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# MOV Motor and Gearbox Performance Under Design Basis Loads

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## ABSTRACT

This paper describes the results of valve testing sponsored by the U.S. Nuclear Regulatory Commission, Office of Nuclear Regulatory Research and conducted at the Idaho National Engineering and Environmental Laboratory. The research objective was to evaluate the capabilities of specific actuator motor and gearbox assemblies under various design basis loading conditions. The testing was performed using the motor-operated valve load simulator, a test fixture that simulates the stem load profiles a valve actuator would experience when closing a valve against flow and pressure loadings. We tested five typical motors (four ac motors and one dc motor) with three gearbox assemblies 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 determined the efficiency of the actuator gearbox. The testing produced the following significant results:

- All five motors operated at or above their rated torque during tests at full voltage and ambient temperature.
- For all five motors (dc as well as ac), the actual torque loss due to voltage degradation was greater than the torque loss predicted using common methods.
- Startup torques in locked rotor tests compared well with stall torques in dynamometer-type tests.
- The methods commonly used to predict torque losses due to elevated operating temperatures sometimes bounded the actual losses, but not in all cases; the greatest discrepancy involved the prediction for the dc motor.
- Running efficiencies published by the manufacturer for actuator gearboxes were higher than the actual efficiencies determined from testing. In some instances, the published pullout efficiencies were also higher than the actual values.
- Operation of the gearbox at elevated temperature did not affect the operating efficiency.

## BACKGROUND

During the past several years, the U.S. Nuclear Regulatory Commission (NRC), Office of Nuclear Regulatory Research has supported research at the Idaho National Engineering and Environmental Laboratory (INEEL) addressing the performance of motor-operated valves (MOVs). The research included tests and analyses to determine the capability of safety-related MOVs to perform their intended functions when subjected to their design-basis conditions. For some of these valves, the design-basis conditions

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include high flow and pressure loads, elevated temperatures (which can reduce the output of the electric motor), and operation of the electric motors at reduced voltage.

This paper presents the results of tests performed to address factors that affect the performance of MOV electric motor and actuator gearbox assemblies. 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?

## TEST EQUIPMENT

We tested six combinations of actuator gearboxes and electric motors, using five motors and three gearboxes. Table 1 summarizes the information provided by the motor manufacturers and the actuator manufacturer about the six actuator configurations. Note that the SMB-1 and the SMB-0 actuators were each tested under two configurations.

The tests were performed on the MOV load simulator (MOVLS), a test fixture owned by the NRC and built by the INEEL for testing valve actuators. The MOVLS, shown in Figure 1, 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/piston assembly and an accumulator that contains a gas overpressure. 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 closing a valve against an actual flow load. The valve seating load is simulated when the piston bottoms out in the cylinder.

The MOVLS is instrumented to take all the measurements that are important for diagnosing valve actuator performance. Motor speed was measured directly, and 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. 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.

Most actuator and motor testing is typically performed by applying a sudden torque load. This is accomplished by applying the brake on a dynamometer, hard-seating a valve without a flow load, or with a locked stem (similar to a locked rotor test). In contrast, we used the MOVLS to produce dynamometer-type tests that imposed a stem thrust load that gradually increased until it caused the motor to stall. Stall occurred before the piston bottomed out in the cylinder. These tests allowed us to determine the actual output torque of the motor and of the gearbox over the entire operating range of the motor. We also conducted locked rotor startup tests, measuring torque, current, and other parameters with no motor shaft 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 elevated 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 each motor with heat tape and insulation to create a custom oven. Environmentally qualified motors were heated to 300°F, while the 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.

## AC MOTOR RESULTS

Our research addresses most of the terms in the typical formula for predicting the output torque of a valve actuator. The formula is:

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

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 actuator ratio (gear ratio)

The first three terms in the equation apply to the motor torque and account for the effects of reduced voltage and elevated temperature. The results concerning the voltage- and temperature-related adjustments are included in this section for the ac motors and in the following section for the dc motor. The application factor ($F_{app}$) was not evaluated in this research. We used an application factor equal to 1.0 in all of the calculations discussed in this paper. The gearbox efficiency section of this paper discusses the final two terms in Equation 1.

Performance Curves for the ac Motors ($T_{motor}$)

Figure 2 presents the manufacturer's torque curves for the 25 ft-lb ac motor. The asterisk on the current trace marks the end of the manufacturer's curve, and the two "X"s are test points from earlier field testing. The remainder of the curve is extrapolated through the published locked rotor current. Figure 2 also shows the actual torque curves for the motor. 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.) Although the two speed/torque curves shown in Figure 2 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 shows a moderate increase followed by a rapid decrease. Both curves show about the same stall torque. Comparisons for the 5 ft-lb and 40 ft-lb motors are similar.

Figure 3 presents the manufacturer's torque curves for the 60 ft-lb ac motor. Again, we extrapolated the current from the asterisk through the published locked rotor stall current. Figure 3 also shows the actual curves derived from our test data. The two speed/torque curves are different over the working range, but the absolute torque values 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 somewhere between 500 and 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, and the manufacturer's curve slightly overestimates the actual performance at stall.

Overall, 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 ac motors exceeded their rated output 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 $\left(\frac{V_{act}}{V_{rat}}\right)^2$

*Equation 1, as applied by the manufacturer, uses the rated starting torque of the electric motor; however, the amount by which the actual torque exceeds the rated torque varies as shown above. Recently, there has been interest in substituting measured values of motor torque for the rated starting torque in the equation. We therefore focused our analysis on the voltage squared term. For our reduced voltage evaluation we compared the measured motor torque output in the baseline (100% voltage) test with the measured motor torque at each reduced voltage condition, as shown in the following equation.*

$$T_{act} = T_{100}\left(\frac{V_{act}}{V_{100}}\right)^2 \tag{2}$$

where

| | | |
|---|---|---|
| $T_{act}$ | = | actual torque at reduced voltage |
| $T_{100}$ | = | actual torque at 100% voltage |
| $V_{act}$ | = | actual voltage |
| $V_{100}$ | = | 100% voltage. |

Figure 4 shows motor speed/torque curves for the 40 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 2000 rpm) and the stall torque at degraded voltage are also shown. For the high speed 40-ft-lb ac motor, the voltage squared calculation overestimates the motor torque by about 1.0 to 2.8 ft-lb (3 to 7%) at 2000 rpm.

To further evaluate the voltage squared method, we rearranged the formula shown in Equation (2) and used the data from all four ac motors as input to solve for the exponent. Figure 5 shows the results of this evaluation. Each data point shown in Figure 5 represents the exponent in Equation 2 that produces a predicted torque that matches the actual torque measured in the corresponding test. The results suggest that for these four ac motors, an exponent of 2.5 instead of 2 in the voltage squared calculation would produce predictions of torque loss that consistently bound the actual torque losses.

Locked Rotor Testing of the ac Motors

The small delta symbols at the bottom of the plot in Figure 4 are the locked rotor startup torques. These individual data points are produced by energizing the motor with a large load imposed on the motor that prevents the rotor from turning. The speed curves in Figure 4 end (at motor stall) very near the locked rotor startup torques, indicating that the motor torque at stall and the startup motor torque with the rotor locked are about the same.

For all four of the ac motors we tested, the locked rotor startup torques were always lower than the peak running torque. We found the locked rotor startup torque to be a useful indication for comparison with the rating of a specific motor.

Elevated Temperature Testing of the ac Motors ($F_{temp}$)

Figure 6 shows 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 for these motors, based on the manufacturer's data (Reference 1). The predictions of torque loss due to elevated temperature bounded the actual losses for three of the four ac motors we tested. However, the results shown in Figure 6 for the 25 ft-lb motor indicate that the predictions might not be appropriate for this motor. Note, however, that this motor is not environmentally qualified, a fact that might affect its output at elevated temperature.

# DC MOTOR RESULTS

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. There are also differences in the responses to degraded voltage conditions and elevated temperature conditions.

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 earthquakes 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 history of the motor and the results of the seismic tests are reported in Reference 2.

Performance Curves for the dc Motor ($T_{motor}$)

As with the ac motors, we developed motor performance curves for the dc motor (motor speed versus motor torque, and motor current versus torque) for comparison with the motor data supplied by the actuator manufacturer. Figure 7 presents the manufacturer's speed/torque and current/torque curves for this 40 ft-lb dc motor. The figure also shows the torque curves derived from our tests. The actual torque output is lower than predicted by the manufacturer's data.

Degraded Voltage Testing of the dc Motor $\left(\frac{V_{act}}{V_{rat}}\right)$

In analytical evaluations of MOV capability, the actuator manufacturer recommends a formula that is identical to the voltage squared method for ac motors, except that the exponent is 1 instead of 2.

Figure 8 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. These results show that the conventional method for predicting torque loss due to operation of dc motors at reduced voltage does not bound actual torque losses.

To further evaluate the method for predicting dc motor output at reduced voltage conditions, we used data from the tests as input so we could solve for the exponent. Similar to our effort to evaluate the voltage squared method 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 the dc motor. The results are shown in Figure 9. The results suggest that for locked rotor (stall) conditions, an exponent of 1.3 would bound the data; for a motor speed of 500 rpm, the results suggest an exponent of 1.8 in the formula to bound the torque output of this dc motor.

Locked Rotor Testing of the dc Motor

Figure 8 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; we shut the motor off while it was still turning very slowly, to prevent overheating of the motor.)

Elevated Temperature Testing of the dc Motor ($F_{temp}$)

As the ambient temperature increases, the dc motor's maximum output torque decreases. 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 3) recommending adjustments to the rated torque value when sizing a nuclear qualified actuator. According to this table, a dc motor with a rated torque of 40 ft-lb would be sized as though it were a 39 ft-lb motor. (The recommended adjustment is greater for larger motors; for example, a motor rated at 60 ft-lb would become a 54 ft-lb motor at 340°F.)

Figure 10 contains the elevated temperature plots for the 40 ft-lb dc motor for 100% voltage. Our results show that the torque losses experienced by this motor at elevated temperature are greater than the losses indicated by the data provided by the manufacturer. The increase from room temperature to 250°F reduced the output torque by 8 to 10 ft-lb at high loads.

## GEARBOX EFFICIENCY

Gearbox efficiency, along with the overall actuator ratio, define the relationship between the input torque and the output torque of an actuator gearbox. The output torque can be represented by

$$T_{output} = T_{input}\ Eff_{gearbox}\ OAR \qquad (3)$$

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 actuator ratio (gear ratio)

The input torque consists of the torque delivered by the electric motor to the input side of the gearbox, and the output torque consists of the torque delivered to the stem nut. The gearbox efficiencies identified by the manufacturer are called the pullout efficiency, stall efficiency, and running efficiency. The pullout efficiency is the lowest of the three. This value applies when a 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 applies when the gearbox is operating at normal motor speed and normal loads.

Figure 11 includes two simple data plots showing the actuator torque (output torque) and the motor torque (input torque) measured during the 100 percent voltage test of the SMB-1 actuator with the 60 ft-lb ac motor. Figure 11 also includes an x-y plot of actuator torque versus motor torque, which represents the gearbox OAR times the actual gearbox efficiency. The two straight lines in the Figure 11 x-y plot are calculated using the OAR times the (a) published running efficiency and (b) he published pullout efficiency.

Figure 12 shows the motor torque and valve stem torque data for the SMB-1-60 reduced voltage tests, suggesting 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, but drops toward the pullout efficiency as the motor experiences higher loads and approaches stall. For this actuator, the published pullout efficiency bounds the actual gearbox efficiency for all tests at torque loads up to the motor's rated torque.

Similar data for the other ac valve actuators are presented in Figures 13 through 15. For the SMB-00-5 (Figure 13), the actual gearbox efficiency is well below the published pullout efficiency. For this actuator, the motor torque required to rotate the gear train without producing output torque (sometimes called the hotel load) is a significant percentage of the total motor torque. A more meaningful comparison of gearbox efficiency can be made by subtracting a hotel load of 0.44 ft-lb motor torque from the SMB-00-5 data. Figure 16 includes this 0.44 ft-lb offset, based on no-load motor torque measurements, to account for the hotel load. This provides a more meaningful comparison; however, the performance is still lower than the pullout efficiency. The data show the importance of considering the hotel load when determining the actuator capability for smaller motors.

Figure 17 presents the data from testing of the SMB-1-40 actuator when powered by the dc motor. The shape of the curves is slightly different than in Figures 12 through 16 (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-1-40 actuator powered by a dc motor, the actual gearbox efficiency was consistently lower than the published running efficiency. As the motor speed drops under high load, the actual efficiency drops to values well below the published pullout efficiency.

Finally, Figure 18 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 results are about the same for all three tests, indicating that the gearbox efficiency was not affected by elevated temperature.

Figure 18 also shows that the measured efficiency was slightly higher than the published pullout efficiency. By comparing this figure to Figure 14, we get an indication of the variation that can result 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.

## CONCLUSIONS

*Performance curves.* Analysis of the test results included a comparison of the published motor performance data with the actual current/torque and speed/torque data. 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 indicated 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.* With the measured ac motor torque at 100% voltage used as the basis for the calculation, the 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 results suggest that for these four ac motors, an exponent of 2.5 instead of 2 in the voltage squared calculation would bound actual torque losses due to operation at reduced voltage.

Using the rated torque in the voltage squared calculation (instead of the actual torque) will not provide a bounding estimate of torque losses unless the actual torque at normal voltage is significantly higher than the rated torque. For three of the ac motors we tested, the actual torque was at least 25% higher than the rated torque. For the other ac motor (the 60-ft-lb motor), the actual torque was very near the rated torque. For this motor, the voltage squared calculation does not provide a bounding estimate of torque losses, for either the rated or actual torque value used as the basis for the calculation.

The dc motor results were similar to the ac motor results; actual torque losses due to voltage degradation were greater than the losses estimated by the typical linear method used for predicting such losses. The results suggest that a formula similar to the voltage squared method, but with an exponent of 1.3, would provide a bounding estimate of the actual torque losses for this dc motor at locked rotor conditions. At a motor at a speed of 500 rpm, an exponent of about 1.8 would produce bounding estimates of torque losses.

*Elevated temperature*. For three of the ac motors, the actual motor output torques measured at elevated temperature were equal to or higher than the industry predictions of motor torque at those conditions. For the 25 ft-lb ac motor (not environmentally qualified), 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 torque prediction based on the actuator manufacturer's data for dc motor performance at elevated temperature overestimated the actual torque measured in the tests, and by a significant margin.

*Gearbox efficiency*. For most motor/gearbox combinations, the actual efficiencies were lower than the running efficiencies specified by the actuator manufacturer. In no case did the published running efficiency provide a lower bound for the actual efficiency of the gearbox when operating against high loads typical of design basis loads. Generally, the published pull-out efficiency bounded the actual gearbox efficiency at moderate loads, but in some instances it did not bound the actual gearbox efficiencies at higher loads at or near motor stall. It is important to consider the hotel load when determining the capabilities of actuators with smaller motors. Operation of the gearbox at elevated temperature did not affect the operating efficiency of the gearbox.

Gearbox efficiency tended to be lower with operation at lower speeds. This is particularly true for actuators powered by dc motors, because dc motors approach their highest output torque at low rpm. Higher gearbox efficiency corresponds 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.

## REFERENCES


1. Limitorque Technical Update #93-03, September 1993.

2. NUREG/CR-4977, *SHAG Test Series—Seismic Research on an Aged United States Gate Valve and on a Piping System in the Decommissioned Heissdampfreaktor (HDR)*, R. Steele, Jr., J. G. Arendts, Idaho National Engineering Laboratory, EGG-2505, 1989.

3. Limitorque SEL-5, November 9, 1988.

**Table 1.** Test hardware.

| | SMB-00-5ac | SMB-0-25ac | SMB-0-25ac | SMB-1-60ac | SB-1-40ac | SMB-1-40dc |
|---|---|---|---|---|---|---|
| Motor rated 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 |
| Motor rated speed (rpm) | 1700 | 1700 | 1700 | 1700 | 3400 | 1900 |
| Motor rated voltage | 460 vac 3$\phi$ | 460 vac 3$\phi$ | 460 vac 3$\phi$ | 460 vac 3$\phi$ | 460 vac 3$\phi$ | 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 |

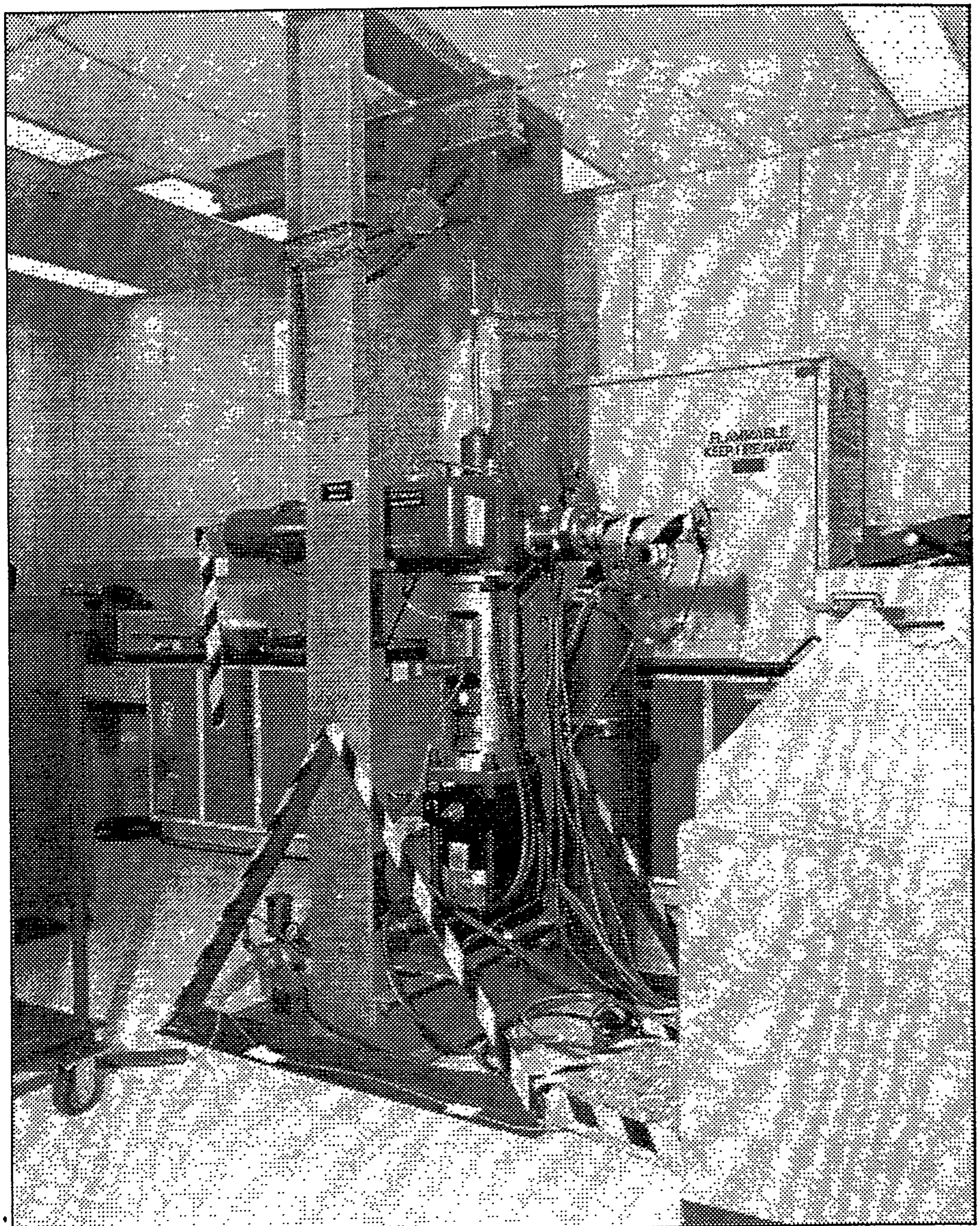

Figure 1. Photograph of the motor-operated valve load simulator (MOVLS).

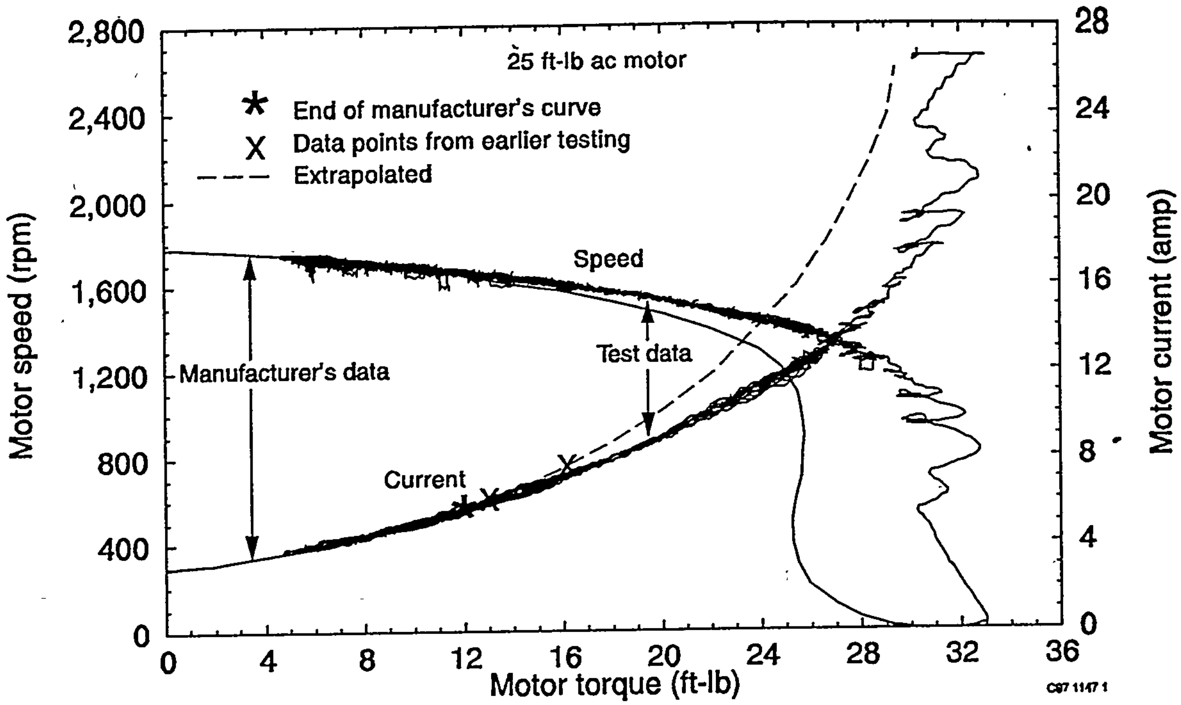


Figure 2. The 25 ft-lb motor produced more torque at the knee (1,000 rpm than predicted by the manufacturer.

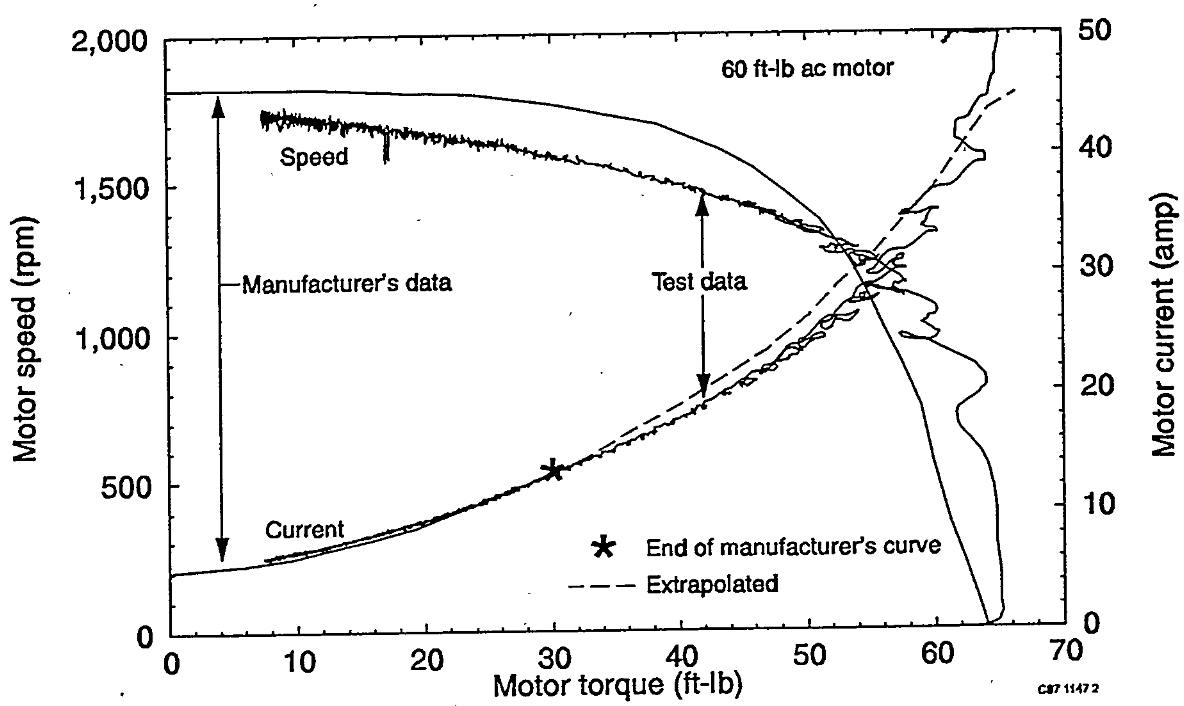


Figure 3. The 60 t-lb ac motor's speed/torque curves are different at lower loads but the torque at the knee (1,000 Rpm) is about the same.

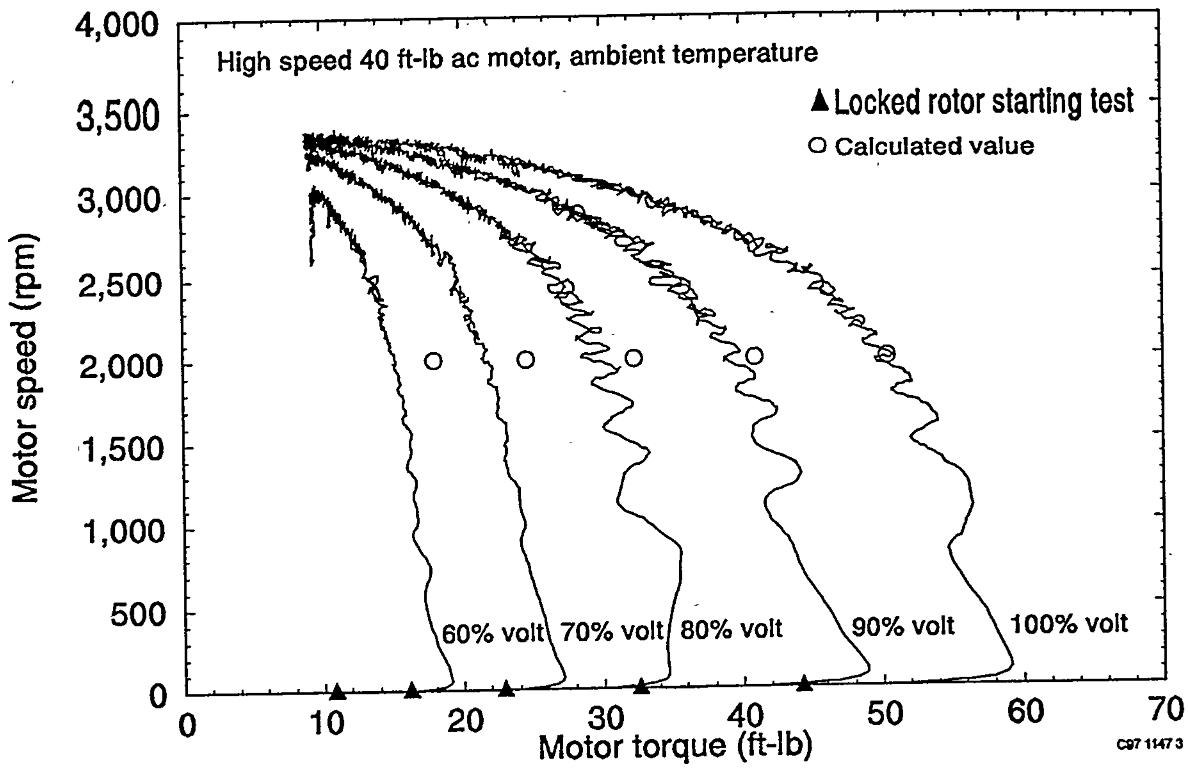


Figure 4. For the 40 ft-lb ac motor, the voltage squared calculation overestimates the actual torque at the knee (2,000 rpm).

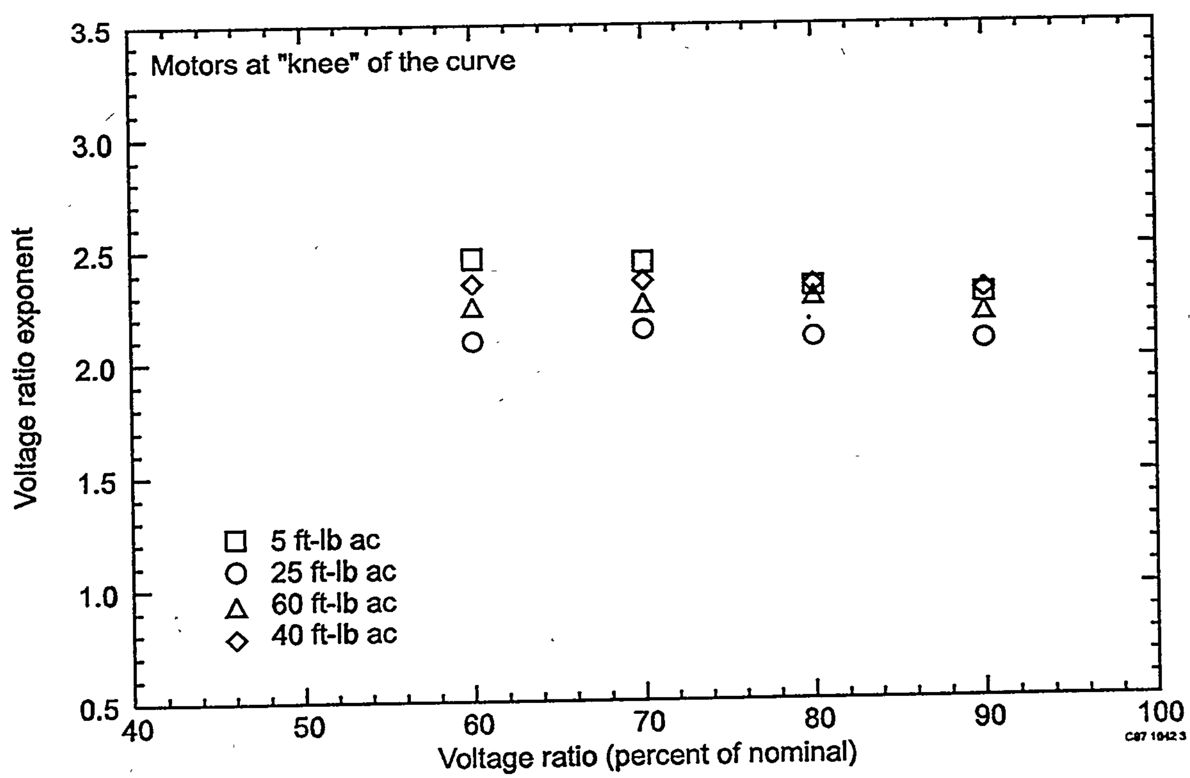


Figure 5. An exponent of 2.5 is a better bound of the INEEL data.

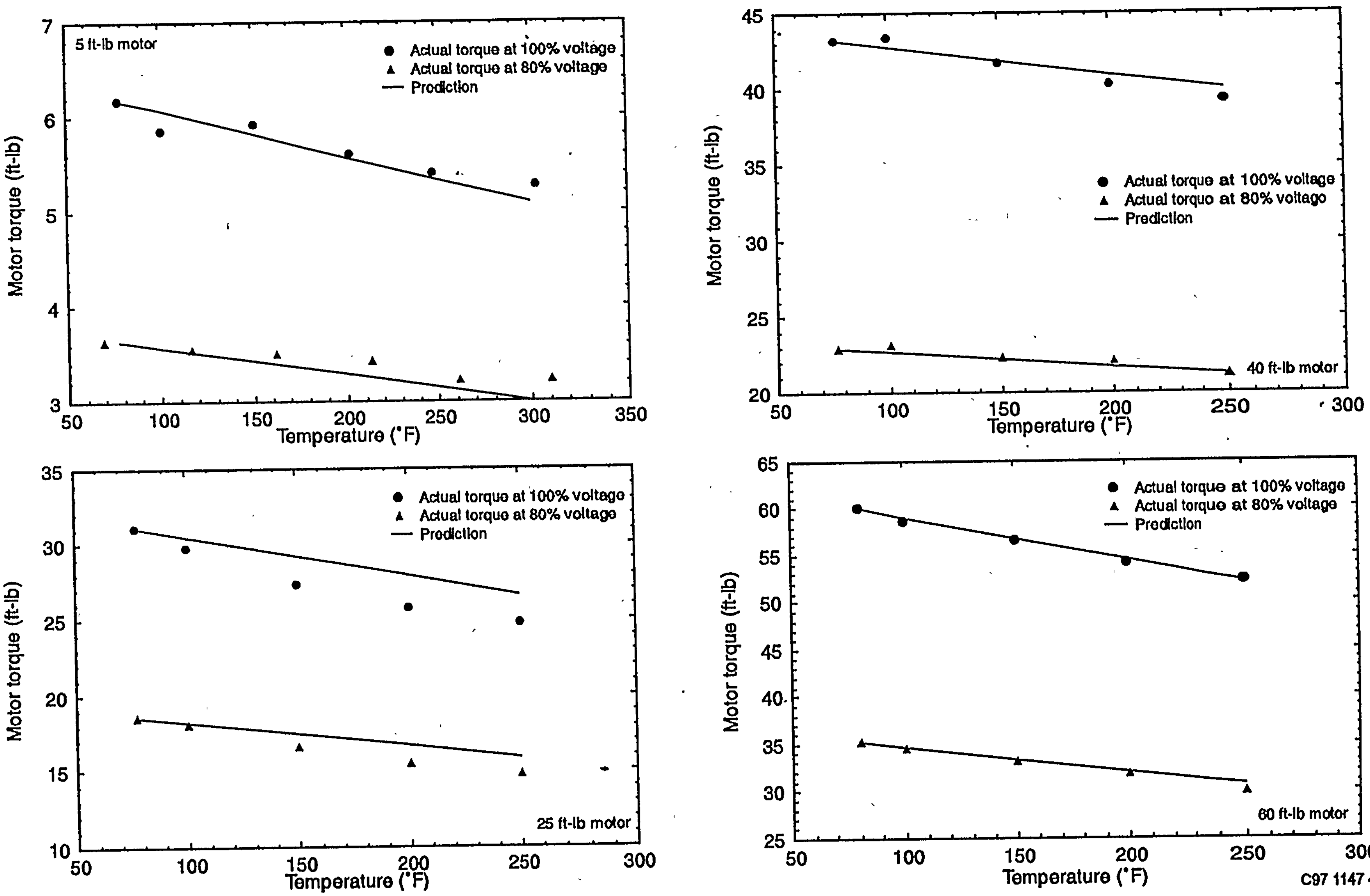


Figure 6. The predicted torque losses due to elevated temperature were equal to or greater than the actual losses for three of the four motors.

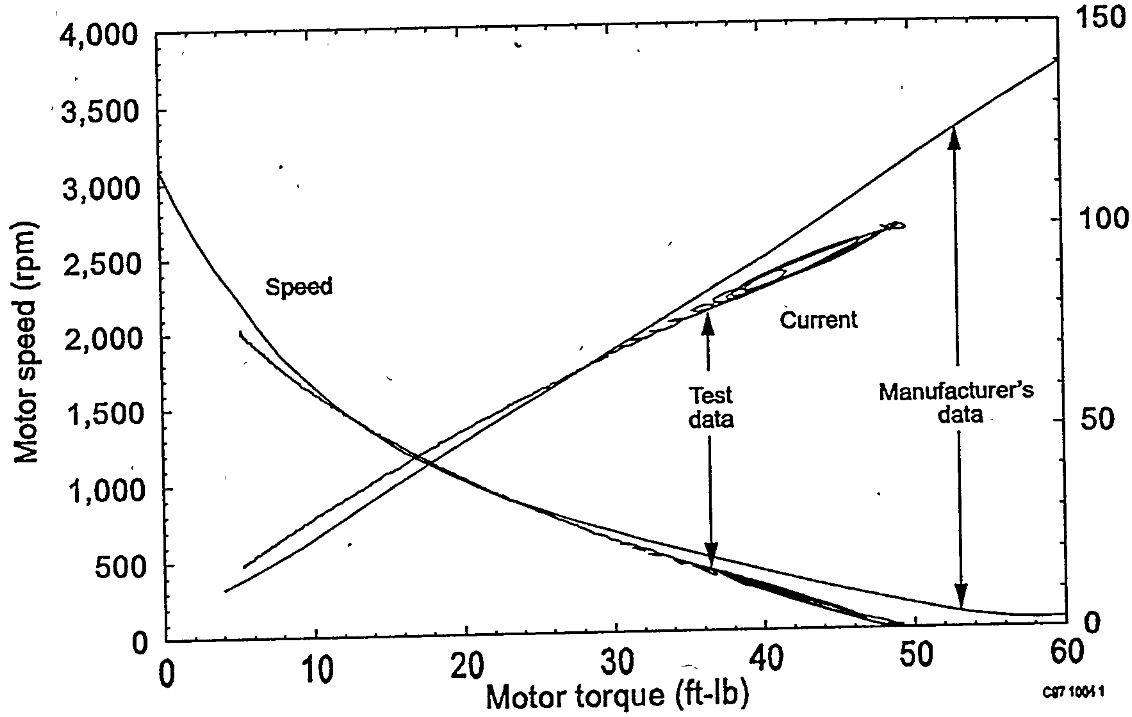


Figure 7. During testing of the 40 ft-lb dc motor, the actual torque output was lower than predicted by the manufacturer's curves.

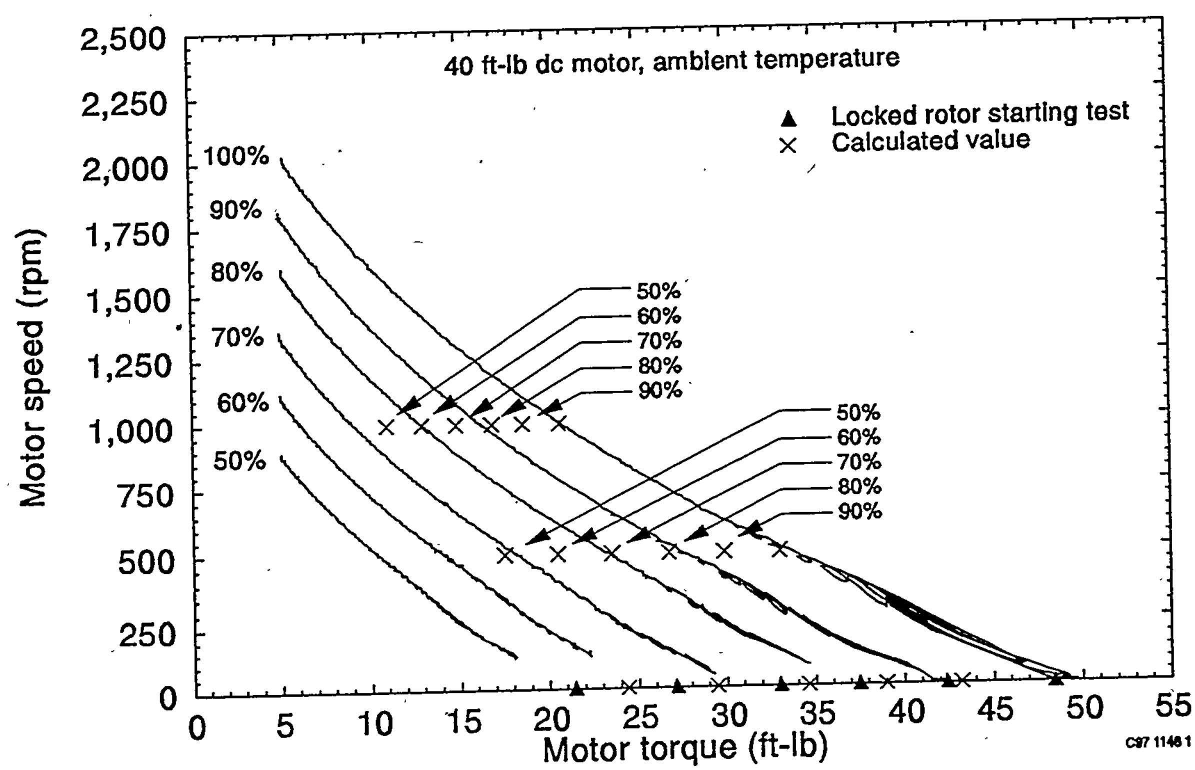


Figure 8. The conventional method for predicting torque loss at reduced voltage underestimated the actual losses.

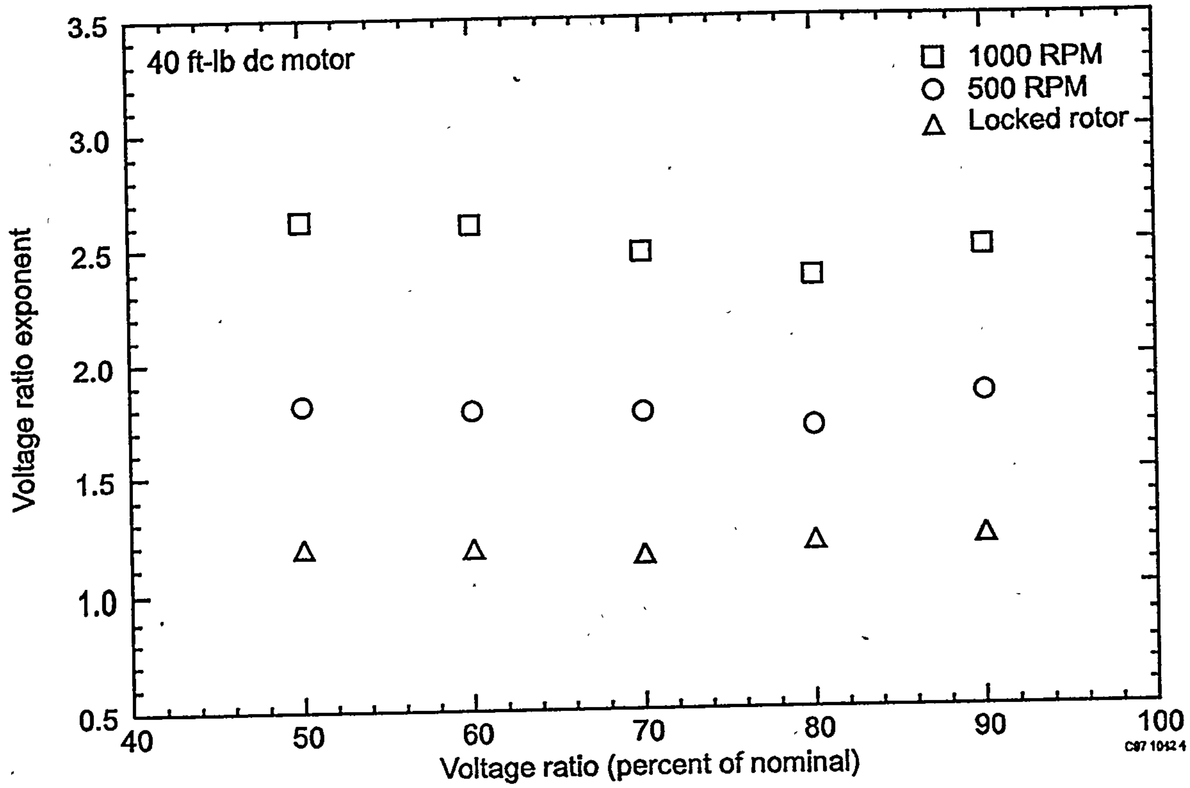


Figure 9. Exponents of 1.3 for locked rotor and 1.8 for 500 rpm would provide a better bound of the INEEL data.

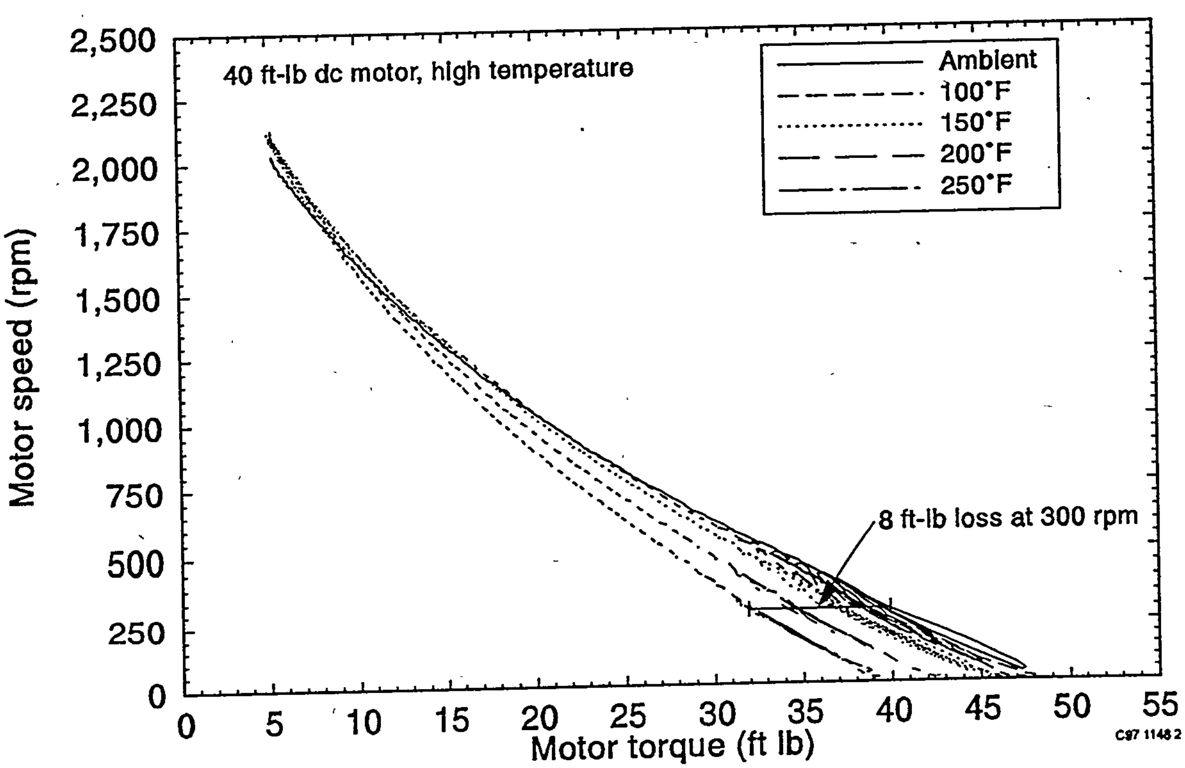


Figure 10. The temperature increase from ambient to 250°F reduced output torque by 8 ft-lb at high loads.

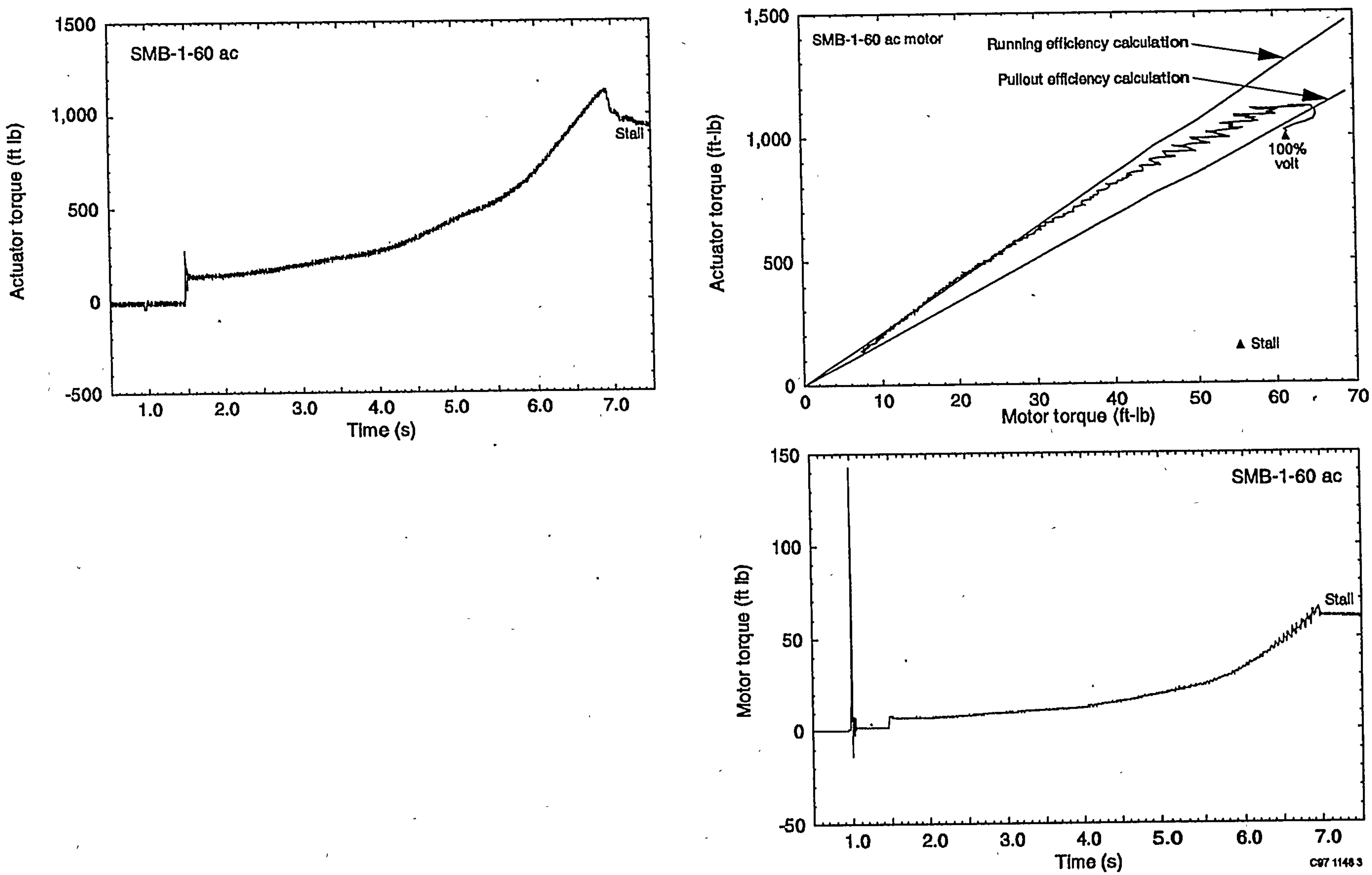


Figure 11. Gearbox efficiency was calculated from actual operator torque (valve stem torque) and motor torque measurements.

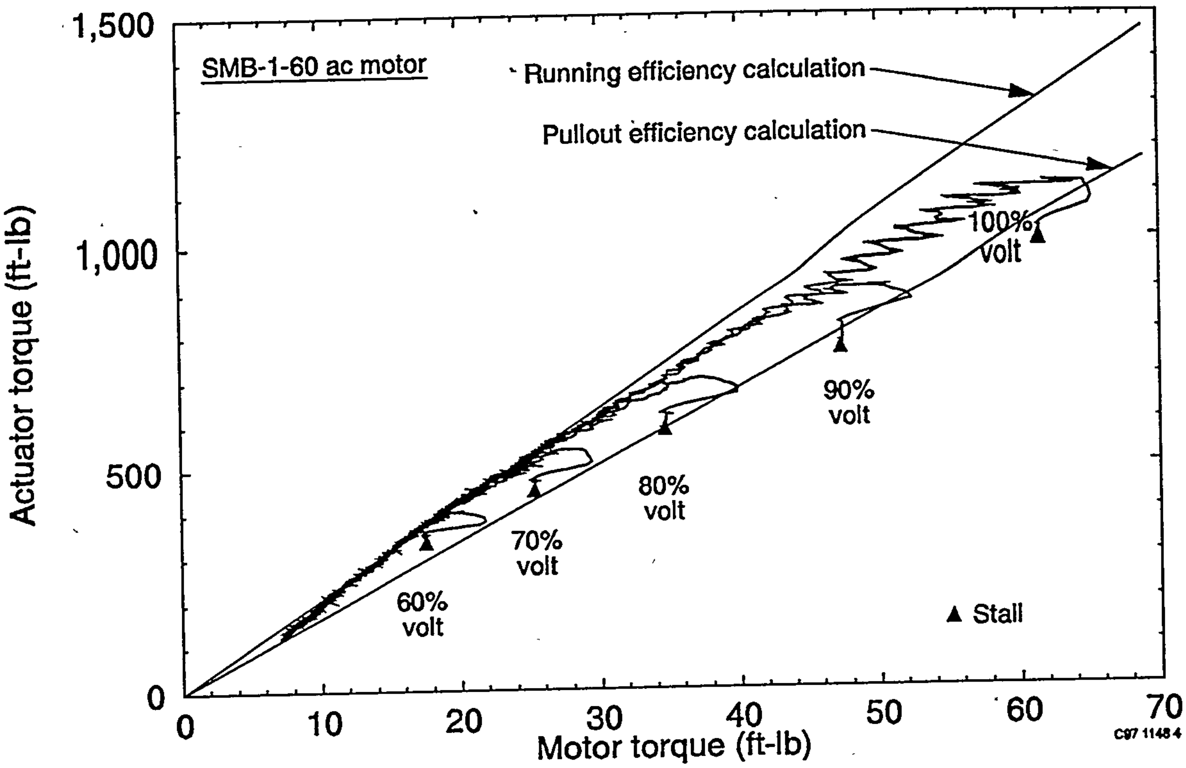


Figure 12. For each of the SMB-1-60 ac actuator reduced voltage tests, gearbox efficiency drops as loads increase and motor speed drops.

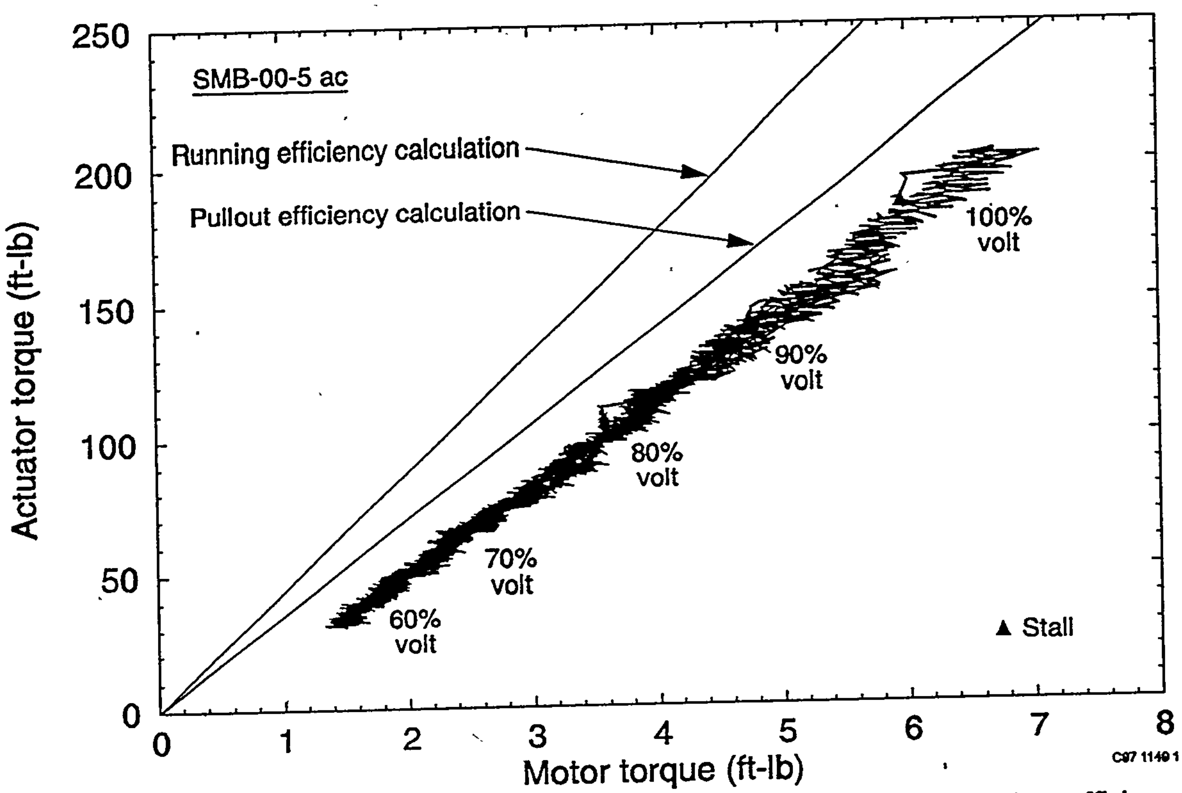


Figure 13. For each of the SMB-00-5 ac actuator reduced voltage tests, gearbox efficiency was below pullout efficiency.

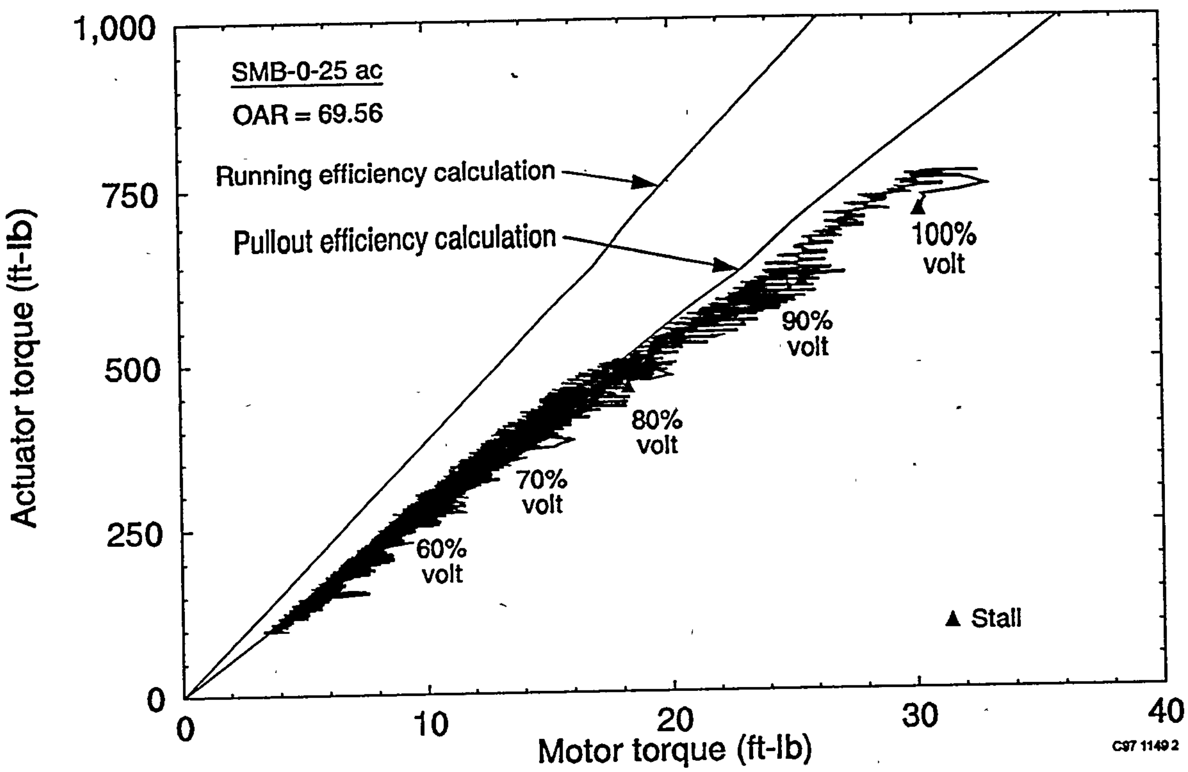


Figure 14. For each of the SMB-0-25 ac actuator reduced voltage tests, gearbox efficiency drops as loads increase and motor speed drops.

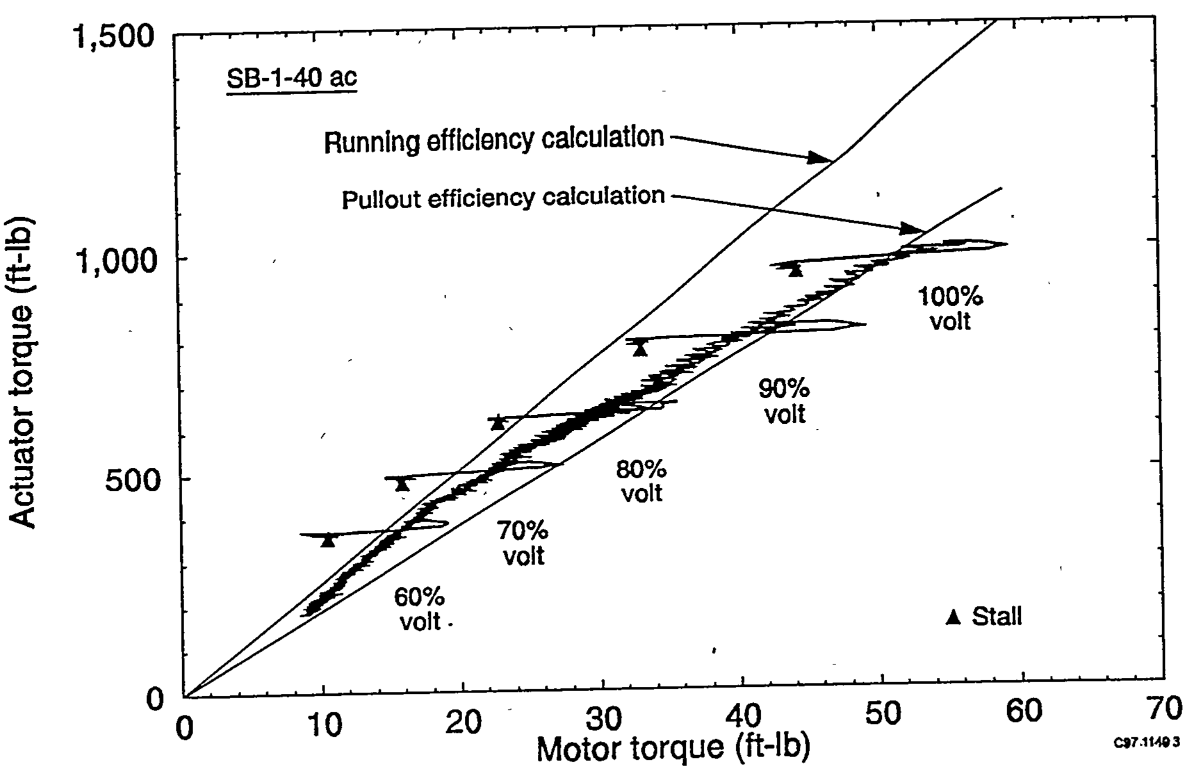


Figure 15. For each of the high speed SB-1-40 ac actuator reduced voltage tests, gearbox efficiency drops as loads increase and motor speed drops.

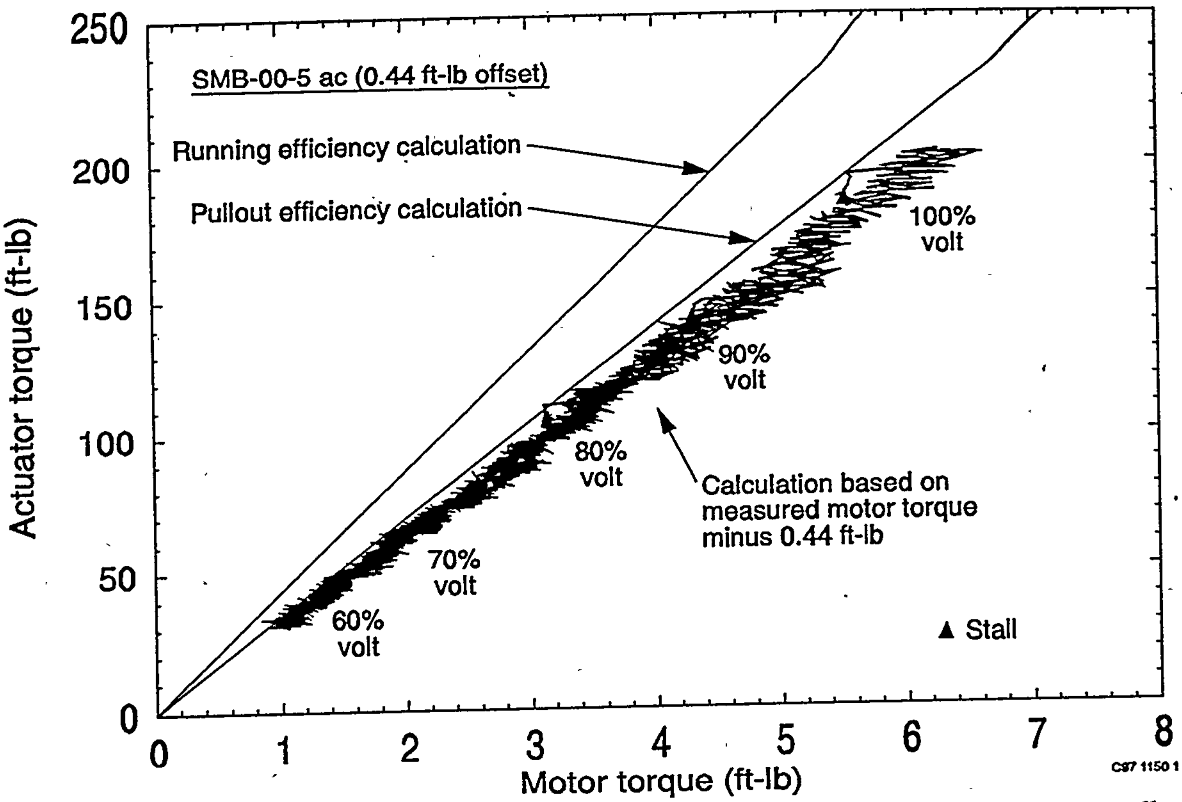


Figure 16. Hotel load should be considered when determining the actuator capability for smaller motors.

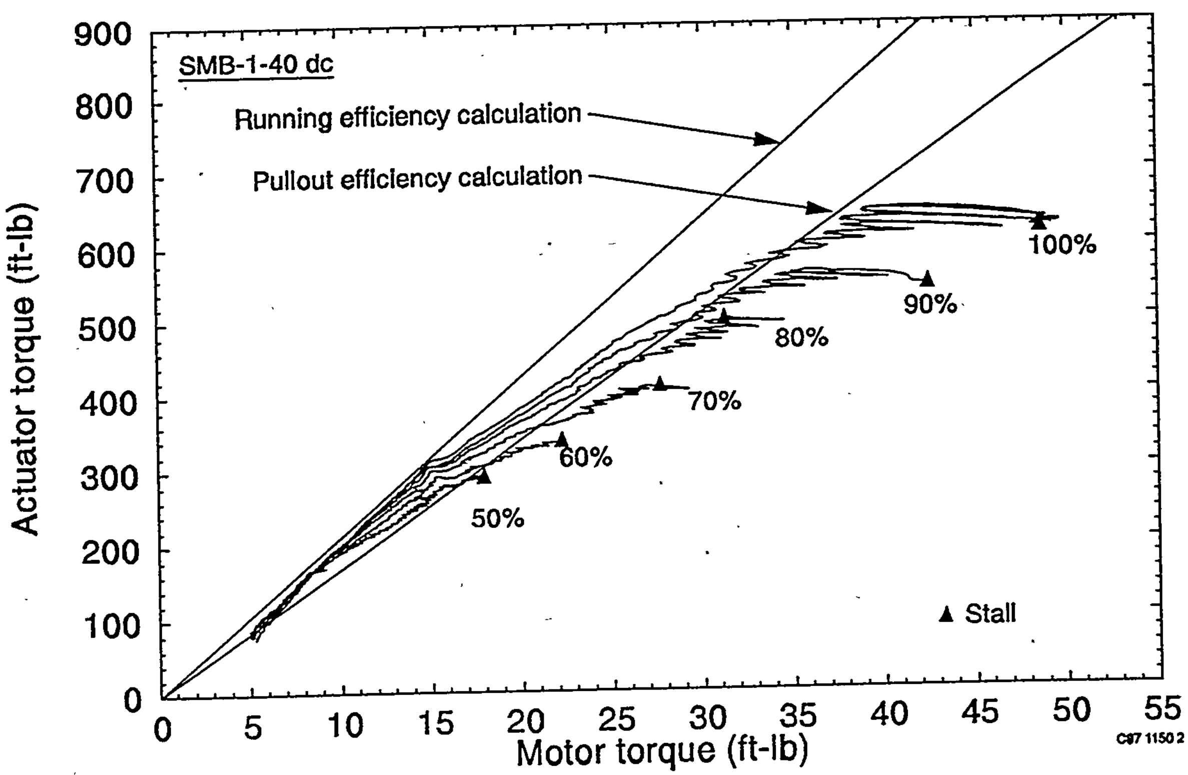


Figure 17. Actuators with dc motors are particularly sensitive to reductions in efficiency at high loads.

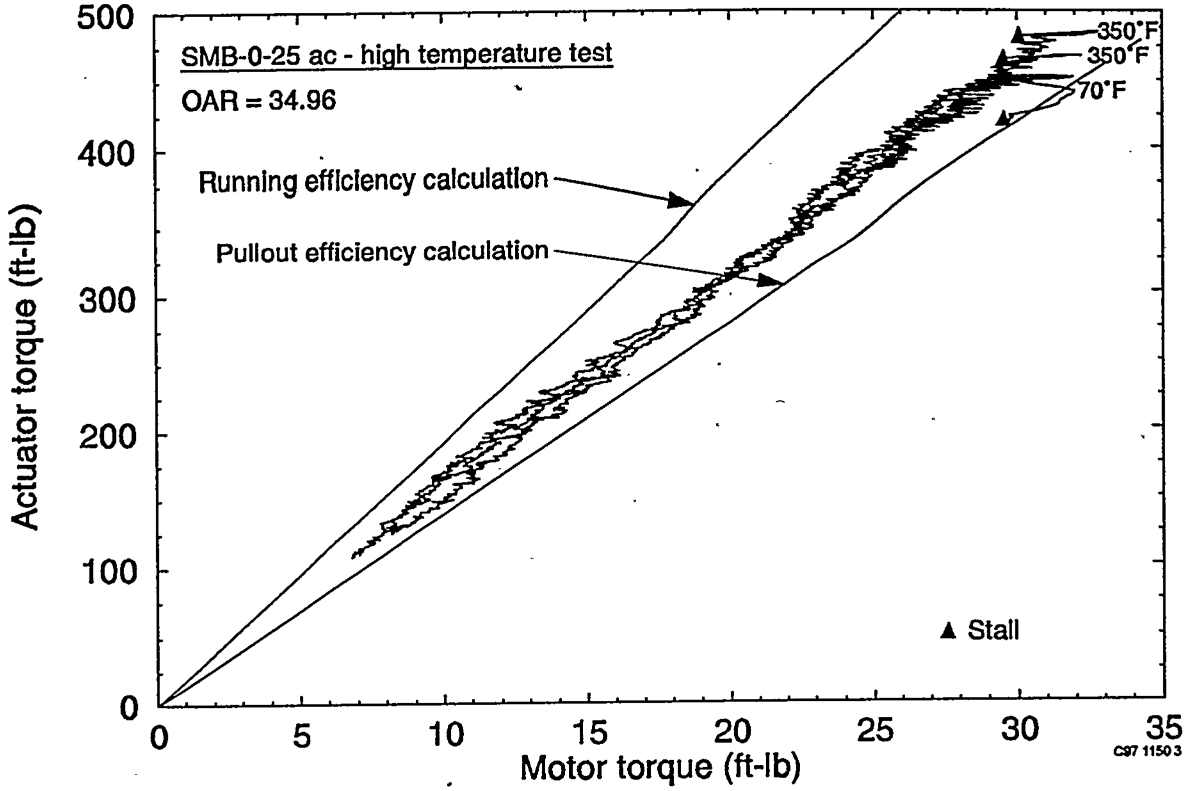


Figure 18. Gearbox efficiency is not affected by elevated temperature; faster gear sets improve actuator gearbox efficiency.