In-Service Motor Testing

Final Report

prepared by

Washington State University
Energy Program

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by Washington State University Cooperative Extension Energy Program
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This research was performed for the Northwest Energy Efficiency Alliance between March 30, 1998 and May 31, 1999. The goals of the project have been to:

1. Assess general interest in on-site motor testing,
2. Assess the availability of potential motor service providers and tools,
3. Determine the usefulness of motor efficiency testing methods and equipment in field applications,
4. Document the impacts of improved knowledge of motor efficiency on plant managers' ability to manage their motor systems,
5. Ascertain the market potential for a motor testing service, and
6. Use the results of this project to develop recommendations for a possible market transformation venture.

The following describes key findings of this research.

Market Survey

Dethman and Associates completed a market survey of motor service providers and motor decision-makers (industrial end-users). A complete copy of the survey was submitted on May 5, 1999 and is included as Appendix C of this report. A brief summary of the findings follows:

Service Providers

The service providers' survey was intended to:

- Gauge interest in, and capability of, providing on-site motor efficiency testing services.
- Identify barriers, if any, to offering motor efficiency testing services.

Most of the service providers were in the business of training or energy auditing. Quite a few offered services in distribution tune-up, preventative/predictive maintenance, and motor inventory management.

One of the most important questions asked of the service providers was to name the important features of an ideal motor efficiency tester. Convenience was at the top of the list. The most prevalent comments were that it be easy to use and easy to transport. Two thirds of the respondents indicated that it was not acceptable to shut down the motor for test. The question had not even posed the issue of uncoupling.

Decision Makers

The decision makers survey was intended to:

- Investigate how on-site motor efficiency testing would affect the industrial motor repair and replacement process.
- Gauge if regional industries would consider modifying their motor repair/replacement policies and/or their new motor acceptance policies if they had more accurate information about the actual energy efficiency of new and existing motors.
- Qualitatively estimate the business potential of an on-site motor efficiency testing service.

One of the most important questions asked of the decision makers was to indicate how valuable a motor efficiency tester would be to them if it were easy to use and non-invasive. The responses clustered around “somewhat valuable” with a few responses of “very valuable” or “not too valuable”. In retrospect, it would have been better to word the question more neutral with respect to ease of use and invasiveness because using the *demonstrated* tester was found to be rather invasive and time consuming.

Obtaining Host Facilities

Two factors hampered our search for host industrial facilities: the requirement to bring in outsiders, and the necessity for uncoupling the motor to demonstrate the most accurate methods. Weyerhaeuser and Boeing have told us that it takes around three hours to uncouple and recouple. There was a similar anecdotal comment on the user survey. The motor has to be loosened on its base and precisely realigned when it is recoupled. It is a problem both in terms of down time and labor cost.

We searched for industrial facilities through several utilities and some direct industrial contacts. We contacted Seattle City Light, Idaho Power, Puget Sound Energy, McMinnville Water and Light, Washington Water Power (now Avista Corporation), and Grays Harbor PUD. The utilities were reluctant to bring their customers into this situation. They tended to take a while to “get back to us,” and then have no industries to nominate. Indeed, the only utility that nominated industries was Washington Water Power. Both of the industrial facilities they nominated declined to participate. By direct contact, we arranged a demonstration at the Weyerhaeuser Cosmopolis plant. After initial encouragement, two site visits, and considerable effort, the Boeing Company declined to host a demonstration. Both industry and utility contacts told us that efficiency is not nearly as high on their priority list as reliability and predictive/preventative maintenance.

Demonstration at Weyerhaeuser Cosmopolis Pulp Mill

The demonstration at Weyerhaeuser's Cosmopolis, Washington, pulp mill was preceded by a dry run on April 6, 1999. The formal testing with invited guests was held April 14, 1999. The people who attended the formal testing are listed in Appendix B.

On April 6, 1999, we briefed the Weyerhaeuser staff on the project's history and objectives. This included the first literature analyses of many methods (done by ORNL), up through the lab testing at the Oregon State University Motor Systems Resource Facility (MSRF). We described the methods to be demonstrated at Weyerhaeuser, which included:

- All MotorMaster+ Methods
    - ✓ Slip
    - ✓ Amp
    - ✓ kW
    - ✓ ORMEL 96
- WSU simple loss analysis method
- ECNZ/Vectron Motor Monitor device

Weyerhaeuser has been quite satisfied with the MotorMaster+ methods because of their user-friendly non-invasive nature. They recognized the accuracy limitations of the MM+ methods, but accept them because of the ease of application. Use of MM+ has helped them conclude to replace all existing standard motors with premium motors, i.e. motors that meet IEEE 841 standards for petro-chemical applications.

The primary purpose of the dry run was to ensure that everything would go smoothly with the Motor Monitor device because it had never been used before by WSU staff, and because staff had not previously seen the candidate motors at Weyerhaeuser. Weyerhaeuser proposed a somewhat new energy efficient 70 HP pump motor for the test. The motor was coupled by belt to the pump. A factor in the choice of this motor for testing was the belt drive, which was somewhat easier to remove and replace than a direct coupling. Still, considerable labor was involved, by two millwrights, to remove the belt guard and loosen the motor mounting bolts to remove the belt. Replacement of the belt required realignment of the motor to ensure the motor and pump shafts were parallel and the pulleys were in the same plane. The motor J-box had to be opened to access the connections for the winding resistance test and to monitor voltage during running. Connections were bolted and taped. Electrical tape had to be removed and the adhesive residue scraped off for good contact with the ohmmeter/voltmeter connections. Actual testing time was somewhat over three hours, most of which was due to preparing and restoring the motor.

The Motor Monitor device records data on the motor in three conditions: unpowered, running uncoupled, and running normally loaded. Once the motor shaft and connections are exposed, the actual work of connecting the device and recording the data is quite brief. Two electrical test clips are connected to each of the three cable connections, and three inductive current transducers are clamped around the three cables. A piece of reflective tape is affixed to the shaft and an optical speed sensor with a magnetic mount is situated nearby and aimed at the reflective tape. Several nameplate parameters are entered into the instrument. For each of the three conditions, a button is pressed to begin the reading. The reading only takes about 20 seconds but the user is cautioned to scroll through the results to ensure that they are all reasonable. An unreasonable result reveals problems such as an incorrect connection, tachometer knocked askew, or incorrect sequence of data entry. An experienced operator should be able to take each reading and inspect the results in only a couple of minutes.

During the dry run WSU staff indeed made an error. This possibility was anticipated and it was the reason for having a dry run first. Some of the nameplate data was entered after one of the readings was taken. That caused the winding resistance to be readjusted by the machine, which led to an erroneous result. Once we detected the error, the manufacturer was able to back calculate the correct result for us.

On April 14, 1999 WSU conducted the formal demonstration with invited guests. The attendees are listed in Appendix B. The ECNZ Vectron device yielded an efficiency within half a percentage point of the nameplate efficiency. It is important to note that the demonstration was to evaluate the field practicality and user acceptance of the methods, not to assess efficiency. Efficiency evaluation requires testing a variety of motors under a variety of conditions in a laboratory situation. This was done in the prior phase of this research. Nonetheless, the close match between measured and nameplate efficiency provided reassurance that the instrument functioned correctly and was properly operated.

The motor performance reports from the Weyerhaeuser testing are provided in Appendix D. These are submitted pursuant to Statement of Work Task 7 requirements. Weyerhaeuser already has a comprehensive motor management plan. The backbone of the plan is MotorMaster+.

Field Demonstration Survey

Dethman and Associates completed a survey of people witnessing the demonstration at Weyerhaeuser. The survey report is attached as Appendix C of this report. The participants were asked to evaluate six demonstrated methods for determining motor efficiency in the field. These were:

- ECNZ Vectron Motor Monitor
- Simple Loss Analysis Method (Spreadsheet)
- MotorMaster+ kW
- MotorMaster+ Amp
- MotorMaster+ Slip
- MotorMaster+ ORMEL96

The participants were initially briefed on all the methods, then proceeded into the plant area to observe data acquisition. The major data acquisition effort occurred on a 40 HP energy efficient motor driving a pump. The data was processed after the group returned to the conference room.

The greatest issue of the tests was the requirement of some methods to uncouple the motor. Next to that was the requirement to expose the connection at the J-box. It was not necessary to disconnect the leads in the J-box for our tests, but Weyerhaeuser did this to facilitate some tests they wished to do using a new power monitor. The motor had a belt drive and the motor had to be realigned after the test to ensure that the shafts were parallel, the sheaves were in the same plane, and the belt tension was correct.

After observing the field testing and data entry and analysis that followed, the attendees recorded their perceptions and opinions in a survey prepared by Dethman and Associates. They were asked about the time and staff required for each test method, their confidence in the methods, and which methods should be promoted. The analysis of survey results by Dethman and Associates is presented in Appendix E. We were not surprised by the participants' estimates of time and staff. They were fairly consistent with our own opinions. A particularly informative question pertained to percent of motors for which each test would be applicable. This reflects the fraction of motors for which each test was presumed worth the trouble and accurate enough to be worthwhile. The most invasive tests were judged applicable to less than 24% of motors. MotorMaster+ kW and ORMEL96, respectively, were judged applicable to testing the most motors, i.e. just under 75%. We assume that the much higher applicability for the latter are associated with their ease of application (the motors do not even need to be shut down) and fairly accurate performance that we reported based upon OSU MSRF testing.

Confidence levels in the various methods were somewhat surprising. Because of this, we invite a close look at the actual question. The participants were asked, "How confident are you that the accuracy of each method will have real, practical value in repair versus replace decisions." We know from the OSU MSRF testing that the ECNZ Vectron device and the simple loss analysis spreadsheet method were far more accurate than any of the MotorMaster+ methods. The findings in this regard were reported to the attendees.

In the demonstration analysis, the former two methods matched the motor nameplate efficiency with less than half a percentage point discrepancy. However, in the survey, over 75% of participants indicate they were somewhat or very confident in the MotorMaster+ kW, Amp, and ORMEL96 methods. Only 25% indicated being somewhat to very confident in the ECNZ Vectron and simple loss analysis spreadsheet method. From the phrasing in the question (…have real, practical value…) we believe the low confidence in the invasive methods could reflect more on the impracticality of accomplishing invasive tests rather than doubts about their accuracy.

Consistent with the confidence results, a strong majority of participants felt the MotorMaster+ kW, Amp, and ORMEL96 methods should be encouraged or promoted to industries in the northwest.

Market Transformation Plan

Statement of Work Task 8 called for a brief action plan for a market transformation venture. In defining that task, it was probably anticipated that the more accurate methods would have been found more acceptable than they have been. In fact, the input gathered in this project indicates that the invasiveness of the accurate methods has to be mitigated before there will be significant acceptance. Notwithstanding the problems, there are several actions that we advocate toward the goal of in-situ motor efficiency testing.

The Northwest Drivepower Initiative will place several circuit riders in the field to assist industrial facilities with motor systems. A lab-in-a-box in-situ tester such as the Motor Monitor could be purchased for under $15,000 to support this project. It would provide the program with an accurate device to assess load and efficiency in larger motors where the testing labor is cost effective, and for motors which have to be uncoupled anyway because they are returning from a service center. It will also allow pretesting of any candidate motors to be sent to the OSU Motor Systems Resource Facility for IEEE 112B testing. This might be an excellent way to keep manufacturers honest. Research by Advanced Energy Corporation of Raleigh, NC has indicated that manufacturers vary considerably in the veracity of their nameplate efficiency.

We would like for this research to stimulate the supply side of the instrumentation market. Throughout all the phases of this research, test equipment manufacturers have watched. A clear challenge to them is to develop a method that will allow accurate determination of efficiency without a high labor or equipment cost.

Two manufacturers are currently exploring devices that work by analyzing the current signature of motors. One of these, Baker Instruments of Colorado, expects to bring an instrument to market in summer of 1999. The current signature technology is already used in devices for fault detection and predictive maintenance. It relies upon a harmonic analysis of the current wave. Higher order and subsynchronous (often-tiny) harmonics of the current wave reveal things like torque pulsation, off center rotor, exact RPM, broken rotor bars, etc. The Baker Instruments product will determine efficiency as output/input.

Output power will be derived from torque and RPM, both of which are obtained from the current signature. RPM will come from modulations in the frequency spectrum caused by very slight imperfections in the rotor. Torque will be obtained by cross multiplication of the stator flux vector and the current vector.

Another approach to reducing cost and labor of field efficiency determination can be achieved with ordinary electrical testing instruments and should be encouraged. This might be deemed a "simple loss analysis" method. It requires measurement of no-load power at a convenient time such as when the motor is run uncoupled at receiving inspection or at the shop following repair. The results can be stored along with measured winding resistance in the motor inventory database (e.g. MotorMaster+) and referenced later when the motor is tested in service. The in-service testing would not require uncoupling or even shutdown. Only kW and amps measured at the Motor Control Center and RPM from a non-contact strobe tach would be required. The "simple loss analysis" procedure is covered in detail in Appendix A.

The simple loss analysis method requires only conventional instruments capable of measuring watts, amps, ohms, speed, and temperature. The biggest equipment hurdle is ensuring that the wattmeter has good accuracy at very low power factor. Power factor can be as low as 4% at no-load and the wattmeter needs to read real power to about ±20% accuracy at this power factor in order to keep errors in calculated motor efficiency within ±1%. At first thought ±20% does not seem too stringent. However, portable wattmeters, power analyzers, etc. are not normally calibrated at such a low range of power factor where indicated watts are very sensitive to ubiquitous current transformer phase lag. WSU has communicated with several watt transducer and power analyzer manufacturers on this subject. The consensus among those consulted is that the accuracy at low power factor is somewhat of a challenge but achievable in the better quality wattmeters without substantial cost increases. Manufacturers of higher end wattmeters and power analyzers should be polled about their products' accuracy at low power factor and encouraged to tighten the calibration at those low power factors.

Conclusions

We are convinced that a highly invasive method requiring uncoupling the motor will not experience significant acceptance by northwest industry. This follows from the response of participants at Weyerhaeuser, our own observations of the methods' application, and our attempts at recruiting demonstration sites. Users appreciate the MotorMaster+ methods, though less accurate, because they do not even require that the motor be shut down.

Improvements in existing efficiency testing methods may occur soon. We have recommended to USDOE that they support the improvement of MotorMaster+ ORMEL96. It could benefit from an input that accepts and adjusts for actual voltage, which may vary somewhat from the nameplate voltage. Also, fairly often ORMEL96 still fails to run due to nameplate data out of the range of the program's built-in expectations. For higher accuracy testing, without uncoupling, the Baker Instruments tester should be evaluated in the laboratory after it enters production (see *Market Transformation Plan* above).

For situations where high accuracy is necessary, we recommend the simple loss analysis method for occasional use, or one of the portable lab-in-a-box devices such as the ECNZ/Vectron Motor Monitor for frequent usage. These more accurate methods can provide an excellent test in situations where the stakes are high, such as with higher horsepower low voltage motors. The higher accuracy methods could also be a valuable asset in a program to spot check various manufacturers' motor product lines for compliance with labeling and EPACT. Motors could be pre-screened with the accurate in-situ methods before costly shipment to a lab for testing per the IEEE 112B standard endorsed by EPACT.

Appendix A

Appendix A

Simple Loss Analysis Method

This method requires acquisition of nameplate and measured motor data using accurate conventional field instruments. Data is entered into a spreadsheet. These data do not have to be taken on the same occasion. For example, unpowered and no-load running data can be taken during receiving inspection of new and rewound motors.

Nameplate Data

Record the following data if present on the nameplate:

1. Insulation Temperature Class
2. Nominal Efficiency
3. Speed
4. Horsepower

Unpowered Data

The motor must have been unpowered long enough to reach the temperature of its ambient surroundings.

1. Record the Celsius ambient temperature near the motor. If there is doubt of sufficient cool-down time, allow at least one minute for each 10 pounds of motor weight and obtain temperature in contact with the motor surface at the warmest spot.
2. Using a micro-ohmmeter, measure and record the line to line resistance between each line pair in normal running configuration[1]. If there are more than three leads, ensure that these are tightly bolted in the run configuration before proceeding. With the motor connected in normal running condition, you need not be concerned whether it is star connected or delta connected. If readings are taken at the MCC, the cable resistance should be calculated from length and gage and subtracted from the reading.

Unloaded Running Data

Ensure that the power supply provides balanced sinusoidal voltage very near the motor nameplate rating.

1. Connect an accurate[2] three-phase power meter.
2. Run the motor for at least 10 minutes then record the input electric power in kW.

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[1] It may be impractical to measure resistance with the motor windings connected in normal star or delta running configuration, such as when measuring at the MCC of a motor with star/delta start. If the windings are measured isolated, multiply readings by 0.6667 for motors that run in delta and by 2.0 for motors that run in star.

[2] The wattmeter needs to be accurate at very low power factor. Consult with the manufacturer. Accuracy needs to be within ±20% at 4% power factor and within ±10% at 10% power factor.

Normal Load Data

The motor must be running long enough for the temperature to stabilize before performing this test. If it is necessary to power off the motor to connect test equipment, let the motor run long enough for temperature stabilization before taking readings. For best accuracy, the power supply should be providing balanced sinusoidal voltage very near the motor nameplate rating.

1. Connect a three phase power meter
2. Record input electric power in kW
3. Record the current of each line.
4. If the motor has an internal temperature sensor, record the Celsius temperature. .
5. Carefully record the speed with an accurate strobe or optical tachometer.

Spreadsheet Entry

Enter the recorded data in the INPUTS section of the Motor Efficiency Calculator spreadsheet.

1. Motor Run # is used for your own reference but not in the calculations.
2. Horsepower is from the nameplate and is used in determining percent load but it is not used in the efficiency determination.
3. L-L Resistance is the mean (average) of the three line to line resistances in ohms.
4. Measured RPM is the exact RPM measured at normal load.
5. Mean Amps is the mean line current of the three phases.
6. Sync Speed is the synchronous speed. With 60 Hz power, it is a round number about 1 to 3% higher than the nameplate RPM, i.e. either 3600, 1800, 1200, or 900.
7. Expected Efficiency is optional. It can be the nameplate efficiency. It is only used as a comparison to see how close calculated efficiency comes to the claimed or expected efficiency.
8. Input kW is the power draw with the motor running at normal load.
9. Input kW No-Load is the power draw determined during the no-load running test.
10. Winding degrees C is the temperature of the motor windings at normal running load. An internal temperature sensor can determine this. Otherwise, use ambient temperature plus about 40°C for fully loaded motors and ambient temperature plus about 20°C for motors at 50% load or less.
11. Ambient degrees C is the temperature of the windings when the winding resistance measurement was performed. Normally it is equal to the ambient temperature but it can be higher if the motor has not had a long cool-down time.

INPUTS											CALCULATIONS						
mot	rlab	slip	nzrpm	ilab	effubjd	lab ef	Input kw	Input kwnoload	wndg temp	amb temp	t-cor resistance	kW I2R loss	kw rotor loss	stray loss	kw total loss	Calculated Efficiency	JD-lab error
1	0.015935	16	1784	330.3	96.7396%	96.30%	233.6	2.554	110	22	0.02137	3.49727	2.02266	1.37998	9.4539	95.9530%	-0.35%
2	0.162986	36	3564	60.27	89.5466%	88.10%	42.25	3.003	94.5	22	0.20905	1.13908	0.38108	0.38004	4.90319	88.3948%	0.29%
3	0.099939	23	1777	117.6	93.8353%	92.50%	79	1.501	74.5	22	0.12039	2.49585	0.95837	0.86355	5.81877	92.6345%	0.13%
4	0.098669	23	1777	116.6	93.9985%	91.20%	78.51	1.4157	74.5	22	0.11886	2.42433	0.95412	0.84461	5.63875	92.8178%	1.62%
5	0.056985	21	1779	187.1	93.9617%	93.00%	123.3	2.601	74.5	22	0.06865	3.60288	1.36612	1.24225	8.81225	92.8530%	-0.15%
1	0.015935	8	1792	178.1	96.3182%	96.50%	116.9	2.554	110	22	0.02137	1.01673	0.50373	0.38011	4.45457	96.1897%	-0.31%
2	0.162986	20	3580	33.78	84.4631%	83.70%	22.08	3.003	94.5	22	0.20905	0.35782	0.104	0.11545	3.58027	83.7850%	0.08%
3	0.099939	11	1789	62.22	93.8360%	93.50%	38.91	1.501	74.5	22	0.12039	0.69921	0.22434	0.23089	2.65543	93.1755%	-0.32%
4	0.098669	11	1789	62.57	94.0442%	92.60%	38.82	1.4157	74.5	22	0.11886	0.69811	0.22432	0.23061	2.56873	93.3830%	0.78%
5	0.056985	9	1791	106.2	93.3922%	92.20%	60.56	2.601	74.5	22	0.06865	1.161	0.28399	0.36125	4.40724	92.7225%	0.52%

Appendix B

Appendix B

Attendees at the Weyerhaeuser Demonstration

Jim Todd	Weyerhaeuser - Cosmopolis
David Scott	Weyerhaeuser - Cosmopolis
Terry McGarrah	Weyerhaeuser - Cosmopolis
Ray Mykra	Weyerhaeuser - Cosmopolis
John Holmquist	Weyerhaeuser - Tacoma
Mike Richler	Weyerhaeuser - Tacoma
Tom Yarborough	Weyerhaeuser - Tacoma
James Rooks	J&R Consulting
Craig Wohlgemuth	CW2 Engineering
Tracy Bennett	Grays Harbor PUD
Steve Mangan	Grays Harbor PUD
Kevin Batycki	Power Measurement Ltd.
John Vollen	Power Measurement Ltd.
Kevin Madison	Electric League of the Northwest
Blair Collins	NW Energy Efficiency Alliance
Jim Hampson	Syntek
Bruce Bolstad	Syntek
Terry Galagher	Rockwell - Reliance
Johnny Douglass	WSU Energy Program
Gil McCoy	WSU Energy Program

Appendix C

Attached separately

Appendix D

Appendix D

Motor Performance Reports

Five methods were used in determining motor efficiency from the testing at Weyerhaeuser Cosmopolis on April 14, 1999. The reports are provided herein in the following sequence:

- ECNZ/Vectron Motor Monitor
- Simple Loss Analysis Method
- MotorMaster+ Amps
- MotorMaster+ kW
- MotorMaster+ Slip
- MotorMaster+ ORMEL96

The motor voltage varied around 590 volts during the testing. This was about 2½% above nameplate voltage. It is within the allowable range of voltage variation per NEMA standards, but it affects the different methods differently. Note also that the motor was somewhat overloaded during the tests. This also affects the different methods differently.

The Motor Monitor report gives several efficiencies. There is the efficiency as the motor was operated, i.e. overloaded and slightly over voltage. It also calculates the efficiency and other parameters at full and part load nominal voltage and presents these in a table named “Normalised Test Results”.

The simple loss analysis method spreadsheet "Motor Efficiency Calculator" is programmed to compute efficiency at the conditions of operation when data was recorded. Each line in the spreadsheet is a different motor. The Weyerhaeuser test motor is the last line, i.e. motor C414.

The key to determining which MotorMaster+ performance report pertains to each MotorMaster+ efficiency calculation method is in the “Field Measurements” box under “Calculations”. The “Load” parameter is percent load. The next column to the right shows the load calculated by each of three methods. The method that matches the “Load” value in the prior column is the one MotorMaster+ used to look up efficiency. If the “Load” does not match any of the three methods, ORMEL96 was used. ORMEL96 load is not shown in the second column.

MotorMaster+ Amps, kW, and Slip all calculate load and then look up efficiency in a lookup table. They correct the load calculation based upon the difference between nameplate and actual terminal voltage. The reader will note that in every case, these three give 94.1% efficiency which is exactly equal to nameplate efficiency. This is because MotorMaster+ uses the actual nameplate efficiency (if it has been entered) for loads equal to or greater than full load. Between 75% and 100% load, it interpolates (based on calculated load) between lookup table values and nameplate efficiency.

MotorMaster+ ORMEL96 works differently from the other MotorMaster+ methods. It operates upon nameplate data and one measured parameter, speed. Using this data, it computes efficiency by generating an electrical equivalent circuit. ORMEL96 will always try to run when the only measured data is RPM. With this motor, limiting data to RPM caused the slip method to run instead. This is because ORMEL96 is still plagued with a nettlesome quirk of not running if some of the input data are not consistent with fairly tight internal assumptions. We were able to make it run by slightly increasing the nameplate power factor from the actual 87.6% to 87.8%. We do not know what effect this had on accuracy. Likewise we do not know what the 2½% overvoltage affect had on accuracy. ORMEL96 does not utilize measured voltage as an input.

Appendix E

Attached separately