor, turbine, roller vane), each pump consists mainly of three structural components: the pumping unit, the permanent magnet driving motor (dc motor), and the end support cover for the electrical and hydraulic connections. See Figure 5.2.1a.

[6] Yu, EFHD, (1991).

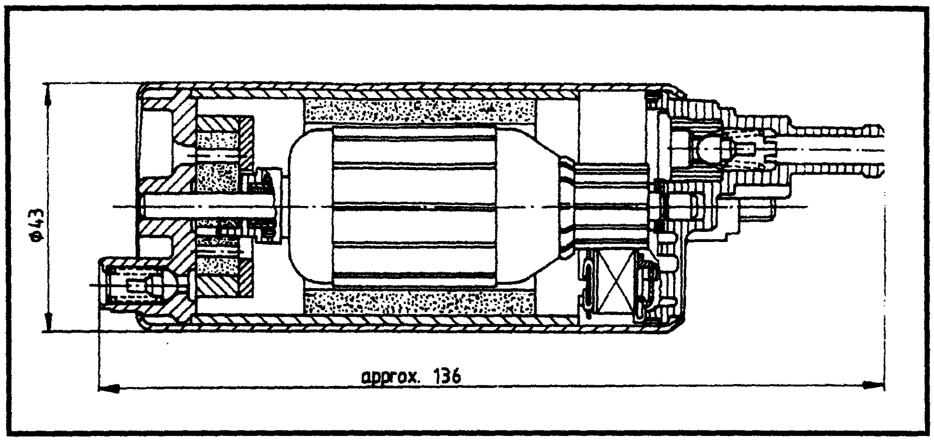

Figure 5.2.1a: Typical Fuel Pump Design[7]

The pump unit, for example, is the inner-outer gears in the gerotor or the impeller in the turbine, with a suction inlet at the base plate. The motor unit, consisting of a rotating armature with a coupling driver to drive the pumping mechanism and the permanent magnets fixed in the housing, receives its voltage through a commutator and carbon brushes arranged in the end support cover. Lastly, this end support (or outlet) subassembly, contains the electrical connections, hydraulic pipe connection, and the check and relief valves (which can also be incorporated in the base plate at the inlet). The total assembly is held together by the pump housing, crimped at the edge.

The mechanical power supplied by the electric motor to the pump unit is rather high considering its dimensions.[8] Overheating of the motor, however, is avoided by the cooling effect of fuel flow around the armature which permits long term continuous operation without substantial degradation.

5.2.2 SUMMARY OF THE OPERATION OF THE ELECTRIC FUEL PUMP[9]

Most vehicles today possess various types of fuel injection systems which operate in many different ways in order to provide the engine with gasoline. All types of systems, therefore, need as a basic component, an electrically driven fuel pump. The main task of the fuel pump is to deliver the system with enough gasoline at a pressure raised to the particular value required (as discussed above with the pressure regulators). As a result, the following basic steps or sequence of operations are performed by any electric fuel pump, whether it is a gerotor or turbine style:

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[7] Yu, EFHD, (1991).
[8] Yu, EFHD, (1991).
[9] Kemmner, Rollwage, and Rose, "New Generation of BOSCH Electrical Fuel Pumps--Improvement in Hot Fuel Handling and Noise", SAE Paper #870120, (1987).

1) in-tank aspiration of fuel by fuel pump (assuming in-tank fuel pump)
2) increase of pressure by compression (gerotor) or momentum transfer (turbine) to a defined value controlled by the pressure regulator (discussed above)
3) transport of the gasoline through the pressure system (supply line) to the injectors on the engine

Additional functions of the fuel pump are performed by the relief valve, which avoids excessive pressure rise in case of blocked fuel lines, and by the check valve, which seals the system completely when the pump is turned off. As also discussed above, all the pump's functions have to be accomplished under varying conditions, such as a voltage supply between 6.0V and 15.0V, fuel temperatures from -40^{o}C to +80^{o}C, short term ambient temperatures up to as high as +100^{o}C, and vibration stress according to driving conditions.

The Gerotor or Positive Displacement Pump

The gerotor pump is a positive displacement pump. For automotive applications, it has evolved into an electrical, in-tank pump run by a DC motor. It has a moving boundary which forces the fuel through the chamber by volume changes. See Figure 5.2.2a. A cavity opens, and the fuel is drawn into the inlet. The cavity is then closed, and the fuel is then squeezed through the outlet. Some of the advantages of its application include low manufacturing cost and complexity, small, economical size, low voltage performance, and minimal sensitivity to the gasoline viscosity. Some of the disadvantages include pressure pulsations and high noise, hot fuel handling/performance, and contamination of gerotor.

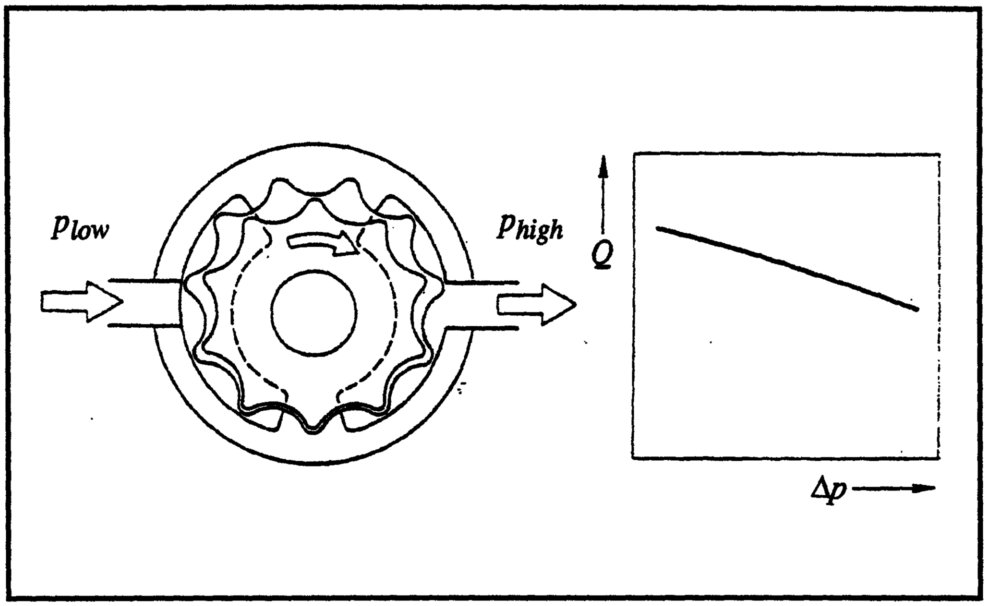

Figure 5.2.2a: The Gerotor Pump Inlet View and Representative P-Q Diagram

The Regenerative Turbine or Dynamic Pump

The regenerative turbine pump is a special type of dynamic pump. A dynamic pump adds momentum to the fuel by means of fast-moving blades or vanes. There is no closed volume as in the gerotor pump. See Figure 5.2.2b. The fuel increases momentum while moving through the open passages. As it moves through these passages or blades, the high velocity fluid particle generates high pressure or a pressure increase as it exits through the outlet or discharge of the pumping chamber. In other words, fuel flows in at the suction and is picked up by the impeller's vanes. After nearly making one revolution in its channel, the fuel particle has a high velocity that sends it out of the discharge. Some of the turbine pumps advantages over the gerotor pump is its low noise/pressure pulsation potential, more stable or repeatable performance curves, and its ability to handle vapor (or good hot fuel handling performance). On the downside, these pumps have a higher manufacturing cost due to the tighter tolerances that must be held. They are much more sensitive to the viscosity of the fuels that they pump. Lastly, they are extremely sensitive and have poor performance under low voltage and low temperature considerations.

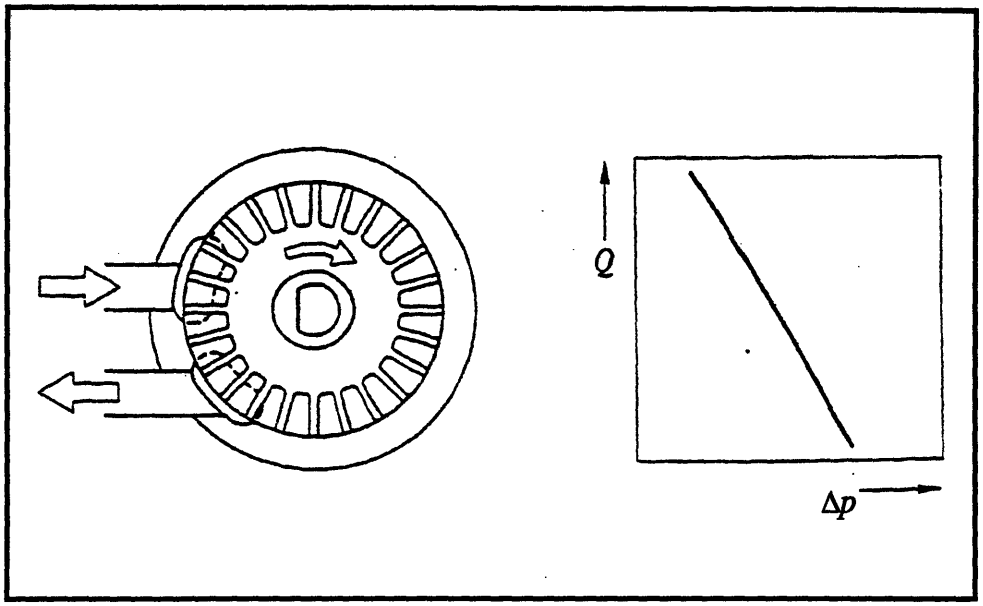

Figure 5.2.2b: The Turbine Pump Inlet View and Representative P-Q Diagram

5.2.3 THE ELECTRIC FUEL PUMP IMPACT ON THE VEHICLE AND THE END USER

Under most conditions, including when the vehicle is at idle or run at wide open throttle, the customer cannot perceive whether the pump is pumping gasoline at a rate of 60 lph or a rate of 70 lph. As long as the engine is getting the specified amount that it needs, the vehicle will operate the way it is intended. There are some degradations that can occur within the fuel pump (and or fuel system) that could not only affect the vehicle but become readily perceived by the end-user. Some of these have to do with the wear-in of the pump over time, the temperature of the fuel/the fuel itself, and the inherent operation or design of the pump.

Wear-in

Typically looked at in terms of the mileage or life of the vehicle, wear-in on a pump can be the shortening of the brushes that make the contact with the surface of the commutator as well as the change in the inner or outer diameter of the gerotor (or gear teeth) due to friction between the inner gear and the outer gear. This is also similar for the turbine type pumps, and depending on the material used to fabricate the impeller, the gasoline can be very corrosive and cause it to decompose. The gasoline could also cause the impeller to swell or expand altering the design tolerances and ultimately the discharge or flow.

Vehicle symptoms due to these wear-in phenomena include engine stalls and stumbles due to lack of necessary pump output. In addition, as the brushes wear down, carbon deposits build up on the commutator as well as filter into the rest of the pump. This could prevent the pump from providing the necessary output (flow or current or speed) as well as cause contamination to enter into the fuel injectors.

Hot Fuel Handling[10 & 11]

The most significant reason for hot fuel problems is the composition of the fuel itself. There are also four major contributing factors to vapor formation: fuel volatility (high Reid vapor pressure (RVP) of the gasoline), low atmospheric pressure, especially at high altitudes, temperature/pressure of gasoline and the fuel system, and vehicle design (the ability of the fuel system to handle vapor). As more and more components of low boiling point are blended in the gasoline, especially in winter time, the generation of vapor bubbles begins at low fuel temperatures and slight vacuum pressures. The effect of vapor bubble generation occurs either by exceeding the boiling curve at a given pressure or by falling short of the vapor pressure at a given temperature. The most important effects of vapor generation occur in the fuel pump itself. The suction or intake of fuel by the pump is normally coupled with the formation of a vacuum. A second effect is the return flow of fuel from outlet to inlet side of the pump through gaps or by dead volumes.

The volume of vapor that fills the inlet or suction chambers of the fuel pump reduces the outlet flow of fuel since the resulting vapor bubbles prohibit the gasoline from entering the pump. Although the pump is operating as designed, and the required operating pressure will be reached, the flow will decrease. Pressure fluctuations may occur when the amount of fuel required by the engine increases abruptly. Lastly, the presence of vapor inside the pump affects the starting conditions of the pump since the vapor either has to be condensated out by compression or exhausted by evaporation before the pressure rises reaches the required system pressure within an acceptable time.

The turbine pumps, however, possess improved hot fuel performance. This is due to the inherent design of the pump, particularly its impeller. Since the impeller blades pick up any fluid, a regenerative

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10 General Motors, 1-4.
11 Kemmer, Rollwage, and Rose, SAE Paper #870120, (1987).

pump can handle vapor as well as liquid, as long as there is sufficient liquid to seal the space between the impeller and the sealing wall of the casing (housing).[12] The pump capacity or flow will equal liquid volume plus the vapor volume entering the impeller. As the impeller turns, fuel is drawn into the pumping section through the inlet ports. Centrifugal force created by the rotating impeller separates and expels vapor from the fuel. After the separation, the heavier liquid fuel is transferred to the outlet body, and vapor is forced back to the fuel tank through a vent at the pump inlet. By separating and rejecting vapor at the pump intake, the pump is able to pump the liquid fuel through the fuel system. As a result, the primary functions of the turbine section of the pump assembly are separating vapor and pumping fuel.[13]

The resulting impact of vapor generation inside and outside the electric, in-tank fuel pump on the vehicle is poor or slow starts, inadequate supply of fuel to engine, engine stumble or stalls, and poor performance. Fuel injection systems cannot tolerate vapor. If vapor is delivered to the injectors, fuel metering is reduced, and the air-fuel mixture delivered to the engine is leaner than desired.[14]

Noise and Vibration[15]

Since the pump is mounted vertically in the fuel tank, connected by hoses and a metal flange plate to the cover of the tank opening, noise transmission into the interior of the vehicle becomes likely. There are generally three causes of noise generation by a fuel pump:

1) According to the pumping principle, the fuel flow has various flow/pressure characteristics. These in turn, cause pulsations which are radiated to the fuel lines on both the inlet and outlet side propagating there with sound velocity.

2) Fuel pumps vibrate due to numerous external (road, surrounding vehicle systems) and internal excitations. The resulting vibrations are transferred by the fuel lines as well as the pumping mounting plate.

3) Vapor bubbles form on the inlet side of the pump, especially with increasing fuel temperature. When the pressure rises in the pump, these cavitation bubbles collapse, producing shock waves with high frequency components and creating corresponding body vibrations.

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[12] Courtesy: Electrical and Fuel Handling Division, "Discussion of Regenerative Pumps".
[13] General Motors, 4-2.
[14] General Motors, 1-9.
[15] Kemmer, Rollwage, and Rose, SAE Paper #870120, (1987).

For the gerotor pump, the pumping chamber volumes are small. This results in flow and pressure variations and a high frequency of pulsations depending on the number of gerotor gear teeth. The main element of the pulsation, however, is due to the geometry of the gears which could lead to run-out or variations in teeth shape. In addition, excitation is created as the teeth make contact, and vibration is generated.

The turbine pump operates on the principle of continuous momentum transfer with non-touching pump parts. As a result, no pressure peaks or impacts occur. The uniformity of the flow is high and is not detectably effected by the repetition frequency of the number of impeller blades. Body vibrations are possible due to the interacting forces between the impeller blades and edges of the flow channels or sealing rims being transferred by the gasoline. In summary, the turbines are better from a noise, vibration, and harshness standpoint than the gerotors. And since they possess a lower overall noise level then the gerotors, the noise excitation by the electric motor, due to the unbalance of the armature, electrical commutation or sliding effects of carbon brushes, which are all normally of minor importance, could become dominant.

5.3 DESCRIPTION OF TEST FLUIDS USED DURING TESTING

Under normal operating conditions in the vehicle, the fuel pump pumps commercial blends of gasoline--summer or winter grades of varying octane numbers. As a result, the Ford Engineering Specifications which specify a set of tests that the pumps must undergo (and pass), require they be tested in gasoline at the Fuel Lab. For winter operation, it is desirable to have high volatility (high RVP) fuel so that it will vaporize quickly at very low temperatures. In summer, it is necessary to have lower RVP fuel so that the fuel will not vaporize before reaching the combustion chamber. Typically, summer fuels are 10.5 (psi) RVP, and winter fuels are 13 to 14 (psi) RVP.[16] These values will vary depending on local conditions (such as temperature and altitude).

Throughout all of the testing that was conducted during this thesis project, it was decided to avoid testing in summer or winter blends of gasoline since they could possess much variability from one drum

[16] General Motors, 1-9.

or blend to the next in terms of vapor pressure and resulting volatility. A "stable" test fluid was desired for the gage capability studies. As a result, all the test fluids that were used during the majority of the testing were non-commercial with the exception of the Eurosuper gasoline that is available for use in Europe and is currently the blend used at the Alba Lab. All these test fluids and some of their properties that are relevant to performance testing will be overviewed below.

5.3.1 ESE-M4C50-D: Unleaded Gasoline

This is a non-commercial gasoline and is specially blended for exhaust and evaporative emissions tests. It is well-refined with controlled lead, phosphorus, and sulfur contents. Its Reid vapor pressure (RVP) is very low and was anticipated to change very slowly at the temperatures at which the fuel pumps were performance tested. This gasoline was used for all the test phases, with the exception of Pre-Phase II. There were several reasons why it was used: to achieve a more accurate gage capability of the performance test equipment at the Labs and the Plants, to obtain an equal comparison between Labs and between the Labs and Plants, to determine the effects of the test fluids on the test stand capabilities, and to obtain a more accurate test fluid correlation.

5.3.2 ESZ 95 (EUROSUPER95): Unleaded Gasoline, Super Grade

This gasoline is the accepted standard for the fuel pump, performance tests at the Alba Fuel Lab. It is a commercial grade of gasoline that has both summer and winter blends. A summer blend was used here. Its European (or British) specification number is also ***Unleaded Gasoline MSZ 11793 or Esz 95.*** This gasoline was only used at the Alba Lab for the turbine pump, test fluid correlation or Phase II testing. In addition, it was difficult to send the fuel to the ETC Lab. Its analysis sheet for the batch that was used for the Phase II testing was reviewed before the testing began.

5.3.3 ESF-M99C82-A: Calibration Solvent or Flow-Test Solvent

This is considered a process material and is an aliphatic hydrocarbon. It is generally received and used in large shipments by both Fuel Labs and Plants. In the past, it was typically used in the flow stands for production testing of all carburetor assemblies. It is a material that is considered "safe" for production floor usage in the elevated temperatures of the surrounding environment (although the pumps are tested at temperatures ranging from 17^{o}C to 23.5^{o}C in the production test stands). Its flash point is

(ASTM D56) is 58.9°C minimum. It is also considered a very stable test fluid, because its RVP is very low (this makes it conducive to plant test usage as it has a long life before it starts to degrade). Consequently, it was used throughout all of the test phases and was a very important control fluid for the gage capability comparisons between the Labs and between the Labs and Plants. It was also the source of controversy regarding the Engineering Specifications for Laboratory testing versus production floor, performance specifications.

In addition, this solvent is a very heavy fluid since it has a viscosity that is nearly three times as much as that of gasoline. Subsequently, it has a great impact on fuel pump flow primarily for the turbine pumps.

5.3.4 ORGANIC FUELS/LUBRICANTS LAB RESULTS

During Phase I testing at the ETC Fuel Lab, Phase II at the ETC Lab, and Phase II at the Alba Lab, test fluid samples were taken throughout the course of the experimental runs. However, only the Eurosuper gasoline was sampled at the Alba Lab to minimize costs. The frequency and manner in which the specimens were taken were decided in order to capture the amount of change in the test fluid during one run. In addition, some of the other underlying objectives in taking test fluid samples were to: 1) determine the integrity of the test fluid throughout the course of "routine" performance testing on a fuel pump and 2) measure the test fluid properties that could potentially affect fuel pump performance; how fast they change or vary with temperature and duration of use before test fluid purge and replenish. These samples (in one liter bottles) were chilled and then sent to local Labs.

Aside from the test fluid temperature, which was measured during each run, the test fluid properties that were measured included Reid vapor pressure (ASTM D 323, method B), specific gravity at 15.6°C and 25°C (ASTM D 4052), and kinematic viscosity at 0°C and 37.8°C (ASTM D 445).[17]

[17] The ASTM methods referenced here can be found at Ford's Technical Library, the Central Lab, any design analysis activity, or any engineering library.

5.4 TEST FLUID PROPERTIES

Since the primary function of any pump is to transport a fluid, it therefore follows that the performance achieved and the means by which the fluid is acted upon must be closely related to the characteristics of the fluid involved.[18] In the case of a fuel pump, the fluid is gasoline which is a volatile, Newtonian fluid. The most significant gasoline properties which impact a pump or handling by a fuel pump, are specific gravity and kinematic viscosity. Both affect the pumping head and capacity (speed) at which the pump can operate, the power input required, and fluid flow. Viscosity, in particular, (and to a lesser extent, specific gravity) is temperature dependent. As indicated above, these properties and test fluid temperature were very closely monitored throughout all of the testing.

5.4.1 PROPERTIES DEFINED

Specific Gravity

This is a dimensionless quantity and is defined as the ratio of the density of the test fluid (or gasoline) at 15°C to the density of water at 4°C:[19]

$$SG_{15^\circ C} = \frac{\rho_{gas @ 15^\circ C}}{\rho_{H_2O @ 4^\circ C}}$$

Specific gravity (or density) variations with temperature may be significant in the fuel system, particularly since a wide temperature range of the gasoline exists as it is pumped from the tank, through the hot engine/engine compartment, and back to the tank. In addition, if the volume of gasoline in the fuel system (primarily tank) changes, there is a greater chance that the specific gravity of the gasoline will vary with temperature. As a result, a standard correction coefficient has been derived for petroleum products to be able to determine the specific gravity at any temperature. This is shown in Table 5.4.1a below for each of the test fluids:[20]

[18] Warring, R. H., Pumps: Selection, Systems, and Applications, (1984), 1.
[19] Warring, R. H., 9.
[20] Warring, R. H., 12.

	M99C82A-Solvent	50-D Gas/Eurosuper
$SG_{15°C}$*	0.78 - 0.82	0.74 - 0.76
Coefficient (C_c) per °C	0.00072	0.00078

*As determined from ASTM D 4052

Table 5.4.1a: Correction Coefficients for Specific Gravities of the Test Fluids

Therefore, the specific gravity of the test fluids at any temperature can be predicted by:[21]

$$SG_{T°C} = SG_{15°C} - [C_c \times SG_{15°C} \times (T - 15°C)]$$

Kinematic Viscosity

This is the property of a fluid that measures its resistance to change of shape (flow or motion) and indicates how quickly a shear force exerted on the surface of a fluid penetrates into its interior.[22] It is also defined as the ratio of a fluid's absolute viscosity to its density at a given temperature:

$$\nu = \frac{\mu}{\rho} \quad (\frac{mm^2}{s})$$

For a given fluid, viscosity is significantly affected by temperature and is exponentially related by: $\nu \approx e^{-c/T}$; where c is a constant (based on the fluid and other factors) and T is temperature. For purposes of this thesis project, and since the temperature ranges tested over were narrow, it was assumed that the viscosity varies linearly with temperature. An example of this is shown below in Figure 5.4.1a for the Eurosuper95 gasoline. Its kinematic viscosity was measured over a broad range of temperatures using the ASTM D 445 method. A line was fitted to the data.

[21] Warring, R. H., 13.
[22] Fay, James A., Introduction to Fluid Mechanics (draft), (1991), 11.

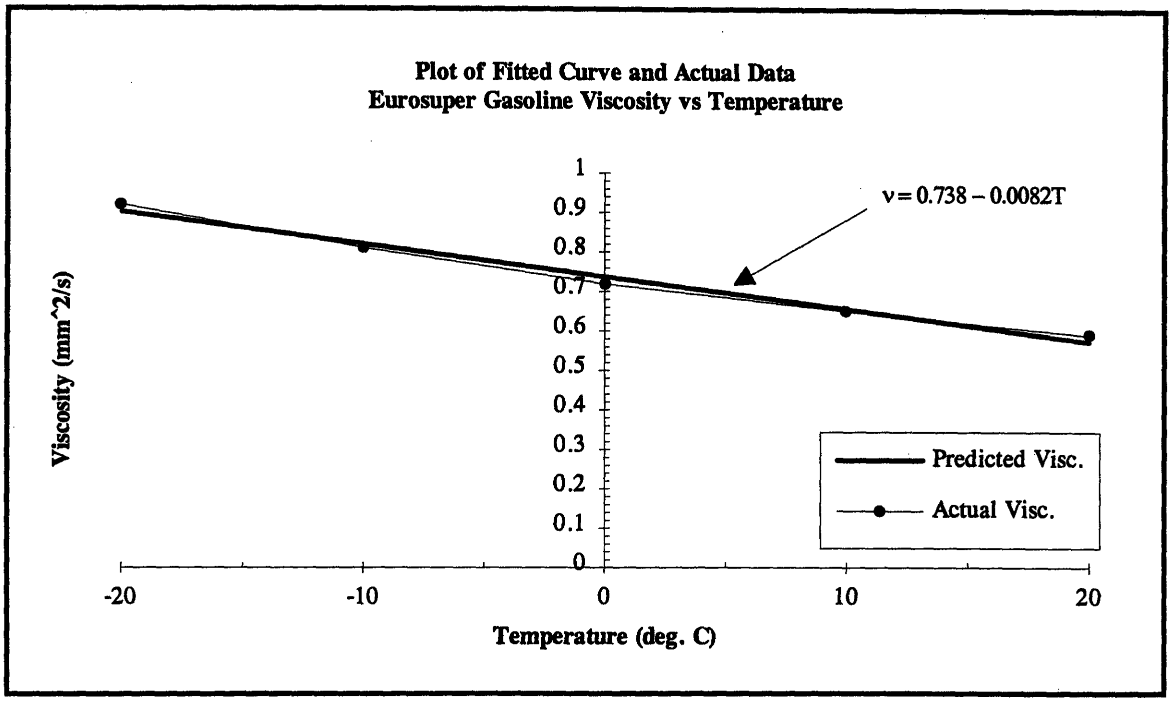


Figure 5.4.1a

For the test phases that were conducted, the temperatures that were measured ranged from 18°C to 27°C across all of the test locations.

The pressure effects on viscosity were ignored because the fuel pumps operate at a fixed pressure. Usually, viscosity increases with pressure, but this is more pronounced at lower temperatures. With oils (and possibly fuels), the effect of pressure can be an increase in viscosity by as much as 30% per 1000 psi.[23] The pressure at which a fuel pump operates is only 45 psi or 310 kPa.

Vapor Pressure

This parameter was also measured for all of the test fluids. The vapor pressure of a liquid is the pressure exerted by the saturated vapor in contact with the liquid surface at a given temperature, and is the absolute pressure at which the liquid will boil at that temperature. As discussed above, vapor pressure can have a significant effect on pump flow in the case of volatile fluids like gasoline causing vaporization in the pumping chamber or inlet. The vapor pressures, determined by ASTM D 323 (method B) for each of the test fluids used in this thesis project, are summarized below in Table 5.4.1b. These values are the averages over all the runs or the number of fluid specimens taken for each fluid:

[23] Warring, R. H., 17.

TEST PHASE	TEST LOCATION	ESE-M4C50-D GASOLINE	M99C82A SOLVENT	EUROSUPER95 GASOLINE
Phase I/Round I	ETC Lab	8.40 psi	0.48 psi	N/A
Phase I/Round II	ETC Lab	8.52 psi	0.42 psi	N/A
Phase II: gerotors	ETC Lab	8.53 psi	0.42 psi	N/A
Phase II: turbines	ETC Lab/Alba Lab	8.43 psi	0.44 psi	6.00 psi

Table 5.4.1b: RVP Summary

Typically, the M99 RVP values ranged from 0.3 to 0.6 psi throughout all of the testing. The 50-D gasoline RVP values were relatively stable. The Eurosuper RVP values varied greatly, ranging from 4.0 psi to 9.0 psi throughout all of the runs. Although the test fluid vapor pressure could be a culprit of vapor lock or hot fuel handling problems, testing at elevated temperatures was not considered here, and the temperatures of the fluid never reached a temperature any higher than 27°C. In addition, the fuel system has mechanisms built in to protect for the occurrence of vapor lock by creating ample net positive suction head in the fuel supply line on the inlet side of the pump.

5.4.2 THE EFFECTS OF TEMPERATURE ON TEST FLUID PROPERTIES

As indicated above, temperature has an effect on the test fluid properties of specific gravity and kinematic viscosity. For all the Phase II results: 1) the specific gravities were estimated from the Central Lab values at 15°C averaged over all the runs, the SG_T formula given above, and the appropriate C_C value at the average fluid temperature, and 2) the kinematic viscosities determined at the average temperature values were based on the average viscosity values at 0°C and 37.8°C (from the Central Lab) over all the runs. For the Eurosuper95 gasoline, the average viscosity at the average temperature was determined from the equation given in Figure 5.4.1a since the viscosity was only measured at 20°C at a local Lab in Hungary. For the Phase I results, the same procedure as for the Phase II results was followed to estimate the specific gravity and viscosity, but since the temperatures were not measured completely for Phase I/Round I at the ETC Lab, a slight deviation was necessary. Instead of computing an average temperature over all the runs, 20°C was used as an average value.

Specific Gravity and Kinematic Viscosity versus Test Fluid Temperature (from Phase II)

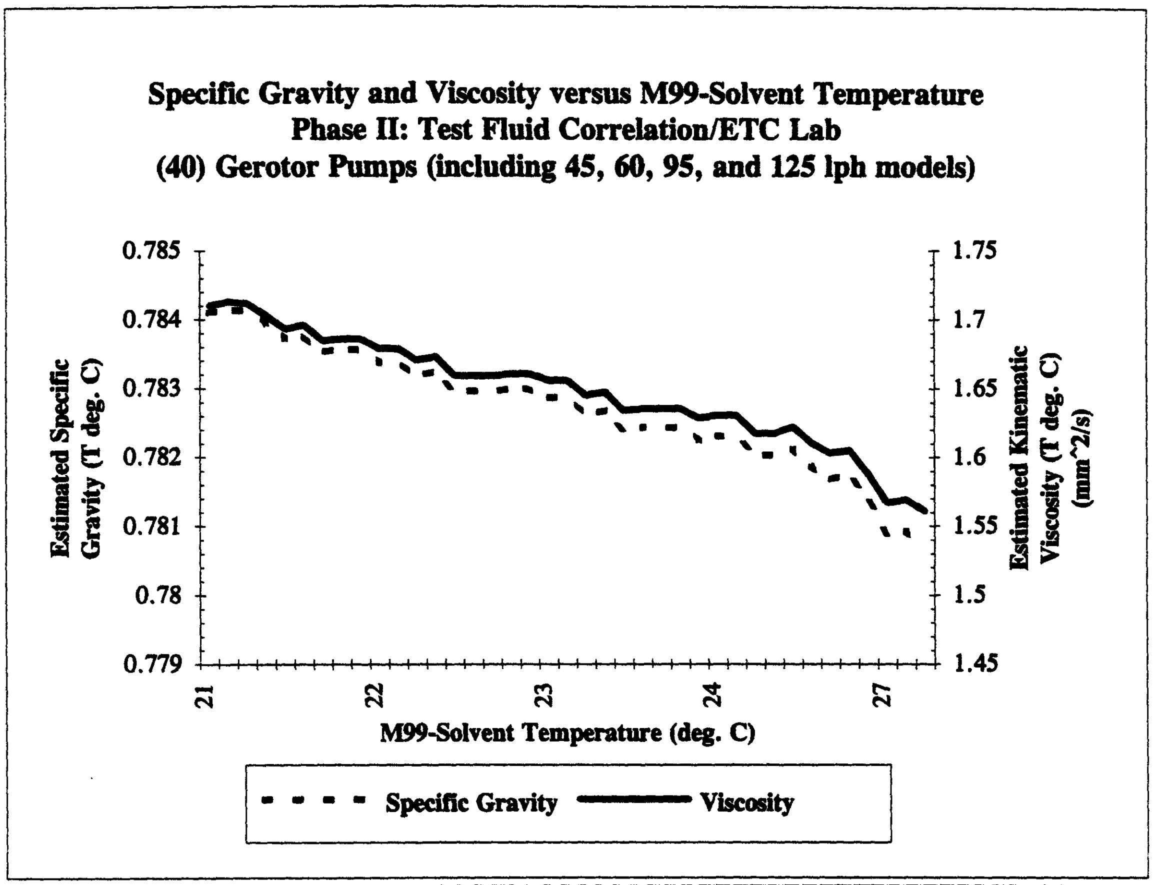
In Figures 5.4.2a through 5.4.2c, the relationship between the estimated test fluid properties at each actual temperature measured during each of the runs is shown. These values were determined using steps (1) and (2) above, but instead of evaluating the *SG* and viscosity at $T_{avg.}$, the actual run temperatures were used. These plots were designed to exaggerate the linearity of the properties over a small temperature range. The properties tended to be very flat or constant over those ranges. This is further evidenced by the slopes, which are very near zero, of both the *SG* and kinematic viscosity versus temperature curves. These slopes also suggest that these properties do not change that rapidly over a 1°C to 7°C range (see *x*-axes of the Figures). A summary of these slopes is shown in Table 5.4.2a:

TEST PHASE	TEST FLUID	T_{end} °C	SG @T_{end} Viscosity @T_{end}	$T_{initial}$ °C	SG @$T_{initial}$ Viscosity @$T_{initial}$	Slope or %Δ/°C SG and Viscosity
Phase II: gerotors	M99	27°C	0.7807 1.5608 mm^2/s	21°C	0.7841 1.7102 mm^2/s	-5.62E^{-4}/°C or 0.06% -2.49E^{-2}(mm^2/s)/°C or 2.49%
	50-D Gas	24°C	0.7410 0.5661 mm^2/s	21°C	0.7431 0.5777 mm^2/s	-6.95E^{-4}/°C or 0.07% -3.88E^{-3}(mm^2/s)/°C or 0.39%
Phase II: turbines	M99	28°C	0.7809 1.5351 mm^2/s	22°C	0.7835 1.6826 mm^2/s	-5.67E^{-4}/°C or 0.06% -2.54E^{-2}(mm^2/s)/°C or 2.54%
	50-D Gas	23°C	0.7418 0.5426 mm^2/s	21°C	0.7432 0.5529 mm^2/s	-5.83E^{-4}/°C or 0.06% -4.29E^{-3}(mm^2/s)/°C or 0.43%
	Eurosuper	25°C	0.7503 N/A	18°C	0.7543 N/A	-5.64E^{-4}/°C or 0.06% -8.20E^{-3}(mm^2/s)/°C* or 0.82%

*** See Figure 5.4.1a**

Table 5.4.2a: Change in Test Fluid Property per °C

Another observation, which can be made here, is that regardless of the fuel pump type tested in each of the fluids, the curves are similar. The range of *SG* and viscosity values over the given temperature range are also similar for the two pump types tested. This is what was expected since test Phase II was designed to only look at a test fluid correlation, not a lab-to-plant or pump-to-pump correlation.



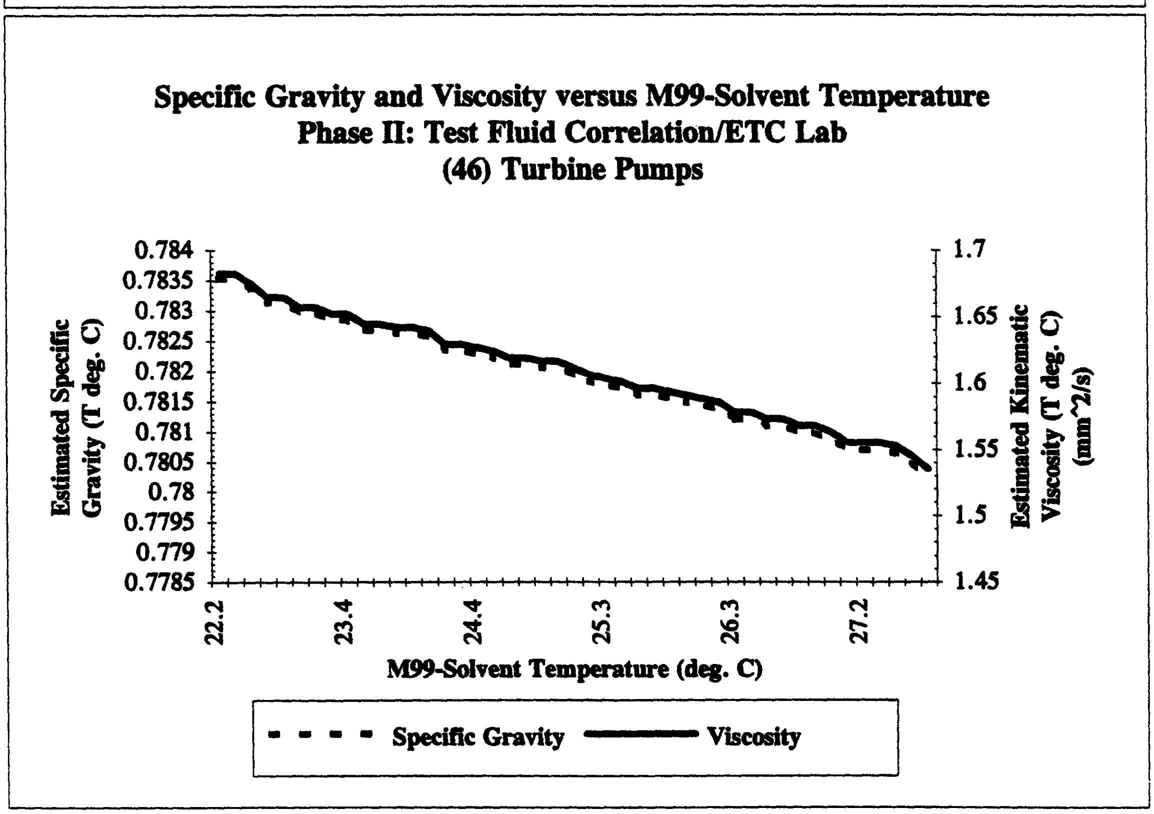
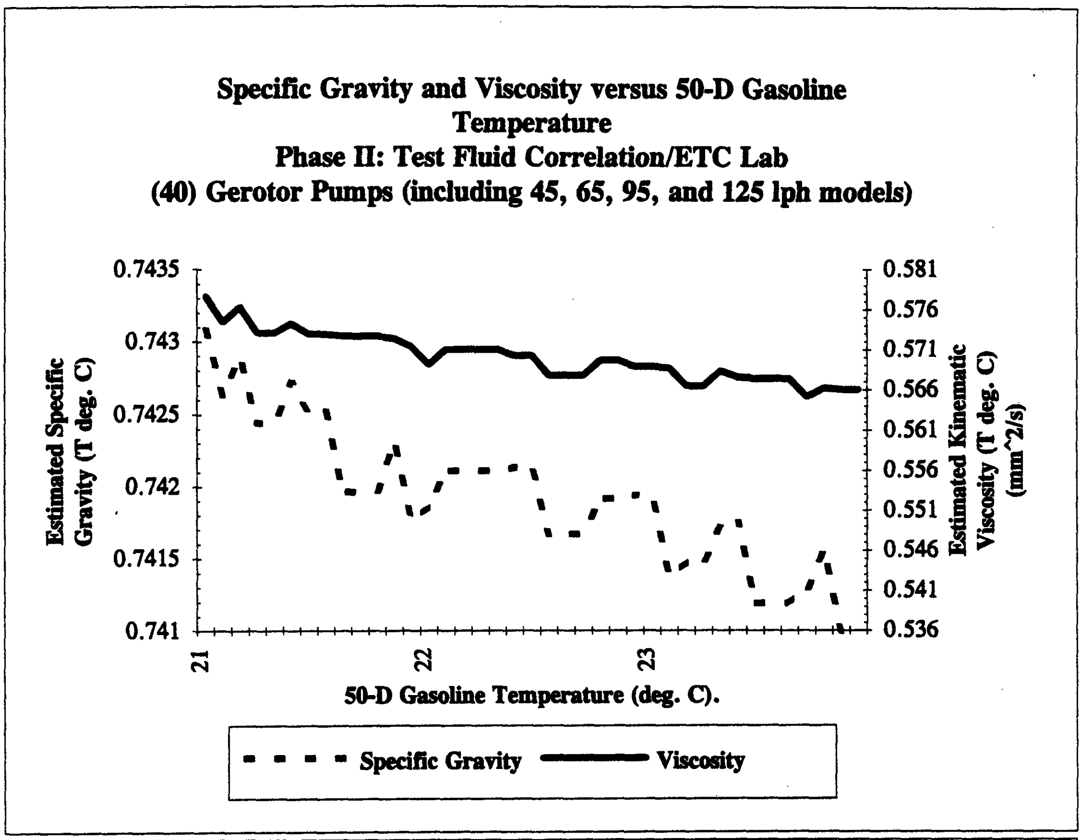


Figure 5.4.2a: Estimated Specific Gravity and Kinematic Viscosity versus M99-Solvent Temperature



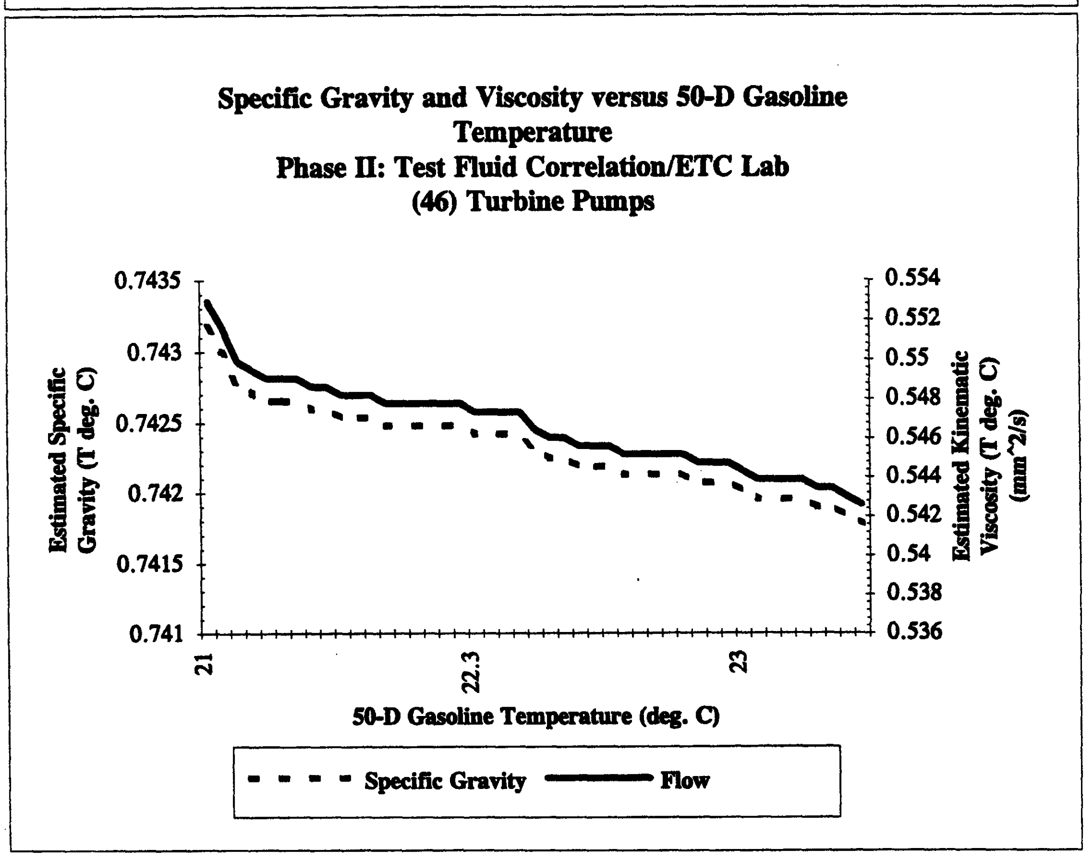


Figure 5.4.2b: Estimated Specific Gravity and Kinematic Viscosity versus 50-D Gasoline Temperature

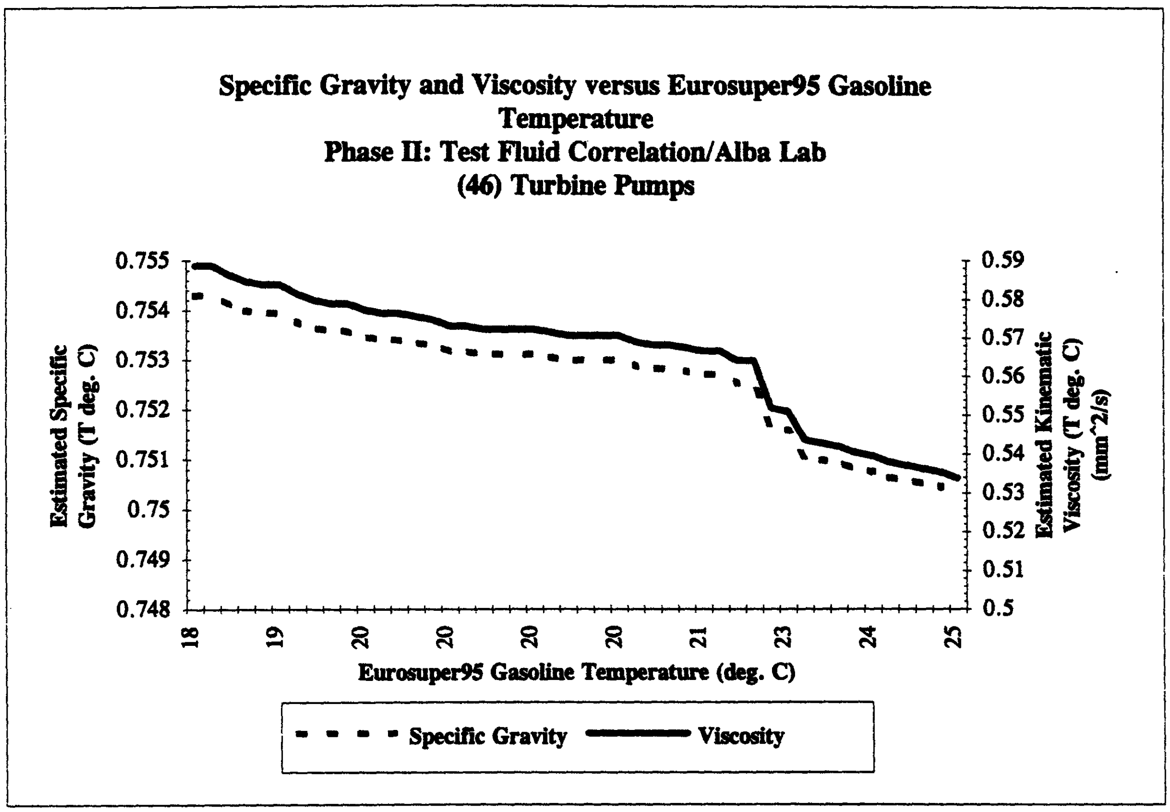


Figure 5.4.2c: Estimated Specific Gravity and Kinematic Viscosity versus Eurosuper95 Gasoline Temperature

5.5 TEST FLUID EFFECTS ON PUMP PERFORMANCE

In this section, the actual effects of the test fluids, as related to temperature, on pump performance are discussed. These effects will be shown using numerous fluid mechanics and turbomachinery principles. As shown in Table 5.4.2a, the test fluid temperature ranges that were experienced in the Lab and Plant environment were narrow, and there were small changes in the test fluid properties, specific gravity and kinematic viscosity, per one degree Celsius. As a result, it can be expected that the actual effects of these properties on the pump performance characteristics such as flow will be small. However, when there are substantially large increases in the test fluid temperature, resulting in specific gravity decreases, viscosity decreases, and vapor pressure increases, these performance characteristics can change dramatically.

5.5.1 GEROTOR AND TURBINE PUMP PERFORMANCE SENSITIVITY TO TEST FLUIDS

As shown from the Phase II test results and other testing performed by the engineers at the Electrical and Fuel Handling Division, different types of pumps will perform differently in the test fluids. The gerotors are less sensitive to pumping different test fluids. The turbine pumps, are much more sensitive to pumping different test fluids primarily because of the viscosity effect. As shown below, with a thicker or more viscous fluid, the pump flows less than what it would flow in gasoline, a thinner, less viscous fluid. The impeller of the turbine pump has to work harder.

Flow and Flow Δ's in the Test Fluids

It is difficult to determine, for the various gerotor models, whether pump flow is larger or smaller in gasoline when comparing it to the flow in the M99-solvent. One would expect that the pump flow would be less in the solvent and that this trend would exist regardless of the gerotor model. The performance test results indicated otherwise. Because the test fluid temperature was not constant, and there is manufacturing variability in the pumps, the small percentage differences calculated between flow in M99 and flow in gas, are likely trivial. These differences could also be masked by the pump-to-pump variability so that it becomes difficult to determine if there are any significant effects of the different test fluids. Nonetheless, the results indicate that the gerotor pumps perform similarly in each of the test fluids.

For the turbine pumps, the flow was, on average, lower in the M99-solvent than in either the 50-D or Eurosuper gasoline. This was a very consistent observation from the Phase II data which resulted from forty-six pumps tested at least three times each. The fluid temperatures, however, were not constant.

Gerotor and Turbine Pump Efficiencies in Different Test Fluids

The fuel pump efficiency can be calculated as the ratio of the mechanical or water power to the electric power of the dc motor:[24]

$$
\begin{aligned}
\eta_{pump} &= \frac{\Delta P \times Q}{V \times I} \\
\Delta P &= P_{out} - P_{in} = \text{Fixed Outlet Pressure for Pumps (Pa)} \\
Q &= \text{Outlet Flow } \left(\frac{m^3}{s}\right) \\
V &= \text{Voltage (volts)} \\
I &= \text{Current (amps)}
\end{aligned}
$$

These values were calculated from the Phase II results: various gerotor models and turbines at numerous voltages and pressures in each of the test fluids.

For the gerotor pumps, the efficiencies vary across different models by design, but were similar across the different test fluids, especially since the voltage and pressure are fixed. For the turbine pumps, the most notable observation was their low efficiency in all the test fluids at the 8.0V/250 kPa operating point.

5.5.2 TURBOMACHINERY, PUMP PERFORMANCE, AND SIMILARITY RULES

A turbomachine is a device which adds energy to a fluid or extracts energy from it. If the machine adds energy to the fluid, it is a pump.[25] The gerotor and turbine pump are turbomachines with electric motors. At a fixed speed or voltage, the fluid viscosity is one of the most significant factors affecting the pumps' performance. This is reviewed and shown in Figure 5.5.2a.

[24] White, Frank M., "Turbomachinery", Chapter 11, Fluid Mechanics, (1979), 633.
[25] White, Frank M., 633.

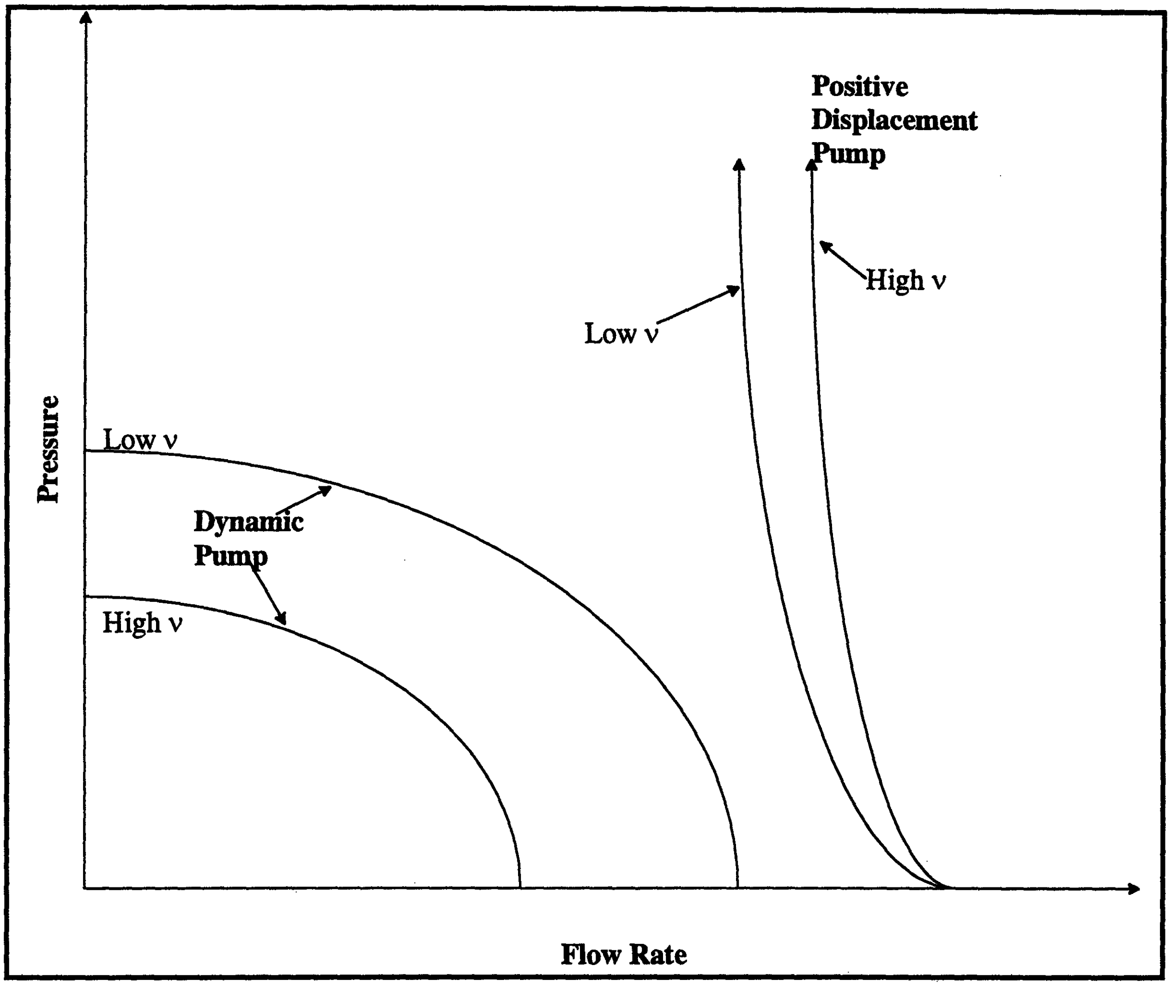


Figure 5.5.2a: Pump Performance and Viscosity[26]

When pumping such fluids as gasolines or even oils, the pump water horsepower (mechanical power), as well as flow, head, and efficiency change due to a large change in viscosity when compared to pumping water. This change is also related to the Reynolds number which is the dimensionless parameter correlating the viscous behavior of all Newtonian fluids:[26]

[26] White, Frank M., 27.

$$Re = \frac{\rho V D}{\mu} = \frac{V D_L}{\nu}$$

ρ = Fluid density ($\frac{kg}{m^3}$)

μ = Absolute Viscosity ($\frac{kg}{m \cdot s}$)

V = Characteristic velocity ($\frac{m}{s}$)

D_L = Characteristic length (m)

ν = Kinematic viscosity ($\frac{mm^2}{s}$)

This number also gives an indication of the nature of the flow of the fluid near its boundary. An Re below 2000 indicates a smooth, laminar flow in a channel or tube. An Re greater than 2000 indicates a fully turbulent flow. These values were calculated for each pump type in each of the test fluids and are summarized in Table 5.5.2a. It is expected that at such high Re numbers for each of the pump types in each of the test fluids that the same or a constant percentage effect of the viscosity will occur at a fixed temperature.

PUMP	TEST FLUID	$T_{avg.}$ (°C)	D_ω (m)	$V_{avg.}$ (m/s)	$\nu_{avg.}$ (mm^2/s)	D_L (m)	Re	$Q_{avg.}$ (lph)
45 lph	M99	22.93°C	0.0254	4.86	1.663	0.003	8767	78.86
	50-D	22.13°C		5.21	0.5719		27,330	74.20
60 lph	M99	23.37°C		6.78	1.6503		12,325	107.46
	50-D	22.33°C		7.02	0.5692		36,999	107.50
95 lph	M99	23.70°C		9.24	1.6445		16,856	148.09
	50-D	22.87°C		9.65	0.5692		50,861	150.73
125 lph	M99	26.00°C		10.13	1.6356		18,580	179.9
	50-D	22.39°C		10.87	0.5702		57,190	186.77
Turbines	M99	25.00°C	0.0254	6.69	1.6114	0.002	8303	89.37
	50-D	22.47°C		11.00	0.5466		40,249	95.53
	EURO	20.98°C		11.00	0.5659		38,976	94.94

Table 5.5.2a: Summary of Re Numbers for Each Pump in Each Fluid at 13.2V/310 kPa

The characteristic length (D_L) was estimated to be 3.00 mm for the gerotor pumps based on the width of the flow passage through the motor on top of the windings. This length was estimated to be

2.00 mm for the turbine pumps based on the clearance between the housing and a blade tip of the impeller. The characteristic velocities for each pump in each test fluid were estimated by the following:

$$\omega = N \cdot 2\pi \cdot \left(\frac{1 \text{ min}}{60 \text{ s}}\right) \left(\frac{\text{rads}}{\text{s}}\right)$$

N_{avg} = Average pump speed in rpm (over all runs for each pump type)*. (These are given in APPENDIX L.)

$$V = \omega \cdot r \left(\frac{\text{m}}{\text{s}}\right)$$

$$r_{\omega} = 0.0127 \text{ m} \quad (D_{\omega} = 0.0254 \text{ m})$$

* Note: For the turbine speed in Eurosuper, this value was estimated by using the N_{avg} in the 50-D gasoline for the turbine pumps tested at the ETC Lab.

These Re values in Table 5.5.2a are more than three times larger in gasoline than in the M99-solvent at fixed temperatures. These large Re numbers, in both fluids, indicate turbulent flow. For the gerotor pump, the viscous effect of each fluid on the pump is the same. This was evidenced by the flow being nearly equal in each test fluid. For the turbine pump, however, the viscous effect of each test fluid on the pump is more apparent as its flow does change in each test fluid. In other words, for the turbine pumps, as the kinematic viscosity decreases, the Re values increase, and the flow increases.

Pump Similarity Rules

To further understand the effects of different fluids on fuel pump performance and verify the findings regarding fuel pump efficiency and the Re values, pump similarity rules were applied to the fluid property data (specific gravity, kinematic viscosity only) that was collected during the Phase II testing. These similarity rules can be used to estimate the effect on performance of changing fluid, speed, or size of any dynamic turbomachine, pump, or turbine within a geometrically similar family. An assumption was made here: these rules could also be applied to the positive displacement or gerotor pumps. If pump #1 and pump #2 are from the same geometric family (size constant) and are operating at the same point (i.e., fixed voltage and pressure), their flow rates, heads, and powers can be related as follows:[27]

[27] White, Frank M, 650.

$\frac{Q_2}{Q_1} = \frac{N_2}{N_1} \cdot (\frac{D_2}{D_1})^3$	FLOW
$\frac{H_2}{H_1} = (\frac{N_2}{N_1})^2 \cdot (\frac{D_2}{D_1})^2$	HEAD
$\frac{\Delta P_2}{\Delta P_1} = \frac{\rho_2}{\rho_1} \cdot (\frac{N_2}{N_1})^2 \cdot (\frac{D_2}{D_1})^2$	PUMP PRESSURE
$\frac{P_2}{P_1} = \frac{\rho_2}{\rho_1} \cdot (\frac{N_2}{N_1})^3 \cdot (\frac{D_2}{D_1})^5$	WATER POWER

Q_i = Flow pump i (lph).
H_i = Pumping head pump i (m).
ΔP_i = Pumping pressure pump i (Pa).
P_i = Power pump i (Watts).
N_i = Speed pump i (rpm).
D_i = Impeller diameter pump i (m).
ρ_i = Density fluid type i ($\frac{kg}{m^3}$).

Since it was decided to determine the effects of different test fluids on fuel pump performance, the above relations could be simplified to the following (derivations shown in APPENDIX L):

$\frac{Q_1}{Q_2} = \sqrt{\frac{SG_2}{SG_1}}$	FLOW
$\frac{H_1}{H_2} = \frac{SG_2}{SG_1}$	HEAD
$\frac{P_1}{P_2} = \sqrt{\frac{SG_2}{SG_1}}$	WATER POWER

Q_i = Flow pump i (lph).
H_i = Pumping head pump i (m).
P_i = Power pump i (Watts).
SG_i = Specific gravity fluid i.

Using results from the Phase II fluid property measurements, the percentage change in the fuel pump performance parameters of flow, head, and water power when pumping the M99-solvent versus the gasolines was calculated. These are shown in Table 5.5.2b below. These relationships apply across all the gerotor models, and the values determined were the same for a 45 lph, 60 lph, 95 lph, or 125 lph pump. The specific gravity values used were the averages across all models at an average temperature.

The average specific gravity was also used for the turbine pumps. In addition, the voltage and pressure at which the pump types were tested do not enter any of these calculations. These similarity relationships gave the same results whether the pumps are tested at 13.2V or 8.0V, because the fluid properties measured were independent of those operating points. However, the similarity values were different between the two different types of pumps, gerotors or turbines, because the relationships cannot be used to compare pumps from two different families.

PUMP TYPE	**FLUID TYPE**	**SG @Tavg**	**%Δ** $Q_{Gas} = Q_{M99} \cdot \sqrt{\frac{SG_{M99}}{SG_{Gas}}}$	**%Δ** $H_{Gas} = H_{M99} \cdot \frac{SG_{M99}}{SG_{Gas}}$	**%Δ** $P_{Gas} = P_{M99} \cdot \sqrt{\frac{SG_{M99}}{SG_{Gas}}}$
Gerotor	M99 50-D	0.7779 0.7419	$Q_{50\text{-}D} = 1.024Q_{M99}$ 2.4%	$H_{50\text{-}D} = 1.048H_{M99}$ 4.85%	$P_{50\text{-}D} = 1.024P_{M99}$ 2.4%
Turbine	M99 50-D	0.7819 0.7423	$Q_{50\text{-}D} = 1.026Q_{M99}$ 2.6%	$H_{50\text{-}D} = 1.053H_{M99}$ 5.3%	$P_{50\text{-}D} = 1.026P_{M99}$ 2.6%
	EURO	0.7526	$Q_{EURO} = 1.019Q_{M99}$ 1.9%	$H_{EURO} = 1.039H_{M99}$ 3.9%	$P_{EURO} = 1.019P_{M99}$ 1.9%
			$Q_{50\text{-}D} = 0.993Q_{EURO}$ (0.70%)	$H_{50\text{-}D} = 0.986H_{EURO}$ (1.37%)	$P_{50\text{-}D} = 0.993P_{EURO}$ (0.70%)

Table 5.5.2b: Effects of Test Fluid on Pump Performance using Pump Similarity Rules

As can be seen from the above results, the percentage change in pump performance when pumping different fluids is small. This is due to the specific gravities of the test fluids only.

BIBLIOGRAPHY

1. Fay, James A. Introduction to Fluid Mechanics. Massachusetts: Unpublished, 1991.

2. White, Frank M. Fluid Mechanics. New York: McGraw-Hill, Inc., 1979.

3. Streeter, Victor L. Fluid Mechanics. New York: McGraw-Hill, Inc., 1979.

4. Karassik, Krutzsch, et. al. Pump Handbook. New York: McGraw-Hill, Inc., 1986.

5. Warring, R. H. Pumps: Selection, Systems and Applications. England: Trade and Technical Press Ltd., 1984.

6. Sabersky, R. H., Acosta, A. J., et. al. Fluid Flow: A First Course in Fluid Mechanics. New York: Macmillan Co., 1971.

7. Holland, F. A. and Chapman, F. S. Pumping of Liquids. New York: Reinhold Publishing Co., 1966.

8. White, Frank M. Viscous Fluid Flow. New York: McGraw-Hill, Inc., 1991.

9. Box, G. E. P., Hunter, and Hunter. Statistics for Experimenters: An Introduction to Design, Data Analysis, and Model Building. New York: John Wiley and Sons, Inc., 1978.

10. Spiegel, Murray R. Schaum's Outline Series: Theory and Problems of Statistics. New York: McGraw-Hill, Inc., 1991.

11. Montgomery, Douglas C. Introduction to Statistical Quality Control. New York: John Wiley and Sons, Inc., 1991.

12. Devore, Jay L. Probability and Statistics for Engineering and the Sciences. California: Wadsworth, Inc., 1987.

13. Montgomery, Douglas C. Design and Analyis of Experiments. New York: John Wiley and Sons, Inc., 1991.

14. Neter, John, Wasserman, William, and Kutner, Michael H. Applied Linear Regression Models. Massachusetts: Richard D. Irwin, Inc., 1989.

15. Cochran, William G. Sampling Techniques. New York: John Wiley and Sons, Inc., 1977.

BIBLIOGRAPHY (Continued)

16. Hogg, Robert V. and Ledolter, Johannes. Applied Statistics for Engineers and Physical Scientists. New York: Macmillan Publishing Co., 1992.

17. A.I.A.G. Measurement Systems Analysis Reference Manual. Troy, Michigan: Sandy Corporation, 1990.

18. Electro-Craft Corporation. DC Motors, Speed Controls, Servo Systems: An Engineering Handbook. Minnesota: 1980.

19. Garret, T. K. Automotive Fuels and Fuel Systems: Volume 1: Gasoline. London: Pentech Press, S.A.E., Inc., 1991.

20. General Motors. AC Spark Plug In-tank Fuel Pump and Fuel Level Sender Application Guide. 1988.

21. ---------------. The Regenerative Pump. Ford Motor Company.

22. ---------------. Fluid Mechanics Book: Chapter 11: Regenerative Pumps.

23. Kobayashi, Hisanori and Nakamura, Toshiaki. Fuel Pump Paper. Japan: Nippondenso.

24. ---------------. The Gerotor Advantage. Unknown Supplier.

25. Hattori, Yoshiyuki and Shinoda, Kazuo. Development of a Turbine In-tank Fuel Pump. Pennsylvania: S.A.E. Inc., 1987. (#870121)

26. Kemmner, Ulrich, Rollwage, Mathias, et. al. New Generation of BOSCH Electrical Fuel-Pumps--Improvement in Hot-Fuel Handling and Noise. Pennsylvania: S.A.E. Inc., 1987. (#870120)

27. Reddy, S. Raghuma. Prediction of Fuel Vapor Generation from a Vehicle Fuel Tank as a Function of Fuel RVP and Temperature. Pennsylvania: S.A.E. Inc., 1989. (#892089)

28. Nakano, Masatoshi and Iwamoto, Tadamitsu. Analysis of the Behavior of Liquid in a Fuel Tank. Pennsylvania: S.A.E. Inc., 1988. (#872145)

29. Schellhase, H. U. and Colwell, M. J. Prediction of Long-Term Storage Stabilities of Fuels by Thermal Analysis (Pressure-DSC). Pennsylvania: S.A.E., Inc., 1987. (#872145)

BIBLIOGRAPHY (Continued)

30. Jones, Colin. Fuel Injection Systems Paper. Ford Motor Company, Electrical and Fuel Handling Division.

31. Yu, Dequan. Fuel Pumps--A Brief Technical Overview. Ford Motor Company, Electrical and Fuel Hanling Division, 1991.

APPENDICES

APPENDIX A

PHASE I: ETC/Alba Fuel Lab Gage Capability Comparison
Two-station Performance Test Stand
Fluids: ESE-M4C50-D Gasoline and ESF-M99C82-A Solvent

Referring to Tables A1 and A2:

1000 Hour 60 lph and 95 lph Gerotor Pumps (ETC only):

- The $6\sigma_{R\&R}$ estimates for the flow, current, and speed measurements at 10.0V are two to three times larger in the gasoline than in the solvent for each gerotor model.
- Independent of voltage, the average flow and speed are equivalent across the test fluids for each model.
- Independent of test fluid and voltage, the $6\sigma_{R\&R}$ estimates for the current draw are two times larger for the 60 lph pumps and exceed one amp for all the models.
- At 10.0V, the 60 lph pumps possess larger $6\sigma_{R\&R}$ estimates for the flow, current, and speed measurements in both test fluids. This does not exist for the 13.2V operating point; both pump types possess similar $6\sigma_{R\&R}$ estimates.

"Master" Turbine Pumps (ETC and Alba):

- In gasoline at all voltages and between both Labs, the $6\sigma_{R\&R}$ estimates for the flow, and speed measurements are similar; on average, the $6\sigma_{R\&R}$ for current is lower at the Alba Lab. (Test stand is repeatable regardless of voltage or fixed pressure across both Labs in gasoline.)
- Independent of operating voltages, average flow and speed values are equivalent between Labs in gasoline; average current is lower at Alba Lab in gasoline.
- The $6\sigma_{R\&R}$ estimates for flow, current, and speed measurements are not equivalent across operating points and test sites in the solvent; are two times higher at the ETC Lab. (Indicates sensitivity of turbine pumps to more viscous fluid, integrity of the same fluid used between the test sites, and other "noise" or variability entering into the results from the ETC Lab.)
- Independent of operating voltages, average flow, current, and speed are not equivalent between the Labs in the solvent; all average values are lower at the Alba Lab. (Indicates same as above.)

PRE-PHASE II: ETC/Rawsonville and Alba/Plant Gage Capability Comparison
Two-station Performance Test Stand/Fuel Pump Production
Test Stands: ESF-M99C82-A Solvent

Referring to Tables A3-A4:

- When testing "master" 60 lph pumps, there is a significant difference between the average flow and current measurements obtained from the two-station stand at the ETC Lab and from the Rawsonville production stands at 13.2V.
- Higher outlet flow indicates higher pressure at 13.2V on the Rawsonville production test stands.
- When testing "master" turbine pumps, there is a difference between the average flow measurements obtained from the production stands and from on the two-station stand at each Lab.

PHASE II: Test Fluid Correlation After Pump Break-in
Two-station Performance Test Stand Gerotors and Turbine Pumps
ESE-M4C50-D Gasoline versus ESF-M99C82-A Solvent versus Eurosuper95

- An approximate one-to-one fluid correlation (good regression model) over the entire flow and current performance curves was determined for the turbine pumps. This does not mean that turbine pump flow in M99 is equivalent to turbine flow in gas. Phase I and Pre-Phase II results indicate lower flow averages at given voltages in the solvent.

- The test fluid type is one of the major sources of variability in the performance measurements between the Alba Plant and Lab for the turbine pumps. The driving force of this variability is the viscosity values of the fluids. Another source of variability, holding the solvent constant, could be the way the turbine pump is positioned in the part pocket of the production stand and the method of outlet sealing by the fixture head; these could result in flow losses.
- Turbine pump performance in the Eurosuper gasoline is equivalent to the ESE-M4C50-D over various voltages and pressures; performance measurements in ESE-M4C50-D versus ESF-M99C82-A are also equivalent to Eurosuper versus ESF-M99C82-A. This is shown in Chapter 4.

Fluid Temp: 19 C - 25 C

		TWO-STATION PERFORMANCE TEST STAND #2					
		ETC FUEL LAB-ESE-M4C50-D GASOLINE			ETC FUEL LAB-M99C82A-SOLVENT		
		FLOW 10.0V/270 KPA (LPH)	CURRENT 10.0V/270 KPA (AMPS)	SPEED 10.0V/270 KPA (RPM)	FLOW 10.0V/270 KPA (LPH)	CURRENT 10.0V/270 KPA (AMPS)	SPEED 10.0V/270 KPA (RPM)
95 LPH (gcv)	GRAND MEAN	101.879	4.518	5085.194	102.535	4.148	4937.583
(2) pumps	6σP&P	12.501	1.205	655.519	7.782	0.596	347.818
60 (LPH)	GRAND MEAN	71.078	3.313	3817.484	73.882	3.004	3757.983
(2) pumps	6σP&P	22.244	2.049	1226.566	9.087	1.145	424.935

(1000 HOUR PUMPS)

Fluid Temp: 19 C - 25 C

		TWO-STATION PERFORMANCE TEST STAND #2					
		ETC FUEL LAB-ESE-M4C50-D GASOLINE			ETC FUEL LAB-M99C82A-SOLVENT		
		FLOW 13.2V/386/310 KPA (LPH)	CURRENT 13.2V/386/310 KPA (AMPS)	SPEED 13.2V/386/310 KPA (RPM)	FLOW 13.2V/386/310 KPA (LPH)	CURRENT 13.2V/386/310 KPA (AMPS)	SPEED 13.2V/386/310 KPA (RPM)
95 LPH (gcv)	GRAND MEAN	139.614	6.156	6877.175	138.949	5.790	6672.686
(2) pumps	6σP&P	15.299	1.402	618.518	15.365	0.654	677.258
60 (LPH)	GRAND MEAN	108.238	3.738	5487.303	109.270	3.646	5358.531
(2) pumps	6σP&P	13.851	1.627	605.772	10.559	1.077	587.302

(95 lph pumps @ 13.2V/386 kPa)
(1000 HOUR PUMPS)

Table A1: PHASE I: Two-station Performance Test Stand Gage Capability in terms of Repeatability and Reproducibility

Fluid Temp: 19 C - 25 C

		TWO-STATION PERFORMANCE TEST STAND #2								
		ESE-M4C50-D GASOLINE			ESE-M4C50-D GASOLINE			ESE-M4C50-D GASOLINE		
		FLOW 8.0V/200 KPA (LPH)	CURRENT 8.0V/200 KPA (AMPS)	SPEED 8.0V/200 KPA (RPM)	FLOW 8.0V/250 KPA (LPH)	CURRENT 8.0V/250 KPA (AMPS)	SPEED 8.0V/250 KPA (RPM)	FLOW 13.2V/310 KPA (LPH)	CURRENT 13.2V/310 KPA (AMPS)	SPEED 13.2V/310 KPA (RPM)
ETC FUEL LAB	GRAND MEAN	30.426	3.093	4717.071	15.650	3.465	4561.163	99.953	5.188	8255.776
	6σP&P	8.664	0.247	348.479	9.841	0.250	364.974	10.390	0.370	510.862
ALBA FUEL LAB	GRAND MEAN	29.000	2.832	4676.826	14.405	3.212	4526.625	99.238	4.855	8262.056
	6σP&P	8.840	0.132	330.084	9.176	0.152	340.883	9.959	0.657	309.001

(2) "MASTER" TURBINE PUMPS

Fluid Temp: 19 C - 25 C

		TWO-STATION PERFORMANCE TEST STAND #2								
		M99C82A-SOLVENT			M99C82A-SOLVENT			M99C82A-SOLVENT		
		FLOW 8.0V/200 KPA (LPH)	CURRENT 8.0V/200 KPA (AMPS)	SPEED 8.0V/200 KPA (RPM)	FLOW 8.0V/250 KPA (LPH)	CURRENT 8.0V/250 KPA (AMPS)	SPEED 8.0V/250 KPA (RPM)	FLOW 13.2V/310 KPA (LPH)	CURRENT 13.2V/310 KPA (AMPS)	SPEED 13.2V/310 KPA (RPM)
ETC FUEL LAB	GRAND MEAN	23.341	3.279	4344.420	5.786	3.537	4242.944	91.417	5.705	7959.592
	6σP&P	15.543	0.273	551.727	21.901	0.343	499.360	8.909	0.337	2160.057
ALBA FUEL LAB	GRAND MEAN	19.274	2.866	4232.500	4.225	3.117	4180.861	85.363	5.060	7579.542
	6σP&P	7.388	0.133	295.217	19.657	0.281	235.607	5.499	0.271	706.906

(2) "MASTER" TURBINE PUMPS

Table A2: PHASE I: Gage Capability Comparison of the Two-station Performance Test Stand Between the ETC and Alba Fuel Labs in Terms of Repeatability and Reproducibility

(2 "Master" Turbine Pumps)

Test Stand #1 Across LH & RH Fixtures	M99-SOLVENT Tolerance	P/T	6σP&P		Grand Mean
Flow @ 13.2V/310 kPa	40 lph	24.58%	9.833	lph	83.933 lph
Curent @ 13.2V/310 kPa	1.5 amps	11.80%	0.177	amps	5.246 amps
Flow @ 8.0V/200 KPA	12 lph	65.52%	7.862	lph	20.244 lph

Test Stand #2 Across LH & RH Fixtures	M99-SOLVENT Tolerance	P/T	6σP&P		Grand Mean
Flow @ 13.2V/310 kPa	40 lph	17.04%	6.817	lph	84.452 lph
Current @ 13.2V/310 kPa	1.5 amps	32.07%	0.481	amps	5.244 amps
Flow @ 8.0V/200 KPA	12 lph	62.89%	7.547	lph	19.734 lph

Test Stand #3 Across LH & RH Fixtures	M99-SOLVENT Tolerance	P/T	6σP&P		Grand Mean
Flow @ 13.2V/310 kPa	40 lph	24.50%	9.798	lph	84.755 lph
Current @ 13.2V/310 kPa	1.5 amps	36.80%	0.552	amps	5.203 amps
Flow @ 8.0V/200 KPA	12 lph	59.34%	7.121	lph	19.629 lph

Test Stand #4 Across LH & RH Fixtures	M99-SOLVENT Tolerance	P/T	6σP&P		Grand Mean
Flow @ 13.2V/310 kPa	40 lph	19.95%	7.979	lph	80.981 lph
Current @ 13.2V/310 kPa	1.5 amps	40.20%	0.603	amps	5.330 amps
Flow @ 8.0V/200 KPA	12 lph	60.18%	7.222	lph	19.417 lph

Test Stand #5 Across LH & RH Fixtures	M99-SOLVENT Tolerance	P/T	6σP&P		Grand Mean
Flow @ 13.2V/310 kPa	40 lph	24.06%	9.622	lph	85.580 lph
Current @ 13.2V/310 kPa	1.5 amps	14.13%	0.212	amps	5.092 amps
Flow @ 8.0V/200 KPA	12 lph	72.72%	8.726	lph	20.248 lph

Table A3: PRE-PHASE II: Alba Plant Gage Repeatability and Reproducibility Study of the Fuel Pump Production Test Stands

	ALBA PLANT			
M99-SOLVENT	Tolerance	P/T All Fixtures	AVERAGE 6σP&P All Fixtures	GRAND MEAN All Fixtures
Flow @ 13.2V/310 kPa	40 lph	22.23%	8.893 lph	83.940 lph
Amps @ 13.2V/310 kPa	1.5 amps	29.47%	0.442 amps	5.223 amps
Flow @ 8.0V/200 kPa	12 lph	64.31%	7.717 lph	19.854 lph

(2 "Master" Turbine Pumps)

	ETC LAB		ALBA LAB	
M99-SOLVENT	AVERAGE 6σP&P 2-Station/#2	GRAND MEAN 2-Station/#2	AVERAGE 6σP&P 2-Station/#2	GRAND MEAN 2-Station/#2
Flow @ 13.2V/310 kPa	9.778 lph	93.947 lph	10.157 lph	91.325 lph
Amps @ 13.2V/310 kPa	0.199 amps	5.692 amps	0.682 amps	5.257 amps

(2 "Master" Turbine Pumps)

	ETC LAB		ALBA LAB	
M99-SOLVENT	AVERAGE 6σP&P 2-Station/#2	GRAND MEAN 2-Station/#2	AVERAGE 6σP&P 2-Station/#2	GRAND MEAN 2-Station/#2
Flow @ 8.0V/200 kPa	12.504 lph	23.744 lph	10.395 lph	20.486 lph
Amps @ 8.0V/200 kPa	0.155 amps	3.216 amps	0.377 amps	2.933 amps

(2 "Master" Turbine Pumps)

Table A4: PRE-PHASE II: Fuel Pump Performance Test Equipment Gage Capability Comparison Between the Alba Plant, ETC Lab, and Alba Lab

APPENDIX B

CONSTANTS USED IN THE AVERAGE AND RANGE AND RANGE METHOD OF ANALYSES FOR THE GAGE CAPABILITY STUDIES**

Trials (m)	K1
2	4.56
3	3.05

K1 = 5.15/d2
where d2 is dependent on m and g where g is >15

Operators	2	3
K2	3.65	2.7

K2 = 5.15/d2
where d2 is dependent on m and g where g is 1,
since there is only one range calculation.

Parts	K3
2	3.65
3	2.7
4	2.3
5	2.08
6	1.93
7	1.82
8	1.74
9	1.67
10	1.62

K3 = 5.15/d2
where d2 is dependent on the number of parts and g, where g is 1,
since there is only one range calculation.

	m (trials)													
g	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	1.41	1.91	2.24	2.48	2.67	2.83	2.96	3.08	3.18	3.27	3.35	3.42	3.49	3.55
2	1.28	1.81	2.15	2.4	2.6	2.77	2.91	3.02	3.13	3.22	3.3	3.38	3.45	3.51
3	1.23	1.77	2.12	2.38	2.58	2.75	2.89	3.01	3.11	3.21	3.29	3.37	3.43	3.5
4	1.21	1.75	2.11	2.37	2.57	2.74	2.88	3	3.1	3.2	3.28	3.36	3.43	3.49
5	1.19	1.74	2.1	2.36	2.56	2.73	2.87	2.99	3.1	3.19	3.28	3.35	3.42	3.49
6	1.18	1.73	2.09	2.35	2.56	2.73	2.87	2.99	3.1	3.19	3.27	3.35	3.42	3.49
7	1.17	1.73	2.09	2.35	2.55	2.72	2.87	2.99	3.1	3.19	3.27	3.35	3.42	3.48
8	1.17	1.72	2.08	2.35	2.55	2.72	2.87	2.98	3.09	3.19	3.27	3.35	3.42	3.48
9	1.16	1.72	2.08	2.34	2.55	2.72	2.86	2.98	3.09	3.18	3.27	3.35	3.42	3.48
10	1.16	1.72	2.08	2.34	2.55	2.72	2.86	2.98	3.09	3.18	3.27	3.34	3.42	3.48
11	1.16	1.71	2.08	2.34	2.55	2.72	2.86	2.98	3.09	3.18	3.27	3.34	3.41	3.48
12	1.15	1.71	2.07	2.34	2.55	2.72	2.85	2.98	3.09	3.18	3.27	3.34	3.41	3.48
13	1.15	1.71	2.07	2.34	2.55	2.71	2.85	2.98	3.09	3.18	3.27	3.34	3.41	3.48
14	1.15	1.71	2.07	2.34	2.54	2.71	2.85	2.98	3.08	3.18	3.27	3.34	3.41	3.48
15	1.15	1.71	2.07	2.34	2.54	2.71	2.85	2.98	3.08	3.18	3.26	3.34	3.41	3.48
>15	1.128	1.693	2.059	2.326	2.534	2.704	2.847	2.97	3.078	3.173	3.258	3.336	3.407	3.472

Table of d2 Values used for the Range and Average and Range Method of Analyses for the Gage Repeatability Studies

g = number of parts * operators

** Adapted from page 21 and pg 44 of Measurements Systems Analysis Manual, 1990.

APPENDIX C

$$SS_p = \sum_{i=1}^{n} \frac{x_{i..}^2}{kr} - \frac{x^2_{...}}{nkr} \qquad TSS = \sum_{i=1}^{n}\sum_{j=1}^{k}\sum_{m=1}^{r} x_{ijk}^2 - \frac{x^2_{...}}{nkr}$$

$$SS_o = \sum_{j=1}^{k} \frac{x_{.j.}^2}{nr} - \frac{x^2_{...}}{nkr} \qquad SS_e = TSS - [SS_o + SS_p + SS_{op}]$$

$$SS_{op} = \sum_{i=1}^{n}\sum_{j=1}^{k} \frac{x_{ij.}^2}{r} - \sum_{i=1}^{n}\frac{x_{i..}^2}{kr} - \sum_{j=1}^{k}\frac{x_{.j.}^2}{nr} + \frac{x^2_{...}}{nkr} \qquad I = 1, \ldots n \quad J = 1, \ldots k \quad M = 1, \ldots r$$

ANOVA

Source	**DF**	**SS**	**MS**	**EMS**	**F**
Operator	k–1	SS_o	$SS_o/k - 1 = MS_o$	$\tau^2 + r\gamma^2 + nr\omega^2$	
Parts	n–1	SS_p	$SS_p/n - 1 = MS_p$	$\tau^2 + r\gamma^2 + kr\sigma^2$	
Oper x Part	(n–1)(k–1)	SS_{op}	$SS_{op}/(n-1)(k-1) = MS_{op}$	$\tau^2 + r\gamma^2$	$\frac{MS_{op}}{MS_e}$
Gage (Error)	nk (r–1)	SS_e	$SS_e/nk(r-1) = MS_e$	τ^2	
Total	nkr – 1	TSS			

Operator – $N(o, \alpha^{2)}$
Parts – $N(0, \omega^2)$
Oper × Part – $N(o, \gamma^2)$
Gage(Error) – $N(o, \tau^2)$

APPENDIX D

	TWO-STATION PERFORMANCE TEST STAND #2					
	(2) "MASTER" 60 LPH GEROTOR PUMPS IN M99-SOLVENT @ 19-25 DEGREES CELSIUS					
	ETC FUEL LAB			ETC FUEL LAB		
	FLOW 10.0V/270 KPA (LPH)	CURRENT 10.0V/270 KPA (AMPS)	SPEED 10.0V/270 KPA (RPM)	FLOW 13.2V/310 KPA (LPH)	CURRENT 13.2V/310 KPA (AMPS)	SPEED 13.2V/310 KPA (RPM)
GRAND MEAN	73.882	3.004	3757.983	109.270	3.646	5358.531
STANDARD DEVIATION ESTIMATES						
Repeatability	1.514	0.191	70.822	1.760	0.180	97.884
Reproducibility (operator)	0.000	0.000	0.000	0.000	0.000	0.000
Interaction (part*operator)	N/A	N/A	N/A	N/A	N/A	N/A
R&R	**1.497**	**0.188**	**69.671**	**1.746**	**0.177**	**96.467**
Part	1.353	0.059	0.000	0.000	0.070	37.425
MEASURES OF SPREAD (6*SIGMA)						
Equipment Variation	9.087	1.145	424.935	10.559	1.077	587.302
Operator Variation	0.000	0.000	0.000	0.000	0.000	0.000
Interaction Variation	N/A	N/A	N/A	N/A	N/A	N/A
R&R Variation	**9.087**	**1.145**	**424.935**	**10.559**	**1.077**	**587.302**
Part Variation	8.118	0.352	0.000	0.000	0.417	224.547
TOTAL VARIATION	**12.185**	**1.198**	**424.935**	**10.559**	**1.155**	**628.765**
% CONTRIBUTION TO TOTAL VARIATION						
Equipment Variation	55.61%	91.34%	100.00%	100.00%	86.95%	87.25%
Operator Variation	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Interaction Variation	N/A	N/A	N/A	N/A	N/A	N/A
R&R Variation	**55.61%**	**91.34%**	**100.00%**	**100.00%**	**86.95%**	**87.25%**
Part Variation	44.39%	8.66%	0.00%	0.00%	13.05%	12.75%
TOTAL VARIATION (WITHOUT PART)	**9.087**	**1.145**	**424.935**	**10.559**	**1.077**	**587.302**

Table D1: Phase I Summary--60 lph Gerotors

	TWO-STATION PERFORMANCE TEST STAND #2					
	(2) "MASTER" 60 LPH GEROTOR PUMPS IN ESE-M4C50-D GAS @ 19-25 DEGREES CELSIUS					
	ETC FUEL LAB			ETC FUEL LAB		
	FLOW 10.0V/270 KPA (LPH)	CURRENT 10.0V/270 KPA (AMPS)	SPEED 10.0V/270 KPA (RPM)	FLOW 13.2V/310 KPA (LPH)	CURRENT 13.2V/310 KPA (AMPS)	SPEED 13.2V/310 KPA (RPM)
GRAND MEAN	71.078	3.313	3817.484	108.238	3.738	5487.303
STANDARD DEVIATION ESTIMATES						
Repeatability	3.707	0.342	204.428	2.308	0.271	100.962
Reproducibility (operator)	0.000	0.000	0.000	0.000	0.000	0.000
Interaction (part*operator)	N/A	N/A	N/A	N/A	N/A	N/A
R&R	**3.666**	**0.337**	**202.855**	**2.274**	**0.268**	**99.495**
Part	1.342	0.070	0.000	2.158	0.135	0.000
MEASURES OF SPREAD (6*SIGMA)						
Equipment Variation	22.244	2.049	1226.566	13.851	1.627	605.772
Operator Variation	0.000	0.000	0.000	0.000	0.000	0.000
Interaction Variation	N/A	N/A	N/A	N/A	N/A	N/A
R&R Variation	**22.244**	**2.049**	**1226.566**	**13.851**	**1.627**	**605.772**
Part Variation	8.049	0.422	0.000	12.945	0.811	0.000
TOTAL VARIATION	**23.656**	**2.092**	**1226.566**	**18.958**	**1.818**	**605.772**
% CONTRIBUTION TO TOTAL VARIATION						
Equipment Variation	88.42%	95.93%	100.00%	53.38%	80.09%	100.00%
Operator Variation	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Interaction Variation	N/A	N/A	N/A	N/A	N/A	N/A
R&R Variation	**88.42%**	**95.93%**	**100.00%**	**53.38%**	**80.09%**	**100.00%**
Part Variation	11.58%	4.07%	0.00%	46.62%	19.91%	0.00%
TOTAL VARIATION (WITHOUT PART)	**22.244**	**2.049**	**1226.566**	**13.851**	**1.627**	**605.772**

Table D2: Phase I Summary--60 lph Gerotors

	TWO-STATION PERFORMANCE TEST STAND #2					
	(2) "MASTER" 95 LPH (gcv) GEROTOR PUMPS IN M99-SOLVENT @ 19-25 DEGREES CELSIUS					
	ETC FUEL LAB			ETC FUEL LAB		
	FLOW 10.0V/270 KPA (LPH)	CURRENT 10.0V/270 KPA (AMPS)	SPEED 10.0V/270 KPA (RPM)	FLOW 13.2V/386 KPA (LPH)	CURRENT 13.2V/386 KPA (AMPS)	SPEED 13.2V/386 KPA (RPM)
GRAND MEAN	102.535	4.148	4937.583	138.949	5.790	6672.686
STANDARD DEVIATION ESTIMATES						
Repeatability	1.289	0.099	56.635	2.561	0.108	112.876
Reproducibility (operator)	0.143	0.000	12.384	0.000	0.016	0.000
Interaction (part*operator)	N/A	N/A	N/A	N/A	N/A	N/A
R&R	**1.297**	**0.098**	**57.973**	**2.526**	**0.109**	**111.504**
Part	1.052	0.000	27.956	1.099	0.000	71.376
MEASURES OF SPREAD (6*SIGMA)						
Equipment Variation	7.735	0.596	339.809	15.365	0.647	677.258
Operator Variation	0.856	0.000	74.305	0.000	0.094	0.000
Interaction Variation	N/A	N/A	N/A	N/A	N/A	N/A
R&R Variation	**7.782**	**0.596**	**347.838**	**15.365**	**0.654**	**677.258**
Part Variation	6.312	0.000	167.739	6.594	0.000	428.253
TOTAL VARIATION	**10.020**	**0.596**	**386.170**	**16.720**	**0.654**	**801.299**
% CONTRIBUTION TO TOTAL VARIATION						
Equipment Variation	59.59%	100.00%	77.43%	84.45%	97.92%	71.44%
Operator Variation	0.73%	0.00%	3.70%	0.00%	2.08%	0.00%
Interaction Variation	N/A	N/A	N/A	N/A	N/A	N/A
R&R Variation	**60.32%**	**100.00%**	**81.13%**	**84.45%**	**100.00%**	**71.44%**
Part Variation	39.68%	0.00%	18.87%	15.55%	0.00%	28.56%
TOTAL VARIATION (WITHOUT PART)	**7.782**	**0.596**	**347.838**	**15.365**	**0.654**	**677.258**

Table D3: Phase I Summary--95 lph Gerotors

	TWO-STATION PERFORMANCE TEST STAND #2					
	(2) "MASTER" 95 LPH (gcv) GEROTOR PUMPS IN ESE-M4C50-D GAS @ 19-25 DEGREES CELSIUS					
	ETC FUEL LAB			ETC FUEL LAB		
	FLOW 10.0V/270 KPA (LPH)	CURRENT 10.0V/270 KPA (AMPS)	SPEED 10.0V/270 KPA (RPM)	FLOW 13.2V/386 KPA (LPH)	CURRENT 13.2V/386 KPA (AMPS)	SPEED 13.2V/386 KPA (RPM)
GRAND MEAN	101.879	4.518	5085.194	139.614	6.156	6877.175
STANDARD DEVIATION ESTIMATES						
Repeatability	2.077	0.201	106.993	2.550	0.234	102.454
Reproducibility (operator)	0.158	0.000	22.109	0.000	0.000	11.396
Interaction (part*operator)	N/A	N/A	N/A	N/A	N/A	N/A
R&R	**2.083**	**0.199**	**109.253**	**2.519**	**0.231**	**103.086**
Part	3.009	0.435	191.942	4.619	0.533	246.267
MEASURES OF SPREAD (6*SIGMA)						
Equipment Variation	12.465	1.205	641.957	15.299	1.402	614.726
Operator Variation	0.946	0.000	132.651	0.000	0.000	68.377
Interaction Variation	N/A	N/A	N/A	N/A	N/A	N/A
R&R Variation	**12.501**	**1.205**	**655.519**	**15.299**	**1.402**	**618.518**
Part Variation	18.053	2.609	1151.653	27.714	3.196	1477.604
TOTAL VARIATION	**21.958**	**2.874**	**1325.145**	**31.656**	**3.490**	**1601.836**
% CONTRIBUTION TO TOTAL VARIATION						
Equipment Variation	32.22%	17.58%	23.47%	23.36%	16.13%	14.73%
Operator Variation	0.19%	0.00%	1.00%	0.00%	0.00%	0.18%
Interaction Variation	N/A	N/A	N/A	N/A	N/A	N/A
R&R Variation	**32.41%**	**17.58%**	**24.47%**	**23.36%**	**16.13%**	**14.91%**
Part Variation	67.59%	82.42%	75.53%	76.64%	83.87%	85.09%
TOTAL VARIATION (WITHOUT PART)	**12.501**	**1.205**	**655.519**	**15.299**	**1.402**	**618.518**

Table D4: Phase I Summary--95 lph Gerotors

	TWO-STATION PERFORMANCE TEST STAND #2					
	(2) "MASTER" TURBINE PUMPS IN M99-SOLVENT @ 19-25 DEGREES CELSIUS					
	ETC FUEL LAB			ALBA FUEL LAB		
	FLOW 8.0V/200 KPA (LPH)	CURRENT 8.0V/200 KPA (AMPS)	SPEED 8.0V/200 KPA (RPM)	FLOW 8.0V/200 KPA (LPH)	CURRENT 8.0V/200 KPA (AMPS)	SPEED 8.0V/200 KPA (RPM)
GRAND MEAN	23.341	3.279	4344.420	19.274	2.866	4232.500
STANDARD DEVIATION ESTIMATES						
Repeatability	2.583	0.044	91.955	1.142	0.022	44.656
Reproducibility (operator)	0.194	0.012	0.000	0.460	0.000	20.658
Interaction (part*operator)	N/A	N/A	N/A	N/A	N/A	N/A
R&R	**2.590**	**0.046**	**91.758**	**1.231**	**0.027**	**49.203**
Part	0.000	0.071	0.000	1.048	0.062	47.396
MEASURES OF SPREAD (6*SIGMA)						
Equipment Variation	15.499	0.264	551.727	6.854	0.133	267.937
Operator Variation	1.166	0.070	0.000	2.759	0.000	123.948
Interaction Variation	N/A	N/A	N/A	N/A	N/A	N/A
R&R Variation	**15.543**	**0.273**	**551.727**	**7.388**	**0.133**	**295.217**
Part Variation	0.000	0.428	0.000	6.286	0.375	284.373
TOTAL VARIATION	**15.543**	**0.508**	**551.727**	**9.700**	**0.398**	**409.904**
% CONTRIBUTION TO TOTAL VARIATION						
Equipment Variation	99.44%	27.06%	100.00%	49.92%	11.12%	42.73%
Operator Variation	0.56%	1.87%	0.00%	8.09%	0.00%	9.14%
Interaction Variation	N/A	N/A	N/A	N/A	N/A	N/A
R&R Variation	**100.00%**	**28.93%**	**100.00%**	**58.01%**	**11.12%**	**51.87%**
Part Variation	0.00%	71.07%	0.00%	41.99%	88.88%	48.13%
TOTAL VARIATION (WITHOUT PART)	**15.543**	**0.273**	**551.727**	**7.388**	**0.133**	**295.217**

Table D5: Phase I Summary--Turbine Pumps at 8.0V/200 kPa

	TWO-STATION PERFORMANCE TEST STAND #2					
	(2) "MASTER" TURBINE PUMPS IN M99-SOLVENT @ 19-25 DEGREES CELSIUS					
	ETC FUEL LAB			ALBA FUEL LAB		
	FLOW 8.0V/250 KPA (LPH)	CURRENT 8.0V/250 KPA (AMPS)	SPEED 8.0V/250 KPA (RPM)	FLOW 8.0V/250 KPA (LPH)	CURRENT 8.0V/250 KPA (AMPS)	SPEED 8.0V/250 KPA (RPM)
GRAND MEAN	5.786	3.537	4242.944	4.225	3.117	4180.861
STANDARD DEVIATION ESTIMATES						
Repeatability	3.650	0.057	83.227	3.276	0.044	39.268
Reproducibility (operator)	0.000	0.000	0.000	0.000	0.015	0.000
Interaction (part*operator)	N/A	N/A	N/A	N/A	N/A	N/A
R&R	**3.593**	**0.056**	**82.354**	**3.252**	**0.047**	**39.057**
Part	1.219	0.070	0.000	0.548	0.054	51.404
MEASURES OF SPREAD (6*SIGMA)						
Equipment Variation	21.901	0.343	499.360	19.657	0.266	235.607
Operator Variation	0.000	0.000	0.000	0.000	0.089	0.000
Interaction Variation	N/A	N/A	N/A	N/A	N/A	N/A
R&R Variation	**21.901**	**0.343**	**499.360**	**19.657**	**0.281**	**235.607**
Part Variation	7.317	0.418	0.000	3.287	0.326	308.427
TOTAL VARIATION	**23.091**	**0.541**	**499.360**	**19.930**	**0.430**	**388.120**
% CONTRIBUTION TO TOTAL VARIATION						
Equipment Variation	89.96%	40.28%	100.00%	97.28%	38.25%	36.85%
Operator Variation	0.00%	0.00%	0.00%	0.00%	4.26%	0.00%
Interaction Variation	N/A	N/A	N/A	N/A	N/A	N/A
R&R Variation	**89.96%**	**40.28%**	**100.00%**	**97.28%**	**42.51%**	**36.85%**
Part Variation	10.04%	59.72%	0.00%	2.72%	57.49%	63.15%
TOTAL VARIATION (WITHOUT PART)	**21.901**	**0.343**	**499.360**	**19.657**	**0.281**	**235.607**

Table D6: Phase I Summary--Turbine Pumps at 8.0V/250 kPa

	TWO-STATION PERFORMANCE TEST STAND #2					
	(2) "MASTER" TURBINE PUMPS IN M99-SOLVENT @ 19-25 DEGREES CELSIUS					
	ETC FUEL LAB			ALBA FUEL LAB		
	FLOW 13.2V/310 KPA (LPH)	CURRENT 13.2V/310 KPA (AMPS)	SPEED 13.2V/310 KPA (RPM)	FLOW 13.2V/310 KPA (LPH)	CURRENT 13.2V/310 KPA (AMPS)	SPEED 13.2V/310 KPA (RPM)
GRAND MEAN	91.417	5.705	7959.592	85.363	5.060	7579.542
STANDARD DEVIATION ESTIMATES						
Repeatability	1.455	0.047	353.835	0.869	0.035	113.649
Reproducibility (operator)	0.299	0.030	66.390	0.290	0.029	31.062
Interaction (part*operator)	N/A	N/A	N/A	N/A	N/A	N/A
R&R	**1.485**	**0.056**	**360.009**	**0.917**	**0.045**	**117.818**
Part	0.000	0.123	186.321	3.566	0.091	125.934
MEASURES OF SPREAD (6*SIGMA)						
Equipment Variation	8.727	0.284	2123.009	5.216	0.209	681.896
Operator Variation	1.793	0.181	398.341	1.741	0.172	186.371
Interaction Variation	N/A	N/A	N/A	N/A	N/A	N/A
R&R Variation	**8.909**	**0.337**	**2160.057**	**5.499**	**0.271**	**706.906**
Part Variation	0.000	0.735	1117.923	21.396	0.544	755.605
TOTAL VARIATION	**8.909**	**0.809**	**2432.200**	**22.091**	**0.608**	**1034.725**
% CONTRIBUTION TO TOTAL VARIATION						
Equipment Variation	95.95%	12.34%	76.19%	5.58%	11.79%	43.43%
Operator Variation	4.05%	5.03%	2.68%	0.62%	8.03%	3.24%
Interaction Variation	N/A	N/A	N/A	N/A	N/A	N/A
R&R Variation	**100.00%**	**17.37%**	**78.87%**	**6.20%**	**19.82%**	**46.67%**
Part Variation	0.00%	82.63%	21.13%	93.80%	80.18%	53.33%
TOTAL VARIATION (WITHOUT PART)	**8.909**	**0.337**	**2160.057**	**5.499**	**0.271**	**706.906**

Table D7: Phase I Summary--Turbine Pumps at 13.2V/310 kPa

	TWO-STATION PERFORMANCE TEST STAND #2					
	(2) "MASTER" TURBINE PUMPS IN ESE-M4C50-D GAS @ 19-25 DEGREES CELSIUS					
	ETC FUEL LAB			ALBA FUEL LAB		
	FLOW 8.0V/200 KPA (LPH)	CURRENT 8.0V/200 KPA (AMPS)	SPEED 8.0V/200 KPA (RPM)	FLOW 8.0V/200 KPA (LPH)	CURRENT 8.0V/200 KPA (AMPS)	SPEED 8.0V/200 KPA (RPM)
GRAND MEAN	30.426	3.093	4717.071	29.000	2.832	4676.826
STANDARD DEVIATION ESTIMATES						
Repeatability	1.444	0.040	58.080	1.432	0.022	47.936
Reproducibility (operator)	0.000	0.009	0.000	0.346	0.000	26.995
Interaction (part*operator)	N/A	N/A	N/A	N/A	N/A	N/A
R&R	**1.430**	**0.041**	**57.968**	**1.473**	**0.022**	**55.014**
Part	2.250	0.035	50.550	2.097	0.006	28.603
MEASURES OF SPREAD (6*SIGMA)						
Equipment Variation	8.664	0.241	348.479	8.593	0.132	287.613
Operator Variation	0.000	0.054	0.000	2.078	0.000	161.969
Interaction Variation	N/A	N/A	N/A	N/A	N/A	N/A
R&R Variation	**8.664**	**0.247**	**348.479**	**8.840**	**0.132**	**330.084**
Part Variation	13.501	0.212	303.300	12.584	0.039	171.617
TOTAL VARIATION	**16.042**	**0.325**	**461.983**	**15.379**	**0.137**	**372.032**
% CONTRIBUTION TO TOTAL VARIATION						
Equipment Variation	29.17%	54.81%	56.90%	31.22%	92.01%	59.77%
Operator Variation	0.00%	2.73%	0.00%	1.83%	0.00%	18.95%
Interaction Variation	N/A	N/A	N/A	N/A	N/A	N/A
R&R Variation	**29.17%**	**57.54%**	**56.90%**	**33.04%**	**92.01%**	**78.72%**
Part Variation	70.83%	42.46%	43.10%	66.96%	7.99%	21.28%
TOTAL VARIATION (WITHOUT PART)	**8.664**	**0.247**	**348.479**	**8.840**	**0.132**	**330.084**

Table D8: Phase I Summary--Turbine Pumps at 8.0V/200 kPa

	TWO-STATION PERFORMANCE TEST STAND #2					
	(2) "MASTER" TURBINE PUMPS IN ESE-M4C50-D GAS @ 19-25 DEGREES CELSIUS					
	ETC FUEL LAB			ALBA FUEL LAB		
	FLOW 8.0V/250 KPA (LPH)	CURRENT 8.0V/250 KPA (AMPS)	SPEED 8.0V/250 KPA (RPM)	FLOW 8.0V/250 KPA (LPH)	CURRENT 8.0V/250 KPA (AMPS)	SPEED 8.0V/250 KPA (RPM)
GRAND MEAN	15.650	3.465	4561.163	14.405	3.212	4526.625
STANDARD DEVIATION ESTIMATES						
Repeatability	1.640	0.040	60.829	1.476	0.025	50.276
Reproducibility (operator)	0.000	0.012	0.000	0.399	0.000	26.460
Interaction (part*operator)	N/A	N/A	N/A	N/A	N/A	N/A
R&R	**1.620**	**0.042**	**60.336**	**1.529**	**0.025**	**56.814**
Part	2.657	0.045	57.575	2.380	0.057	49.585
MEASURES OF SPREAD (6*SIGMA)						
Equipment Variation	9.841	0.238	364.974	8.859	0.152	301.656
Operator Variation	0.000	0.075	0.000	2.393	0.000	158.760
Interaction Variation	N/A	N/A	N/A	N/A	N/A	N/A
R&R Variation	**9.841**	**0.250**	**364.974**	**9.176**	**0.152**	**340.883**
Part Variation	15.942	0.271	345.452	14.277	0.342	297.507
TOTAL VARIATION	**18.735**	**0.368**	**502.537**	**16.972**	**0.375**	**452.450**
% CONTRIBUTION TO TOTAL VARIATION						
Equipment Variation	27.59%	41.79%	52.75%	27.24%	16.53%	44.45%
Operator Variation	0.00%	4.13%	0.00%	1.99%	0.00%	12.31%
Interaction Variation	N/A	N/A	N/A	N/A	N/A	N/A
R&R Variation	**27.59%**	**45.92%**	**52.75%**	**29.23%**	**16.53%**	**56.76%**
Part Variation	72.41%	54.08%	47.25%	70.77%	83.47%	43.24%
TOTAL VARIATION (WITHOUT PART)	**9.841**	**0.250**	**364.974**	**9.176**	**0.152**	**340.883**

Table D9: Phase I Summary--Turbine Pumps at 8.0V/250 kPa

	TWO-STATION PERFORMANCE TEST STAND #2					
	(2) "MASTER" TURBINE PUMPS IN ESE-M4C50-D GAS @ 19-25 DEGREES CELSIUS					
	ETC FUEL LAB			ALBA FUEL LAB		
	FLOW 13.2V/310 KPA (LPH)	CURRENT 13.2V/310 KPA (AMPS)	SPEED 13.2V/310 KPA (RPM)	FLOW 13.2V/310 KPA (LPH)	CURRENT 13.2V/310 KPA (AMPS)	SPEED 13.2V/310 KPA (RPM)
GRAND MEAN	99.953	5.188	8255.776	99.238	4.855	8262.056
STANDARD DEVIATION ESTIMATES						
Repeatability	1.648	0.052	80.325	1.544	0.109	49.734
Reproducibility (operator)	0.530	0.033	28.236	0.609	0.000	13.372
Interaction (part*operator)	N/A	N/A	N/A	N/A	N/A	N/A
R&R	**1.732**	**0.062**	**85.144**	**1.660**	**0.108**	**51.500**
Part	3.049	0.000	57.748	3.105	0.050	62.096
MEASURES OF SPREAD (6*SIGMA)						
Equipment Variation	9.890	0.314	481.952	9.264	0.657	298.402
Operator Variation	3.182	0.196	169.417	3.655	0.000	80.235
Interaction Variation	N/A	N/A	N/A	N/A	N/A	N/A
R&R Variation	**10.390**	**0.370**	**510.862**	**9.959**	**0.657**	**309.001**
Part Variation	18.295	0.000	346.489	18.630	0.298	372.579
TOTAL VARIATION	**21.039**	**0.370**	**617.280**	**21.125**	**0.721**	**484.042**
% CONTRIBUTION TO TOTAL VARIATION						
Equipment Variation	22.10%	71.86%	60.96%	19.23%	82.90%	38.00%
Operator Variation	2.29%	28.14%	7.53%	2.99%	0.00%	2.75%
Interaction Variation	N/A	N/A	N/A	N/A	N/A	N/A
R&R Variation	**24.39%**	**100.00%**	**68.49%**	**22.22%**	**82.90%**	**40.75%**
Part Variation	75.61%	0.00%	31.51%	77.78%	17.10%	59.25%
TOTAL VARIATION (WITHOUT PART)	**10.390**	**0.370**	**510.862**	**9.959**	**0.657**	**309.001**

Table D10: Phase I Summary--Turbine Pumps at 13.2V/310 kPa

APPENDIX E

TWO-STATION PERFORMANCE TEST STAND SIDE#2 ETC FUEL LAB/M99-SOLVENT @ 20-25 DEGREES CELSIUS (3) "MASTER" 60 LPH GEROTOR PUMPS	FLOW 13.2V/310 KPA (LPH)	CURRENT 13.2V/310 KPA (AMPS)	SPEED 13.2V/310 KPA (RPM)
GRAND MEAN	113.429	3.738	5490.633
STANDARD DEVIATION ESTIMATES			
Repeatability	0.805	0.042	149.499
Reproducibility (operator)	0.914	0.058	69.225
Interaction (part*operator)	N/A	N/A	N/A
R&R	**1.218**	**0.071**	**164.748**
Part	1.344	0.046	71.887
MEASURES OF SPREAD (6*SIGMA)			
Equipment Variation	4.831	0.254	896.993
Operator Variation	5.485	0.346	415.347
Interaction Variation	N/A	N/A	N/A
R&R Variation	**7.309**	**0.429**	**988.489**
Part Variation	8.064	0.275	431.320
TOTAL VARIATION (WITH PART)	**10.884**	**0.510**	**1078.493**
% CONTRIBUTION TO TOTAL VARIATION INCLUDING PART VARIATION			
Equipment Variation	19.70%	24.85%	69.17%
Operator Variation	25.40%	45.97%	14.83%
Interaction Variation	N/A	N/A	N/A
R&R Variation	**45.10%**	**70.82%**	**84.01%**
Part Variation	54.90%	29.18%	15.99%
TOTAL VARIATION (WITHOUT PART)	**7.309**	**0.429**	**988.489**
% CONTRIBUTION TO TOTAL VARIATION EXCLUDING PART VARIATION			
Equipment Variation	43.68%	35.08%	82.34%
Operator Variation	56.32%	64.92%	17.66%
Interaction Variation	N/A	N/A	N/A
R&R Variation	100.00%	100.00%	100.00%

Table E1: Pre-Phase II Summary--60 lph Gerotors at ETC Fuel Lab

	TEST STAND #1														
	FIXTURE A					FIXTURE B					FIXTURE C				
	DEAD HEAD PRESS. (KPA) 13.2V	OUTLET FLOW (LPH) 13.2V	CURRENT (AMPS) 13.2V	OUTLET LEAK (CCM)	CURRENT (AMPS) 1.5V	DEAD HEAD PRESS. (KPA) 13.2V	OUTLET FLOW (LPH) 13.2V	CURRENT (AMPS) 13.2V	OUTLET LEAK (CCM)	CURRENT (AMPS) 1.5V	DEAD HEAD PRESS. (KPA) 13.2V	OUTLET FLOW (LPH) 13.2V	CURRENT (AMPS) 13.2V	OUTLET LEAK (CCM)	CURRENT (AMPS) 1.5V
GRAND MEAN	554.075	130.013	3.408	0.867	0.735	551.675	129.663	3.449	1.183	0.741	559.300	130.146	3.446	0.421	0.734
SIGMA															
Repeatability	7.004	0.515	0.020	0.050	0.010	7.332	0.797	0.036	0.094	0.011	6.317	0.656	0.019	0.071	0.011
Reproducibility (load vs test side)	0.000	0.000	0.020	0.000	0.008	1.477	0.536	0.023	0.023	0.000	0.000	0.346	0.008	0.021	0.000
Interaction (part*load vs test))	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
R&R	6.729	0.499	0.029	0.048	0.013	7.479	0.961	0.042	0.096	0.010	6.166	0.742	0.021	0.074	0.011
Part	20.264	0.207	0.077	0.000	0.084	19.346	0.284	0.069	0.000	0.079	22.469	1.253	0.106	0.000	0.086
5.15*SIGMA															
Equipment Variation	36.073	2.653	0.104	0.258	0.052	37.761	4.107	0.183	0.482	0.056	32.531	3.380	0.100	0.364	0.058
Load vs Test Side Variation	0.000	0.000	0.105	0.000	0.043	7.606	2.761	0.119	0.118	0.000	0.000	1.784	0.043	0.109	0.000
Interaction Variation	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
R&R Variation	36.073	2.653	0.148	0.258	0.067	38.519	4.948	0.219	0.496	0.056	32.531	3.822	0.109	0.380	0.058
Part Variation	104.361	1.064	0.398	0.000	0.434	99.632	1.462	0.356	0.000	0.407	115.715	6.455	0.544	0.000	0.445
TOTAL VARIATION	110.420	2.858	0.425	0.258	0.439	106.819	5.166	0.418	0.496	0.411	120.201	7.502	0.555	0.380	0.449
% CONTRIBUTION TO TOTAL VARIATION															
Equipment Variation	10.67%	86.15%	5.94%	100.00%	1.38%	12.50%	63.35%	19.21%	94.38%	1.84%	7.32%	20.30%	3.23%	91.72%	1.65%
Load vs Test Side Variation	0.00%	0.00%	6.12%	0.00%	0.96%	0.51%	28.63%	8.14%	5.62%	0.00%	0.00%	5.65%	0.60%	8.28%	0.00%
Interaction Variation	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
R&R Variation	10.67%	86.15%	12.06%	100.00%	2.34%	13.00%	91.97%	27.34%	100.00%	1.84%	7.32%	25.96%	3.83%	100.00%	1.65%
Part Variation	89.33%	13.85%	87.94%	0.00%	97.66%	87.00%	8.03%	72.66%	0.00%	98.16%	92.68%	74.04%	96.17%	0.00%	98.35%

	TEST STAND #2														
	FIXTURE A					FIXTURE B					FIXTURE C				
	DEAD HEAD PRESS. (KPA) 13.2V	OUTLET FLOW (LPH) 13.2V	CURRENT (AMPS) 13.2V	OUTLET LEAK (CCM)	CURRENT (AMPS) 1.5V	DEAD HEAD PRESS. (KPA) 13.2V	OUTLET FLOW (LPH) 13.2V	CURRENT (AMPS) 13.2V	OUTLET LEAK (CCM)	CURRENT (AMPS) 1.5V	DEAD HEAD PRESS. (KPA) 13.2V	OUTLET FLOW (LPH) 13.2V	CURRENT (AMPS) 13.2V	OUTLET LEAK (CCM)	CURRENT (AMPS) 1.5V
GRAND MEAN	559.863	130.379	3.425	1.608	0.741	562.008	128.929	3.385	2.192	0.733	570.721	123.600	3.435	0.563	0.738
SIGMA															
Repeatability	12.791	0.943	0.055	0.046	0.007	19.566	0.420	0.023	0.050	0.013	39.615	1.415	0.029	0.186	0.017
Reproducibility (load vs test side)	2.687	0.000	0.021	0.020	0.005	0.000	1.048	0.020	0.045	0.009	0.000	2.405	0.021	0.162	0.009
Interaction (part*load vs test))	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
R&R	13.071	0.904	0.059	0.050	0.009	19.428	1.129	0.031	0.067	0.016	39.427	2.790	0.036	0.247	0.019
Part	19.584	0.138	0.104	0.022	0.081	18.718	0.807	0.107	0.007	0.082	21.267	2.270	0.094	0.081	0.086
5.15*SIGMA															
Equipment Variation	65.876	4.855	0.282	0.235	0.036	100.764	2.161	0.118	0.258	0.069	204.017	7.288	0.147	0.958	0.089
Load vs Test Side Variation	13.838	0.000	0.110	0.101	0.025	0.000	5.396	0.104	0.231	0.044	0.000	12.386	0.110	0.835	0.045
Interaction Variation	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
R&R Variation	67.313	4.855	0.303	0.256	0.044	100.764	5.819	0.157	0.346	0.082	204.017	14.371	0.184	1.271	0.099
Part Variation	100.859	0.709	0.537	0.114	0.415	96.396	4.154	0.551	0.035	0.424	109.527	11.689	0.485	0.416	0.441
TOTAL VARIATION	121.238	4.907	0.616	0.280	0.417	139.447	7.164	0.573	0.348	0.432	231.550	18.525	0.519	1.337	0.452
% CONTRIBUTION TO TOTAL VARIATION															
Equipment Variation	29.51%	97.91%	20.92%	70.59%	0.76%	52.21%	9.15%	4.24%	54.82%	2.55%	77.63%	15.48%	8.05%	51.30%	3.84%
Load vs Test Side Variation	1.30%	0.00%	3.17%	12.94%	0.36%	0.00%	57.05%	3.28%	44.16%	1.05%	0.00%	44.71%	4.53%	39.02%	0.98%
Interaction Variation	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
R&R Variation	30.83%	97.91%	24.10%	83.53%	1.13%	52.21%	66.19%	7.53%	98.98%	3.60%	77.63%	60.18%	12.58%	90.33%	4.82%
Part Variation	69.18%	2.09%	75.90%	16.47%	98.87%	47.79%	33.81%	92.47%	1.02%	96.40%	22.37%	39.82%	87.42%	9.67%	95.18%

Table E2: Pre-Phase II ANOVA Summary--Rawsonville Plant

TEST STAND #3

	FIXTURE A					FIXTURE B					FIXTURE C				
	DEAD HEAD PRESS. (KPA) 13.2V	OUTLET FLOW (LPH) 13.2V	CURRENT (AMPS) 13.2V	OUTLET LEAK (CCM)	CURRENT (AMPS) 1.5V	DEAD HEAD PRESS. (KPA) 13.2V	OUTLET FLOW (LPH) 13.2V	CURRENT (AMPS) 13.2V	OUTLET LEAK (CCM)	CURRENT (AMPS) 1.5V	DEAD HEAD PRESS. (KPA) 13.2V	OUTLET FLOW (LPH) 13.2V	CURRENT (AMPS) 13.2V	OUTLET LEAK (CCM)	CURRENT (AMPS) 1.5V
GRAND MEAN	561.325	118.167	3.364	0.967	0.723	570.288	129.783	3.406	0.721	0.725	562.588	129.025	3.375	0.713	0.720
SIGMA															
Repeatability	9.203	0.387	0.023	0.094	0.007	23.477	1.288	0.075	0.041	0.011	15.530	0.417	0.019	0.432	0.008
Reproducibility (load vs test side)	0.000	0.221	0.005	0.078	0.000	7.143	0.000	0.013	0.000	0.006	0.000	0.492	0.011	0.193	0.000
Interaction (part*load vs test))	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
R&R	9.109	0.446	0.024	0.122	0.007	24.540	1.268	0.077	0.040	0.012	15.109	0.645	0.022	0.473	0.008
Part	20.211	0.864	0.101	0.097	0.085	20.114	0.648	0.105	0.013	0.081	25.561	1.455	0.112	0.286	0.077
5.15*SIGMA															
Equipment Variation	47.394	1.995	0.120	0.482	0.038	120.907	6.633	0.388	0.210	0.055	79.980	2.147	0.097	2.223	0.042
Load vs Test Side Variation	0.000	1.137	0.025	0.401	0.000	36.786	0.000	0.067	0.000	0.029	0.000	2.535	0.057	0.995	0.000
Interaction Variation	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
R&R Variation	47.394	2.396	0.122	0.627	0.038	126.379	6.633	0.394	0.210	0.063	79.980	3.322	0.113	3.435	0.042
Part Variation	104.087	4.450	0.520	0.501	0.436	103.588	3.336	0.542	0.066	0.417	131.638	7.492	0.575	1.475	0.395
TOTAL VARIATION	114.369	4.997	0.534	0.803	0.437	161.408	7.425	0.679	0.220	0.431	154.030	8.195	0.586	3.847	0.398
% CONTRIBUTION TO TOTAL VARIATION															
Equipment Variation	17.17%	15.87%	5.03%	36.02%	0.75%	54.75%	79.81%	33.57%	91.14%	1.68%	26.96%	6.86%	2.73%	60.96%	1.12%
Load vs Test Side Variation	0.00%	5.16%	0.21%	25.01%	0.00%	5.07%	0.00%	0.99%	0.00%	0.49%	0.00%	9.57%	0.95%	12.21%	0.00%
Interaction Variation	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
R&R Variation	17.17%	21.03%	5.24%	61.03%	0.75%	59.81%	79.81%	34.56%	91.14%	2.17%	26.96%	16.43%	3.69%	73.16%	1.12%
Part Variation	82.83%	78.97%	94.76%	38.97%	99.25%	40.19%	20.19%	65.44%	8.86%	97.83%	73.04%	83.57%	96.31%	26.84%	98.88%

TEST STAND #4

	FIXTURE A					FIXTURE B					FIXTURE C				
	DEAD HEAD PRESS. (KPA) 13.2V	OUTLET FLOW (LPH) 13.2V	CURRENT (AMPS) 13.2V	OUTLET LEAK (CCM)	CURRENT (AMPS) 1.5V	DEAD HEAD PRESS. (KPA) 13.2V	OUTLET FLOW (LPH) 13.2V	CURRENT (AMPS) 13.2V	OUTLET LEAK (CCM)	CURRENT (AMPS) 1.5V	DEAD HEAD PRESS. (KPA) 13.2V	OUTLET FLOW (LPH) 13.2V	CURRENT (AMPS) 13.2V	OUTLET LEAK (CCM)	CURRENT (AMPS) 1.5V
GRAND MEAN	566.525	128.542	3.496	0.119	0.723	577.100	131.900	3.528	0.204	0.730	566.992	129.000	3.601	0.542	0.694
SIGMA															
Repeatability	25.269	0.545	0.028	0.150	0.021	19.193	0.319	0.021	0.108	0.020	36.124	0.524	0.028	0.196	0.006
Reproducibility (load vs test side)	0.000	0.249	0.000	0.000	0.000	0.000	0.474	0.021	0.000	0.016	0.000	0.883	0.033	0.000	0.004
Interaction (part*load vs test))	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
R&R	24.300	0.599	0.027	0.147	0.020	18.554	0.572	0.030	0.104	0.025	34.721	1.026	0.043	0.188	0.007
Part	22.902	0.876	0.068	0.038	0.091	19.718	0.657	0.038	0.033	0.112	29.228	1.239	0.079	0.054	0.078
5.15*SIGMA															
Equipment Variation	130.137	2.805	0.146	0.773	0.106	98.843	1.642	0.107	0.556	0.101	186.039	2.697	0.142	1.008	0.030
Load vs Test Side Variation	0.000	1.283	0.000	0.000	0.000	0.000	2.443	0.108	0.000	0.080	0.000	4.547	0.168	0.000	0.019
Interaction Variation	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
R&R Variation	130.137	3.085	0.146	0.773	0.106	98.843	2.943	0.152	0.556	0.129	186.039	5.286	0.230	1.008	0.036
Part Variation	117.948	4.511	0.348	0.195	0.469	101.549	3.385	0.196	0.170	0.577	150.526	6.380	0.407	0.280	0.400
TOTAL VARIATION	175.634	5.465	0.378	0.798	0.481	141.713	4.486	0.248	0.582	0.591	239.308	8.285	0.463	1.047	0.401
% CONTRIBUTION TO TOTAL VARIATION															
Equipment Variation	54.90%	26.35%	14.96%	94.00%	4.87%	48.65%	13.40%	18.70%	91.47%	2.91%	60.44%	10.59%	9.38%	92.83%	0.55%
Load vs Test Side Variation	0.00%	5.51%	0.00%	0.00%	0.00%	0.00%	29.65%	18.95%	0.00%	1.82%	0.00%	30.11%	13.19%	0.00%	0.23%
Interaction Variation	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
R&R Variation	54.90%	31.86%	14.96%	94.00%	4.87%	48.65%	43.05%	37.65%	91.47%	4.73%	60.44%	40.71%	22.57%	92.83%	0.78%
Part Variation	45.10%	68.14%	85.04%	6.00%	95.13%	51.35%	56.95%	62.35%	8.53%	95.27%	39.56%	59.29%	77.43%	7.17%	99.22%

Table E2 (continued): Pre-Phase II ANOVA Summary--Rawsonville Plant

	TEST STAND #1														
	FIXTURE A					FIXTURE B					FIXTURE C				
	DEAD HEAD PRESS. (KPA) 13.2V	OUTLET FLOW (LPH) 13.2V	CURRENT (AMPS) 13.2V	OUTLET LEAK (CCM)	CURRENT (AMPS) 1.5V	DEAD HEAD PRESS. (KPA) 13.2V	OUTLET FLOW (LPH) 13.2V	CURRENT (AMPS) 13.2V	OUTLET LEAK (CCM)	CURRENT (AMPS) 1.5V	DEAD HEAD PRESS. (KPA) 13.2V	OUTLET FLOW (LPH) 13.2V	CURRENT (AMPS) 13.2V	OUTLET LEAK (CCM)	CURRENT (AMPS) 1.5V
GRAND MEAN	554.075	130.013	3.408	0.867	0.735	551.675	129.663	3.449	1.183	0.741	559.300	130.146	3.446	0.421	0.734
TOLERANCE (for 60 lph pumps)	355.00	25.31	2.84	5.00	1.00	355.00	25.31	2.84	5.00	1.00	355.00	25.31	2.84	5.00	1.00
% OF TOLERANCE: REPEATABILITY	6.23%	10.65%	13.82%	4.49%	5.24%	6.16%	14.79%	4.61%	7.49%	4.49%	6.20%	14.06%	3.69%	4.49%	5.61%
% OF TOLERANCE: REPRODUCIBILITY	0.81%	1.56%	4.18%	0.00%	4.56%	3.69%	11.90%	2.78%	3.65%	1.22%	1.75%	8.06%	1.82%	3.04%	0.61%
% OF TOLERANCE: COMBINED R&R	6.28%	10.76%	5.66%	4.49%	6.95%	7.18%	18.98%	5.39%	8.33%	4.65%	6.44%	16.21%	4.11%	5.42%	5.65%
5.15*SIGMA															
FIXTURE VARIATION	22.120	2.690	0.110	0.220	0.050	21.860	3.740	0.130	0.370	0.040	22.010	3.560	0.100	0.220	0.060
OPERATOR VARIATION (load vs test)	2.860	0.400	0.120	0.000	0.050	13.110	3.010	0.080	0.180	0.010	6.210	2.040	0.005	0.150	0.010
R&R VARIATION	22.304	2.728	0.160	0.220	0.071	25.490	4.801	0.153	0.411	0.041	22.869	4.103	0.120	0.266	0.061
PART VARIATION	99.283	1.418	0.368	0.077	0.445	99.590	2.108	0.368	0.192	0.426	100.663	7.053	0.533	0.077	0.449
TOTAL VARIATION	101.758	3.067	0.401	0.233	0.450	102.800	5.243	0.398	0.454	0.427	103.228	8.160	0.546	0.277	0.453
% CONTRIBUTION TO TOTAL VARIATION															
FIXTURE VARIATION	4.73%	76.92%	7.51%	89.17%	1.23%	4.52%	50.88%	10.65%	66.44%	0.88%	4.55%	19.03%	3.35%	63.04%	1.76%
OPERATOR VARIATION (load vs test)	0.08%	1.70%	8.94%	0.00%	1.23%	1.63%	32.96%	4.03%	15.73%	0.05%	0.36%	6.25%	0.01%	29.31%	0.05%
R&R VARIATION	4.80%	78.62%	15.90%	89.17%	2.47%	6.15%	83.84%	14.68%	82.17%	0.93%	4.91%	25.28%	4.83%	92.34%	1.81%
PART VARIATION	95.20%	21.38%	84.10%	10.83%	97.53%	93.85%	16.16%	85.32%	17.83%	99.07%	95.09%	74.72%	95.17%	7.66%	98.19%

	TEST STAND #2														
	FIXTURE A					FIXTURE B					FIXTURE C				
	DEAD HEAD PRESS. (KPA) 13.2V	OUTLET FLOW (LPH) 13.2V	CURRENT (AMPS) 13.2V	OUTLET LEAK (CCM)	CURRENT (AMPS) 1.5V	DEAD HEAD PRESS. (KPA) 13.2V	OUTLET FLOW (LPH) 13.2V	CURRENT (AMPS) 13.2V	OUTLET LEAK (CCM)	CURRENT (AMPS) 1.5V	DEAD HEAD PRESS. (KPA) 13.2V	OUTLET FLOW (LPH) 13.2V	CURRENT (AMPS) 13.2V	OUTLET LEAK (CCM)	CURRENT (AMPS) 1.5V
GRAND MEAN	559.863	130.379	3.425	1.608	0.741	562.008	128.929	3.385	2.192	0.733	570.721	123.600	3.435	0.563	0.738
TOLERANCE (for 60 lph pumps)	355.00	25.31	2.84	5.00	1.00	355.00	25.31	2.84	5.00	1.00	355.00	25.31	2.84	5.00	1.00
% OF TOLERANCE: REPEATABILITY	11.12%	16.27%	5.67%	3.74%	3.37%	20.82%	8.14%	4.22%	4.49%	6.74%	43.82%	23.50%	5.01%	18.71%	7.86%
% OF TOLERANCE: REPRODUCIBILITY	6.64%	1.08%	4.50%	2.43%	2.74%	7.49%	21.49%	3.86%	4.87%	4.87%	15.65%	44.96%	1.39%	22.51%	0.91%
% OF TOLERANCE: COMBINED R&R	12.95%	16.30%	7.23%	4.46%	4.34%	22.13%	22.98%	5.71%	6.63%	8.31%	46.54%	50.73%	5.20%	29.27%	7.91%
5.15*SIGMA															
FIXTURE VARIATION	39.480	4.120	0.160	0.190	0.030	73.910	2.060	0.120	0.220	0.070	155.580	5.950	0.140	0.940	0.080
OPERATOR VARIATION (load vs test)	23.570	0.270	0.130	0.120	0.030	26.500	5.440	0.110	0.240	0.050	55.570	11.380	0.040	1.130	0.010
R&R VARIATION	45.981	4.129	0.206	0.225	0.042	78.517	5.817	0.163	0.326	0.086	165.206	12.842	0.146	1.470	0.081
PART VARIATION	99.015	2.147	0.541	0.153	0.422	99.360	4.217	0.571	0.115	0.429	150.228	9.775	0.441	0.575	0.445
TOTAL VARIATION	109.170	4.654	0.578	0.272	0.424	126.639	7.185	0.594	0.345	0.438	223.297	16.139	0.464	1.578	0.452
% CONTRIBUTION TO TOTAL VARIATIO															
FIXTURE VARIATION	13.08%	78.38%	7.65%	48.78%	0.50%	34.06%	8.22%	4.08%	40.60%	2.56%	48.54%	13.59%	9.09%	35.47%	3.13%
OPERATOR VARIATION (load vs test)	4.66%	0.34%	5.05%	19.46%	0.50%	4.38%	57.33%	3.43%	48.31%	1.30%	6.19%	49.72%	0.74%	51.26%	0.05%
R&R VARIATION	17.74%	78.72%	12.70%	68.23%	1.00%	38.44%	65.55%	7.51%	88.91%	3.86%	54.74%	63.31%	9.84%	86.73%	3.18%
PART VARIATION	82.26%	21.28%	87.30%	31.77%	99.00%	61.56%	34.45%	92.49%	11.09%	96.14%	45.26%	36.69%	90.16%	13.27%	96.82%

Table E3: Pre-Phase II Average and Range Method Summary--Rawsonville Plant

	TEST STAND #3														
	FIXTURE A					FIXTURE B					FIXTURE C				
	DEAD HEAD PRESS. (KPA) 13.2V	OUTLET FLOW (LPH) 13.2V	CURRENT (AMPS) 13.2V	OUTLET LEAK (CCM)	CURRENT (AMPS) 1.5V	DEAD HEAD PRESS. (KPA) 13.2V	OUTLET FLOW (LPH) 13.2V	CURRENT (AMPS) 13.2V	OUTLET LEAK (CCM)	CURRENT (AMPS) 1.5V	DEAD HEAD PRESS. (KPA) 13.2V	OUTLET FLOW (LPH) 13.2V	CURRENT (AMPS) 13.2V	OUTLET LEAK (CCM)	CURRENT (AMPS) 1.5V
GRAND MEAN	561.325	118.167	3.364	0.967	0.723	570.288	129.783	3.406	0.721	0.725	562.588	129.025	3.375	0.713	0.720
TOLERANCE (for 60 lph pumps)	355.00	25.31	2.84	5.00	1.00	355.00	25.31	2.84	5.00	1.00	355.00	25.31	2.84	5.00	1.00
% OF TOLERANCE: REPEATABILITY	7.65%	7.23%	3.82%	9.73%	3.74%	18.81%	14.23%	8.30%	2.99%	5.28%	12.98%	8.13%	3.03%	20.21%	2.25%
% OF TOLERANCE: REPRODUCIBILITY	3.36%	5.06%	1.50%	8.52%	0.30%	14.32%	2.39%	4.61%	0.61%	3.32%	3.89%	10.34%	1.82%	23.73%	0.61%
% OF TOLERANCE: COMBINED R&R	8.36%	8.82%	4.11%	12.93%	3.75%	23.64%	14.53%	9.49%	3.06%	6.23%	13.55%	13.15%	3.54%	31.17%	2.33%
5.15*SIGMA															
FIXTURE VARIATION	27.170	1.830	0.110	0.490	0.040	66.770	4.450	0.240	0.150	0.050	46.070	2.060	0.090	1.010	0.020
OPERATOR VARIATION (load vs test)	11.920	1.280	0.040	0.430	0.000	50.830	0.700	0.130	0.030	0.030	13.810	2.620	0.050	1.190	0.010
R&R VARIATION	29.670	2.233	0.117	0.652	0.040	83.916	4.505	0.273	0.153	0.058	48.095	3.333	0.103	1.561	0.022
PART VARIATION	85.445	4.140	0.560	0.575	0.460	112.202	4.485	0.529	0.115	0.426	128.225	7.475	0.587	1.572	0.410
TOTAL VARIATION	90.450	4.704	0.572	0.869	0.462	140.111	6.357	0.595	0.191	0.429	136.948	8.184	0.595	2.215	0.411
% CONTRIBUTION TO TOTAL VARIATION															
FIXTURE VARIATION	9.02%	15.13%	3.70%	31.78%	0.75%	22.71%	49.01%	16.26%	61.43%	1.36%	11.32%	6.34%	2.28%	20.79%	0.24%
OPERATOR VARIATION (load vs test)	1.74%	7.40%	0.49%	24.47%	0.00%	13.16%	1.21%	4.77%	2.46%	0.49%	1.02%	10.25%	0.71%	28.86%	0.06%
R&R VARIATION	10.76%	22.54%	4.19%	56.24%	0.75%	35.87%	50.22%	21.03%	63.89%	1.84%	12.33%	16.58%	2.99%	49.65%	0.30%
PART VARIATION	89.24%	77.46%	95.81%	43.76%	99.25%	64.13%	49.78%	78.98%	36.11%	98.16%	87.67%	83.42%	97.01%	50.35%	99.70%

	TEST STAND #4														
	FIXTURE A					FIXTURE B					FIXTURE C				
	DEAD HEAD PRESS. (KPA) 13.2V	OUTLET FLOW (LPH) 13.2V	CURRENT (AMPS) 13.2V	OUTLET LEAK (CCM)	CURRENT (AMPS) 1.5V	DEAD HEAD PRESS. (KPA) 13.2V	OUTLET FLOW (LPH) 13.2V	CURRENT (AMPS) 13.2V	OUTLET LEAK (CCM)	CURRENT (AMPS) 1.5V	DEAD HEAD PRESS. (KPA) 13.2V	OUTLET FLOW (LPH) 13.2V	CURRENT (AMPS) 13.2V	OUTLET LEAK (CCM)	CURRENT (AMPS) 1.5V
GRAND MEAN	566.525	128.542	3.496	0.119	0.723	577.100	131.900	3.528	0.204	0.730	566.992	129.000	3.601	0.542	0.694
TOLERANCE (for 60 lph pumps)	355.00	25.31	2.84	5.00	1.00	355.00	25.31	2.84	5.00	1.00	355.00	25.31	2.84	5.00	1.00
% OF TOLERANCE: REPEATABILITY	26.32%	10.63%	4.48%	11.98%	8.23%	14.18%	6.64%	3.43%	9.73%	8.98%	42.44%	10.63%	4.61%	19.46%	2.99%
% OF TOLERANCE: REPRODUCIBILITY	3.31%	6.00%	0.00%	4.26%	2.43%	3.71%	9.72%	3.96%	0.61%	9.13%	4.44%	18.25%	6.10%	1.22%	2.43%
% OF TOLERANCE: COMBINED R&R	26.53%	12.21%	4.48%	12.71%	8.59%	14.66%	11.77%	5.24%	9.75%	12.90%	42.67%	21.12%	7.65%	19.50%	3.86%
5.15*SIGMA															
FIXTURE VARIATION	93.450	2.690	0.130	0.600	0.080	50.340	1.680	0.100	0.490	0.090	150.670	2.690	0.130	0.970	0.030
OPERATOR VARIATION (load vs test)	11.740	1.520	0.000	0.210	0.020	13.170	2.460	0.110	0.030	0.090	15.760	4.620	0.170	0.060	0.020
R&R VARIATION	94.185	3.090	0.130	0.636	0.082	52.034	2.979	0.149	0.491	0.127	151.492	5.346	0.214	0.972	0.036
PART VARIATION	139.840	4.523	0.383	0.383	0.468	110.017	3.757	0.215	0.268	0.602	175.835	6.287	0.406	0.498	0.380
TOTAL VARIATION	168.600	5.478	0.405	0.742	0.475	121.701	4.794	0.261	0.559	0.615	232.094	8.252	0.459	1.092	0.381
% CONTRIBUTION TO TOTAL VARIATION															
FIXTURE VARIATION	30.72%	24.12%	10.31%	65.33%	2.84%	17.11%	12.28%	14.67%	76.71%	2.14%	42.14%	10.63%	8.01%	78.88%	0.62%
OPERATOR VARIATION (load vs test)	0.48%	7.70%	0.00%	8.00%	0.18%	1.17%	26.33%	17.75%	0.29%	2.14%	0.46%	31.34%	13.70%	0.30%	0.28%
R&R VARIATION	31.21%	31.82%	10.31%	73.33%	3.02%	18.28%	38.60%	32.41%	77.00%	4.28%	42.60%	41.97%	21.72%	79.18%	0.89%
PART VARIATION	68.79%	68.18%	89.69%	26.67%	96.98%	81.72%	61.40%	67.59%	23.00%	95.72%	57.40%	58.03%	78.28%	20.82%	99.11%

Possible cause for low flow average for fixture #2C:

Hole in part pocket causing the O-ring of the fixture head not to seal properly over the outlet due to the intake of air through the hole. This created flow variation (low flow) in the pump measurements.

Table E3 (continued): Pre-Phase II Average and Range Method Summary--Rawsonville Plant

APPENDIX F

	TWO-STATION PERFORMANCE TEST STAND STATION#2					
	(2) "MASTER" TURBINE PUMPS IN M99-SOLVENT @ 20-25 DEGREES CELSIUS					
	ETC FUEL LAB			ALBA FUEL LAB		
	FLOW 8.0V/200 KPA (LPH)	CURRENT 8.0V/200 KPA (AMPS)	SPEED 8.0V/200 KPA (RPM)	FLOW 8.0V/200 KPA (LPH)	CURRENT 8.0V/200 KPA (AMPS)	SPEED 8.0V/200 KPA (RPM)
GRAND MEAN	23.744	3.216	4423.657	20.486	2.933	4328.296
STANDARD DEVIATION ESTIMATES						
Repeatability	2.084	0.026	57.906	1.732	0.032	55.652
Reproducibility (operator)	0.000	0.000	0.000	0.000	0.054	0.000
Interaction (part*operator)	N/A	N/A	N/A	N/A	N/A	N/A
R&R	**2.048**	**0.026**	**56.958**	**1.711**	**0.063**	**54.379**
Part	2.541	0.104	0.000	1.124	0.073	62.360
MEASURES OF SPREAD (6*SIGMA)						
Equipment Variation	12.504	0.155	347.435	10.395	0.193	333.912
Operator Variation	0.000	0.000	0.000	0.000	0.323	0.000
Interaction Variation	N/A	N/A	N/A	N/A	N/A	N/A
R&R Variation	**12.504**	**0.155**	**347.435**	**10.395**	**0.377**	**333.912**
Part Variation	15.247	0.624	0.000	6.742	0.436	374.161
TOTAL VARIATION	**19.719**	**0.643**	**347.435**	**12.390**	**0.576**	**501.492**
% CONTRIBUTION TO TOTAL VARIATION						
Equipment Variation	40.21%	5.78%	100.00%	70.39%	11.25%	44.33%
Operator Variation	0.00%	0.00%	0.00%	0.00%	31.50%	0.00%
Interaction Variation	N/A	N/A	N/A	N/A	N/A	N/A
R&R Variation	**40.21%**	**5.78%**	**100.00%**	**70.39%**	**42.75%**	**44.33%**
Part Variation	59.79%	94.22%	0.00%	29.61%	57.25%	55.67%
TOTAL VARIATION (WITHOUT PART)	**12.504**	**0.155**	**347.435**	**10.395**	**0.377**	**333.912**
% CONTRIBUTION TO TOTAL VARIATION EXCLUDING PART VARIATION						
Equipment Variation	**100.00%**	**100.00%**	**100.00%**	**100.00%**	26.31%	**100.00%**
Operator Variation	0.00%	0.00%	0.00%	0.00%	**73.69%**	0.00%
Interaction Variation	N/A	N/A	N/A	N/A	N/A	N/A
R&R Variation	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%

*** PUMP #1 REMOVED DUE TO RESIDUE WEAR-OFF**

Table F1: Pre-Phase II ANOVA Summary--Turbine Pumps @ 8.0V/200 kPa

	TWO-STATION PERFORMANCE TEST STAND STATION#2					
	(2) "MASTER" TURBINE PUMPS IN M99-SOLVENT @ 20-25 DEGREES CELSIUS					
	ETC FUEL LAB			ALBA FUEL LAB		
	FLOW 13.2V/310 KPA (LPH)	CURRENT 13.2V/310 KPA (AMPS)	SPEED 13.2V/310 KPA (RPM)	FLOW 13.2V/310 KPA (LPH)	CURRENT 13.2V/310 KPA (AMPS)	SPEED 13.2V/310 KPA (RPM)
GRAND MEAN	93.947	5.692	8236.443	91.325	5.257	7785.136
STANDARD DEVIATION ESTIMATES						
Repeatability	1.630	0.032	370.666	1.676	0.060	97.478
Reproducibility (operator)	0.000	0.008	333.206	0.234	0.097	0.000
Interaction (part*operator)	N/A	N/A	N/A	N/A	N/A	N/A
R&R	**1.630**	**0.033**	**498.417**	**1.693**	**0.114**	**97.132**
Part	0.886	0.050	263.491	2.653	0.000	136.636
MEASURES OF SPREAD (6*SIGMA)						
Equipment Variation	9.778	0.193	2223.996	10.059	0.357	584.870
Operator Variation	0.000	0.048	1999.233	1.407	0.581	0.000
Interaction Variation	N/A	N/A	N/A	N/A	N/A	N/A
R&R Variation	**9.778**	**0.199**	**2990.500**	**10.157**	**0.682**	**584.870**
Part Variation	5.318	0.300	1580.948	15.920	0.000	819.815
TOTAL VARIATION	**11.131**	**0.360**	**3382.675**	**18.884**	**0.682**	**1007.059**
% CONTRIBUTION TO TOTAL VARIATION						
Equipment Variation	77.17%	28.67%	43.23%	28.37%	27.39%	33.73%
Operator Variation	0.00%	1.79%	34.93%	0.56%	72.61%	0.00%
Interaction Variation	N/A	N/A	N/A	N/A	N/A	N/A
R&R Variation	**77.17%**	**30.46%**	**78.16%**	**28.93%**	**100.00%**	**33.73%**
Part Variation	22.83%	69.54%	21.84%	71.07%	0.00%	66.27%
TOTAL VARIATION (WITHOUT PART)	**9.778**	**0.199**	**2990.500**	**10.157**	**0.682**	**584.870**
% CONTRIBUTION TO TOTAL VARIATION EXCLUDING PART VARIATION						
Equipment Variation	**100.00%**	**94.13%**	**55.31%**	**98.08%**	27.39%	**100.00%**
Operator Variation	0.00%	5.87%	44.69%	1.92%	**72.61%**	0.00%
Interaction Variation	N/A	N/A	N/A	N/A	N/A	N/A
R&R Variation	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%

*** PUMP #1 REMOVED DUE TO RESIDUE WEAR-OFF**

Table F2: Pre-Phase II ANOVA Summary--Turbine Pumps @ 13.2V/310 kPa

	TEST STAND #1					
	LEFTHAND FIXTURE			RIGHTHAND FIXTURE		
	FLOW 13.2V/310 KPA (LPH)	CURRENT 13.2V/310 KPA (AMPS)	FLOW 8.0V/200 KPA (LPH)	FLOW 13.2V/310 KPA (LPH)	CURRENT 13.2V/310 KPA (AMPS)	FLOW 8.0V/200 KPA (LPH)
GRAND MEAN	84.937	5.185	20.134	82.928	5.307	20.354
STANDARD DEVIATION ESTIMATES						
Repeatability	0.984	0.030	1.012	0.995	0.028	0.754
Reproducibility (operator)	0.825	0.007	0.697	1.653	0.000	1.164
Interaction (part*operator)	N/A	N/A	N/A	N/A	N/A	N/A
R&R	**1.284**	**0.031**	**1.229**	**1.930**	**0.028**	**1.387**
Part	0.769	0.012	2.925	0.409	0.000	2.458
MEASURES OF SPREAD (6*SIGMA)						
Equipment Variation	5.902	0.179	6.074	5.973	0.171	4.522
Operator Variation	4.948	0.044	4.182	9.919	0.000	6.985
Interaction Variation	N/A	N/A	N/A	N/A	N/A	N/A
R&R Variation	**7.702**	**0.184**	**7.375**	**11.578**	**0.171**	**8.321**
Part Variation	4.613	0.075	17.548	2.451	0.000	14.749
TOTAL VARIATION	**8.978**	**0.199**	**19.035**	**11.835**	**0.171**	**16.934**
% CONTRIBUTION TO TOTAL VARIATION						
Equipment Variation	48.11%	80.91%	10.18%	25.47%	100.00%	7.13%
Operator Variation	31.41%	4.89%	4.83%	70.24%	0.00%	17.01%
Interaction Variation	N/A	N/A	N/A	N/A	N/A	N/A
R&R Variation	**79.53%**	**85.80%**	**15.01%**	**95.71%**	**100.00%**	**24.14%**
Part Variation	20.47%	14.20%	84.99%	4.29%	0.00%	75.86%
TOTAL VARIATION (WITHOUT PART)	**7.702**	**0.184**	**7.375**	**11.578**	**0.171**	**8.321**
% CONTRIBUTION TO TOTAL VARIATION EXCLUDING PART VARIATION						
Equipment Variation	**58.73%**	**94.30%**	**67.84%**	26.61%	**100.00%**	29.53%
Operator Variation	41.27%	5.70%	32.16%	**73.39%**	0.00%	**70.47%**
Interaction Variation	N/A	N/A	N/A	N/A	N/A	N/A
R&R Variation	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%

Table F3: Pre-Phase II ANOVA Summary--Alba Plant

	TEST STAND #2					
	LEFTHAND FIXTURE			RIGHTHAND FIXTURE		
	FLOW 13.2V/310 KPA (LPH)	CURRENT 13.2V/310 KPA (AMPS)	FLOW 8.0V/200 KPA (LPH)	FLOW 13.2V/310 KPA (LPH)	CURRENT 13.2V/310 KPA (AMPS)	FLOW 8.0V/200 KPA (LPH)
GRAND MEAN	87.569	5.176	19.847	81.334	5.312	19.621
STANDARD DEVIATION ESTIMATES						
Repeatability	0.861	0.095	0.961	1.202	0.057	1.228
Reproducibility (operator)	0.515	0.023	0.655	0.361	0.000	0.552
Interaction (part*operator)	N/A	N/A	N/A	N/A	N/A	N/A
R&R	**1.003**	**0.098**	**1.163**	**1.255**	**0.056**	**1.346**
Part	0.269	0.000	3.860	1.268	0.000	2.440
MEASURES OF SPREAD (6*SIGMA)						
Equipment Variation	5.163	0.573	5.764	7.212	0.341	7.366
Operator Variation	3.092	0.139	3.933	2.169	0.000	3.313
Interaction Variation	N/A	N/A	N/A	N/A	N/A	N/A
R&R Variation	**6.018**	**0.589**	**6.978**	**7.531**	**0.341**	**8.077**
Part Variation	1.615	0.000	23.161	7.608	0.000	14.642
TOTAL VARIATION	**6.231**	**0.589**	**24.189**	**10.705**	**0.341**	**16.722**
% CONTRIBUTION TO TOTAL VARIATION						
Equipment Variation	68.65%	94.45%	5.68%	45.39%	100.00%	19.41%
Operator Variation	24.63%	5.55%	2.64%	4.10%	0.00%	3.92%
Interaction Variation	N/A	N/A	N/A	N/A	N/A	N/A
R&R Variation	**93.28%**	**100.00%**	**8.32%**	**49.50%**	**100.00%**	**23.33%**
Part Variation	6.72%	0.00%	91.68%	50.50%	0.00%	76.67%
TOTAL VARIATION (WITHOUT PART)	**6.018**	**0.589**	**6.978**	**7.531**	**0.341**	**8.077**
% CONTRIBUTION TO TOTAL VARIATION EXCLUDING PART VARIATION						
Equipment Variation	**73.60%**	**94.45%**	**68.24%**	**91.71%**	**100.00%**	**83.18%**
Operator Variation	26.40%	5.55%	31.76%	8.29%	0.00%	16.82%
Interaction Variation	N/A	N/A	N/A	N/A	N/A	N/A
R&R Variation	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%

Table F3 (continued): Pre-Phase II ANOVA Summary--Alba Plant

	TEST STAND #3					
	LEFTHAND FIXTURE			RIGHTHAND FIXTURE		
	FLOW 13.2V/310 KPA (LPH)	CURRENT 13.2V/310 KPA (AMPS)	FLOW 8.0V/200 KPA (LPH)	FLOW 13.2V/310 KPA (LPH)	CURRENT 13.2V/310 KPA (AMPS)	FLOW 8.0V/200 KPA (LPH)
GRAND MEAN	83.687	5.261	19.244	85.822	5.144	20.013
STANDARD DEVIATION ESTIMATES						
Repeatability	1.424	0.114	1.212	1.809	0.039	1.098
Reproducibility (operator)	0.115	0.044	0.191	0.144	0.020	0.324
Interaction (part*operator)	N/A	N/A	N/A	N/A	N/A	N/A
R&R	**1.428**	**0.123**	**1.227**	**1.815**	**0.044**	**1.145**
Part	0.857	0.062	3.301	1.955	0.046	2.159
MEASURES OF SPREAD (6*SIGMA)						
Equipment Variation	8.541	0.687	7.274	10.855	0.235	6.589
Operator Variation	0.688	0.262	1.146	0.867	0.118	1.942
Interaction Variation	N/A	N/A	N/A	N/A	N/A	N/A
R&R Variation	**8.569**	**0.735**	**7.364**	**10.890**	**0.263**	**6.869**
Part Variation	5.145	0.370	19.806	11.731	0.277	12.956
TOTAL VARIATION	**9.995**	**0.823**	**21.131**	**16.006**	**0.382**	**14.665**
% CONTRIBUTION TO TOTAL VARIATION						
Equipment Variation	73.03%	69.66%	11.85%	46.00%	37.75%	20.19%
Operator Variation	0.47%	10.10%	0.29%	0.29%	9.59%	1.75%
Interaction Variation	N/A	N/A	N/A	N/A	N/A	N/A
R&R Variation	**73.50%**	**79.76%**	**12.15%**	**46.29%**	**47.34%**	**21.94%**
Part Variation	26.50%	20.24%	87.85%	53.71%	52.66%	78.06%
TOTAL VARIATION (WITHOUT PART)	**8.569**	**0.735**	**7.364**	**10.890**	**0.263**	**6.869**
% CONTRIBUTION TO TOTAL VARIATION EXCLUDING PART VARIATION						
Equipment Variation	**99.35%**	**87.34%**	**97.58%**	**99.37%**	**79.75%**	**92.01%**
Operator Variation	0.65%	12.66%	2.42%	0.63%	20.25%	7.99%
Interaction Variation	N/A	N/A	N/A	N/A	N/A	N/A
R&R Variation	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%

Table F3 (continued): Pre-Phase II ANOVA Summary--Alba Plant

	TEST STAND #4					
	LEFTHAND FIXTURE			RIGHTHAND FIXTURE		
	FLOW 13.2V/310 KPA (LPH)	CURRENT 13.2V/310 KPA (AMPS)	FLOW 8.0V/200 KPA (LPH)	FLOW 13.2V/310 KPA (LPH)	CURRENT 13.2V/310 KPA (AMPS)	FLOW 8.0V/200 KPA (LPH)
GRAND MEAN	81.501	5.319	19.241	80.460	5.340	19.592
STANDARD DEVIATION ESTIMATES						
Repeatability	1.173	0.114	1.026	1.117	0.063	1.322
Reproducibility (operator)	0.000	0.000	0.000	0.956	0.057	0.311
Interaction (part*operator)	N/A	N/A	N/A	N/A	N/A	N/A
R&R	**1.148**	**0.111**	**1.000**	**1.470**	**0.085**	**1.359**
Part	1.003	0.000	3.210	0.488	0.000	3.088
MEASURES OF SPREAD (6*SIGMA)						
Equipment Variation	7.036	0.683	6.154	6.702	0.378	7.935
Operator Variation	0.000	0.000	0.000	5.739	0.344	1.867
Interaction Variation	N/A	N/A	N/A	N/A	N/A	N/A
R&R Variation	**7.036**	**0.683**	**6.154**	**8.823**	**0.511**	**8.151**
Part Variation	6.015	0.000	19.259	2.927	0.000	18.528
TOTAL VARIATION	**9.256**	**0.683**	**20.218**	**9.296**	**0.511**	**20.242**
% CONTRIBUTION TO TOTAL VARIATION						
Equipment Variation	57.77%	100.00%	9.26%	51.97%	54.68%	15.37%
Operator Variation	0.00%	0.00%	0.00%	38.11%	45.32%	0.85%
Interaction Variation	N/A	N/A	N/A	N/A	N/A	N/A
R&R Variation	**57.77%**	**100.00%**	**9.26%**	**90.09%**	**100.00%**	**16.22%**
Part Variation	42.23%	0.00%	90.74%	9.91%	0.00%	83.78%
TOTAL VARIATION (WITHOUT PART)	**7.036**	**0.683**	**6.154**	**8.823**	**0.511**	**8.151**
% CONTRIBUTION TO TOTAL VARIATION EXCLUDING PART VARIATION						
Equipment Variation	**100.00%**	**100.00%**	**100.00%**	**57.69%**	**54.68%**	**94.76%**
Operator Variation	0.00%	0.00%	0.00%	42.31%	45.32%	5.24%
Interaction Variation	N/A	N/A	N/A	N/A	N/A	N/A
R&R Variation	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%

Table F3 (continued): Pre-Phase II ANOVA Summary--Alba Plant

	TEST STAND #5					
	LEFTHAND FIXTURE			RIGHTHAND FIXTURE		
	FLOW 13.2V/310 KPA (LPH)	CURRENT 13.2V/310 KPA (AMPS)	FLOW 8.0V/200 KPA (LPH)	FLOW 13.2V/310 KPA (LPH)	CURRENT 13.2V/310 KPA (AMPS)	FLOW 8.0V/200 KPA (LPH)
GRAND MEAN	85.739	5.114	20.606	85.420	5.070	19.890
STANDARD DEVIATION ESTIMATES						
Repeatability	1.077	0.028	1.002	1.293	0.035	1.446
Reproducibility (operator)	1.025	0.002	0.326	1.124	0.022	1.014
Interaction (part*operator)	N/A	N/A	N/A	N/A	N/A	N/A
R&R	**1.486**	**0.028**	**1.053**	**1.713**	**0.041**	**1.766**
Part	0.000	0.015	3.475	0.000	0.000	2.815
MEASURES OF SPREAD (6*SIGMA)						
Equipment Variation	6.461	0.168	6.011	7.756	0.211	8.677
Operator Variation	6.148	0.015	1.954	6.745	0.130	6.085
Interaction Variation	N/A	N/A	N/A	N/A	N/A	N/A
R&R Variation	**8.919**	**0.169**	**6.320**	**10.278**	**0.248**	**10.599**
Part Variation	0.000	0.088	20.852	0.000	0.000	16.887
TOTAL VARIATION	**8.919**	**0.190**	**21.789**	**10.278**	**0.248**	**19.937**
% CONTRIBUTION TO TOTAL VARIATION						
Equipment Variation	52.48%	78.14%	7.61%	56.94%	72.63%	18.94%
Operator Variation	47.52%	0.58%	0.80%	43.06%	27.37%	9.32%
Interaction Variation	N/A	N/A	N/A	N/A	N/A	N/A
R&R Variation	**100.00%**	**78.72%**	**8.41%**	**100.00%**	**100.00%**	**28.26%**
Part Variation	0.00%	21.28%	91.59%	0.00%	0.00%	71.74%
TOTAL VARIATION (WITHOUT PART)	**8.919**	**0.169**	**6.320**	**10.278**	**0.248**	**10.599**
% CONTRIBUTION TO TOTAL VARIATION EXCLUDING PART VARIATION						
Equipment Variation	**52.48%**	**99.26%**	**90.44%**	**56.94%**	**72.63%**	**67.03%**
Operator Variation	47.52%	0.74%	9.56%	43.06%	27.37%	32.97%
Interaction Variation	N/A	N/A	N/A	N/A	N/A	N/A
R&R Variation	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%

Table F3 (continued): Pre-Phase II ANOVA Summary--Alba Plant

APPENDIX G

INITIAL PERFORMANCE TESTING

ESE-M4C50-D GASOLINE				MEAN	MEAN	MEAN	STDEV	STDEV	STDEV	AVG FLUID
COUNT	PUMP	VOLTS	PRESSURE	CURRENT	FLOW	SPEED	CURRENT	FLOW	SPEED	TEMP
30	45 LPH	10.0V	100 KPA	1.50	40.53	3344.65	0.09	2.74	621.71	N/A
30	45 LPH	10.0V	110 KPA	1.59	37.73	3280.89	0.10	2.82	639.81	N/A
30	45 LPH	13.2V	100 KPA	1.53	69.39	3822.67	0.09	2.59	408.18	N/A
30	45 LPH	13.2V	110 KPA	1.60	67.28	3793.85	0.09	2.66	445.03	N/A
30	60 LPH	10.0V	270 KPA	4.28	52.53	3077.93	0.28	4.65	175.00	N/A
30	60 LPH	10.0V	310 KPA	4.88	43.80	2768.90	0.33	5.53	198.72	N/A
30	60 LPH	13.2V	270 KPA	4.31	95.12	4952.83	0.28	3.80	148.58	N/A
30	60 LPH	13.2V	310 KPA	4.73	88.71	4726.42	0.30	4.10	167.70	N/A
30	88 LPH	10.0V	270 KPA	6.24	81.01	4418.90	0.22	3.46	119.57	N/A
30	88 LPH	10.0V	310 KPA	6.89	73.08	4141.18	0.24	3.88	138.66	N/A
30	88 LPH	13.2V	270 KPA	6.70	134.85	6790.67	0.23	3.41	110.30	N/A
30	88 LPH	13.2V	310 KPA	7.21	128.33	6563.01	0.24	3.63	117.51	N/A
27	125 LPH	10.0V	270 KPA	6.86	112.56	5275.53	0.31	4.66	169.86	N/A
27	125 LPH	10.0V	310 KPA	7.50	104.44	5018.81	0.33	4.66	178.62	N/A
27	125 LPH	13.2V	270 KPA	7.91	174.07	7788.96	0.24	3.99	140.15	N/A
27	125 LPH	13.2V	310 KPA	8.41	167.60	7591.36	0.27	4.33	151.72	N/A

Table G1: Phase II Gerotor Pump Test Fluid Correlation--Initial Performance

CORRELATION-AFTER 500 HOURS BREAK-IN

ESE-M4C50-D GASOLINE				MEAN	MEAN	MEAN	STDEV	STDEV	STDEV	AVG FLUID
COUNT	PUMP	VOLTS	PRESSURE	CURRENT	FLOW	SPEED	CURRENT	FLOW	SPEED	TEMP
30	45 LPH	10.0V	100 KPA	1.32	47.62	3663.17	0.17	5.09	409.97	22.13
30	45 LPH	10.0V	110 KPA	1.41	45.10	3439.66	0.19	5.70	483.03	22.13
30	45 LPH	13.2V	100 KPA	1.31	75.85	3928.93	0.08	3.09	238.04	22.13
30	45 LPH	13.2V	110 KPA	1.36	74.20	3921.10	0.09	3.42	262.36	22.13
30	60 LPH	10.0V	270 KPA	3.65	68.51	3571.80	0.40	4.20	203.14	22.33
30	60 LPH	10.0V	310 KPA	4.15	61.57	3338.29	0.51	5.31	317.69	22.33
30	60 LPH	13.2V	270 KPA	3.67	112.02	5436.50	0.23	2.42	123.68	22.33
30	60 LPH	13.2V	310 KPA	3.95	107.50	5280.16	0.25	2.97	140.51	22.33
30	88 LPH	10.0V	270 KPA	5.05	101.64	5025.65	0.62	6.40	280.47	22.87
30	88 LPH	10.0V	310 KPA	5.65	94.42	4758.19	0.74	7.79	336.25	22.87
30	88 LPH	13.2V	270 KPA	5.42	155.07	7413.54	0.34	3.02	130.08	22.87
30	88 LPH	13.2V	310 KPA	5.78	150.73	7259.65	0.40	3.15	146.48	22.87
27	125 LPH	10.0V	270 KPA	5.83	135.94	5997.40	0.59	5.92	284.05	22.33
27	125 LPH	10.0V	310 KPA	6.39	129.22	5793.83	0.74	7.98	316.83	22.33
27	125 LPH	13.2V	270 KPA	6.82	194.53	8404.44	0.33	2.93	151.26	22.33
27	125 LPH	13.2V	310 KPA	7.17	190.78	8272.00	0.39	3.59	155.50	22.33

CORRELATION-AFTER 500 HOURS BREAK-IN

M99-SOLVENT				MEAN	MEAN	MEAN	STDEV	STDEV	STDEV	AVG FLUID
COUNT	PUMP	VOLTS	PRESSURE	CURRENT	FLOW	SPEED	CURRENT	FLOW	SPEED	TEMP
30	45 LPH	10.0V	100 KPA	1.06	52.37	3405.97	0.07	1.74	609.88	22.93
30	45 LPH	10.0V	110 KPA	1.10	51.09	3362.48	0.07	1.75	585.00	22.93
30	45 LPH	13.2V	100 KPA	1.19	76.74	3670.25	0.09	1.68	229.30	22.93
30	45 LPH	13.2V	110 KPA	1.23	75.86	3652.65	0.09	1.70	256.53	22.93
30	60 LPH	10.0V	270 KPA	3.06	74.05	3615.29	0.15	2.09	118.24	23.37
30	60 LPH	10.0V	310 KPA	3.37	69.82	3462.14	0.17	2.60	134.95	23.37
30	60 LPH	13.2V	270 KPA	3.33	110.89	5219.59	0.12	3.02	143.42	23.37
30	60 LPH	13.2V	310 KPA	3.55	107.46	5100.14	0.13	3.36	163.10	23.37
30	88 LPH	10.0V	270 KPA	4.28	105.38	5025.15	0.23	2.00	62.47	23.70
30	88 LPH	10.0V	310 KPA	4.61	101.83	4906.20	0.23	2.31	76.10	23.70
30	88 LPH	13.2V	270 KPA	5.10	150.92	7030.54	0.28	3.07	129.70	23.70
30	88 LPH	13.2V	310 KPA	5.37	148.09	6946.76	0.28	2.99	123.23	23.70
27	125 LPH	10.0V	270 KPA	5.51	133.17	5692.60	0.36	3.32	121.16	24.19
27	125 LPH	10.0V	310 KPA	5.92	128.69	5535.74	0.43	3.60	118.60	24.19
27	125 LPH	13.2V	270 KPA	6.60	186.67	7782.11	0.33	3.87	218.47	24.19
27	125 LPH	13.2V	310 KPA	6.96	183.43	7689.30	0.39	3.96	198.03	24.19

Table G2: Phase II Gerotor Pump Test Fluid Correlation--Performance After 500 hours in M99 and Gasoline

Figure G1: Linear Regression Model

Phase II: Gerotor Pump Test Fluid
Correlation (45, 60, 95, & 125 lph)

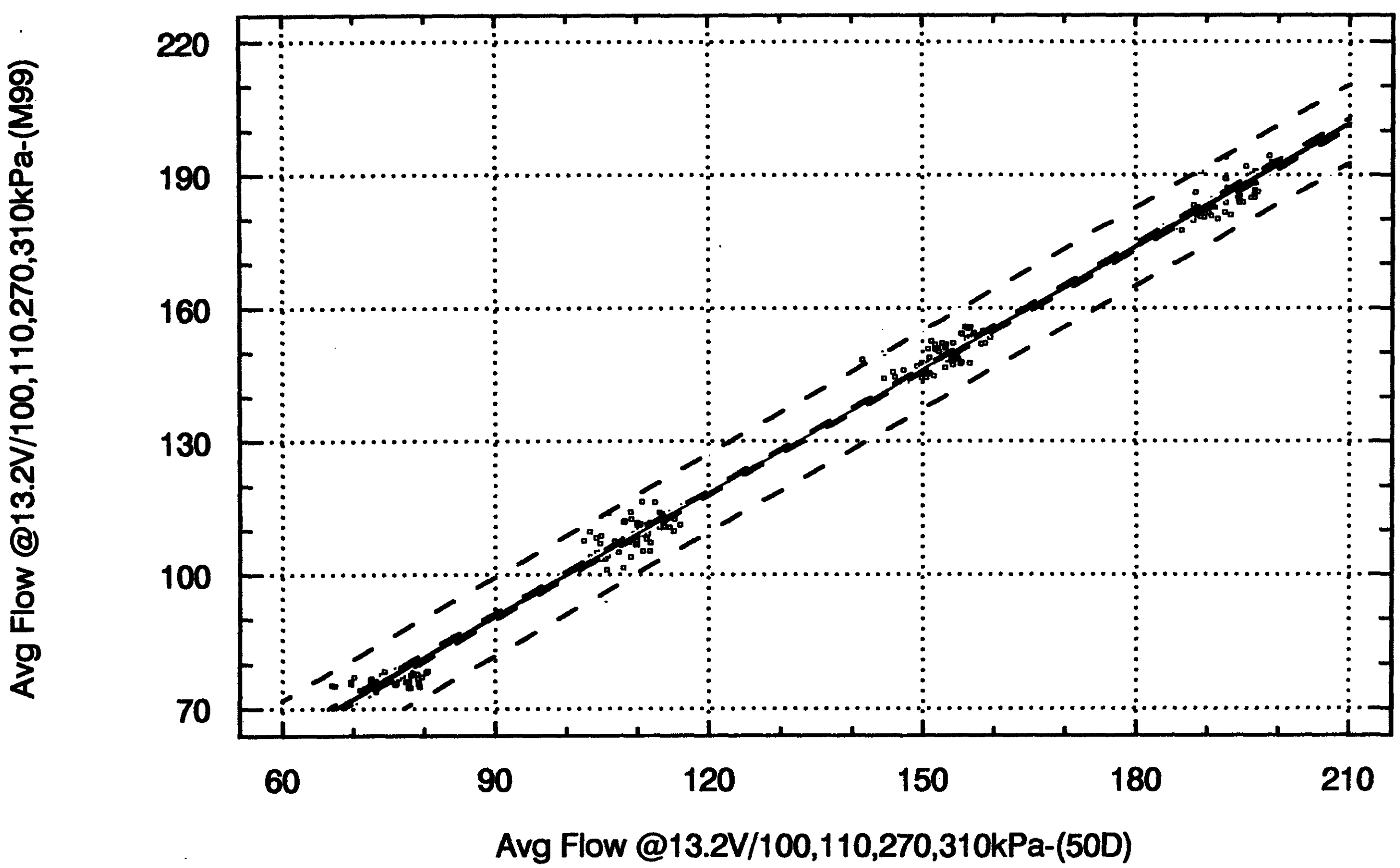


Figure G2: Linear Regression Model

Phase II: Gerotor Pump Test Fluid
Correlation (45, 60, 95, & 125 lph)

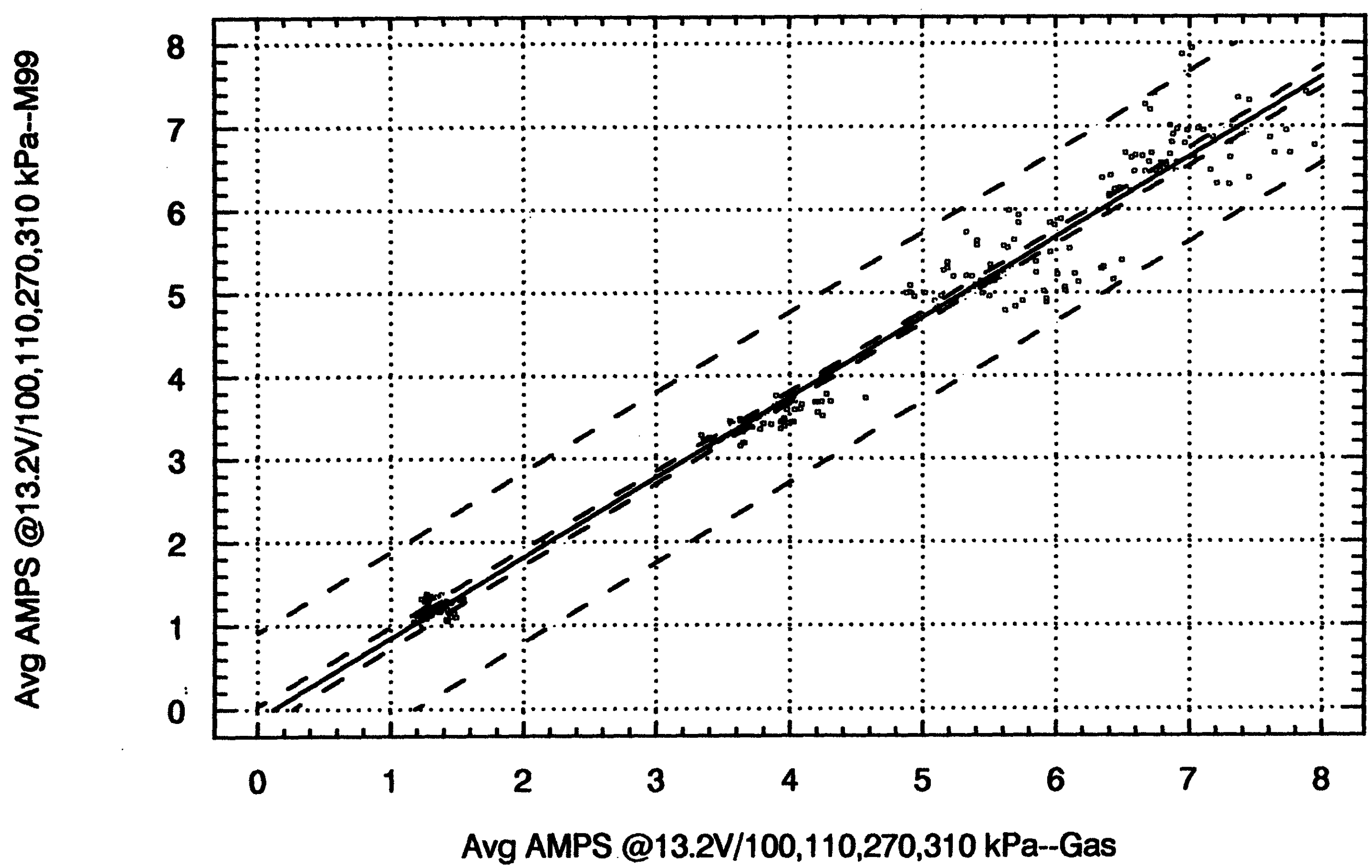
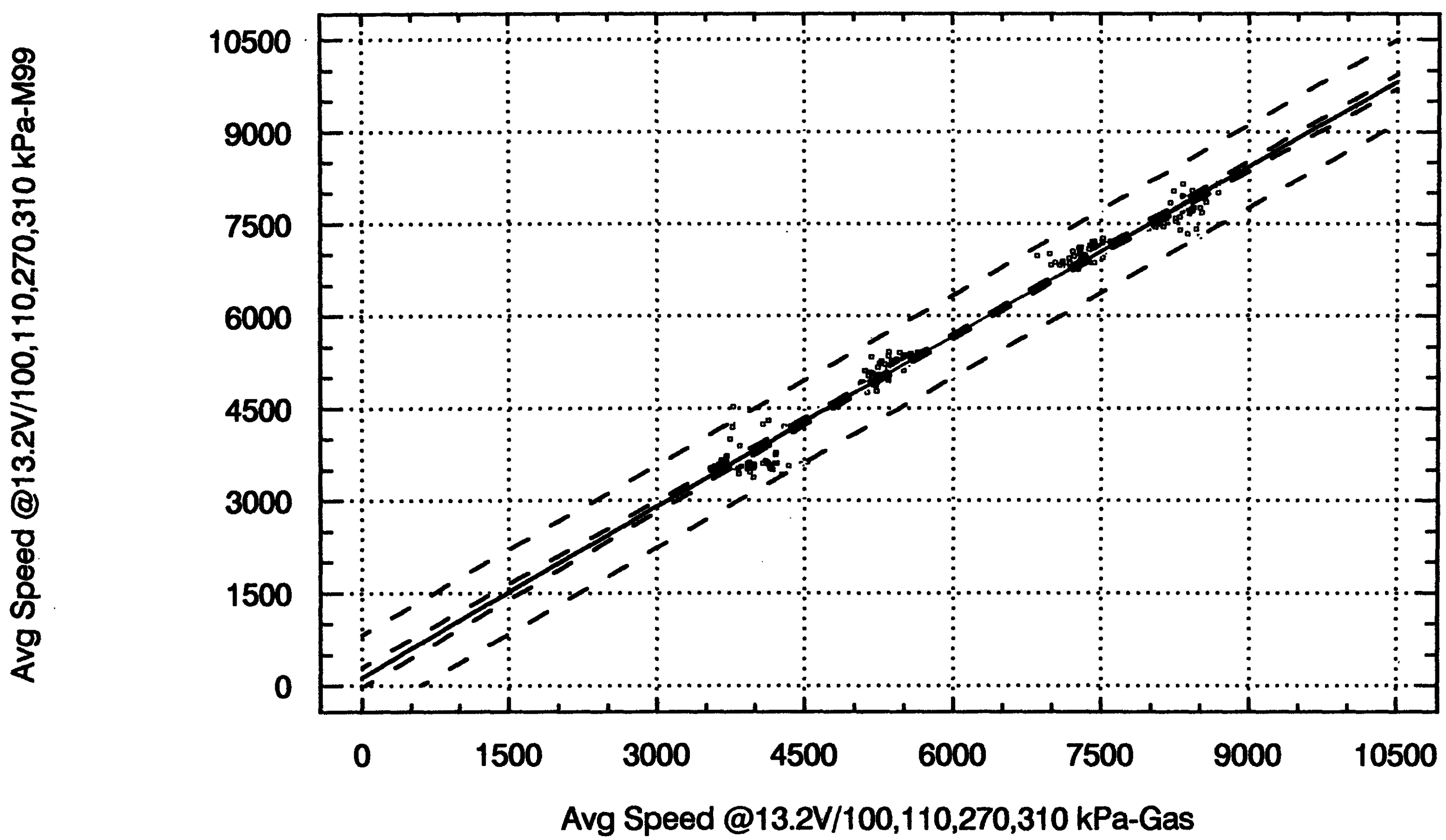


Figure G3: Linear Regression Model

Phase II: Gerotor Pump Test Fluid
Correlation (45, 60, 95, & 125 lph)



APPENDIX H

ESE-M4C50-D GASOLINE			MEAN AMPS	MEAN FLOW	MEAN SPEED	STDEV AMPS	STDEV FLOW	STDEV SPEED
COUNT	VOLTS	PRESS						
19	8V	22	1.85	93.97	5341.96	0.06	2.02	74.74
46	8V	200.2	3.22	28.69	4859.44	0.11	3.84	223.53
46	13.2V	200.2	4.71	122.89	8622.58	0.13	3.83	93.90
46	13.2V	310.1	5.38	96.44	8455.16	0.14	5.04	379.11

M99-SOLVENT			MEAN AMPS	MEAN FLOW	MEAN SPEED	STDEV AMPS	STDEV FLOW	STDEV SPEED
COUNT	VOLTS	PRESS						
46	8V	22	2.04	83.02	5137.42	0.11	3.01	463.35
46	8V	200.2	3.34	24.70	5152.72	0.17	3.58	1121.62
45	13.2V	200.2	4.95	110.15	8059.59	0.20	5.18	419.05
45	13.2V	310.1	5.64	87.23	8072.46	0.23	5.52	953.04

Table H1: Phase II Turbine Pump Test Fluid Correlation (ETC Fuel Lab)
Initial Performance

ESE-M4C50-D GASOLINE			MEAN	MEAN	MEAN	STDEV	STDEV	STDEV	AVG FLUID
COUNT	VOLTS	PRESS	AMPS	FLOW	SPEED	AMPS	FLOW	SPEED	TEMP
48	8V	22	1.85	91.15	5212.83	0.06	1.57	59.47	22.47
138	8V	200.2	3.18	27.25	4701.05	0.09	3.49	70.99	22.47
138	8V	250	3.59	12.28	4544.19	0.12	3.53	72.64	22.47
46	8.5V	250	3.65	21.82	4928.90	0.11	3.93	80.92	22.47
46	9V	250	3.73	31.56	5308.99	0.11	4.06	86.75	22.47
135	13.2V	200.2	4.63	121.41	8497.69	0.12	3.62	92.07	22.47
135	13.2V	250	4.90	109.85	8396.46	0.12	4.04	94.84	22.47
135	13.2V	310.1	5.27	95.53	8263.48	0.13	4.56	103.98	22.47

M99-SOLVENT			MEAN	MEAN	MEAN	STDEV	STDEV	STDEV	AVG FLUID
COUNT	VOLTS	PRESS	AMPS	FLOW	SPEED	AMPS	FLOW	SPEED	TEMP
48	8V	22	2.03	82.31	5389.59	0.11	2.38	1216.49	24.97
138	8V	200.2	3.35	28.39	5033.55	0.17	4.84	1009.03	24.97
138	8V	250	3.70	14.04	5063.35	0.18	4.74	1106.06	24.97
44	8.5V	250	3.77	20.98	5357.78	0.16	3.55	1166.62	24.97
44	9V	250	3.85	28.94	5913.87	0.16	3.42	1281.07	24.97
135	13.2V	200.2	4.92	111.35	8488.68	0.23	4.63	1083.52	24.97
135	13.2V	250	5.20	101.45	8580.69	0.23	4.79	1245.81	24.97
135	13.2V	310.1	5.57	89.38	8709.22	0.24	4.89	1492.92	24.97

Table H2: Phase II Turbine Pump Test Fluid Correlation (ETC Fuel Lab) Performance After X Minutes

INITIAL CHECK-(46) PRODUCTION LEVEL PUMPS
ALBA FUEL LAB--TWO-STATION PERFORMANCE TEST STAND/#2

ESE-M4C50-D GASOLINE			AVERAGE	AVERAGE	AVERAGE	STDEV	STDEV	STDEV	AVERAGE
COUNT	VOLTS	PRESSURE	CURRENT	FLOW	SPEED	CURRENT	FLOW	SPEED	TEMP
46	8V	200 KPA	3.00	25.64	4762.43	0.10	3.78	79.61	21.02
46	13.2V	310 KPA	5.02	92.60	8512.00	0.14	5.35	718.16	21.02

(CORRELATION PERFORMANCE TESTING IN ESE-M4C50-D GASOLINE
ALBA FUEL LAB--TWO-STATION PERFORMANCE TEST STAND/#2

ESE-M4C50-D GASOLINE			AVERAGE	AVERAGE	AVERAGE	STDEV	STDEV	STDEV	AVERAGE
COUNT	VOLTS	PRESSURE	CURRENT	FLOW	SPEED	CURRENT	FLOW	SPEED	TEMP
37	8V	16 KPA	1.64	94.34	1143.54	0.06	1.38	95.82	22.05
46	8V	200 KPA	3.02	26.89	2126.66	0.10	3.19	92.93	22.05
46	8V	250 KPA	3.43	11.89	2384.25	0.12	3.30	137.65	22.05
46	8.5V	200 KPA	3.10	37.08	2102.61	0.10	3.27	72.66	22.05
46	8.5V	250 KPA	3.51	22.19	2354.94	0.12	3.57	109.16	22.05
46	8.5V	310 KPA	3.99	5.52	2625.91	0.15	3.49	100.75	22.05
46	9.0V	200 KPA	3.19	46.63	2085.24	0.10	3.31	34.36	22.05
46	9.0V	250 KPA	3.59	32.04	2324.04	0.12	3.58	58.07	22.05
46	9.0V	310 KPA	4.08	14.97	2604.41	0.14	3.87	6.84	22.05
46	13.2V	200 KPA	4.39	120.99	2077.60	0.13	3.40	7.03	22.05
46	13.2V	250 KPA	4.67	109.35	2316.39	0.14	3.65	10.26	22.05
46	13.2V	310 KPA	5.04	94.83	2607.58	0.14	4.17	14.49	22.05

(CORRELATION PERFORMANCE TESTING IN EUROSUPER GASOLINE
ALBA FUEL LAB--TWO-STATION PERFORMANCE TEST STAND/#2

EUROSUPER GASOLINE			AVERAGE	AVERAGE	AVERAGE	STDEV	STDEV	STDEV	AVERAGE
COUNT	VOLTS	PRESSURE	CURRENT	FLOW	SPEED	CURRENT	FLOW	SPEED	TEMP
29	8V	16 KPA	1.70	96.63	1175.98	0.07	1.94	73.28	20.98
46	8V	200 KPA	3.02	28.91	2115.99	0.11	3.29	87.97	20.98
46	8V	250 KPA	3.42	13.93	2371.03	0.13	3.40	125.38	20.98
46	8.5V	200 KPA	3.08	38.12	2078.70	0.10	3.31	9.01	20.98
46	8.5V	250 KPA	3.48	23.42	2320.85	0.12	3.59	18.44	20.98
46	8.5V	310 KPA	3.95	7.02	2609.02	0.15	3.59	15.67	20.98
46	9.0V	200 KPA	3.16	47.08	2077.28	0.10	3.38	9.36	20.98
46	9.0V	250 KPA	3.55	32.66	2319.57	0.12	3.60	24.89	20.98
46	9.0V	310 KPA	4.04	16.03	2608.06	0.14	3.89	19.95	20.98
46	13.2V	200 KPA	4.38	120.57	2078.55	0.14	3.54	17.63	20.98
46	13.2V	250 KPA	4.66	109.08	2316.86	0.15	3.91	12.67	20.98
46	13.2V	310 KPA	5.03	94.94	2606.63	0.15	4.25	18.13	20.98

(CORRELATION PERFORMANCE TESTING IN M99-SOLVENT
ALBA FUEL LAB--TWO-STATION PERFORMANCE TEST STAND/#2

M99-SOLVENT			AVERAGE	AVERAGE	AVERAGE	STDEV	STDEV	STDEV	AVERAGE
COUNT	VOLTS	PRESSURE	CURRENT	FLOW	SPEED	CURRENT	FLOW	SPEED	TEMP
16	8V	16 KPA	1.85	84.19	1171.53	0.13	3.07	86.11	21.52
46	8V	200 KPA	3.09	25.70	2097.20	0.16	4.51	64.65	21.52
46	8V	250 KPA	3.42	11.39	2357.49	0.17	4.51	118.44	21.52
46	8.5V	200 KPA	3.20	33.80	2100.84	0.16	4.37	69.62	21.52
46	8.5V	250 KPA	3.54	20.56	2349.53	0.17	4.54	107.12	21.52
46	8.5V	310 KPA	3.97	5.07	2617.61	0.18	3.81	82.21	21.52
46	9.0V	200 KPA	3.32	42.47	2082.53	0.16	4.26	41.67	21.52
46	9.0V	250 KPA	3.66	29.73	2324.03	0.17	4.12	58.38	21.52
46	9.0V	310 KPA	4.08	14.19	2619.21	0.19	4.02	89.39	21.52
46	13.2V	200 KPA	4.70	111.01	2083.63	0.26	5.06	37.34	21.52
46	13.2V	250 KPA	4.98	100.88	2321.80	0.25	5.24	53.40	21.52
46	13.2V	310 KPA	5.35	88.70	2606.94	0.26	5.13	18.42	21.52

Table H3: Phase II Turbine Pump Test Fluid Correlation (Alba Lab)

Figure H1: Linear Regression Model

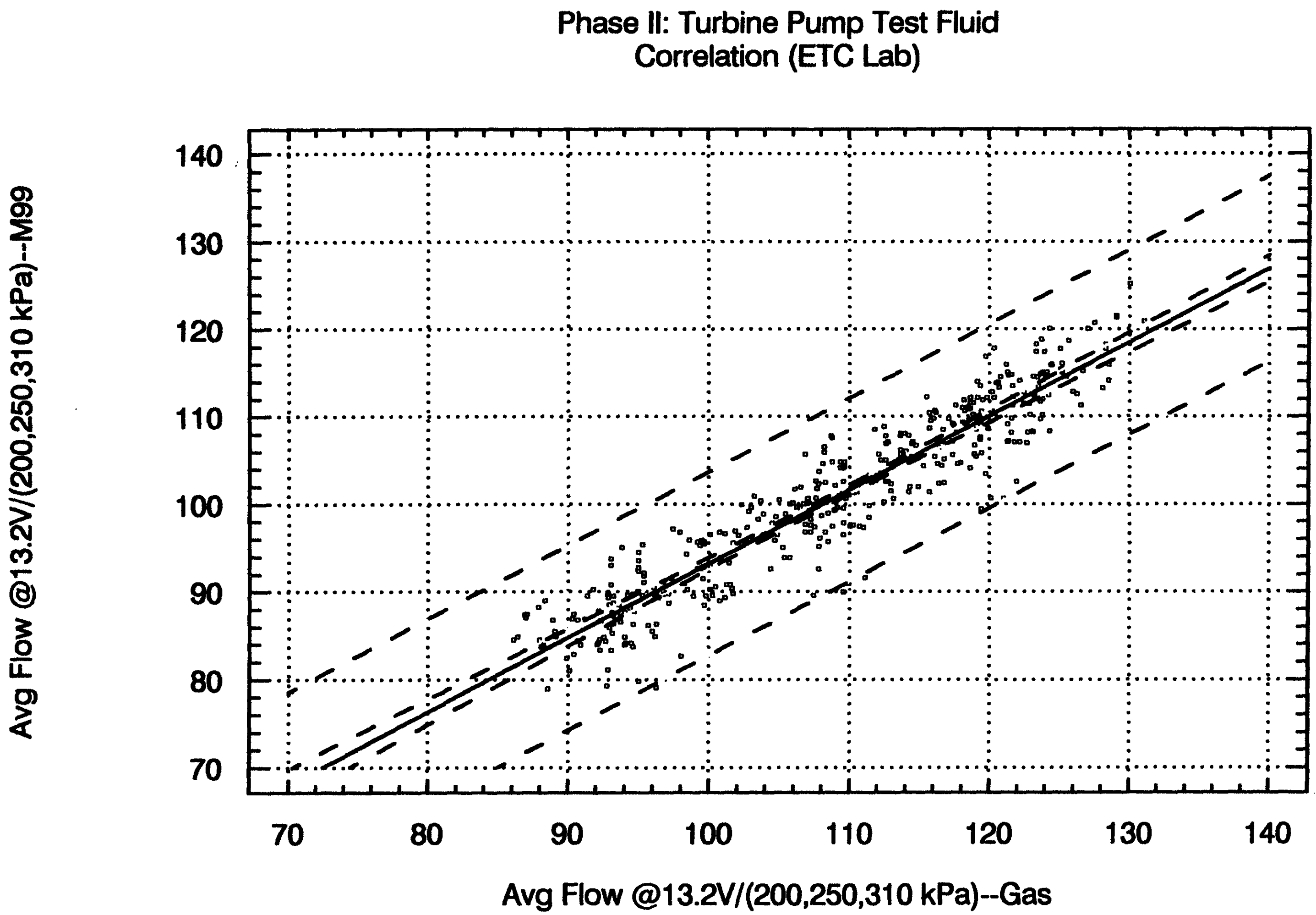


Figure H2: Linear Regression Model

Phase II: Turbine Pump Test Fluid
Correlation (ETC Lab)

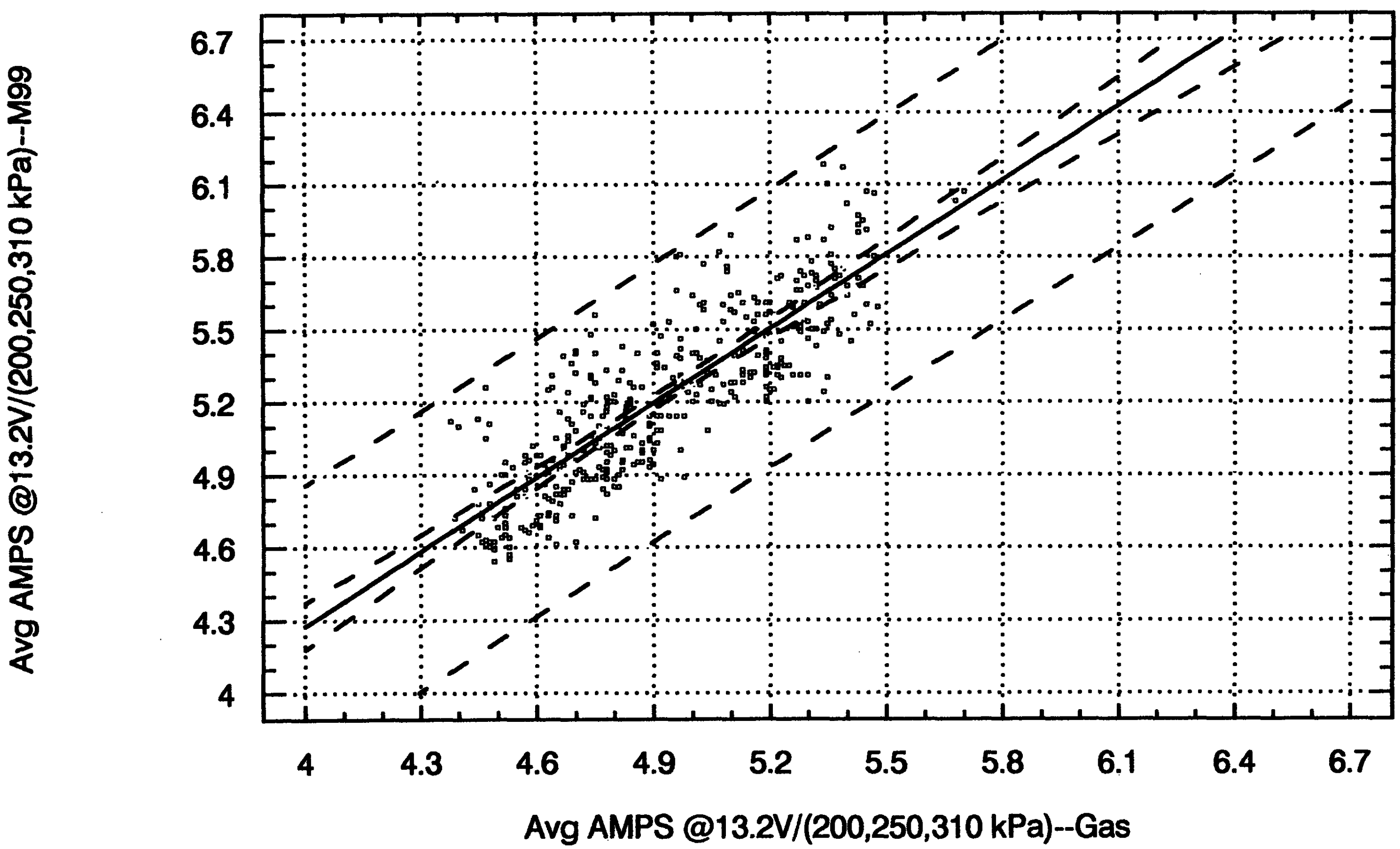


Figure H3: Linear Regression Model

Phase II: Turbine Pump Test Fluid Correlation (ETC Lab)

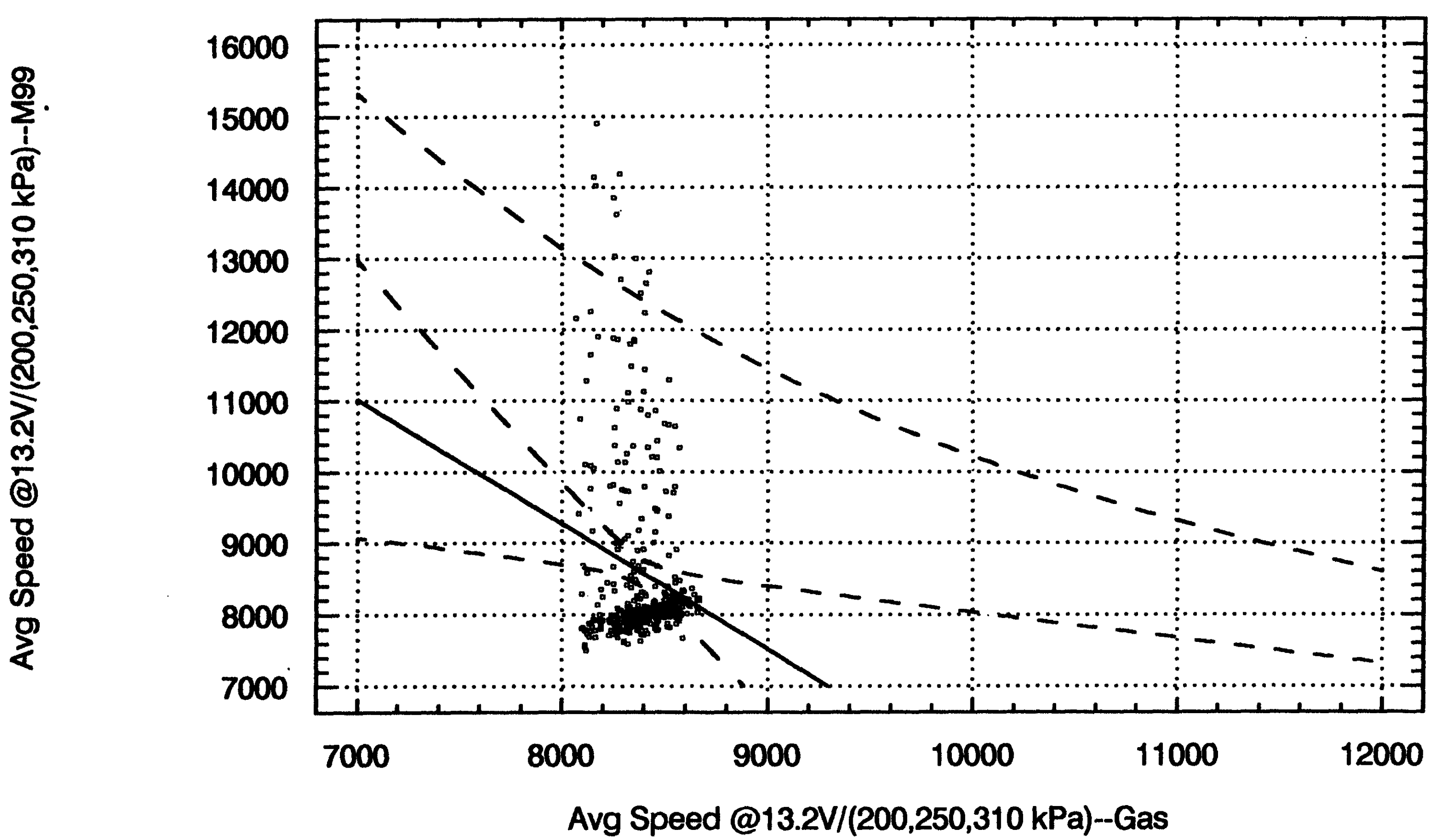
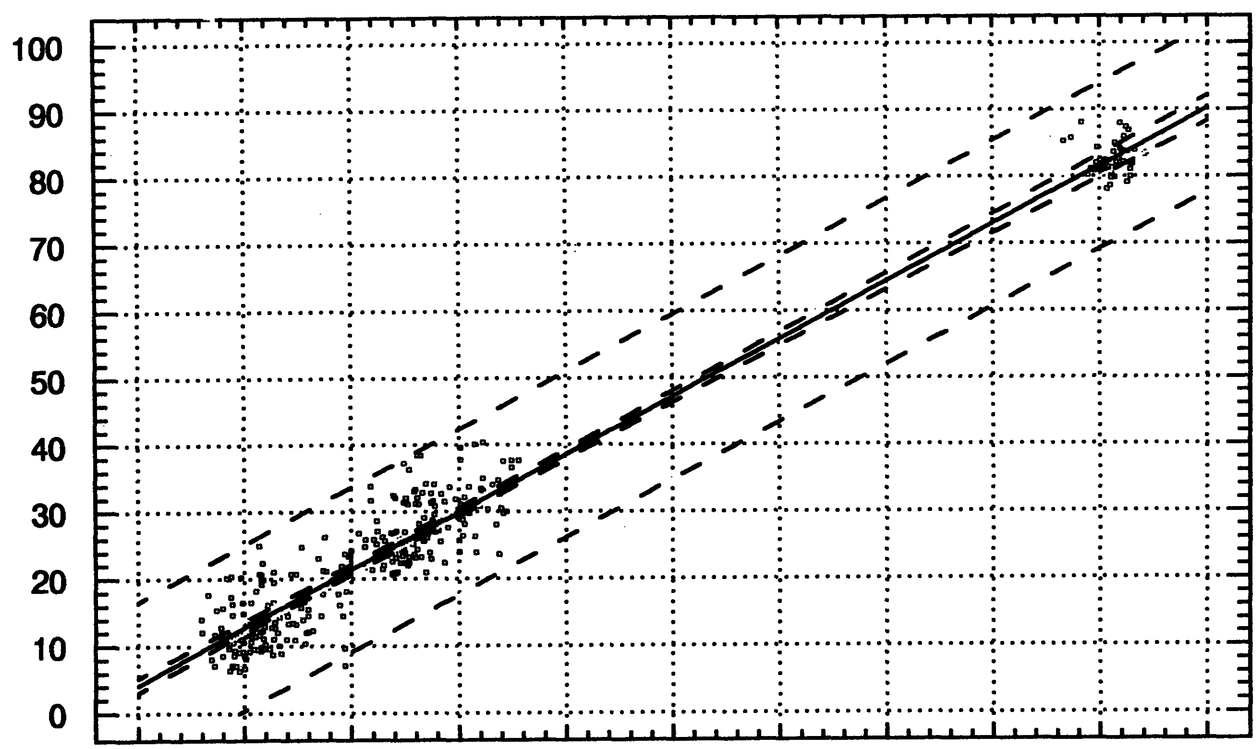


Figure H4: Linear Regression Model

Phase II: Turbine Pump Test Fluid
Correlation (ETC Lab)



APPENDIX I

Pressure (kPa)	ESE-M4C50-D Gasoline													
	Average Temperature C	Average Current @ 13.2V (amps)	σ (amps)	(μ−3σ) (amps)	(μ+3σ) (amps)	Average Flow @ 13.2V (lph)	σ (lph)	(μ−3σ) (lph)	(μ+3σ) (lph)	Mean Speed @ 13.2V (rpm)	σ (rpm)	(μ−3σ) (rpm)	(μ+3σ) (rpm)
24.9	23.43	3.69	0.09	3.41	3.96	164.49	2.27	157.67	171.30	8824.59	69.85	8615.04	9034.14
87.9	23.43	3.99	0.10	3.70	4.28	145.92	2.29	139.05	152.79	8765.80	71.37	8551.69	8979.91
163.1	23.43	4.35	0.10	4.05	4.64	127.56	2.90	118.85	136.27	8614.79	73.63	8393.90	8835.67
237.8	23.43	4.73	0.10	4.43	5.03	109.68	3.49	99.20	120.16	8461.05	75.02	8235.99	8686.11
310.1	23.43	5.18	0.11	4.85	5.50	91.77	4.21	79.13	104.42	8273.73	80.31	8032.79	8514.66
388.2	23.43	5.77	0.13	5.39	6.16	70.89	5.28	55.05	86.73	8052.45	132.21	7655.82	8449.08
462.9	23.43	6.35	0.15	5.90	6.80	50.53	6.63	30.65	70.41	7874.83	422.81	6606.41	9143.25
538.1	23.43	6.95	0.20	6.33	7.56	15.74	6.32	-3.23	34.72	7780.81	715.52	5634.25	9927.37

Pressure (kPa)	ESF-M99C8-A-Solvent													
	Average Temperature C	Average Current @ 13.2V (amps)	σ (amps)	(μ−3σ) (amps)	(μ+3σ) (amps)	Average Flow @ 13.2V (lph)	σ (lph)	(μ−3σ) (lph)	(μ+3σ) (lph)	Mean Speed @ 13.2V (rpm)	σ (rpm)	(μ−3σ) (rpm)	(μ+3σ) (rpm)
24.9	24.83	3.82	0.14	3.42	4.23	148.22	2.43	140.95	155.50	8153.92	118.98	7796.98	8510.86
87.9	24.83	4.18	0.14	3.75	4.61	132.11	3.09	122.84	141.38	8210.16	165.68	7713.14	8707.19
163.1	24.83	4.55	0.15	4.10	4.99	115.75	3.74	104.53	126.98	8122.70	338.43	7107.42	9137.98
237.8	24.83	4.95	0.16	4.47	5.43	100.34	3.76	89.05	111.63	8026.33	384.53	6872.74	9179.92
310.1	24.83	5.40	0.18	4.86	5.94	85.51	4.38	72.37	98.65	7958.46	533.57	6357.76	9559.17
388.2	24.83	5.92	0.20	5.31	6.53	68.29	4.90	53.60	82.98	7867.98	852.15	5311.53	10424.43
462.9	24.83	6.43	0.21	5.80	7.06	48.51	4.72	34.34	62.68	7845.68	1101.50	4541.17	11150.18
538.1	24.83	6.95	0.23	6.26	7.64	17.59	6.35	-1.47	36.65	7806.81	1355.31	3740.87	11872.75

Table I1: Phase II Turbine Pump Test Fluid Correlation--(Redo at ETC Lab)
Performance Summary at 13.2V (46 pumps averaged at each pressure)

	ESE-M4C50-D Gasoline					ESF-M99C8-A Solvent				
Pressure (kPa)	Average Temperature C	Average Flow @ 8.0V (lph)	σ (lph)	$(\mu-3\sigma)$ (lph)	$(\mu+3\sigma)$ (lph)	Average Temperature C	Average Flow @ 8.0V (lph)	σ (lph)	$(\mu-3\sigma)$ (lph)	$(\mu+3\sigma)$ (lph)
24.9	23.26	88.58	2.07	82.37	94.79	24.54	83.83	3.66	72.84	94.81
49.8	23.26	67.17	3.04	58.03	76.30	24.54	58.99	4.38	45.85	72.14
75.2	23.26	66.00	2.33	59.00	72.99	24.54	61.27	3.42	51.00	71.54
100.1	23.26	58.52	2.40	51.32	65.72	24.54	55.98	3.28	46.13	65.83
125	23.26	49.58	2.56	41.91	57.24	24.54	49.23	3.21	39.59	58.86
149.9	23.26	41.27	2.68	33.22	49.32	24.54	42.48	3.26	32.69	52.27
174.8	23.26	33.31	2.88	24.66	41.95	24.54	35.79	3.20	26.20	45.37
200.2	23.26	25.29	3.16	15.82	34.77	24.54	28.77	3.41	18.53	39.02
250	23.26	11.14	3.00	2.13	20.16	24.54	14.97	3.00	5.97	23.98

Table I2: Phase II Turbine Pump Test Fluid Correlation--(Redo at ETC Lab)
Performance Summary at 8.0V (46 pumps averaged at each pressure)

Figure I1: Phase II: Test Fluid Correlation--ETC Fuel Lab (Redo)
Two-Station Performance Test Stand (Station #2)
(46) Alba Production Turbine Pumps
Average Flow at 13.2V in Gasoline and M99-solvent

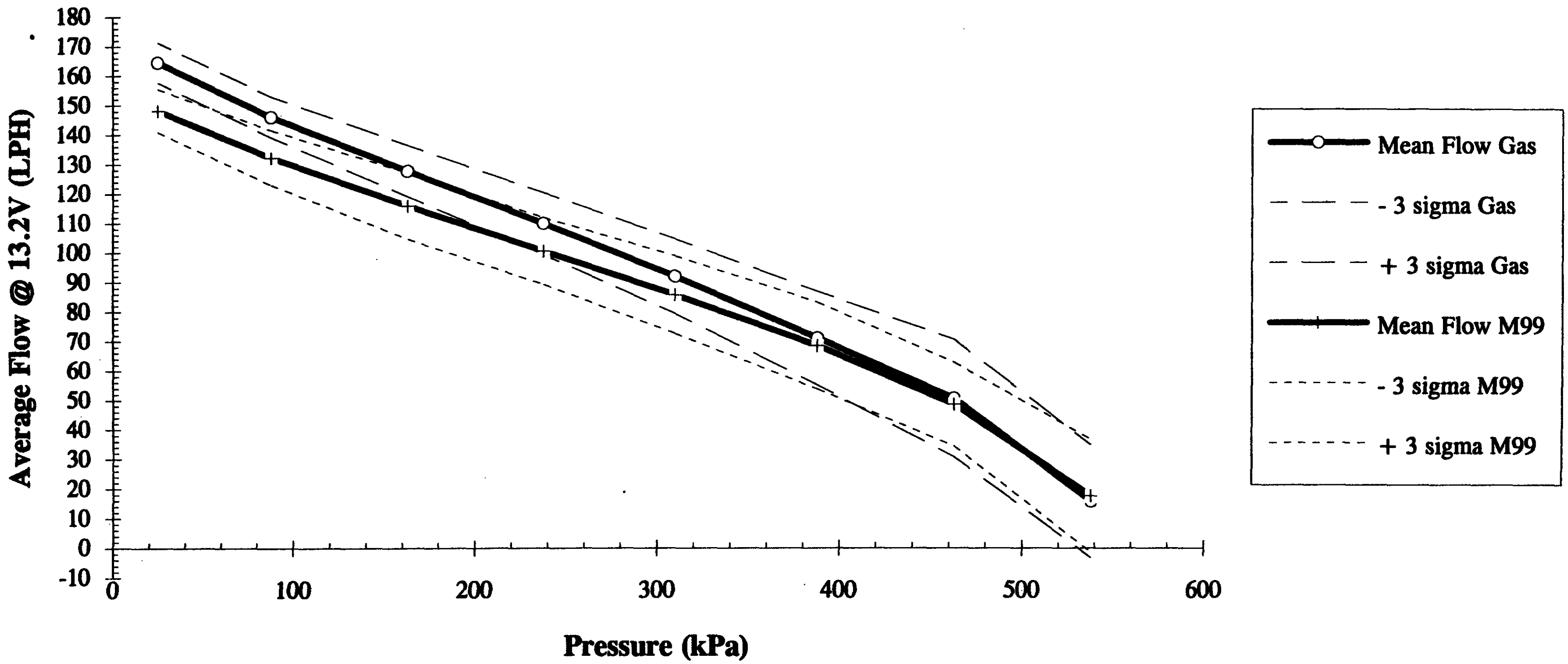


Figure I2: Phase II: Test Fluid Correlation--ETC Fuel Lab (Redo)
Two-Station Performance Test Stand (Station #2)
(46) Alba Production Turbine Pumps
Average Current at 13.2V in Gasoline and M99-solvent

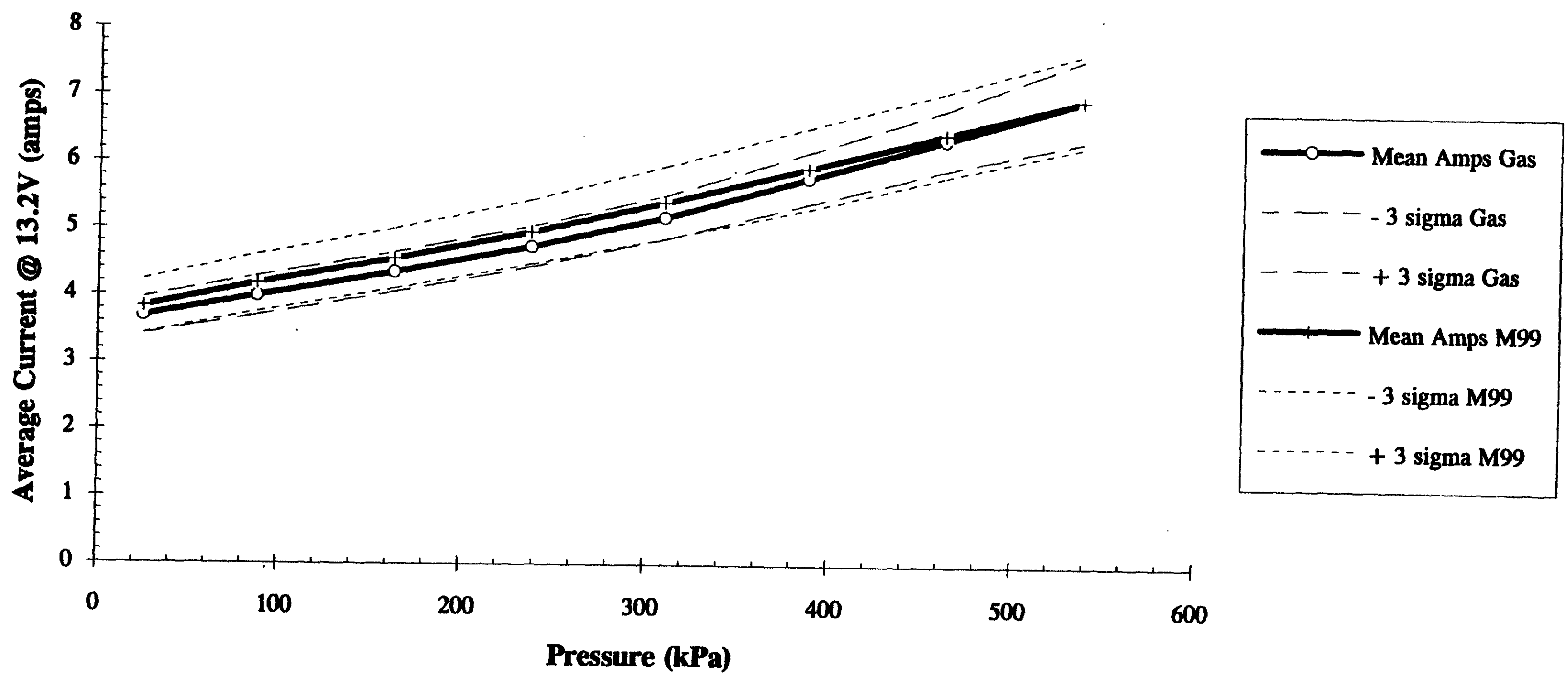


Figure I3: Phase II: Test Fluid Correlation--ETC Fuel Lab (Redo)
Two-Station Performance Test Stand (Station #2)
(46) Alba Production Turbine Pumps
Average Speed at 13.2V in Gasoline and M99-solvent

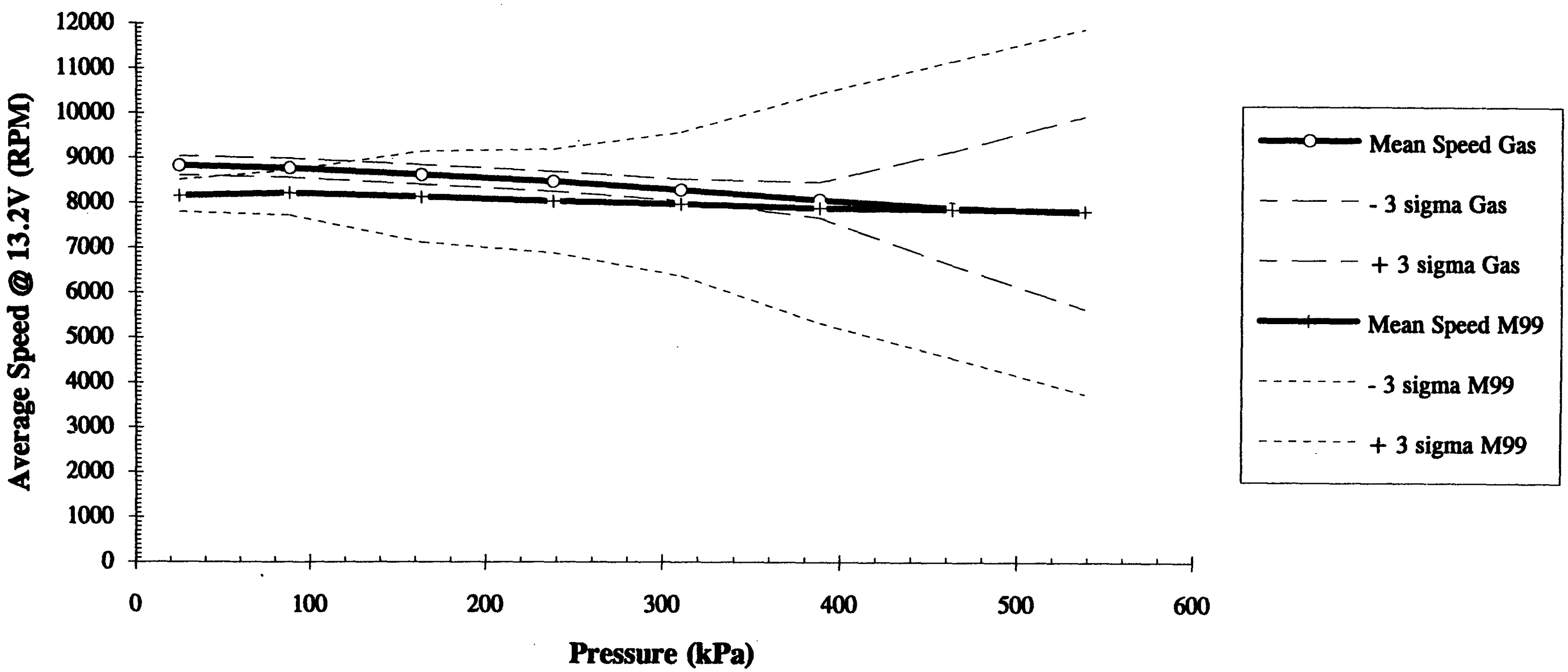


Figure I4: Phase II: Test Fluid Correlation--ETC Fuel Lab (Redo)
Two-Station Performance Test Stand (Station #2)
(46) Alba Production Turbine Pumps
Average Flow at 8.0V in Gasoline and M99-solvent

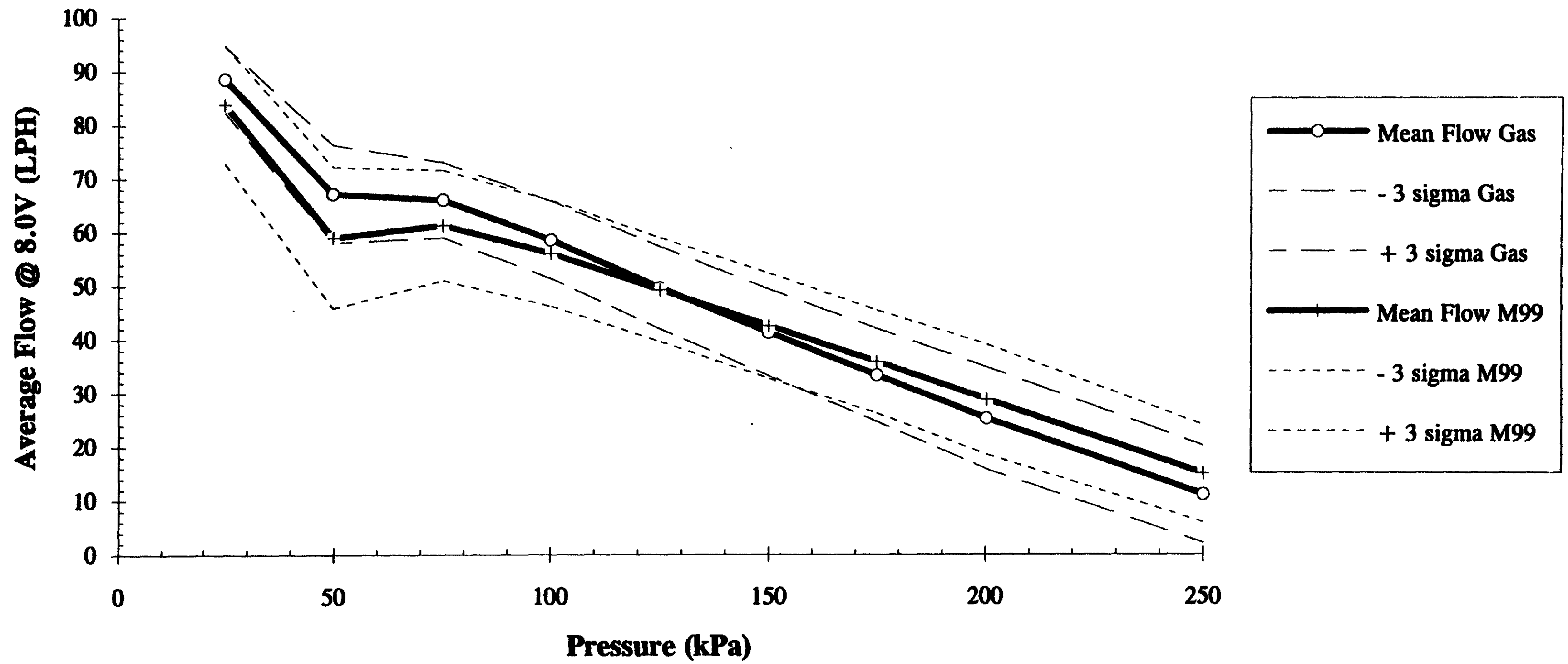


Figure I5: Linear Regression Model

Phase II: Turbine Pump Test Fluid
Correlation Redo (ETC Lab)

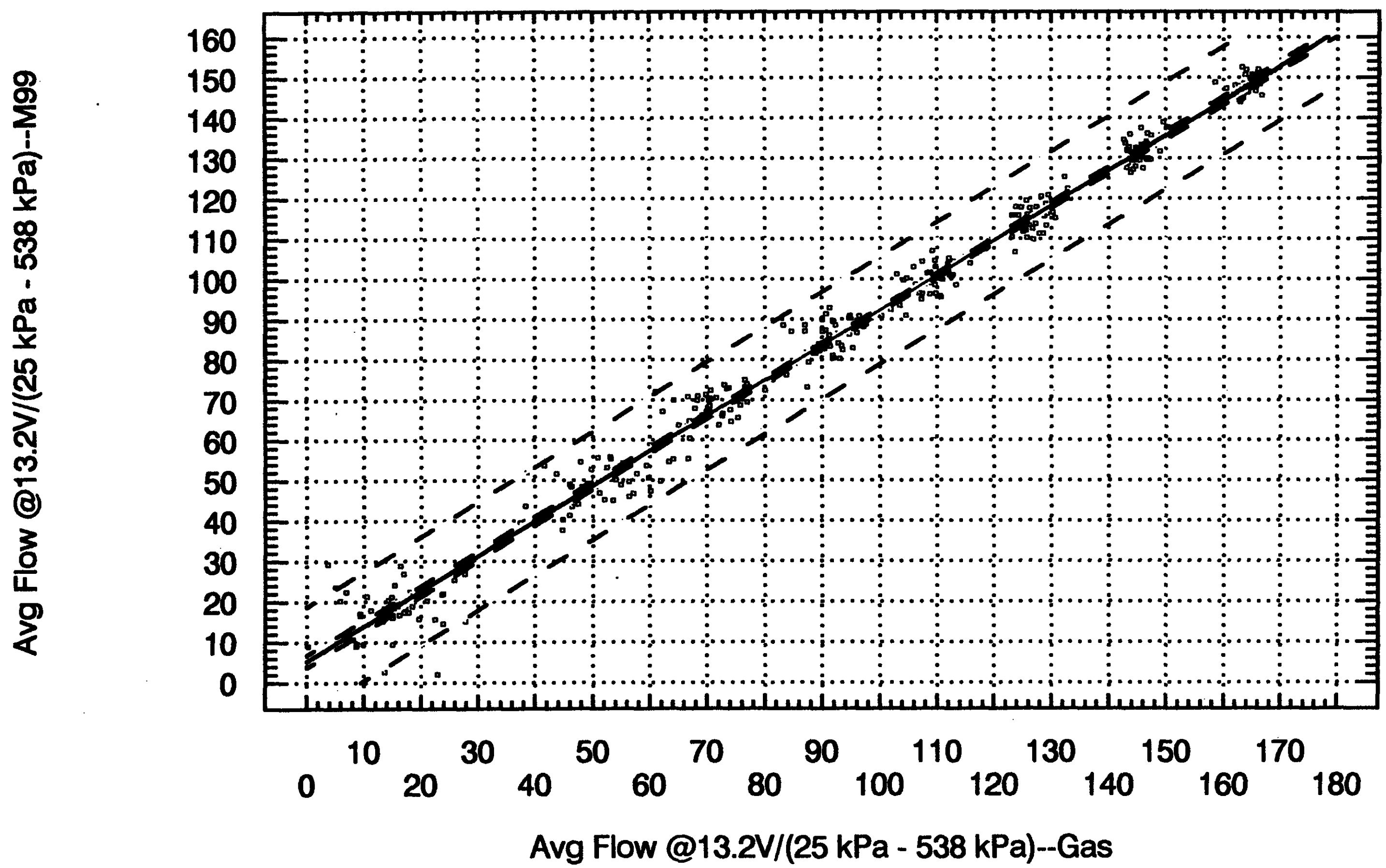


Figure I6: Linear Regression Model

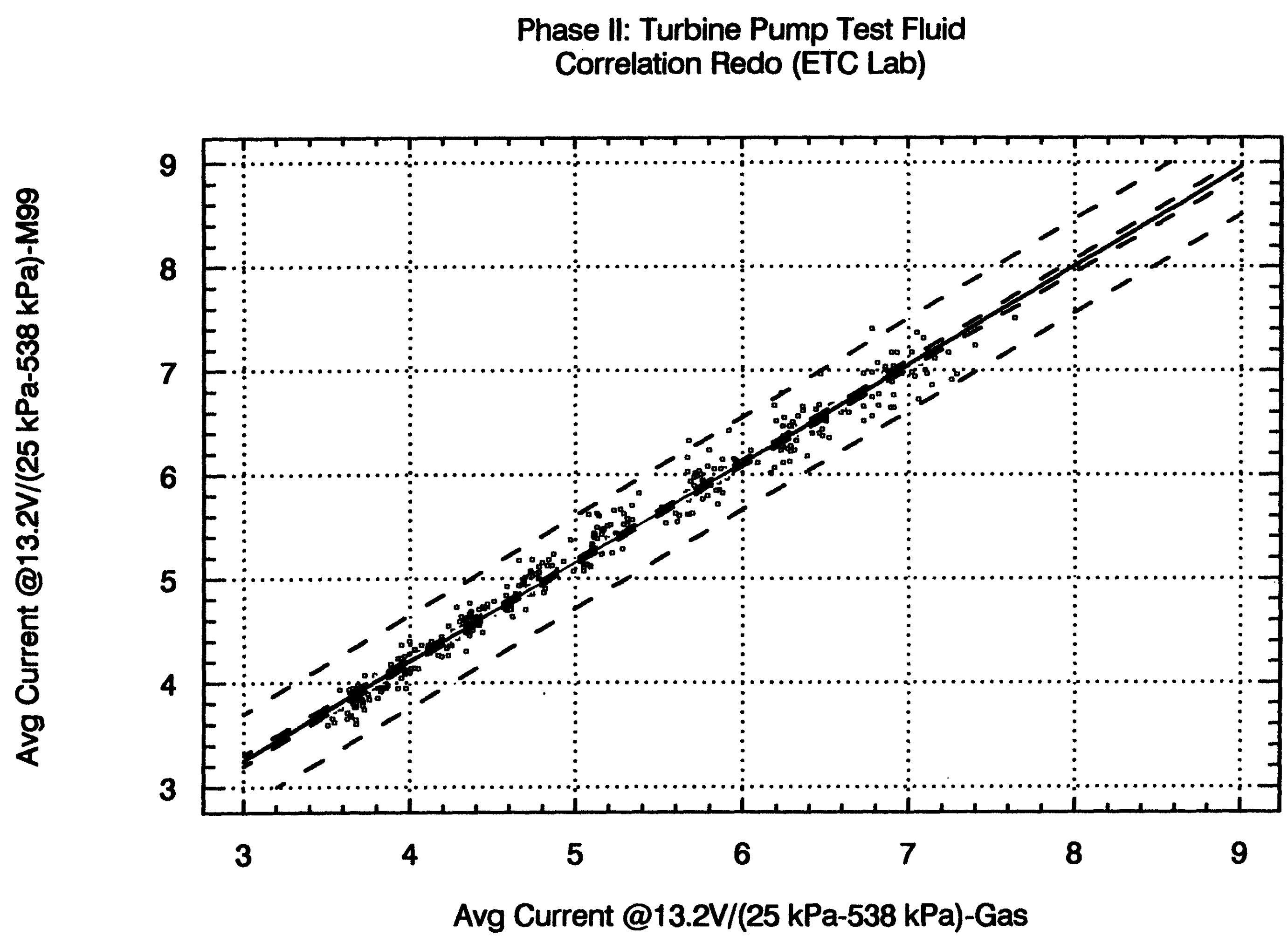
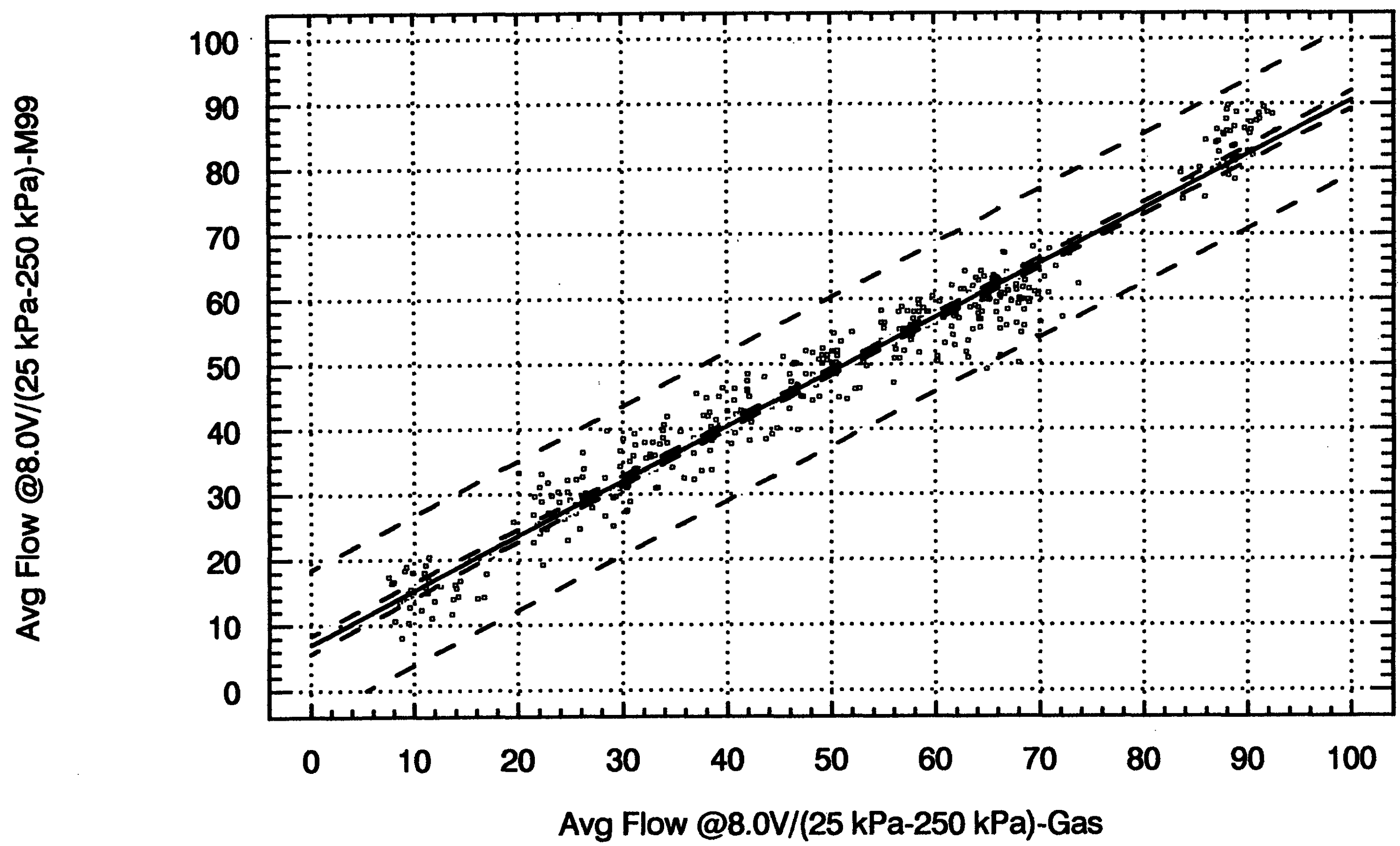


Figure I7: Linear Regression Model

Phase II: Turbine Pump Test Fluid
Correlation Redo (ETC Lab)



APPENDIX J

Reference	Step or Explanation	Data Name
		Result
Column B	Individual results by lab	
		number
Summary	Count the individual results =COUNT(Results)	
Test	If less than 3 results, no stats calculated.	
		median_x
Summary	Calculate the median of original results =MEDIAN(Results)	
		beta
Summary	Calculate the Beta adjusted by the number of results =0.778	
		Cee
Summary	Calculate C value =1.5*(SQRT((number-1)/number))	
		Dev
Column C	Calculate the deviation from the median of each result =Result-median_x	
		Abs_Dev
Column D	Calculate the absolute value of each deviation =ABS(Dev)	
		m_abs_dev
Summary	Calculate the median of the absolute deviations =MEDIAN(Abs_Dev)/0.6745	
		upper
Summary	Calculate the Upper Limit =median_x+(Cee*m_abs_dev)	
		lower
Summary	Calculate the Lower Limit =median_x-(Cee*m_abs_dev)	
		R_Result
Column F	If result falls within upper and lower limits,keep original result. Else if its above upper limit use upper limit or if its below the lower use the lower limit. =IF(AND(Result>=lower,Result<=upper),Result,IF(Result<lower,lower,upper))	

Page 1

Robust Stats with Excel

EXCEL MACROS GENERATED FROM FOLLOWING ARTICLES.

Summary	Calculate the Robust Mean	
	=AVERAGE(R_Result)	R_mean
Summary	Calculate the Robust Standard Deviation	
	=STDEV(R_Result)/SQRT(beta)	r_std_dev
Loop	Substitute Robust Mean and Robust Standard Deviation into calculation of Upper and Lower Limits	
	=R_mean+(Cee*r_std_dev)	
	=R_mean-(Cee*r_std_dev)	
	Recalculate	
	When Robust Mean and Robust Standard Deviation stabilize, exit loop	
Summary	Calculate 3 Robust Standard Deviations	
	=3*r-std_dev	
Summary	Create Error 1 Limits, Robust Mean +and - 3 Robust Standard Deviations	sd_3up
		sd_3dn
Column G	Test original results for fit within Error 1 limits.	Error 1
	=IF(AND(Result>=sd_3dn,Result<=sd_3up),"","Error 1")	
Summary	Create ASTM Repro	ASTM_R
	For this standard its a constant of 17.00	
Summary	Adjust ASTM Repro	
	=ASTM_R*3/2.77	
Summary	Create Error 2 (ASTM Repro) Limits. Robust Mean + and - ASTM Repro	astm_up
		astm_dn
Column H	Test original results for fit within Error 2 limits.	Error 2
	=IF(AND(Result>=astm_dn,Result<=astm_up),"","Error 1")	

Robust Statistics—How Not to Reject Outliers

Part 1. Basic Concepts

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The subject of outliers has been controversial whenever analytical data have been processed. Modern statistical theory provides an alternative to outlier rejection, in which outlying observations are retained but given less weight. This approach is known as robust statistics and is beginning to find favour with analytical chemists. An introduction to robust statistics is given and some examples are described.

Keywords: *Outlier; robust statistics; mean; median; variance*

The Analytical Methods Committee has received and has approved for publication the following report from its Statistical Sub-Committee.

Report

The constitution of the Sub-committee responsible for the preparation of this report was: Dr. M. Thompson (Chairman), Mr. H. M. Bee, Dr. W. H. Evans, Mr. M. J. Gardner, Dr. E. J. Greenhow, Dr. R. Howarth, Dr. E. J. Newman, Professor B. D. Ripley and Dr. R. Wood with Mr. J. J. Wilson as Secretary.

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Introduction

Occasionally sets of analytical data occur in which a few observations appear discordant with the remainder. Such observations are known as outliers. For example, considering the following 24 determinations of copper ($\mu g\,g^{-1}$) in wholemeal flour

2.9 3.1 3.4 3.4 3.70 3.7 2.8 2.5 2.4 2.4 2.7 2.2
5.28 3.37 3.03 3.03 28.95 3.77 3.4 2.2 3.5 3.6 3.7 3.7 (1)

one value, 28.95, stands out from the remainder. In this instance we may be particularly suspicious of the value, as a simple explanation suggests itself. Although recording and range errors are almost certainly the major cause of outliers, mistakes can also occur in many other parts of the analytical process and from contamination and transposition of specimens.

The almost universal practice amongst analytical chemists has been to regard outliers as errors, and to delete them from the set of data. In some circumstances this is plainly wrong, and in others there are much safer procedures. Why should we be interested in outliers? One good reason is to catch transcription errors while the original laboratory records are easily accessible. In such an instance we would want to check *all* the extreme results whether or not they are rejected by an outlier test (such as the tests of Dixon[1] or Grubbs[2]). The traditional procedure[3] for dataset (1) would be to compute

$$\max\left[\frac{x(3)-x(1)}{x(22)-x(1)}, \frac{x(24)-x(22)}{x(24)-x(3)}\right] = 0.948$$

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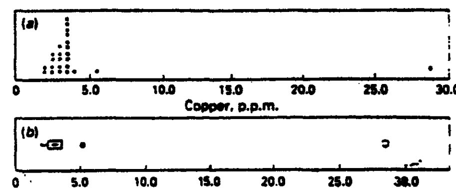

Fig. 1. Two views of dataset (1) from the statistical package MINITAB. (*a*) A dot plot; and (*b*) a box plot. * and O, extreme observations; +, the median; and □, the quantiles

where $x(1)$, ..., $x(24)$ are the observations sorted into increasing order:

2.2 2.2 2.4 2.4 2.5 2.7 2.8 2.9 3.03 3.03 3.1 3.37
3.4 3.4 3.4 3.5 3.6 3.7 3.7 3.7 3.70 3.77 5.28 28.95

and therefore reject $x(24) = 28.95$. For the remaining 23 observations the Dixon[1] test statistic is 0.549, so $x(23) = 5.28$ would also be rejected. Using the test yet again gives 0.133, this being judged not significant. Grubbs' test gives the same results.

The traditional procedure has the merit of pointing out the second outlier, 5.28, but this would have been obvious from any plot of the data (Fig. 1). The second-largest value will be significant (at 5%) only if it exceeds 4.80. However, surely we would want to check a value of 4.77 for a transcription error? If the purpose of detecting outliers is to check the values, it is their extremeness and the plausibility of simple explanations that should weigh in the decision, and *not* the statistical significance.

Outlier rejection is positively wrong when included in a procedure to assess the variability of an analytical method. The outlier rejection procedure used above is that of BS5497[4]; the illustrative dataset (1) is taken from a co-operative trial.[5] The mean and variance of the whole set are 4.28 and 28.1, respectively, whereas after outlier rejection they are 3.11 and 0.281, respectively. If the second-largest observation had been 4.77 we would have obtained 3.19 and 0.387, respectively. From this, two conclusions can be drawn that are true generally. The traditional procedure is (*a*) sensitive to the actual data values and (*b*) seriously underestimates the variance that is attainable in practice. The outliers in our dataset are only revealed because we have 24 replicates. Duplication might throw doubt on a value of 28.95, but it is very unlikely to do so on 5.28. On the other hand, estimating the variance by 28.1 is also unfair, as values as large as 28.95 might be spotted and are much rarer than 1 in 24.

Barnett and Lewis[6] discussed the outlier problem in considerable detail and described a whole battery of outlier rejection tests. The change of emphasis from their first edition (1978) to the second edition (1984) reflects a change in statistical practice from outlier *rejection* to outlier *accommodation*. The prevailing philosophy is known as robust statistics (or, occasionally, as resistant statistics) and is expounded in a number of recent monographs,[7-10] some of which are forbidding even to professional statisticians.

Robust statistics have been used occasionally by chemists, especially in geochemistry.[11-15] These papers concentrate on establishing reference values, whereas robust methods can be as useful in assessing variability as for central tendency.

Philosophy of Robust Statistics

The normal distribution pervades statistical methodology, and its very name suggests widespread applicability. Yet careful studies show that real errors do not fit the normal distribution! Users of statistics point to a theoretical result, the central limit theorem, to justify the assumption, whereas theoreticians believe its applicability to have been proved empirically. The central limit theorem is, of course, a perfectly correct result about sums of many small independent errors having (approximately) a normal distribution. The problem is that outliers result from single large errors. It is also generally accepted that real error distributions have "heavier tails" than the normal distribution, *i.e.*, large deviations (in either direction) are more likely than under a normal distribution. One of the bases of robust statistics is to use procedures that work well for such distributions.

The second basis is to protect against gross errors. We observed from our example that recording 28.95 rather than 2.895 increased the sample mean considerably (to 4.28 from 3.19). Recording 289.5 and 2895 would give 15.1 and 123.7, respectively. Hence the effect of a missing decimal point is disastrous for the mean. On the other hand, the *median* is almost unchanged, from 3.24 with 2.895 to 3.38 with any value greater than 3.40. This property is shared by a *trimmed mean*. Suppose we discard the smallest r and the largest r observations out of the total, n, and then take the mean of the remainder. [This is called a $(100r/n)(\%)$ trimmed mean.] Discarding $r = 1$ and $r = 2$ gives estimates of the mean of 3.25 and 3.21, respectively, both being insensitive to the actual size of 28.95. Trimmed means obey both principles of robust statistics; they are insensitive to small numbers of gross errors, and they work well for heavy-tailed distributions close to the normal. The mean fails the first of these, the median the second.

The sample variance is even more sensitive to outliers than the sample mean, increasing from 0.46 (when 28.95 is replaced by 2.895) to 28.1. The inter-quartile range (IQR) is the difference between observations one quarter in from each end, the 6th and 19th in the present example, so IQR = 1.0. For a normal distribution the IQR would be expected to be about 1.35σ, which suggests that we determine σ^2 by $(\text{IQR}/1.35)^2 = 0.55$. Again this is insensitive to gross errors; it is in fact unchanged if 28.95 is replaced by 2.895 or 289.5.

The trimmed mean and the IQR were developed in the days when all data were analysed by hand. Computers have allowed more sophisticated methods to be used. Many such procedures exist, but we will only describe some of the simplest which are known to perform well. A whole book[16] has been devoted to comparisons of 68 procedures! The references disagree as to the best procedure, but all accept those described here as amongst the best.

Measuring "True Values"

Both the sample mean and median are estimates of the location of a distribution of results. This distribution can be

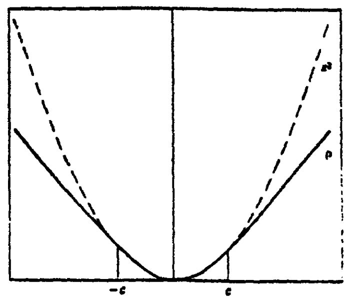

Fig. 2. A robust loss function ρ. Note that $\rho(x) = x^2$ for $|x| \leq c$, but $\rho(x) < x^2$ for large $|x|$

considered as a "true value", μ, plus errors, and we want to find an estimate of μ. We assume that μ is the mean of the "reliable" results, but not of the whole error distribution, as in analytical chemistry the distribution of errors will almost always be asymmetric. Consider n data points $x_1, \ldots, x_n$. The sample mean minimises the sum of squares $SS = \Sigma(x_i - \mu)^2$ and this is the source of its sensitivity to gross errors as large errors inflate SS significantly. Suppose we minimise $SS = \Sigma\rho(x_i - \mu)$ where $\rho(\varepsilon)$ does not weight large errors, ε, as much as ε^2. A good choice is the function

$$\rho(\varepsilon) = \begin{cases} (\varepsilon/\sigma)^2, & |\varepsilon| \leq c\sigma \\ c(2|\varepsilon/\sigma| - c), & |\varepsilon| \geq c\sigma \end{cases}$$

illustrated in Fig. 2 where σ^2 is a robust variance and c is a constant in the range 1–2. This penalises errors larger than $c\sigma$ less severely than x^2. The corresponding location estimate, $\hat{\mu}$, is the mean of *pseudo-values* $\tilde{x}_i$

$$\tilde{x}_i = \begin{cases} x_i & \text{if } |x_i - \hat{\mu}| \leq c\sigma \\ \hat{\mu} - c\sigma & \text{if } x_i < \hat{\mu} - c\sigma \\ \hat{\mu} + c\sigma & \text{if } x_i > \hat{\mu} + c\sigma \end{cases} \quad \ldots \quad \ldots \quad (2)$$

and also the weighted mean of x_i, with weights w_i

$$w_i = \begin{cases} 1 & \text{if } |x_i - \hat{\mu}| \leq c\sigma \\ c\sigma/|x_i - \hat{\mu}| & \text{if } |x_i - \hat{\mu}| > c\sigma \end{cases}$$

Hence extreme values can be thought of as being either brought in or downweighted. We can compute $\hat{\mu}$ from either of these properties. To start with take any estimate $\hat{\mu}^{(0)}$, say the mean or the median. At each stage compute $\hat{\mu}^{(j)}$ as the weighted mean with weights $\min(1, c\sigma/|x_i - \hat{\mu}^{(j-1)}|)$ or as the mean of the values $\tilde{x}_i$ [with $\hat{\mu} = \hat{\mu}^{(j-1)}$]. [The function $\min(x, y)$ denotes the smaller value of x and y.] The values $\hat{\mu}^{(j)}$ converge rapidly to $\hat{\mu}$.

The value of $c = 1.5$ has wide support. Suppose we knew σ to be 0.70, then starting from the mean

$$\hat{\mu}^{(j)} = 4.28, 3.56, 3.27, 3.22, 3.21, \ldots$$

and starting from the median

$$\hat{\mu}^{(j)} = 3.39, 3.24, 3.21, \ldots$$

It is usually unrealistic to assume that σ is known, although only a rough estimate is needed, which might be available from past trials. One rough estimate is based on the median absolute deviation (MAD): MAD = median ($|x_i$ − median$|$), $\hat{\sigma}$ = MAD/0.6745, which is similar to the re-scaled IQR, and in our example gives $\hat{\sigma} = 0.53$ and $\hat{\mu} = 3.207$. (The scale factor 0.6745 is used to obtain the correct answer for normally distributed data.) More sophisticated estimates are considered later. However, this simple proposal is already very reliable. The corresponding estimator of location is sometimes known as A15.

Table 1. Values of the constants β and θ for a range of cut-off values c. Further values can be obtained from $\theta = P(|N| < c)$, $\beta = \theta + c^2(1-\theta) - 2c\exp(-c^2/2)/\sqrt{2\pi}$ where N is a standard normal deviate

c	1.0	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9	2.0
β	0.516	0.578	0.635	0.688	0.736	0.778	0.816	0.849	0.877	0.900	0.921
θ	0.683	0.729	0.770	0.806	0.838	0.866	0.890	0.911	0.928	0.943	0.954

Measuring "Precision"

If it is supposed that we are in the somewhat more realistic position of knowing μ (say from a reference sample) and wish to estimate σ, then we could use the sample variance or the scaled IQR, or

$$\hat{\sigma}_m = \text{median}(|x_i - \mu|)/0.6745$$

A robust procedure is to solve

$$\Sigma \min(|x_i - \mu|/\sigma, c)^2 = n\beta \quad \ldots \quad (3)$$

where again β is chosen to obtain the correct answer for normally distributed data. Some values of β are given in Table 1.

There are a number of ways to solve (3). One of the easiest is to compute a sequence of values $\hat{\sigma}^{(j)}$ with $\hat{\sigma}^{(0)} = \hat{\sigma}_m$ and

$$[\hat{\sigma}^{(j)}]^2 = \frac{1}{n\beta}\Sigma(\tilde{x}_i - \mu)^2$$

where

$$\tilde{x}_i = \begin{cases} x_i & \text{if } |x - \mu| < c\hat{\sigma}^{(j-1)} \\ \mu - c\hat{\sigma}^{(j-1)} & \text{if } x_i < \mu - c\hat{\sigma}^{(j-1)} \\ \mu + c\hat{\sigma}^{(j-1)} & \text{if } x_i > \mu + c\hat{\sigma}^{(j-1)} \end{cases}$$

which converges rapidly to the solution of (3).

Suppose for dataset (1) that we knew that μ = 3.68 (which is the consensus of a much larger set of measurements), then

$\hat{\sigma}^j$ = 0.911, 0.927, 0.934, 0.938, 0.939, 0.940, 0.941, ...

so σ can be estimated by 0.941. Note that $\beta\hat{\sigma}^2$ is the variance of the pseudo-values $\tilde{x}_i$ (with divisor n as μ is known).

Unknown "true value"

The more sophisticated approach referred to in a previous section involves estimating σ alongside μ. Hence at each iteration we form pseudo-values $\tilde{x}$, and compute their mean, $\bar{\tilde{x}}$, and variance, s^2. Then $\hat{\mu}^{(i)} = \bar{\tilde{x}}$ and $\hat{\sigma}^{(i)} = \sqrt{(s^2/\beta)}$. This is repeated until the values stabilise, starting from (median, $\hat{\sigma}_m$). The present example gives

$\hat{\mu}$ =	3.385	3.255	3.213	3.206	3.205	3.205	...	3.205
$\hat{\sigma}$ =	0.526	0.595	0.639	0.657	0.666	0.671	...	0.674

The following shows the insensitivity to the outlier(s):

$x_{(24)}$	$\hat{\mu}$	$\hat{\sigma}$
28.95	3.205	0.674
2.895	3.146	0.613
289.5	3.205	0.674

and in fact $(\hat{\mu}, \hat{\sigma})$ do not depend on any of the exact values greater than $\hat{\mu} + c\hat{\sigma} = 4.22$. Hence it is irrelevant whether the value 5.28 is considered an outlier or not; all that matters is that it exceeds 4.22. This combined estimator is known as H15 or "Huber proposal 2."

When n, the number of observations, is small, a small-sample correction should be made. The variance of $x_i - \hat{\mu}$ will be about $\sigma^2(n-1)/n$ and so the cut-off point, c, should be reduced to $c\sqrt{(1 - 1/n)}$ in forming the pseudo-values. This will be important in Part 2.[17] (It reduces $\hat{\sigma}$ to 0.662 in our example.)

Discussion

We have observed that robust procedures can be constructed to estimate the true value and precision of a set of data by relatively simple iterative calculations. These are very tedious to do manually but easy to program. (The longest part of the program will be to find the starting values, see Appendix.) The robust estimates are completely insensitive to how outlying the extreme data values are and obtain most of their information from the values in the centre of the dataset.

The cut-off value c should in theory be chosen depending on how frequent outliers are thought to be, although it is safer to choose a smaller value of c if in doubt. About 1% of outliers suggest c = 2.0 and about 5% suggest c = 1.4. The value c = 1.5 is widely used. The actual estimates obtained are not very sensitive to c:

c =	1.0	15	2.0
$\hat{\mu}$ =	3.229	3.205	3.234
$\hat{\sigma}$ =	0.648	0.662	0.678

If we really wanted to look for outliers to check them against the original records, a useful rule would be to check x_i values outside $\hat{\mu} \pm 2\hat{\sigma}$. In dataset (1) this suggests that all values greater than 4.53 would be checked.

Use of robust estimates

Some considerable care is needed in interpreting $\hat{\mu}$ and $\hat{\sigma}$. They do *not* estimate the mean and standard deviation of the observations (note, *not* the population), and this is an asset rather than a liability. Rare but very large outliers will affect the theoretical mean μ considerably when, as in analytical chemistry, they will almost always occur in one direction. Instead we should regard μ as measuring the mean of the "reliable" observations, a consensus value which is the nearest we can get to a "true value". (This interpretation is only possible if the "reliable" observations form the majority. Examples do occur in which the outliers are the only valid observations, but no statistical procedure can redeem such a disastrous trial.)

In a similar manner $\hat{\sigma}$ measures the standard deviation of the "reliable" observations. If we take m replicates then the robust measure $\hat{\mu}$ obtained from these will have a variance of about $\hat{\sigma}^2/m$ for moderate m. [In fact $\hat{\sigma}^2/m \times \beta/\theta^2$ where $\theta = P(|x_i - \mu|/\sigma \leq c)$, where P is the probability, which can be estimated either from the normal distribution or by the proportion of the dataset with $\tilde{x}_i = x_i$. As Table 1 shows, the correction factor β/θ^2 is only just larger than one.] However the (population) variance of one observation will usually much exceed $\hat{\sigma}^2$, as outliers cannot be downweighted. Duplicates also do not help, as we always find that $\hat{\mu} = (x_1 + x_2)/2$. At least three replicates are needed to allow downweighting, and this may not be sufficient unless σ is known *a priori*. If we had recorded just the three observations 2.9, 3.1 and 28.95, then

Mean =	11.65	s =	14.98
Median =	3.1	$\hat{\sigma}_m$ =	0.297
A15 =	3.222		
H15 =	11.65	$\hat{\sigma}$ =	16.98

There are two plausible explanations for this triple of observations. One, favoured by (A15, $\hat{\sigma}_m$), is of two reliable

Program*

```
      program robl
c
c       program from 'Robust Statistics - How Not to Reject Outliers'
c       Analyst
c       (C) B.D.Ripley
c
      parameter (NMAX = 100)
      real x(NMAX), ws(NMAX)
      real median, h15
      integer i, n
      real xmed, xm, xs
      character name*50
      print *, 'File name  '
      read '(a)', name
      open (1, file=name, status='old')
      print *, '# data points '
      read *, n
      read (1,*) (x(i), i=1,n)
      close (1)
      xmed = median(x, n, ws)
      print *, 'median ',xmed
      xm = a15(x, n, xs, ws)
      print *, 'a15, sigma ', xm, xs
      xm = h15(x, n, xs, ws)
      print *, 'h15, sigma ', xm, xs
      end

      real function median(x, n, ws)
      real x(n), ws(*), v
      integer i, j, h, n, n2
      do 10 i = 1, n
10      ws(i) = x(i)
      h = 1
20    h = 3*h+1
      if (h .le. n) goto 20
30    h = h/3
      do 50 i = h+1, n
        v = ws(i)
        j = i
40      if (ws(j-h) .le. v) goto 50
        ws(j) = ws(j-h)
        j = j-h
        if (j .gt. h) goto 40
50      ws(j) = v
      if (h .gt. 1) goto 30
      n2 = n/2
      if (2*n2 .eq. n) then
        median = 0.5*(ws(n2)+ws(n2+1))
      else
        median = ws(n2+1)
      endif
      end

      real function smad(xm, x, n, ws)
      real median, xm, x(n), ws(*)
      real sm, sum
      integer i, n
      do 10 i = 1,n
10      ws(i) = abs(x(i)-xm)
      sm = median(ws, n, ws)
      if (sm .le. 0.0) then
        sum = 0.0
        do 20 i = 1, n
20        sum = sum + ws(i)
        sm = sum/n
      endif
      smad = sm/0.6745
      end

      real function a15(x, n, xs, ws)
      real median, x(n), ws(*)
      real c, xm, xm0, xs, xs0, xc, sum
      integer i, n
      data c/1.5/
      xm = median(x, n, ws)
      xs = smad(xm, x, n, ws)
      xc = c*xs
10    xm0 = xm
      sum = 0.0
      do 20 i = 1, n
20      sum = sum + min(xm0+xc, max(xm0-xc, x(i)))
      xm = sum/n
      if (abs(xm-xm0) .gt. (1.0e-4)*xs) go to 10
      a15 = xm
      end

      real function h15(x, n, xsc, ws)
      real median, x(n), ws(*), xsc
      real a, beta, c, c1, xm, xm0, xs, xs0, xc, sum, sum2
      integer i, n
      data c, beta /1.5, 0.778/
c     c1 = c   without small-sample correction
      c1 = c * sqrt(1.0-1.0/n)
      xm = median(x, n, ws)
      xs = smad(xm, x, n, ws)
10    xm0 = xm
      xs0 = xs
      sum = 0.0
      sum2 = 0.0
      xc = c1*xs
      do 20 i = 1, n
        a = min(xm+xc, max(xm-xc, x(i)))
        sum = sum + a
20      sum2 = sum2 + (a-xm)*(a-xm)
      xm = sum/n
      xs = sqrt(sum2/(beta*(n-1)))
      if ((abs(xm-xm0) .gt. 1.0e-4*xs0) .or.
     & abs(xs/xs0-1.0) .gt. 1.0e-4) go to 10
      h15 = xm
      xsc = xs
      end
```


observations plus one outlier. On the other hand, (H15, $\hat{\sigma}$) regards the sample as three variable observations. We know only from other data which explanation is correct.

No statistical method can make sense of disastrous trials.

Abbey[14] quoted 31 determinations of the nickel content (μg g^{-1}) of Canadian syenite rock:

5.2 6.5 6.9 7 7 7 7.4 8 8 8 8 8.5 9 9 10
11 11 12 12 13.7 14 14 14 16 17 17 18 24 28 34 125

Under log transform only one outlier.
Under reciprocal none.

which gives

$$\text{Mean} = 16.01 \quad s = 21.27$$
$$\text{Median} = 11.00 \quad \hat{\sigma}_m = 4.45$$
$$\text{A15} = 11.55$$
$$\text{H15} = 11.70 \quad \hat{\sigma} = 5.19$$

suggesting a standard error of the robust mean of *ca.* 1.0 ($= \hat{\sigma}/\sqrt{m}$). Abbey quoted other robust estimators of $\hat{\mu}$, but all agreed to within the (considerable) uncertainty. However, this uncertainty is so large that very little has been learnt from 31 determinations.

In general, outliers are not a problem when data are looked at carefully. Increasingly data are not looked at at all. They are recorded in machine-readable form and summarised by computer programs. In such circumstances robust statistics are preferable to conventional ones, and a marked difference between them should give a warning that the data should be examined carefully.

Appendix

Computation

The exact form of the algorithms used to calculate robust estimates can be deduced from the FORTRAN 77 program shown. They cover the most general case of unknown μ and σ, but are easily modified to handle other instances.

Medians are found by sorting the data by the sort algorithm of Shell.[18] There are ways to find medians without sorting that will be faster for large values of n, but these are considerably more awkward to program correctly. One other difficulty is that $\hat{\sigma}_m$ could turn out to be zero, but only if half the data are equal to the median. In that instance we would report $\Sigma|x_i - \text{median}|/n$, which is zero only if *all* the data are equal to the median.

The programs use a common workspace (ws) which should be as large as the data array. One trap for the unwary: median and H15 are real qualities, despite the implicit rules of FORTRAN. To aid translation to other languages, all variables used are declared. NMAX can be set as required.

Professor Peter Rousseeuw's comments were most helpful in clarifying an earlier draft.

References

1. Dixon, W. J., *Ann. Math. Statist.*, 1950, **21**, 488.
2. Grubbs, F. E., *Technometrics*, 1969, **11**, 1.
3. Crow, E. L., Davis, F. A., and Maxfield, M. W., "Statistical Manual," Dover, New York, 1960.
4. "Precision of Test Methods," BS 1979, No. 5497, British Standards Institution, Milton Keynes.
5. Analytical Methods Committee, *Analyst*, 1989, **114**, 1489.
6. Barnett, V., and Lewis, J., "Outliers in Statistical Data," Second Edition, Wiley, Chichester, 1984.
7. Huber, P. J., "Robust Statistical Procedures," SIAM, Pennsylvania, 1976.
8. Huber, P. J., "Robust Statistics," Wiley, New York, 1981.
9. Hampel, F. R., Ronchetti, E. M., Rousseeuw, P. J., and Stahel, W. A., "Robust Statistics: The Approach Based on Influence Functions," Wiley, New York, 1986.
10. Rousseeuw, P. J., and Leroy, A. M., "Robust Regression and Outlier Detection," Wiley, New York, 1987.
11. Lister, B., *Geostand. Newsl.*, 1984, **8**, 171.
12. Lister, B., *Geostand. Newsl.*, 1987, **11**, 11.
13. Abbey, S., *Geostand. Newsl.*, 1986, **10**, 159.
14. Abbey, S., *Geostand. Newsl.*, 1988, **12**, 241.
15. Rock, N. M. S., *Math. Geol.*, 1988, **20**, 243.
16. Andrews, D. F., Bickel, P. J., Hampel, F. R., Huber, P. J., Rogers, W. H., and Tukey, J. W., "Robust Estimates of Location," Princeton University Press, 1972.
17. Analytical Methods Committee, *Analyst*, 1989, **114**, 1699.
18. Sedgewick, R., "Algorithms," Addison Wesley, Reading, MA, 1983.

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Robust Statistics—How Not to Reject Outliers

Part 2.* Inter-laboratory Trials

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Robust statistics can be used to find estimates of true values and precision that are insulated from the effect of outliers. In this paper these procedures have been extended to inter-laboratory trials.

Keywords: *Outlier; robust statistics; collaborative trial; co-operative trial*

The Analytical Methods Committee has received and has approved for publication the following report from its Statistical Sub-Committee.

Report

The constitution of the Sub-Committee responsible for the preparation of this report was: Dr. M. Thompson (chairman), Mr. H. M. Bee, Dr. W. H. Evans, Mr. M. J. Gardner, Dr. E. J. Greenhow, Dr. R. Howarth, Dr. E. J. Newman, Professor B. D. Ripley and Dr. R. Wood with Mr. J. J. Wilson as Secretary.

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Introduction

Robust statistics is a methodology for producing estimates of consensus values, μ, and precisions, σ, from data that may contain a small proportion of outliers, either as errors or abnormal results. Part 1[1] has described their application to a series of repeated measurements in one laboratory. In this paper the methods are applied to inter-laboratory trials.

The type of trial we had in mind involves a series of specimens being split into portions and analysed in several laboratories for specified analyte(s). The method may be specified closely (a collaborative trial) or left unspecified (a co-operative trial). In each instance the main aim was to determine the precision that could be achieved. For a collaborative trial this is the precision of the method, whereas a co-operative trial aims to assess the variability in the everyday practice of different laboratories. In some trials of either type, determination of bias is also important. Other inter-laboratory trials are undertaken as part of a quality control procedure, to help identify laboratories whose performance is below that expected, and to establish reference values.

The approach described here is closely related to those of Rocke[2] and Lischer[3] but differs in small but important details.

Traditional Procedures

A whole family of statistical analyses for collaborative trials have been proposed that differ in their fine detail.[4–7] All consider trials involving L laboratories, each of which analyse a specimen r times or perform a split-level test. This procedure is repeated for a number of specimens. For simplicity let us consider only "uniform-level" experiments. Then for one particular specimen the data are y_{ik}, $i = 1, \ldots, L$ representing the laboratory and $k = 1, \ldots, r$ representing the replicate.

The procedure in BS5497 stipulates that the standard deviations, s_i, of $y_{i1}, \ldots, y_{ir}$ are first tested for homogeneity by Cochran's test. Then if heterogeneity is found, Dixon's test is applied to the results for that laboratory. The latter test is also applied to the laboratory averages. As a result of this series of tests some or all of the results for each laboratory are deleted. Note that because each of the tests will make errors, some of the data will be deleted even if there are no actual outliers. The effect of this is to systematically underestimate the variances of the sources of error and hence the "repeatability" and "reproducibility." Other procedures differ in detail but have the same failing. The overestimation of precision can be serious when real outliers are prone to occur. Robust procedures downweight extreme observations *and* compensate for that downweighting.

Robust Procedures

First, consider experiments with two sources of random error. The observation y_{ik} is considered to be the sum of (a) a true value, μ; (b) a laboratory bias, ξ_i, with variance, σ_L^2; and (c) a measurement error, ε_{ik}, with variance, σ_e^2.

The robust procedure has two steps. First, the observations (y_{ii}) are analysed as a whole to estimate laboratory means, $\hat{\mu}_i = \mu + \xi_i$, and the variance, σ_e^2. The means $(\hat{\mu}_i)$ are then analysed to estimate μ and $\sigma_1^2 = \sigma_L^2 + \sigma_e^2/r$. This exactly parallels the traditional approach, which uses $\hat{\mu}_i = \bar{y}_i$. Estimating μ and σ_1 is carried out exactly by the procedure described in Part 1,[1] *i.e.*, by solving the equations

$$\sum_i \tilde{z}_i(\mu,\sigma_1) = L\mu$$
$$\sum_i [\tilde{z}_i(\mu,\sigma_1) - \mu]^2 = (L-1)\beta\sigma_1^2 \quad \ldots \quad (1)$$

where $z_i = \hat{\mu}_i$ are the estimated laboratory means, β is chosen to obtain the correct answer for normally distributed data, and

$$\tilde{z}_i(\mu,\sigma) = \begin{cases} z_i & \text{if } |z_i - \mu| < c_1\sigma \\ \mu - c_1\sigma & \text{if } z_i < \mu - c_1\sigma \\ \mu + c_1\sigma & \text{if } z_i > \mu + c_1\sigma \end{cases}$$

with $c_1 = c\sqrt{(1 - 1/L)}$, where c is a constant in the range 1–2. Equations (1) are solved iteratively by setting the right-hand side equal to the left-hand side. This process converges, sometimes very slowly.

The laboratory means z_i are found in a similar way. Then we solve

$$\sum_k \tilde{y}_{ik}(\mu_i,\sigma_e) = r\mu_i, \quad i = 1, \ldots, L$$
$$\sum_{i,k} [\tilde{y}_{ik}(\mu_i,\sigma_e) - \mu_i]^2 = (r-1)L\beta\sigma^2 \quad \ldots \quad (2)$$

where

$$\tilde{y}_{ik}(\mu,\sigma) = \begin{cases} y_{ik} & \text{if } |y_{ik} - \mu| < c_2\sigma \\ \mu - c_2\sigma & \text{if } y_{ik} < \mu - c_2\sigma \\ \mu + c_2\sigma & \text{if } y_{ik} > \mu + c_2\sigma \end{cases}$$

* For Part 1 of this series, see reference 1.

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Table 1. A trial of the determination of nitrate (mg l^{-1}) in drinking water[3]

	Laboratory													
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Replicate 1	48.5	44.4	46.4	45.7	44.1	48.8	45.1	45.5	43.8	45.0	50.7	45.8	49.0	42.9
Replicate 2	48.3	44.5	46.6	46.0	45.0	48.5	45.6	49.3	44.2	45.2	50.6	46.1	50.0	42.9

Table 2. Statistical analyses for nitrate (Table 1)

	$\hat{\mu}$	$\hat{\sigma}_L$	$\hat{\sigma}_e$
Full data set	46.38	2.189	0.781
Omitting laboratory 8	46.30	2.319	0.318
Omitting laboratories 13 and 8 ..	46.03	2.208	0.261
Robust procedure	46.33	2.451	0.315

and $c_2 = c\sqrt{(1 - 1/r)}$. As r is usually small (2 or 3), c_2 is much less than c. Once again, equations (2) are solved by iteration. For starting values, μ_i can be taken as the median of the observations in laboratory i, and

$$\hat{\sigma} = \text{median}(|y_{ik} - \mu_i|)/[0.6745\sqrt{(1 - 1/r)}]$$

with, again, a small-sample correction.

In the special instance of two replicates equations (2) can be simplified. By symmetry, $\hat{\mu}_i = \bar{y}_i$ whatever the value of σ. If we let $w_i = (y_{i2} - y_{i1})/2$ be half the difference between the results from laboratory i, then σ can be found from

$$L\beta\sigma^2 = 2\sum_i \min(|w_i|, c\sigma/\sqrt{2})^2$$

or

$$L\beta\theta^2 = \sum_i \min(|w_i|, c\theta)^2$$

where $\theta^2 = \sigma^2/2$ is the variance of w_i. An appropriate starting value is

$$\hat{\theta} = \text{median}(|w_i|)/0.6745$$

In practice it can be as easy to solve (2) directly.

This argument indicates the advantage of having more than two replicates. With just two replicates we can be suspicious of them both because their difference is too large, but it is impossible to know which is the outlier and so to correct our estimate of the laboratory mean. With three or more replicates possible outliers can be downweighted.

Example

Table 1 gives duplicate determinations of nitrate in drinking water from 14 laboratories.[3] The two values returned by laboratory 8 appear to be discordant, and those in laboratories 5 and 13 are substantially more discordant than the rest. Cochran's test gives a value of 0.846 and so rejects laboratory 8 but not laboratory 13 if repeated. Table 2 shows the traditional results and the robust ones. It is clear that rejecting all the laboratories whose results are suspicious can easily cause variances to be underestimated; this appears to be an example.

Trials with Batches

A report on co-operative trials[8] recommended considering an additional layer of variability, the *batch*. In such a trial, specimens are sent to the laboratories on $b \geq 2$ occasions in order to assess the variability of a laboratory over time. Consider Table 3 of reference 8, in which six laboratories analysed specimens twice in each of three batches. Each of the seven specimens is considered separately. We have observations

$$y_{ijk},\ i = 1, \ldots, L;\ j = 1, \ldots, b;\ k = 1, \ldots, r$$

from replicate k of batch j in laboratory i. There are three sources of random variation, so

Table 3. Robust estimates for a co-operative trial (g kg^{-1}). Data are taken from Table 3 of reference 8 (for specimen 5, line 2, 6.8 should read 6.9)

	Robust				Traditional[x]			
Specimen	$\hat{\mu}$	$\hat{\sigma}_L$	$\hat{\sigma}_B$	$\hat{\sigma}_e$	$\bar{y}$	$\hat{\sigma}_L$	$\hat{\sigma}_B$	$\hat{\sigma}_e$
1	0.41	0.08	0	0.04	0.51	0.25	0.07	0.08
2	0.22	0.02	0	0.04	0.37	0.37	0.23	0.08
3	1.04	0.27	0.05	0.09	1.08	0.32	0.12	0.10
4	0.64	0.13	0.08	0.05	0.64	0.0	0.28	0.07
5	7.83	0.95	0.20	0.32	7.76	0.67	0.50	0.31
6	1.73	0.30	0.08	0.12	1.79	0.30	0.20	0.16
7	1.29	0.33	0.08	0.16	1.31	0.34	0.08	0.16

$$y_{ijk} = \mu + \xi_i + \eta_{ij} + \varepsilon_{ijk}$$

with the variances of ξ_i, η_{ij} and ε_{ijk} being σ_L^2, σ_B^2 and σ_e^2, respectively.

The traditional analysis uses (a) mean and variance of $\bar{y}_i$ to estimate μ and $\sigma_1^2 = \sigma_L^2 + \sigma_B^2/b + \sigma_e^2/br$, (b) the variance of $\bar{y}_{ij}$ about $\bar{y}_i$ to estimate $\sigma_2^2 = \sigma_B^2 + \sigma_e^2/r$ and (c) the variance of y_{ijk} about y_{ij} to estimate σ_e^2. A robust version can be produced for each of these steps. The procedure of the previous section is applied to the data y_{ijk} with a separate mean for each batch in each laboratory (*i.e.*, with bL "laboratories") to find $\hat{\mu}_{ij}$ and $\hat{\sigma}_e$. Then the whole procedure is applied again with data $\hat{\mu}_{ij}$ to find $\hat{\mu}$, $\hat{\mu}_i$, σ_1^2 and $\hat{\sigma}_2^2$. From these we obtain $\hat{\mu}$, $\hat{\sigma}_L$, $\hat{\sigma}_B$ and $\hat{\sigma}_e$.

The main example of reference 8 has seven specimens, six laboratories, three batches and two replicates. Table 3 shows the results, together with those from Table 4 of reference 8. The results are similar for specimens 3–7, which have the highest analyte levels. The results for the first two specimens are influenced heavily by the downweighting of laboratory 4. For specimen 5 note that the estimate of σ_L is increased somewhat, because the first batch of laboratory 6 is downweighted.

This particular co-operative trial is unusual in that reference values are available for specimens 6 and 7 (1.5 and 0.9 g kg^{-1}, respectively). The estimates $\hat{\mu}_i$ are given by

	Laboratory					
	1	2	3	4	5	6
Specimen 6	1.41	1.71	1.48	2.43	1.88	1.75
Specimen 7	0.99	1.22	0.98	1.86	1.28	1.50
giving biases						
Specimen 6	−0.09	0.21	−0.02	0.93	0.38	0.25
Specimen 7	0.09	0.32	0.08	0.96	0.38	0.60

a remarkably consistent pattern! The variances of each $\hat{\mu}_i$ about μ_i are approximately $\sigma_B^2/b + \sigma_e^2/br = (0.068)^2$ and $(0.081)^2$, respectively, so we can safely conclude that all laboratories except 1 and 3 have an upwards bias. On the other hand, to test whether a laboratory is an outlier we have to add the variance σ_L^2, to get $(0.30)^2$ and $(0.34)^2$. In each instance only laboratory 4 is identified as giving unusually high results amongst laboratories in the trial.

Some care is needed in using the results of a robust procedure. The variances refer to the centre of the distribution of observations, the "good" results. With "real" error distributions, considerably more observations will occur beyond the mean $\pm k\sigma$ than for a normal distribution. The normal-theory results can be used as a guide, but with caution so that results beyond 3σ rather than 2σ are regarded as outliers.

Program*

```
      program rob2
c
c        program from 'Robust Statistics - II Interlaboratory Trials'
c        Analyst
c        (C) B.D.Ripley
c
c        needs function median from part I
c
      parameter (NLAB=20, NREP=10, NTOT=NLAB*NREP, tol=1.0e-4)
      real data(NLAB, NREP),labs(NLAB)
      real wlab(NLAB), wrep(NLAB, NREP), ws(NTOT)
      real msl, mse, median
      integer i, ib, k, nb, nlabs, nreps
      real am,ap,as,as0,beta,c,c1,f,s,se,sl,sum1,sum2,sse,ssl
      character name*50
      data c, beta /1.5, 0.778/
      print *, 'File name  '
      read '(a)', name
      open (1, file=name, status='old')
      open (2, file='results.lis')
      print *, '#specimens #labs #reps '
      read *, nb, nlabs, nreps
      do 1000 ib = 1, nb
      write (2, *) 'specimen ', ib

c       find traditional results
      do 10 i = 1, nlabs
   10   read(1, *) (data(i,k), k = 1, nreps)
      do 30 i = 1, nlabs
        s = 0.0
        do 20 k = 1, nreps
   20     s = s + data(i,k)
   30     labs(i) = s/nreps
      s = 0.0
      do 40 i = 1, nlabs
   40   s = s + labs(i)
      am = s/nlabs
      write (2, *) 'mean = ', am
      s = 0.0
      do 50 i = 1, nlabs
   50   s = s + (labs(i)-am)**2
      ssl = s*nreps
      s = 0.0
      do 60 i = 1, nlabs
        do 60 k = 1, nreps
   60     s = s + (data(i,k)-labs(i))**2
      sse = s
      msl = ssl/(nlabs-1)
      mse = sse/((nreps-1)*nlabs) 
      se = sqrt(mse)
      sl = sqrt(max(0.0, msl-mse)/nreps)
      write (2, *) 'sigma - ',sl,se
      write (2, *) 'Robust results:'

c        do reps
      do 210 i = 1, nlabs
        do 200 k = 1, nreps
  200     ws(k) = data(i,k)
  210   labs(i) = median (ws, nreps, ws)
      do 220 i = 1, nlabs
        do 220 k = 1, nreps
  220     ws(k+(i-1)*nreps) = abs(data(i,k)-labs(i))
      f = real(nreps)/(nreps-1.0)
      as = median (ws, nlabs*nreps, ws)*sqrt(f)/0.6745
c        protect against too many labs with equal results
      if (as .le. 0.0) as = sqrt(mse)
      c1 = c*sqrt((nreps-1.0)/nreps)
  230   as0 = as
        sum2 = 0.0
        do 250 i = 1, nlabs
          wlab(i) = 0.0
          do 250 k = 1, nreps
            wrep(i,k) = max(-c1*as,min(c1*as,data(i,k)-labs(i)))
            wlab(i) = wlab(i) + wrep(i,k)
            sum2 = sum2 + wrep(i,k)**2
  250       continue
        ap = 0.0
        do 260 i = 1, nlabs
          ap = max(ap, abs(wlab(i)/nreps))
  260     labs(i) = labs(i) + wlab(i)/nreps
        as = sqrt(sum2/(beta*nlabs*(nreps-1)))
        if (((as/as0-1.0) .gt. tol) .or.
     &    (ap .gt. tol*as0)) go to 230
      mse = as*as

c        now do labs
      am = median (labs, nlabs, ws)
      do 300 i = 1, nlabs
  300   ws(i) = abs(labs(i)-am)
      as = median(ws, nlabs, ws)/0.6745
      if (as .le. 0.0) as = sqrt(msl/nreps)
  310   as0 = as
        sum1 = 0.0
        sum2 = 0.0
        do 320 i = 1, nlabs
          wlab(i) = max(-c*as,min(c*as,labs(i)-am))
          sum1 = sum1 + wlab(i)
          sum2 = sum2 + wlab(i)**2
  320     continue
        sum1 = sum1/nlabs
        as = sqrt(sum2/(beta*(nlabs-1)))
        am = am + sum1
        if ((abs(as/as0-1.0) .gt. tol) .or.
     &    (abs(sum1) .gt. tol*as0)) go to 310

      msl = as*as*nreps
      write (2, *) 'mean = ',am
      se = sqrt(mse)
      sl = sqrt(max(0.0,msl-mse)/nreps)
      write (2, *) 'sigma - ',sl,se
      write (2, *)
 1000 continue
      close (1)
      close (2)
      end
```


Large Co-operative Trial

Reference 9 gives an account of a co-operative trial of the determination of nitrogen, copper and lead in foodstuffs. Twenty laboratories participated, which were sent duplicate samples in each of three batches. Six specimens were used. The results of the robust procedure are given in Table 4. The results are similar to those given in reference 9 excluding the two worst laboratories, but with, in general, slightly lower variances as outliers are downweighted. The results in reference 9 aim to estimate the precision attainable in day-to-day analysis whereas those of Table 4 estimate the variability of the good results.

Apart from two rogue laboratories, two outliers (in copper for wholemeal, 28.95; and in lead for soya, 97.94) stood out in the original dataset, and both are heavily downweighted in the robust results. Adjusting the decimal point in these two values gives results for the variances much closer to the robust results. The trial showed that such apparent range errors do occur, but at a rate of *ca.* 1 in 1000 amongst the main body of laboratories. On the other hand, moderate outliers (beyond say 3σ from the consensus value) are fairly frequent, a few percent, rather than the 0.25% expected from a normal distribution.

Conclusions

Even well conducted inter-laboratory trials can be difficult to interpret, and the problems can be compounded by failures to observe the protocols. The robust procedures described here will usually produce a sensible interpretation even in the

Table 4. Robust results for a co-operative trial[9]

	μ	$\hat{\sigma}_L$	$\hat{\sigma}_B$	$\hat{\sigma}_e$	$\hat{\sigma}_{overall}$
Nitrogen, % m/m—					
Agar	0.14	0.028	0.011	0.017	0.035
Wholemeal	2.50	0.022	0.028	0.040	0.053
Milk powder	5.60	0.060	0.050	0.044	0.089
Soya	14.01	0.183	0.099	0.130	0.245
Compounded feedstuff	2.09	0.035	0.034	0.034	0.060
Fishmeal	4.98	0.332	0.293	0.198	0.485
Copper/μg g⁻¹—					
Agar	0.95	0.18	0.18	0.18	0.31
Milk powder	1.33	0.32	0.27	0.24	0.48
Wholemeal	3.59	0.67	0.50	0.33	0.90
Soya	11.58	1.05	0.62	0.45	1.30
Fishmeal	13.31	1.57	1.76	2.03	3.12
Compounded feedstuff	19.71	1.95	0.92	1.80	2.80
Lead/μg g⁻¹—					
Wholemeal	0.28	0.17	0.06	0.13	0.22
Milk powder	0.30	0.26	0.04	0.14	0.30
Soya	0.49	0.22	0.10	0.13	0.28
Agar	1.18	0.43	0.20	0.21	0.52
Compounded feedstuff	3.18	1.58	0.79	0.45	1.82
Fishmeal	2.97	2.19	0.58	0.29	2.28

presence of a fair proportion of problem results, without the overestimation of precision to which the classical procedures are prone. We recommend that robust procedures are always used for the statistical analysis of inter-laboratory trials, either alone or in comparison with classical least-squares procedures.

Appendix

Computation

The program shown illustrates the computation needed for robust estimates. It is written in standard FORTRAN 77 and deals with trials without batches. The data are assumed to be rows of replicates for columns of laboratories, but this can easily be changed. Both classical and robust analyses are reported to a file ("results.lis" as written).

One trap which is guarded against is the occurrence of initially zero values of $\hat{\sigma}$. The one example that we encountered had half the laboratories with constant results, recorded to too low an accuracy. Convergence of the iterative schemes is tested on both $\hat{\mu}$ and $\hat{\sigma}$ and is quite stringent. However, do not reduce "tol" unless computer time is excessive as convergence can be slow.

To aid translation to other languages, all variables used are declared. The function "median" is given in Part 1.[1]

References

1. Analytical Methods Committee, *Analyst*, 1989, 114, 1693.
2. Rocke, D. M., *Biometrika*, 1983, 70, 421.
3. Lischer, P., *Lebensm. Wiss. Technol.*, 1987, 20, 167.
4. Youden, W. J., "Statistical Techniques for Collaborative Trials," Association of Official Analytical Chemists, Washington, DC, 1969.
5. Steiner, E. H., "Planning and Analysis of Results of Collaborative Tests," supplement to 4, 1974.
6. "Precision of Test Methods," BS 1979, No. 5497, Part 1, British Standards Institution, Milton Keynes.
7. "Precision of Test methods," ISO 1981 No. 5725, International Standards Organisation.
8. Analytical Methods Committee, *Analyst*, 1987, 112, 679.
9. Analytical Methods Committee, *Analyst*, 1989, 114, 1489.

NOTE—Reference 1 is to Part 1 of this series.

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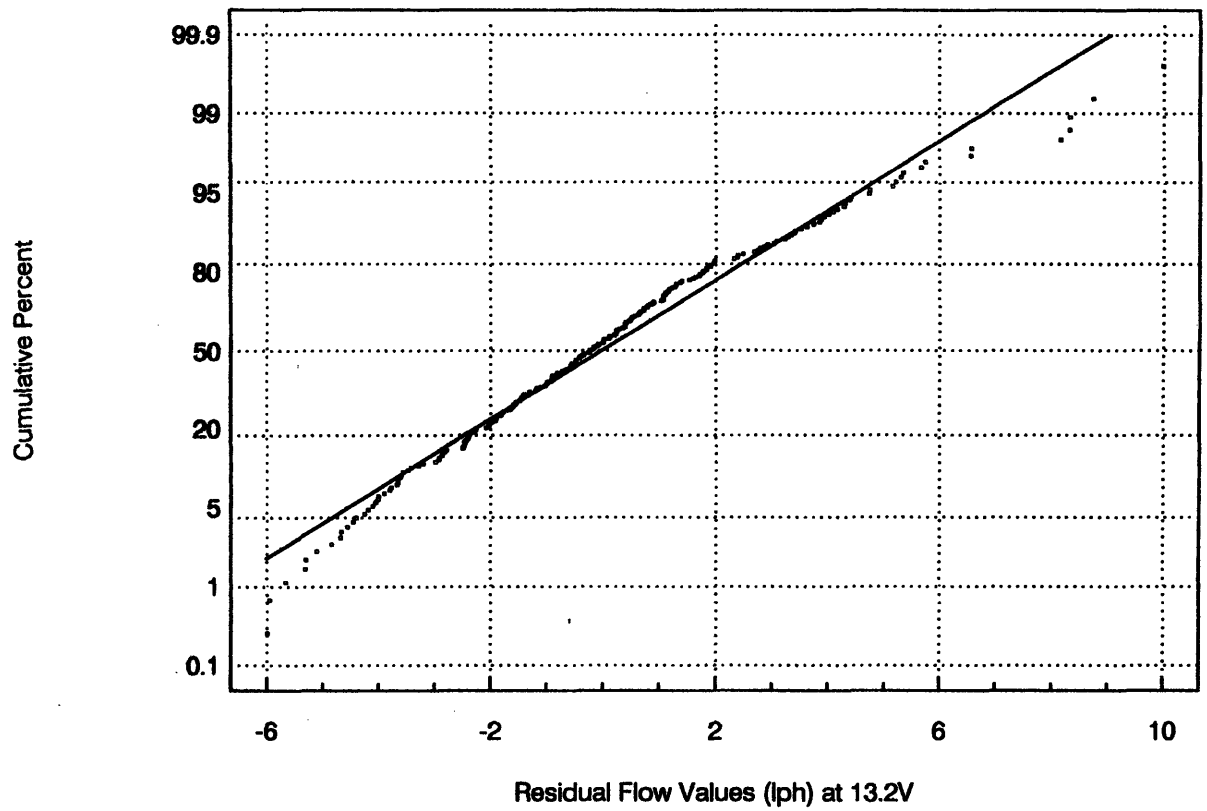
APPENDIX K

Normal Probability Plot Example from
Phase II Gerotor Pump Test Fluid Correl.



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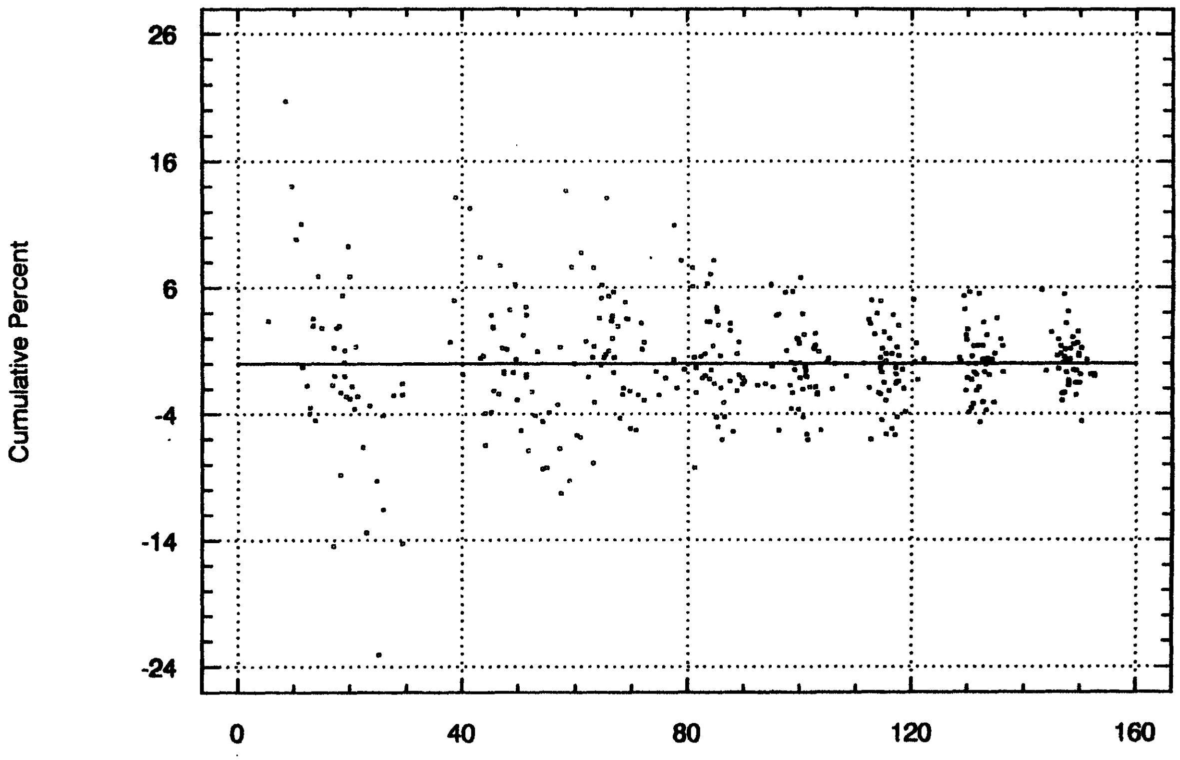
Normal Probability Plot Example from
Phase II Turbine Pump Test Fluid Correl.



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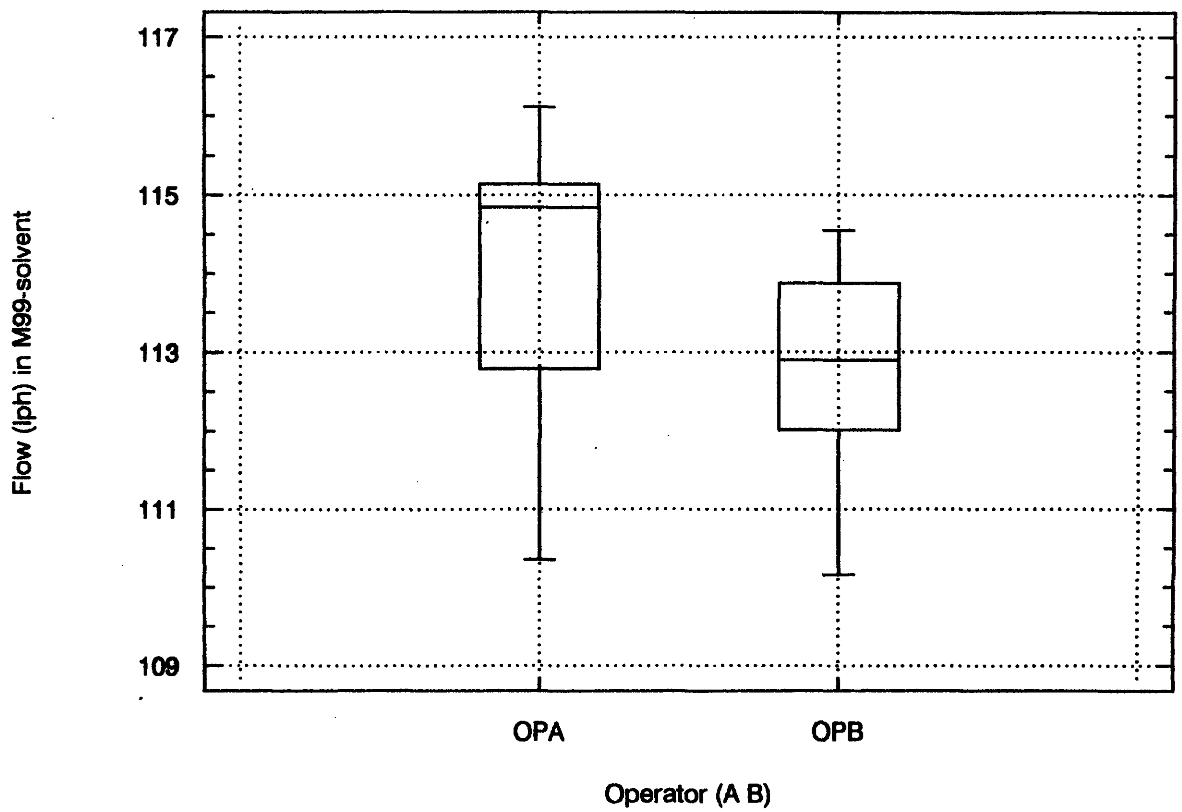
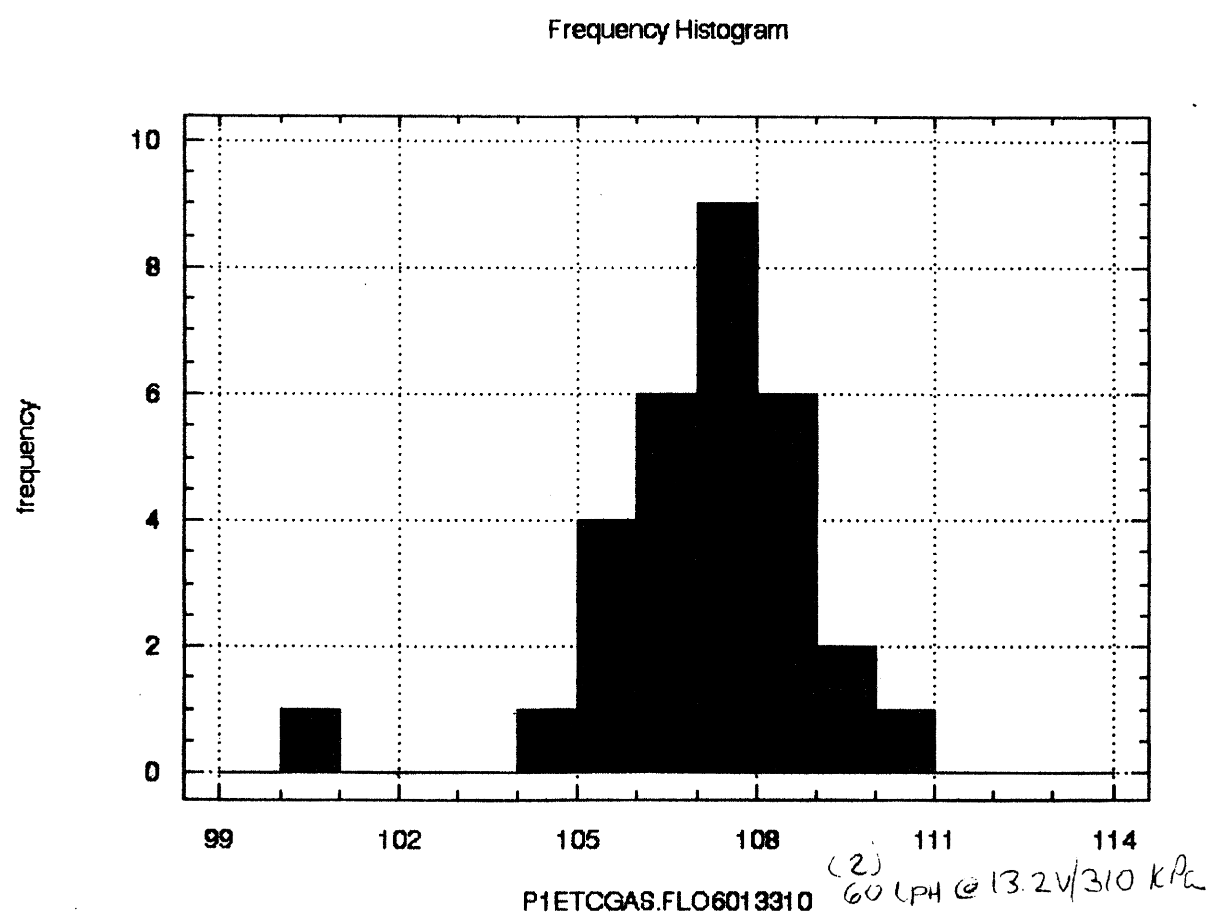
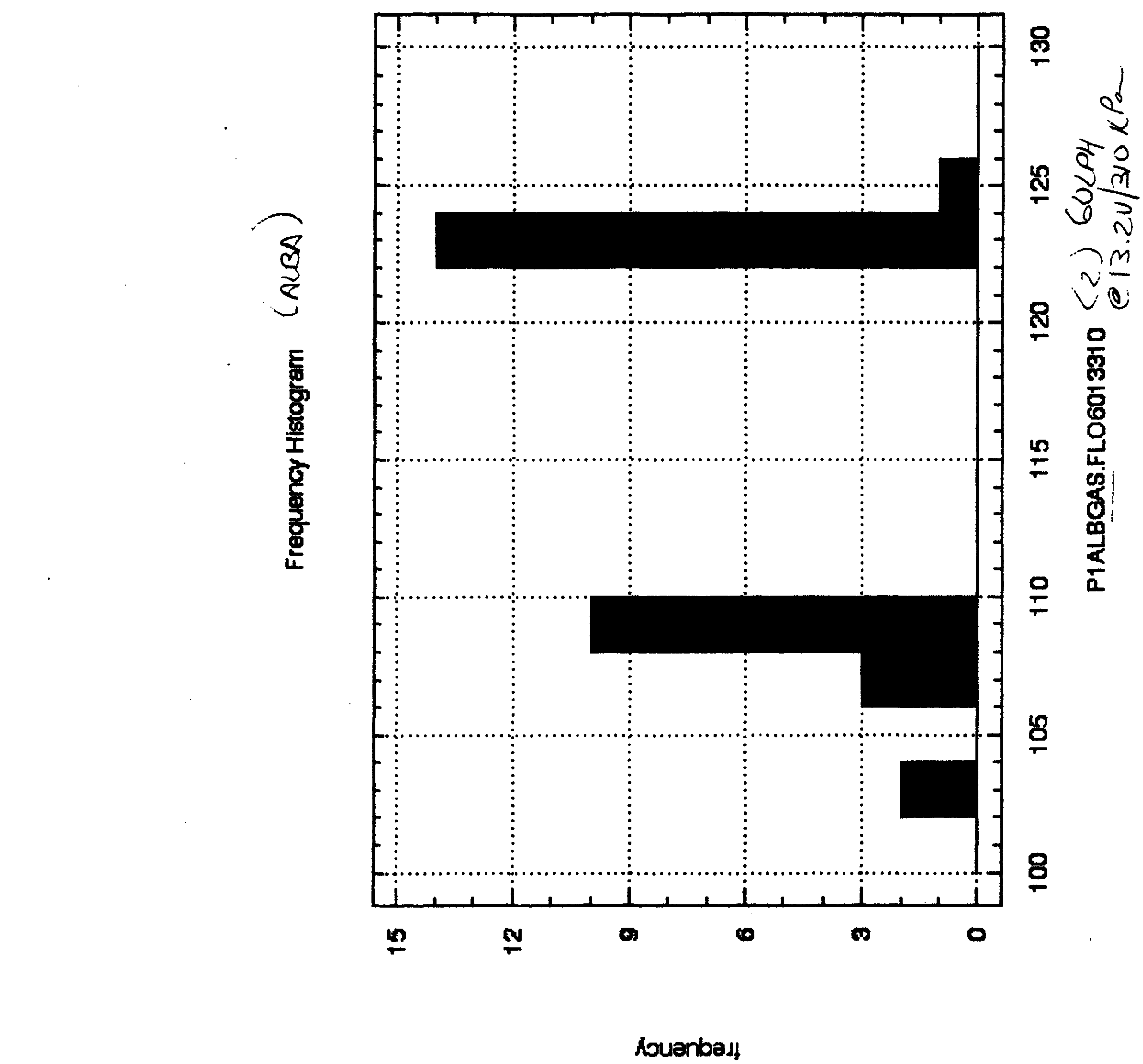
Box and Whisker Plot--Pre-Phase II
Gerotor Pumps at ETC Lab



This was completed for current & speed.

All Following → From Phase I : Round I/II
ETC LAB

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frequency
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3
6
9
12
15
100
105
110
115
120
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130
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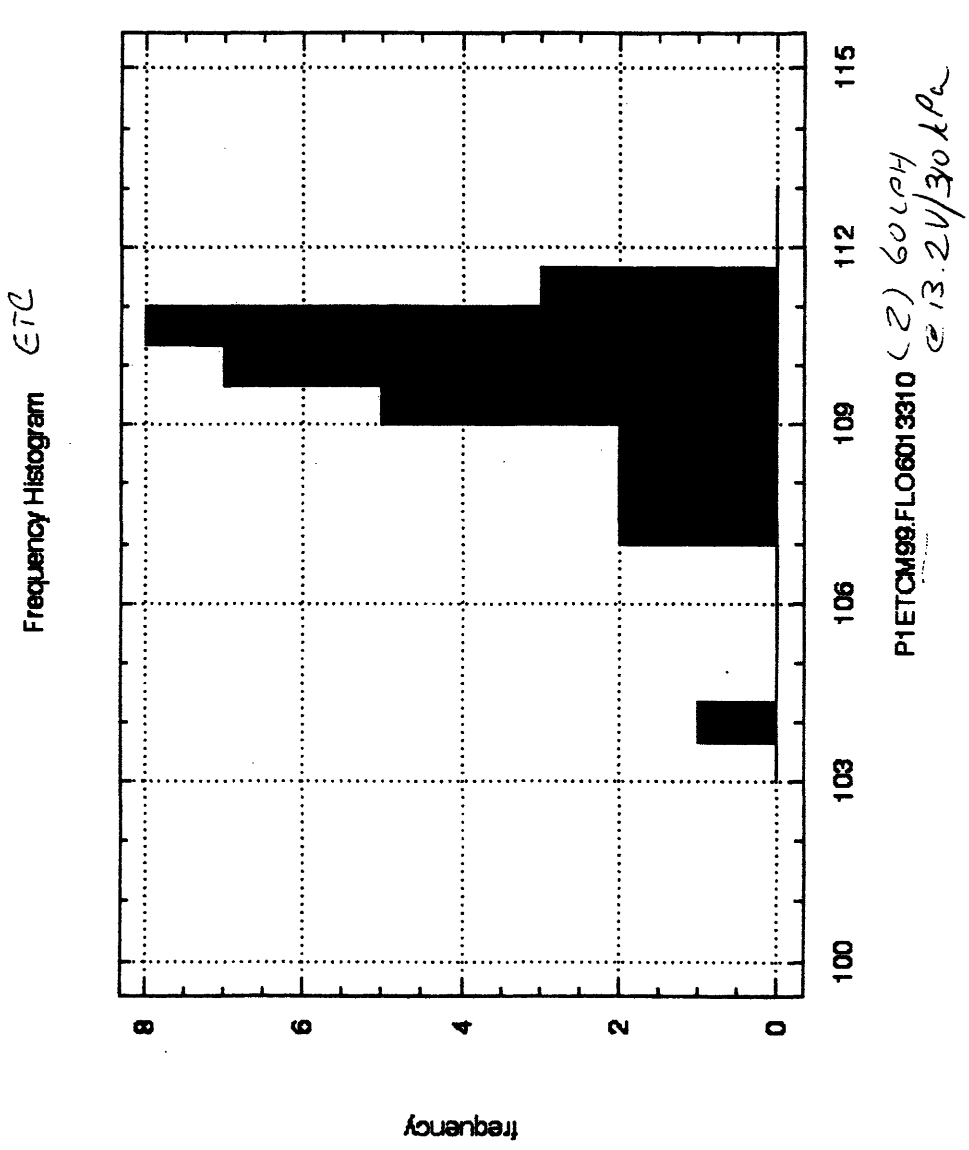

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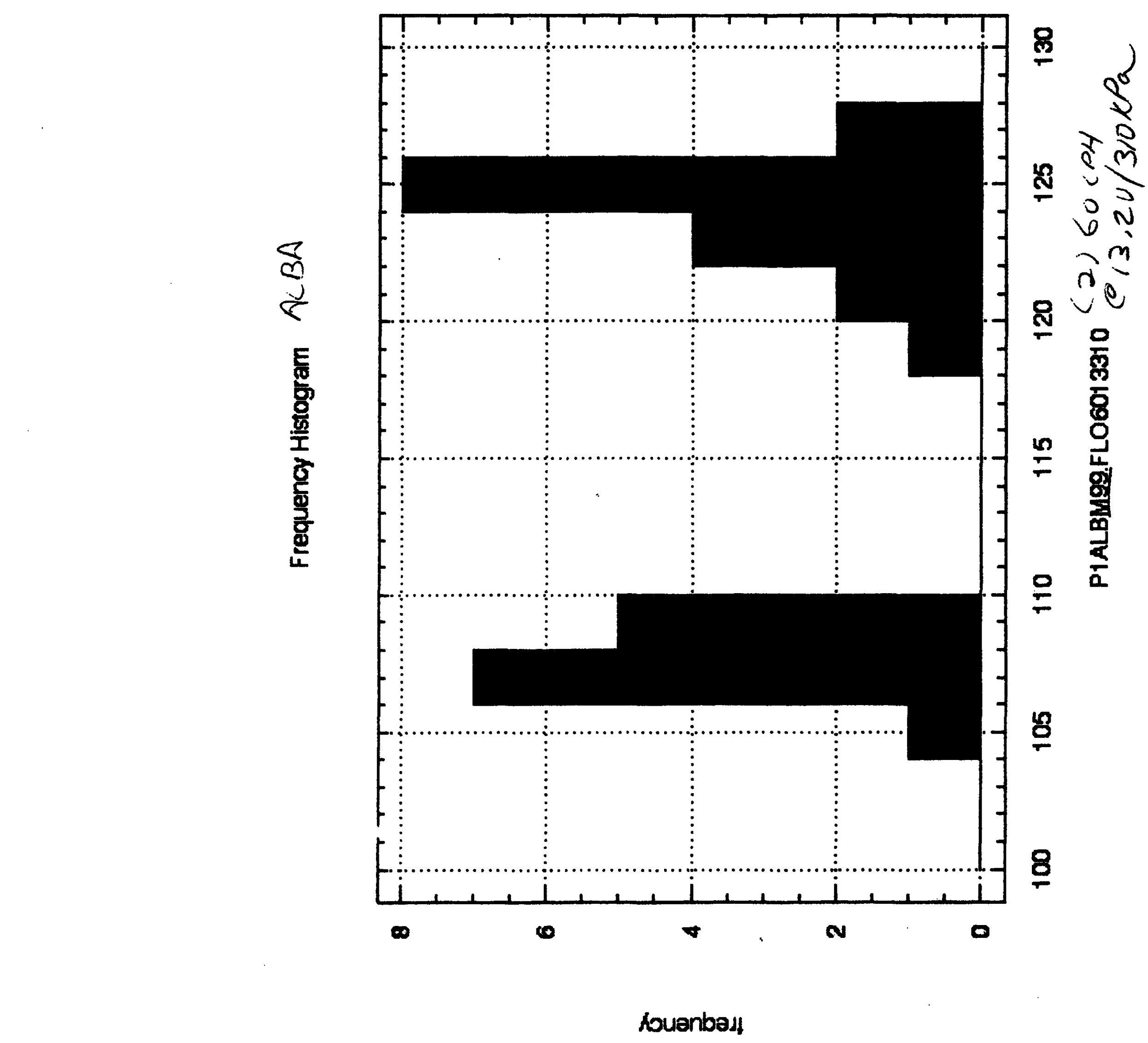
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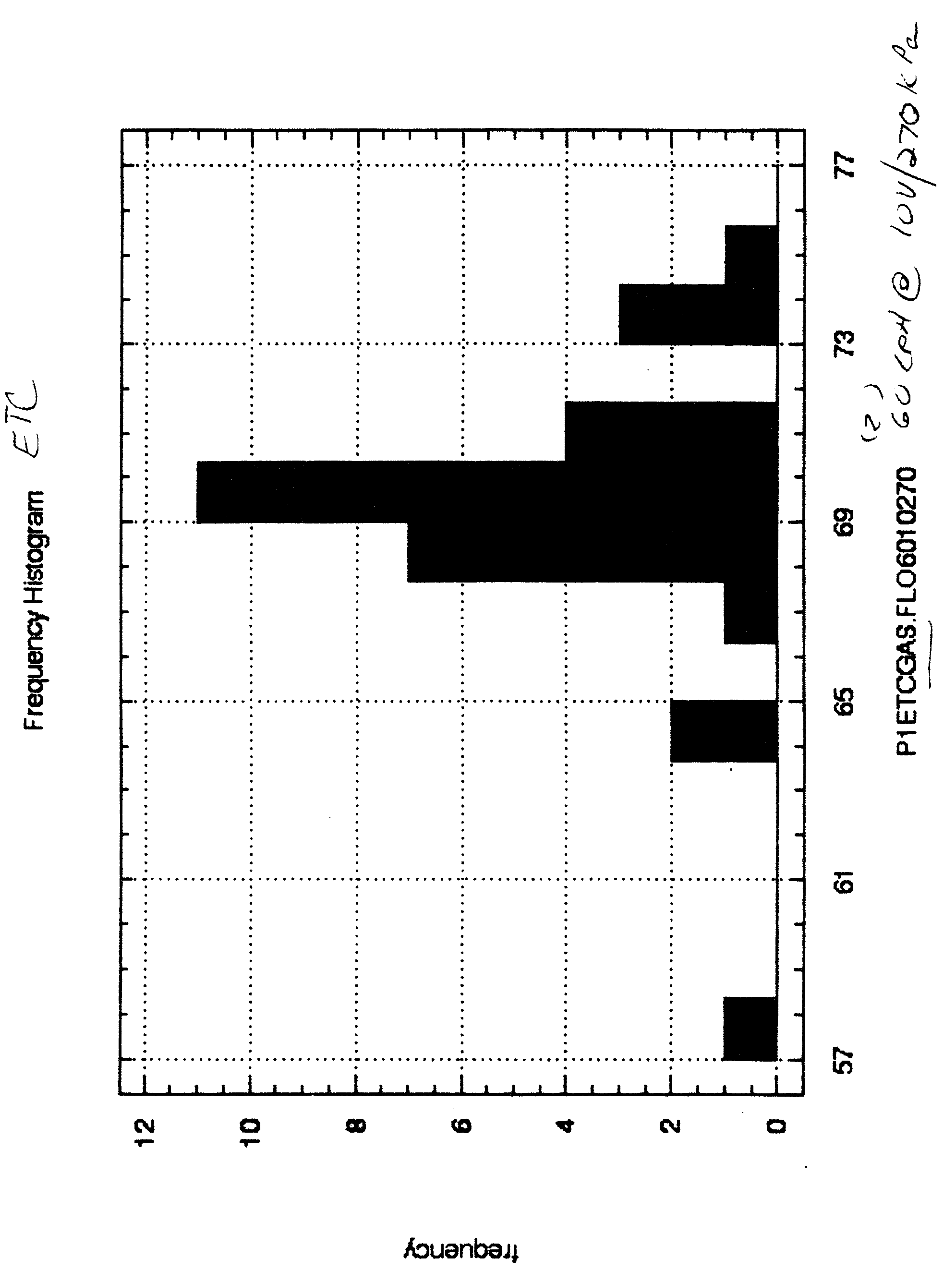
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ETC
frequency
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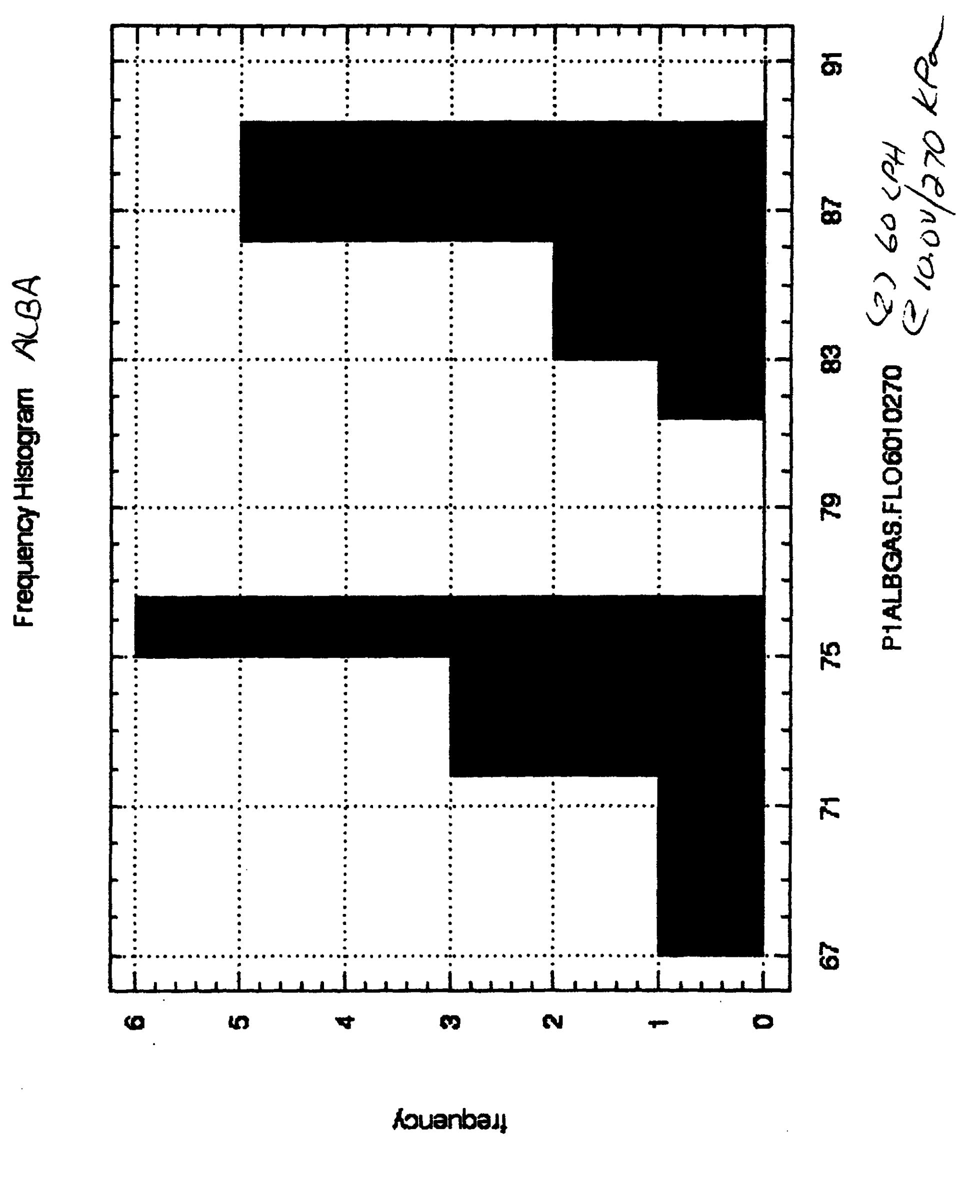
Frequency Histogram ALBA
frequency
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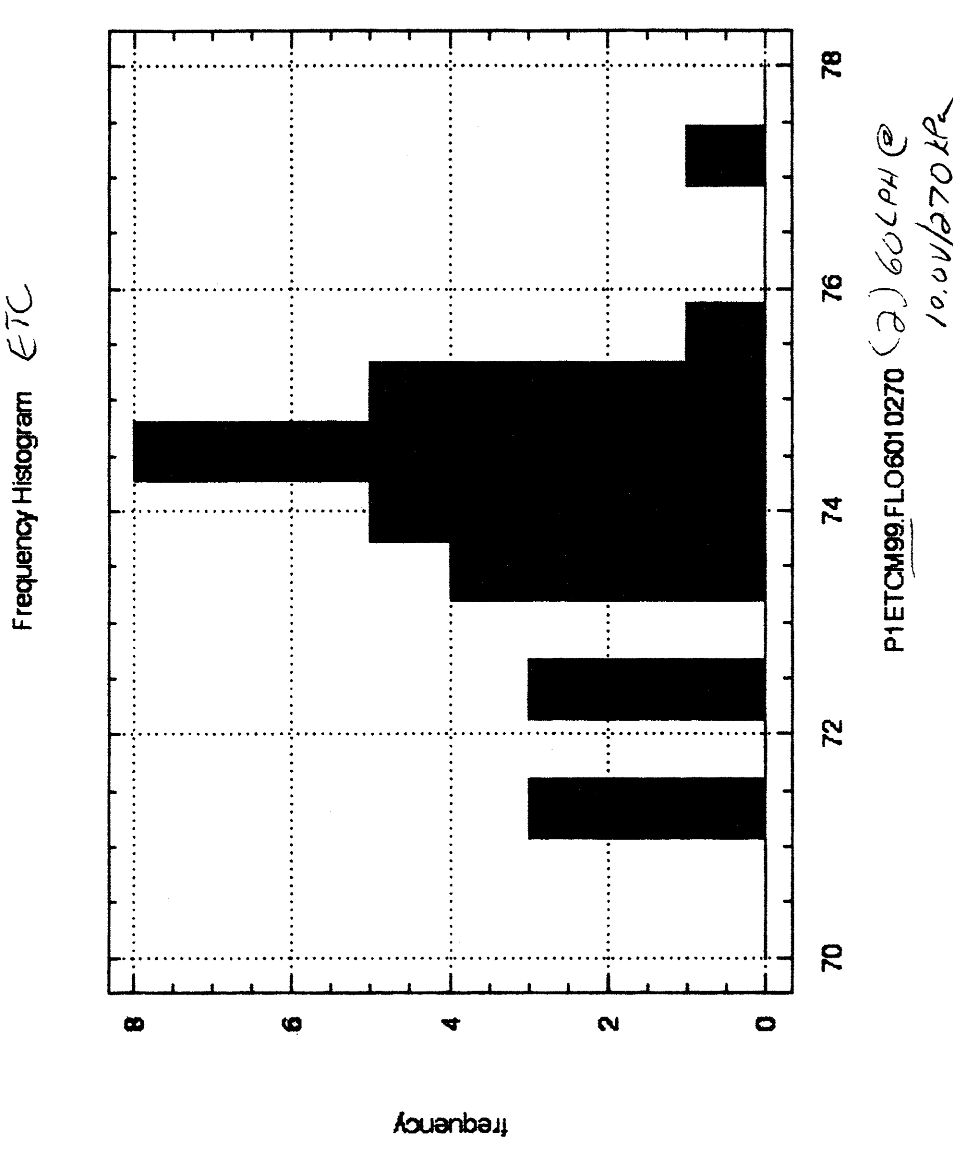
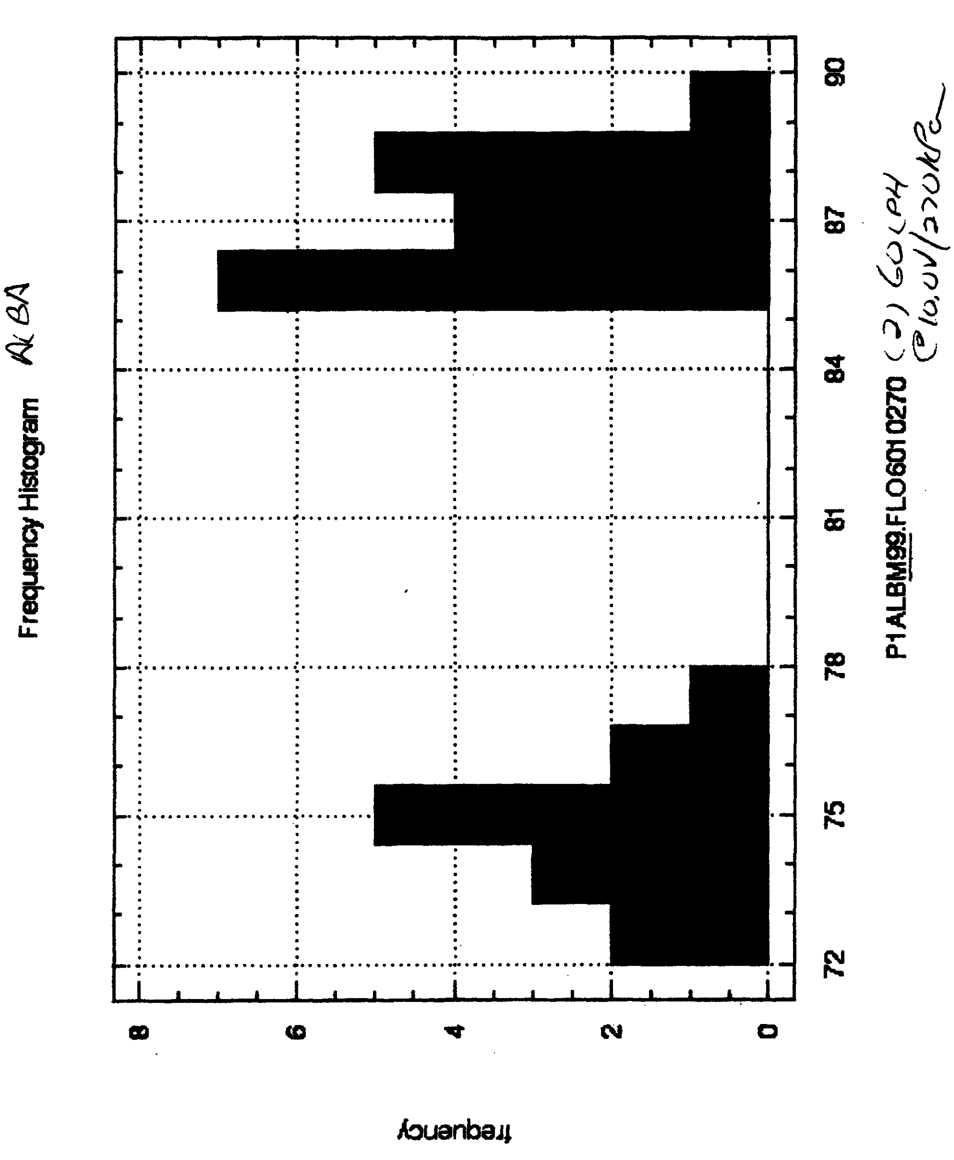
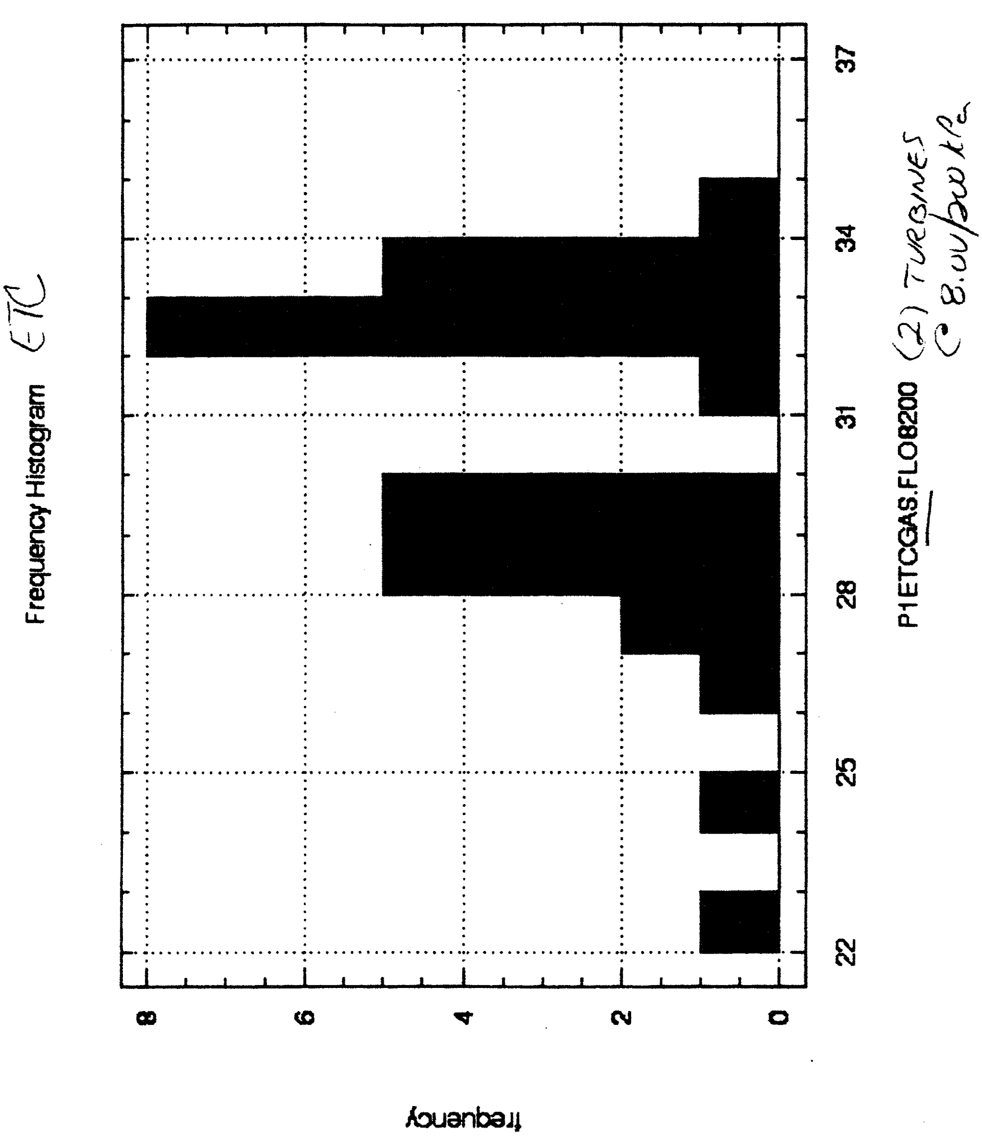
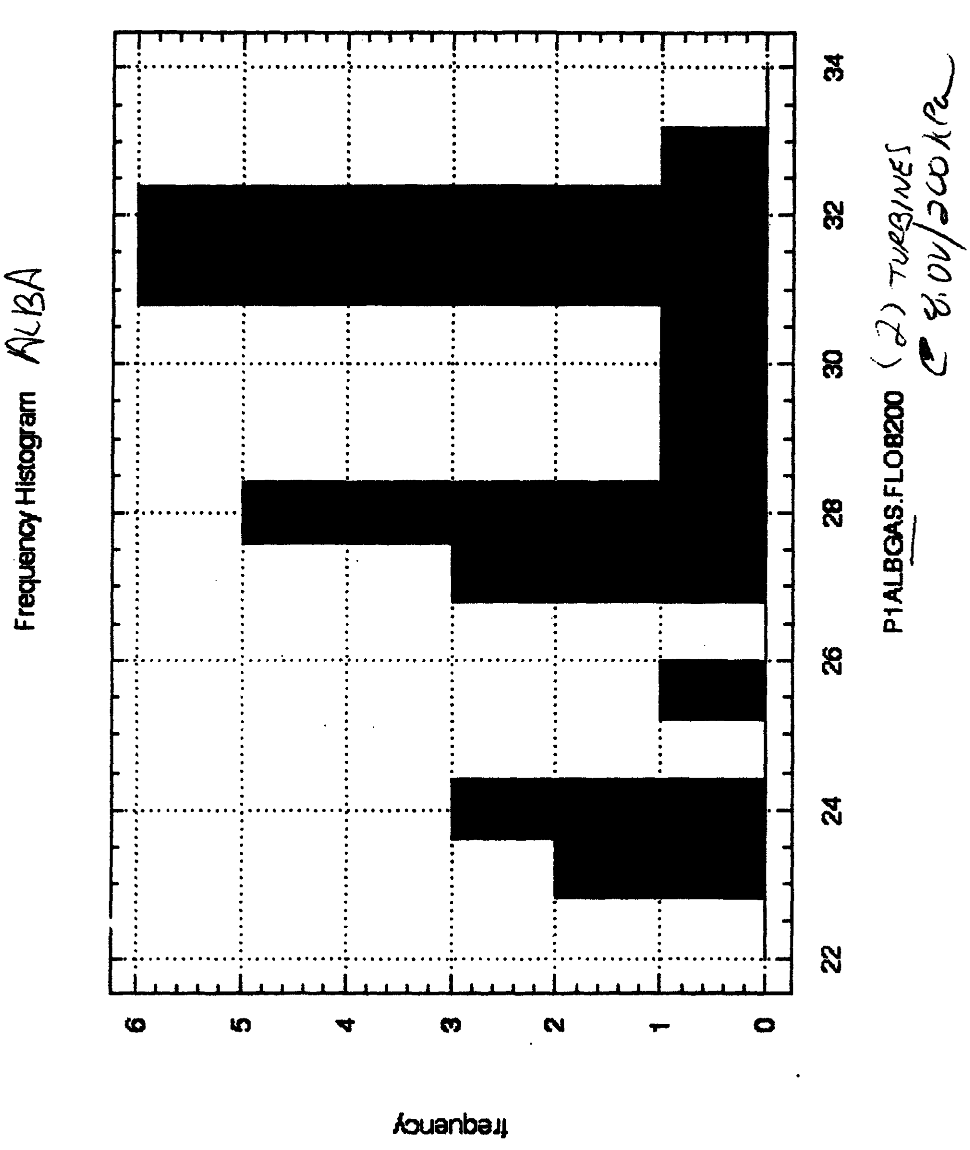
2
3
4
5
6
67
71
75
79
83
87
91
P1ALBGAS.FLO6010270
(2) 60 LPH
@ 10.0V/270 KPa

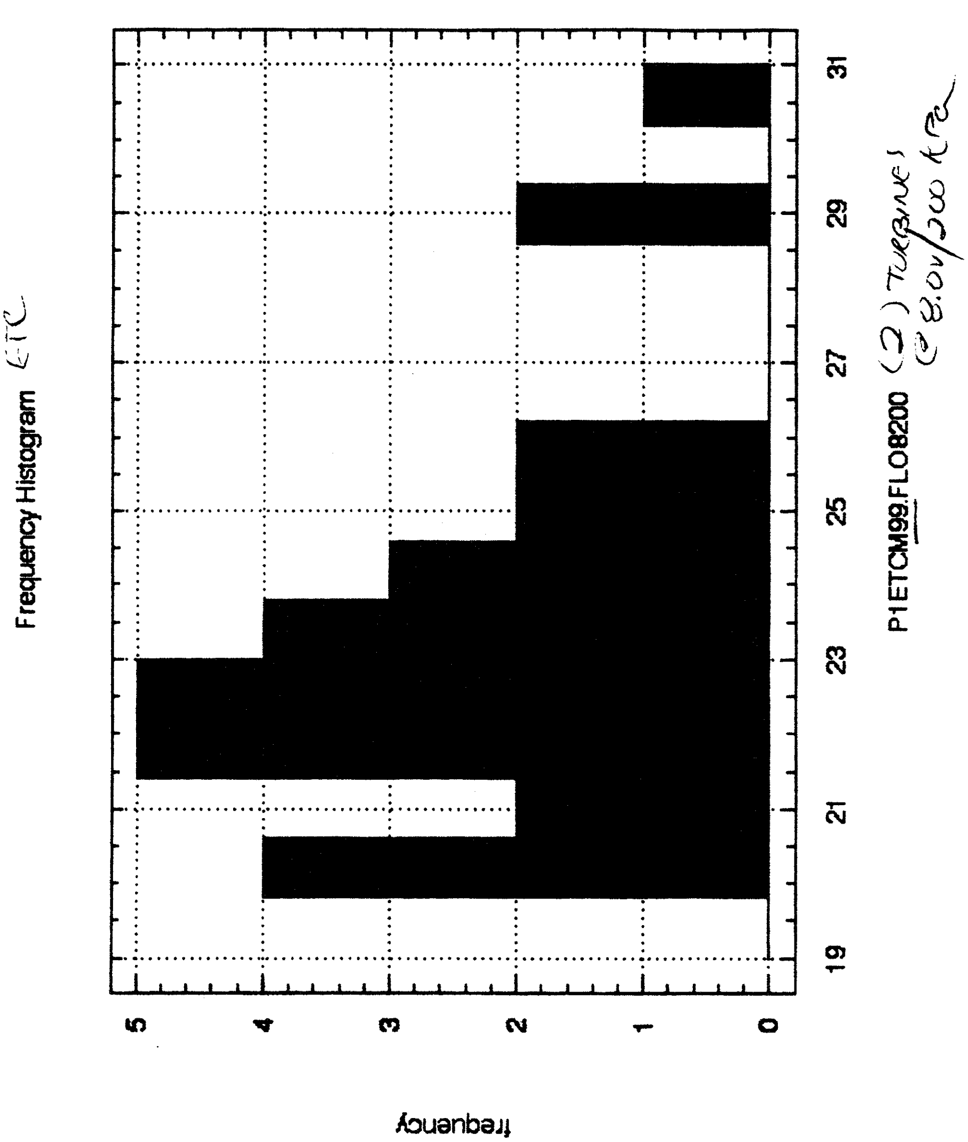


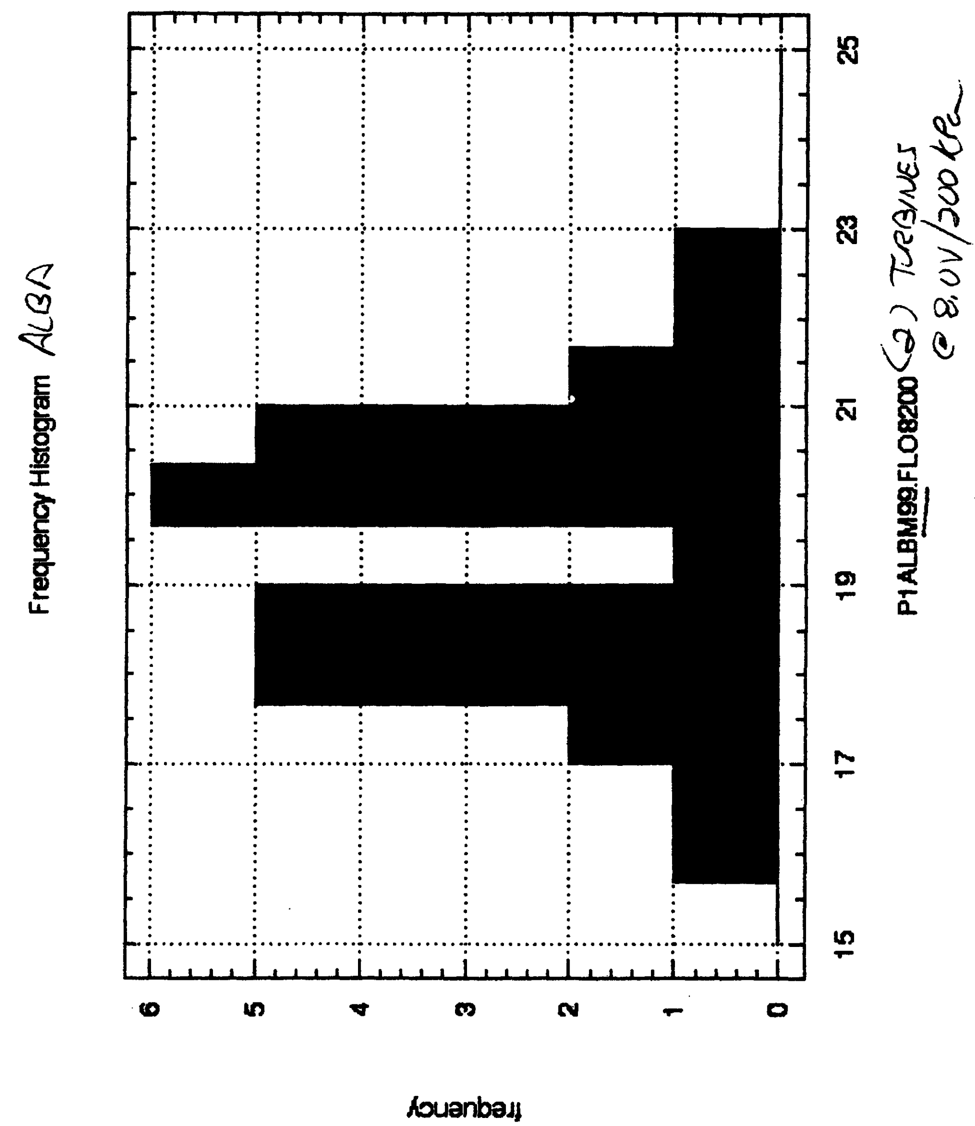
Frequency Histogram
ETC
frequency
0
2
4
6
8
70
72
74
76
78
P1ETCM99.FLO6010270
(2) 60 LPH @
10.0V/270 kPa

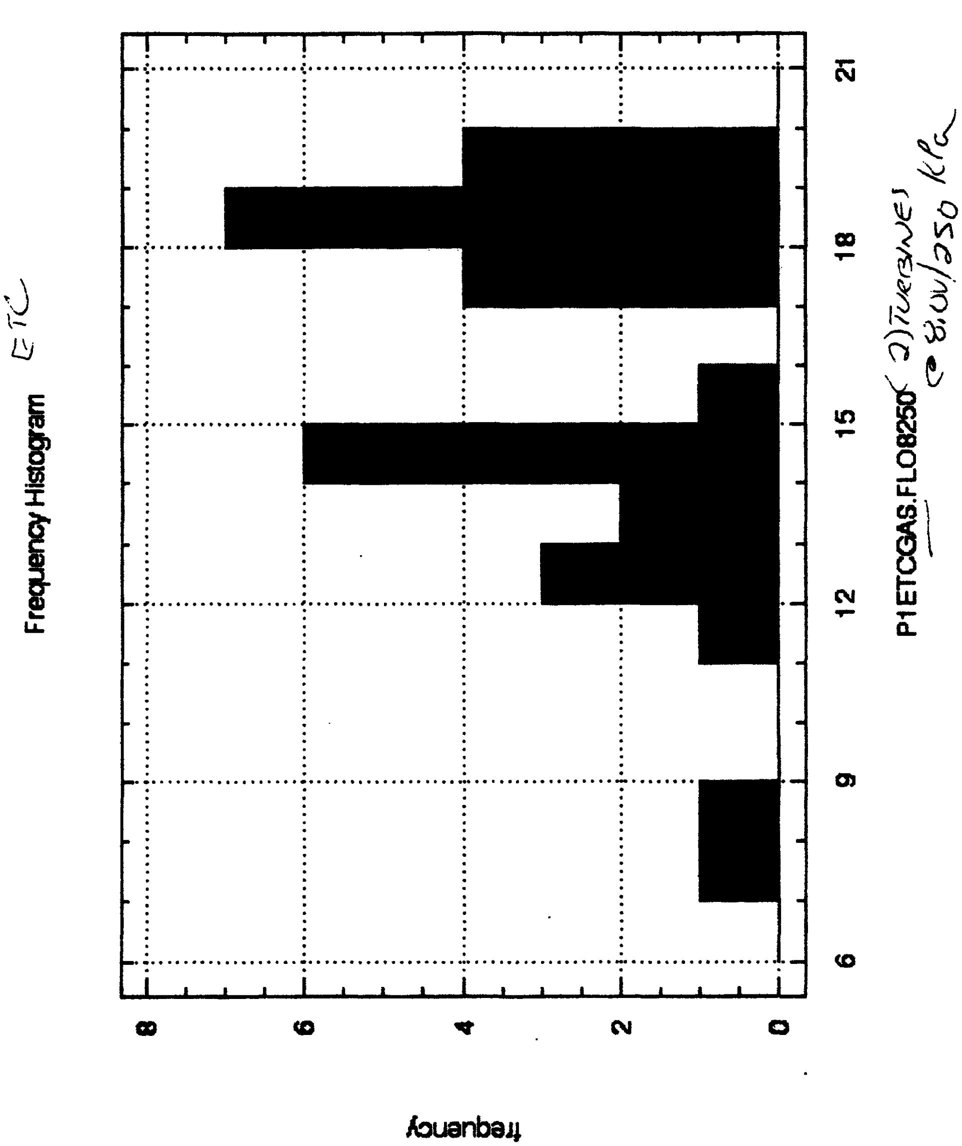

Frequency Histogram
frequency
0
2
4
6
8
72
75
78
81
84
87
90
P1ALBM99.FLO6010270

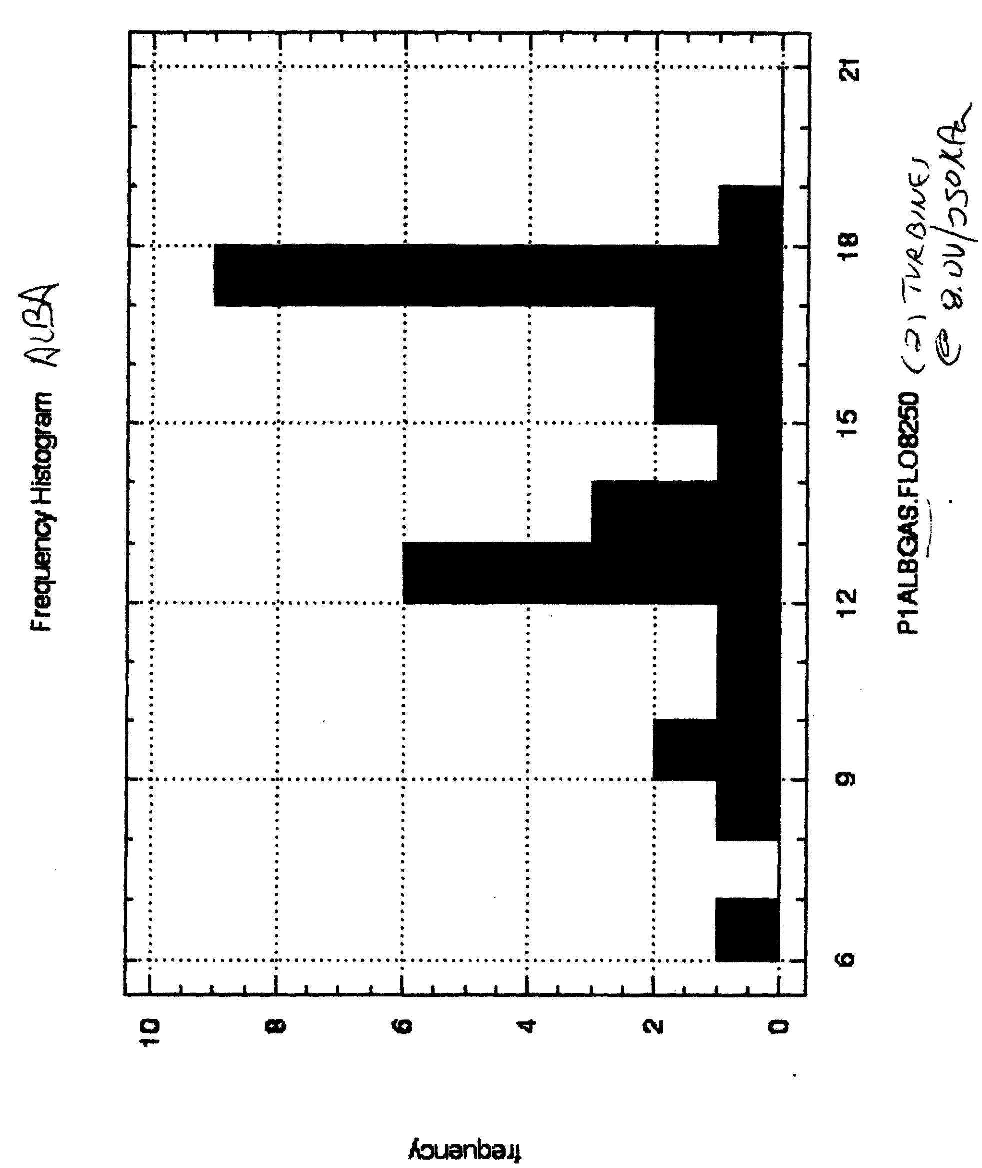

Frequency Histogram
ETC
frequency
0
2
4
6
8
22
25
28
31
34
37
P1ETCGAS.FLO8200
(2) TURBINES

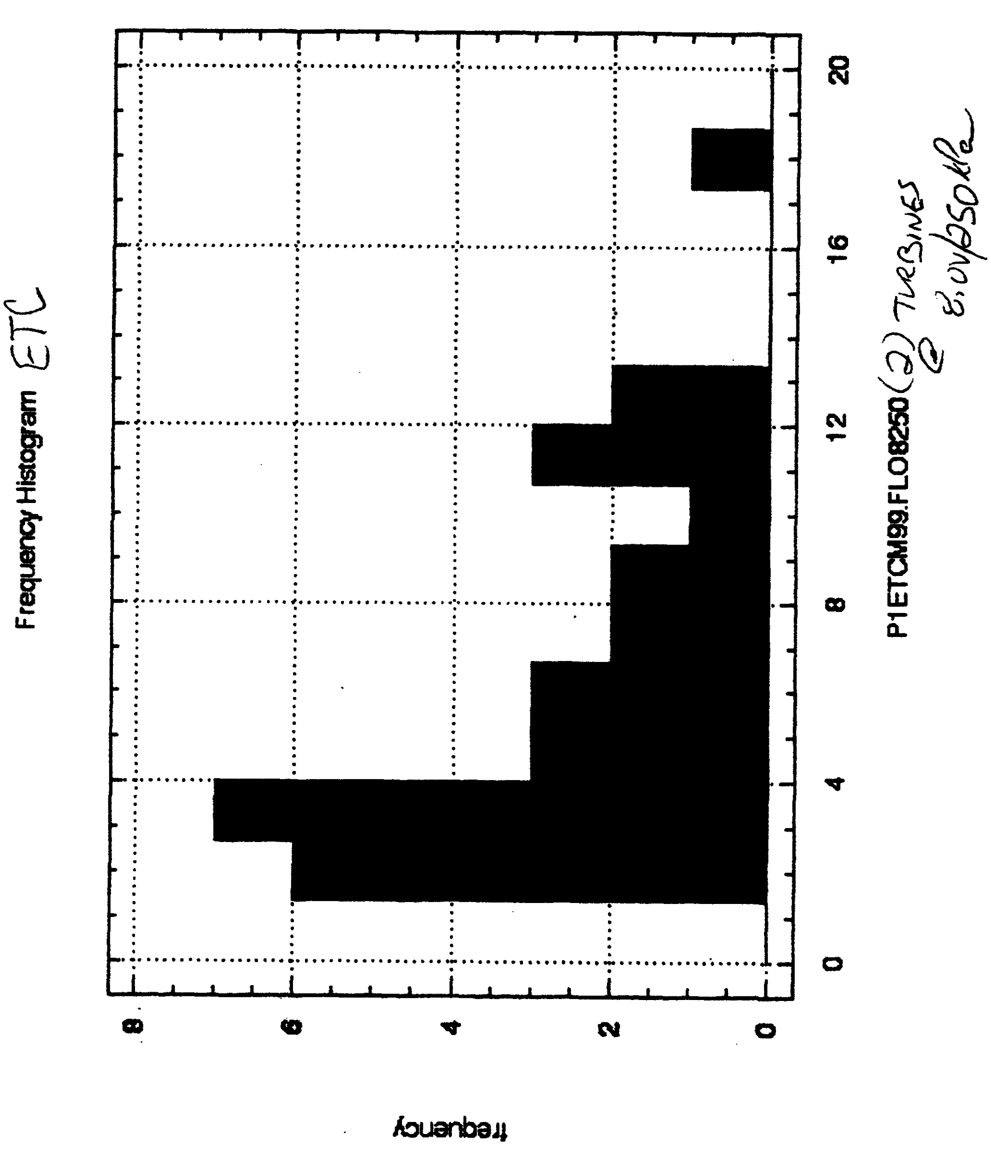

Frequency Histogram
ALBA
frequency
0
1
2
3
4
5
6
22
24
26
28
30
32
34
P1ALBGAS.FLOB200
(2) TURBINES
@ 8.0V/200KPa

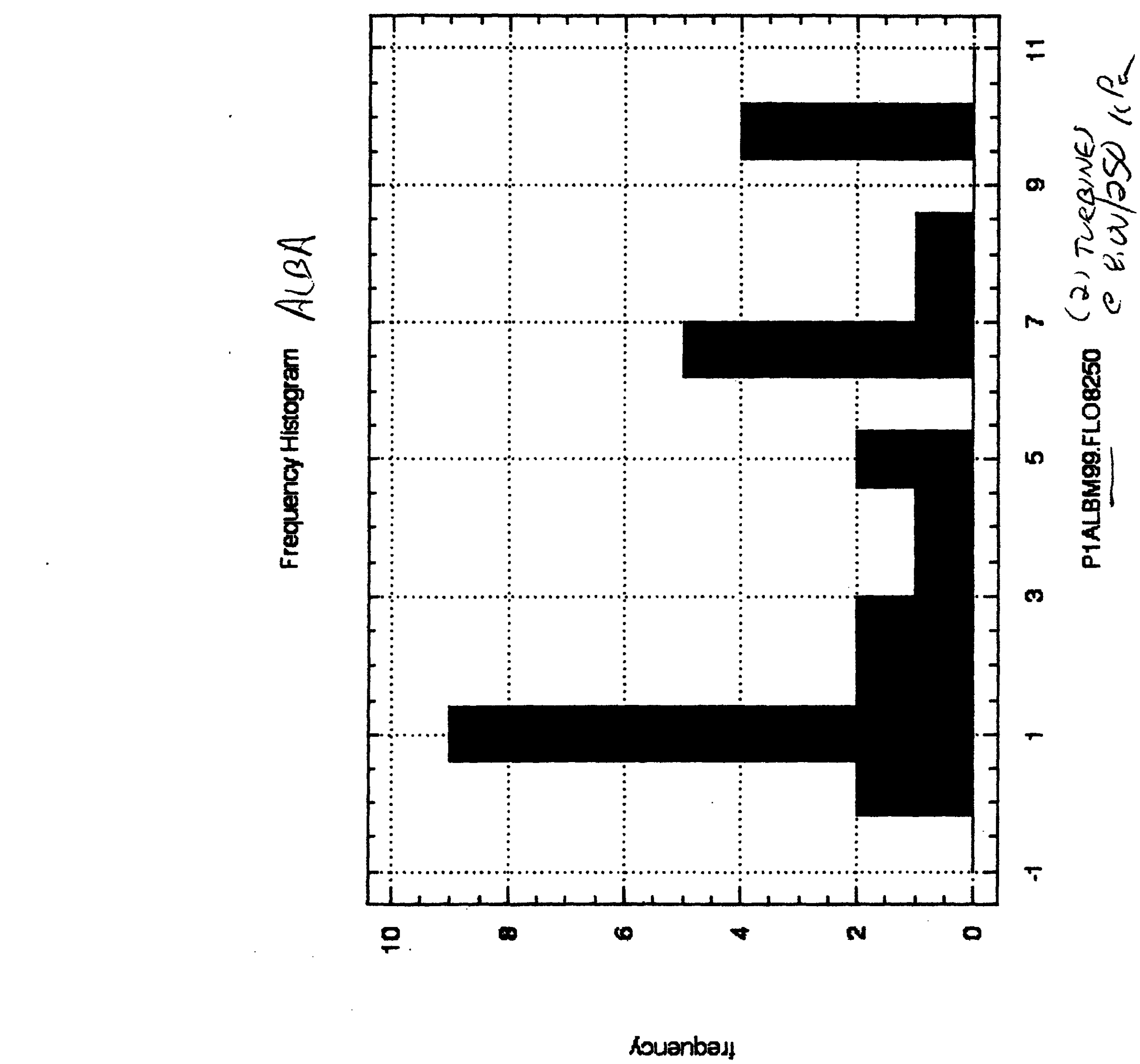

Frequency Histogram
ETC
frequency
0
1
2
3
4
5
19
21
23
25
27
29
31
P1ETCM99.FLO8200
(2) TURBINES
@ 8.0V/200 KPa

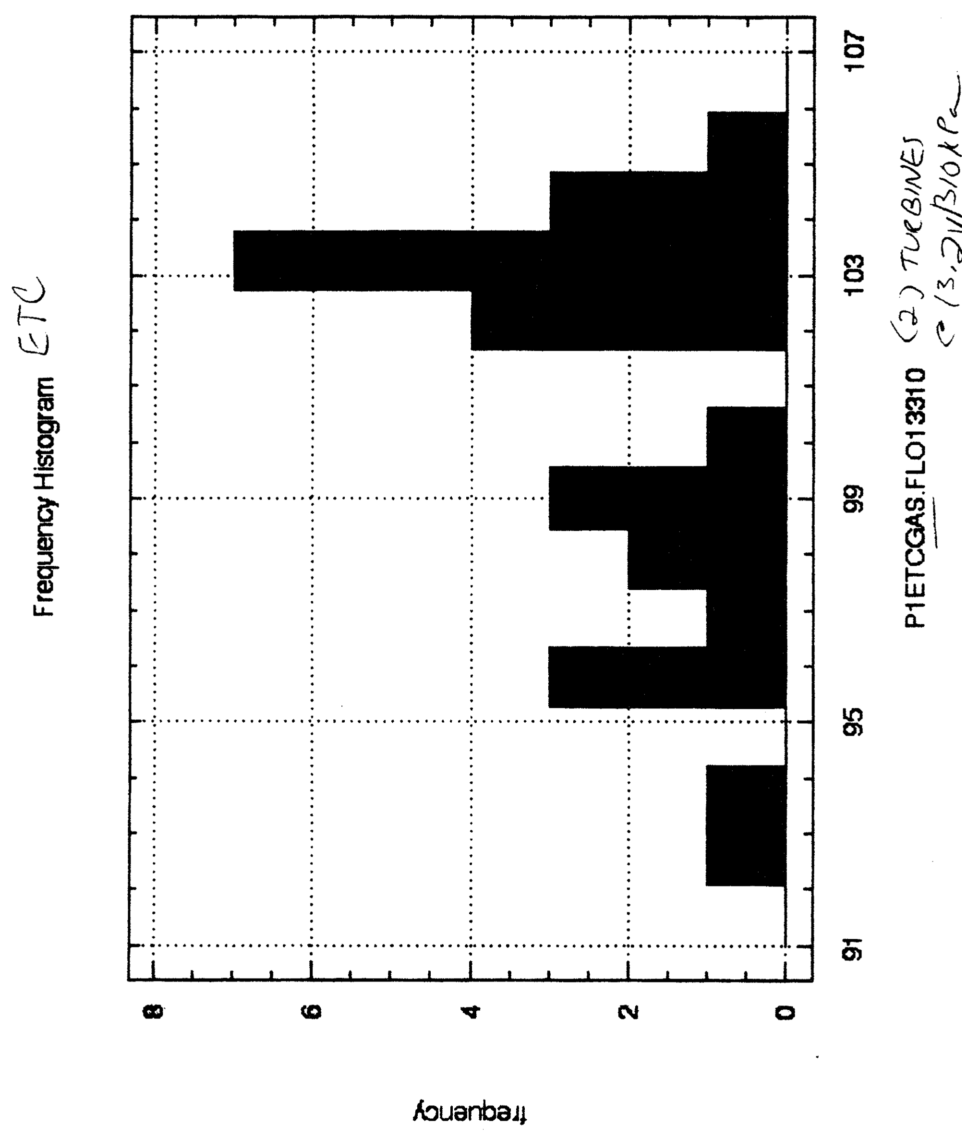

Frequency Histogram ALBA
frequency
0
1
2
3
4
5
6
15
17
19
21
23
25
P1ALBM99.FLO8200 (2) TURBINES
@ 8.0V/200 kPa


Frequency Histogram
frequency
0
2
4
6
8
6
9
12
15
18
21
P1ETCGAS.FLO8250

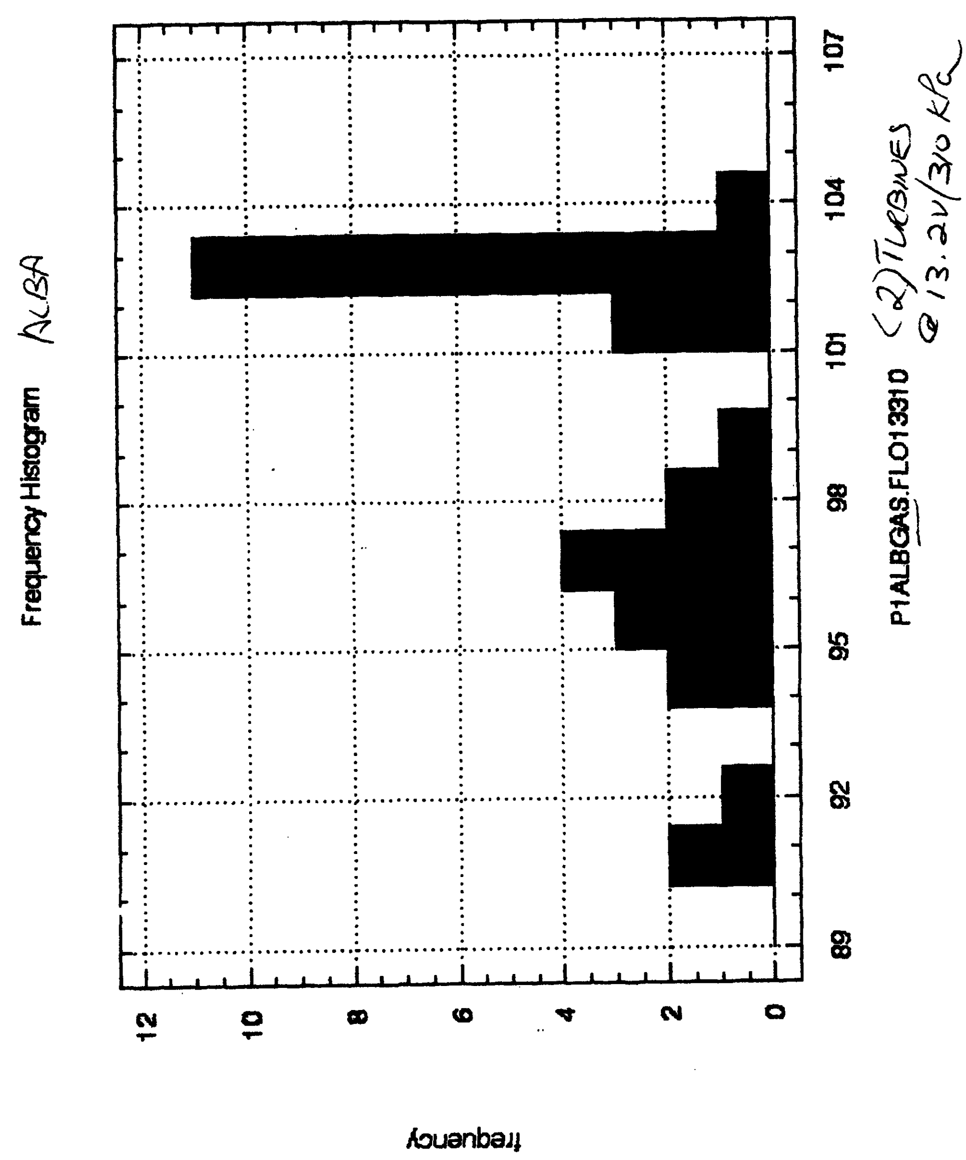

Frequency Histogram
ALBA
frequency
0
2
4
6
8
10
6
9
12
15
18
21
P1ALBGAS.FLO8250
(2) TURBINES

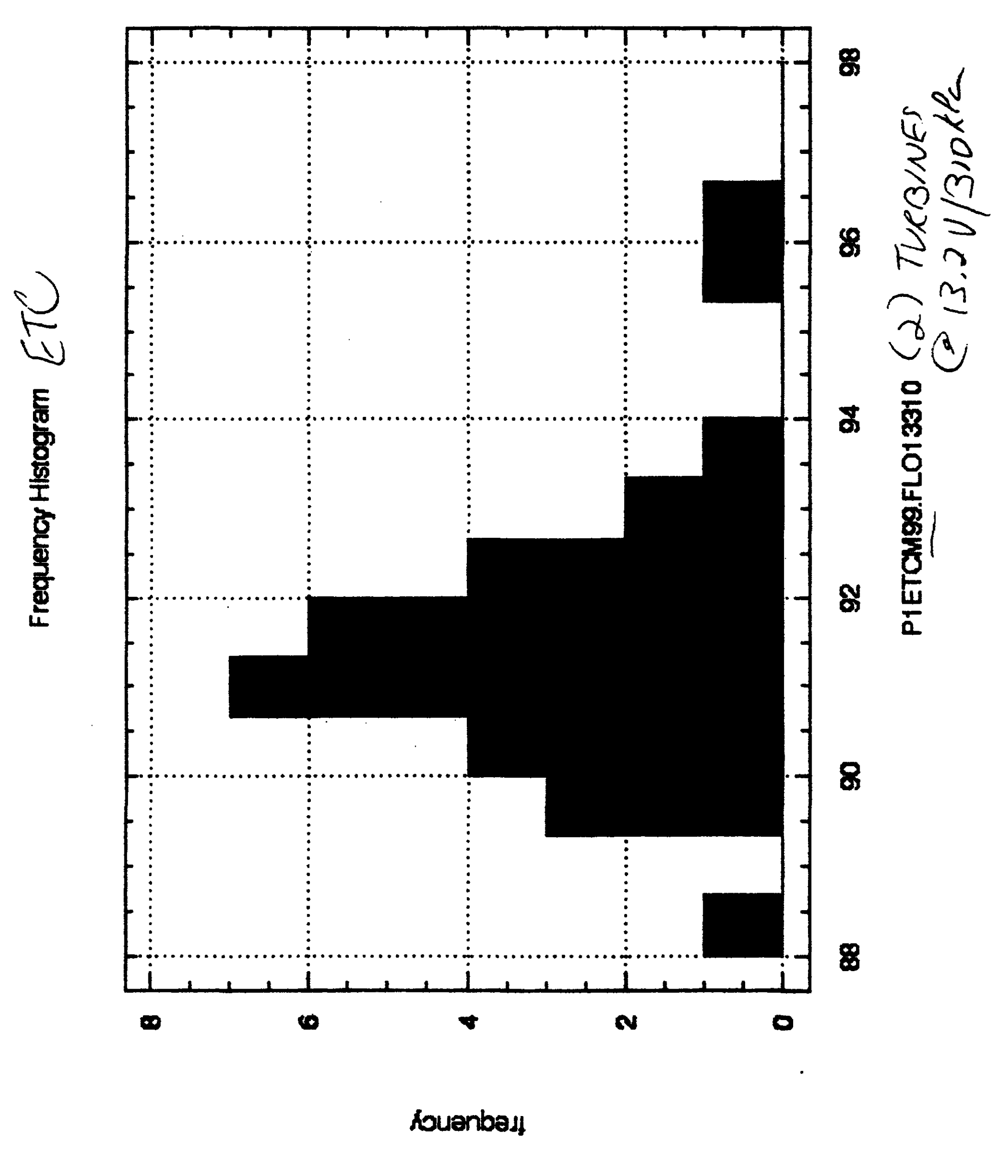

Frequency Histogram ETC
frequency
0
2
4
6
8
0
4
8
12
16
20
P1ETCM99.FLO8250 (2) TURBINES @ 8.0V/250kPa

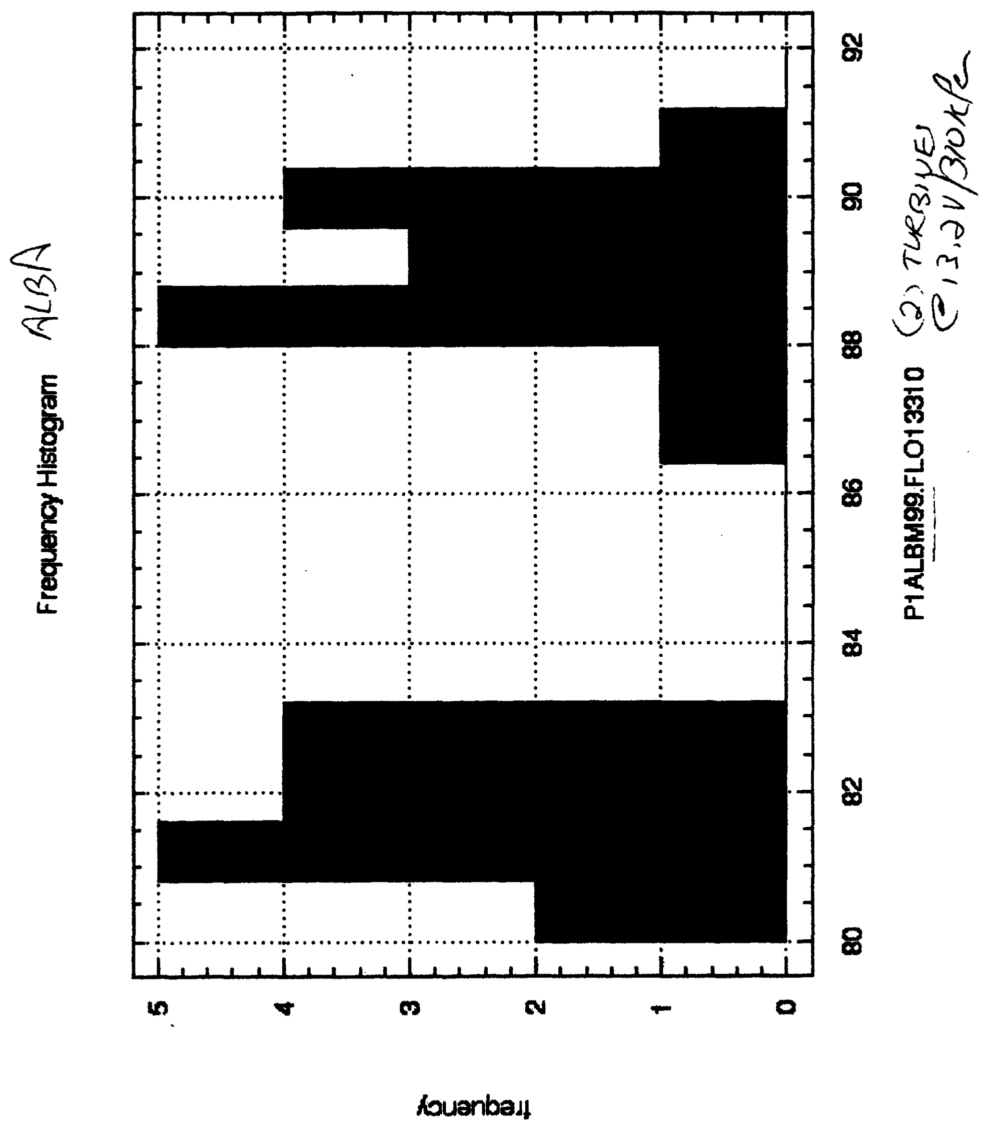

Frequency Histogram
ALBA
P1ALBM99.FLO8250
frequency
-1
1
3
5
7
9
11
0
2
4
6
8
10

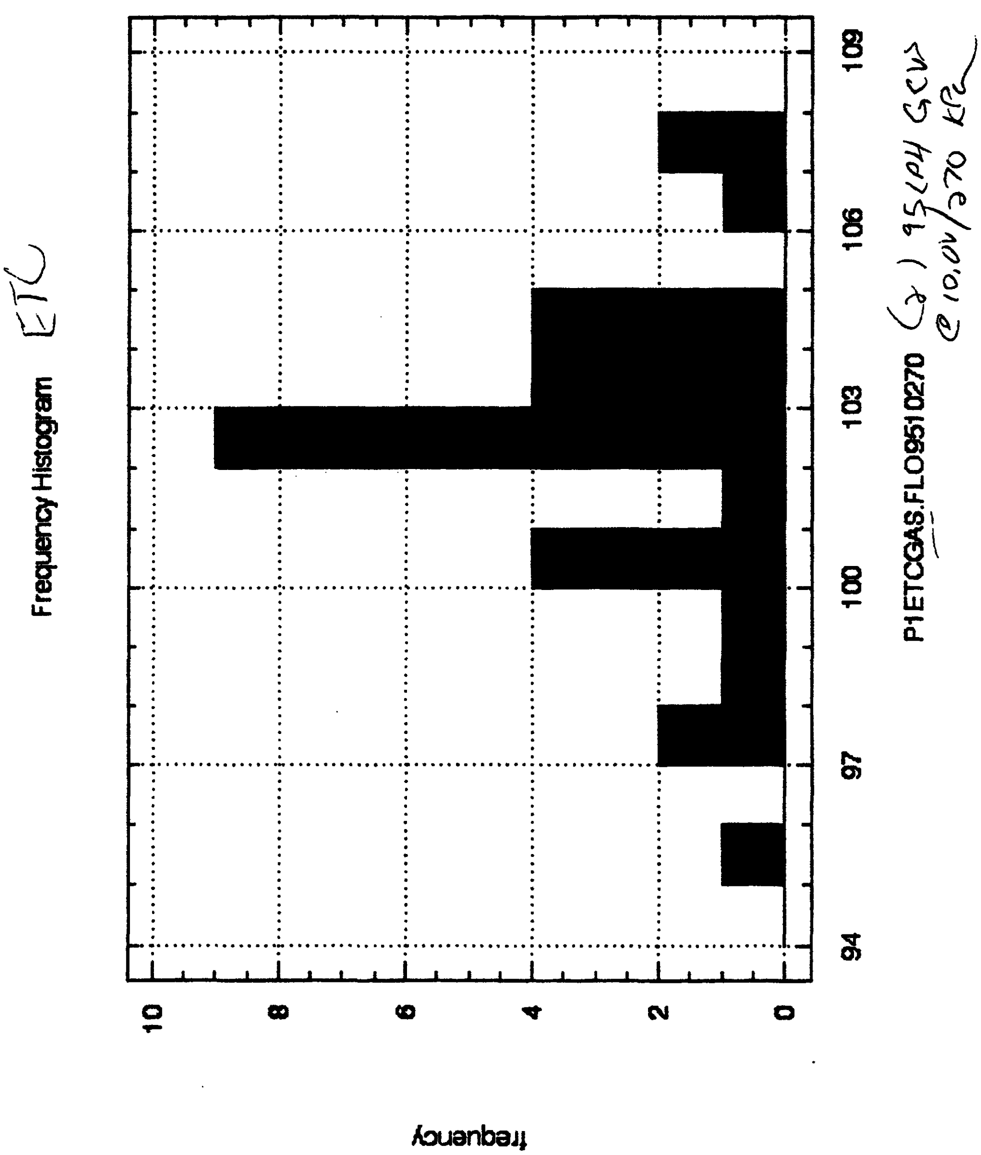


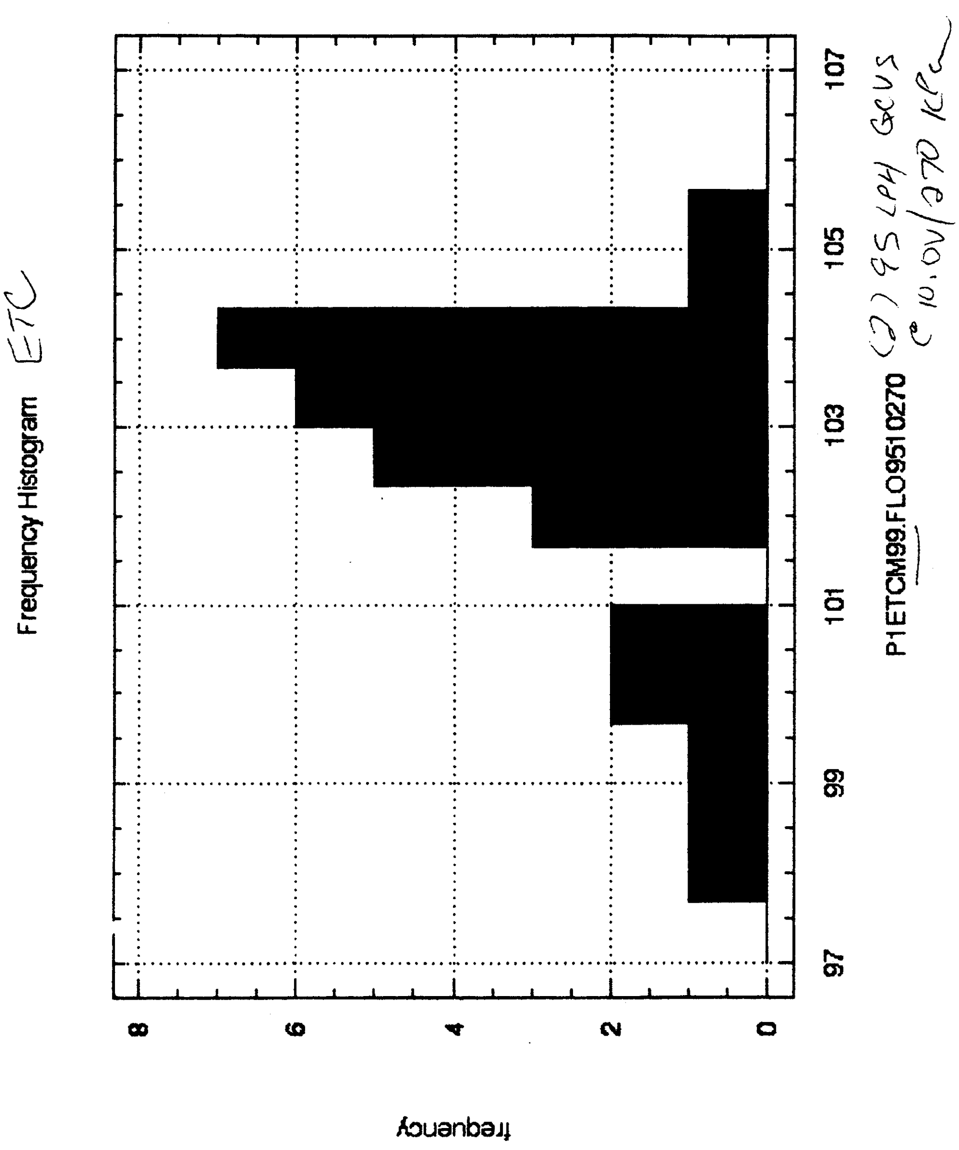
Frequency Histogram
ETC
frequency
0
2
4
6
8
91
95
99
103
107
P1ETCGAS.FLO13310
(2) TURBINES

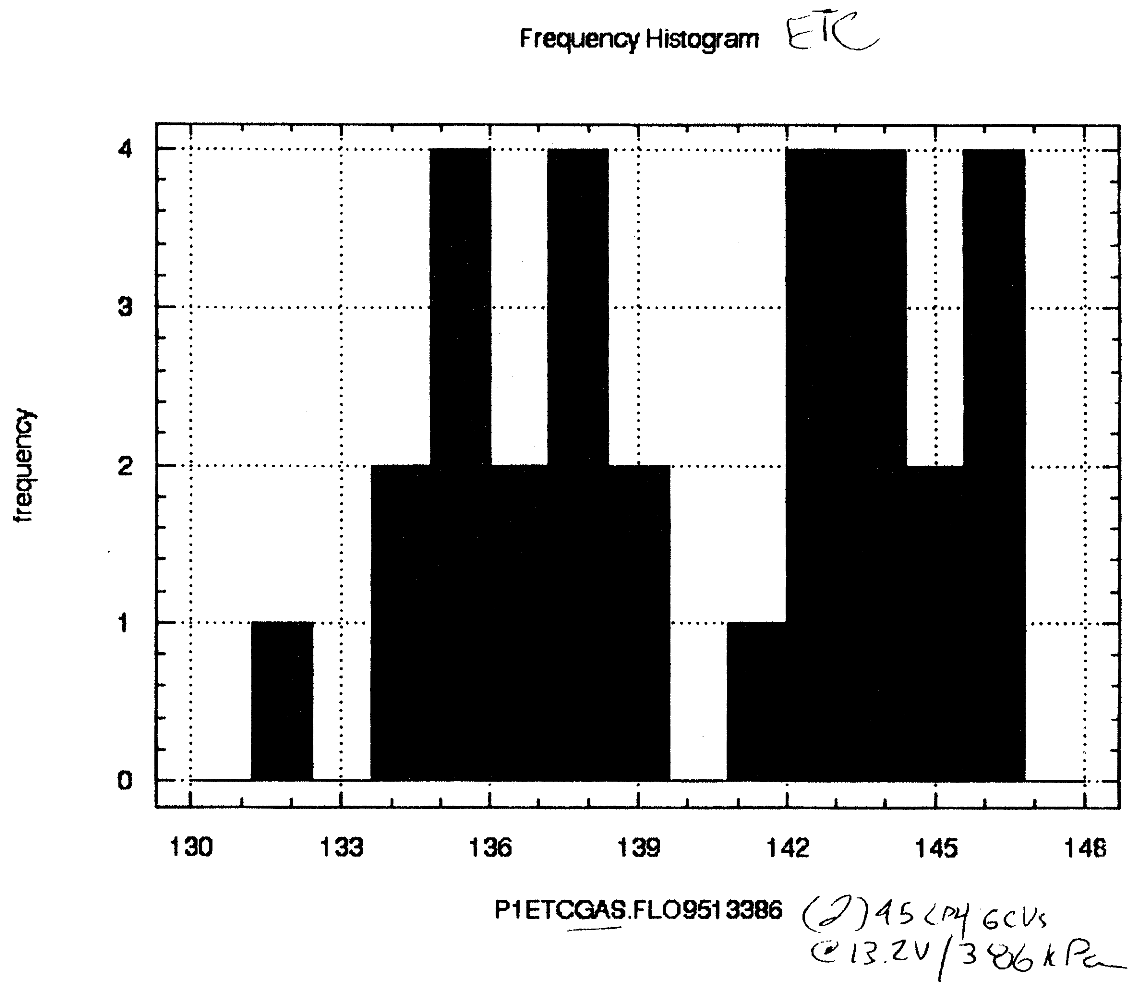

Frequency Histogram
ALBA
P1ALBGAS.FLO1331 0
(2) TURBINES @ 13.2V/310 KPa
frequency
0
2
4
6
8
10
12
89
92
95
98
101
104
107

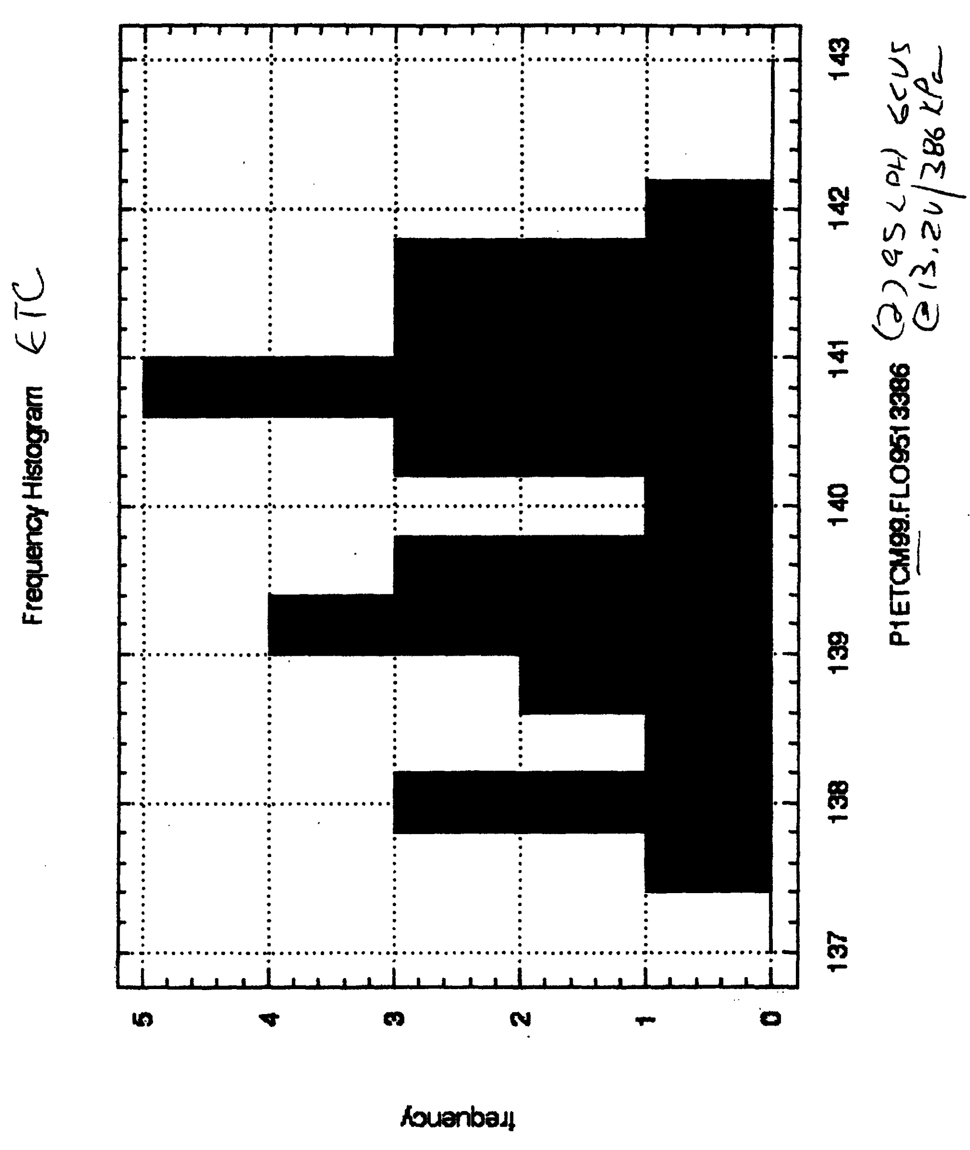

Frequency Histogram ETC
P1ETCM99.FLO13310 (2) TURBINES @ 13.2V/310kPa
frequency
0
2
4
6
8
88
90
92
94
96
98


Frequency Histogram
ALBA
frequency
0
1
2
3
4
5
80
82
84
86
88
90
92
P1ALBM99.FLO13310


Frequency Histogram
frequency
0
2
4
6
8
10
94
97
100
103
106
109
P1ETCGAS.FLO951 0270


Frequency Histogram
ETC
frequency
0
2
4
6
8
97
99
101
103
105
107
P1ETCM99.FLO9510270


Frequency Histogram
ETC
frequency
0
1
2
3
4
130
133
136
139
142
145
148
P1ETCGAS.FLO951 3386
(2) 45 CH4 GCVs
@ 13.2V / 386 kPa


Frequency Histogram
ETC
frequency
0
1
2
3
4
5
137
138
139
140
141
142
143
P1ETCM99.FLO9513386

APPENDIX L

AVERAGE PUMP SPEEDS USED IN THE DETERMINATION OF THE RE NUMBERS (FROM PHASE II CORRELATION TESTING/ETC LAB)

PUMP	TEST FLUID	SETTING	N_{avg} (rpm)
45 lph	M99	13.2V/110 kPa	3653
	50-D		3921
60 lph	M99	13.2V/310 kPa	5100
	50-D		5280
95 lph	M99	13.2V/310 kPa	6947
	50-D		7260
125 lph	M99	13.2V/310 kPa	7615
	50-D		8171
Turbine	M99	8.0V/200 kPa	5033
		8.0V/250 kPa	5063
		13.2V/310 kPa	8709
	50-D	8.0V/200 kPa	4701
		8.0V/250 kPa	4544
		13.2V/310 kPa	8263
	EURO*	8.0V/200 kPa	4677
		8.0V/250 kPa	4527
		13.2V/310 kPa	8262

* Estimated from ETC data in 50-D gasoline.

DERIVATION OF SIMPLIFIED FUEL PUMP PERFORMANCE SIMILARITY RULES:

Given: $\frac{\Delta P_1}{\Delta P_2} = (\frac{N_1}{N_2})^2 \cdot (\frac{D_1}{D_2})^2 \cdot (\frac{\rho_1}{\rho_2})$ PUMP PRESSURE

ΔP_i = Fixed pressure at 200 kPa, 250 kPa, or 310 kPa regardless of test fluid type.

D_i = Fixed diameter for each pump regardless of test fluid type.

$$\therefore\ 1 = (\frac{N_1}{N_2})^2 \cdot (\frac{1}{1})^2 \cdot (\frac{\rho_1}{\rho_2})$$

but $(\frac{\rho_1}{\rho_2}) = (\frac{SG_1}{SG_2})$

and $(\frac{N_1}{N_2}) = \sqrt{\frac{SG_2}{SG_1}}$

Substituting this relationship into the pump similarity rules for flow (Q), pump head (H), and water power (P), results in:

$$\frac{Q_1}{Q_2} = (\frac{N_1}{N_2}) \cdot (\frac{D_1}{D_2})^3 = \sqrt{\frac{SG_2}{SG_1}}$$

$$\frac{H_1}{H_2} = (\frac{N_1}{N_2})^2 \cdot (\frac{D_1}{D_2})^2 = \frac{SG_2}{SG_1}$$

$$\frac{P_1}{P_2} = (\frac{N_1}{N_2})^3 \cdot (\frac{D_1}{D_2})^5 \cdot (\frac{\rho_1}{\rho_2}) = \sqrt{\frac{SG_2}{SG_1}}$$

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