Motor-Operated Valve (MOV) Actuator Motor and Gearbox Testing

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ABSTRACT

This report documents the results of valve research sponsored by the U.S. Nuclear Regulatory Commission (NRC) and conducted at the Idaho National Engineering and Environmental Laboratory (INEEL). The research provides technical bases to the NRC in support of their effort regarding motor-operated valves (MOVs) in nuclear power plants. Specifically, the research measured the capabilities of typical valve actuators during operation at simulated design basis loads and operating conditions. Using a test stand that simulates the stem load profiles a valve actuator would experience when closing a valve against flow and pressure, we tested five typical electric motors (four ac motors and one dc motor) and three gearboxes at conditions a motor might experience in a power plant, including such off-normal conditions as operation at high temperature and reduced voltage. We also monitored the efficiency of the actuator gearbox. The testing produced the following results:

- All five motors operated at or above their rated starting torque during tests at normal voltages and temperatures.

- For all five motors (dc as well as ac), actual motor torque losses due to voltage degradation were greater than the losses calculated by methods typically used for predicting motor torque at degraded voltage conditions.

- Startup torques in locked rotor tests compared well with stall torques in dynamometer-type tests.

- For three of the ac motors, the actual motor torque losses due to elevated operating temperatures were equal to or lower than losses calculated by the typical predictive method; for the dc motor, the actual losses were significantly greater than the predictions.

- For all three actuator gearboxes, the actual running efficiencies determined from testing were lower than the running efficiencies published by the manufacturer. In most instances, the actual pullout efficiencies were lower than the published pullout efficiencies.

- Operation of the gearbox at elevated temperature did not affect the operating efficiency.

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EXECUTIVE SUMMARY

A typical nuclear power plant contains hundreds of motor-operated valves (MOVs) that are actuated by an assembly consisting of an electric motor and a gearbox. Many of these MOVs are *safety-related*, a term that means that the safety of the plant depends on the ability of these valves to close (or open) when called upon to operate at the conditions specified in the plant's design documents. For some valves, these conditions include very high flows and pressures. In response to initiatives by the Nuclear Regulatory Commission (NRC), utilities have developed programs that use testing and analysis to verify MOV design basis capability. The NRC has sponsored the Idaho National Engineering and Environmental Laboratory (INEEL) in performing laboratory tests to provide the NRC with the technical basis for evaluating these utility responses. This report presents the results of tests evaluating the operation of the electric motor and the actuator gearbox at typical design basis conditions, including operation at degraded voltage and elevated temperature conditions.

The tests used motor/gearbox combinations configured from equipment purchased by the NRC and used in previous research projects. Each motor/gearbox combination was subjected to baseline tests and parametric tests at various voltages and temperatures. Specific questions addressed by the tests are:

- How does the measured output torque of the actuator motor compare with the torque characteristics published by the actuator manufacturer?

- How much does the measured output torque of the motor decrease at various reductions in the voltage supplied to the motor? How do these measured values of torque degradation compare with values calculated using methods recommended by the actuator manufacturer for estimating degradation due to low voltage?

- How much does the measured output torque of the motor decrease as the motor's operating temperature increases? How do these measured values of torque degradation compare with values calculated using methods recommended by the actuator manufacturer for estimating degradation due to motor heating?

- What is the actual efficiency of the actuator gearbox, especially at high loadings and elevated temperatures? How does the actual efficiency compare with the efficiency values published by the actuator manufacturer?

The tests were conducted at the INEEL on the motor-operated valve load simulator (MOVLS), an instrumented test stand that provides dynamometer-type testing of valve actuators using load profiles that are very similar to the load profile a valve actuator would experience when closing a valve against a flow load. For these tests, we imposed a gradually increasing load on the valve actuator until the load caused the motor to stall, while taking continuous measurements of motor speed, motor voltage and current, motor torque, actuator torque (gearbox output torque), motor temperature, and other measurements.

We tested a total of six combinations of actuator gearboxes and electric motors:

- An SMB-00 actuator equipped with a 5 ft-lb ac motor

- An SMB-0 actuator equipped with a 25 ft-lb ac motor

- The same SMB-0 actuator and motor, but running with a different gear set

- An SMB-1 actuator equipped with a 60 ft-lb ac motor

- The same SMB-1 actuator equipped with a 40 ft-lb 125-vdc motor

- The SMB-1 actuator converted to an SB-1 actuator and equipped with a high speed (3600 rpm) 40 ft-lb ac motor.

All four ac motors were configured for 460-volt, 3-phase operation.

The tests included baseline tests at room temperature and normal voltage, a series of tests at various stages of degraded voltage or elevated operating temperature, and tests at selected combinations of the two conditions. We also conducted locked rotor tests for comparing motor current and motor torque at locked rotor startup to the results at stall in the dynamometer-type tests. Continuous measurements of motor torque (gearbox input torque) and actuator torque (gearbox output torque) allowed us to monitor the gearbox efficiency during the entire test. The results of these tests are summarized in the following paragraphs.

The results showed that the data plots of motor current versus torque and motor speed versus torque, produced by the baseline tests, compared fairly well with the published data. However, there were some minor differences in the shape of the ac motor curves, indicating that the load threshold at which the motor drops off to a stall occurs at a different rpm, or at a different torque load, than indicated by the published data. All five motors met or exceeded their rated starting torques.

We compared the results of the degraded voltage tests to the results of predictions produced by methods typically used in analytical evaluations of motor capability. For the ac motors, the typical method is the voltage squared method. In all cases, the voltage squared method underestimated the actual torque losses experienced by the motors at degraded voltage conditions. For the dc motor, the typical method (a linear method) for predicting torque loss likewise underestimated the actual torque loss.

The results of the locked rotor startup tests compared favorably with the results of the dynamometer-type tests at stall. We found the simple locked rotor startup test to be useful for

evaluating a motor's actual performance (torque produced and current drawn), for comparison with published data (rated torque) or with the data stamped on the name plate.

The results of the elevated temperature tests were compared with the results of predictions based on the actuator manufacturer's data. The results of our tests showed that for three of the ac motors, the measured motor torque values at elevated temperatures were equal to or a little higher than the predictions. For one of the ac motors, the actual torque was lower than the prediction.

We also compared the motor current results from the elevated temperature tests to predictions based on the manufacturer's data. For all four ac motors, the measured values were lower than the predictions.

For the dc motor, the results from the elevated temperature tests were compared to the actuator manufacturer's data on the torque output of dc motors at elevated temperature. The torque measured in the tests was lower than the prediction, by a large margin.

The results of the gearbox efficiency tests were compared with the efficiency values published by the actuator manufacturer. The published values include a running efficiency, applicable at normal motor speeds and low to moderate loads, and a pull-out efficiency, applicable when the motor is lugging at low speed against a high load. For most motor/gearbox combinations, the actual running efficiencies and pullout efficiencies were lower than the published values. In no case was the published running efficiency adequate for predicting the actual efficiency of the gearbox when operating against a significant load. The published pull-out efficiency appeared to be adequate or nearly so in most cases for predicting the gearbox efficiency at the loads expected during valve operation, but it was in some instances inadequate for predicting the gearbox efficiency at or near motor stall.

Lower operating speeds tended to correspond with lower gearbox efficiency. This result has significance for dc-powered valve actuators,

because when challenged by loads approaching the motor's rated load, dc motors operate at much lower speed than ac motors.

We tested one actuator gearbox at elevated temperature. The elevated temperature did not affect the operating efficiency of the gearbox.

MOV Actuator Motor and Gearbox Testing

INTRODUCTION

During the past several years, the Nuclear Regulatory Commission (NRC) has supported research addressing the performance of motor-operated gate valves (Figure 1) and other motor-operated valves (MOVs) installed in nuclear power plants. The research included tests and analysis to determine the capability of safety-related MOVs to close (or open) when subjected to their design basis conditions. For some safety-related valves, these design-basis conditions include high flow and pressure loads, high temperatures (which can reduce the output of the electric motor), and operation of the electric motor at reduced voltage.

This report documents the results of tests sponsored by the NRC and performed by the Idaho National Engineering and Environmental Labora-tory (INEEL) to address factors that affect the performance of MOV electric motors and the actuator gearboxes.

Background

Most of the past MOV research conducted at the INEEL focused on gate valves and the identification of variables that most affect MOV performance. These variables include:

a.   The system conditions at the valve (the differential pressure across the disc, and the system temperature, flow, and pressure)

b.   The friction at the disc/guide and disc/seat interfaces, and possible damage to the sliding surfaces at these interfaces
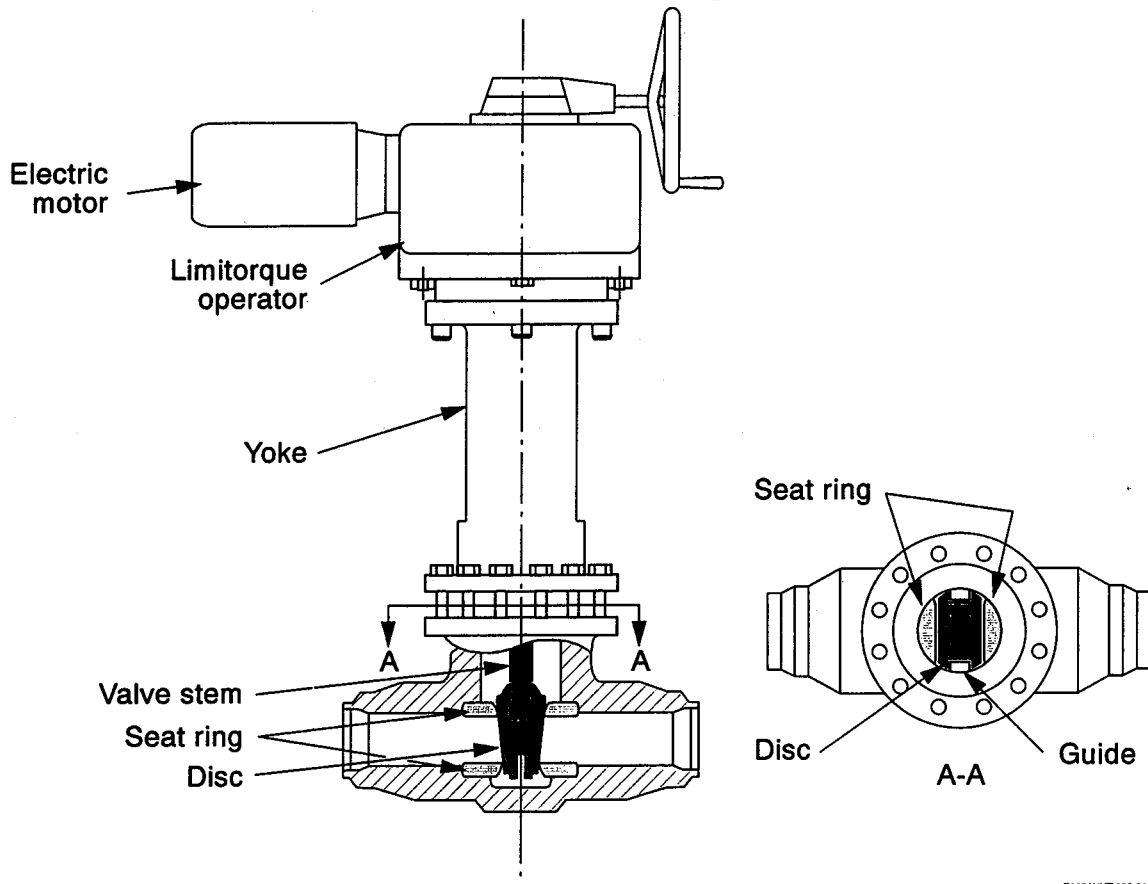
Figure 1.   Diagram of a motor-operated gate valve.

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c. The load due to packing friction

d. The friction at the stem/stem-nut interface

e. The control switch setting

f. The efficiency of the actuator gearbox

g. The torque capability of the actuator motor at normal conditions

h. The effects of reduced voltage on the torque capability of the motor

i. The effects of motor heating and high temperature on the torque capability of the motor.

Of these variables, the ones that are most difficult to determine are items b, d, f, g, h, and i. The tests documented in this report focused on items f through i. Items b and d have been addressed by recent tests, including NRC/INEEL tests briefly described below under "Earlier Testing."

Figure 2 shows the components and forces involved in items a and b above. F_{stem} in Figure 2 indicates the force needed to move the stem in a downward direction to close the valve. The main force that the actuator must overcome is the resistance to motion at the disc (the vertical force designated V in Figure 2), caused mainly by the differential pressure (F_{up} minus F_{down}) acting on the effective disc area, forcing the disc against the downstream seat (or guide) and thus contributing to the friction drag at the disc/seat (or disc/guide) interface. The horizontal force H represents the resistance to horizontal disc motion, provided by the valve seats. Other minor forces are also involved, including the stem rejection load ($F_{stem\ rej}$), the packing friction load ($F_{packing}$), and the load caused by pressure acting on various surfaces of the wedge-shaped disc (F_{top} minus F_{bottom}).

Figure 3 shows the components involved in items d through i in a typical valve actuator. The interface between the stem and the stem nut is the point where the rotary motion of the actuator gearbox is converted to linear motion of the stem

and disc (the stem nut rotates on the threaded stem, driving the stem downward during closure, while the stem and disc are prevented from rotating). Friction at this interface contributes to the load that the valve actuator must overcome in order to move the disc. Thus, it can be said that items a through d combined create a load that makes the stem nut difficult to turn on the stem, and that the actuator must deliver a certain amount of torque to the worm-gear/stem-nut assembly in order to overcome that load.

While items a through d involve forces that must be overcome by the valve actuator, items f through i involve the torque the actuator must be capable of providing to overcome those forces. The torque switch (item e) acts to limit the amount of torque the worm can apply to the worm gear. When resistance to motion of the stem/disc assembly makes the stem nut very difficult to turn, the worm moves to the right in relation to the worm gear (Figure 3), compressing the torque spring as it slides on the splined shaft until it trips the torque switch, which trips a relay that shuts off the motor. Under certain unfavorable conditions (for example, too high a torque switch setting, an underpowered motor, or degradation of motor output due to motor heating or reduced voltage), it is possible that the motor will stall before the torque switch trips. In that case, the output of the motor, not the torque switch setting, limits the actuator's torque output. In some applications the torque switch is bypassed. In this case, too, the output of the motor limits the actuator's output torque.

Earlier Testing

Earlier MOV research at the INEEL addressed many of the issues related to valve performance. In one of those earlier research programs, for example, the NRC sponsored the INEEL in conducting two sets of full-scale tests involving six gate valves. The purpose of those tests was to evaluate the response of the valves when operating against high-flow (blowdown) loads. Those tests focused on determining the force required to open and close the gate, which depends partly on the friction at the disc/seat interface, and on the
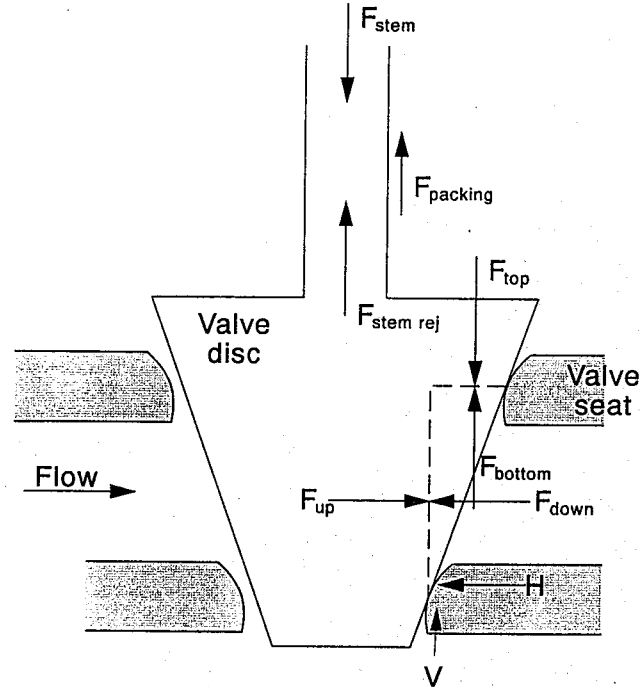
Figure 2. Sketch of the internal components of a gate valve, showing the main forces involved in a valve closure.
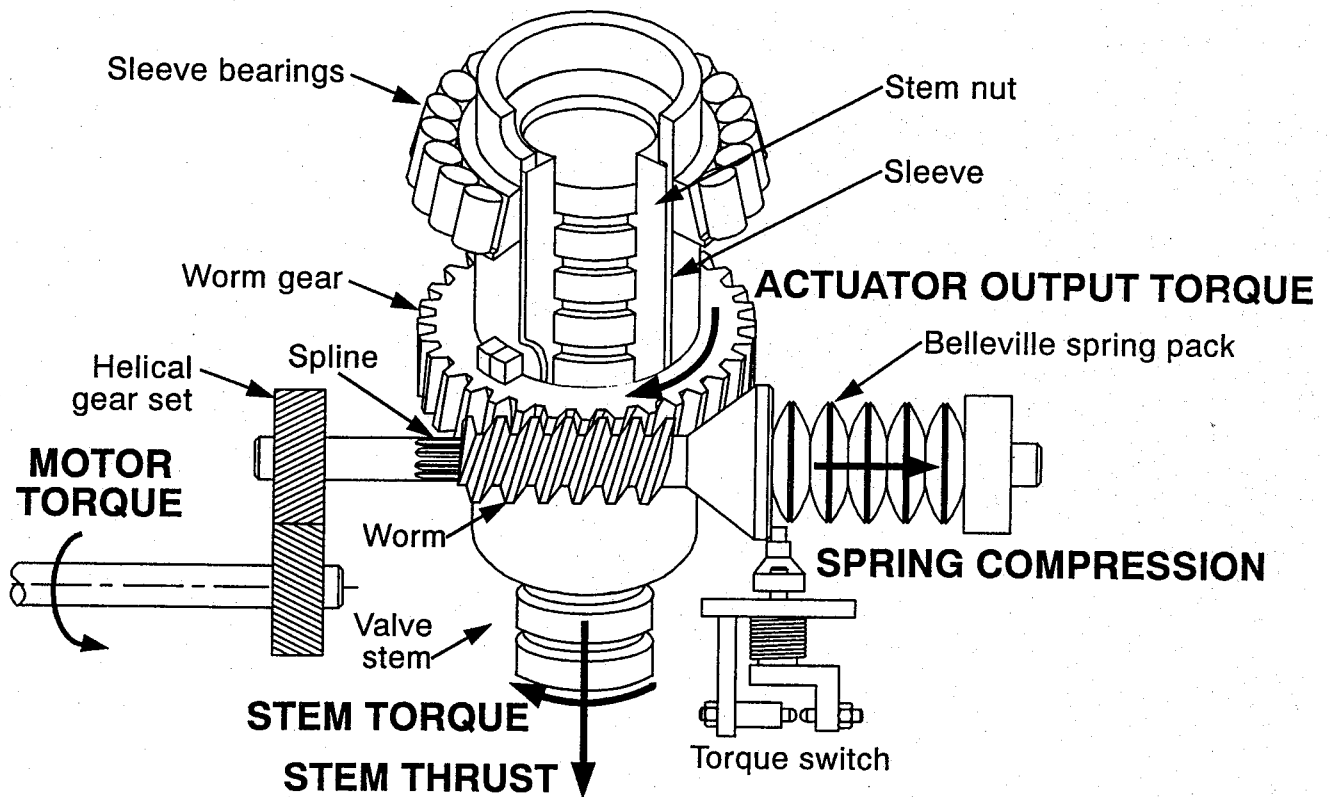
Figure 3. Diagram of the main components inside an actuator gearbox.

possibility of damage to the disc, seats, and guides when the valve closes against very high flows (item b above). The importance of those tests was that they were among the first full-scale tests ever conducted where one of the specific objectives was to quantify the actual disc factor (a term that includes friction at the disc/seat interface) at high flow loads. The results showed that the stem forces experienced by gate valves at these high loads were greater than the values predicted by typical formulas in use at the time, largely because the disc factors were higher than had been used in the formulas.

Other tests focused on friction at the interface between the valve stem and the stem nut in the valve actuator (item d above). Friction at the stem/stem-nut interface is one of the variables that affects the conversion of actuator torque to valve thrust. Here again, it was important to quantify this friction coefficient, and to understand the changes likely to occur in this friction coefficient, in order to be able to properly predict valve capability. The results of the earlier tests—the full-scale blowdown valve tests as well as the actuator tests—are documented in References 1 through 4.

The INEEL also conducted NRC-sponsored tests in Germany that included a dc-powered motor-operated gate valve (Reference 5). Those tests focused on the effects of seismic loads on MOV and piping performance; however, the tests also provided important results addressing operation of dc-powered valves at reduced voltage and other valve issues. A brief review of those results, as they relate to the tests reported here, is provided later in this report.

Scope

The testing described in this report focused on the capability of the electric motor and on the efficiency of the actuator gearbox. Specifically, the testing addressed the following questions:

- How does the actual, measured output torque of the actuator motor compare with the torque characteristics published by the manufacturer?

- How much does the output torque of the motor decrease at various reductions in the voltage supplied to the motor? How do these measured values of torque reduction compare with the reductions calculated by typical analytical predictions?

- How much does the output torque of the motor decrease as the motor's operating temperature increases? How do these measured values of torque reduction compare with the reductions calculated by typical analytical predictions?

- What is the actual efficiency of the actuator gearbox, especially at high loadings and elevated temperatures? How does the actual efficiency compare with the manufacturer's published efficiency values?

The testing also provided information about stall characteristics, inrush current, unbalanced voltage (ac only), and motor momentum. Preliminary results of some of the tests were published in Reference 4; a full report on the results is presented here.

We tested six combinations of actuator gearboxes and electric motors, using five motors and three gearboxes (see Table 1). All of the equipment was well conditioned from previous use in other test programs. The SMB-1 actuator was tested with two different motors installed. The SMB-0 actuator with the 25-ft-lb motor was tested with two different sets of helical gears in the gearbox, one of them a set of high-speed gears. Table 1 summarizes the information provided by the motor manufacturers and the actuator manufacturer about the six actuator combinations, including the gear ratios of the helical gear sets.

Table 1. Test hardware[a]

	SMB-00-5ac	SMB-0-25ac	SMB-0-25ac	SMB-1-60ac	SB-1-40ac	SMB-1-40dc
Rated starting torque (ft-lb)	5	25	25	60	40	40
Specified stall torque (ft-lb)	6.5	29.5	29.5	66.0	49.0	63.0
Rated speed (rpm)	1700	1700	1700	1700	3400	1900
Rated voltage	460 vac 3ϕ	460 vac 3ϕ	460 vac 3ϕ	460 vac 3ϕ	460 vac 3ϕ	125 vdc
Overall ratio	87.8	69.56	34.96	42.50	32.13	42.50
Worm gear ratio	45 to 1	37 to 1	37 to 1	34 to 1	34 to 1	34 to 1
Helical gear set	22/43	25/47	37/35	32/40	37/35	32/40
Running efficiency	0.50	0.50	0.55	0.50	0.60	0.50
Pullout efficiency	0.40	0.40	0.40	0.40	0.45	0.40
Stall efficiency	0.50	0.50	0.55	0.50	0.60	0.50
Application factor	0.90	0.90	0.90	0.90	0.90	0.90
Motor frame	K56	P56	P56	FE56	184R2	D202G

a. Data as provided by Reliance Electric Company (for the ac motors), and Peerless Electric Division, H. K. Porter Company, Inc. (for the dc motor), and Limitorque (for the actuator gearboxes). Gearbox efficiency data from References 6 and 7.

TEST EQUIPMENT

This research focuses on the performance of the motor and the actuator gearbox under loaded conditions, separate from the performance of the valve disc and seat. This being the case, it is not necessary to conduct the tests with an entire valve assembly with a flow load imposed on the valve. For this research, it was possible to test the valve actuator under simulated loads.

The tests were performed on the motor-operated valve load simulator (MOVLS), a test stand owned by the NRC and built by the INEEL for testing valve actuators. The MOVLS, shown in Figure 4, uses actuators, valve yokes, and valve stems the same as they are assembled on the valves. The MOVLS simulates valve loads by using a hydraulic cylinder and an accumulator that contains a gas overpressure. As the actuator lowers the end of the valve stem (as if it were closing the valve), the end of the stem pushes on the piston in the cylinder, which discharges water to the accumulator. The specific valve load profile is controlled by the initial water level and gas pressure in the accumulator. This configuration allows us to impose a steadily increasing load on the stem, very similar to what an actuator would experience when actually closing a valve against a flow load. The valve seating load is simulated when the cylinder bottoms out.

The MOVLS is instrumented to take all the measurements that are important for diagnosing valve actuator performance. Motor speed was measured directly. On the ac motors, the electrical measurements included RMS (root mean square) voltage between phases 2 and 3, RMS and peak-to-peak current on all three phases, motor power, and phase angle. On the dc motor the electrical measurements included voltage and current. Motor temperature was measured using a combination of thermocouples and an infrared sensor, allowing us to monitor the actual internal rotor temperature. The output torque of the electric motor was measured by a torque cell mounted between the motor and the gearbox. The output torque of the gearbox was measured by a calibrated torque arm attached to the valve stem. (The torque arm measures the reaction torque in the stem, which is equal to the output torque of the gearbox, that is, the torque applied to the stem nut by the worm gear. See Figure 3.) With direct measurement of both the output torque of the motor and the output torque of the gearbox, we were able to continuously monitor the efficiency of the gearbox.
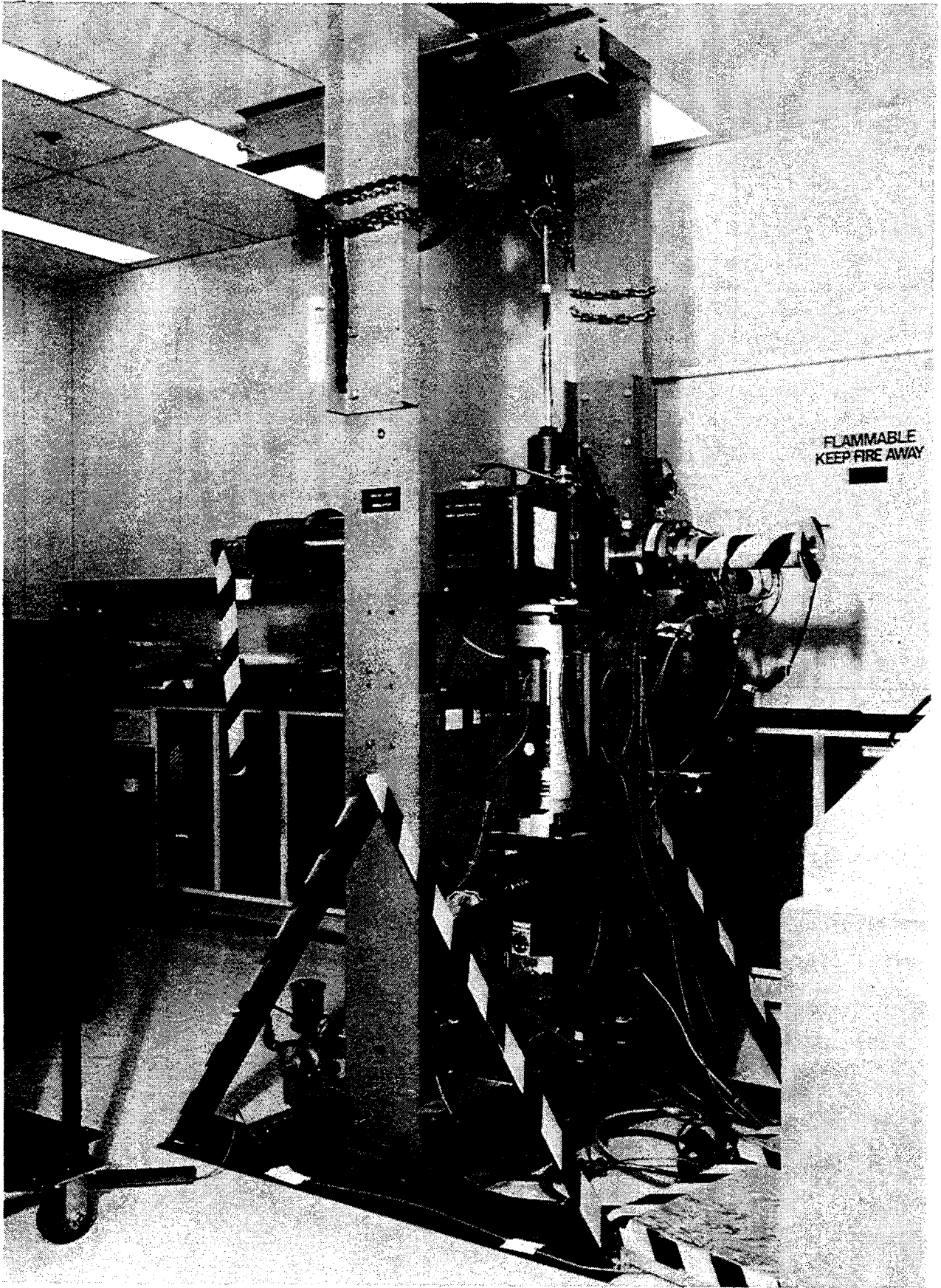
Figure 4. Photograph of the motor-operated valve load simulator (MOVLS).

TEST MATRIX

Most actuator and motor testing is typically performed by applying a sudden torque load (applying the brake on a dynamometer or hard-seating a valve without a flow load) or with a locked stem (similar to a locked rotor test). Our tests used the MOVLS to conduct dynamometer-type tests that imposed a load that gradually increased until it caused the motor to stall; a gradually increasing load is characteristic of the load an actuator will experience when closing a valve against a high flow load. Unlike earlier tests on the MOVLS, these tests used the hydraulic cylinder but not the accumulator to created the loads. The cylinder was extended and filled with gas (no water), the valve between the cylinder and the accumulator was closed, and the actuator was required to compress the gas in the cylinder until the resistance caused the actuator motor to stall. Stall occurred before the cylinder bottomed out. These tests allowed us to determine the actual output torque of the motor and of the gearbox for the entire operating range of the motor. We also conducted locked rotor startup tests, measuring torque, current, and other parameters with no motor rotation.

For each motor/gearbox combination, baseline tests were conducted with the assembly at normal conditions, then tests were conducted at various stages of reduced voltage, at various levels of operating temperature, and with selected combinations of the two. A three-phase, 60-amp-per-leg auto transformer was used to perform the degraded voltage tests. This same auto transformer was used as the supply to the dc power source to permit degraded voltage tests for the dc motor. In the elevated temperature tests, we wrapped the motor with heat tape, controlled by thermocouples and variable voltage control. The motor was also insulated, creating a custom oven on each motor. Environmentally qualified motors were heated to 300°F. However, because of wiring insulation concerns, other motors were heated only to 250°F. All testing at ambient temperature was conducted with an internal motor temperature between 70 and 80°F.

RESULTS

The results of our research address all the terms in the typical formula for predicting the output torque of a valve actuator. The formula begins with the motor's rated output torque at normal conditions, then multiplies that value by specified factors to account for torque losses due to voltage degradation and motor heating. The formula also includes an application factor to account for motor differences and minor fluctuations in the supply voltage. The resulting value is the predicted output torque of the electric motor. Also included in the formula is an efficiency factor to account for losses due to friction in the actuator gearbox, and a multiplier to account for the torque increase associated with the gear reduction in the gearbox. The product of this formula is the estimated output torque of the actuator. The formula is:

$$T_{output} = T_{motor} \left(\frac{V_{act}}{V_{rat}}\right)^n F_{temp} \; F_{app} \; Eff_{gearbox} \; OAR \quad (1)$$

where

T_{output}	=	output torque of the valve actuator
T_{motor}	=	rated starting torque of the electric motor
V_{act}	=	actual voltage supplied to the motor
V_{rat}	=	the motor's rated voltage
n	=	2 for ac motors, 1 for dc motors
F_{temp}	=	factor to account for losses due to motor heating
F_{app}	=	application factor
$Eff_{gearbox}$	=	gearbox efficiency
OAR	=	overall gear ratio.

The term $(V_{act}/V_{rat})^2$ for ac motors is the voltage squared relationship, a calculation commonly used for predicting torque losses due to reduced voltage operation. For dc motors, the formula $(V_{act}/V_{rat})^1$ represents a linear adjustment where the percent loss in torque is equal to the percent loss in voltage. For the term F_{temp}, information published by the actuator manufacturer indicates that this factor ranges from about 0.76 to 1.0, depending on the temperature and on the particular motor. The application factor (F_{app}) is usually 0.9, but the operator manufacturer suggests using 1.0 under certain circumstances, discussed later in this report. For a given actuator gearbox, the actuator manufacturer publishes three values for the gearbox efficiency ($Eff_{gearbox}$); usually these values are in the range of 0.4 to 0.6. The overall gear ratio (OAR) in rising-stem MOV actuators is always a number larger than one; it accounts for the torque increase produced by the gear reduction in the gearbox.

The following discussion presents the results of valve actuator tests and compares those results to the predictions produced by the typical methods represented in Equation (1). Specifically, this section of the report presents results on the following topics:

- Actual motor performance curves for the four ac motors tested at normal (baseline) conditions. Motor performance data published by the actuator manufacturer are included for comparison.

- Tests of the ac motors at degraded voltage, with measurements of motor torque. Estimates of motor torque produced by the voltage squared relationship are included for comparison; the application factor is also reviewed in this context.

- Locked rotor testing of the ac motors.

- Tests of ac motors at elevated temperature, with measurements of motor torque and motor current. Estimates based on data

issued by the actuator manufacturer are included for comparison.

- Tests of the dc motor for the topics listed above (as applicable)

- Gearbox efficiency data derived from measurements of gearbox input torque and gearbox output torque. Efficiency data published by the manufacturer are included for comparison.

Relevant data plots are presented along with a discussion of the results.

Performance Curves for the ac Motors

Figure 5 shows motor speed versus motor torque and motor current versus torque from our baseline test of the 5 ft-lb ac motor. As mentioned earlier, these curves are produced by running the motor at normal speed and then applying a constantly increasing load until the load causes the motor to stall. The oscillations in the data curves are due to gear train noise and to normal surges that occur when the electric motor lugs down under high loads. Figure 5 also shows the manufacturer's speed/torque and current/torque curves for this motor. The asterisk on the current trace marks the end of the manufacturer's published curve; we extrapolated the current trace from the point of the asterisk through the published stall value. Note that this particular motor is rated at 5 ft-lb, and the data from our test show that it produces more than 6 ft-lb of torque as it approaches stall.

Figure 6 presents the torque curves from our baseline test of the 25 ft-lb ac motor. Figure 6 also shows the manufacturer's torque curves for this motor. The two Xs on the extrapolated portion of the current trace are test points from earlier field testing. The two speed/torque curves are quite similar in shape; both indicate that at about 1200 rpm the motor begins to stall. Very little additional torque is produced after the motor speed drops below 1200 to 1000 rpm. (This part of the trace is called the knee of the curve. The knee of

the curve is an important part of the analysis, because it generally represents the peak useable torque before the motor stalls. Beyond the knee, the motor will stall if there is virtually any increase in the load.) Although the two speed/torque curves shown in Figure 6 are similar in shape, they show a difference in available torque. The test data show about 30 ft-lb torque available in this rpm range (1000 to 1200), while the manufacturer's curve shows about 25 ft-lb. Another difference is at very low rpm (less than 200). The manufacturer's curve shows a significant increase in torque as the motor approaches stall, while the test data show a moderate increase followed by a rapid decrease. Both curves show about the same stall torque.

Figure 7 presents the torque curves from our baseline test of the 60 ft-lb ac motor. The figure also shows the manufacturer's torque curves for this motor. The two speed/torque curves are somewhat similar in shape, and the absolute torque values indicated are similar. However, the curve from our test data indicates a knee at about 1200 rpm and 58 ft-lb, while the knee of the manufacturer's curve is at about 1300 rpm and 52 ft-lb. The actual peak torque of about 64 ft-lb occurs at 500 to 1000 rpm. The manufacturer's curve shows a peak torque of about 64 ft-lb at stall. This motor's output torque is close to its 60 ft-lb rating.

Figure 8 presents the torque curves from our baseline test of the high-speed (3600 rpm) 40 ft-lb ac motor. The figure also shows the manufacturer's torque curves for this motor. In this instance the manufacturer's current curve shows data all the way to motor stall, so no extrapolation was necessary. The shapes of the curves from our tests are a little different for the high-speed motor, as compared with the curves for the other ac motors, especially at very low rpm. Unlike the other ac motors, the stall torque for the high speed motor is much lower than the torque just before stall. However, the motor continues to provide some additional torque as the motor speed drops from 2500 to 1000 rpm. In this rpm range, the output torque increases to a value well above the motor's 40 ft-lb rating, peaking at about 55 ft-lb.

Figure 5. Motor performance curves derived from testing of the 5 ft-lb ac motor; manufacturer's published data are also shown.

Figure 6. Motor performance curves derived from testing of the 25 ft-lb ac motor; manufacturer's published data are also shown.
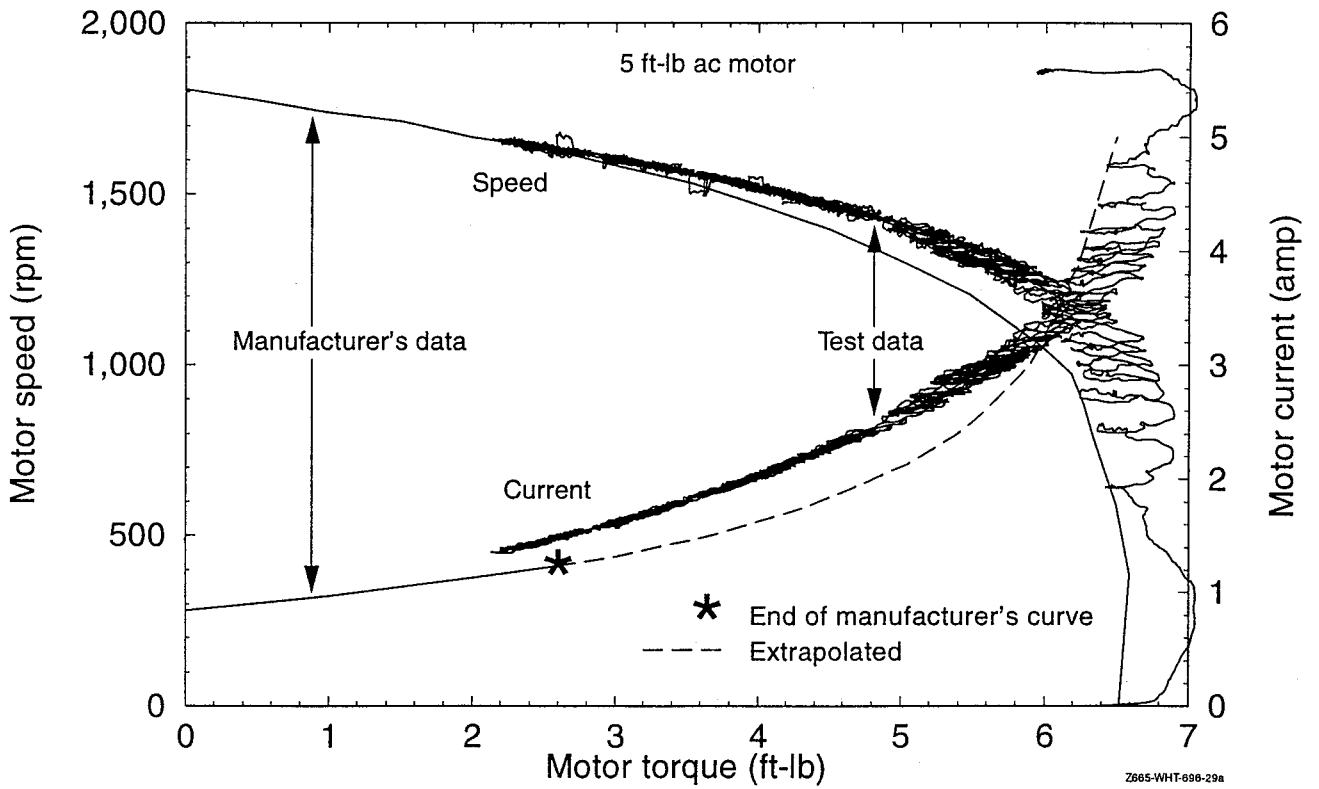
Figure 7. Motor performance curves derived from testing of the 60 ft-lb ac motor; manufacturer's published data are also shown.

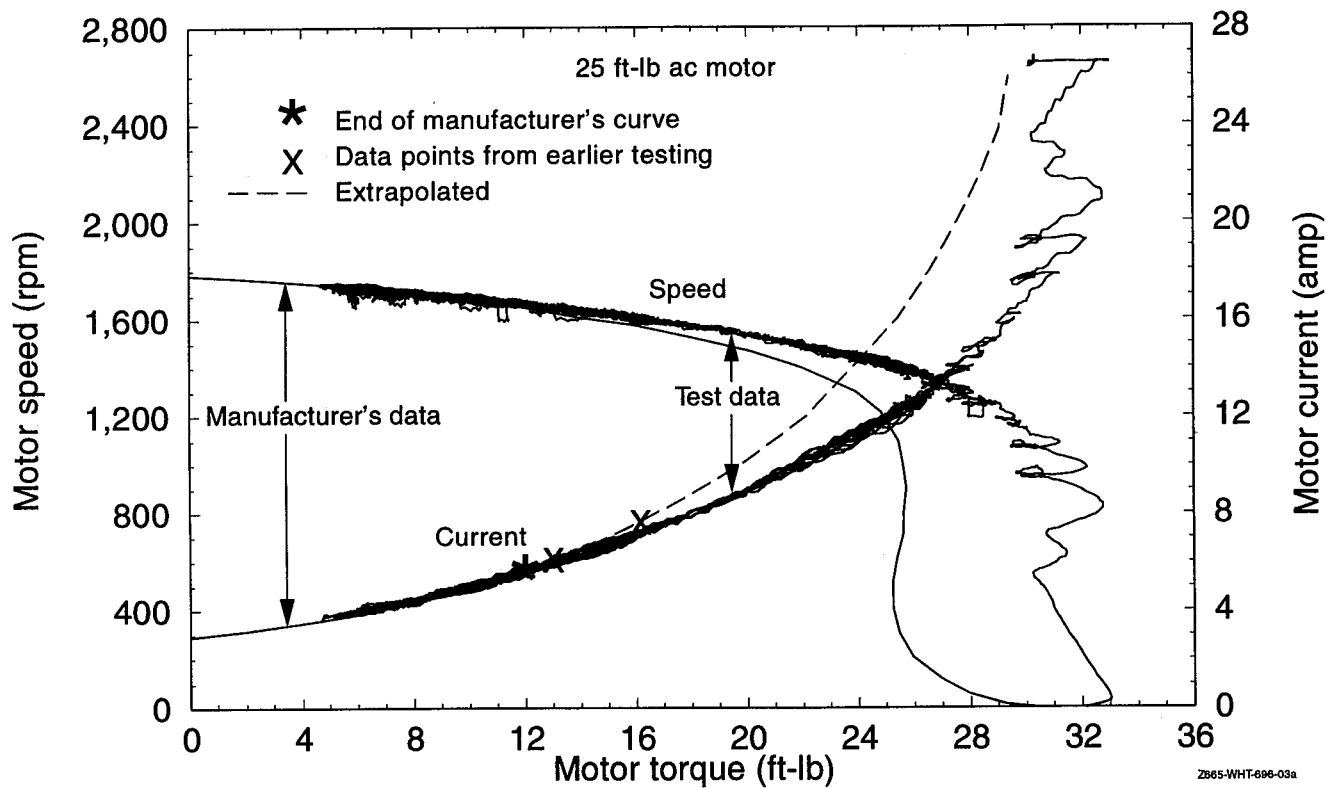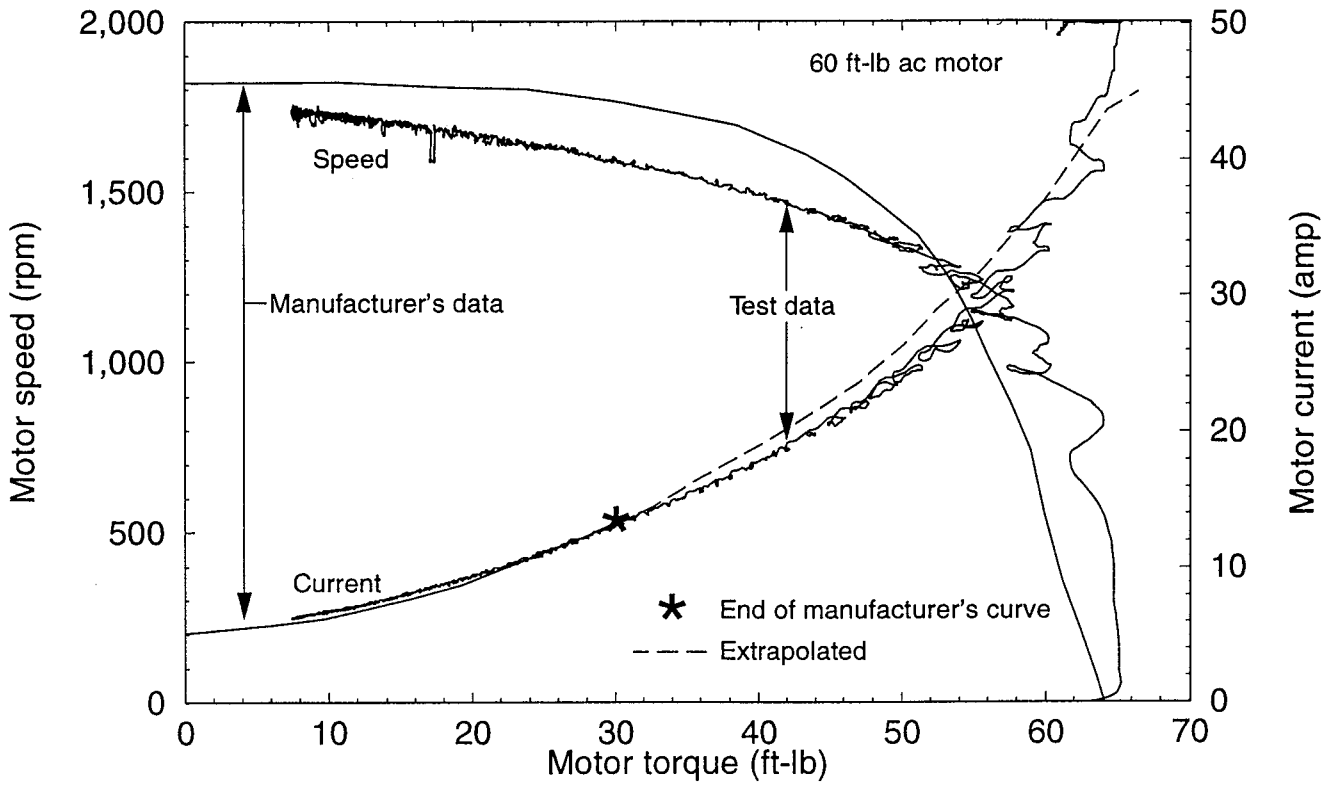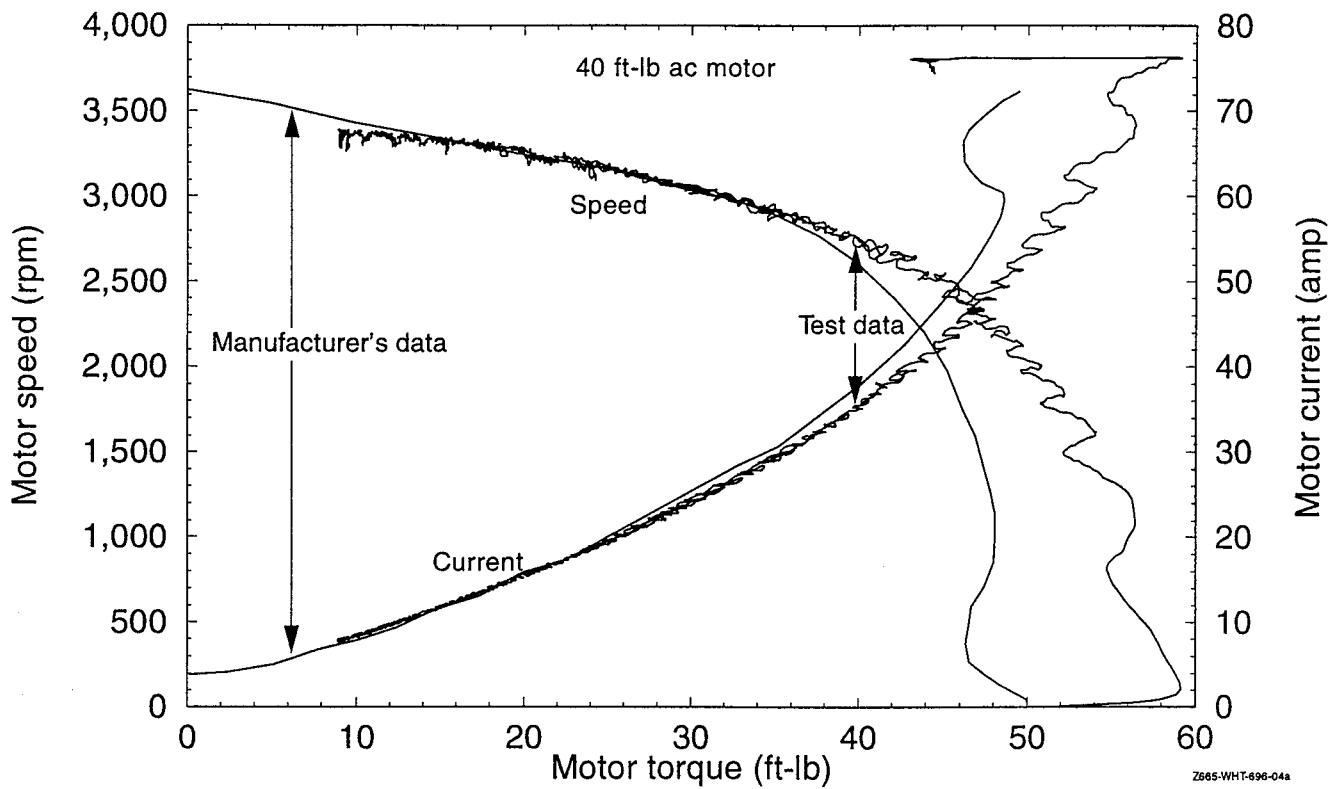**Figure 8.** Motor performance curves derived from testing of the high-speed 40 ft-lb ac motor; manufacturer's published data are also shown.

Conclusions

The test data show that the load threshold at which the motor will drop to a stall (the knee of the curve) does not always occur at the motor speed or at the load threshold indicated by the published data; however, the actual torque output at the knee of the curve (1200 to 1000 rpm for the three 1800 rpm motors, and 2400 to 2000 rpm for the high-speed 3600 rpm motor) is consistently higher than indicated by the manufacturer's curves.

There is some variation between the published rated torque and the torque we measured at high loadings and at stall. All four motors exceeded their rated starting torque, some by larger margins than others. Also, the torque at the knee of the curve was greater than or equal to the stall torque for all four of these ac motors.

Degraded Voltage Testing of the ac Motors

For some actuator motors, operation at reduced voltage is one of the design-basis conditions that must be considered in analytical evaluations of MOV capability. Our test program included tests to determine how much torque loss resulted from operation at reduced voltage.

For ac motors, the voltage squared calculation is used extensively to predict motor output at degraded voltage conditions. According to the voltage squared calculation, the theoretical relationship of torque to voltage at constant speed is:

$$T_{act} = T_{rat} \left(\frac{V_{act}}{V_{rat}}\right)^2$$

(2)

where

T_{act} = actual torque

T_{rat} = rated torque

V_{act} = actual voltage

V_{rat} = rated voltage.

Figure 9 shows motor speed/torque curves for the 5 ft-lb motor at degraded voltages down to 60% of the nominal 460 vac. The results of a voltage squared calculation to predict a single value of the running torque (near the knee of the curve, at 1000 rpm) and the stall torque at degraded voltage are also shown. These predicted values are calculated from the actual torque output at 100% voltage, not the rated starting torque. As shown in Figure 9, the voltage squared calculation overestimates the actual running torque (at 1000 rpm) at degraded voltage by 0.16 to 0.49 ft-lb, or about 3 to 10% of the motor's rated torque. With the 25 ft-lb motor (Figure 10), the voltage squared calculation overestimates the actual running torque (at 1000 rpm) by 0.21 to 0.74 ft-lb (about 1 to 3%), and with the 60 ft-lb motor (Figure 11), the calculation overestimates by 1.05 to 2.61 ft-lb (about 2 to 4%). With the high speed 40-ft-lb ac motor (Figure 12), the calculation overestimates by 1.32 to 3.00 ft-lb (about 3 to 7%) at 2000 rpm.

The actuator manufacturer's literature specifies that an application factor of 0.9 be used in the calculation to account for torque losses due to voltage degradation down to 90% of the nominal voltage. For voltages at 90% and lower, the manufacturer allows the application factor to be 1.0 and specifies that the voltage squared calculation be used. Figure 11 shows that at 1000 rpm (near the knee of the curve), the 60 ft-lb motor delivers its rated torque of 60 ft-lb. If the application factor of 0.9 is used, the available output torque at 90% voltage would be predicted to be 54 ft-lb. The voltage squared calculation (with an application factor of 1.0) would predict a value of 48.6 ft-lb at 90% voltage. The actual measured torque at 90% voltage at 1000 rpm was 47 ft-lb. At 80% voltage, the voltage squared calculation (with an application factor of 1.0) predicts an available motor torque of 38.4 ft-lb; the measured torque was 35.4 ft-lb.

Our evaluation included a look at the effects of degraded voltage combined with the effects of operation at elevated temperature (a subject discussed later in this report). Figure 13 shows speed/torque curves for 100% and 80% voltage
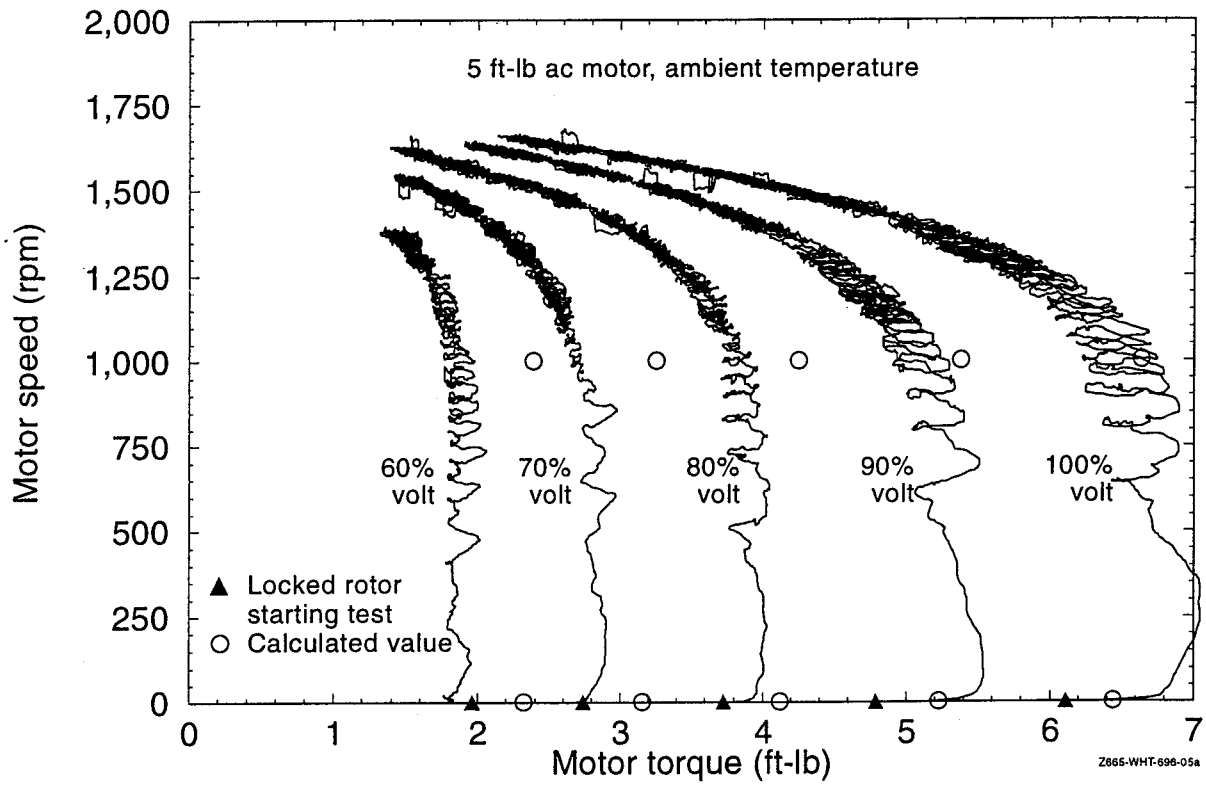
Figure 9. Motor speed versus torque, derived from testing of the 5 ft-lb motor at degraded voltage.
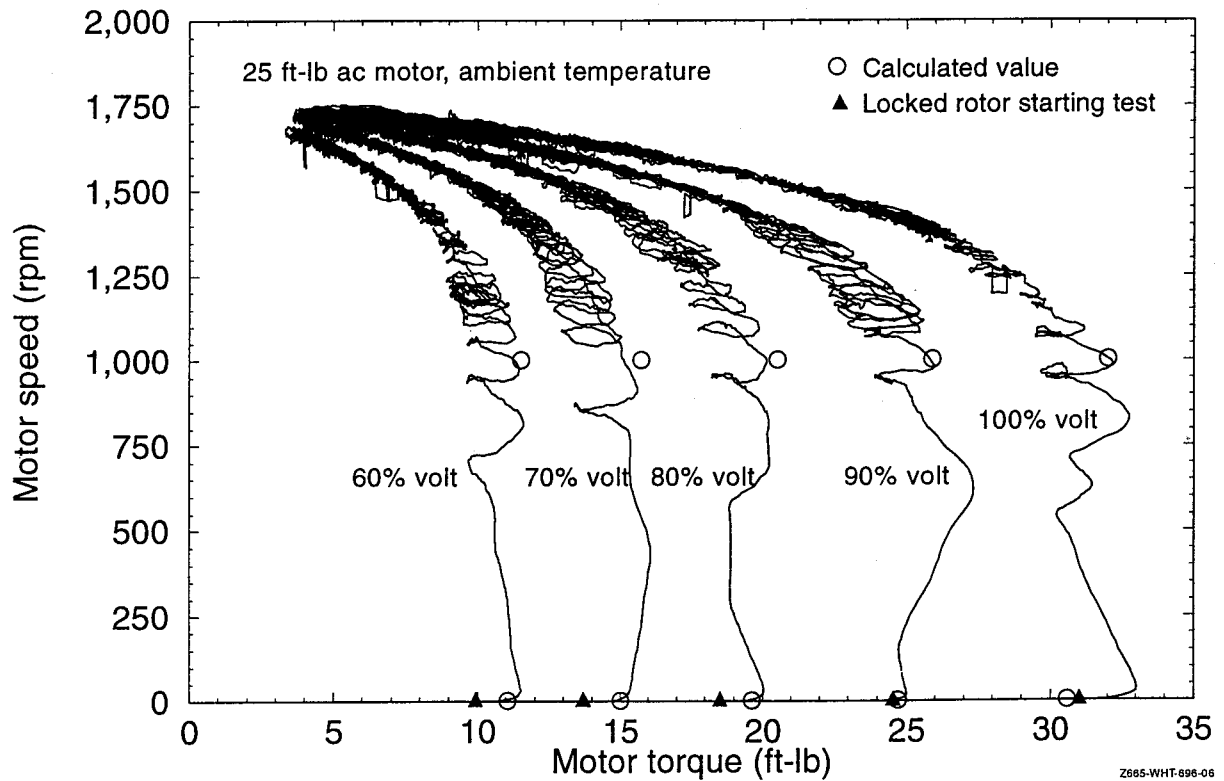
Figure 10. Motor speed versus torque, derived from testing of the 25 ft-lb motor at degraded voltage.
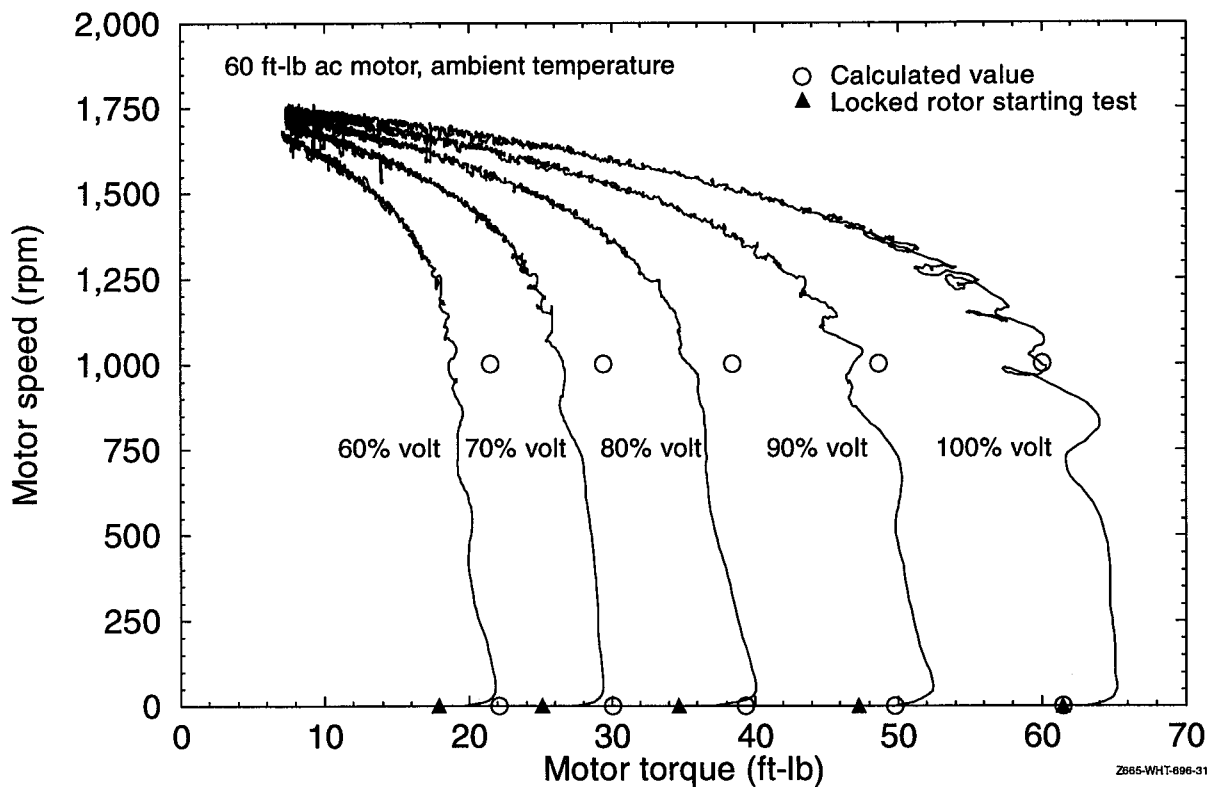
Figure 11. Motor speed versus torque, derived from testing of the 60 ft-lb motor at degraded voltage.
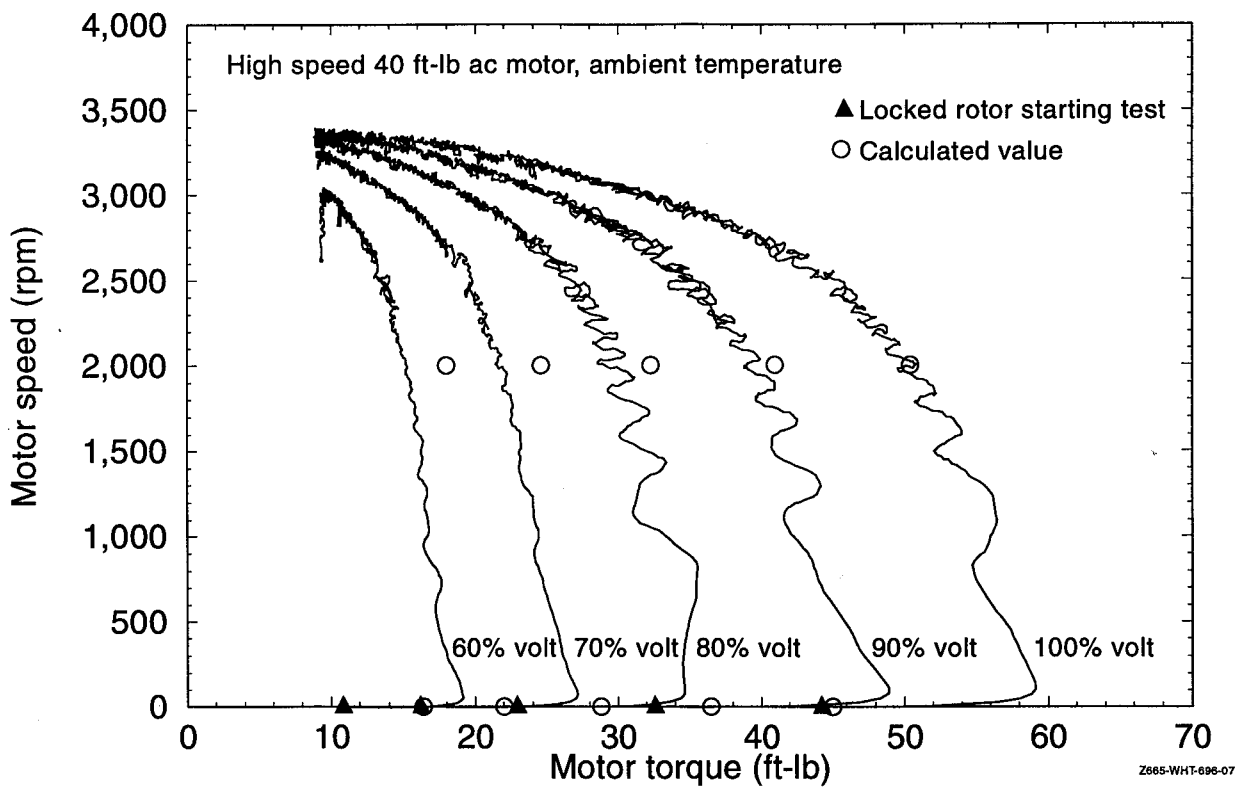
Figure 12. Motor speed versus torque, derived from testing of the high-speed 40 ft-lb ac motor at degraded voltage.
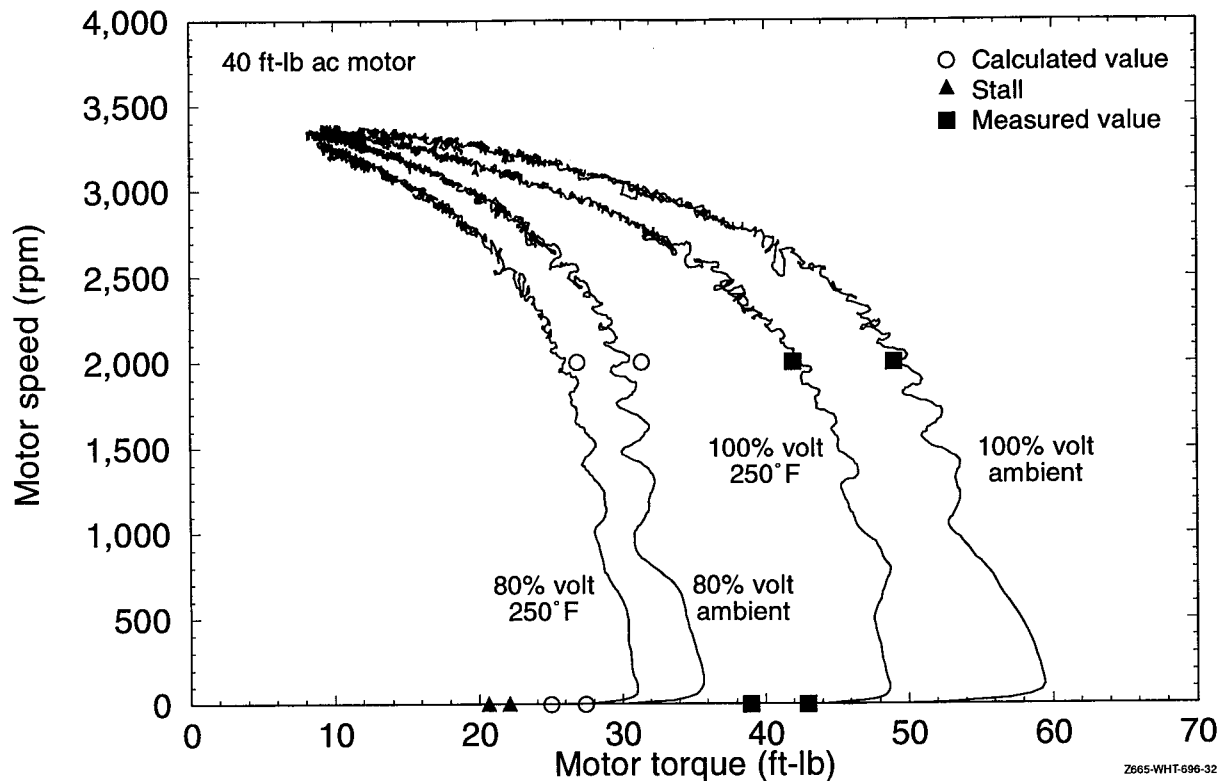
Figure 13. Motor current versus torque, derived from testing of the 40 ft-lb ac motor at degraded voltage at room temperature and at 250°F.

and for room temperature (80°F) and elevated (250°F) temperature for the 40 ft-lb motor. Predictions produced by the voltage squared calculation are also shown, with the predictions based on the actual torque at 100% voltage for the two temperatures. The figure shows that the voltage squared calculation overestimates the available torque not only at room temperature, but also at elevated temperature. The results with the other ac motors are similar.

To further evaluate the voltage squared calculation, we rearranged the formula shown in Equation (2) and used the data from the tests results as input so we could solve for the exponent n. The purpose of this effort was to determine whether an exponent other than 2 might be consistent with the test results. We began by modifying the names of the terms slightly, as follows:

$$T_{reduced} = T_{100\%} \left(\frac{V_{reduced}}{V_{100\%}} \right)^n \qquad (3)$$

where

$T_{reduced}$	=	torque measured at reduced voltage
$T_{100\%}$	=	torque measured at 100% voltage
$V_{reduced}$	=	the reduced voltage for the test
$V_{100\%}$	=	the full voltage for the test
n	=	the unknown exponent

Rearranging and solving for the exponent n yields

$$n = \frac{\ln \left(\frac{T_{reduced}}{T_{100\%}} \right)}{\ln \left(\frac{V_{reduced}}{V_{100\%}} \right)} \qquad (4)$$

Using results from full voltage and reduced voltage tests of the four ac valves as input to Equation (4), we solved for the exponent n and plotted the results in Figure 14. The results shown
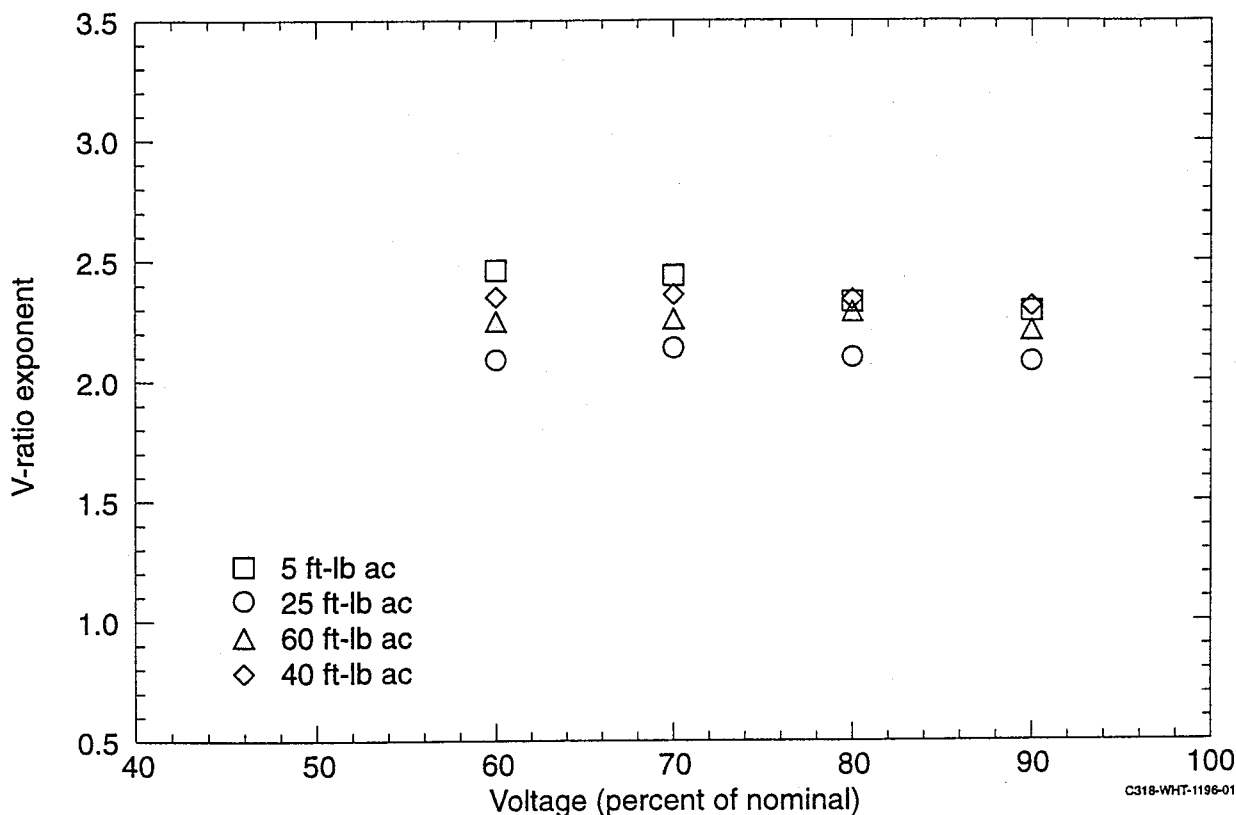
Figure 14. Results of testing of the four ac motors at reduced voltage, with the data plotted as the solution for the exponent n in the voltage squared formula.

here are based on motor torque at the knee of the curve, namely, 1,000 rpm for the 1,800-rpm motors, and 2,000 rpm for the 3,600-rpm motor. This analysis does not consider an application factor (in other words, the application factor is assumed to be 1.0). The results suggest that for these four motors, an exponent of 2.5 instead of 2 in the voltage squared calculation would produce predictions of torque loss that are consistently equal to or higher than the actual torque losses. (Note, again, that these analyses use the actual motor torque at 100% voltage, not the motor's rated torque, as the basis for the calculation.)

Conclusions

These results show that the voltage squared calculation consistently underestimates motor torque losses at degraded voltage conditions. These results are based on using the motor's actual output torque at 100% voltage as the basis for the calculation. Using the rated starting motor torque (instead of the actual motor torque at 100% voltage) in the voltage squared calculation

for the 5, 25, and 40 ft-lb motors we tested provides predictions of motor torque that are lower than the measured values, but only because the rated starting torque provides a lower basis for the calculation than the actual torque. For the 60 ft-lb motor, the actual torque is very close to the rated torque. Here, the voltage squared calculation underpredicts the torque losses at reduced voltage conditions regardless of whether the rated starting torque or the actual torque (at 100% voltage) is used as the basis of the calculation. Our analysis of the results indicates that the use of a different exponent (2.5 instead of 2) in the voltage squared calculation would produce more useful predictions.

Locked Rotor Testing of the ac Motors

The small delta symbols at the bottom of the plot in Figure 9 are the locked rotor startup torques. These individual data points are produced by energizing the motor with an artificial load imposed on the motor that prevents the rotor

from turning. Note in Figure 9 that the speed curves end (at motor stall) very near the locked rotor startup torques, indicating that the motor torque at stall and the startup motor torque with a locked rotor for this motor are about the same. The same is true of Figures 10, 11, and 12 for the other three ac motors.

Figure 15 shows torque versus time for two tests: a locked rotor startup test (on the left) and an ordinary dynamometer-type test running at increasing load to stall. These results are from the 5 ft-lb ac motor tested at 100% voltage at room temperature. Notice that the stall torque produced by the locked rotor startup test is very similar to the stall torque produced by the ordinary dynamometer-type test.

Conclusions

For all four of the ac motors we tested, the locked rotor startup torques were always lower than the peak running torque. In addition, the locked rotor startup torques matched very well

with the stall torques from dynamometer-type tests. We found the locked rotor startup torque to be a useful indication of where a specific motor is with respect to its rating.

For the high-speed (3400 rpm) 40 ft-lb motor (Figure 12), the results show a greater loss of torque immediately before motor stall than do the three 1800-rpm ac motors we tested. The effect is that the stall torque (as well as the locked rotor startup torque) for the high speed motor is far below the running torque in the rpm range of interest (2000 to 2800 rpm). Still, the stall torque is higher than the rated torque. We do not know whether this behavior is typical of high-speed motors in general.

Elevated Temperature Testing of the ac Motors

For some actuator motors, operation at elevated temperature is one of the design-basis conditions that must be considered in analytical evaluations of MOV capability. The output of the
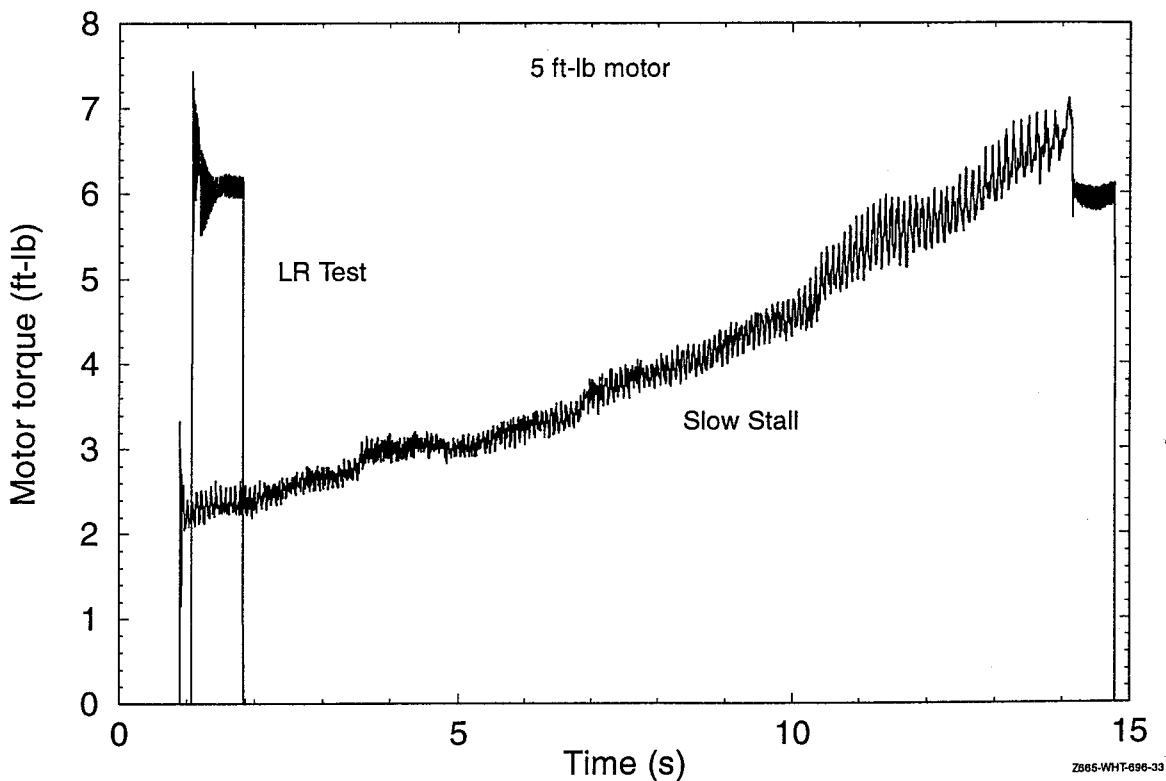
Figure 15. Torque histories from a locked rotor test and a dynamometer-type test of the 5 ft-lb motor.

electric motor tends to degrade at higher temperature, mostly because of increased resistance in the motor windings. This is the case regardless of whether the increase in the motor temperature is caused by ambient conditions or by motor operation. Some motors are expected to operate at high ambient temperatures. Also, some motors might experience high internal temperatures if they are operated continuously or very frequently at high loads.

Figure 16 shows the performance of the 5 ft-lb ac motor during the elevated temperature testing at 100% voltage and at 80% voltage. (In this figure and the next, we smoothed the data using the mean of the oscillations to make it easier to distinguish the individual traces.) The 5 ft-lb motor is an environmentally qualified motor, so we heated it to a typical design basis temperature of 300°F. The motor was tested at both voltage conditions at room temperature, at 100°F, and at increments of 50°F up to 300°F.

Compare the curve on the far right (80°F, 100% voltage) with the curve on the far left (300°F,

80% voltage). Taken together, the reduction caused by both the reduced voltage conditions and the elevated temperature conditions amounts to about half of the motor's capability, compared with normal voltage and room temperature conditions.

The results for the other three motors are similar to the results shown in Figure 16. These three motors are not qualified for service in a harsh environment, so they were heated only to 250°F.

Figure 17, presented here as an example, shows the current/torque traces for the 60-ft-lb ac motor tested at elevated temperature. We used these current/torque data (and similar data for the other three ac motors) to evaluate the actual degraded performance of the motor, in terms of torque loss and current loss, for comparison with the actuator manufacturer's data (Reference 8). The manufacturer's data on torque and current loss for motor operation at elevated ambient temperatures for motors that correspond (in rated output) with the four ac motors we tested are shown in Table 2.
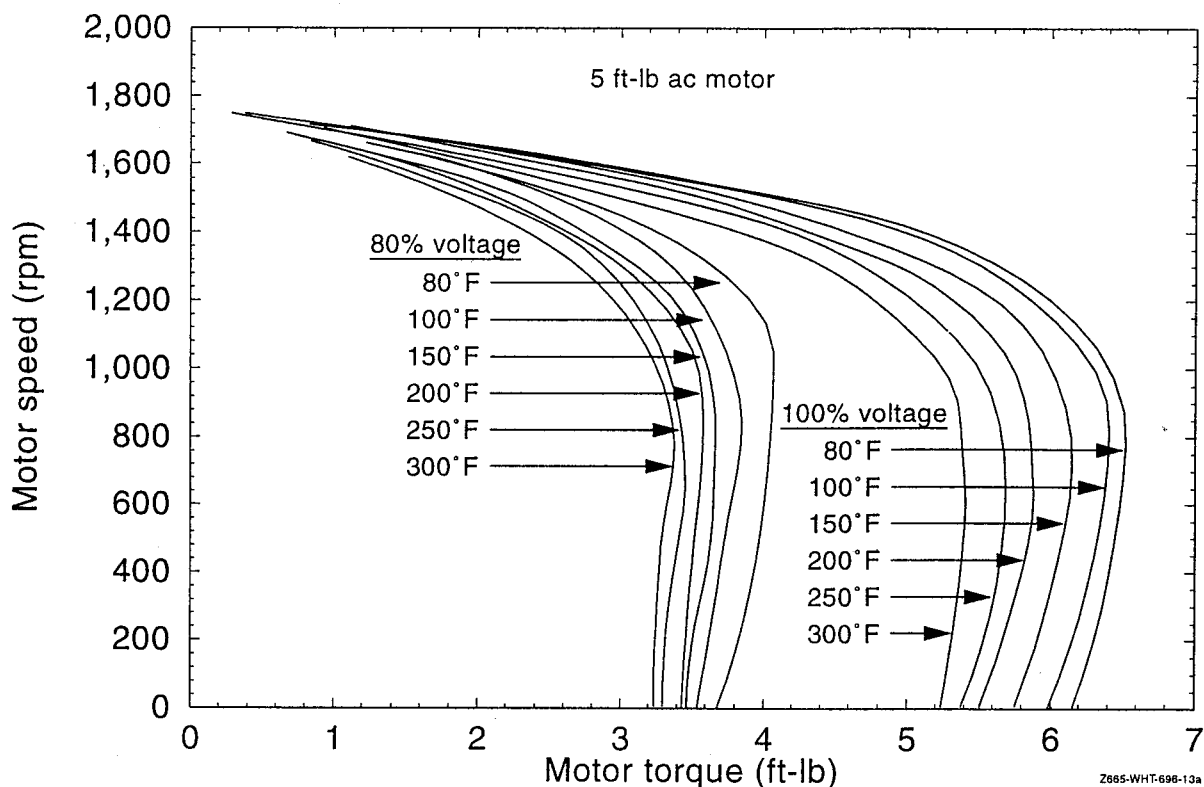
Figure 16. Motor speed versus torque, derived from elevated temperature testing of the 5 ft-lb motor at 100% voltage and at 80% voltage.

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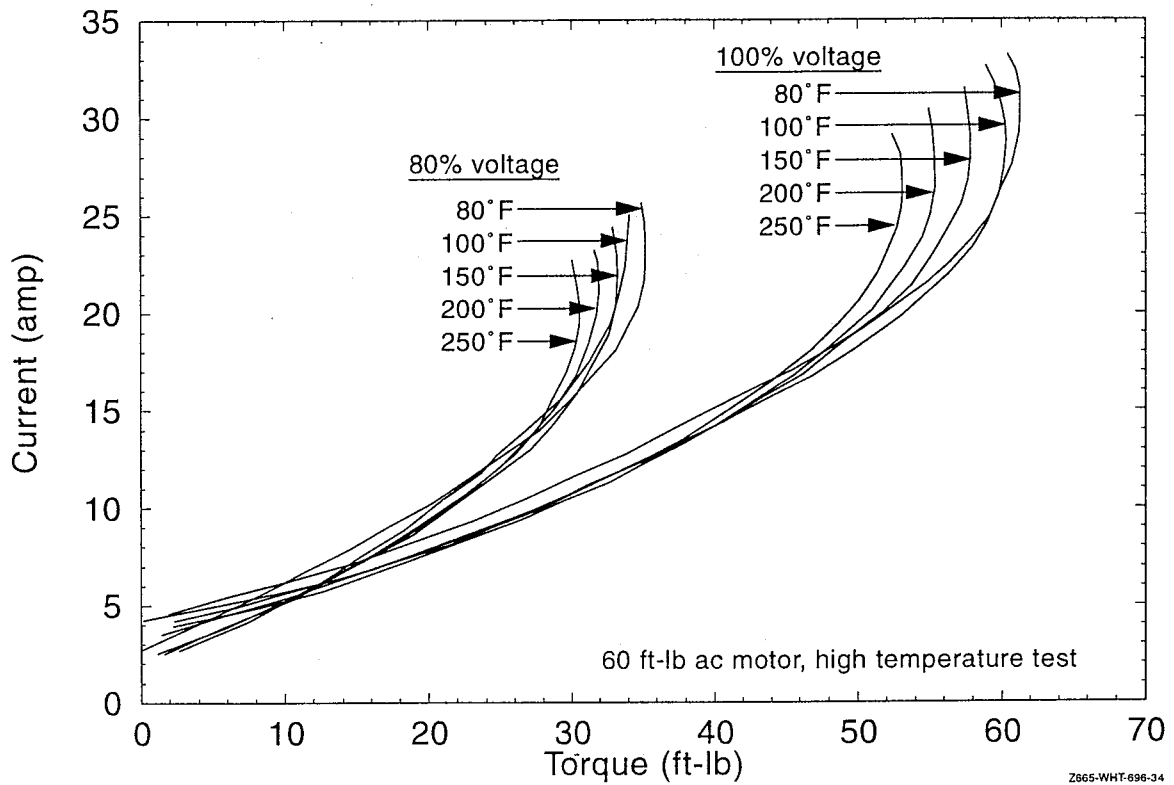
Figure 17. Motor current versus torque, derived from elevated temperature testing of the 60 ft-lb motor at 100% voltage and at 80% voltage.

Table 2. Manufacturer's predictions of loss in ac motor performance with increased temperature.

Motor temperature	Current loss (%)				Torque loss (%)			
	5 ft-lb motor	25 ft-lb motor	60 ft-lb motor	40 ft-lb motor	5 ft-lb motor	25 ft-lb motor	60 ft-lb motor	40 ft-lb motor
77°F (25°C)	0	0	0	0	0	0	0	0
100°F (38°C)	1.80	1.90	1.71	1.34	1.81	1.91	1.72	0.97
150°F (66°C)	5.70	6.04	5.44	4.24	5.73	6.07	5.47	3.09
200°F (93°C)	9.61	10.18	9.17	7.14	9.65	10.23	9.21	5.20
250°F (121°C)	13.52	14.32	12.90	10.05	13.58	14.39	12.96	7.32
300°F (149°C)	17.42	18.46	16.63	12.95	17.50	18.54	16.71	9.43
356°F (180°C)	21.80	23.10	20.80	16.20	21.90	23.20	20.90	11.80

Figures 18, 19, 20, and 21 show the actual motor torque measured at elevated temperature for 100% voltage and for 80% voltage for the four ac motors we tested. The figures also show the predictions, based on the manufacturer's data, for these motors. For three of the motors (Figures 18, 20, and 21), the actual torque values measured in the tests follow the predictions fairly well. For the 25 ft-lb motor (Figure 19), the predicted torque is higher than the actual available torque, by 3 to 8%. Thus, for this motor, the predictions of torque loss underestimate the actual losses.

Figure 22 shows the actual motor currents measured in the elevated temperature testing of the 5 ft-lb motor. The predictions are also shown. The results from the other motors are similar to the results shown here. For the 60 ft-lb motor (Figure 23), the actual currents follow the predicted values quite closely. For the other three ac motors, the predictions overestimate the current drawn at elevated temperature, as illustrated in Figure 22 for the 5 ft-lb motor.

Conclusions

The predictions of torque loss due to elevated temperature were about equal to or greater than the actual losses for three of the four ac motors we tested. However, the results shown in Figure 19 for the 25 ft-lb motor indicate that the predictions might not be appropriate for this motor. Note, however, that this motor is not qualified for nuclear service, a fact that might affect its output at elevated temperature.

Testing of the dc Motor

The performance of a dc motor is somewhat different than that of an ac motor. An ac motor tends to stall quickly when the load reaches a certain threshold. This is because above that threshold, very little additional torque is available to handle an increase in the load. In contrast, a dc motor responds to a load increase by continuing to produce additional torque, albeit at lower rpm, until the motor finally stalls at a peak torque

value. Figure 24 compares a typical speed/torque curve for an ac motor (this one from our 40 ft-lb high-speed ac motor) with the speed/torque curve from the 40 ft-lb dc motor we tested. Both of these curves are from 100% voltage tests at room temperature (80°F).

There are also differences in the responses to degraded voltage conditions and elevated temperature conditions, and differences in the ways these conditions are dealt with analytically.

Earlier Studies

The 40 ft-lb dc motor used in this test program was the same one that had been used in earlier testing to evaluate the effects of seismic loadings on valve operation and on piping system and piping support system integrity. We procured the valve in the mid-1980s from the decommissioned Shippingport nuclear power station and subjected it to the seismic tests. The results of those tests are reported in Reference 5. A brief summary of pertinent results is presented here.

During the seismic tests, the dc-powered valve was closed against a high static pressure load and a moderate pump flow load while the building was subjected to a simulated design-basis earthquake. During some of those tests, the torque switch in the actuator failed to trip, and the motor stalled. An extensive investigation was conducted to identify the cause of the problem. That investigation produced two findings that relate specifically to dc-powered valves and that pertain to this research:

- Resistance caused by heating in the dc motor degraded the motor's torque output, especially at higher loads. During dynamometer testing, torque output degraded about 10 ft-lb during 20 seconds of continuous operation at a high load (40 to 50 ft-lb) with the motor lugging at about 200 rpm. Heating incurred during a given valve closure affected the motor's output in subsequent closures if the motor did not have a chance to cool between runs.

Z665-WHT-696-18a

Figure 18. Motor torque versus elevated temperature at 100% voltage and 80% voltage for the 5 ft-lb ac motor; predictions are also shown.

Z665-WHT-696-20a

Figure 19. Motor torque versus elevated temperature at 100% voltage and 80% voltage for the 25 ft-lb ac motor; predictions are also shown.

Z192-WHT-394-21a

Figure 20. Motor torque versus elevated temperature at 100% voltage and 80% voltage for the 60 ft-lb ac motor; predictions are also shown.

Z665-WHT-696-22a

Figure 21. Motor torque versus elevated temperature at 100% voltage and 80% voltage for the 40 ft-lb ac motor; predictions are also shown.

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Z665-WHT-696-19a

Figure 22. Motor current versus elevated temperature at 100% voltage and 80% voltae for the 5 ft-lb ac motor; predictions are also shown.

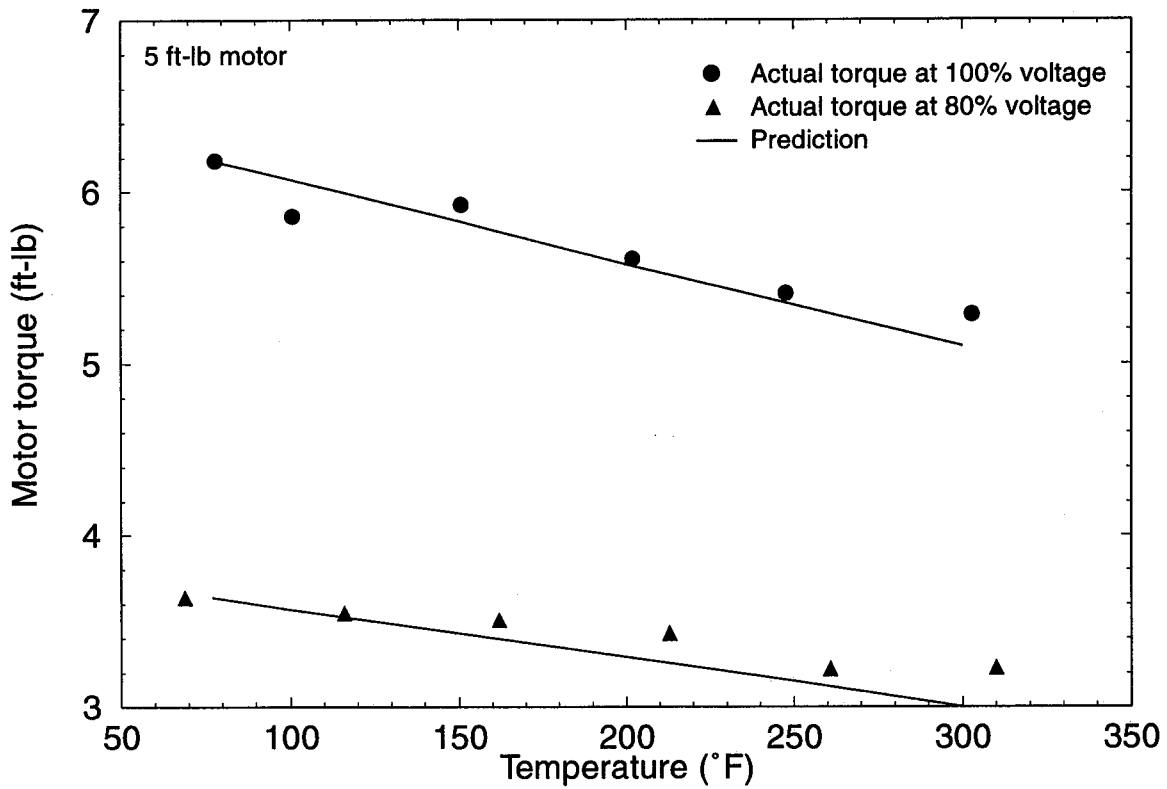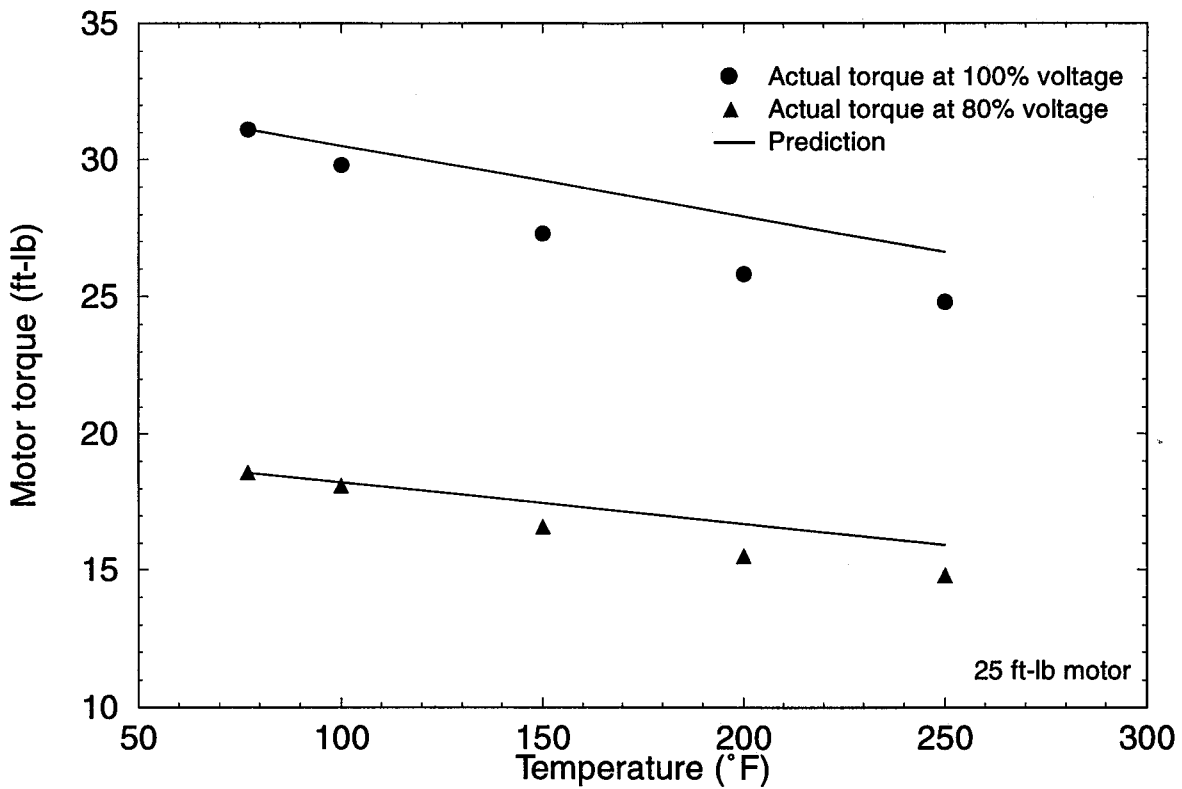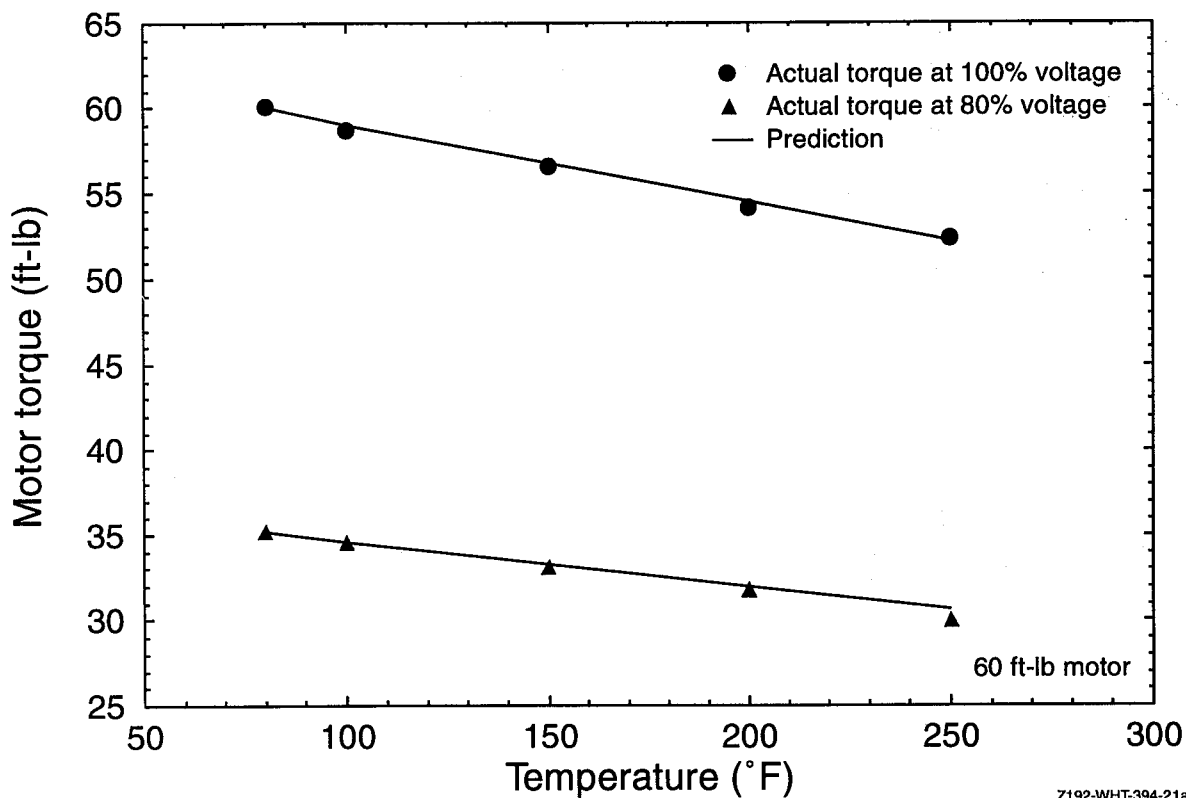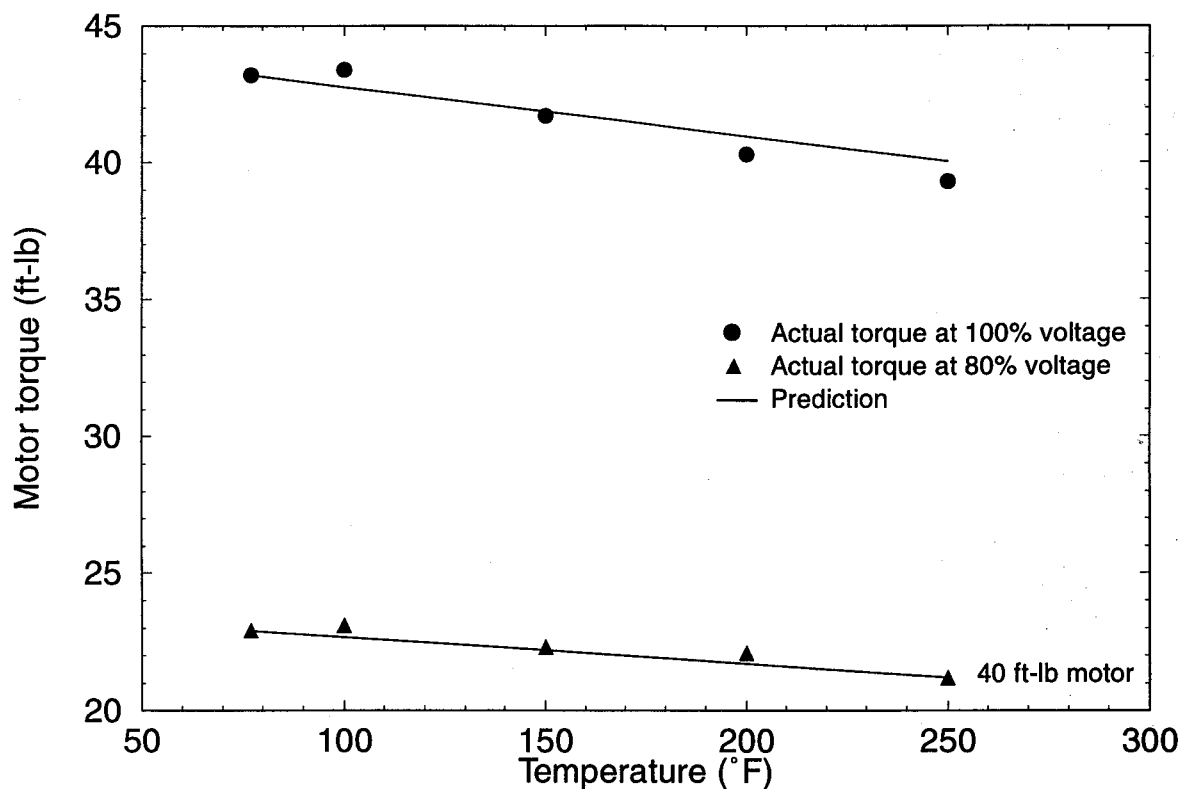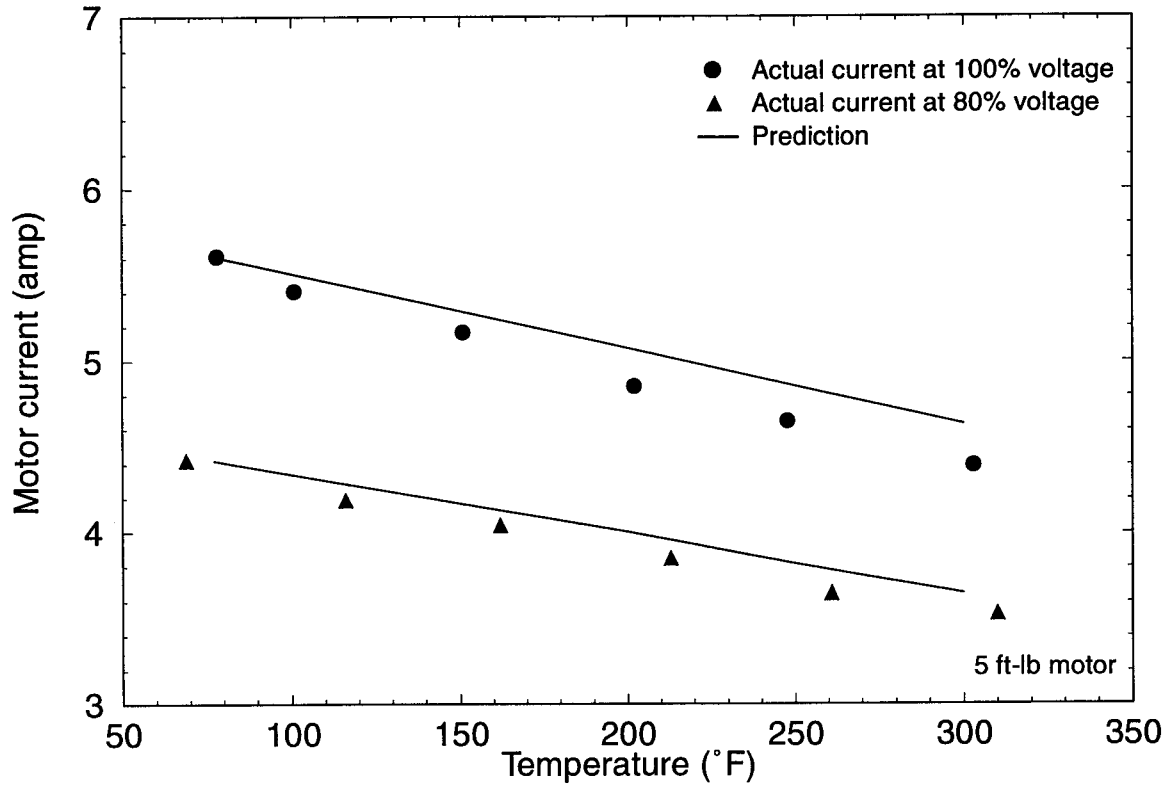Z192-WHT-394-22a

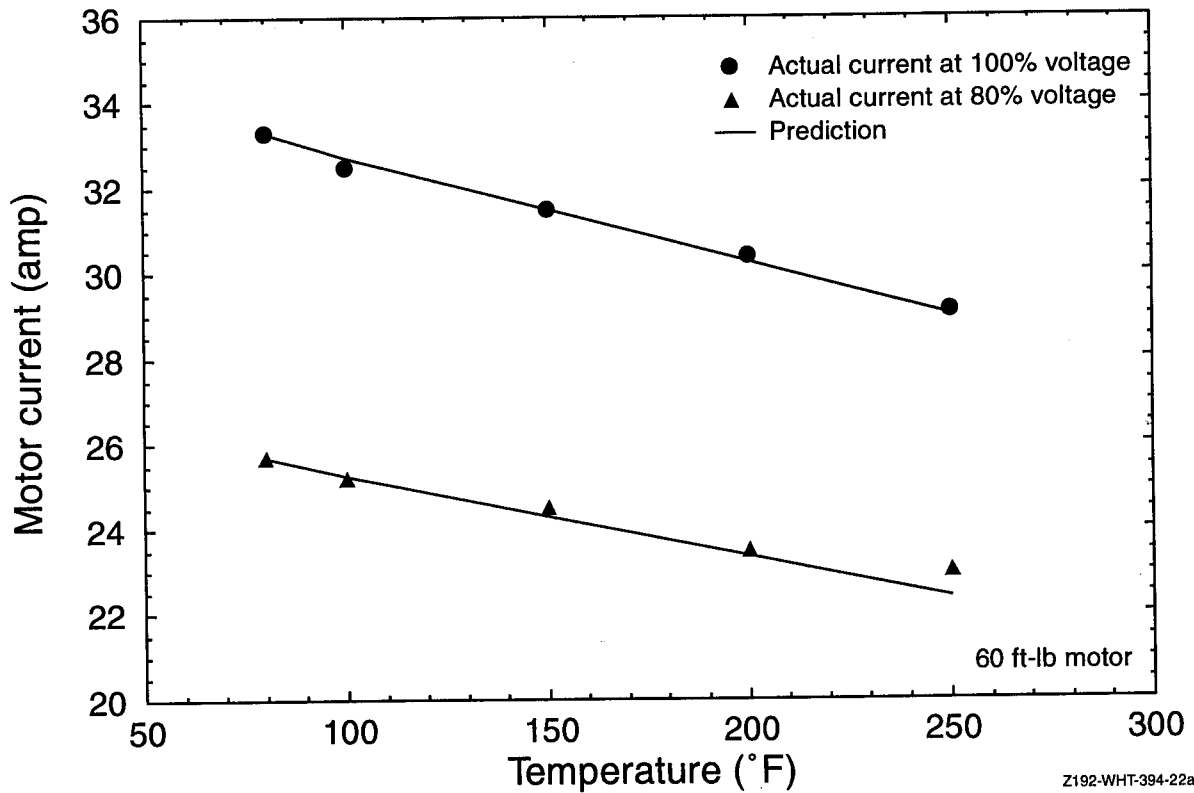**Figure 23.** Motor current versus elevated temperature at 100% voltage and 80% voltage for the 60 ft-lb ac motor; predictions are also shown.
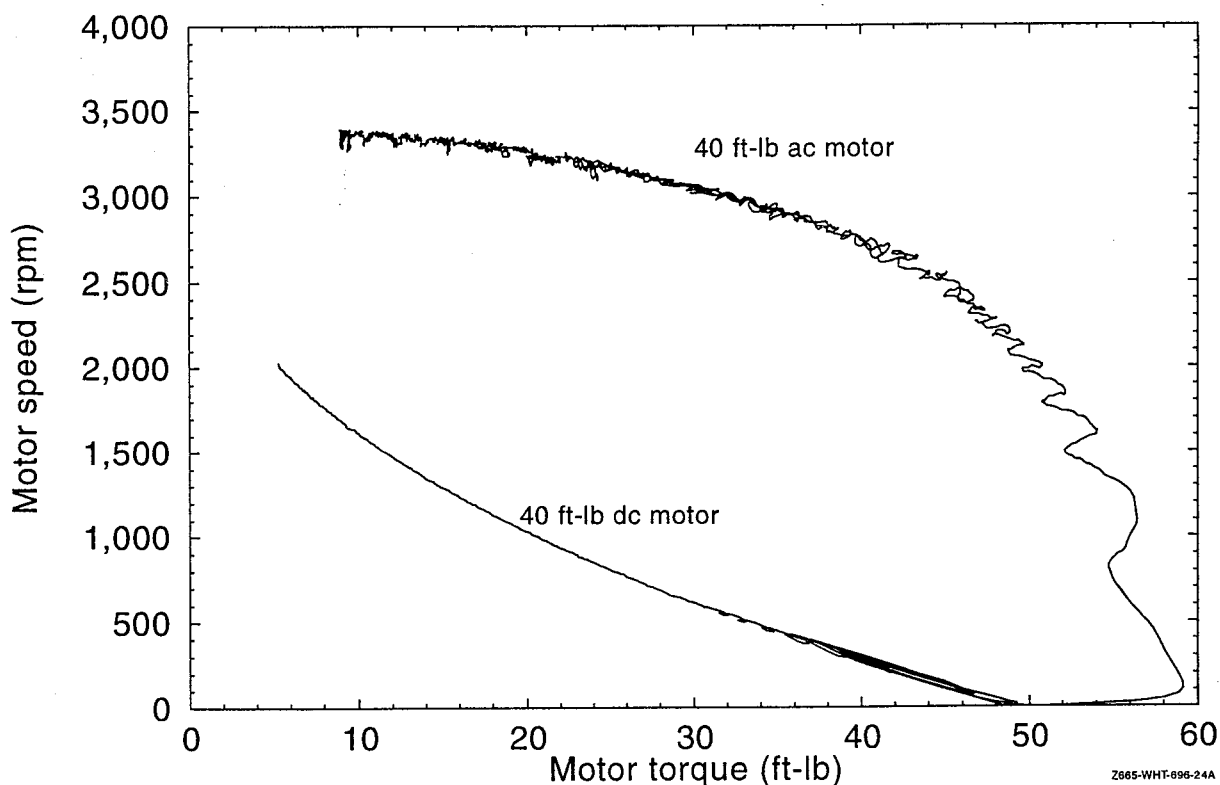
Figure 24. Performance curves (speed versus torque) from testing of the 40 ft-lb ac motor and the 40 ft-lb dc motor, for comparison.

• Resistance in the circuit supplying power to the actuator motor degraded the motor's output at high loads. The configuration of the motor circuit was conventional, but it was such that four long cable runs contributed to the resistance, not just two, as had been assumed in the analysis that served as the basis for the selection of cable size. The circuit configuration also made it very difficult to measure the voltage drop across all four cable runs.

These two factors (motor heating and undersized cables) combined to cause the motor to produce too little torque to trip the torque switch in some of the seismic tests.

During subsequent investigations of the anomalous performance of the actuator motor, we had the dc motor overhauled, including new windings, and restored to its original condition. This same dc motor, with the new windings, was used in the tests that are reported in the following discussion.

Performance Curves for the dc Motor

As with the ac motors, we developed motor performance curves for the dc motor (motor speed versus motor torque, and motor current versus torque). Figure 25 presents the speed/torque and current/torque curves derived from testing of this 40 ft-lb dc motor. The figure also shows the motor data supplied by the actuator manufacturer. The test results show that the actual torque output is lower than predicted by the manufacturer's curve.

Degraded Voltage Testing of the dc Motor

Operation at degraded voltage is a design-basis condition for some dc-powered motor-operated valves. We conducted tests operating our 125-volt dc motor at 50, 60, 70, 80, 90, and 100% of the rated voltage to determine the actual torque produced at these voltages.

Figure 25. Motor performance curves derived from testing of the 40 ft-lb dc motor; manufacturer's published data are also shown.

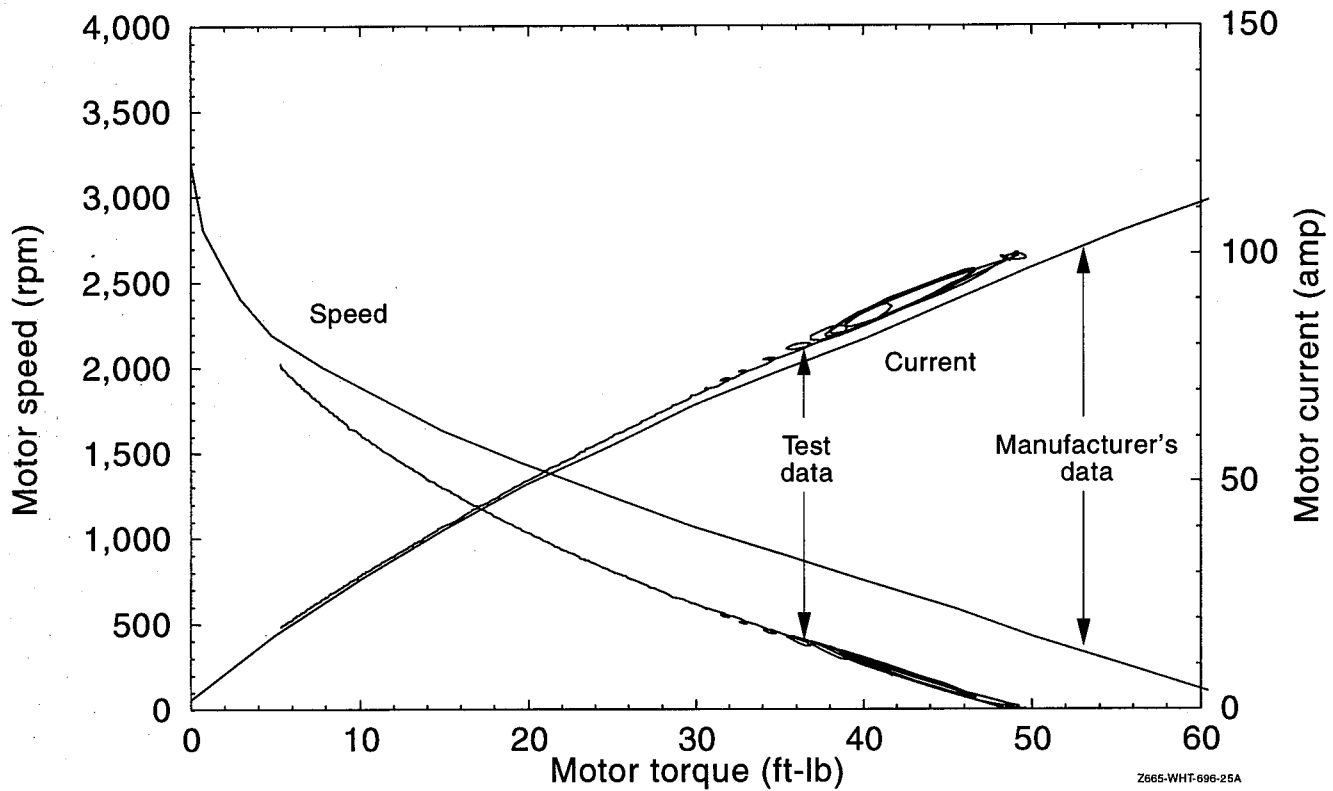Analytical evaluations of MOV capability typically use the following formula to account for reduced dc motor output at degraded voltage conditions:

$$T_{act} = T_{rat} \left(\frac{V_{act}}{V_{rat}}\right)^1 \tag{5}$$

The formula is identical to the voltage squared calculation used for ac motors, except that the exponent is 1 instead of 2. As part of our data analysis, we compared the results of the degraded voltage tests to estimates calculated using Equation (5).

Figure 26 shows the speed versus torque curves for the degraded voltage tests. Values representing estimates based on the method described above are also shown, identified by x. The estimates are based on the results of the 100% voltage test at 1000 rpm, 500 rpm, and stall. The estimate for 80% voltage (80% of the nominal voltage of 125 vdc) overestimates the actual torque by about 4 ft-lb (10% of the motor's rated torque), and the estimate for 50% voltage overestimates the actual torque by about 7 ft-lb (18%).

To further evaluate the method for predicting dc motor output at reduced voltage conditions, we used the formula shown in Equation (4) and used the data from the tests results as input so we could solve for the exponent. Similar to our effort to evaluate the voltage squared calculation for the ac motors, the purpose of this effort was to determine whether an exponent other than 1 might be consistent with the test results for this dc motor. The results of this effort are shown in Figure 27. For locked rotor (stall) conditions, the results suggest use of an exponent of about 1.3 in the formula to estimate the actual torque losses of this motor at reduced voltage; for a motor speed of 500 rpm, the results suggest use of an exponent of 1.9 to estimate the actual torque losses.

Conclusions. These results show that the conventional linear method for predicting torque loss due to operation of dc motors at reduced voltage
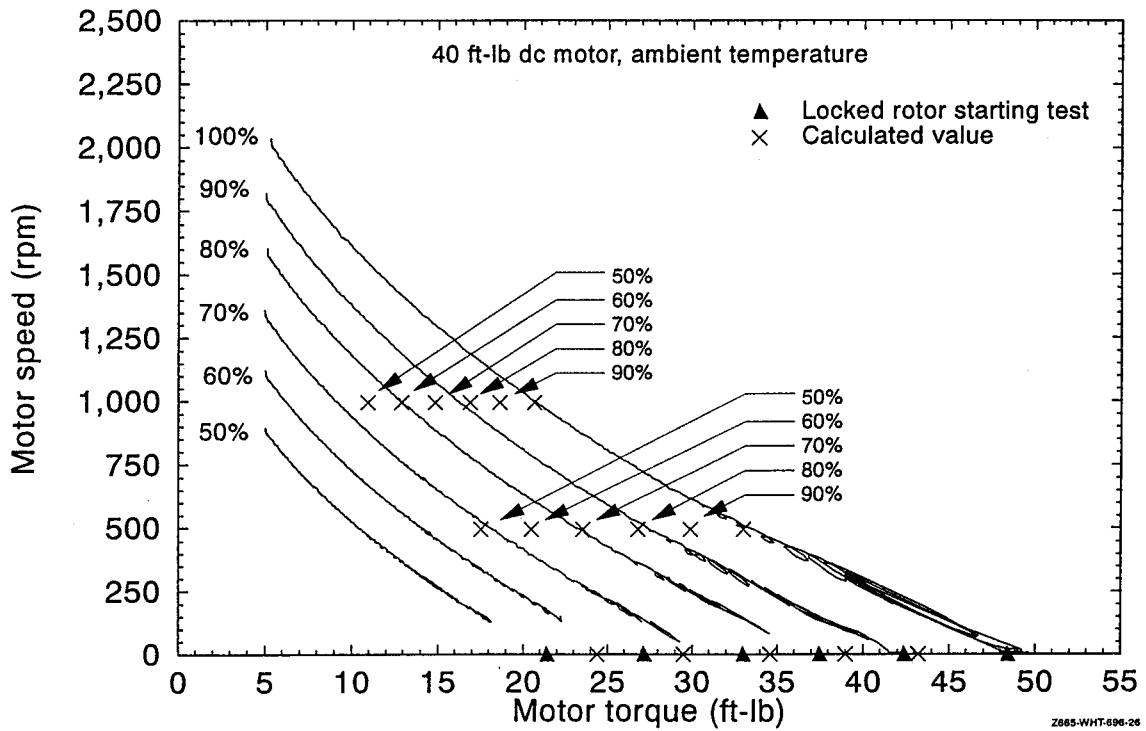
Figure 26. Motor speed versus torque, derived from testing of the 40 ft-lb dc motor at degraded voltage at room temperature.
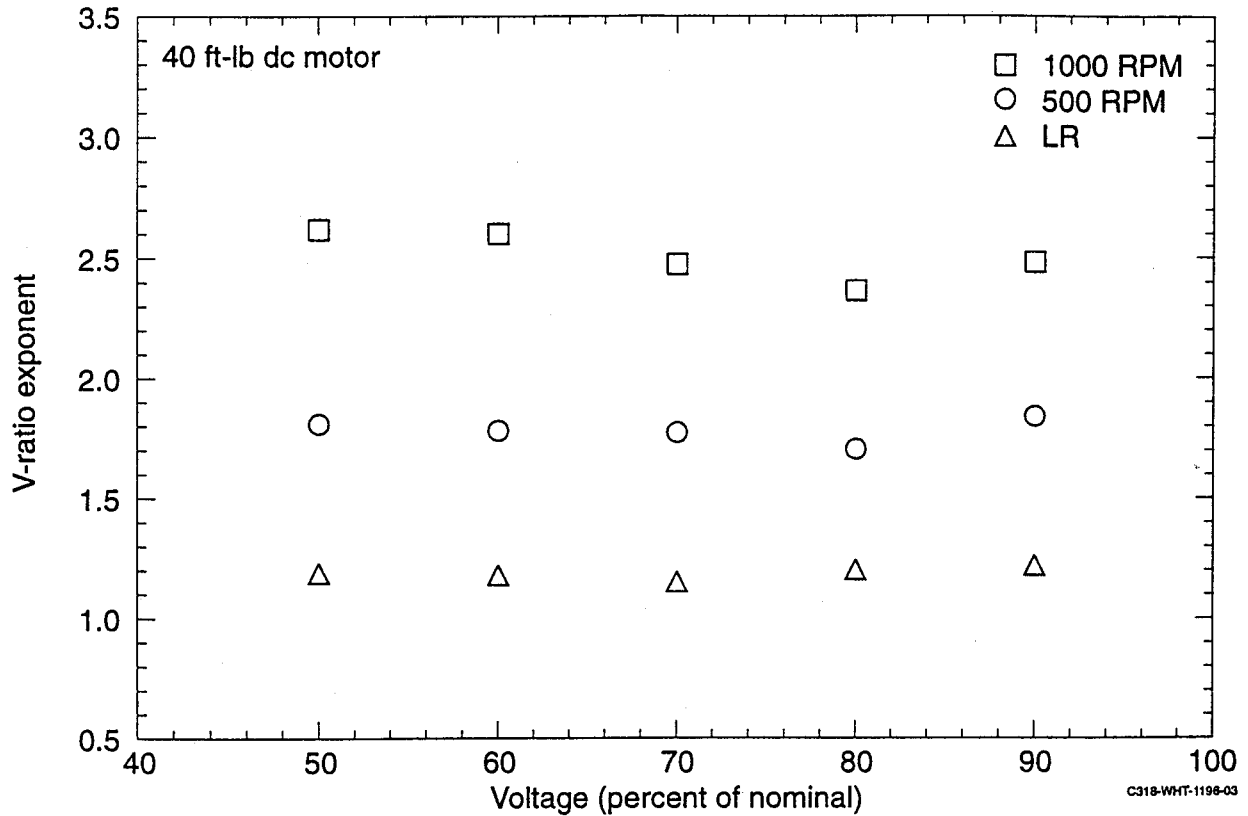

Figure 27. Results from testing of the 40 ft-lb dc motor, with the data plotted as the solution to the exponent *n* in Equation (4).

underestimates the actual torque losses. Our analysis of the results shows that a formula similar to the voltage squared calculation, with an exponent of at least 1.3, would produce more useful predictions.

Locked Rotor Testing of the dc Motor

Figure 26 also shows the locked rotor startup torques for the dc motor. The locked rotor results show fair agreement with the stall torques indicated at the ends of (or extrapolated from the ends of) the traces representing the running tests. (Note that some of the traces for the running tests do not reach zero rpm, because the motor was shut off while it was still turning very slowly. This inadvertence makes the comparison less exact than it otherwise would have been.)

Figure 28 shows the current/torque data for the 40 ft-lb motor tested at reduced voltage. A line representing the manufacturer's published performance data is also shown. Locked rotor data are included as well. The six traces from tests at vari-

ous voltages lie on top of each other, indicating that although reduced voltage causes the dc motor to run more slowly (Figure 26), and although reduced voltage causes a reduction in the peak torque (and the peak current) at low-speed, high-torque conditions, the output torque of the dc motor at a given current is about the same regardless of the voltage. Figure 28 also shows that, as expected, the current/torque relationship for the dc motor is almost linear. However, at higher loads (above about 30 ft-lb) the manufacturer's published curve slightly underestimates the current the motor draws to produce a given amount of torque.

Elevated Temperature Testing of the dc Motor

Figures 29 and 30 are the elevated temperature plots for the 40 ft-lb dc motor for 100% and 80% voltage, respectively. This motor was heated to 250°F. The increase in temperature from room temperature to 250°F reduced the output torque
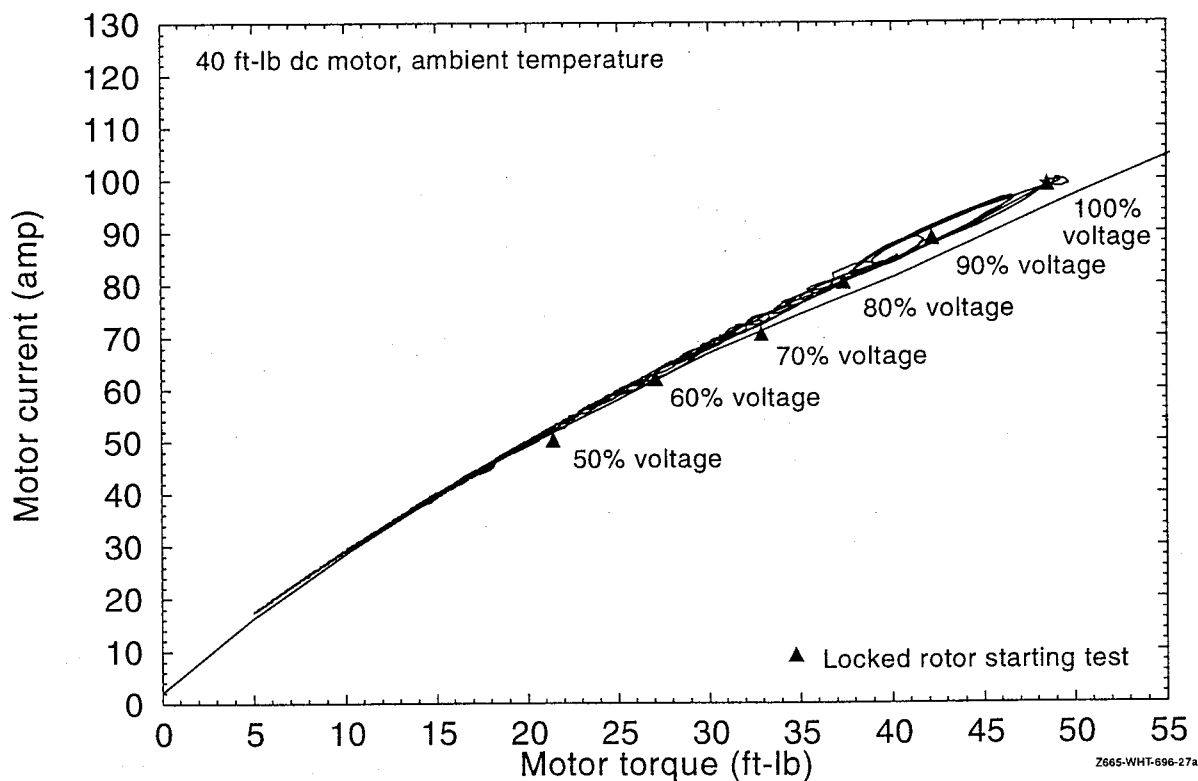
Figure 28. Motor current versus torque, derived from testing of the 40 ft-lb dc motor at degraded voltage at room temperature.
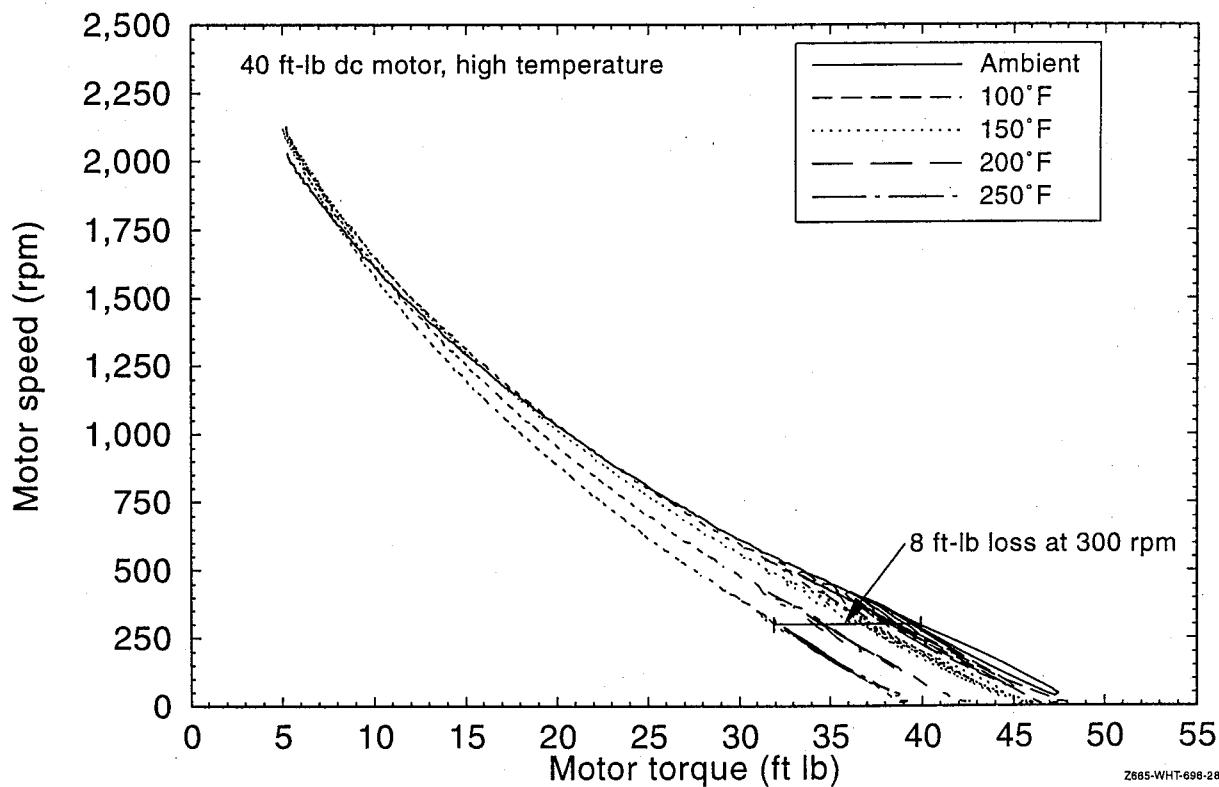
Figure 29. Motor speed versus torque, derived from elevated temperature testing of the 40 ft-lb dc motor at 100% voltage.
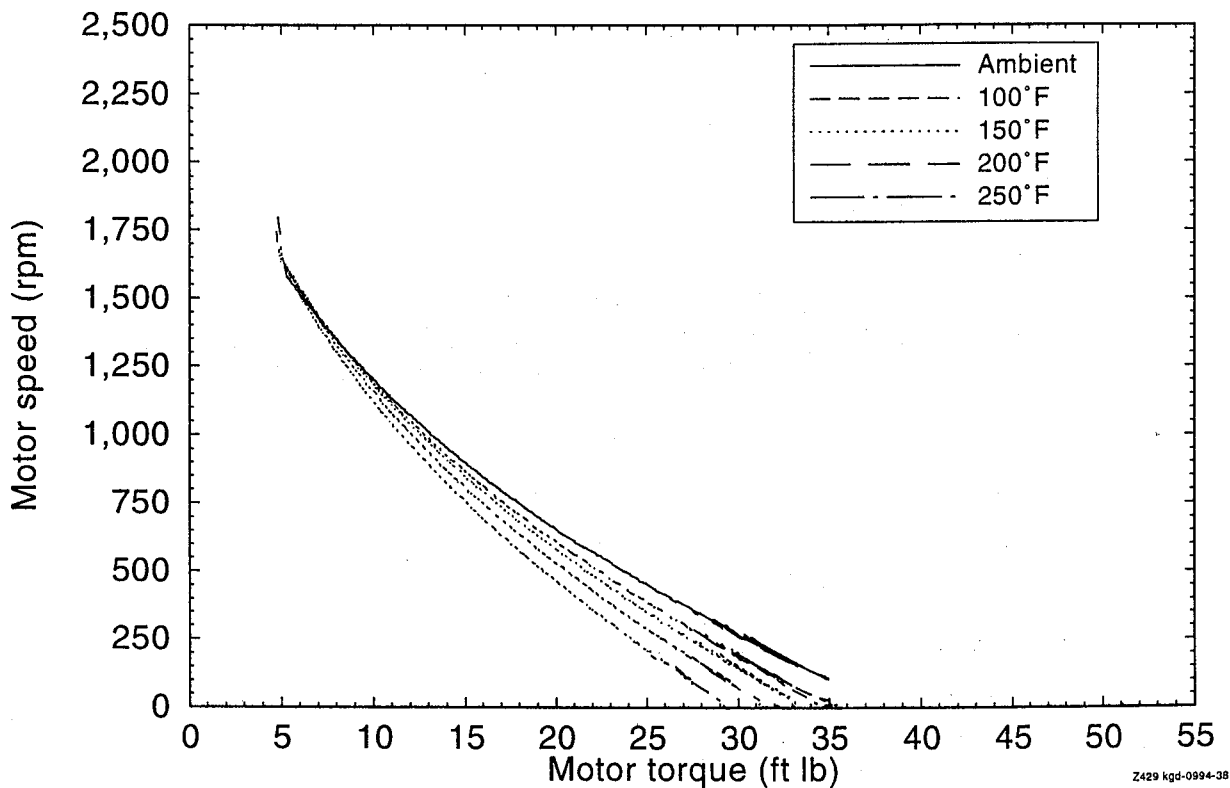

Figure 30. Motor speed versus torque, derived from elevated temperature testing of the 40 ft-lb dc motor at 80% voltage.

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by 8 to 10 ft-lb at high loads. For example, at 300 rpm, elevated temperature caused output to fall from the rated torque of 40 ft-lb to a value of 32 ft-lb.

The manufacturer's dc actuator qualification requires the actuator to perform at 340°F. For dc motors operating at this temperature, the manufacturer provides a table (Reference 9) recommending adjustments to the rated torque value when sizing a nuclear qualified actuator. According to this table, a rated torque of 40 ft-lb would be adjusted to 39 ft-lb. (The adjustment is greater for larger motors; for example, a rated torque of 60 ft-lb would be adjusted to 54 ft-lb.)

Conclusions. The results of elevated temperature testing of this dc motor show that the adjustment recommended by the manufacturer for accounting for torque losses due to motor heating underestimated the actual torque losses. Specifically, the predicted torque loss was 1 ft-lb at 340°F for this 40 ft-lb dc motor, while the test results showed an actual torque loss of 8 ft-lb at only 250°F.

Actuator Gearbox Efficiency

Gearbox efficiency is part of the relationship between the input torque and the output torque of an actuator gearbox. The output torque can be represented by

$$T_{output} = T_{input} \, (Eff_{gearbox} \; OAR) \quad (6)$$

where

T_{output} = output torque

T_{input} = input torque (motor torque after adjustments described earlier in this report)

$Eff_{gearbox}$ = the efficiency of the gearbox

OAR = overall gear ratio.

The input torque consists of the torque delivered by the electric motor to the input side of the gear-

box, and the output torque consists of the torque delivered to the stem nut (through the worm gear) by the worm. The overall gear ratio is the total gear reduction in the gearbox--the number of motor revolutions required for one revolution of the stem nut. Overall gear ratios for the actuators we tested (Table 1) range from about 32 to about 88. The gear reduction in the gearbox, which includes the reduction in the helical gear set as well as the reduction at the worm gear, greatly increases the torque output (at the stem nut) but reduces the rotational speed of the stem nut. The gearbox efficiency accounts for losses to friction at the helical gear set, the worm/spline interface, the worm/worm-gear interface, and the associated bearings. Typical efficiency values for operator gearboxes are in the range of 0.4 to 0.6. The more efficient the gearbox performance (the less the loss to friction), the higher the efficiency value. The gearbox efficiency value does not include friction in the motor or friction at the stem/stem-nut interface, which are separate calculations. The main drive train components of an actuator gearbox are shown in Figure 3, referred to earlier in this report.

Typical gearbox efficiencies are referred to as pullout efficiency, stall efficiency, and running efficiency. The pullout efficiency is the lowest of the three. This value applies when the motor is lugging at very low speed under a load or starting up against a load. The stall efficiency is higher than the others because it includes consideration of motor inertia during a sudden stall; it is typically used in evaluations of possible overload problems. The running efficiency is typically used to estimate the efficiency of the gearbox at normal motor speed and normal loads.

Table 1 (referred to earlier in this report) lists the actuators we tested and the published operating efficiencies (running, pull-out, and stall) for these actuators, along with other pertinent information. The published running efficiencies of the actuators vary between 50 and 60%. These efficiency values indicate that it takes about half the input motor power to overcome losses (primarily friction) in the gearbox.

Our tests, conducted on the MOVLS, were designed to determine actual gearbox efficiencies with the gearboxes subjected to a full range of various possible loads. By measuring the motor torque (which is the torque input to the gearbox) and the actuator output torque (which is the gearbox output torque, measured as the actuator torque reacted by the torque arm attached to the valve stem in the MOVLS), and by accounting for the gear reduction, we were able to continuously monitor the efficiency of a gearbox at various loads. Figure 31 shows the actuator torque (output torque) measured during the 100 percent voltage test of the SMB-1 actuator with the 60 ft-lb ac motor. The negative convention for this measurement indicates that the actuator was being operated in the closing direction. Note that the actuator output torque gradually increases in a manner representative of a closure under design-basis flow. Figure 32 shows the motor torque measured during the same test. Figure 33 shows the actual gearbox efficiency calculation made from the data in Figures 31 and 32; the published running and pullout efficiencies are also shown. The gearbox efficiency begins at about 0.41 at low load and slowly rises to 0.51 while the actuator is still under moderate load. However, the efficiency drops as the load increases, dropping below the published pullout efficiency at stall.

Figure 34 shows the same information as Figures 31 through 33, but in a different format. Here we have plotted output torque (actuator torque) versus input torque (motor torque) using data from the reduced voltage parametric study to produce the traces. The format of the figure is based on Equation (6); the slope from the origin (0,0) to any point on one of the data traces represents the gearbox overall ratio times the *actual* gearbox efficiency for that data point. The two straight lines in Figure 34 represent the overall gear ratio times (a) the published *running* efficiency, and (b) the published *pullout* efficiency. This format allows comparison of the actual gearbox efficiency over the entire operating range (in terms of torque load) with the published values. For example, Figure 34 shows that for this actuator, the actual gearbox efficiency lies mostly between the published running efficiency and the published

pullout efficiency. However, at higher loads the actual gearbox efficiency approaches the pullout efficiency.

In addition, Figure 34 indicates a relationship between the gearbox efficiency and the load imposed on the actuator. At a motor torque load of about 18 ft-lb, the actual efficiency is at or above the running efficiency for all five tests. However, the actual efficiency falls below the published running efficiency at medium to high loads. These results suggest that as the load goes up, the efficiency of the gearbox goes down. This general decline in efficiency, most evident in the middle portion of the data where the traces lie on top of each other, is at least partly independent of motor speed (see Figure 11 for corresponding motor speed curves).

A careful examination of Figure 34 also reveals a relationship between efficiency and the speed of the SMB-1-60 ac valve actuator. In each of the reduced voltage tests, the measured efficiency is near the published running efficiency when the motor is near its normal speed (early in the stroke), but drops toward the pullout efficiency as the motor approach stall. Here, the results suggest that as the motor speed goes down, the efficiency of the gearbox goes down. In the 60% voltage test, the efficiency approaches the pullout value at a motor torque of 22 ft-lb, in the 70 percent test at 29 ft-lb, and so on. In each instance, the specific decline in efficiency, most evident on the tail of the trace near motor stall, corresponds more with the change in motor speed than with the change in motor torque. For any of the four low-voltage traces (90 to 60% voltage), the efficiency at the peak torque (just before stall) is notably lower than the efficiency indicated by higher-voltage traces at the same torque value but at higher motor speeds. The effect of motor speed, independent of motor torque, is even more evident in the dc motor data, described later in this discussion.

For the other ac valve actuators, data similar to Figure 34 are presented in Figures 35 through 37. For the SMB-00-5 (Figure 35), the actual gearbox efficiency is well below the published pullout
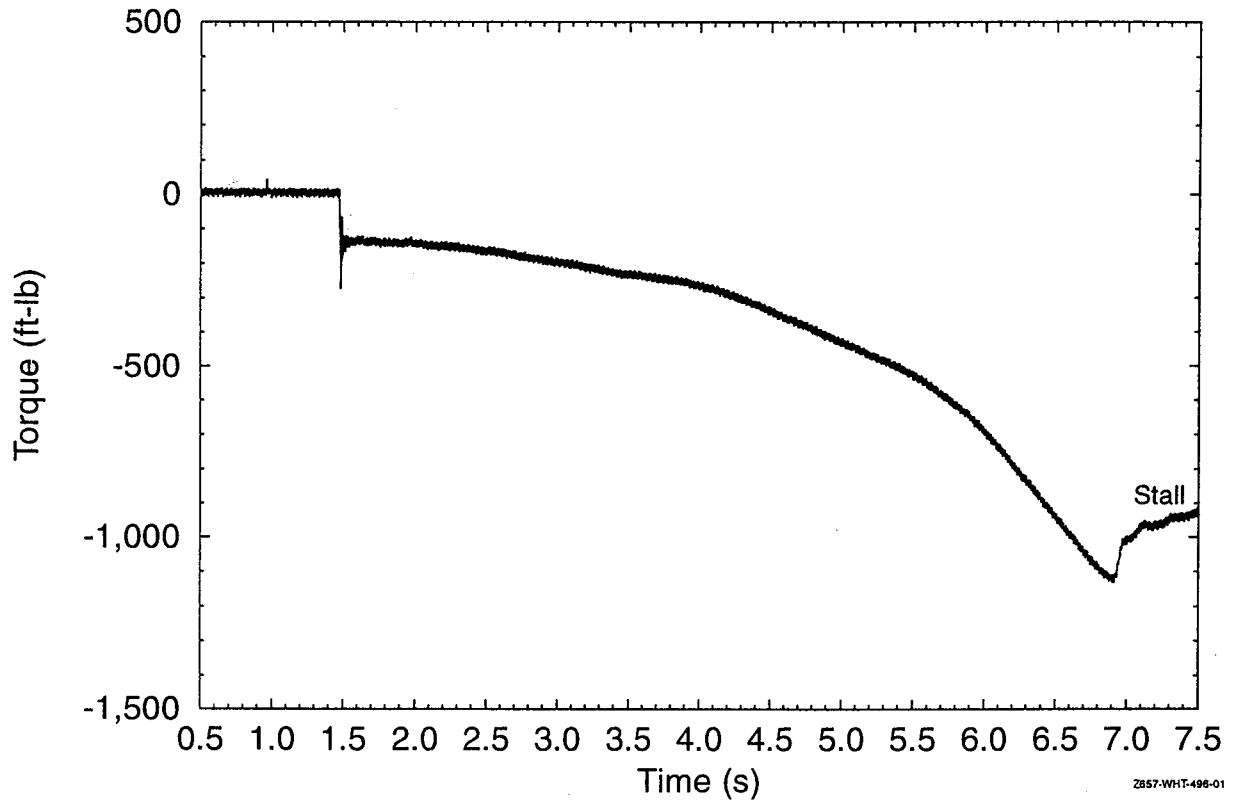
Figure 31. Actuator torque history from a test of the SMB-1-60 ac actuator (output torque).
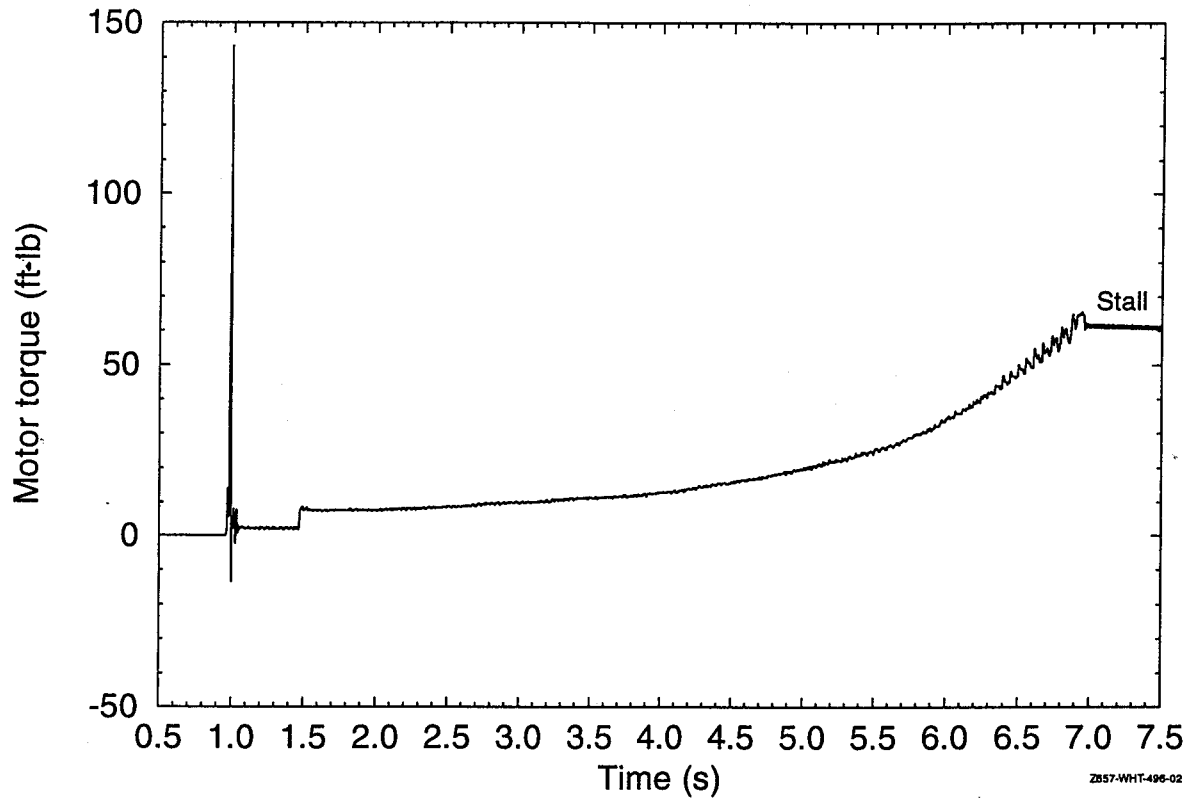
Figure 32. Motor torque history from a test of the SMB-1-60 ac actuator (input torque).

Figure 33. Running calculation of the gearbox efficiency, derived from the data shown in Figures 31 and 32.

Figure 34. Gearbox efficiency calculations derived from stall testing of the SMB-1-60 ac valve actuator.

Figure 35. Gearbox efficiency calculations derived from testing of the SMB-00-5 ac valve actuator.

Figure 36. Gearbox efficiency calculations derived from testing of the SMB-0-25 ac valve actuator.

Figure 37. Gearbox efficiency calculations derived from testing of the SB-1-40 ac high speed valve actuator.

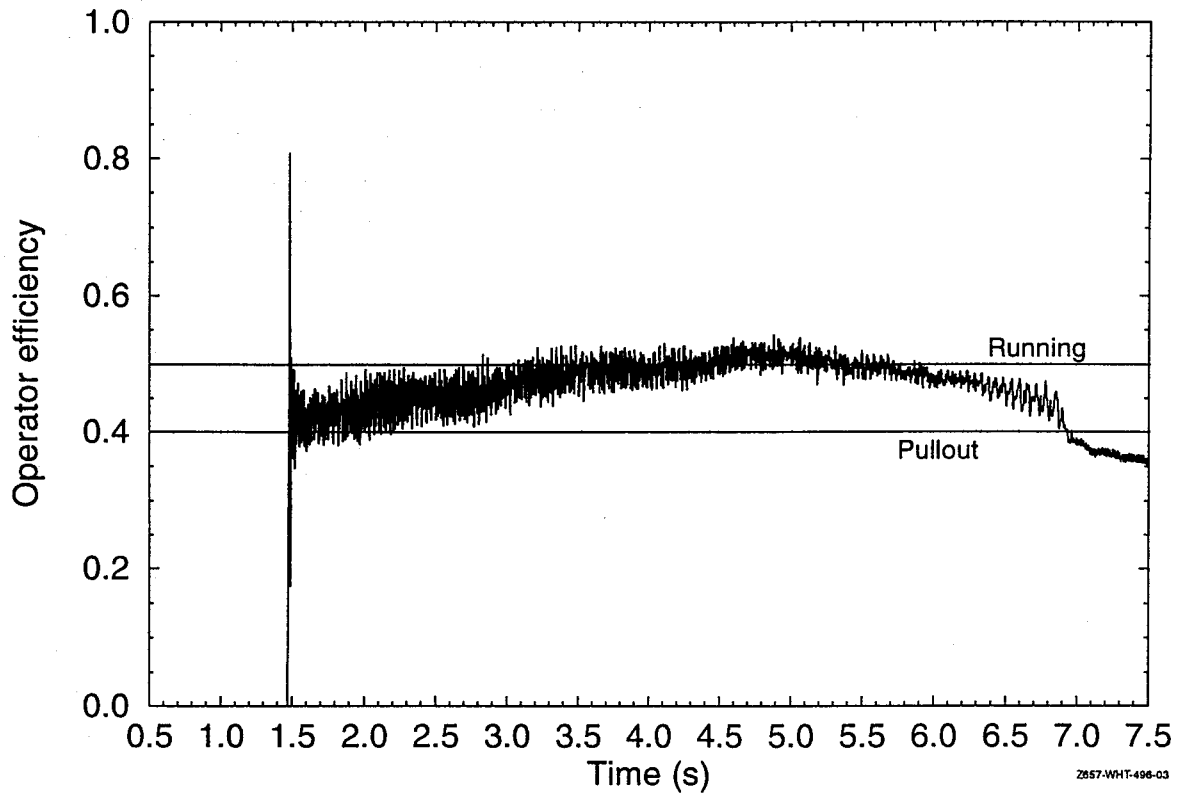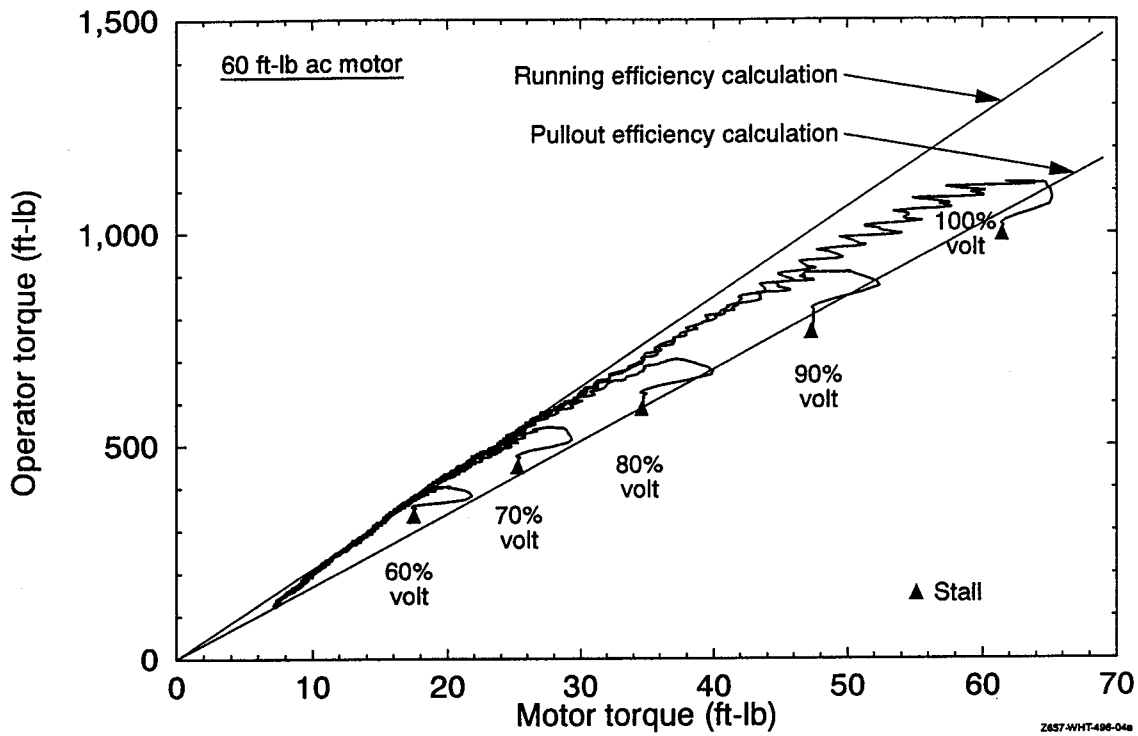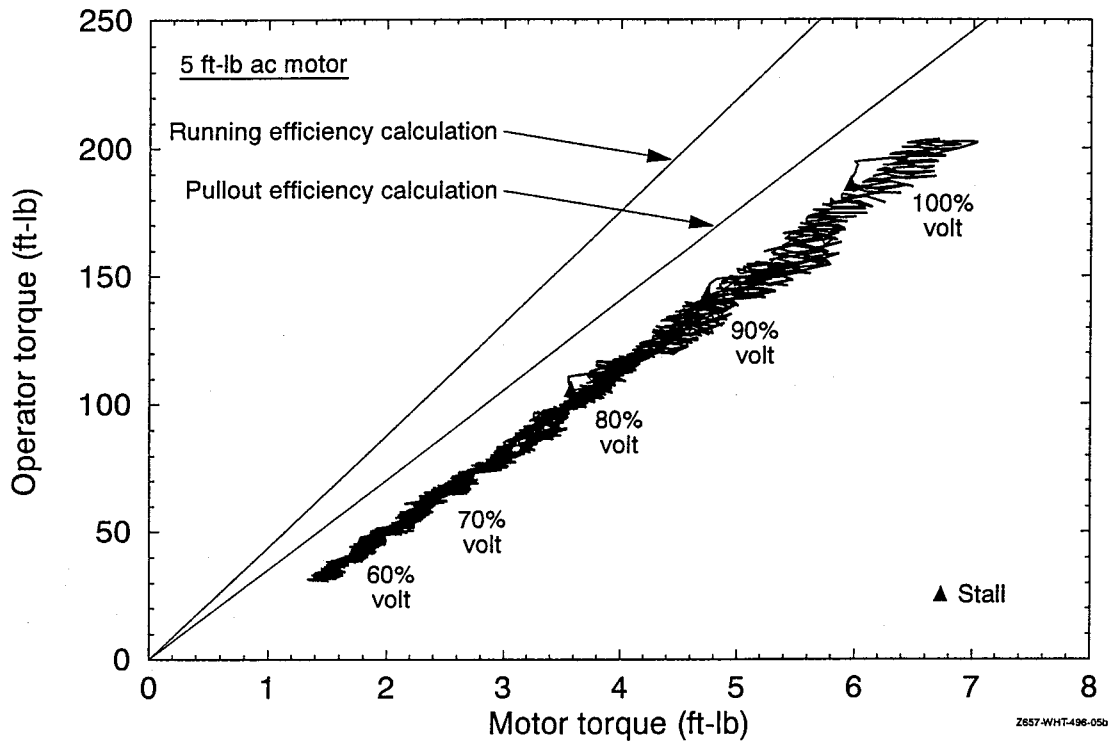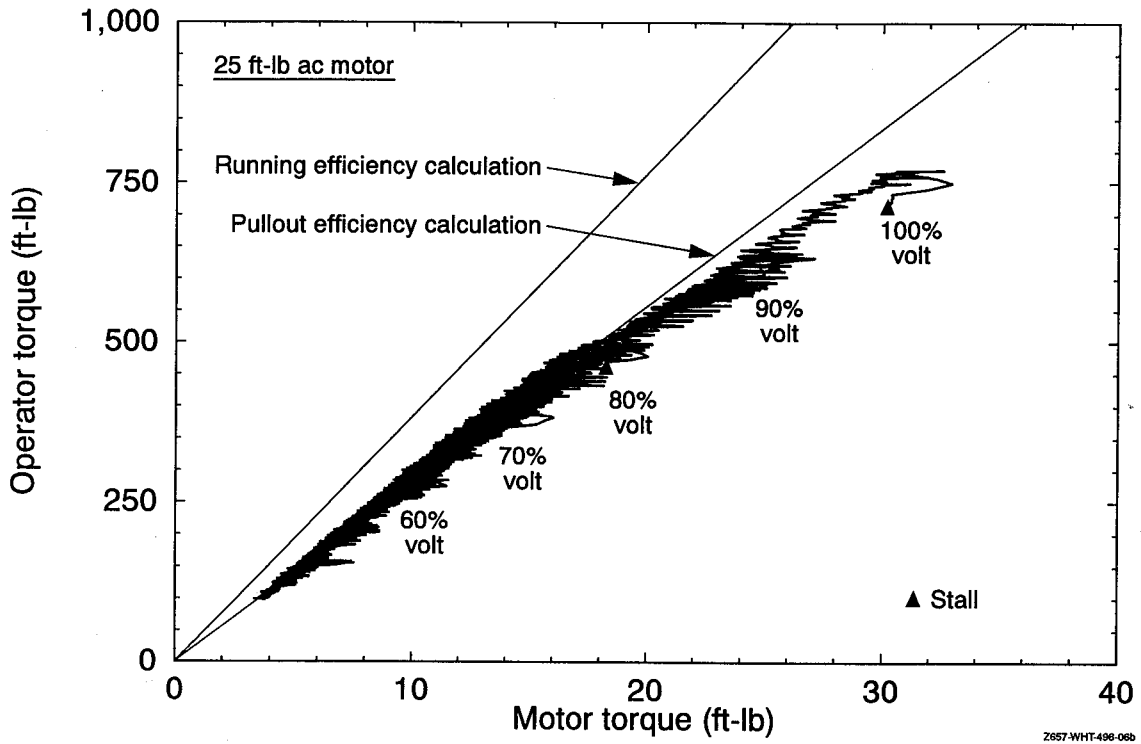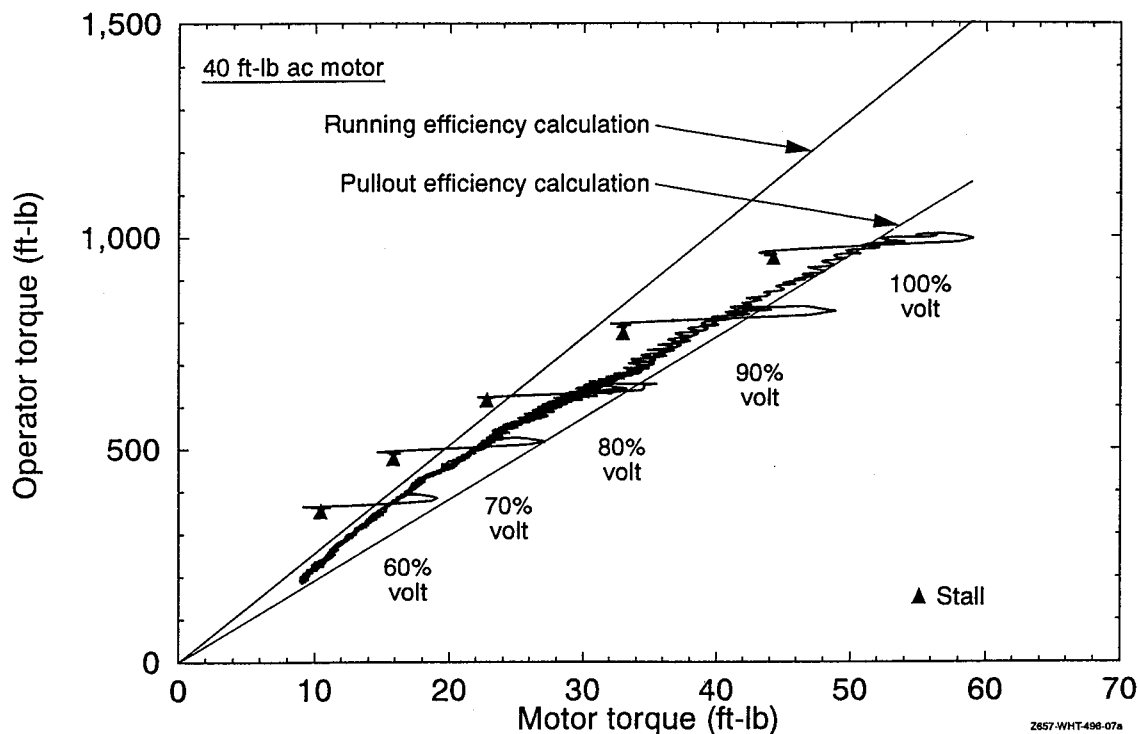efficiency. For this actuator, the motor torque required to spin the gear train without producing output torque (sometimes called the hotel load) is a significant percentage of the total motor torque. (For actuators powered by larger motors, the hotel load is negligible, it being a much smaller percentage of the total motor torque.) For the SMB-00-5, we measured a hotel load of 0.44 ft-lb; that is, the input torque was 0.44 ft-lb when the output torque was zero. For this motor/gearbox combination, a more meaningful comparison of gearbox efficiency can be made by subtracting 0.44 ft-lb from the motor torque data to account for this hotel load. Figure 38 shows the same results as Figure 35, but with this 0.44 ft-lb offset to the motor torque data. As this analysis shows, it is important to consider the hotel load when determining the actuator capability for smaller motors.

Figures 34 through 37 show that for each actuator we tested, the published running efficiency overpredicts the actual actuator efficiency at higher loads and lower speeds. Further, the two

smaller actuators exhibited efficiencies lower than the published pullout efficiency. This result is indicated whenever the trace drops below the line whose slope represents the pullout efficiency.

Figure 39 presents the data from testing of the SMB-1 actuator when powered by the dc motor. The shape of the curves is different than in Figures 34 through 37 (the difference is due to the speed versus torque relationship of dc motors as compared to ac motors), but the general trends are similar to those seen with the ac motors. For this SMB-1 actuator powered by a dc motor, the actual gearbox efficiency is consistently lower than the published running efficiency. As the motor speed drops under high load, efficiency drops to values below the pullout efficiency. Because the dc motor produces progressively higher torque at lower speed (corresponding motor speed curves are shown in Figure 26), the traces shown in Figure 39 for the various low voltages are more distinctly separate than in the ac motor tests. For example, at a motor torque of
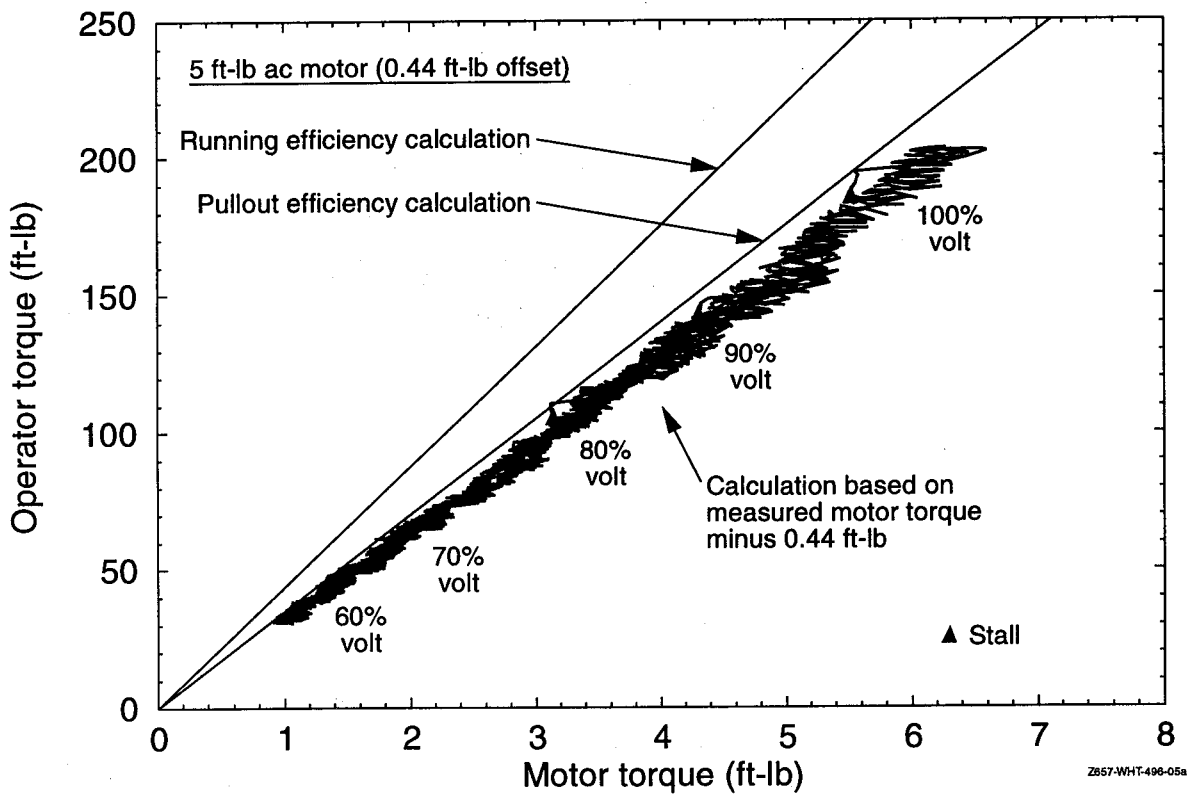
Results

Figure 38. Gearbox efficiency calculations derived from testing of the SMB-00-5 ac valve actuator, with the motor torque adjusted to compensate for the hotel load.
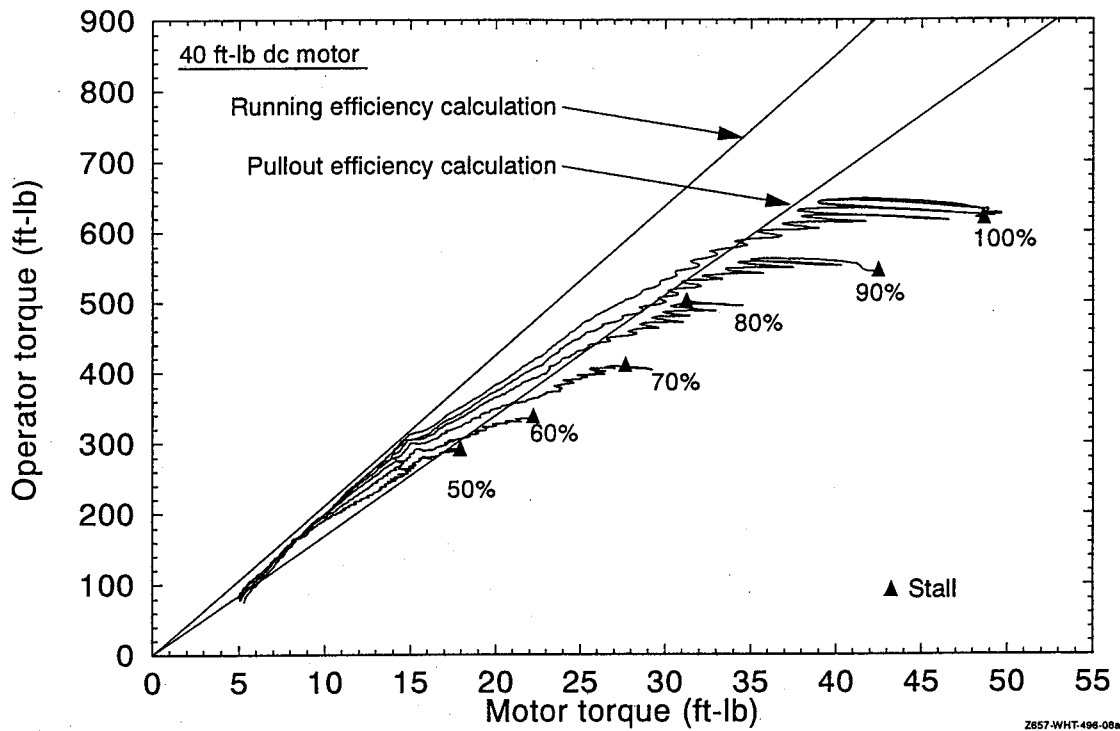

Figure 39. Gearbox efficiency calculations derived from testing of the SMB-1-40 dc valve actuator.

27 ft-lb, the efficiency for the 70% voltage test is lower than the efficiency for the 100% test at the same motor torque. This difference is due entirely to a difference in motor speed. These results show that the gearbox efficiency drops at lower speeds as well as at higher torques.

This result might have significance for dc-powered valve actuators. In contrast to ac motors, which produce their rated torque at moderate speeds (typically at about 1200 rpm for 1800-rpm ac motors), dc motors produce their rated torque at much lower speeds; Figure 25 shows this dc motor producing its rated torque at about 300 rpm. Thus, a dc-powered actuator will have a lower efficiency than an ac-powered actuator when operated under the conditions that demand the rated output torque from the motor.

This finding is evident in a comparison of Figures 34 and 39, which show the efficiency results from the same SMB-1 actuator powered by the 60-ac motor and the 40-dc motor, respectively. If the SMB-1-40 had operated with the same effi-

ciency as the SMB-1-60, it would have produced about 14% more output torque at its rated input torque of 40 ft-lb (740 ft-lb output torque instead of 650 ft-lb).

Figure 40 shows the results of testing of the SMB-0-25 ac actuator to determine if gearbox efficiency is affected by elevated temperature. In these tests, the second gear ratio shown in Table 1 was used (a different gear set than in the tests described earlier). Three tests were performed. The first test was a baseline test to show gearbox efficiency at room temperature. The second and third tests were performed with the gearbox heated to 350°F. The third test was performed immediately after the second to evaluate repeatability. The results are about the same for all three tests. Figure 40 shows that the gearbox efficiency was not affected by elevated temperature.

For this gear set, the measured efficiency was slightly higher than the published pullout efficiency. By comparing this figure to Figure 36, we get an indication of the variation that can result
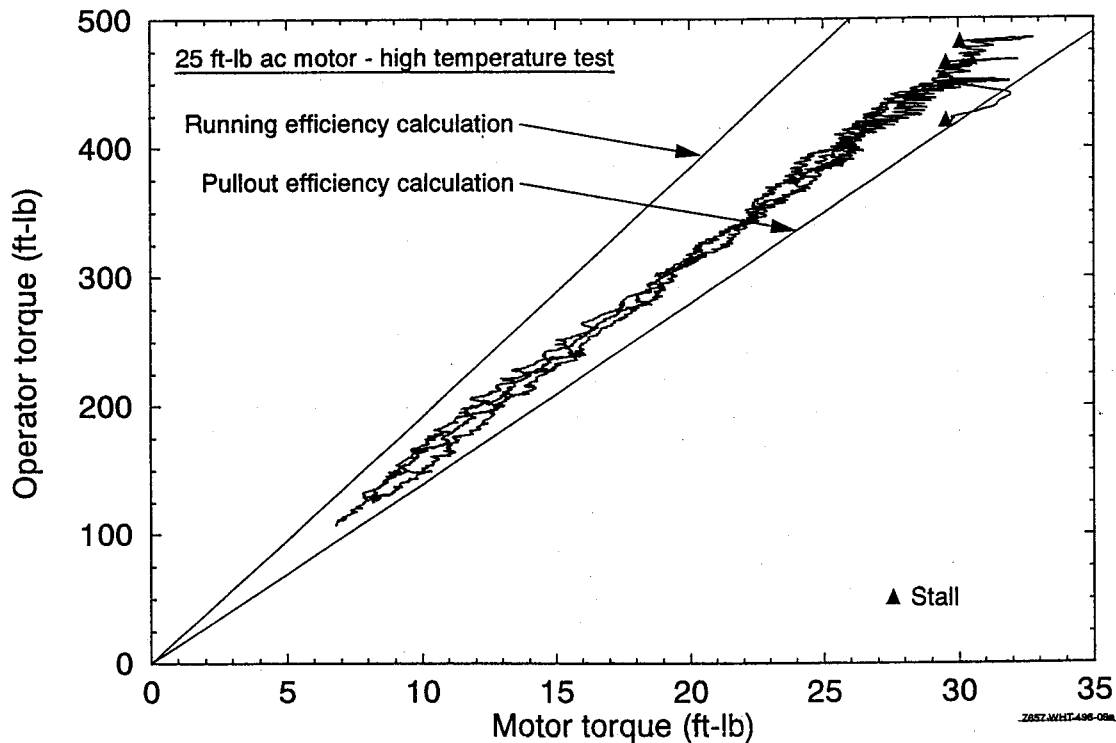

Figure 40. Gearbox efficiency calculations derived from elevated temperature testing of the SMB-0-25 ac motor-actuator.

from using different gear sets in the same actuator. Tests using a gear set with a lower gear ratio (higher output speed, lower output torque) produced a higher gearbox efficiency. This result is consistent with the results from tests of the SMB-1-40 dc actuator (Figure 39), where lower speeds, even at the same motor torque values, corresponded with lower gearbox efficiency values.

Conclusions

Overall, the test results show that actual efficiencies can differ from those published by the actuator manufacturer. For the actuators we tested, the published running efficiency was generally not adequate for predicting actual performance of the gearboxes, especially at higher loads. The published pull-out efficiency was adequate for predicting gearbox performance for some gearboxes and at some conditions (moderate loads), but some of the actual efficiency data fell below the published pullout efficiency. The results also show that different gear sets with different gear ratios operate at different efficiencies, even in the same gearbox. The gearbox efficiency was not affected by elevated temperatures.

Gearbox efficiency is affected by motor speed as well as by the torque load imposed on the actuator. Lower motor speed and higher motor torque correspond with lower gearbox efficiency. At reduced voltages, the measured efficiency near motor stall drops well below the values measured at full voltage (and higher speed) for the same motor torque. The SMB-1 actuator operated with lower efficiency near maximum torque output when powered by the 40 ft-lb dc motor, as compared to operation with the 60 ft-lb ac motor; the difference is because the dc motor runs at lower speed near its maximum output.

The actuator no-load motor torque, or hotel load, can be significant for smaller motors. Hotel load consumed almost ten percent of the motor rated torque for our SMB-00-5 actuator.

OVERALL CONCLUSIONS

A summary of the conclusions is presented in the following paragraphs. More details are provided at the end of each subsection in the results section of the report.

Performance curves. Published motor performance data matched the actual current/torque and speed/torque data fairly well. There were some minor differences in the shape of the ac motor curves near the knee of the curve, indicating that the load threshold at which the motor drops off to a stall occurs at a different rpm, or at a different torque load, than shown by the published data. For all five motors, the stall torque, the running torque before stall, and the locked rotor startup torque exceeded the rated torque. Some of the motors had more margin between the actual and rated values than others.

Degraded voltage. Actual torque losses due to voltage degradation were greater than the losses estimated by the voltage squared calculation. This was true for all four ac motors at all the various reduced voltages we tested. The voltage squared calculation typically overpredicted the actual motor torque by 1 to 10%. The results suggest that for these four ac motors, an exponent of about 2.5 instead of 2 in the voltage squared calculation would produce adequate predictions of torque losses due to operation at reduced voltage.

Results were similar for the dc motor; actual torque losses due to voltage degradation were greater than the losses estimated by the typical linear method used for predicting such losses. At 80% voltage, the method overpredicted the actual motor torque at 500 rpm by 9%. The results suggest that a formula similar to the voltage squared calculation, but with an exponent of about 1.3, would produce adequate predictions for this dc motor at locked rotor conditions. For a motor speed of 500 rpm, an exponent of about 1.8 would produce adequate predictions.

The results of the locked rotor startup tests compared favorably with the results of the dynamometer-type tests at stall.

Elevated temperature. For three of the ac motors, the actual motor output torques measured at elevated temperature were equal to or higher than the predictions of motor torque at those conditions. (The predictions in this instance are based on the actuator manufacturer's data.) For one of the ac motors (the 25 ft-lb motor), the actual torques were lower than the predictions, by 3 to 8%. The actual motor currents measured during the tests were lower than the predictions.

For the dc motor, a prediction based on the actuator manufacturer's data for dc motor performance at elevated temperature overestimated the actual torque measured in the tests by about 22%.

Gearbox efficiency. For most motor/gearbox combinations, the actual efficiencies were lower than the running efficiencies specified by the actuator manufacturer. In no case was the published running efficiency adequate for predicting the actual efficiency of the gearbox when operating against a significant load. Generally, the published pull-out efficiency was adequate for predicting the gearbox efficiency at moderate loads, but in some instances it was inadequate for predicting the gearbox efficiencies at higher loads at or near motor stall.

Gearbox efficiency tended to be lower with operation at lower speeds. This finding is particularly true for actuators powered by dc motors, because dc motors approach their highest output torque at low rpm. Higher gearbox efficiency corresponded with operation at higher speeds. This finding was indicated in all the test results and confirmed by results from testing of the same ac-powered actuator with two different helical gear sets. The gear set with the lower gear ratio (lower output torque, higher output speed) operated with higher efficiency.

Operation of the gearbox at elevated temperature did not affect the operating efficiency of the gearbox.

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10. SUPPLEMENTARY NOTES

11. ABSTRACT *(200 words or less)*

Researchers at the Idaho National Engineering and Environmental Laboratory tested the performance of electric motors and actuator gearboxes typical of the equipment installed on motor-operated valves used in nuclear power plants. Using a test stand that simulates valve closure loads against flow and pressure, we tested five electric motors (four ac and one dc) and three gearboxes at conditions a motor might experience in a power plant, including such off-normal conditions as operation at high temperature and reduced voltage. We also monitored the efficiency of the actuator gearbox. All five motors operated at or above their rated starting torque during tests at normal voltages and temperatures. For all five motors, actual torque losses due to voltage degradation were greater than the losses calculated by methods typically used for predicting motor torque at degraded voltage conditions. For the dc motor the actual torque losses due to elevated operating temperatures were greater than the losses calculated by the typical predictive method. The actual efficiencies of the actuator gearboxes were generally lower than the running efficiencies published by the manufacturer and were generally nearer the published pull-out efficiencies. Operation of the gearbox at elevated temperature did not affect the operating efficiency.

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ac motor
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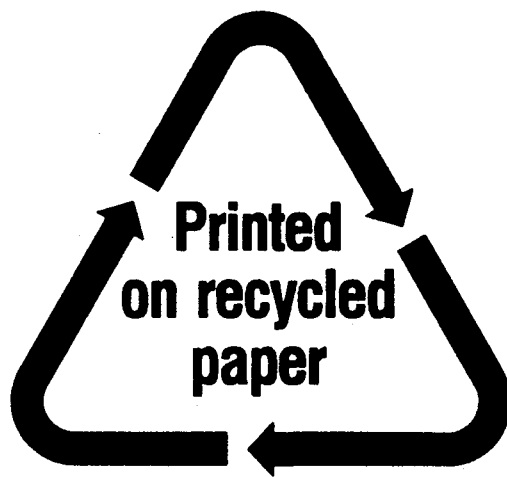
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