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Testing of dc-Powered Actuators for Motor-Operated Valves

Idaho National Engineering and Environmental Laboratory
Lockheed Martin Idaho Technologies Company

U.S. Nuclear Regulatory Commission
Office of Nuclear Regulatory Research
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ABSTRACT

This report documents the results of dc-powered motor-operated valve (MOV) 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 MOVs in nuclear power plants. The tests described in this report measured the capabilities of typical dc-powered valve actuators during operation at simulated 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 four typical dc electric motors and two 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 and the efficiency of the actuator-torque/stem-thrust conversion at the valve-stem/stem-nut interface (stem nut coefficient of friction). The testing produced the following results:

- For both of the actuator gearboxes we tested, the actual running efficiencies were lower than the published running efficiencies. Below certain motor speeds, actual pullout efficiencies were lower than the published pullout efficiencies. Because of the decrease in gearbox efficiency at low-speed, high-torque operation, increases in motor torque at motor speeds lower than about 200 to 300 rpm failed to produce a corresponding increase in actuator output torque. Thus, in these MOV applications, a dc motor speed threshold of about 200 to 300 rpm represents the lower limit for production of usable output.

- For the motors we tested, estimates that anticipated linear reductions in both motor torque and motor speed fell very close to actual dc motor performance at reduced voltage. However, in some instances the actual and predicted performance fell below the motor speed threshold identified in the previous paragraph. The conventional linear method used in the industry for predicting reduced-voltage-related torque losses underestimated the actual torque losses; this comparison looked at the same motor speed in tests at different voltages.

- For all four motors, the actual motor torque losses due to elevated temperature conditions were significantly greater than losses indicated by the manufacturer's published data. The motor torque loss was approximately linear with the change in temperature.

- For all four motors, changes in running load had significant effects on valve stroke times. Longer stroke times combined with operation at low speeds and high loads cause additional motor heating and further degradation in motor performance.

- At normal voltages and temperatures, two motors produced torque at or above the torque indicated by the manufacturer's published torque/current and torque/speed curves. Two motors produced less torque than indicated by the manufacturer's curves.

- For all four motor/gearbox combinations, the high loads and slower speeds had little effect on the stem nut coefficient of friction.

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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 design basis 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 dc-powered electric motors and actuator gearboxes 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:

- *Gearbox efficiency.* What is the actual efficiency of the actuator gearbox, and how do high loadings and low motor speeds affect the actual efficiency? How does the actual efficiency compare with the manufacturer's published efficiency values?

- *Reduced voltage.* How does the output torque, current, and speed of the dc motors change as the voltage supplied to the motor decreases? How do these measured values of torque, current, and speed compare with estimates produced by typical analytical predictions?

- *Elevated temperature.* How does the output torque, current, and speed of the dc motors change as the operating temperature of the motor increases? How do these measured values of torque, current, and speed compare with estimates produced by typical analytical predictions?

- *Stroke times.* How does the output torque, current, and speed of the dc motors change as the motors heat up under high load conditions? How does stroke time change with increasing load?

- *Performance curves.* How does the actual output torque, current, and speed of the dc motor compare with the torque, current, and speed characteristics published by the manufacturer?

- *Stem/stem-nut coefficient of friction.* What are the actual valve-stem/stem-nut efficiency and load-sensitive behavior characteristics? How do the high loadings and low motor speeds affect these characteristics?

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 parameters.

In this test program, we tested three combinations of actuator gearboxes and electric motors:

- An SMB-0 actuator equipped with a 10-ft-lb dc motor
- An SMB-0 actuator equipped with a 25-ft-lb dc motor
- An SMB-1 actuator equipped with a 40-ft-lb dc motor.

Our research also included analysis of data from previous testing of an SMB-1 actuator with an older 40-ft-lb dc motor.

The tests included normal stroke tests and stall tests, with baseline tests at room temperature and normal voltage, a series of tests at various stages of degraded voltage, a series of tests at various stages of elevated operating temperature, and tests at selected combinations of the two conditions. 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. Likewise, continuous measurements of valve stem torque and thrust allowed us to monitor the stem nut coefficient of friction during the entire test.

We observed that the motor temperature typically increased by about 30 to 50°F during a single stroke with the motor operating at a load approaching the motor stall load. We also observed a small reduction in voltage at the motor during the stroke. This voltage reduction was due to line losses and to a voltage drop at the laboratory's dc power supply. These motor heating and voltage reduction phenomena are similar to phenomena that are likely to occur in the field. In these tests, the motor heating and voltage reduction phenomena affect the analysis of the results as they relate to the degraded voltage tests, the elevated temperature tests, and the motor performance curve evaluations. To account for these phenomena in the degraded voltage and elevated temperature tests, we used the actual voltage and the actual motor temperature, rather than the nominal starting voltage and temperature, in all analyses of the data, including analyses that involve predicted performance using either industry standard tools or INEEL tools. Using this approach allowed us to leave the test data intact (report actual performance), while accounting for the temperature and voltage differences in the predictions. The evaluation of motor performance curves compares test data with the theoretical performance data published by the manufacturer. In those evaluations, we accounted for the temperature and voltage differences by adjusting the test data, creating a theoretical curve, based on test data, for comparison with the theoretical curves published by the manufacturer.

The results of the tests are summarized in the following paragraphs, with main topics indicated in italics.

Gearbox efficiency. 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 pullout efficiency was adequate for predicting gearbox performance for some gearboxes and at some conditions (moderate loads), but at very low speeds, some of the actual efficiency data fell below the published pullout efficiency.

Each gearbox appears to have a minimum speed below which the pullout efficiency is not longer bounding. This friction effect resulted in a threshold motor speed below which additional motor torque produced little or no additional actuator torque. For all four actuators we tested, this motor speed threshold was at about 200 to 300 rpm. For these actuators, motor torque produced at high loads below this motor speed threshold cannot be relied upon to produce the necessary actuator output torque.

Degraded voltage. For the motors we tested, estimates that anticipated linear reductions in both motor torque and motor speed fell very close to actual dc motor performance at reduced voltage. Note, however, that in some instances, the actual and predicted performance fell below the motor speed threshold identified in the previous paragraph. (High motor torque values that fall below the threshold cannot be relied upon to produce correspondingly high actuator output torque.) The conventional linear method used in the industry for predicting reduced-voltage-related torque losses underestimated the actual torque losses; this comparison looked at the same motor speed in tests at different voltages.

Elevated temperature. In elevated temperature testing of the dc motors we tested, the adjustments recommended by the manufacturer for accounting for torque losses due to motor heating underestimated the actual torque losses. Elevated temperature had an immediate effect on dc motor output torque; the motor torque reduction was approximately linear with the change in temperature.

Stroke times. Changes in running load had significant effects on valve stroke times. The results suggest that longer stroke times combined with operation at low speeds and high loads can cause additional motor heating, which would further degrade motor performance.

Performance curves. The actual performance of three of the four dc motors (torque output at a given speed) was below that indicated by the manufacturer's generic curves. For example, the manufacturers published curve for the 25-ft-lb motor indicated a torque of 40 ft-lb at motor stall, while the test data showed a torque of about 30 ft-lb. However, some line voltage drop and motor heating occurred during the run. With the motor speed data and the motor torque data adjusted for voltage drop, and with motor torque data adjusted for temperature, the performance of the 10-ft-lb dc motor was well above that predicted by the manufacturer's curves, while the performance of the 25-ft-lb dc motor matched the manufacturer's curves very well.

The newer 40-ft-lb dc motor performed about the same as the older 40-ft-lb dc motor. The performance of both motors was below that predicted by the manufacturer's generic curves, even after adjustments for voltage and temperature.

Stem/stem-nut coefficient of friction. The high loads and slower speeds had little effect on the stem/stem-nut coefficient of friction in the actuators we tested. We found no additional rate-of-loading concerns for dc motor actuators beyond those applicable to ac motor actuators.

ACKNOWLEDGMENTS

We acknowledge the following INEEL staff who assisted in making this project a success. We thank Jerry Edson for this help with the electrical inspections of the test hardware and for his technical insights on the performance of dc motors. Thanks also to Mark Holbrook for keeping us in touch with reality. A special thanks to Christine White, the graphic artist who prepared the many data plots for this report.

We acknowledge Rodger Carr and Chris Smith of Crane Nuclear, Inc. for providing technical insights that helped to make this project a success and for providing a dc motor for the test program.

Testing of dc-Powered Actuators for Motor-Operated Valves

1. INTRODUCTION

During the past several years, the Nuclear Regulatory Commission (NRC) has supported research addressing the performance of motor-operated valves (MOVs) installed in nuclear power plants. This research included tests and analysis to determine the capability of safety-related MOVs to close (or open) when subjected to the conditions specified in the plant's design documents. For some safety-related MOVs, 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 recent tests sponsored by the NRC and performed by the Idaho National Engineering and Environmental Laboratory (INEEL) to address factors that affect the performance of MOV dc electric motors and actuator gearboxes on rising stem valves (gate valves and globe valves).

1.1 Background

A typical motor-operated gate valve (Figure 1) consists of two main components: the actuator and the valve. The actuator assembly includes an electric motor (either ac or dc) and a gearbox. The gearbox typically includes a set of reduction gears and a worm/worm-gear/stem-nut assembly that drives the valve stem (see Figure 2). The main concern is whether the actuator is capable of producing sufficient thrust in the stem to open or close the valve against specific design basis loads. Several variables can affect the performance dc-powered valve actuators. These variables include:

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

b. The control switch setting

c. The efficiency of the actuator gearbox

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

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

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

Of these variables, the only one that can be determined easily is item *b*.

Figure 2 shows the components involved in items *a* through *f* in a typical valve actuator. The worm drives the worm gear, which turns the stem nut on the stem, driving the stem in either the open or closed direction. The stem/stem-nut interface is the point where the rotary motion in the actuator gearbox is converted to linear motion of the valve stem and disc. Friction at this interface contributes to the load that the actuator must overcome in order to move the disc. Thus, it can be said that item *a* combined with the valve stem load creates a load that makes the stem nut difficult to turn on the stem, and that the actuator must deliver a certain amount of torque (actuator output torque) to the worm-gear/stem-nut assembly in order to overcome that load.

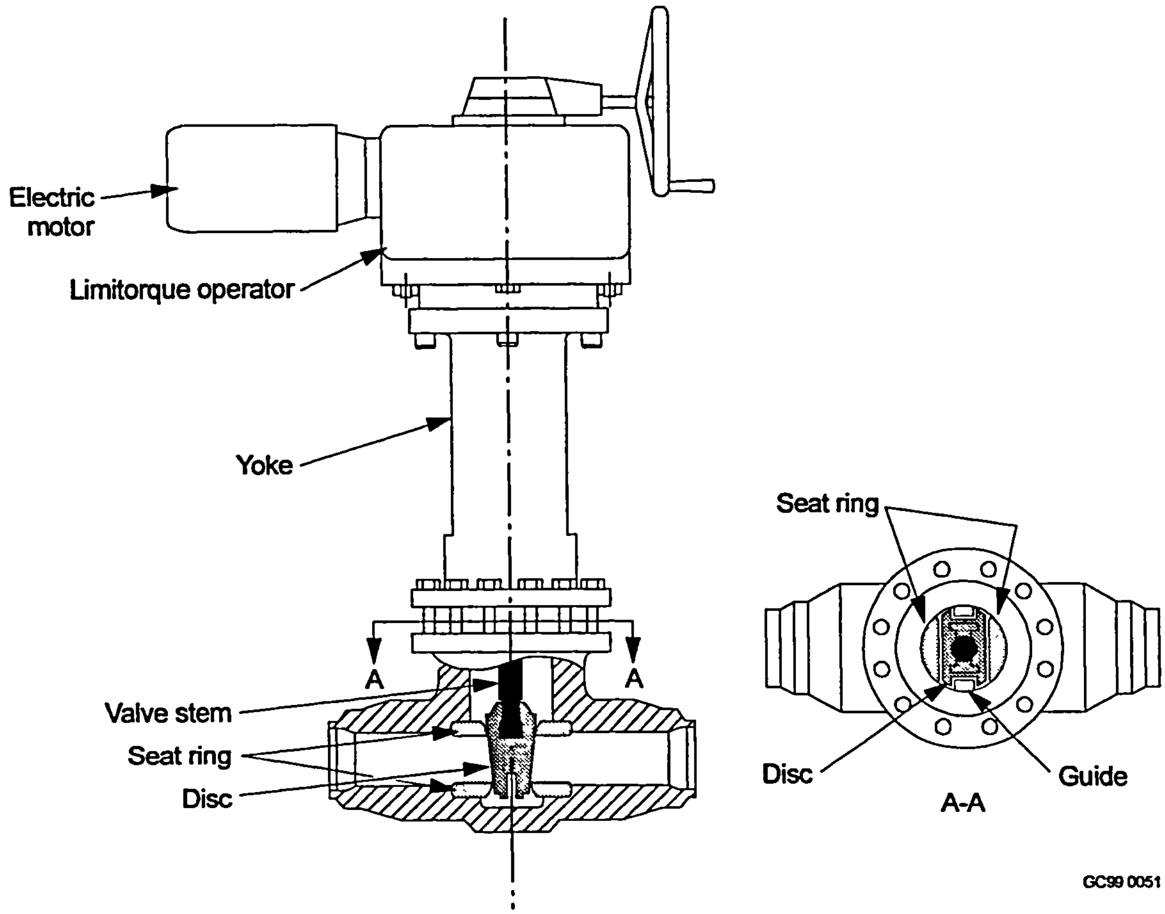


Figure 1. Diagram of a motor-operated gate valve.

While item *a* involves forces that must be overcome by the valve actuator, items *c* through *f* involve the torque the actuator can provide to overcome those forces. The torque switch (item *b*) 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 2), 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.

1.2 Earlier Testing

In 1995 and 1996, we performed research to evaluate the operation of the electric motor and the actuator gearbox at typical design basis conditions, including operation at degraded voltage and elevated temperature (Reference 1). We tested five typical electric motors (four ac motors and one dc motor) and three gearboxes at conditions a valve actuator might experience in a power plant, including such

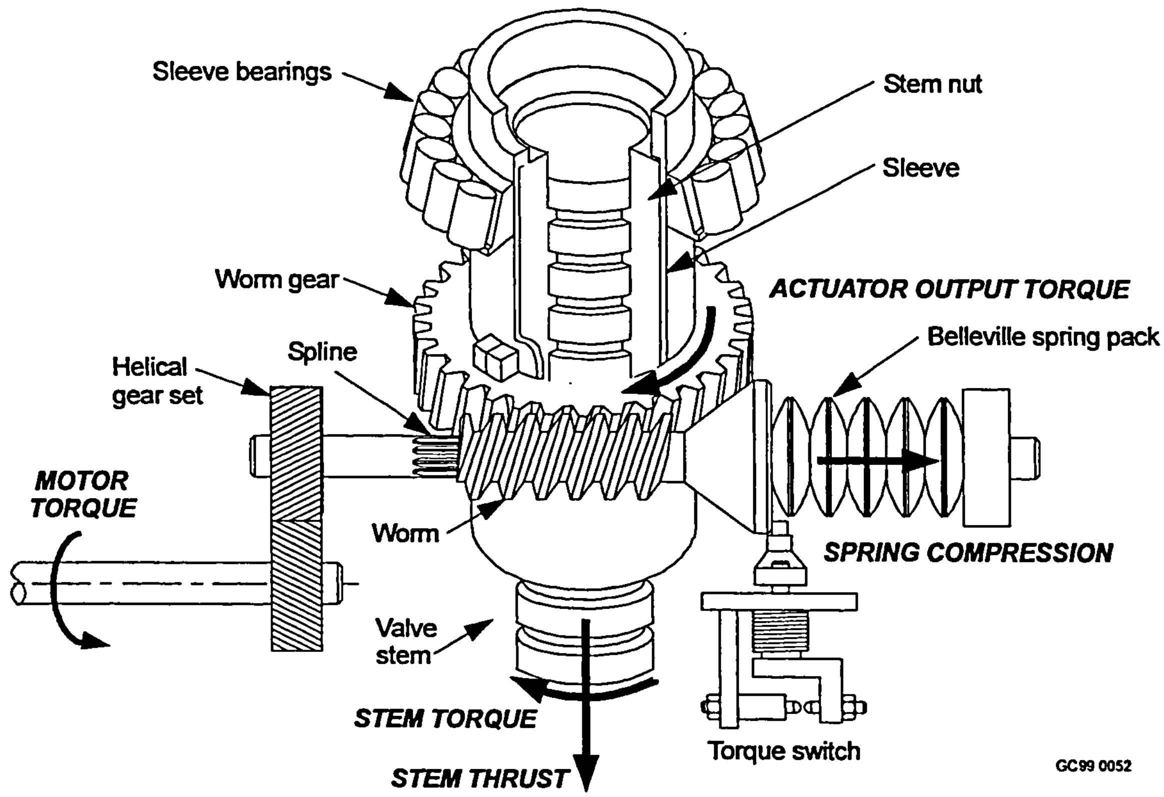


Figure 2. Diagram of the main components inside an actuator gearbox.

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

All of the equipment was well conditioned from previous use in other test programs. The dc motor came from the decommissioned Shippingport nuclear power station. It had been subjected to several seismic tests and had been rewound (in Germany) and tested by the manufacturer.

After the results of the earlier actuator tests were published in 1997, the actuator manufacturer developed updated technical information for its ac-powered valve actuators (References 2 and 3). However, some concerns remained about the applicability of the results of the dc motor testing, because of the small sample size (one motor) and because of the motor's age and repair history. To answer those concerns, we conducted another set of tests investigating the performance of three additional dc-powered valve actuators. This report describes those tests and presents the results. Where applicable, results from the earlier testing of the older dc motor are included and reevaluated.

1.3 Scope

The testing described in this report focused on the performance characteristics of dc motors, on the efficiency of the actuator gearbox, and on the efficiency of operation at the valve-stem/stem-nut interface. Specifically, the testing addressed the following questions:

- What is the actual efficiency of the actuator gearbox, and how do high loadings and low motor speeds affect the actual efficiency? How does the actual efficiency compare with the manufacturer's published efficiency values?
- How does the output torque, current, and speed of the dc motors change as the voltage supplied to the motor decreases? How do these measured values of torque, current, and speed compare with estimates produced by typical analytical predictions?
- How does the output torque, current, and speed of the dc motors change as the operating temperature of the motor increases? How do these measured values of torque, current, and speed compare with estimates produced by typical analytical predictions?
- How does the output torque, current, and speed of the dc motors change as the motors heat up under high load conditions? How does stroke time change with increasing load?
- How does the actual output torque, current, and speed of the dc motor compare with the torque, current, and speed characteristics published by the manufacturer?
- What are the actual valve-stem/stem-nut efficiency and load sensitive behavior characteristics? How do the high loadings and low motor speeds affect these characteristics?

2. TEST DESIGN

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 was not necessary to conduct the tests with an entire valve assembly with a flow load imposed on the valve. Instead, it was possible to test the valve actuator under simulated loads. The actuator was fully instrumented to measure important parameters, and each actuator was subjected to a series of tests designed to simulate various normal and off-normal conditions.

2.1 Test Equipment

The tests were performed on the motor-operated valve load simulator (MOVLS), a test stand owned by the NRC and built by the INEEL. The MOVLS, shown in Figure 3, 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 initial water level and gas pressure in the accumulator control the specific valve load profile. 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 piston bottoms out in the cylinder.

For the dc power supply in these tests, we used a large battery charger removed from the decommissioned Shippingport nuclear power station as part of the NRC's Aging Research Program. We connected the battery charger to a three-phase, 60-amp-per-leg ac autotransformer, which was connected, in turn, to the laboratory's 460-volt ac power supply. Standard output for the dc battery charger was 125 volts dc. To conduct the reduced voltage tests, we changed the settings on the ac autotransformer that supplied the battery charger.

We tested three combinations of actuator gearboxes and electric motors, using three dc motors and two gearboxes. The gearboxes were well conditioned from previous use in other test programs. The 10-ft-lb motor was purchased from the spare parts supply of a nuclear plant that had shut down. The 25-ft-lb motor was purchased new, fully qualified, from the FTI Nuclear Parts Center, the parts supplier approved by the actuator manufacturer. The newer 40-ft-lb motor was lent to us by Crane's valve diagnostic test program.

The SMB-1 actuator was tested with the 40-ft-lb dc motor installed. The SMB-0 actuator was tested with two different dc motors, the 25-ft-lb motor and 10-ft-lb motor, and two different sets of helical gears in the gearbox. Table 1 summarizes the information provided by the motor manufacturers and the actuator manufacturer about the three actuator combinations, including the gear ratios of the helical gear sets. Table 1 also includes information about the older 40-ft-lb motor and the actuator tested under the previous research effort. Table 2 shows the motor nameplate information for each motor. Both the newer 40-ft-lb motor and the older 40-ft-lb motor are equipped with Class B electrical insulation. The 10-ft-lb motor and the 25-ft-lb motor are environmentally qualified motors equipped with RH insulation.

The Class B insulation designation refers to an industry standard classification of the thermal tolerance of the motor winding. The classification indicates the maximum (hot spot) temperature at which the insulation can be operated for the normal expected service life of the motor. Class H insulation has a longer nominal life at a given operating temperature than Class B, or for a given life it can survive higher temperature. Class H insulation is qualified for the nuclear containment environment, while Class B insulation is qualified only for the milder, non-containment environment. The Type R designation is used for insulation designed to meet special requirements for radiation resistance.

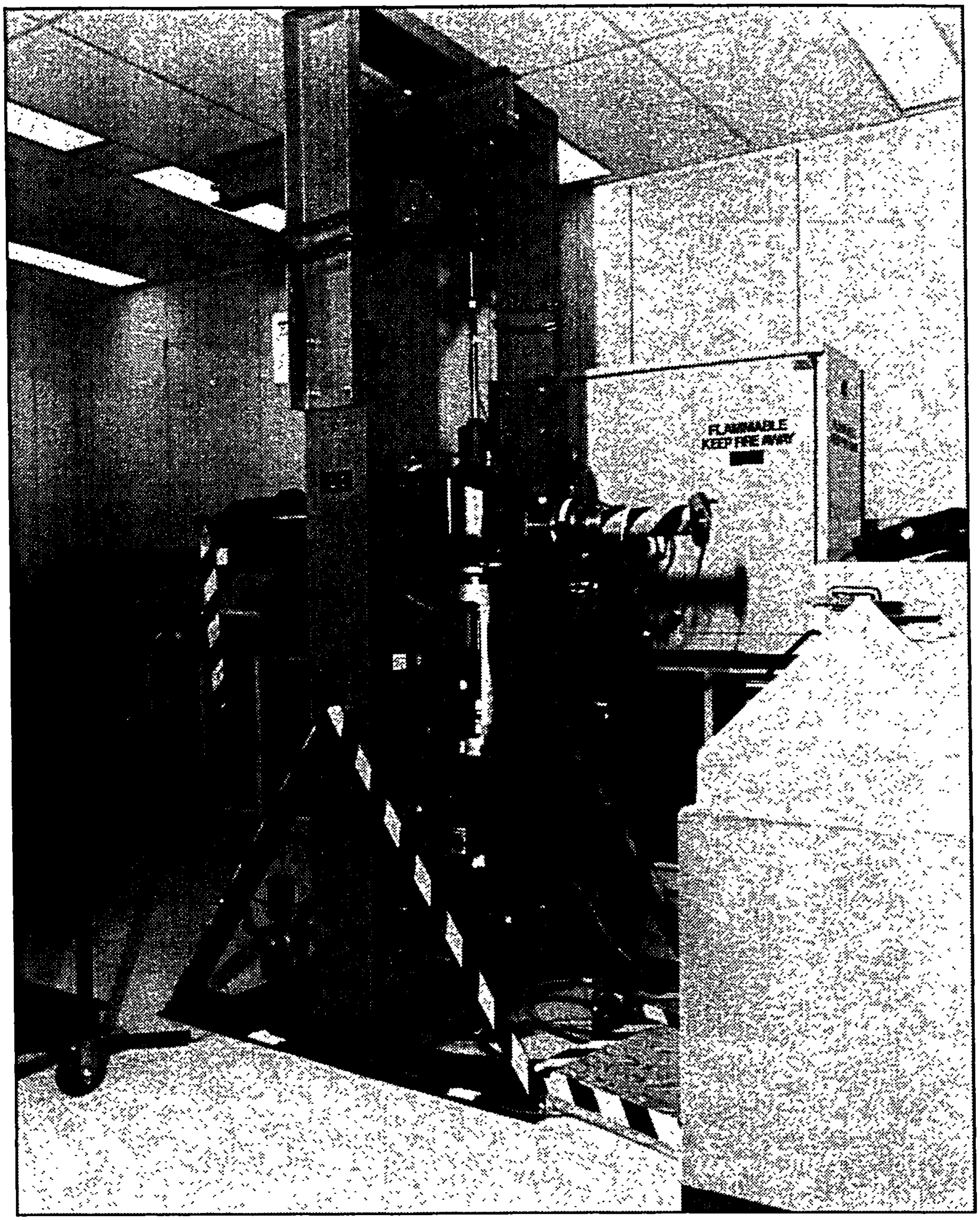


Figure 3. Photograph of the motor-operated valve load simulator (MOVLS).

Table 1. Actuator information.[a]

	SMB-1-40	SMB-0-25	SMB-0-10	Old SMB-1-40
Motor Rated Torque (ft-lb)	40	25	10	40
Motor Stall Torque (ft-lb)	62	40	16	63
Motor Speed (rpm)	1900	1900	1900	1750
Motor Gear Set Ratio	32:40	37:35	25:47	32:40
Worm Gear Ratio	34:1	37:1	37:1	34:1
Overall Ratio (OAR)	42.50	34.96	69.56	42.50
Running Efficiency	0.50	0.55	0.50	0.50
Pullout Efficiency	0.40	0.40	0.40	0.40
Stall Efficiency	0.50	0.55	0.50	0.50
Stem Diameter (in)	2.13	1.75	1.25	2.13
Stem Pitch/Lead	1/4:1/2	1/4:1/4	1/4:1/2	1/4:1/2
Stem Speed (in/min)	22.4	13.6	13.7	22.4

a. Data provided by Peerless Electric Division, H. K. Porter Company, Inc. and Limitorque. Gearbox efficiency data from References 4 and 5.

2.2 Instrumentation

The MOVLS was instrumented to take all the measurements that are important for diagnosing valve actuator performance. Motor speed was measured with a tachometer connected directly to the motor shaft with a timing belt. The electrical measurements included dc line current and voltage, as well as current and voltage for the individual motor components (shunt field, series field, and armature). Motor temperature was determined by a combination of motor winding resistance measurements and thermocouples applied to the motor surface. (Since resistance is a function of conductor temperature, motor winding temperature can be calculated from current and voltage measurements.) Manual motor winding resistance measurements were also recorded periodically during the testing. 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 2.) 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. Table 3 lists the instruments and instrumentation calibration requirements used in the testing.

Table 2. Motor nameplate information.

	40-ft-lb motor	25-ft-lb motor	10-ft-lb motor	Old 40-ft-lb motor
Manufacturer	Porter Peerless	Peerless-Winsmith	Peerless-Winsmith	Porter Peerless
Frame	D202G	DK56H	DG56D	D202G
Voltage (vdc)	125	125	125	125
Time rating	—	—	—	—
Duty	5 min	5 min	5 min	5 min
Serial number	XF64300	ZV47576	QW49138	HG50272
Torque (ft-lb)	40	25	10	40
HP	2.89	1.805	0.72	—
KW	—	—	—	—
Insulation type/class	B	RH	RH	B
Shunt Field Amps	—	—	—	—
RPM	1900	1900	1900	1750
Amps	24	14.5	6.5	-
Rise °C	115	115	115	-
Ambient °C	40	40	40	-
Type Winding	Comp.	Comp.	Comp.	Comp.
	175-34-0009-0	176-18-0048-0	176-18-0047-0	

2.3 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. (The torque switch was bypassed so that motor stall occurred without tripping the torque switch.) 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.

Table 3. Test instrumentation (600 Hz).

TCS Channel	Description	Calibrated?
Channel 55	dc line current (L2)	Yes
Channel 71	dc line voltage (L1 to L2)	Yes
Channel 76	Motor series field current (S1)	Yes
Channel 77	Motor shunt field current (F1)	Yes
Channel 78	Motor armature current (A1)	Yes
Channel 73	Motor series field voltage (S1 to S2)	Yes
Channel 74	Motor shunt field voltage (F1 to F2)	Yes
Channel 75	Motor armature voltage (A1 to A2)	Yes
Channel 72	Motor speed	Yes
Channel 40	Motor torque	Yes
Channel 01	Motor temperature, Surface Thermocouple	No, Ref. Only
Channel 02	Motor temperature, Surface Thermocouple	No, Ref. Only
Channel 15	Thermocouple Reference Junction	No, Ref. Only
Channel 66	Torque switch trip	No, Ref. Only
Channel 64	Torque spring pack deflection	Yes
Channel 33	Torque spring pack force	Yes
Channel 48	Stem torque	Yes
Channel 49	Stem torque	Yes
Channel 32	Stem thrust	Yes
Channel 65	Stem position	No, Ref. Only

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, generally as follows:

- Baseline test at 100% voltage and at room temperature
- Reduced voltage tests at 90, 80, 70, and 60% voltage and at room temperature
- Elevated temperature tests at 100% voltage and at four or five elevated temperatures ranging from 100 to 300°F
- Elevated temperature tests at 80% voltage and at four or five elevated temperatures.

In the elevated temperature tests, we wrapped the motor with heat tape, controlled by a variable voltage control and monitored by thermocouples on the surface of the motor. We also placed insulation around the motor, creating a custom oven on each motor. The RH insulated motors were heated to 300°F. However, because of wiring insulation concerns, the Class B motor was heated only to 250°F. All tests at room temperature began with an internal motor temperature between 70 and 80°F.

3. RESULTS

The following discussion applies the results of our research to 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 (that is, the torque applied to the stem nut by the worm gear). The following formula, applicable to ac- and dc-powered actuators, represents information provided in the Limitorque selection procedures (Reference 6 and 7).

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

where

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

The term $(V_{act} / V_{rat})^n$, where n is equal to 1 for dc motors, represents a linear adjustment where the percent loss in torque is equal to the percent loss in voltage. The term F_{temp}, is currently used in the industry for ac-powered actuators only. The elevated temperature adjustment for dc-powered actuators consists of a change in the rated starting torque (Tq_{motor}) for some specific dc motor sizes (Reference 8). The application factor (F_{app}) has been typically used to account for voltage losses down to 90% voltage and possibly to account for other considerations in specific applications. Typically the industry uses an application factor of 0.9 or 1.0. We did not evaluate the application factor in the research reported here; we used an application factor of 1.0 in all the calculations discussed in this report. For a given actuator gearbox, the actuator manufacturer publishes three values for the gearbox efficiency ($Eff_{gearbox}$). These three values are referred to as the running efficiency, pull-out efficiency, and stall efficiency, representing the gearbox efficiency under normal motor load and speed, high load and low speed, and sudden stall (with motor inertia considerations), respectively. Usually, these values are in the range of 0.4 to 0.6

(Reference 4). The overall gear ratio (*OAR*) in rising-stem MOV actuators is 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, in the following sequence:

- Gearbox efficiency data derived from measurements of gearbox input torque and gearbox output torque. Efficiency data published by the manufacturer are included for comparison. Also included is an evaluation that shows that a minimum motor speed exists below which the actuator produces no additional useful output torque.

- Degraded voltage testing of dc motors, with emphasis on the speed and output torque characteristics of the motor. Comparisons to the manufacturer's torque prediction methodology are included.

- Elevated temperature testing of dc motors, with emphasis on the speed and output torque characteristics of the motor. Estimates based on data issued by the actuator manufacturer are included for comparison.

- Motor heating during normal and high load tests, with a look at the longer stroke times characteristic of operation at higher loads.

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

- Valve-stem/stem-nut friction data derived from measurements of valve stem torque (gearbox output torque) and valve stem thrust. [This torque/thrust relationship is not addressed by the formula presented in Equation (1); it is addressed by a separate calculation, presented later in this report.]

Relevant data plots are presented in the following subsections of the report, along with a discussion of the results. Not all the data plots produced by the analysis are included in this discussion. A complete set of data plots for the four dc-powered actuators we tested is provided in Appendix A.

Figure 4 presents data plots from a typical test of the 10-ft-lb dc motor. This figure serves as a representative example of motor speed and motor torque over time for the same test. The negative convention for the torque measurement indicates that the actuator was being operated in the closing direction. As mentioned earlier, these curves are produced by starting the motor at a low load and corresponding high speed, and then applying an increasing load until the load causes the motor to stall. The oscillations in the data are due to gear train noise and to normal surges that occur when the electric motor lugs down under high loads. These oscillations appear in all the data plots; the shape of oscillations differs with different analysis methods. This simple look at the data (torque versus time, rpm versus time) serves as an introduction to the more complex analysis tools presented later in the report.

3.1 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 the following formula:

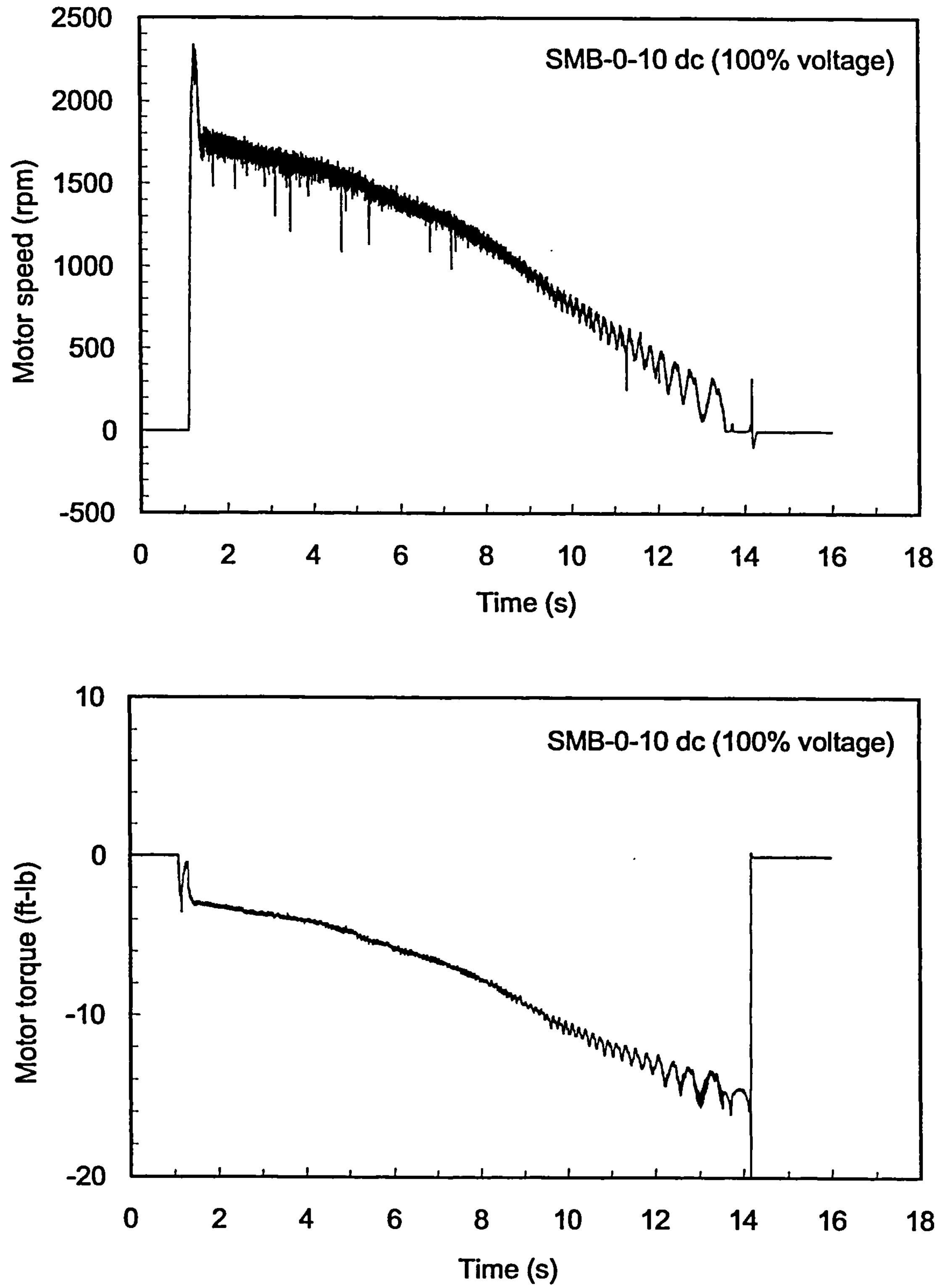


Figure 4. Motor torque and motor speed versus time, derived from testing of the 10-ft-lb dc motor at 100% voltage and room temperature.

$$Tq_{output} = Tq_{input}(Eff_{gearbox}\, OAR) \qquad (2)$$

where

Tq_{output}	=	output torque
Tq_{input}	=	input torque (motor torque after adjustments described elsewhere in this report)
$Eff_{gearbox}$	=	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 gearbox, and the output torque consists of the torque delivered to the stem nut by the worm gear. 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 35/1 to about 70/1. 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 (compared to the rotational speed of the motor). 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 actuator 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 motor effects 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 2, 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, pullout, and stall) for these actuators, along with other pertinent information. The published running efficiencies of the actuators range from 0.5 to 0.6. 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. In Figure 5, the upper left plot shows the actuator torque (output torque) measured during the baseline test (100% voltage, room temperature) of the SMB-0 actuator with the 10-ft-lb dc 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 representing valve closure against a high-flow load. The lower right plot in Figure 5 shows the motor torque measured during the same test. By plotting the output torque (actuator torque) versus the input torque (motor torque), we can produce an XY plot of gearbox performance, as shown in the upper right plot on Figure 5. The format of this plot is based on Equation (2); the slope from the origin (0,0) to any point on one of the data

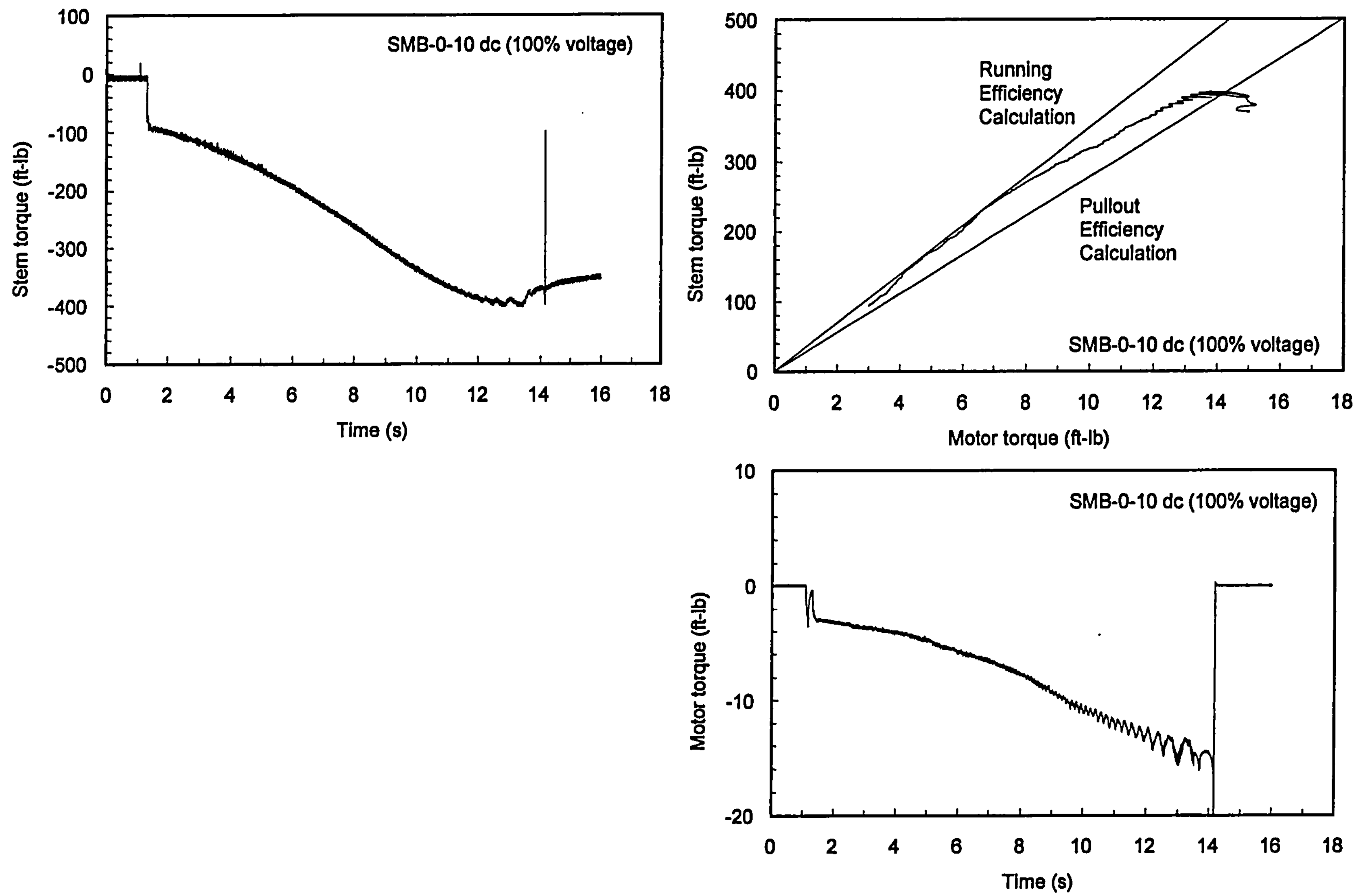


Figure 5. Actuator gearbox input torque (motor torque), output torque (stem torque), and efficiency calculations, derived from testing of the SMB-0-10 dc actuator.

traces represents the gearbox overall ratio times the *actual* gearbox efficiency for that data point. The two straight lines represent the overall gear ratio times (a) the published *running* efficiency, and (b) the published *pullout* efficiency. This format allows comparison of the published gearbox efficiencies with the actual gearbox efficiency over the entire operating range (in terms of torque load). For example, Figure 5 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 and then crosses below the published pullout efficiency.

Figure 6 shows the gearbox performance data for the SMB-0-10 dc actuator for the reduced voltage tests (upper right), elevated temperature tests at 100% voltage (lower left), and elevated temperature tests at 80% voltage (lower right). A careful examination of Figure 6 reveals a relationship between gearbox efficiency and the speed of the actuator. In each of the 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 crosses the pullout value at a motor torque of 8 ft-lb, in the 70% test at 9.5 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 motor torque (stall) is notably lower than the efficiency indicated by higher-voltage traces at the same motor torque value but at higher motor speeds.

For the other dc actuators, data similar to Figure 6 are presented in Figures 7 through 9. These figures show that for each of the dc actuators we tested, the gearbox runs at or near the published running efficiency at low to moderate loads, but the published running efficiency overpredicts the actual actuator efficiency at higher loads and lower speeds. As the motor speed drops under high load, the efficiency drops to values below the pullout efficiency.

Because the dc motor produces progressively higher torque at lower speed, the traces shown in Figures 6 through 9 for the various low voltages are more distinctly separate than in typical ac actuator tests (See Reference 1). 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. 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.

Figure 10 shows gearbox efficiency versus motor speed for the SMB-1-40 dc actuator during the reduced voltage tests. Although each trace starts (on the right) at a different position, all the traces converge (at the left) as loads increase and the motor speed drops, and all the traces cross below the pullout efficiency value of 0.4 at about the same motor speed. This behavior is typical of all the stall-type tests for all four dc-powered actuators we tested, indicating that there may be a minimum motor speed (or perhaps a minimum worm shaft speed) below which the pullout efficiency is no longer bounding.

Refer again to Figures 6 through 9. Note that as the motor approaches stall, the trace becomes approximately horizontal, indicating that no increase in stem torque occurs, even though the motor torque continues to increase. Figure 11 provides a closer look at this phenomenon, by plotting actuator output torque versus worm shaft speed; these data are from the degraded voltage tests of the 10-ft-lb motor. Notice that this measurement is *actuator* torque, not *motor* torque. These data traces show that there is a worm shaft speed threshold below which the actuator produces no additional actuator torque. This is the case even though the motor does in fact produce additional torque below the threshold speed. The worm shaft speed threshold ranges from about 130 to 200 rpm (an eyeball estimate), corresponding with motor speeds of about 250 to 370 rpm in this actuator.

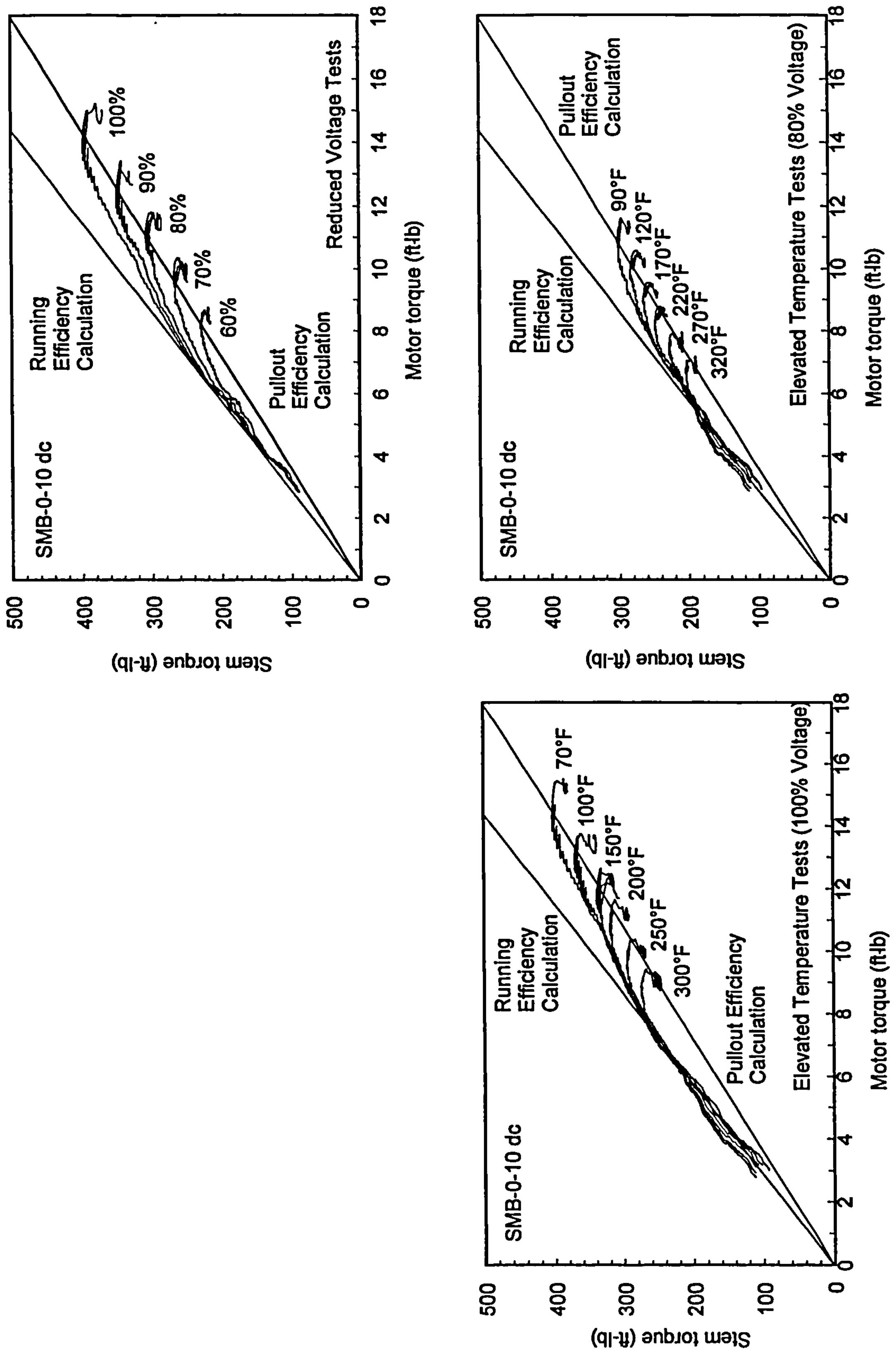


Figure 6. Gearbox efficiency calculations derived from testing of the SMB-0-10 dc actuator.

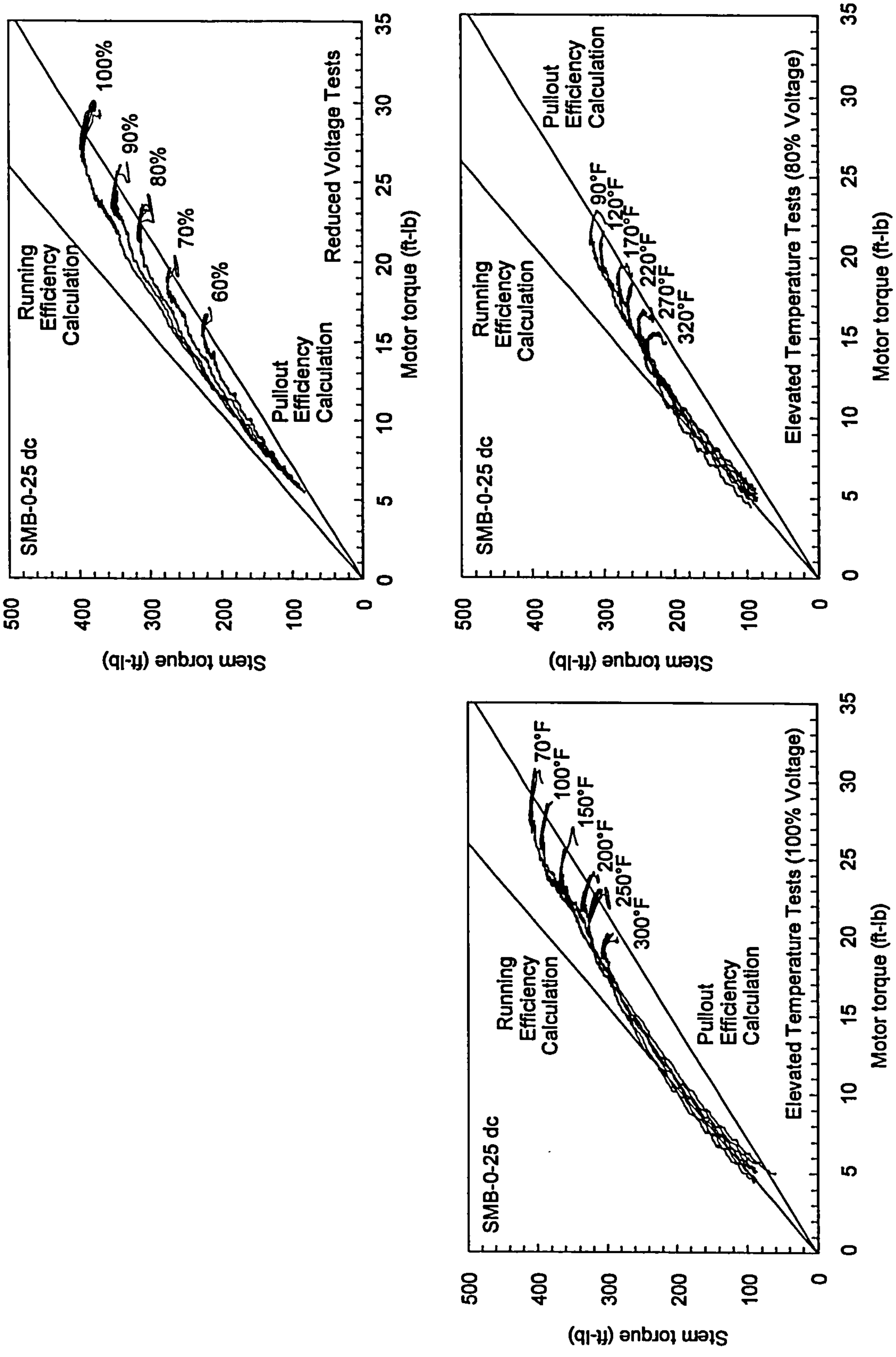


Figure 7. Gearbox efficiency calculations derived from testing of the SMB-0-25 dc actuator.

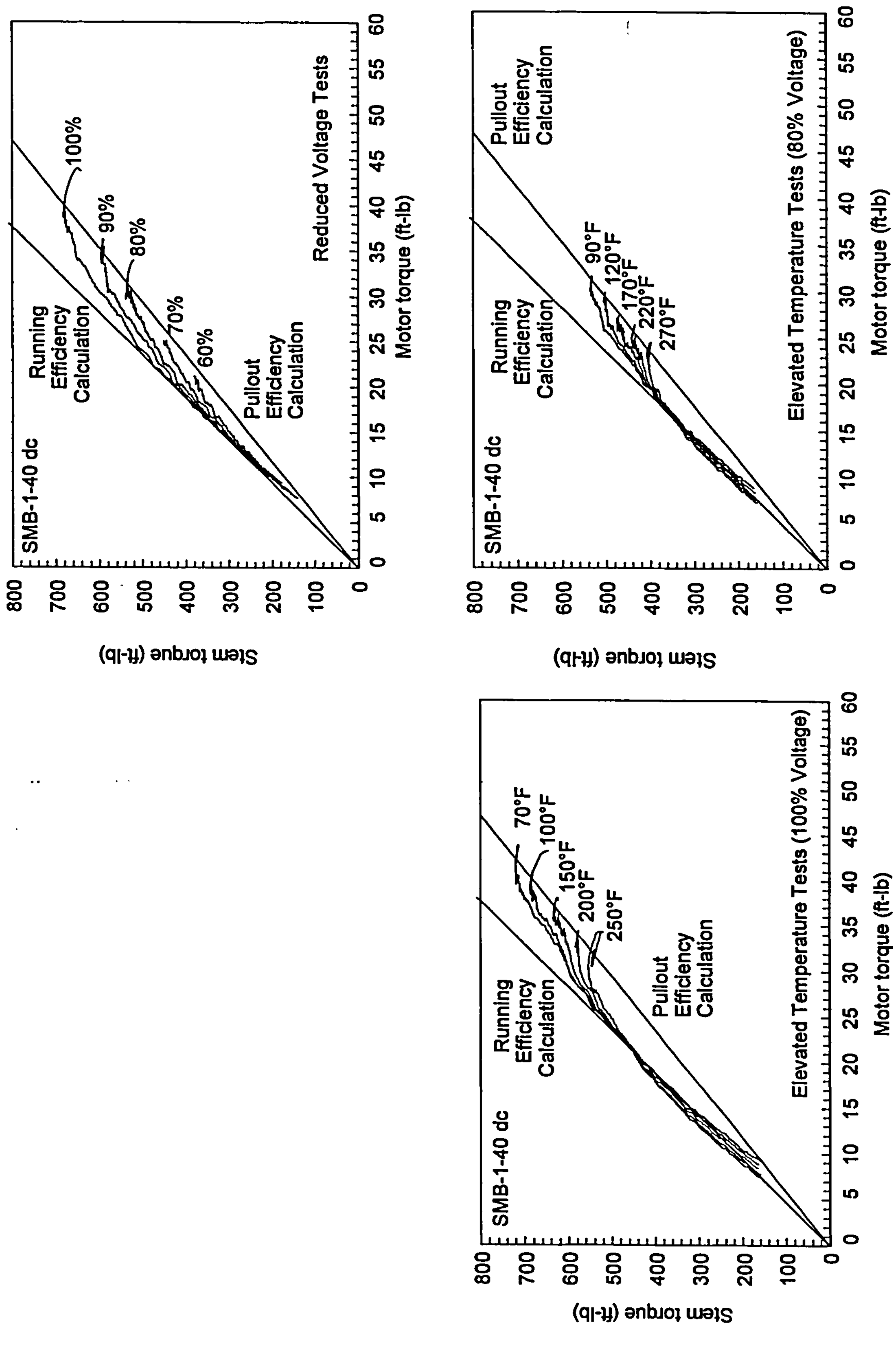


Figure 8. Gearbox efficiency calculations derived from testing of the SMB-1-40 dc actuator.

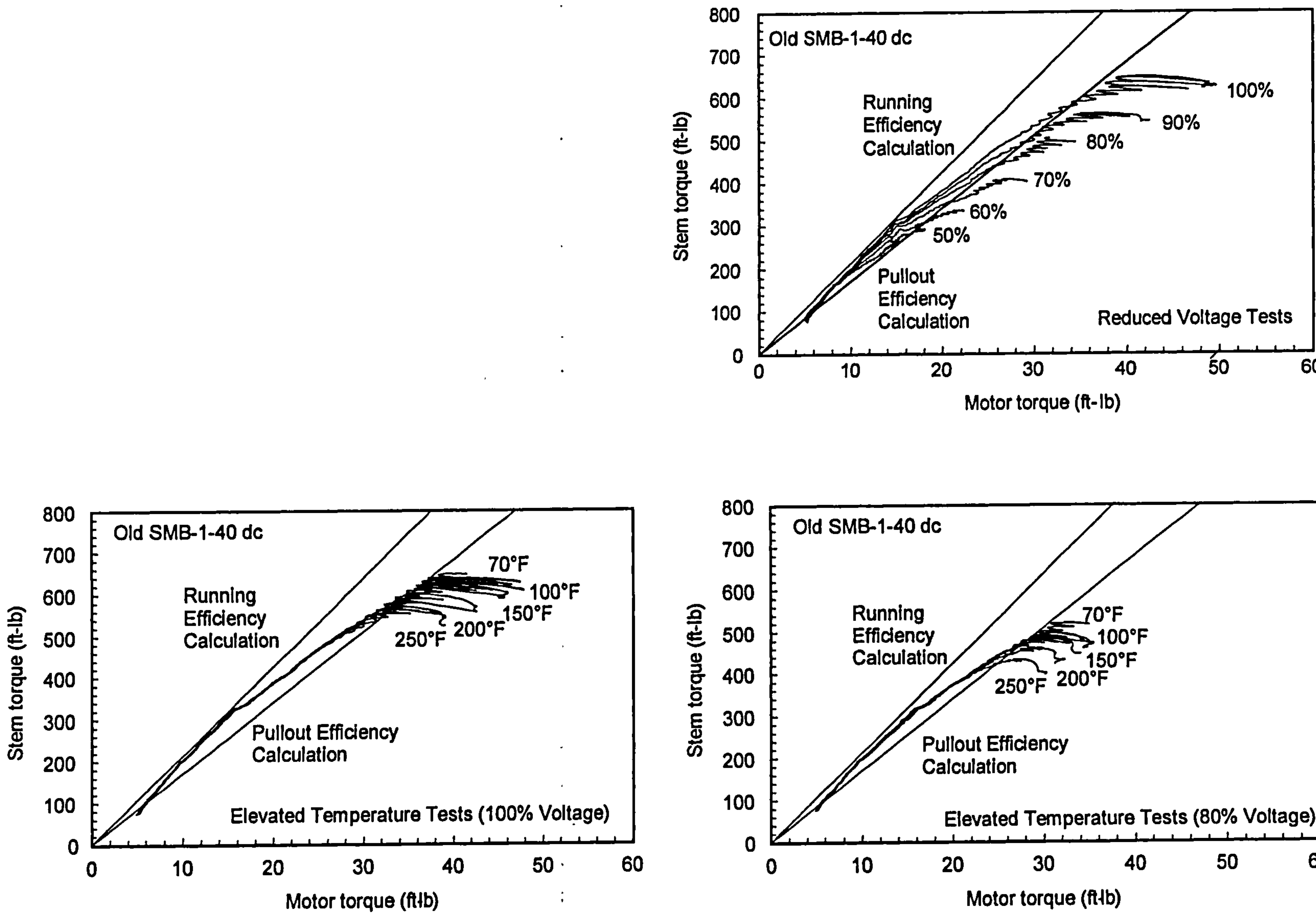


Figure 9. Gearbox efficiency calculations derived from earlier testing of the SMB-1 actuator with the older 40-ft-lb dc motor.

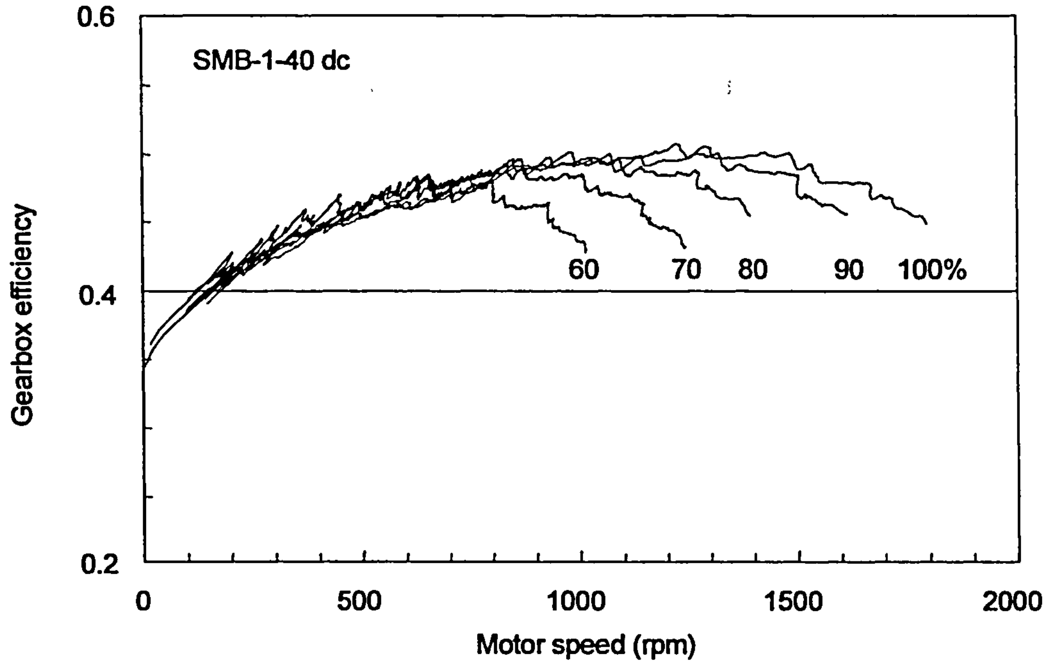


Figure 10. Gearbox efficiency calculations versus motor speed, derived from testing of the SMB-1-40 dc actuator at degraded voltage.

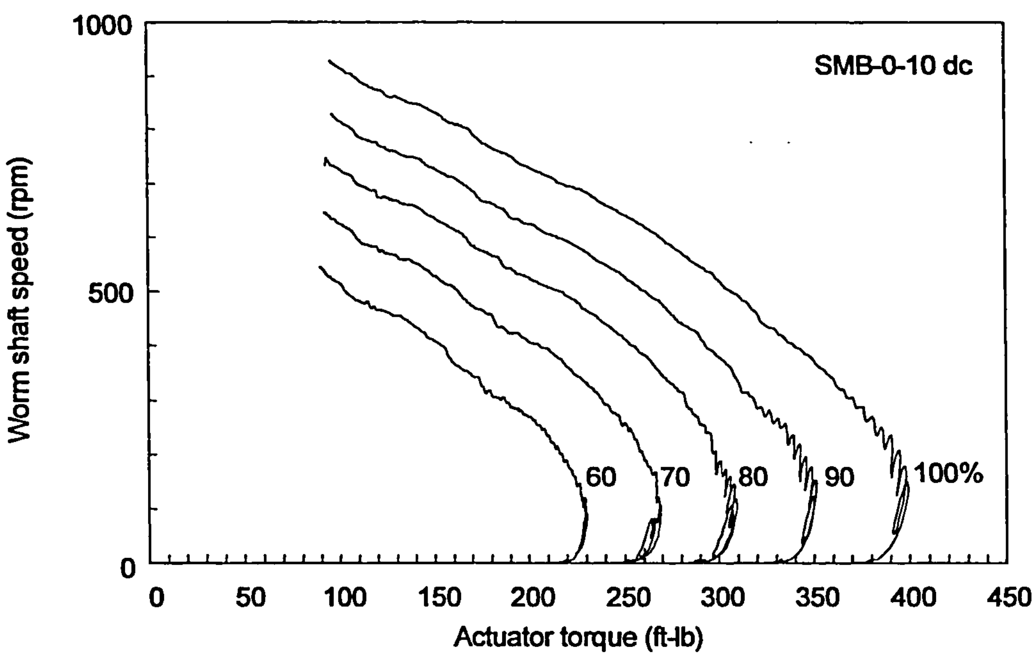


Figure 11. Worm shaft speed versus actuator output torque, derived from testing of the SMB-0-10 dc actuator at degraded voltage.

Figures 12 through 14 show the same data for the other three actuators. The threshold is likewise evident in these plots. For these three actuators, the data show that a worm shaft speed of about 150 to 250 rpm is the threshold below which no additional actuator torque can be expected, corresponding with a motor speed threshold of about 140 to 300 rpm. The worm shaft speed threshold is about the same for all four motors, and tends to be lower with lower loads. The relationship between worm shaft speed and motor speed is different for different actuators, because of differences in the ratios of the motor gear sets, as listed in Table 1. In this report, for simplicity, we refer to the threshold as a *motor* speed threshold of 200 to 300 rpm.

In summary, the test results show that actual gearbox 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.

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. Each gearbox appears to have a minimum speed below which the pullout efficiency is no longer bounding.

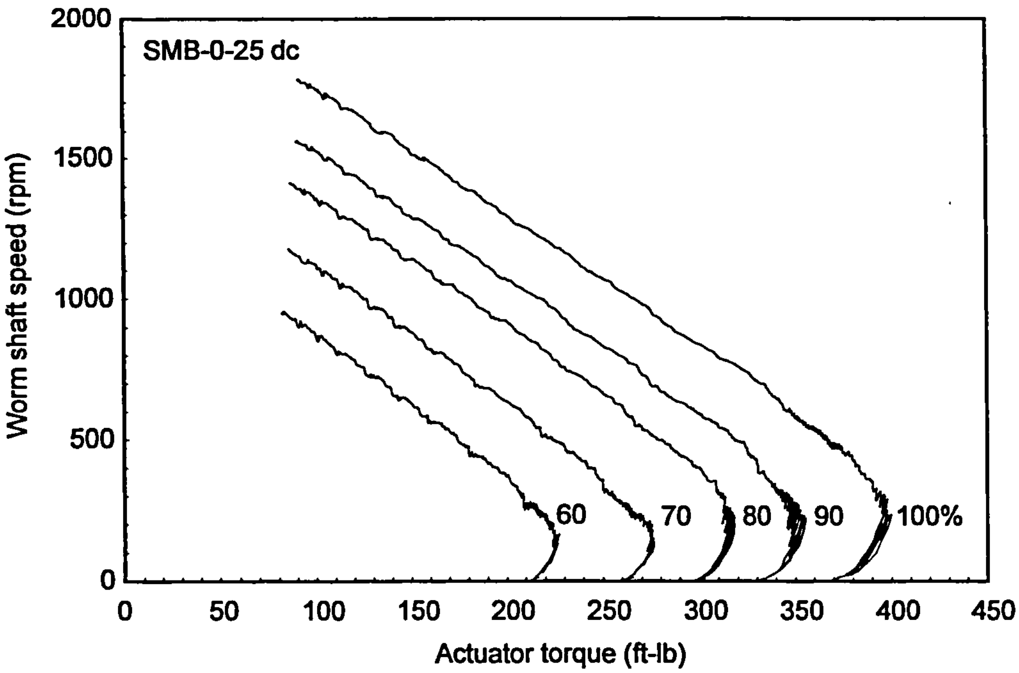


Figure 12. Worm shaft speed versus actuator output torque, derived from testing of the SMB-0-25 dc actuator at degraded voltage.

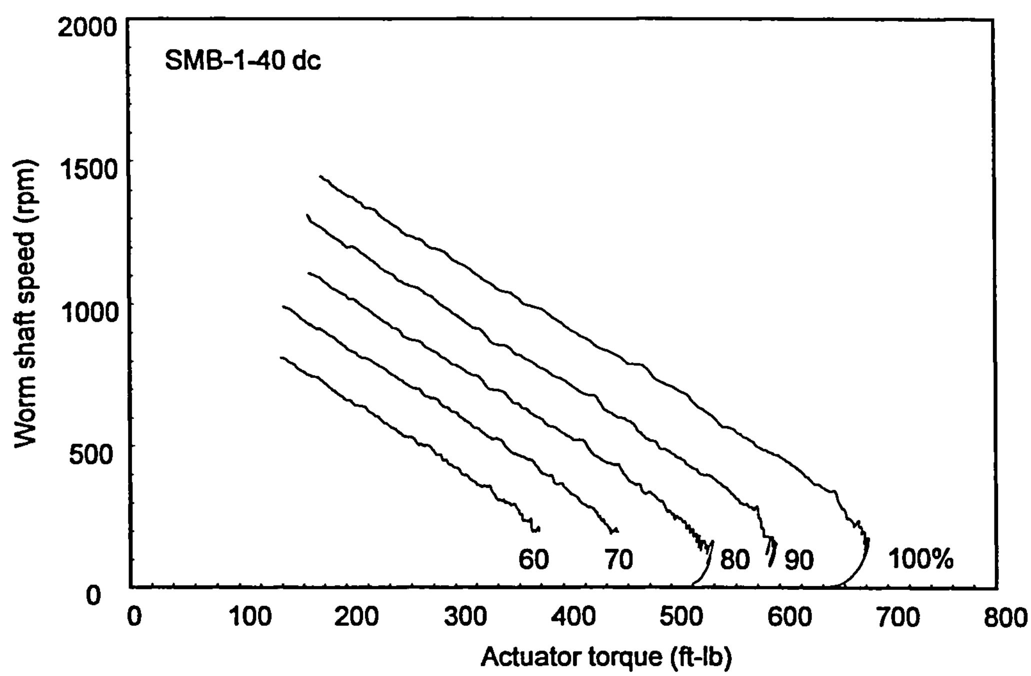


Figure 13. Worm shaft speed versus actuator output torque, derived from testing of the SMB-1-40 dc actuator at degraded voltage.

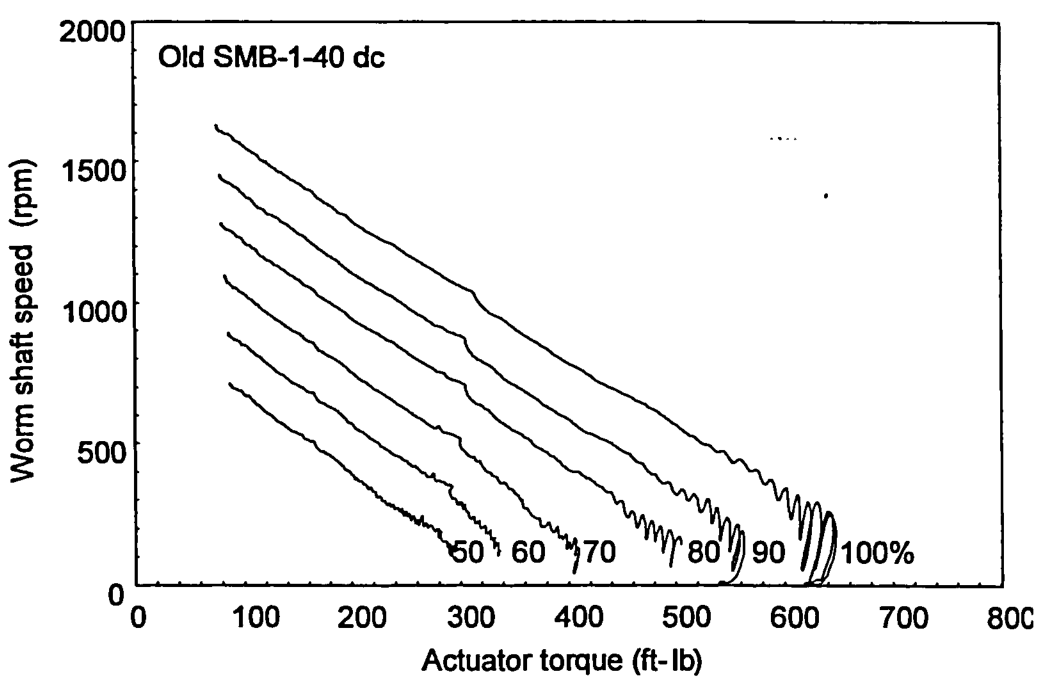


Figure 14. Worm shaft speed versus actuator output torque, derived from earlier testing of the SMB-1 actuator with the older 40-ft-lb dc motor at degraded voltage.

The loss of efficiency at lower speeds creates a worm shaft speed threshold below which the actuator fails to produce additional output torque in relation to the additional motor torque being produced as the motor slows down against an increasing load. For these four actuators, a worm shaft speed corresponding with a motor speed of about 200 to 300 rpm was a conspicuous threshold below which no additional actuator torque can be expected. The identification of this threshold is significant: when one of these actuators operates against design basis loads and under design basis voltage and temperature conditions, the motor must achieve its required torque at a speed above this threshold.

3.2 Degraded Voltage Testing of dc Motors

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

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

$$Tq_{act} = Tq_{rat}\left(\frac{V_{act}}{V_{rat}}\right)^{1} . \tag{3}$$

This 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 from Equation (3).

Figure 15 shows data from the reduced voltage tests of the 10-ft-lb dc motor. The figure presents four data plots addressing the parameters of primary interest. Corresponding data plots from testing of the other three motors are included in Appendix A. The upper left plot shows the temperature of the motor series field as a function of motor torque for the five reduced voltage tests. (As mentioned earlier, these temperature values are calculated from electrical resistance values derived from measurements of the series field voltage and current.) Note that each test began near 70°F and experienced a 30 to 50°F temperature rise by the end of the run. This temperature increase represents the motor heating that occurs during the run as the motor operates against a load. The voltage plot (lower left) shows that although each test began at its assigned nominal voltage, a voltage drop occurred during the run. This voltage drop is due to line losses and to losses that occurred in the dc power supply during actuator motor operation. Similar motor heating, line losses, and voltage drops are likely to occur during dc-powered valve operation in the plants.

The speed/torque plot (lower right) shows the effect of reduced voltage on the performance of this motor. Figure 16 shows the same speed/torque plot, with estimates included for comparison purposes. The two sets of estimates are based on the results of the 100% voltage test at two speeds, corresponding with 10 ft-lb (the speed at which the motor achieves it rated torque in the baseline test) and 6 ft-lb (an arbitrary choice). These estimates are the torque values predicted by the standard industry prediction method, represented by Equation (3), using the actual voltage (at that point in time) as the value for V_{act} and for V_{rat}. Using the actual voltage rather than the nominal voltage eliminates any bias that would otherwise be introduced to the prediction by the voltage drop that occurs during the run. To provide the prediction with additional validity, we also adjusted the prediction to account for the increased resistance due to motor heating that occurs during the run, using the formula presented in the next section of this report.

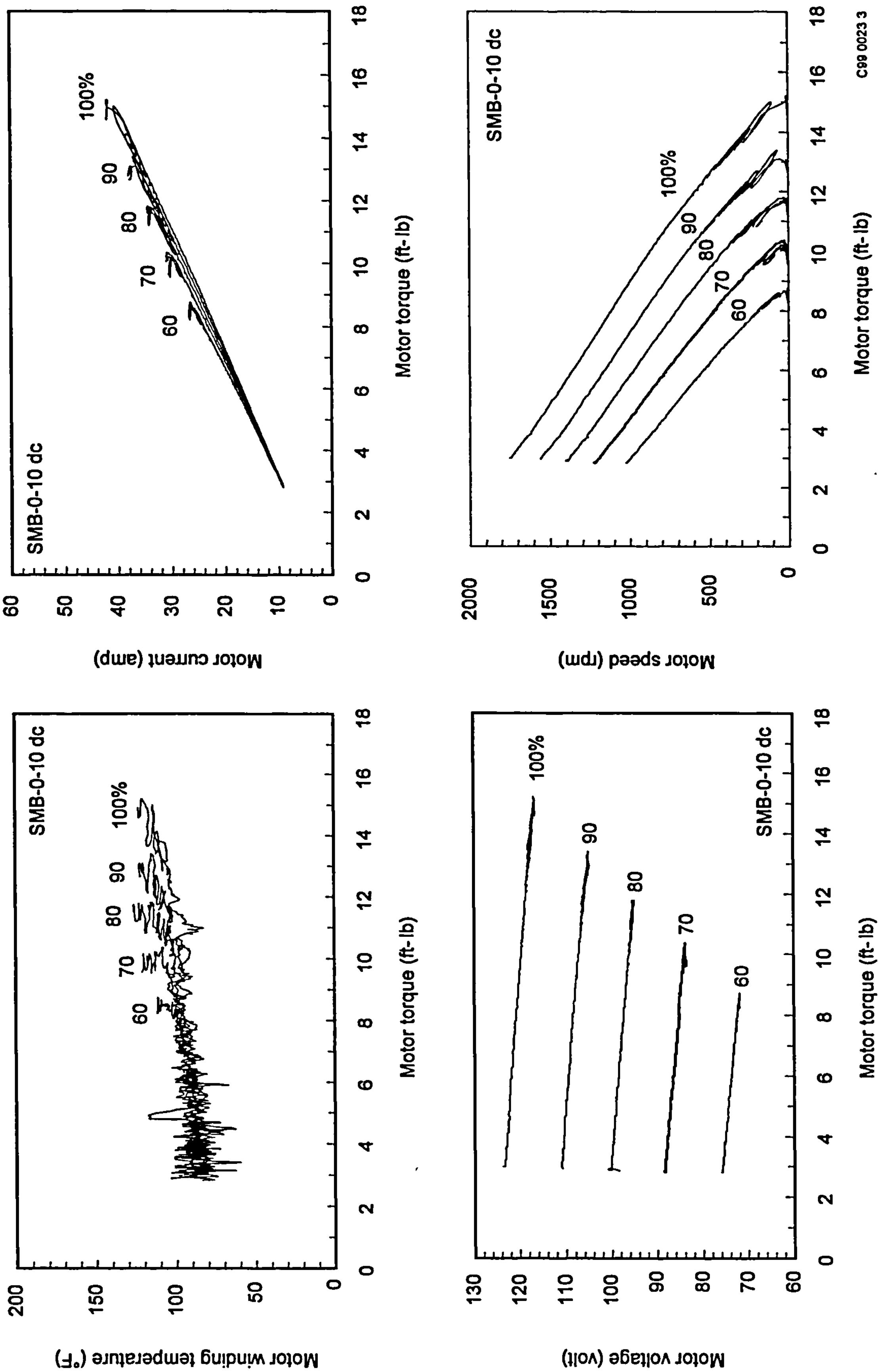


Figure 15. Motor temperature, current, voltage, and speed versus torque, derived from testing of the 10-ft-lb dc motor at degraded voltage.

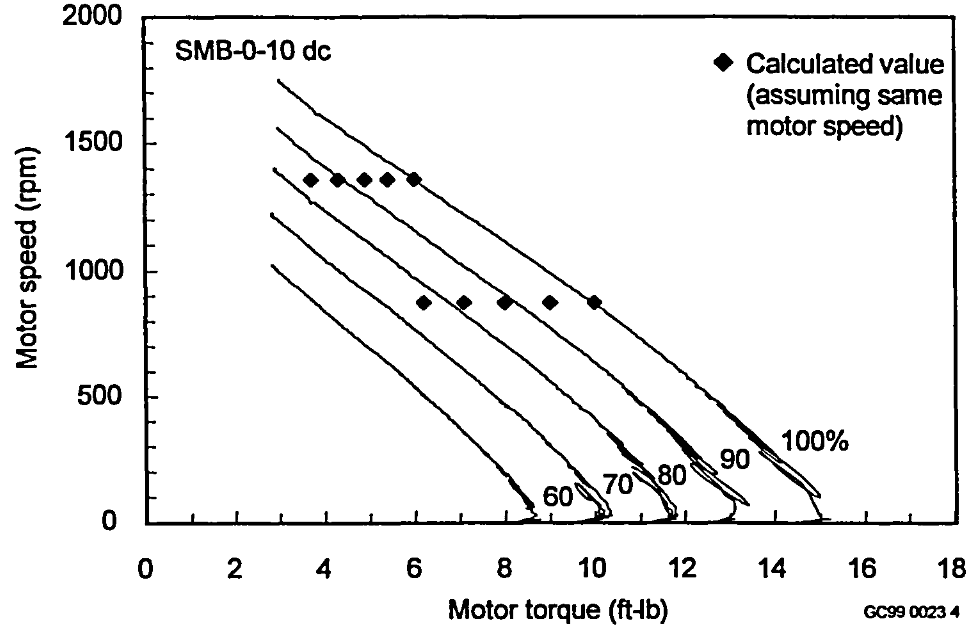


Figure 16. Motor speed versus torque, derived from testing of the 10-ft-lb dc motor at degraded voltage, with predictions of torque loss at a given speed.

For example, an estimate ignoring temperature effects and assuming a nominal voltage of 100 volts and a baseline voltage of 125 volts would predict a torque output of 8 ft-lb for the 80% test. However, the actual voltage in the baseline test (100% voltage) at 871 rpm was 120 volts. The actual voltage in the 80% voltage test at 871 rpm was 97 volts. Using Equation (3), 97/120 = 81%, or 8.1 ft-lb torque. Furthermore, the actual motor temperatures corresponding with the data points in question were 91°F in the 100% test and 97°F in the 80% test. Adjusting the estimate to account for this difference in temperature produces a prediction of 8.0 ft-lb torque. This is the estimate shown in Figure 16. All estimates presented in this subsection were calculated in this fashion.

The comparison shown in Figure 16, which looks at torque losses at a given speed, shows that the actual torque losses are greater than predicted by Equation (3). For example, at 871 rpm, a voltage reduction from 120 volts to 97 volts (the actual voltage at that moment during the 80% nominal test) causes a loss of 3.2 ft-lb, a loss notably greater than the 2.0 ft-lb loss predicted by Equation (3). Note, however, that the motor does achieve the predicted 8.0 ft-lb torque, albeit at a lower speed than 871 rpm.

The comparison method shown in Figure 16 (comparing actual versus predicted torque output at a given motor speed) has merit, in that it acknowledges motor speed as an important operating characteristic. For some valves, operability denotes not only that the valve will successfully close (or open), but also that it will do so within a specified stroke time. Also, operation of the dc actuator motor at very high loads and very low speeds introduces other concerns related to motor heating and high friction in the gearbox (concerns addressed elsewhere in this report). Nevertheless, the comparison method shown in Figure 16 fails to account for the lower speed at which the motor does in fact achieve the predicted torque output.

The visual pattern projected by the five traces in Figure 16 indicates step changes not only toward the left side of the plot, indicating reduced motor torque with reduced voltage, but also toward the bottom of the plot, indicating reduced motor speed. We inferred from this pattern, and from the inadequacy of the comparison method described in the previous paragraphs, that reduced voltage produces a linear shift in the curves for both motor torque and motor speed. We therefore applied a linear relationship [similar to the torque relationship in Equation (3)] to the motor speed, as follows:

$$S_{act} = S_{rat}\left(\frac{V_{act}}{V_{rat}}\right)^{1}. \qquad (4)$$

Figure 17 shows the results of this calculation for the 10-ft-lb dc motor. The estimates shown in this figure predict that operation at reduced voltage causes a reduction in motor speed as well as a reduction in motor torque. These estimates are very close to the actual measurements over the full range of test conditions. As before, the estimates shown in Figure 17 are based on the actual voltage at that point in the test, not the nominal voltage at which the test began. These estimates also account for the temperature increase that occurs during the test. Figures 18, 19, and 20 present the results of this analysis for the other three dc motors. In all cases, the estimates produced by addressing both torque and speed match the actual data well.

The 10-ft-lb motor operating at reduced voltage achieves its predicted torque at motor speeds well above the 200- to 300-rpm threshold identified in the previous subsection. The 25-ft-lb motor achieves its predicted torque at motor speeds very close to the threshold. The two 40-ft-lb motors achieve the predicted torque at motor speeds below the threshold.

In summary, the results show that the conventional linear method for predicting dc motor torque loss due to operation at reduced voltage needs to also consider the accompanying motor speed reduction. An evaluation that considers losses in both motor torque and motor speed produces an estimate that comes very close to actual dc motor performance. The estimate predicts a linear reduction in both the torque and the speed at reduced voltage. Note, however, that in some instances, the predicted and actual motor torque values fall below the motor speed threshold (at about 200 to 300 rpm) where high gearbox friction renders additional motor torque useless.

3.3 Elevated Temperature Testing of dc 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 electric motor tends to degrade at higher temperature, mostly because of the 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 for extended periods or at high loads.

The actuator manufacturer recognizes this effect, and for dc motors that are expected to operate at high ambient temperatures, the manufacturer recommends the use of environmentally qualified RH insulated dc motors. The RH insulated motors are qualified for operation at 340°F, and the manufacturer provides information regarding the maximum temperature at which the motor nameplate torque can be produced for each motor design (Reference 9). The manufacturer also provides a table (Reference 8) recommending adjustments to the rated torque value for sizing a nuclear qualified actuator. According to this table, a dc motor with a rated torque of 40 ft-lb expected to operate at 340°F would be treated as if it were a 39-ft-lb dc motor. (The adjustment is greater for larger motors; for example, the adjusted torque of a dc motor with a rated torque of 60 ft-lb would be 54 ft-lb.) According to the table, dc motors with rated

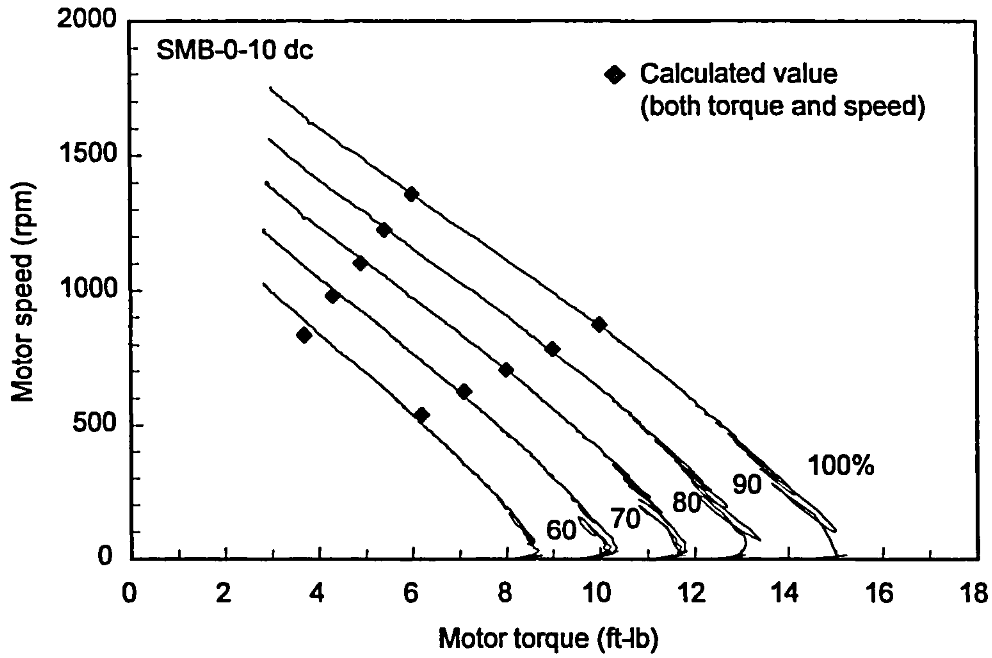


Figure 17. Motor speed versus torque, derived from testing of the 10-ft-lb dc motor at degraded voltage, with predictions based on the voltage ratio applied to both motor torque and motor speed.

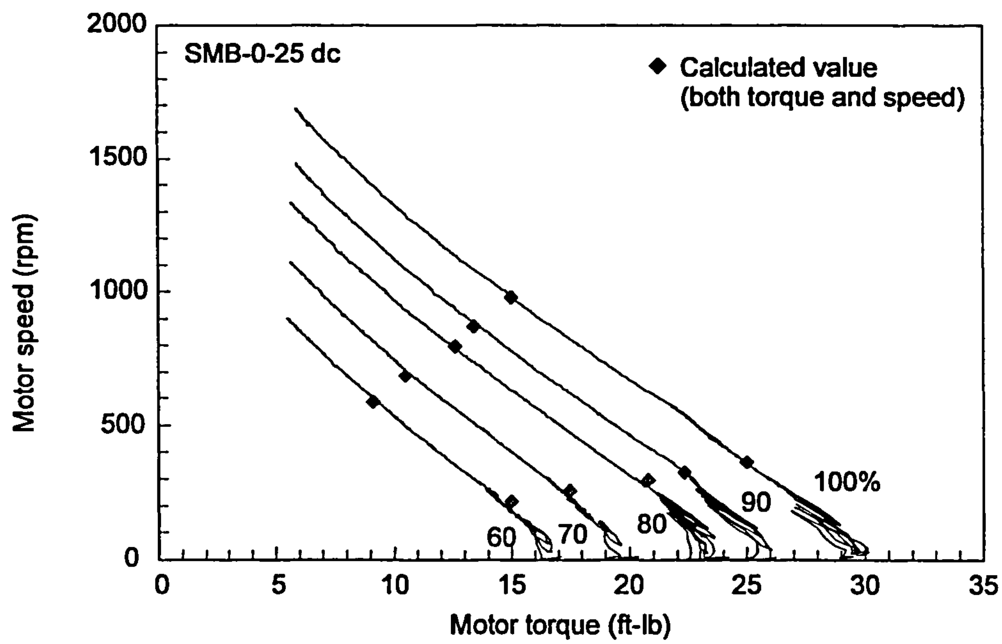


Figure 18. Motor speed versus torque, derived from testing of the 25-ft-lb dc motor at degraded voltage, with predictions based on the voltage ratio applied to both motor torque and motor speed.

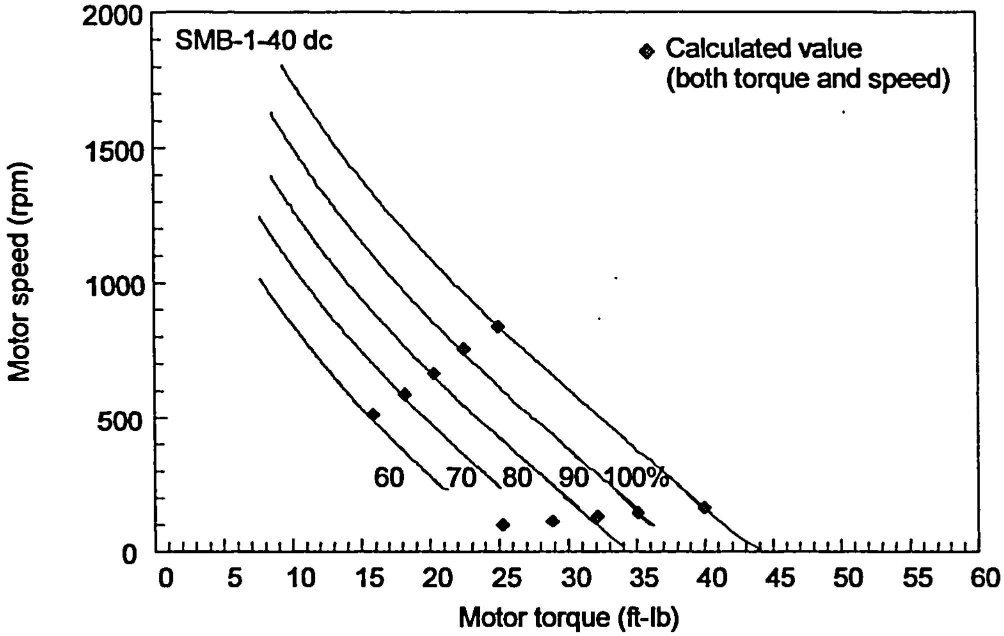


Figure 19. Motor speed versus torque, derived from testing of the 40-ft-lb dc motor at degraded voltage, with predictions based on the voltage ratio applied to both motor torque and motor speed.

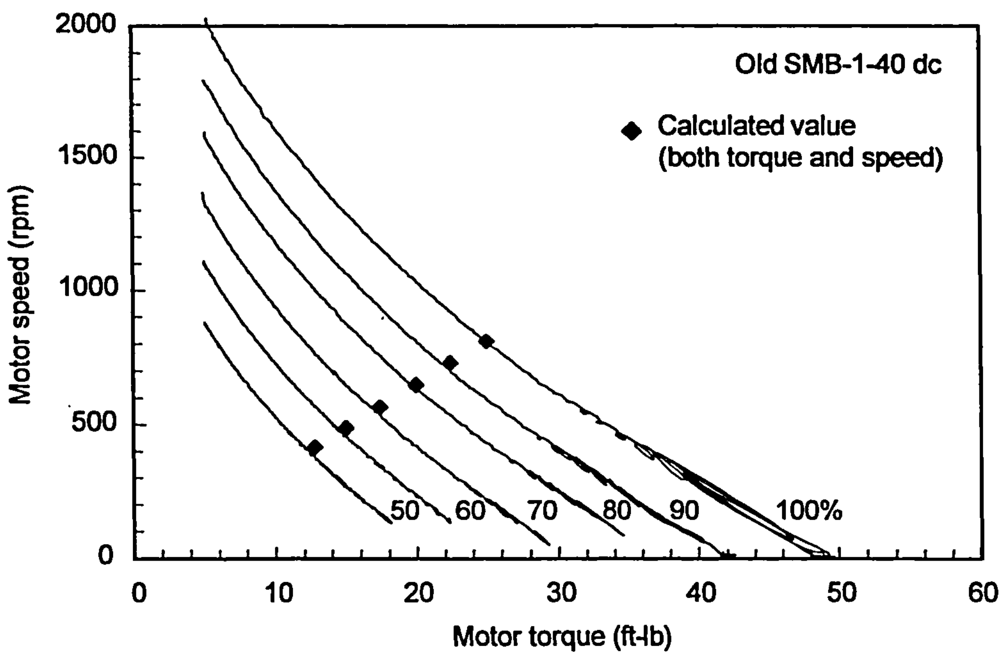


Figure 20. Motor speed versus torque, derived from earlier testing of the older 40-ft-lb dc motor at degraded voltage, with predictions based on the voltage ratio applied to both motor torque and motor speed.

torques of 25 and 10 ft-lb require no adjustment for operation at 340°F. There are no requirements for torque adjustments on dc motors operating at elevated temperatures below 340°F or for motors that might experience heating during operation.

Figure 21 shows the performance of the 10-ft-lb dc motor during the elevated temperature testing at 100% voltage. The figure presents four data plots addressing the parameters of primary interest. The upper left plot shows the temperature of the motor series field (derived from measurements of the series field voltage and current) as a function of motor torque for the six elevated temperature tests. The tests began at 70, 100, 150, 200, 250, and 300°F, and in each case the motor experienced a temperature increase of about 30 to 50°F during the test. In these tests, we used heaters to impose a simulated elevated ambient temperature on the motors to achieve the nominal starting temperature for each test. An additional increase in temperature occurred during the test, as the motor heated up during operation under load. This increase is evident in the upper left data plot in Figure 21.

As before, the motor voltage plot (lower left) shows that although each test began at its assigned nominal voltage, a voltage drop occurred during the run. The motor speed/torque plot (lower right) presents the family of curves that illustrate the effect of elevated temperature on dc motor performance. These data traces, from tests at 100% nominal voltage, show a clear drop in torque as the temperature increases, even for the first small step (from 70 to 100°F nominal).

Figure 22 provides an enlarged view of the lower right plot on Figure 21. This motor is an RH insulated motor qualified to 340°F. The increase from a nominal starting temperature of about 70°F to a nominal starting temperature of 300°F reduced the motor's torque output by 3.8 ft-lb at 889 rpm, the speed at which the motor achieved its rated torque of 10 ft-lb in the 70°F test. In both the 300°F test and the 70°F test, the actual temperatures at the data points in question were a little higher than the nominal starting temperatures (see upper left plot in Figure 21), a fact that does not detract from the validity of the comparison. Similarly, the small voltage drop that occurred during the tests does not detract from the validity of this comparison; the data points in question were both taken with the motor operating at within about 1% of the same voltage (see lower left plot, Figure 21).

Figure 23 shows the same data from testing at 80% voltage. The 80% voltage tests began at temperatures of 90, 120, 170, 220, 270, and 320°F. The purpose of these tests was to examine the combined effects of reduced voltage and elevated temperature. For the 80% voltage tests, at 889 rpm, elevated temperature reduced the output torque by 2.5 ft-lb.

Figures 24 and 25 are the elevated temperature plots for the 25-ft-lb dc motor for 100% and 80% voltage, respectively. This motor is also RH insulated; the 100% voltage test at high temperature began at 300°F. The increase from room temperature to 300°F reduced the motor's torque output by 8 ft-lb at the rated torque of 25 ft-lb at 390 rpm. For the 80% voltage test, at 390 rpm, elevated temperature reduced the output by 6 ft-lb.

Figures 26 and 27 are the same plots for the 40-ft-lb dc motor. This is a Class B motor, so we heated it only to 250°F. In the 100% voltage tests, the increase from room temperature to 250°F reduced the motor's torque output by 10 ft-lb at the rated torque of 40 ft-lb at 245 rpm. For the 80% voltage test, at 245 rpm, elevated temperature reduced the output by 8 ft-lb.

The results of the earlier elevated temperature tests performed with the older 40-ft-lb motor (also a Class B motor) are shown in Figures 28 and 29. In the 100% voltage tests, the increase from room temperature to 250°F reduced the motor's torque output by 8 ft-lb at the rated torque of 40 ft-lb and 274 rpm. For the 80% voltage test, at 274 rpm, elevated temperature reduced the output by 6 ft-lb.

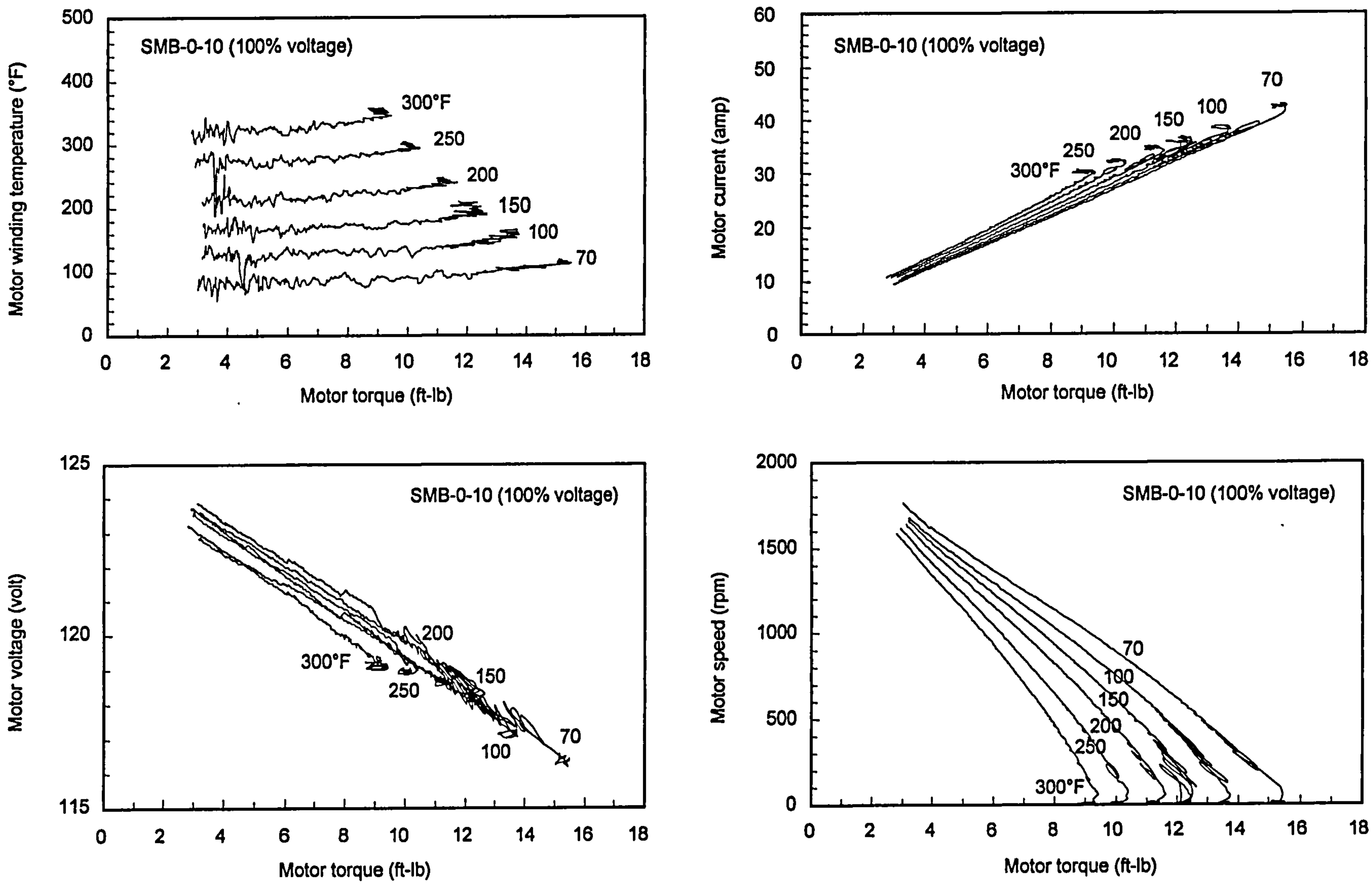


Figure 21. Motor temperature, current, voltage, and speed versus torque, derived from testing of the 10-ft-lb dc motor at elevated temperature and 100% voltage.

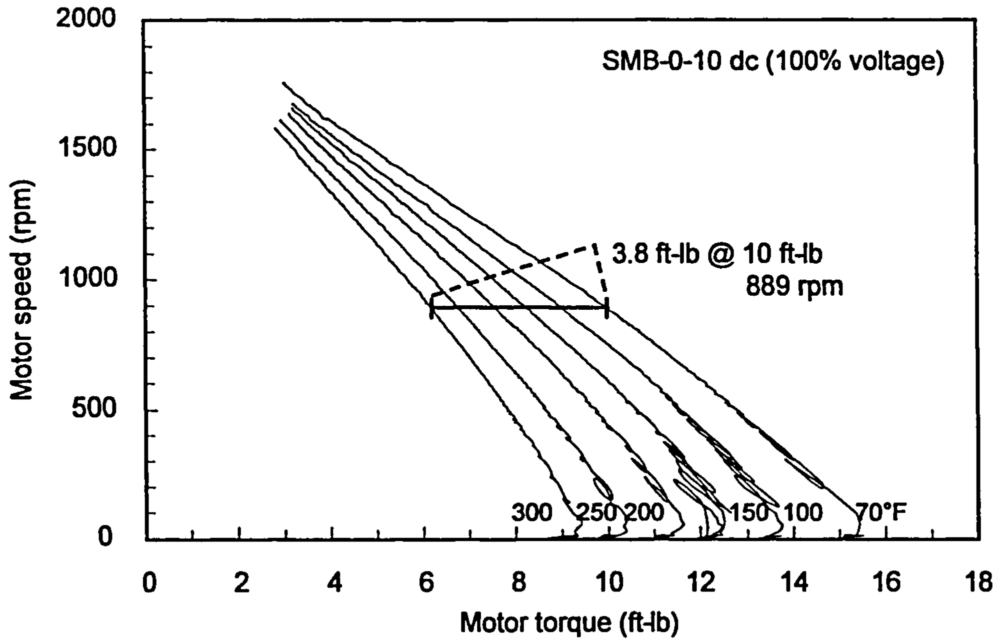


Figure 22. Motor speed versus torque, derived from testing of the 10-ft-lb dc motor at elevated temperature and 100% voltage.

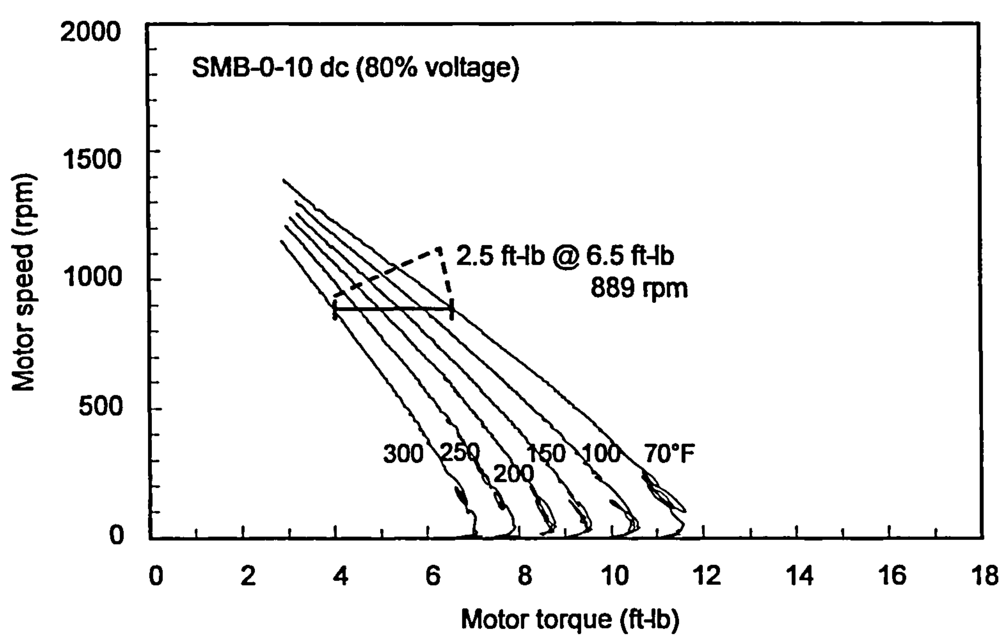


Figure 23. Motor speed versus torque, derived from testing of the 10-ft-lb dc motor at elevated temperature and 80% voltage.

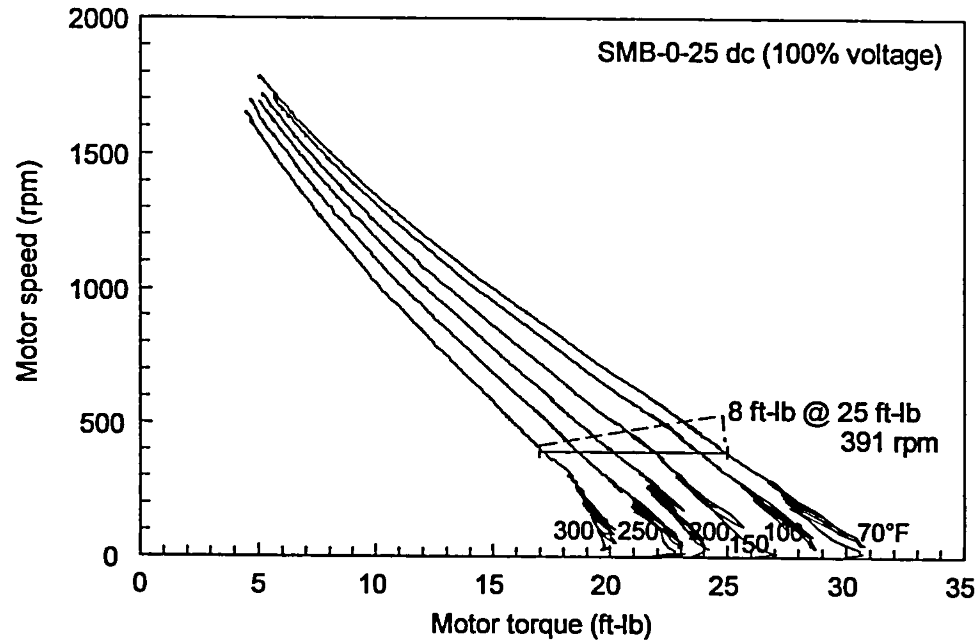


Figure 24. Motor speed versus torque, derived from testing of the 25-ft-lb dc motor at elevated temperature and 100% voltage.

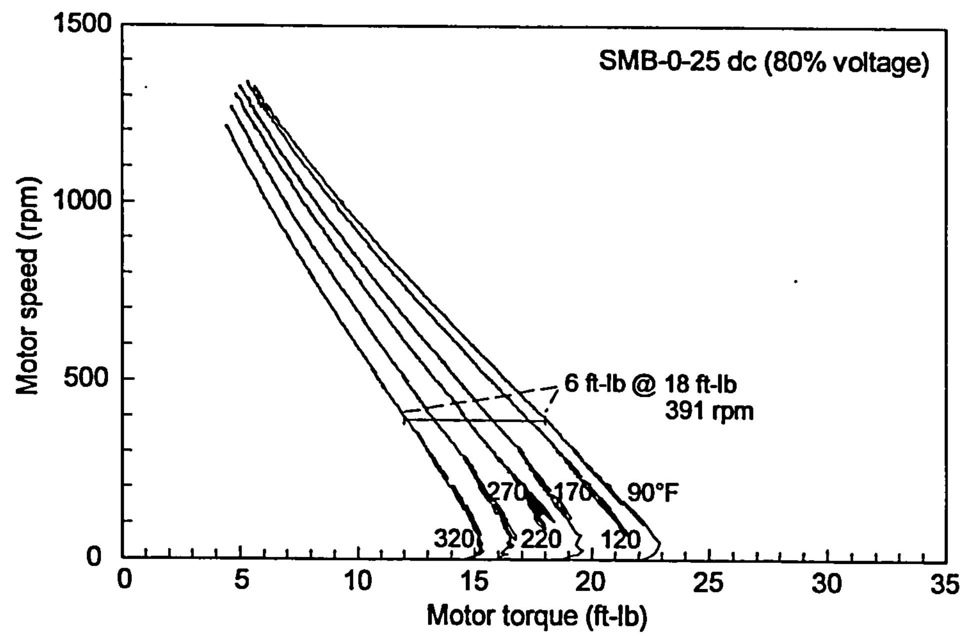


Figure 25. Motor speed versus torque, derived from testing of the 25-ft-lb dc motor at elevated temperature and 80% voltage.

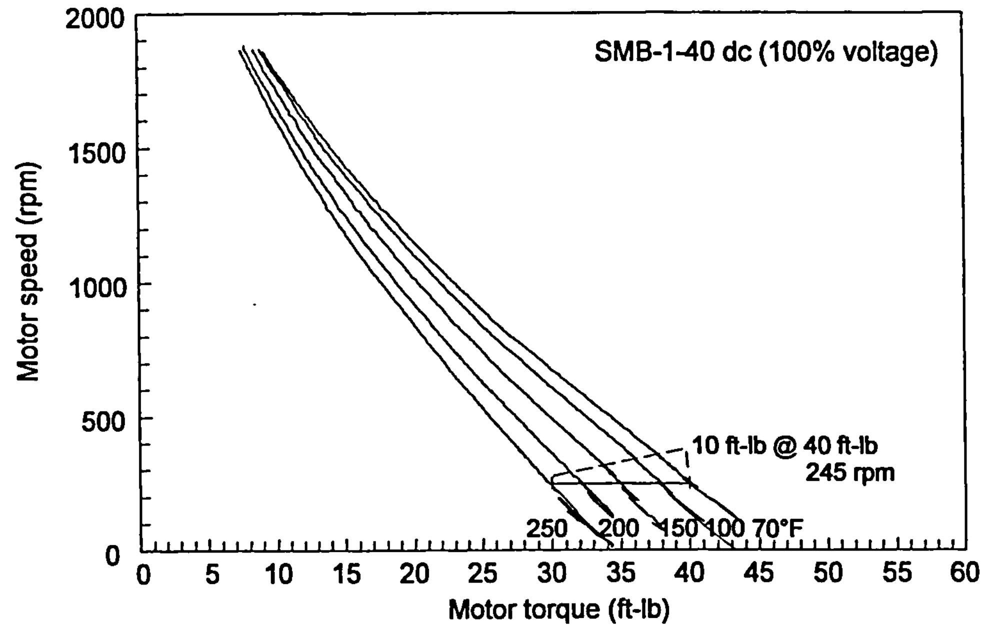


Figure 26. Motor speed versus torque, derived from testing of the 40-ft-lb dc motor at elevated temperature and 100% voltage.

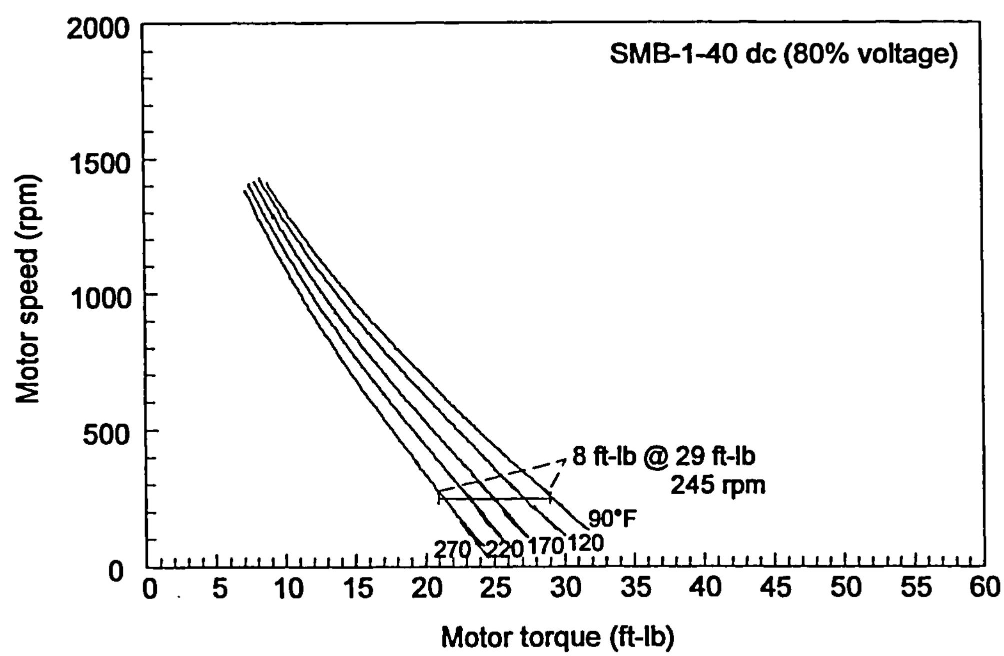


Figure 27. Motor speed versus torque, derived from testing of the 40-ft-lb dc motor at elevated temperature and 80% voltage.

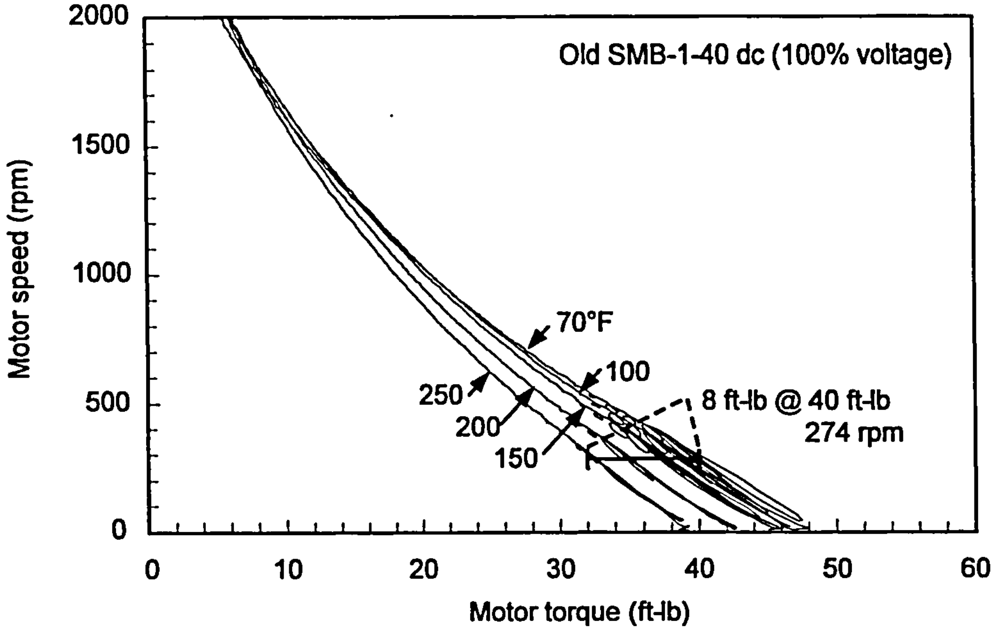


Figure 28. Motor speed versus torque, derived from earlier testing of the older 40-ft-lb dc motor at elevated temperature and 100% voltage.

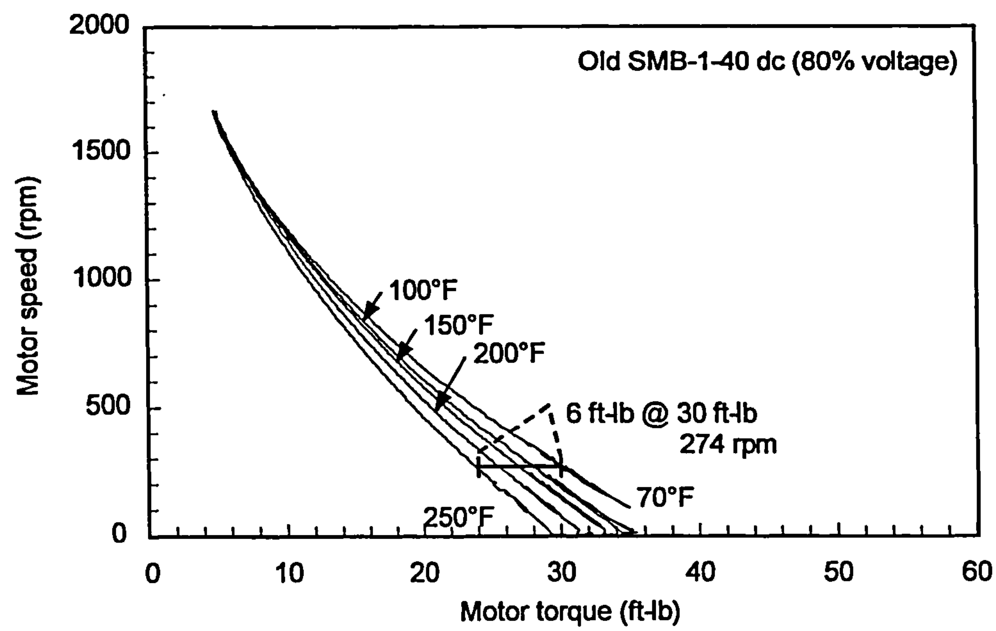


Figure 29. Motor speed versus torque, derived from earlier testing of the older 40-ft-lb dc motor at elevated temperature and 80% voltage.

A comparison between the guidance provided by Reference 8 and the observed response on Figures 22 through 29 shows that the guidance consistently overestimates the capability of the motor under elevated temperature conditions. (The guidance provides for no loss in capability for the two smaller motors, and a loss of only 1 ft-lb for the 40-ft-lb motors.) This result is based on an analysis that compares motor output torque at the same motor speed but at various temperature conditions. This analysis approach has merit, because it recognizes that some actuators are expected to close or open a valve within a specified stroke time. In instances where stroke time is not an issue, it might be possible to use a different analysis approach that recognizes motor output torque at lower speeds, for comparison with predicted values.

However, such an approach would need to account for the motor speed threshold below which the motor produces no additional useful actuator output torque, an issue discussed earlier in this report. A review of Figure 22 (elevated temperature tests at 100% voltage) indicates that the 10-ft-lb motor failed to produced its rated torque in the 300°F test, and produced its rated torque in the 250°F test at a motor speed below the threshold. It produced its rated torque at a motor speed above the threshold in the other tests (at lower nominal temperatures). The 25-ft-lb motor (Figure 24) produced its rated torque at a motor speed above the threshold only in the 70°F and the 100°F tests. The performance of the two 40-ft-lb motors (Figures 26 and 28) was similar to that of the 25-ft-lb motor.

Based on our observation of the response of the motors during the elevated temperature tests, it was apparent that temperature has a linear effect on output torque, similar to the temperature effect on the resistance of copper wire. Also, the shift in the motor speed versus torque curves appears to be a horizontal shift (motor torque axis) only. For example, compare Figure 15 with Figure 21 and note the difference in the pattern projected by the traces in the lower right plots.

We also recognized that only the shunt field in a compound-wound dc motor is a strong function of resistance, and that treating the entire motor as resistance-dependent would result in overprediction of the temperature effect. We therefore applied a linear relationship to estimate the actual torque from the rated torque, based on the ratio of the change in temperature to the temperature above absolute zero. This relationship is

$$Tq_{act} = Tq_{rat}\left(1 - \frac{T_e - T_a}{T_a - T_z}\right) \quad (5)$$

where:

Tq_{rat} = actual motor torque

Tq_{act} = rated motor torque

T_e = elevated temperature

T_a = ambient temperature (room temperature of about 70°F)

T_z = absolute zero (-273.15°C or -459.67°F).

Figures 30 and 31 show the results of this calculation for the 10-ft-lb dc motor, for 100% and 80% voltage, respectively. We have arbitrarily selected 500 and 1,000 rpm as the motor speeds for which we perform the analysis. In these figures, Equation (5) has been applied to the motor torque to estimate the elevated temperature performance. This produces an estimate that is reasonably close to the actual measurements. In all cases, these estimates are based on the actual motor temperature at that point in time in the test, not the nominal temperature at which the test began. We also adjusted the estimates to account for any differences in voltage that might result from the voltage drop that occurs during the test, as discussed in the preceding section of this report. Figures 32 and 33 present the results of this analysis for the 25-ft-lb motor, and Figures 34 and 35 present the results for the 40-ft-lb motor. For all three motors, the estimates produced by the linear temperature relationship shown in Equation (5) are very close to the actual data. Corresponding data plots for the older 40-ft-lb motor are not included here, because the instrumentation scheme used in the earlier test program did not provide sufficient data for this analysis to be performed.

In addition to the analysis described here, we also used Equation (5) to account for motor heating effects on the reduced voltage predictions discussed in the previous subsection.

In summary, the results of elevated temperature testing show that for these dc motors, the adjustments recommended by the manufacturer to account for torque losses due to motor heating underestimate the actual torque losses. Specifically, the 10- and 25-ft-lb motors experienced torque losses of 3.8 and 8 ft-lb, respectively, at motor speeds corresponding to the motors' rated torques. For these motors, no adjustment is specified by the manufacturer. For the 40-ft-lb motor, the published torque loss was 1 ft-lb at 340°F, while the test results showed an actual torque loss of 10 ft-lb at only 250°F. The calculation of these torque losses assumes the same motor speed for the different elevated temperature conditions.

Assuming that torque output at lower motor speeds—down to the 200- to 300-rpm threshold—is acceptable, the results from the 100% voltage tests at elevated temperature indicate that the 10-ft-lb motor achieved its rated torque only in tests at nominal temperatures of 200°F and lower. The performance of the 10-ft-lb motor at elevated temperature was better than that of the other motors, because this smaller motor has more margin above its rated torque than the larger motors. The 25-ft-lb motor and the older 40-ft-lb motor achieved their rated torques only in tests at nominal temperatures of 100°F and lower. The newer 40-ft-lb motor achieved its rated torque only in the room temperature (70°F) test. Both 40-ft-lb motors failed to produce the published 39 ft-lb torque when subjected to temperatures even remotely approaching the 340°F specified by the manufacturer.

A step increase in temperature resulted in a step decrease in dc motor output torque. The motor torque reduction was approximately linear with the change in temperature. Separate from the scheduled step increases, motor temperature increased during operation against high loads. Typically, the temperature increased 30 to 50°F during operation for about 15 seconds against an increasing load approaching and reaching motor stall. Note, however, that about 40% of that increase occurred during the last few seconds of the stroke, with the motor lugging at speeds below the 200- to 300-rpm threshold. This means that for these motors, operation with the torque switch set to trip before the motor lugs down to the threshold will produce less heating than the 30 to 50°F seen in these stall tests.

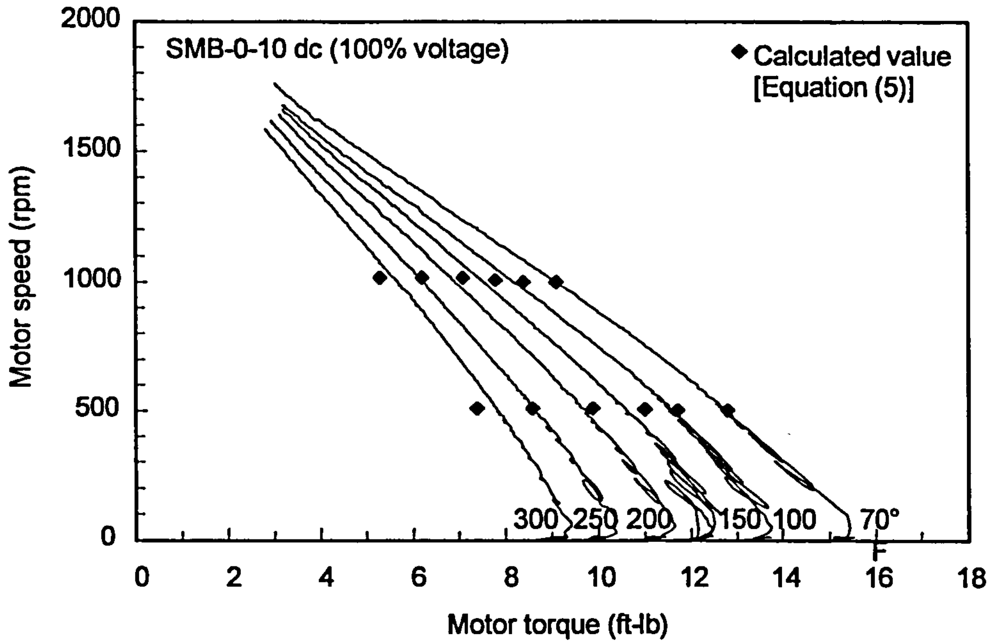


Figure 30. Motor speed versus torque, derived from testing of the 10-ft-lb dc motor at elevated temperature and 100% voltage, with predictions based on Equation (5).

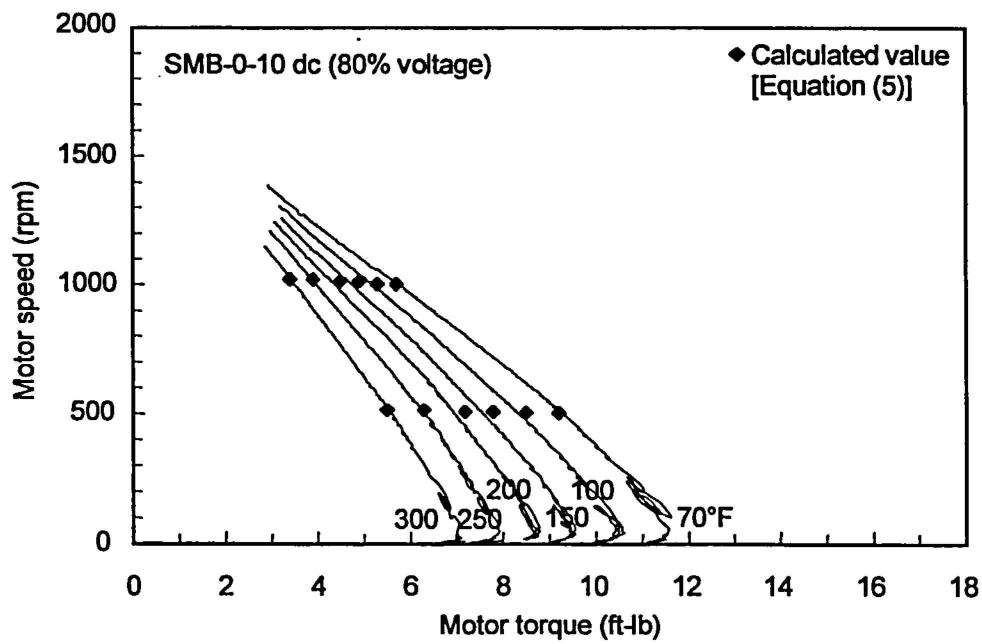


Figure 31. Motor speed versus torque, derived from testing of the 10-ft-lb dc motor at elevated temperature and 80% voltage, with predictions based on Equation (5).

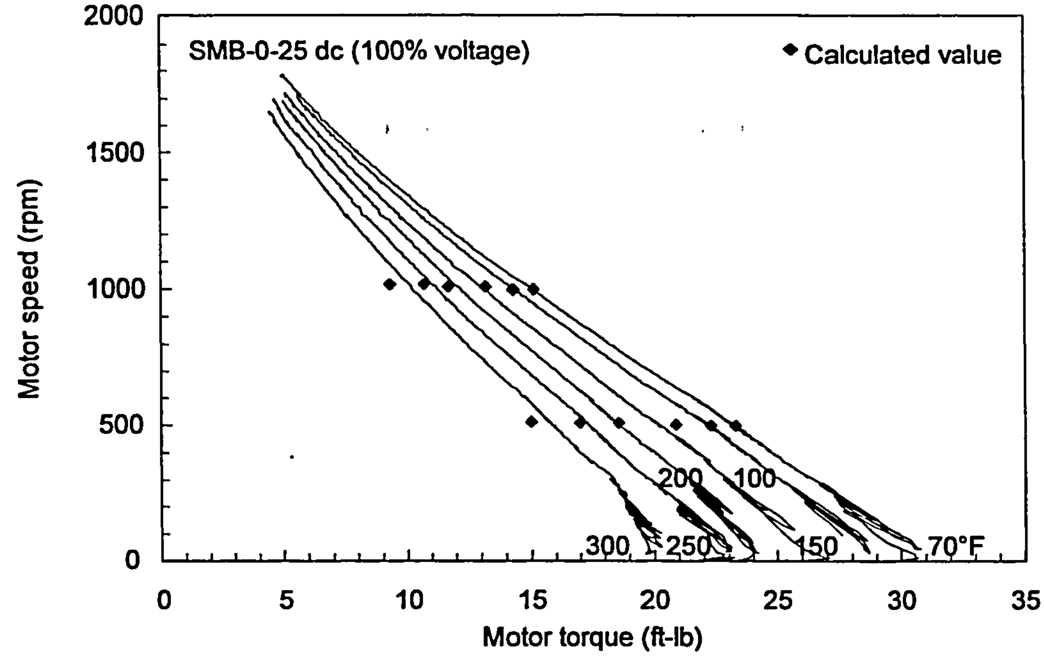


Figure 32. Motor speed versus torque, derived from testing of the 25-ft-lb dc motor at elevated temperature and 100% voltage, with predictions based on Equation (5).

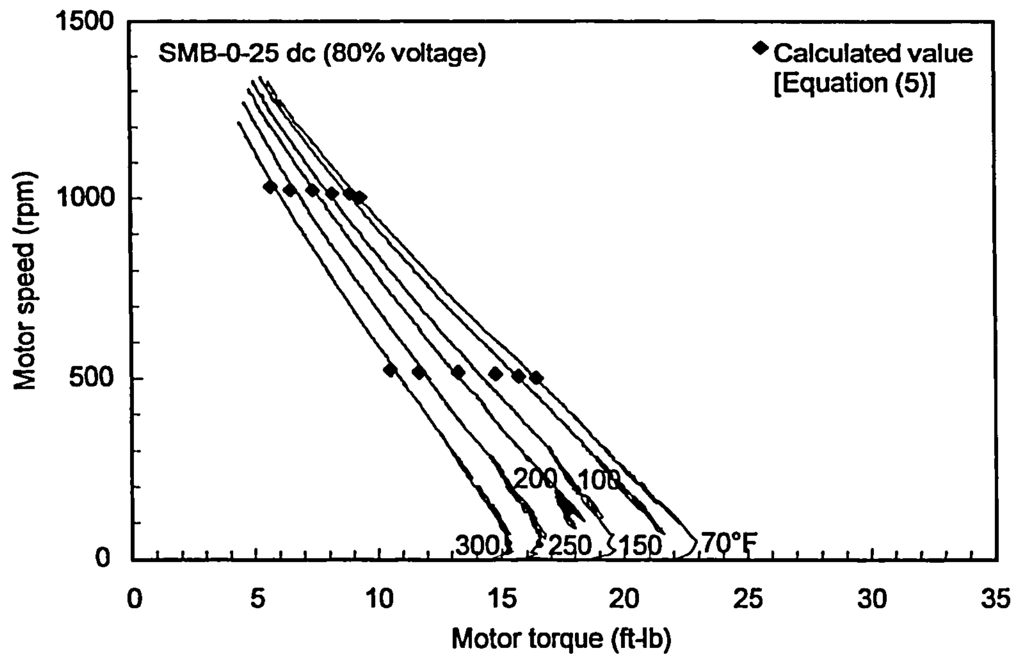


Figure 33. Motor speed versus torque, derived from testing of the 25-ft-lb dc motor at elevated temperature and 80% voltage, with predictions based on Equation (5).

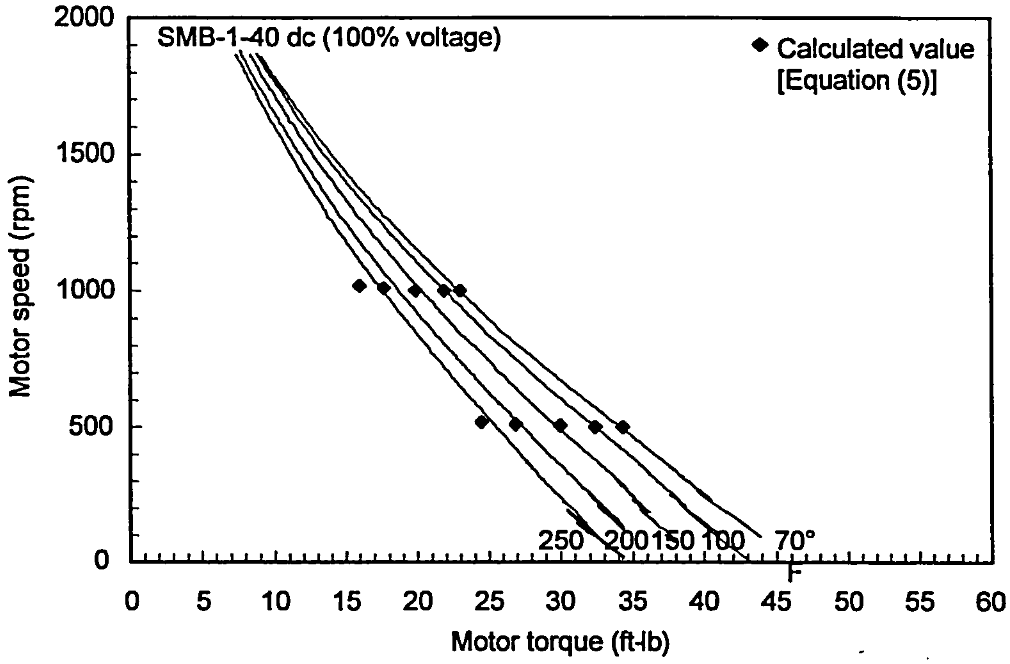


Figure 34. Motor speed versus torque, derived from testing of the 40-ft-lb dc motor at elevated temperature and 100% voltage, with predictions based on Equation (5).

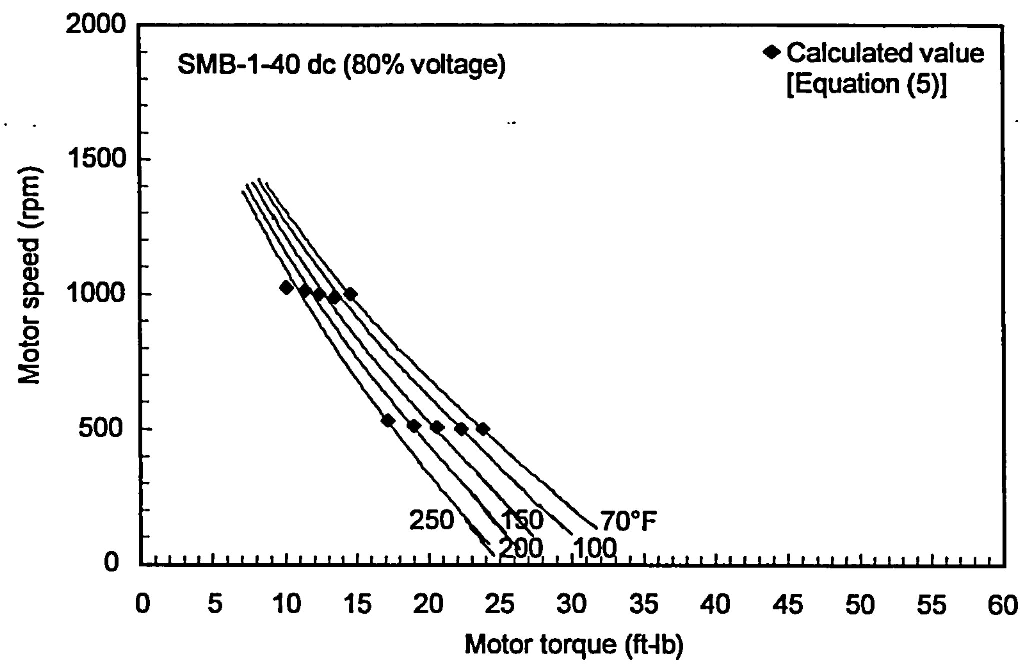


Figure 35. Motor speed versus torque, derived from testing of the 40-ft-lb dc motor at elevated temperature and 80% voltage, with predictions based on Equation (5).

3.4 Effects of Load on Stroke Times and Motor Heating

Figure 36 shows the results of six tests of the SMB-0-10 dc-powered actuator. In these tests, the MOVLS was set up to use both the cylinder and the accumulator to create a fairly constant load for the entire stroke until the cylinder bottomed out, simulating valve wedging. Varying the initial accumulator pressure created variations in the magnitude of the load. The top plot presents results from three tests with loads nominally designated low, medium, and high at 100% voltage, and the bottom plot presents results from tests at 80% voltage. At 100% voltage, the 3,000-lb running load produced an 8-sec stroke time; the stroke time was greater by 1 sec, or 12.5%, in the test with the 7,000-lb load. Combining this load increase with a voltage reduction to 80% yielded a 3.5-sec increase in stroke time, a 44% increase.

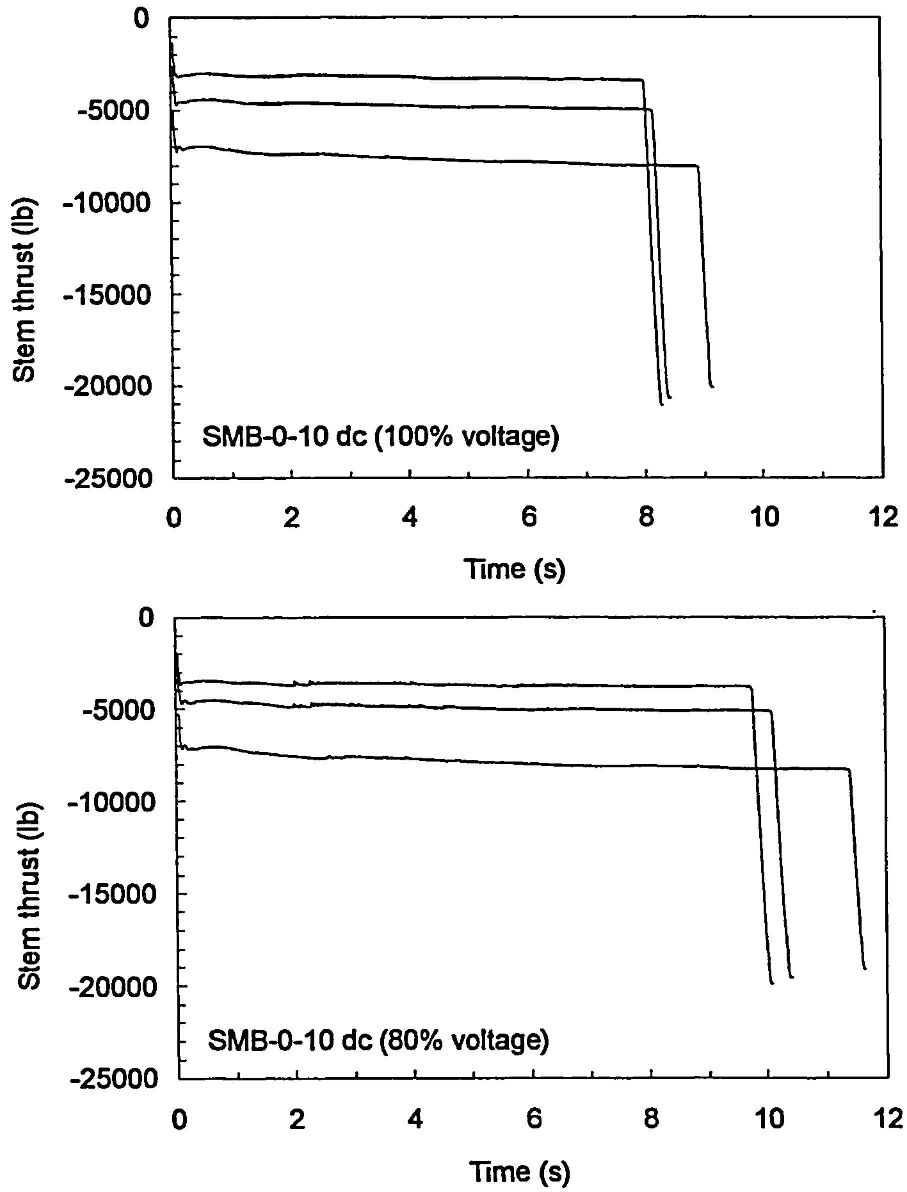


Figure 36. Valve stem thrust versus time, derived from stroke testing of the SMB-0-10 dc actuator at both 100% and 80% voltage.

Figures 37 and 38 show similar data for the other two dc actuators, with similar results. The increase in stroke time, as represented by these test results, mainly considers the decrease in motor speed at higher loads. The effects of motor heat-up during the run are excluded; the loads were not high enough to produce more than a very small increase in motor temperature.

Figures 39, 40, and 41 show the temperature increase that can occur during operation at higher loads (loads approaching the rated output of the motor in tests that end at motor stall). These data show that the motor temperature typically increased at least 30°F and as much as 50°F or more during a single stroke at high loading. About 40% of that increase occurred during the last few seconds of the stroke, with

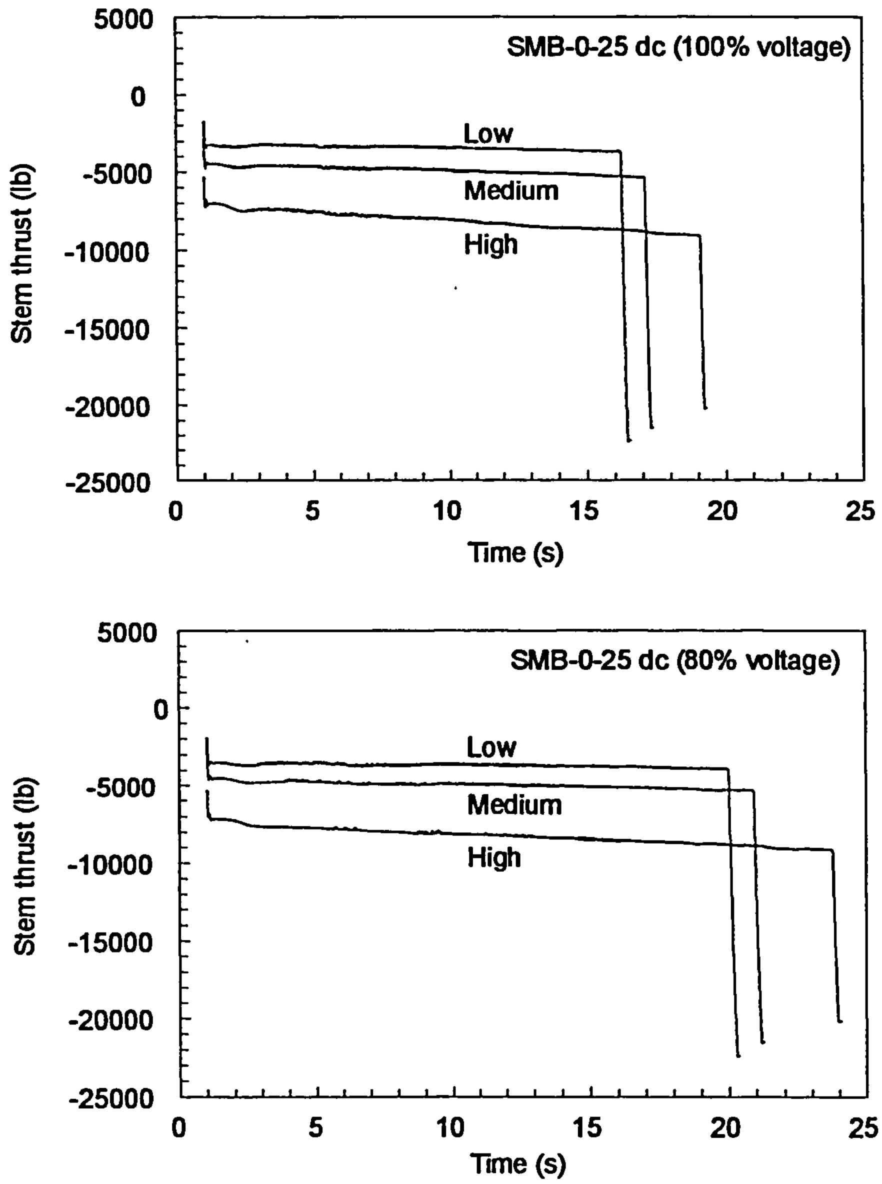


Figure 37. Valve stem thrust versus time, derived from stroke testing of the SMB-0-25 dc actuator at both 100% and 80% voltage.

the motor lugging at speeds below the 200- to 300-rpm threshold. This means that for these motors, operation with the torque switch set to trip at loads before the motor lugs down to the threshold will produce less heating than the 30 to 50°F seen in these stall tests.

In summary, changes in running load can have significant effects on valve stroke time. Increased stroke time and operation at low speeds and high loads can lead to additional motor heating, which can further reduce the torque output of the motor. Increase stroke time is also a concern for valves that are expected to complete the opening or closing stroke within a specified amount of time.

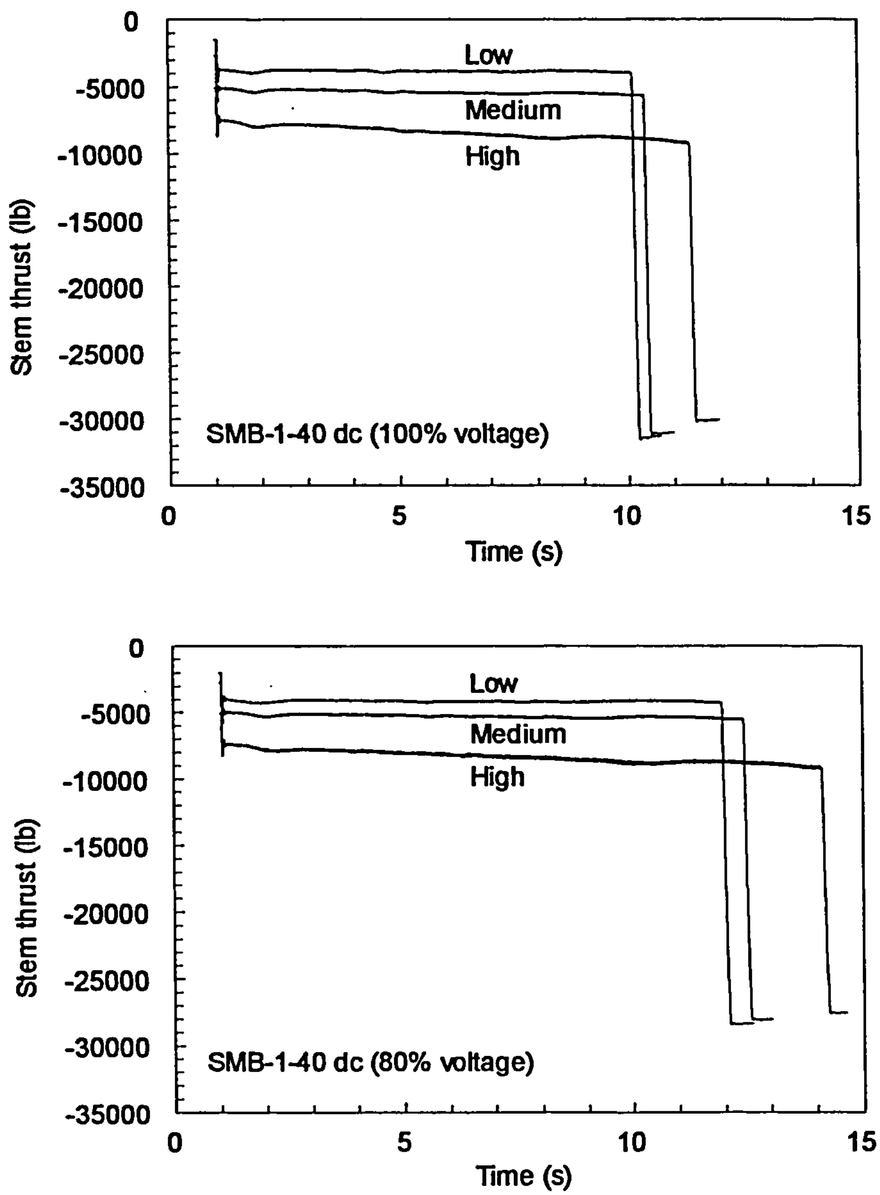


Figure 38. Valve stem thrust versus time, derived from stroke testing of the SMB-1-40 dc actuator at both 100% and 80% voltage.

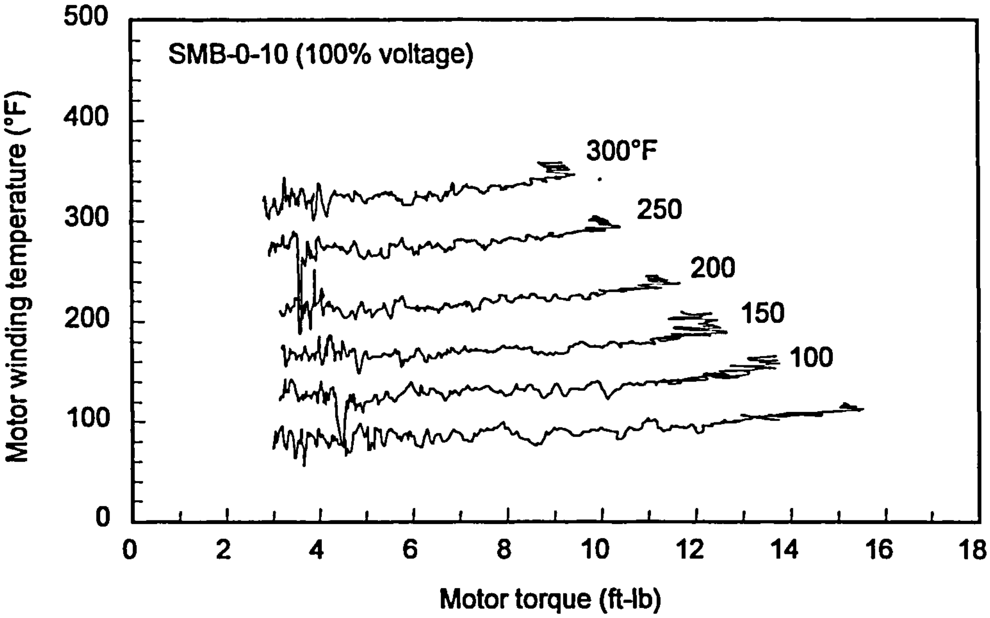


Figure 39. Motor series field temperature versus torque, derived from testing of the 10-ft-lb dc motor at elevated temperature and 100% voltage.

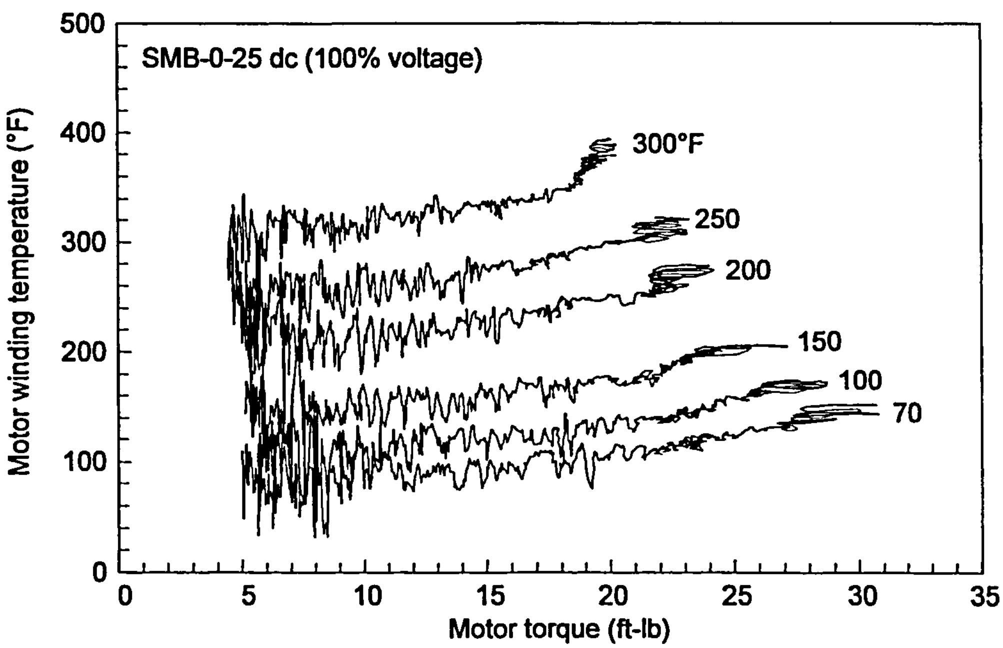


Figure 40. Motor series field temperature versus torque, derived from testing of the 25-ft-lb dc motor at elevated temperature and 100% voltage.

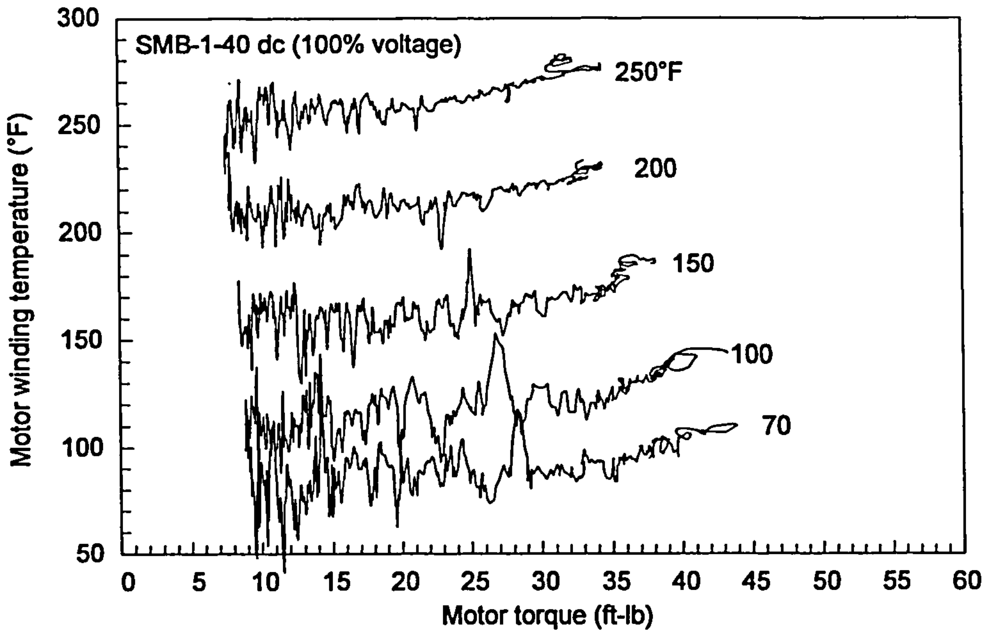


Figure 41. Motor series field temperature versus torque, derived from testing of the 40-ft-lb dc motor at elevated temperature and 100% voltage.

3.5 Performance Curves for dc Motors

The following discussion takes a close look at the performance of the motors at 100% voltage and room temperature (70 to 80°F) and compares the measured performance to the theoretical performance curves published by the actuator manufacturer.

Figure 42 presents data plots showing motor current versus torque (upper plot) and motor speed versus torque (lower plot) from our baseline test of the 10-ft-lb dc motor. Figure 42 also shows the manufacturer's generic current/torque and speed/torque curves for this motor design. This motor required slightly more current than indicated by the manufacturer's curve: 26 amp at the 10 ft-lb rated torque, compared with 25 amp on the manufacturer's curve. The actual torque at a given speed is greater than indicated by the manufacturer's curve, particularly in the middle of the speed range; the actual torque is about the same as the predicted value at locked rotor. Consider, however, that the actual data include the effects of voltage drop and motor heatup during the run.

The manufacturer's curve is a theoretical curve that does not account for the motor heat-up and voltage drop that occur during the run. For comparison purposes, we have included in the lower plot in Figure 42 a curve representing the actual speed versus torque data, adjusted for voltage drop and temperature. This adjustment is based on a linear voltage relationship for motor torque and motor speed, as described in Section 3.2 of this report, and a linear temperature relationship based on the resistance in the series field, as described in Section 3.3. Our intention in this analysis is to create a *theoretical* performance curve derived from measurements, for comparison with the *theoretical* curve published by the manufacturer. The adjusted data indicate that the motor theoretically would produce 18 ft-lb at stall in the absence of motor heating and voltage drop effects, compared to 16 ft-lb indicated by the actual measurement.

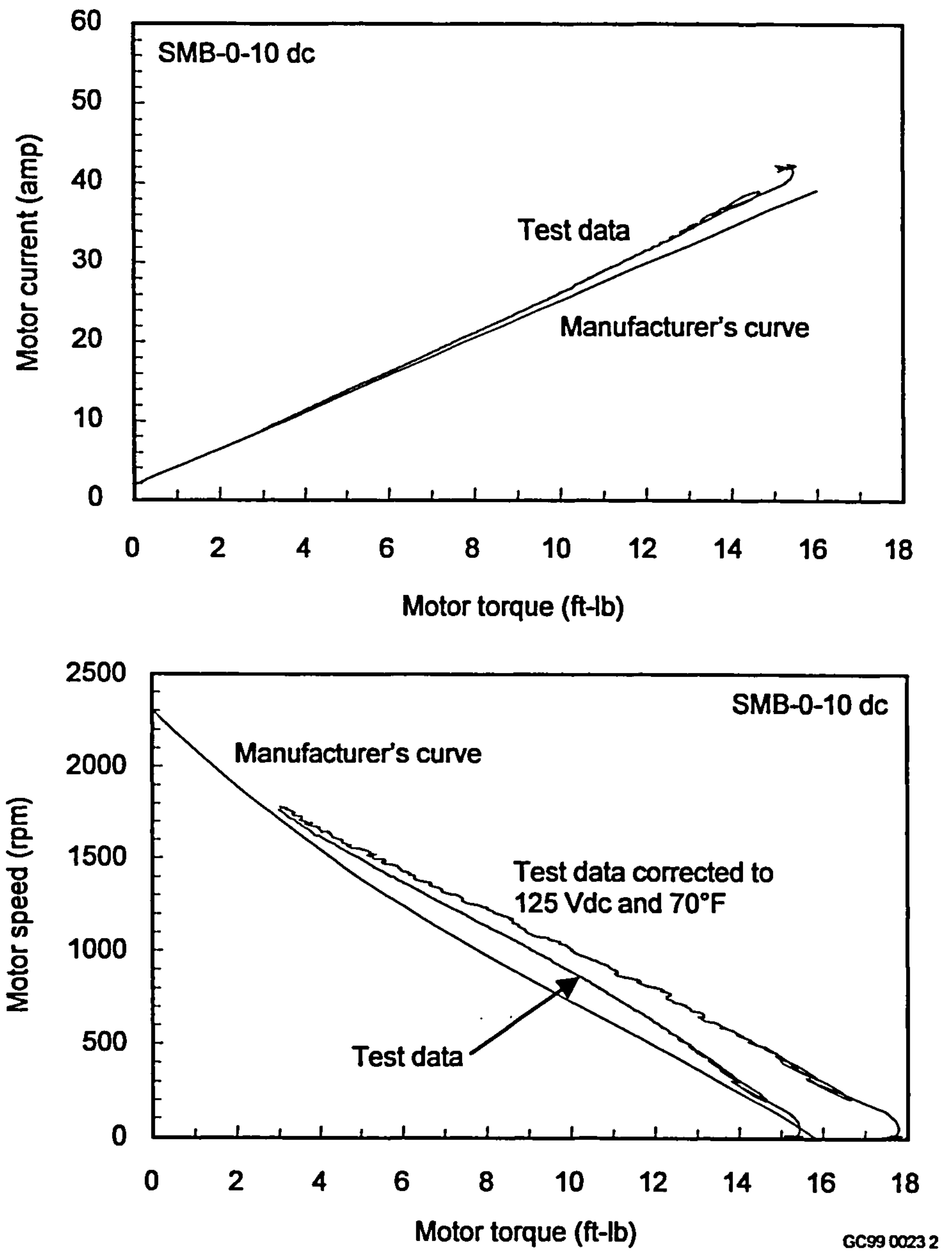


Figure 42. Motor performance curves derived from testing of the 10-ft-lb dc motor; manufacturer's published data are also shown.

Figure 43 presents the same data for the 25-ft-lb dc motor. This motor required slightly more current than indicated by the manufacturer's curve: 56 amp at the 25 ft-lb rated torque, compared with 54 amp on the manufacturer's curve. The actual torque at a given speed is lower than indicated by the manufacturer's curve, reaching stall at 31 ft-lb, compared with 40 ft-lb on the manufacturer's curve. However, adjusting the test data to remove the effects of voltage drop and motor heatup during the run (as described in the previous paragraph) produces a curve that matches the manufacturer's curve.

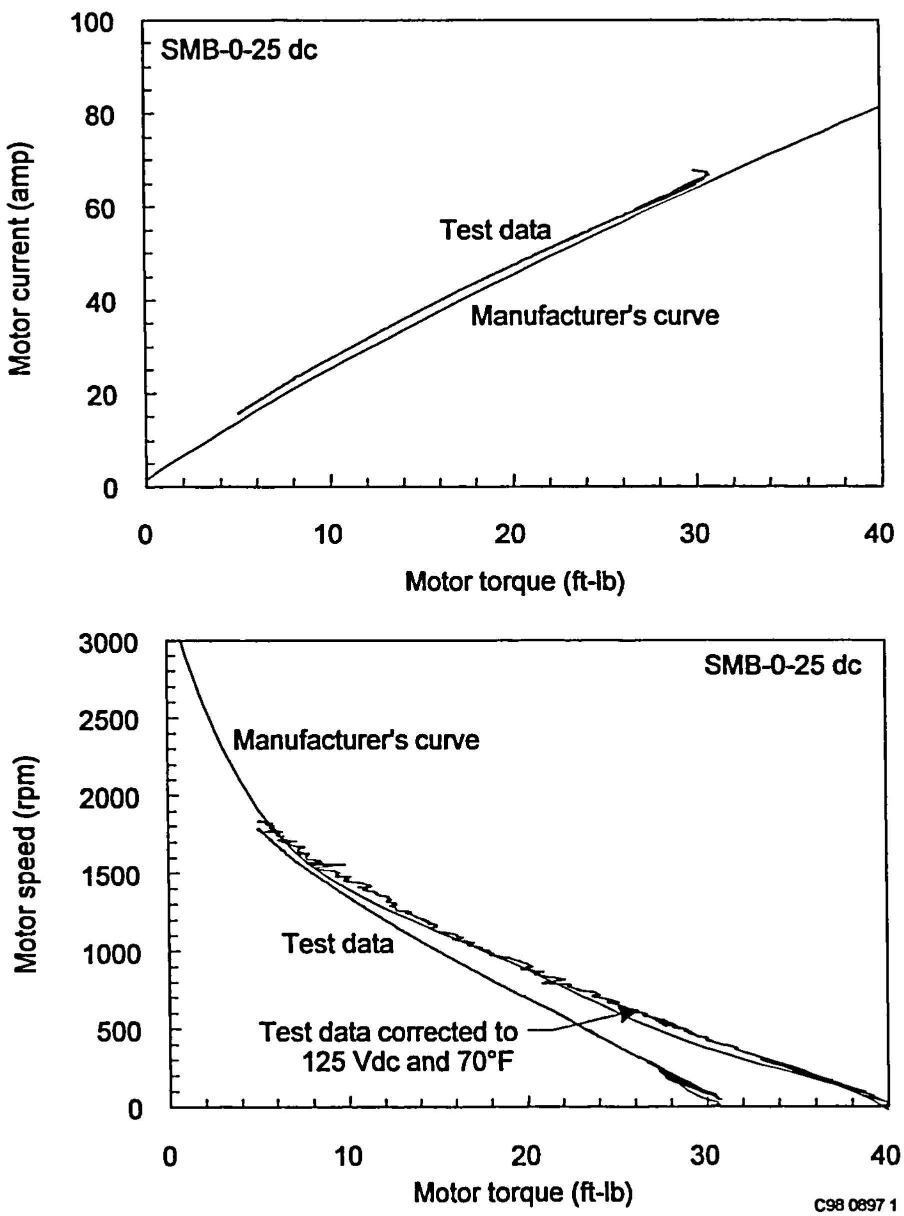


Figure 43. Motor performance curves derived from testing of the 25-ft-lb dc motor; manufacturer's published data are also shown.

Figure 44 presents the same data for the 40-ft-lb motor. This motor required notably more current than indicated by the manufacturer's curve: 95 amp at the 40 ft-lb rated torque, compared with 82 amp on the manufacturer's curve. The actual torque at a given speed is lower than indicated by the manufacturer's curve, with the motor reaching stall at 46 ft-lb, compared with 63 ft-lb on the manufacturer's curve. With the adjustment, the torque data are still somewhat lower than indicated by the manufacturer's curve, with the motor reaching stall at 60 ft-lb.

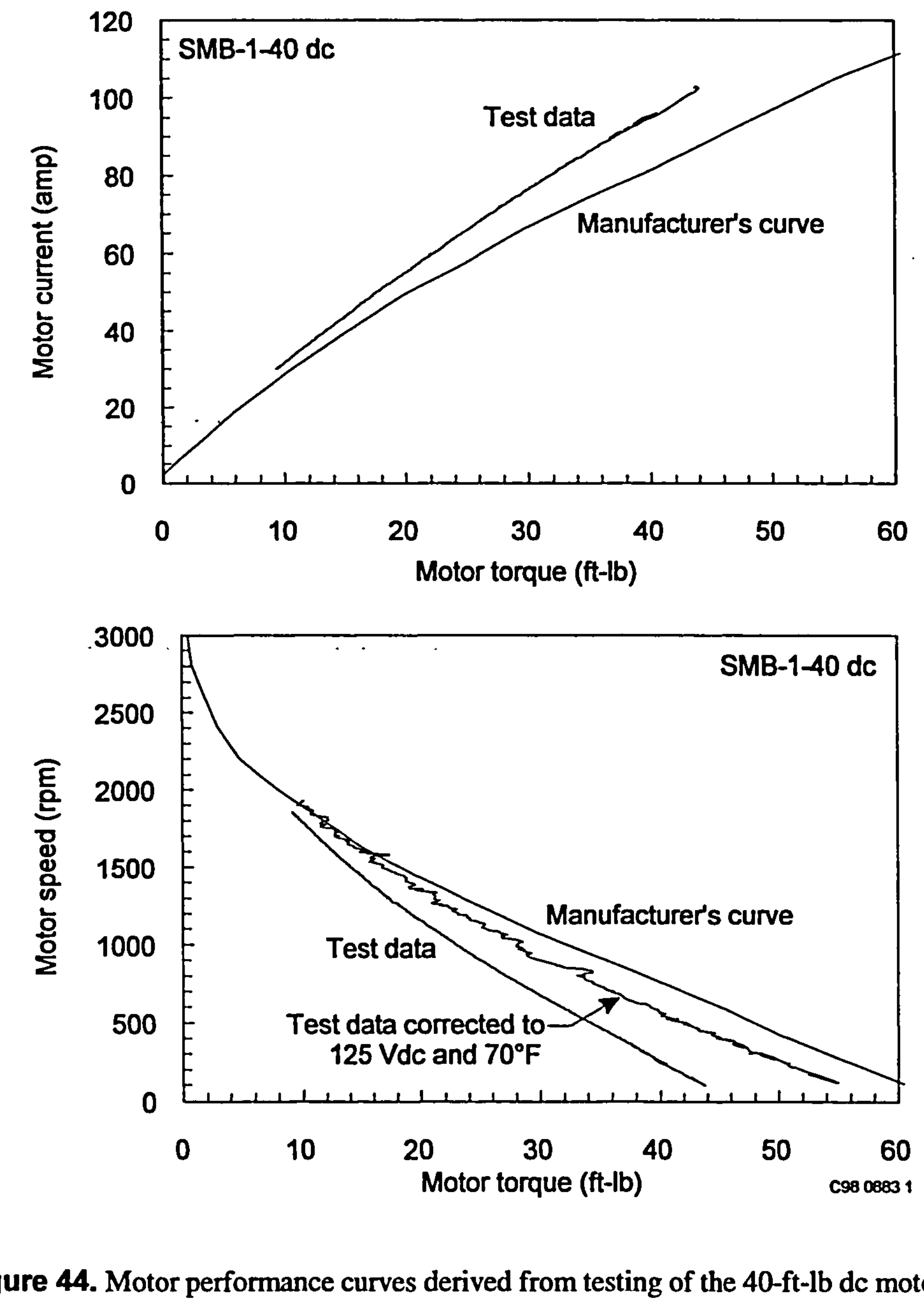


Figure 44. Motor performance curves derived from testing of the 40-ft-lb dc motor; manufacturer's published data are also shown.

Figure 45 presents the same data from earlier testing of the older 40-ft-lb dc motor. With this motor, the torque/current trace matches the manufacturer's curve more closely than with the newer motor (84 amp at the 40 ft-lb rated torque compared with 82 on the manufacturer's curve). The actual torque at a given speed is lower than indicated by the manufacturer's curve, with the motor reaching stall at 49 ft-lb compared with 63 ft-lb on the manufacturer's curve. With the adjustment (voltage adjustment only), the torque data are still a little lower than indicated by the manufacturer's curve, with the motor reaching stall at 57 ft-lbs. (Temperature adjustment was not possible, because a different method was used to monitor temperature during the earlier testing.)

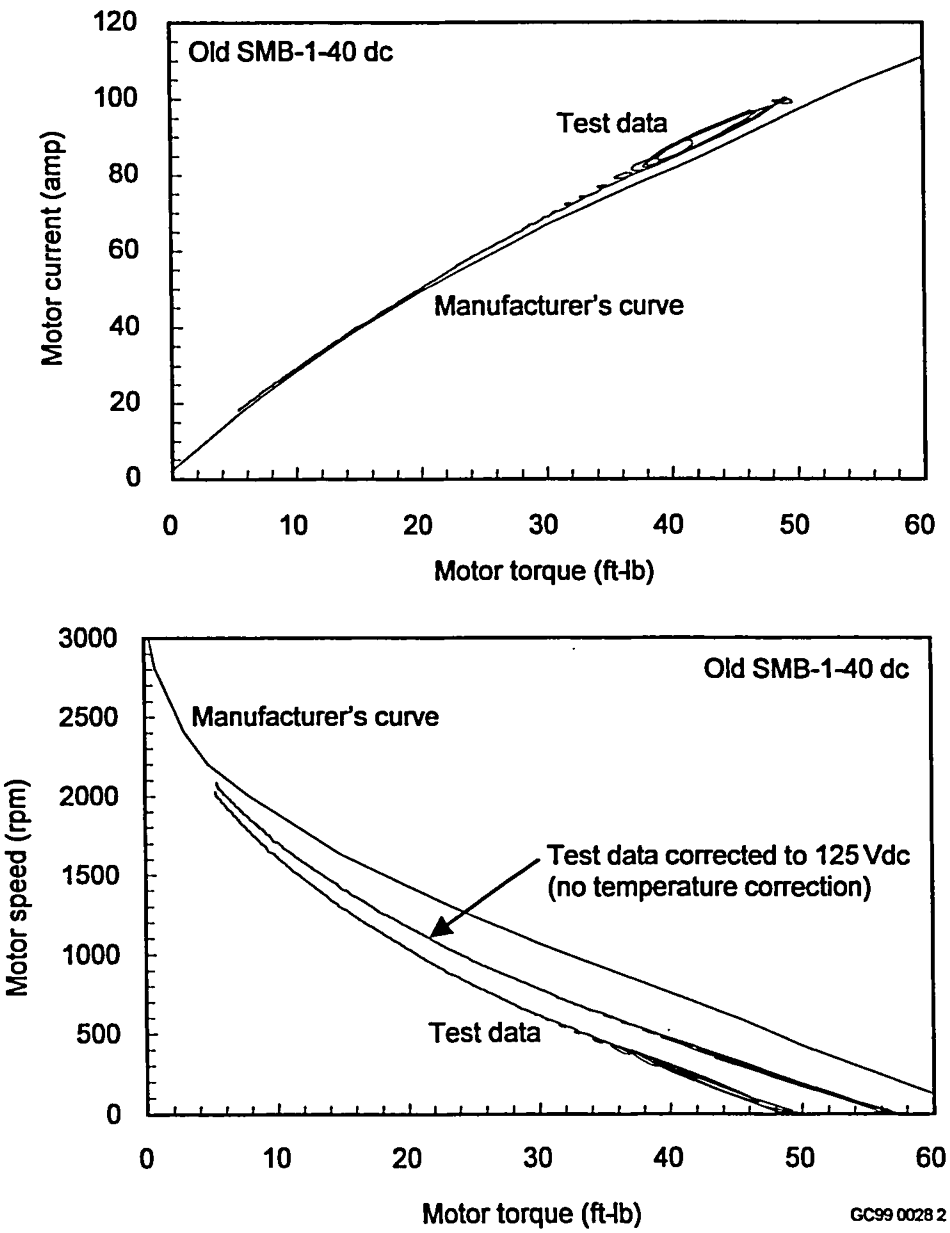


Figure 45. Motor performance curves derived from testing of the older 40-ft-lb dc motor; manufacturer's published data are also shown.

Figure 46 presents a comparison between the manufacturer's generic speed/torque curve for a 40-ft-lb dc motor and the manufacturer's test curve for the old 40-ft-lb dc motor. These test data were taken at the manufacturer's test facility after the motor was rewound and testing in Germany was completed (Reference 10). Note that the torque at a given speed, as indicated by the manufacturer's testing of this motor, is lower than indicated by the generic curve for 40-ft-lb dc motors.

In summary, the actual torque output of three of the four dc motors (torque at a given current) was lower than predicted by the manufacturer's curves. However, some line voltage drop occurred, and the motors were observed to heat up during the testing. With both motor speed and motor torque adjusted for voltage drop, and with motor torque adjusted for temperature, the torque output of the 10-ft-lb dc motor was well above that predicted by the manufacturer's curves, while the output of the 25-ft-lb dc motor closely matched the manufacturer's curves.

The performance of the newer 40-ft-lb dc motor was about the same as that of the older 40-ft-lb dc motor. The torque output of both motors, including the output measured in the manufacturer's test of the older motor, was below that predicted by the generic manufacturer's curves.

For all four motors, the motor current was slightly higher (at a given torque output) than indicated by the manufacturer's curves.

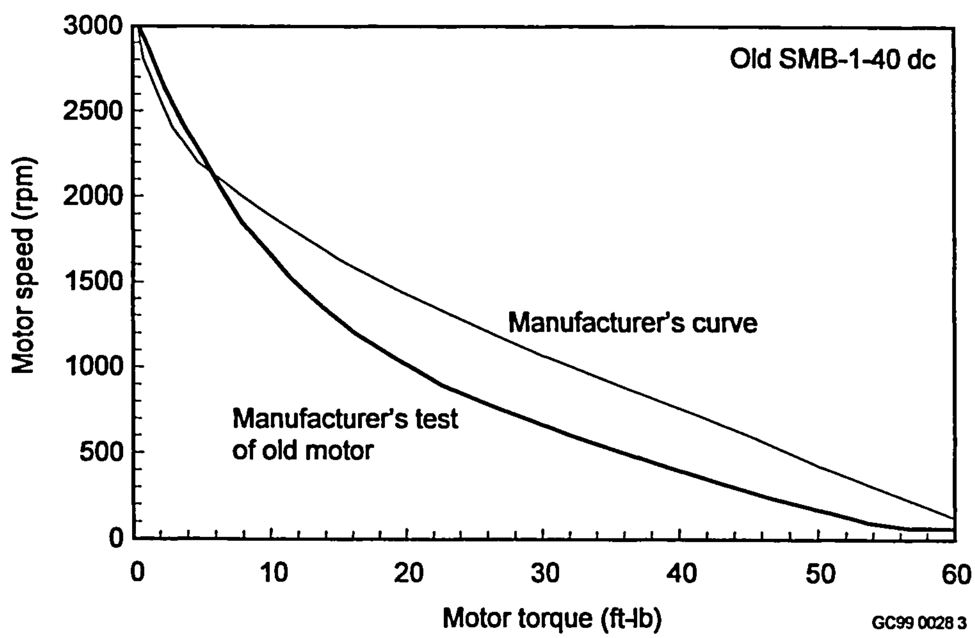


Figure 46. Motor performance curves derived from manufacturer testing of the older 40-ft-lb dc motor; manufacturer's published data are also shown.

3.6 Stem/Stem-Nut Friction

In rising stem MOVs, the conversion of actuator torque output to a stem thrust output occurs at the stem nut, as shown earlier on Figure 2. The ratio of actuator torque to stem thrust is generally referred to as the stem factor. For a specific valve stem and stem nut, the only variable in the conversion of torque to thrust is the coefficient of friction, as shown in the following power screw equation.

$$\frac{Tq_{output}}{Th_{stem}} = \frac{d(0.96815 \tan a + \mu)}{24(0.96815 - \mu \tan a)} = \text{stem factor} \qquad (6)$$

where

Tq_{output} = output torque of the valve actuator

Th_{stem} = valve stem thrust

d = $O.D._{Stem} - \frac{1}{2} Pitch$

$\tan a$ = $\frac{Lead}{\pi d}$

μ = stem/stem-nut coefficient of friction.

The above equation (Reference 11) is written for U.S. Customary units, where torque is in foot-pounds, thrust is in pounds force, and stem diameter and thread pitch and lead are in inches. The pitch is the distance from the peak of one thread to the peak of an adjacent thread (inches/thread). The lead is the distance the stem travels in one revolution of the stem nut (inches/stem revolution). As an example, if the configuration consists of two threads spiraling the stem instead of one, the lead is different from the pitch. The diameter, pitch, and lead information for the stems we tested is listed in Table 1. The output torque consists of the torque delivered to the stem nut, which is equal to the torque reacted by the valve stem. The stem thrust is the thrust applied to the valve stem to move the stem and valve disc. The ratio of torque to thrust, shown in Equation (6), is the stem factor. The term d represents the mean diameter of the stem in terms of the thread contact area, and the term $\tan a$ is the slope of the thread. The *Pitch*, *Lead*, and *O.D.* for each stem are listed in Table 1. The behavior of the friction coefficient μ in the reduced voltage and elevated temperature tests deserves close examination, because dc-powered actuators slow down much more than ac-powered actuators do when subjected to high load, reduced voltage, and elevated temperature.

In Figure 47, the upper left plot shows the valve stem thrust measured during the 100% voltage test of the SMB-0 actuator with the 10-ft-lb dc motor. The negative convention for this measurement indicates that the actuator was being operated in the closing direction. Note that the valve stem thrust gradually increases in a manner representing a valve closure against a high-flow load. The lower right plot in Figure 47 shows the actuator torque (output torque) measured during the same test. By plotting the valve stem thrust versus the actuator output torque, we can produce an XY-plot of stem/stem-nut efficiency,

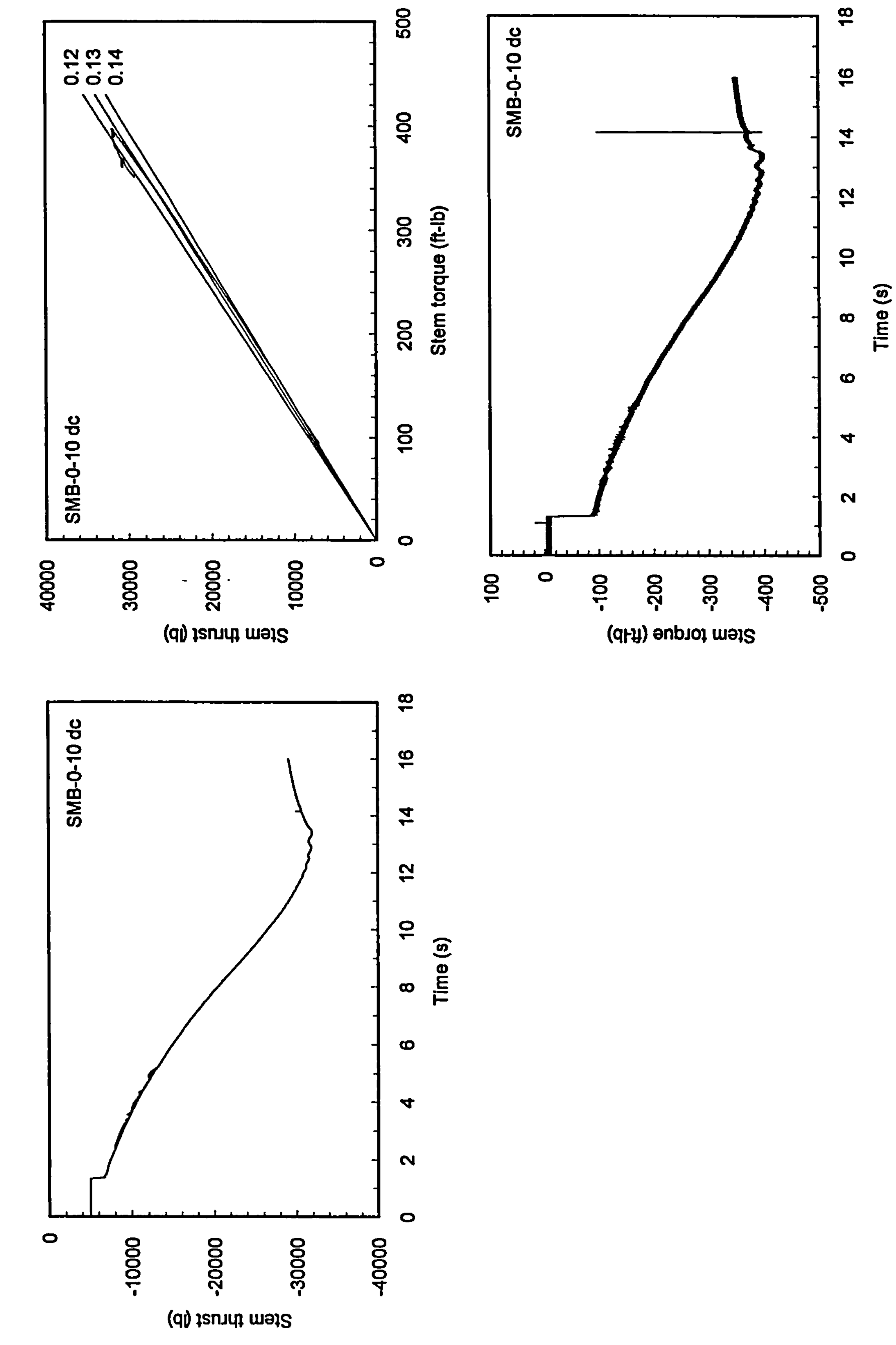


Figure 47. Valve stem thrust, stem torque, and stem factor calculations, derived from testing of the SMB-0-10 dc actuator.

as shown in the upper right plot on Figure 47. The format of this plot is based on Equation (6); the slope from the origin (0,0) to any point on the data trace represents the inverse of the stem factor for that data point:

$$Th_{stem} = \frac{1}{SF} Tq_{output} \quad (7)$$

The three straight lines represent stem/stem-nut coefficients of friction of 0.12, 0.13, and 0.14. This format allows comparison of these fixed values with the actual stem nut performance over the entire operating range (in terms of torque load). For example, Figure 47 shows that for this actuator, the actual stem nut coefficient of friction starts out near 0.14; as the load increases, the friction improves to near 0.13. The data crosses 0.12 near the very end of the stroke, but because the motor is essentially at stall, this occurrence is not important for this analysis.

Figure 48 shows the stem nut friction data for the reduced voltage tests (upper right), elevated temperature at 100% voltage (lower left), and elevated temperature at 80% voltage (lower right) for the SMB-0-10 actuator. In each of the tests, the actual friction is very consistent, indicating that the increasing loads and decreasing actuator speeds have very little if any influence on stem nut friction. We also see a gradual decline in stem nut friction as the test program proceeds (the friction tends to be a little higher in tests performed later in the program). This observation is consistent with earlier research on stem nut issues (Reference 12).

For the other dc actuators, data similar to Figure 48 are presented in Figures 49 and 50. These figures show that for each of the dc actuators we tested, the stem nut performance stabilizes at high loads and changes very little with motor speed.

In summary, high loads and slower speeds had little effect on the stem nut coefficient of friction in these tests. We found no additional rate-of-loading concerns for dc actuators beyond those applicable to ac actuators.

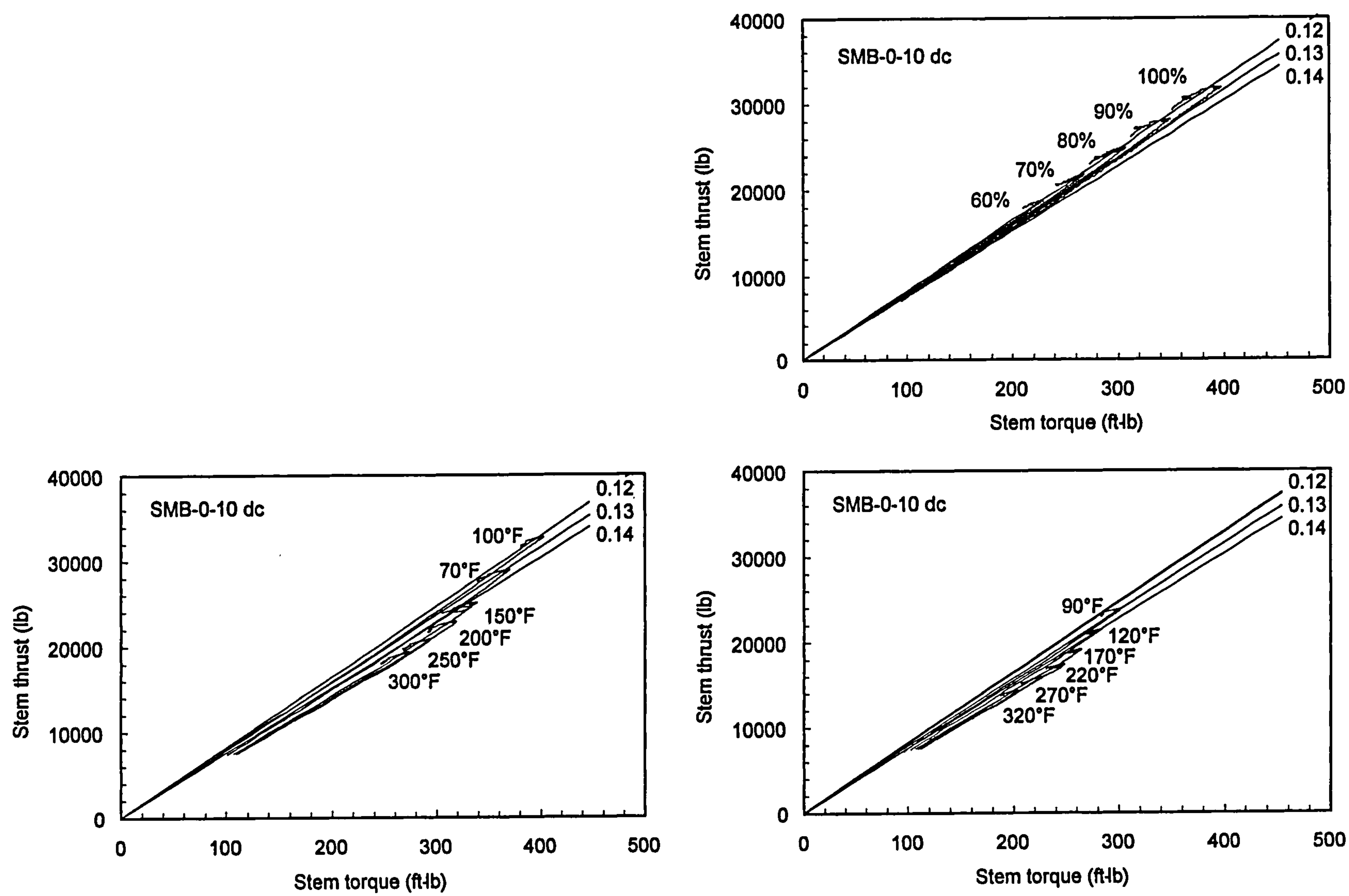


Figure 48. Valve stem factor calculations derived from testing of the SMB-0-10 dc actuator.

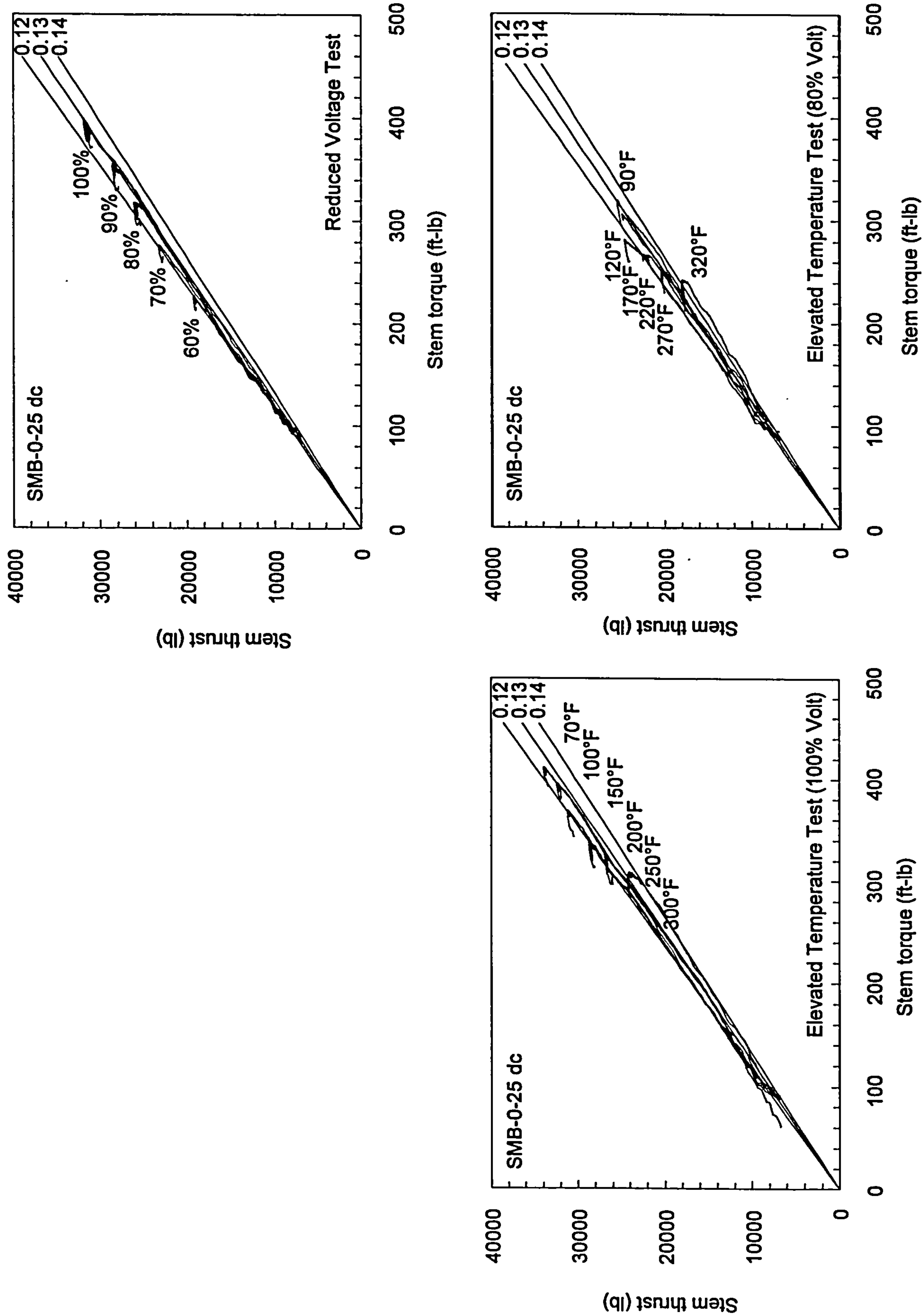


Figure 49. Valve stem factor calculations derived from testing of the SMB-0-25 dc actuator.

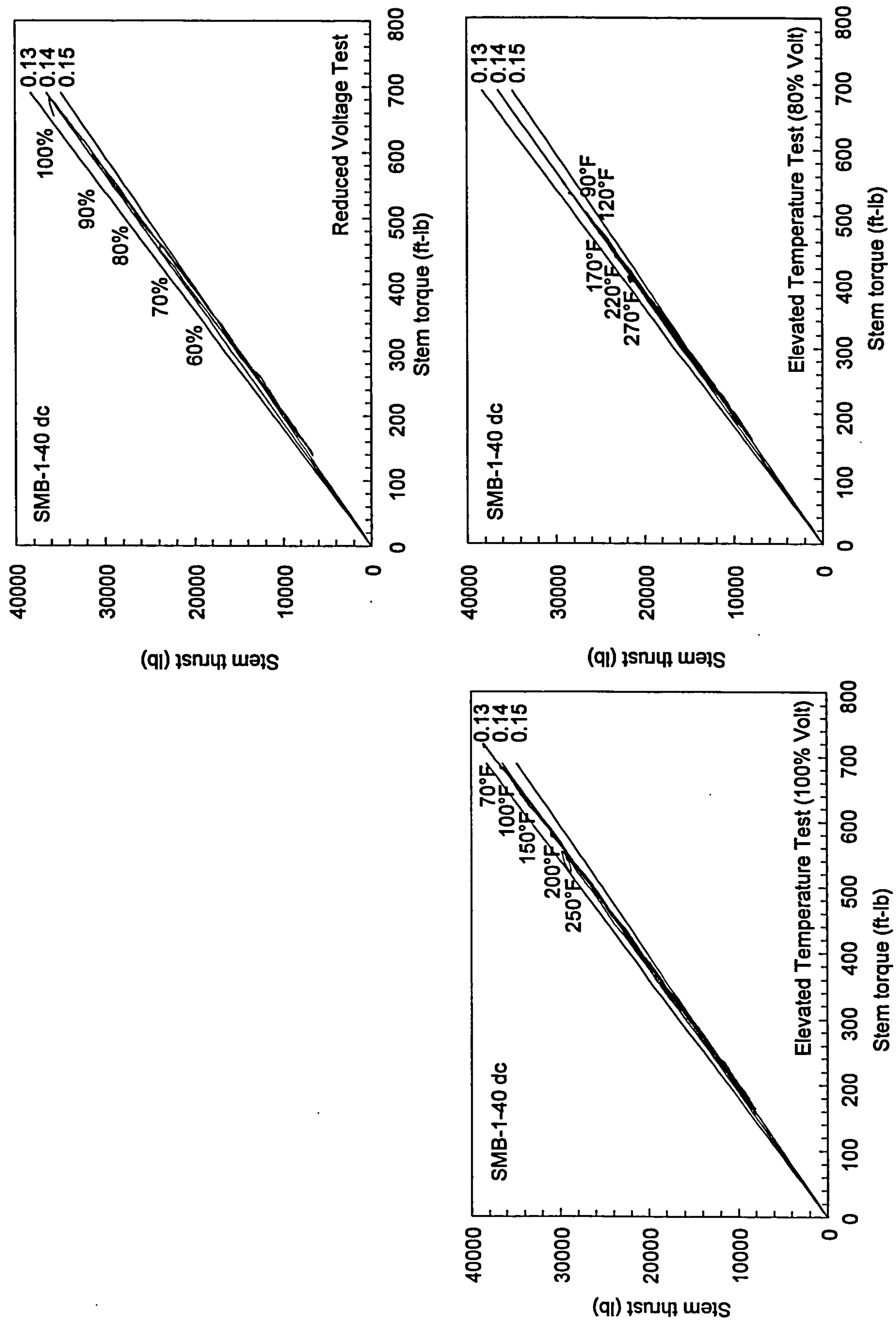


Figure 50. Valve stem factor calculations derived from testing of the SMB-1-40 dc actuator.

4. SUMMARY AND CONCLUSIONS

Gearbox efficiency. 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 pullout efficiency was adequate for predicting gearbox performance for some gearboxes and at some conditions (moderate loads), but at very low speeds, some of the actual efficiency data fell below the published pullout efficiency.

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 dropped well below the values measured at full voltage (and higher speed) for the same motor torque. Each gearbox appears to have a minimum speed below which the pullout efficiency is not longer bounding.

Motor speed threshold. The loss in gearbox efficiency created a minimum motor speed threshold below which additional motor torque produced little or no additional actuator torque. For all four actuators we tested, this motor speed threshold was about 200 to 300 rpm. For these actuators, motor torque produced at high loads below this motor speed threshold cannot be relied upon to produce the necessary actuator output torque.

Degraded voltage. For the motors we tested, estimates that anticipated linear reductions in both motor torque and motor speed fell very close to actual dc motor performance at reduced voltage. Note, however, that in some instances, the actual and predicted performance fell below the motor speed threshold identified in the previous paragraph. (High motor torque values that fall below the threshold cannot be relied upon to produce correspondingly high actuator output torque.) The conventional linear method used in the industry for predicting reduced-voltage-related torque losses underestimated the actual torque losses; this comparison looked at the same motor speed in tests at different voltages.

Elevated temperature. In elevated temperature testing of the dc motors we tested, the adjustments recommended by the manufacturer for accounting for torque losses due to motor heating underestimated the actual torque losses. Specifically, the 10- and 25-ft-lb motors experienced torque losses of 3.8 and 8 ft-lb, respectively, at the motor speed that corresponded with the rated torque (The manufacturer recommendation does not specify an adjustment for these motors). The torque loss anticipated by the manufacturer's recommendation was 1 ft-lb at 340°F for the 40-ft-lb dc motor, while the test results showed an actual torque loss of 10 ft-lb at only 250°F. Those comparisons look at the same motor speed in tests at different temperatures. In comparisons admitting lower speeds (down to the 200- to 300-rpm threshold), the results show that in many of the elevated temperature tests, the motors failed to achieve the torque anticipated by the recommendation, even at lower motor speeds. The performance of the 10-ft-lb motor was better than that of the other three motors.

Elevated temperature had an immediate effect on dc motor output torque. The motor torque reduction was approximately linear with the change in temperature. Typically, the dc motor temperature increased 30 to 50°F during an individual high-load stall test.

Stroke times. Changes in running load had significant effects on valve stroke times. During the high-load stall tests, the motor winding temperature increased about 30 to 50°F or more. About 40% of that increase occurred during the last few seconds of the stroke, with the motor lugging at speeds below the 200- to 300-rpm threshold. This means that for these motors, operation with the torque switch set to trip at loads before the motor lugs down to the threshold will produce less heating than the 30 to 50°F seen in these stall tests. Overall, the results suggest that longer stroke times combined with operation at low speeds and high loads can cause additional motor heating, which would further degrade motor performance.

Performance curves. The actual performance of three of the four dc motors (torque output at a given speed) was below that indicated by the manufacturer's generic curves. For example, the manufacturers published curve for the 25-ft-lb motor indicated a torque of 40 ft-lb at motor stall, while the test data showed a torque of about 30 ft-lb. However, some line voltage drop and motor heating occurred during the run. With the motor speed data and the motor torque data adjusted for voltage drop, and with motor torque data adjusted for temperature, the performance of the 10-ft-lb dc motor was well above that predicted by the manufacturer's curves, while the performance of the 25-ft-lb dc motor matched the manufacturer's curves very well.

The newer 40-ft-lb dc motor performed about the same as the older 40-ft-lb dc motor. The performance of both motors (torque output at a given speed), as well as the manufacturer's test of the older motor, was below that predicted by the manufacturer's generic curves, even after adjustments for voltage and temperature.

The motor current (at a given torque) was slightly higher than the manufacturer's curves for all tested motors.

Stem nut friction. The high loads and slower speeds had little effect on the stem nut coefficient of friction in the actuators we tested. We found no additional rate-of-loading concerns for dc-powered actuators beyond those applicable to ac-powered actuators.

5. REFERENCES

1. NUREG/CR-6478, *Motor-Operated Valve (MOV) Actuator Motor and Gearbox Testing*, K. G. DeWall, J. C. Watkins, D. Bramwell, Idaho National Engineering and Environmental Laboratory, INEL-96/0219, 1997.

2. Limitorque Technical Update #98-01, May 15, 1998.

3. Limitorque Technical Update #98-01 Supplement #1, July 17, 1998.

4. Limitorque SEL-7, November 1989.

5. Limitorque Technical Update #92-02, October 9, 1992

6. Limitorque SEL-3, July 1, 1977.

7. Limitorque SEL-4, July 1, 1977.

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

9. Limitorque 10 CFR Part 21 Notification, November 3, 1998.

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

11. Limitorque SEL-10, March 1988.

12. NUREG/CR-6100, *Gate Valve and Motor-Operator Research Findings*, R. Steele, Jr., K. G. DeWall, J. C. Watkins, M. J. Russell, D. Bramwell, Idaho National Engineering Laboratory, INEL-94/0156, 1995.

Appendix A

Complete Data Sets

APPENDIX A

Complete Data Sets

Not all the data plots produced by the analysis are included in the main body of the report. This Appendix contains a complete set of data plots for each of the three dc-powered valve actuators tested under this research program. It also contains data, as applicable, from earlier testing of the older actuator.

The appendix consists of four sections. Each section presents the data plots from testing of one of the valve actuators, as follow:

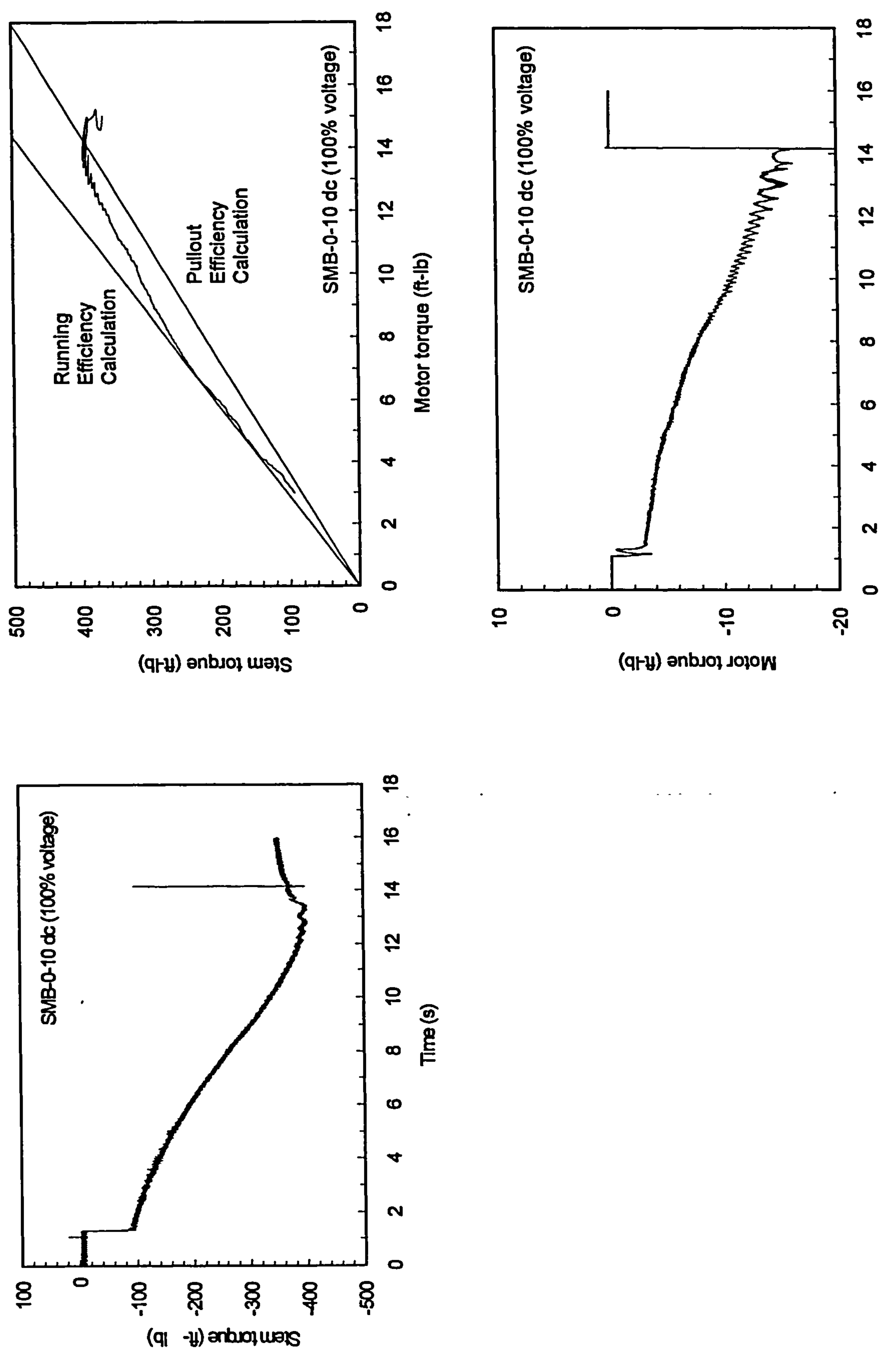
- Section 1 SMB-0-10 10-ft-lb dc motor, SMB-0 actuator
- Section 2 SMB-0-25 25-ft-lb dc motor, SMB-0 actuator
- Section 3 SMB-1-40 40-ft-lb dc motor, SMB-1 actuator
- Section 4 SMB-1-40 older 40-ft-lb dc motor, SMB-1 actuator.

In each section, the data plots are presented by topic in approximately the same order as the presentation of topics in the main body of the report:

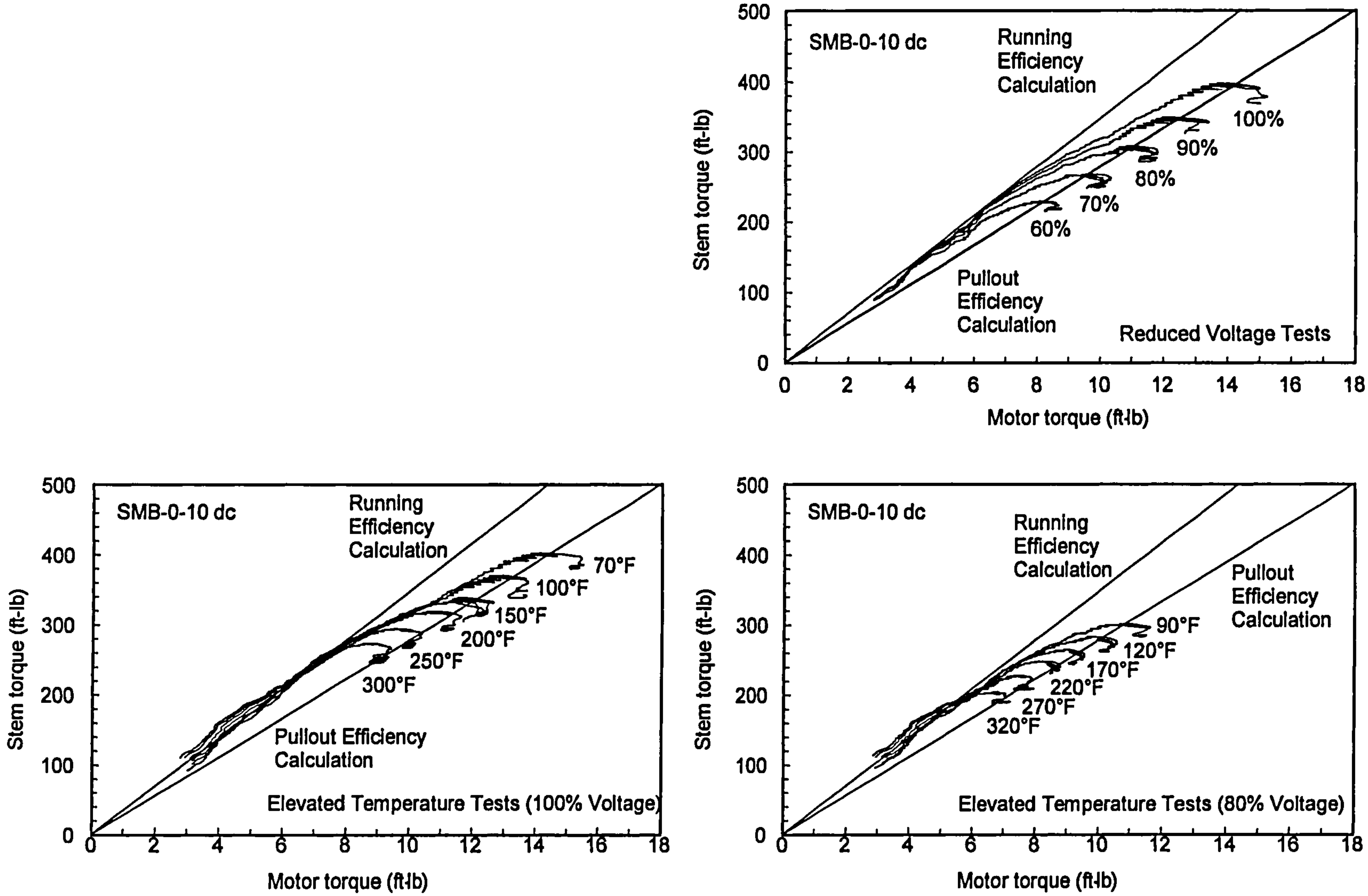
- Gearbox efficiency
- Degraded voltage testing
- Elevated temperature testing
- Stroke times
- Performance curves
- Valve-stem/stem-nut friction.

The set of data plots presented in this appendix is similar in content to the quick-look data that were published earlier and made available in the NRC public document room.

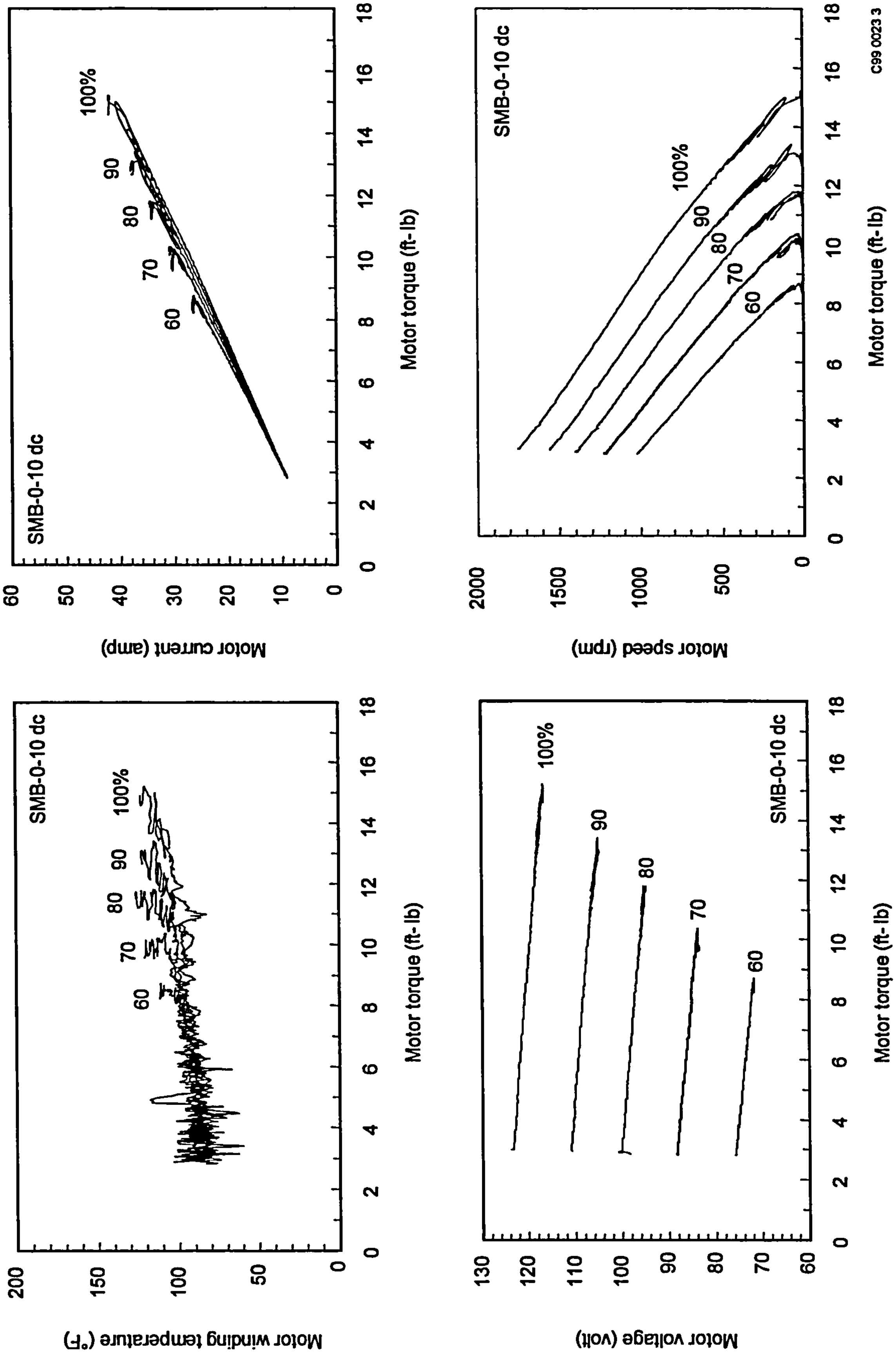
A-1. DATA PLOTS, SMB-0-10



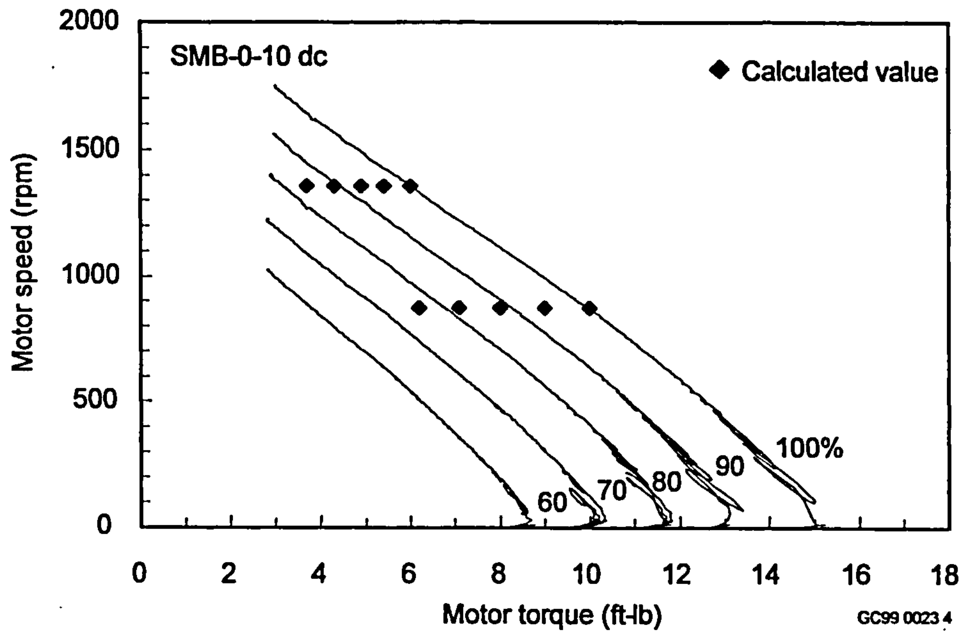
Gearbox efficiency.

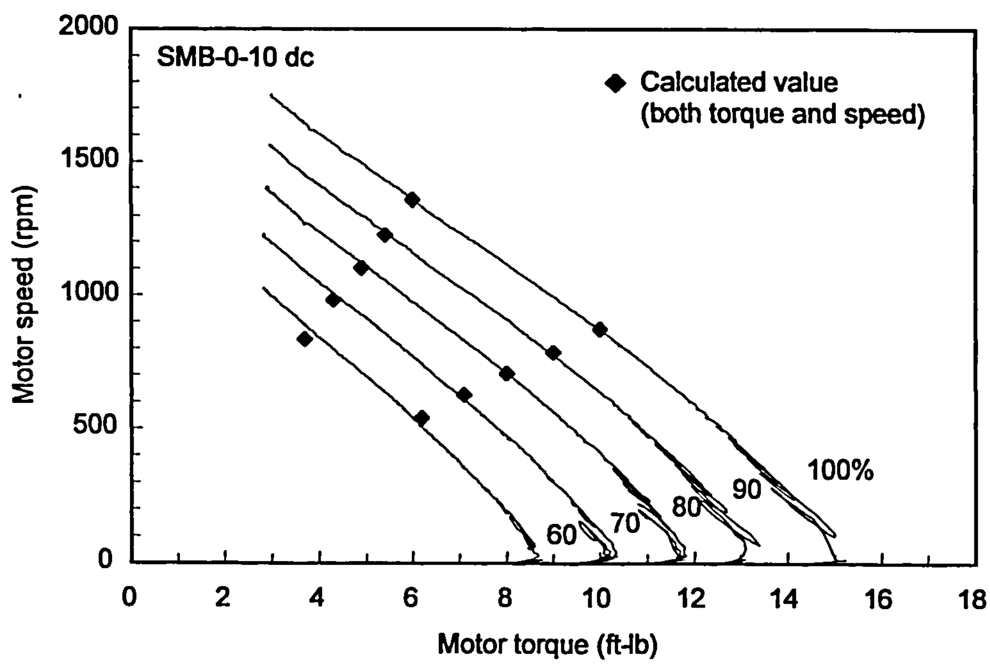


Gearbox efficiency.

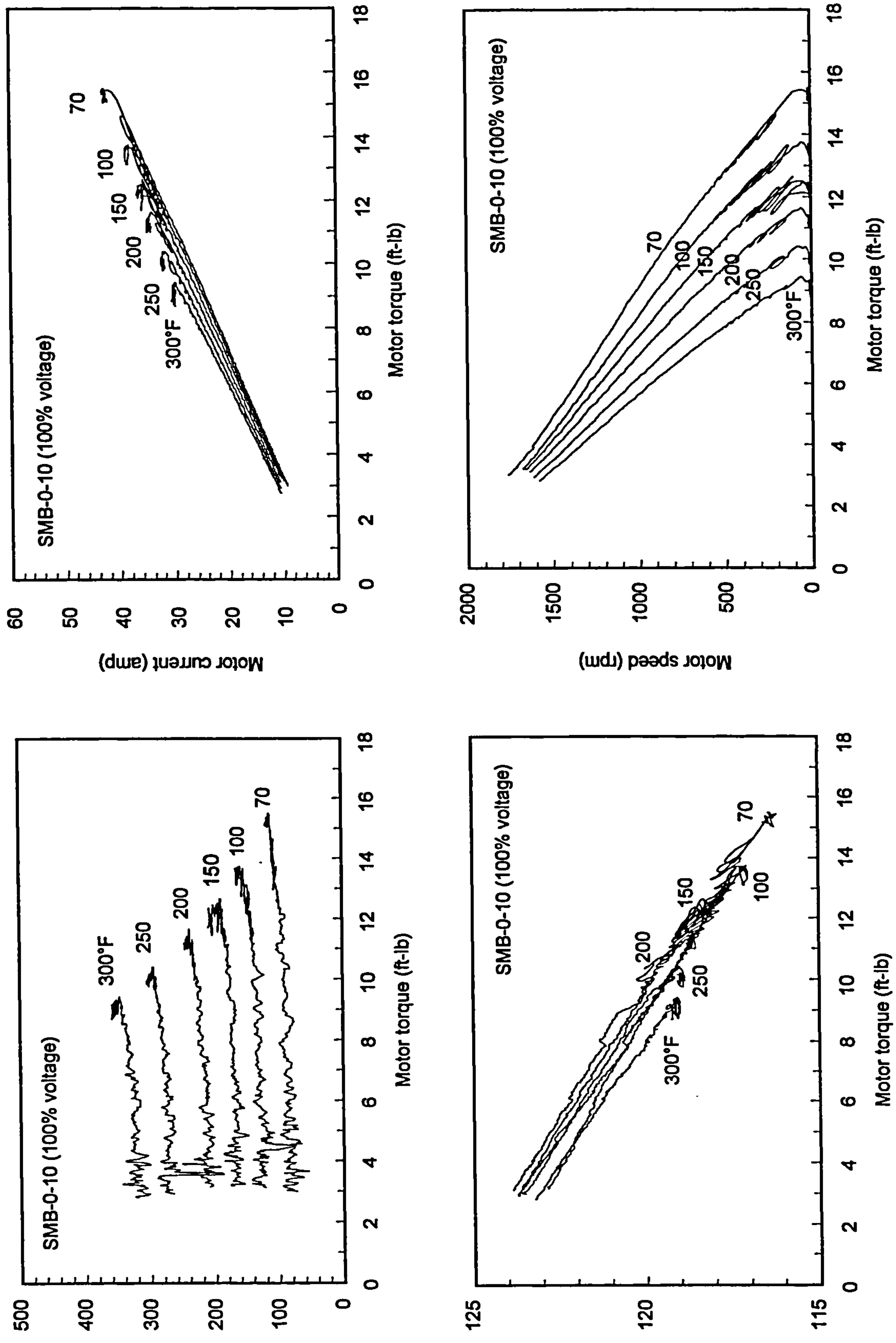


Degraded voltage tests.

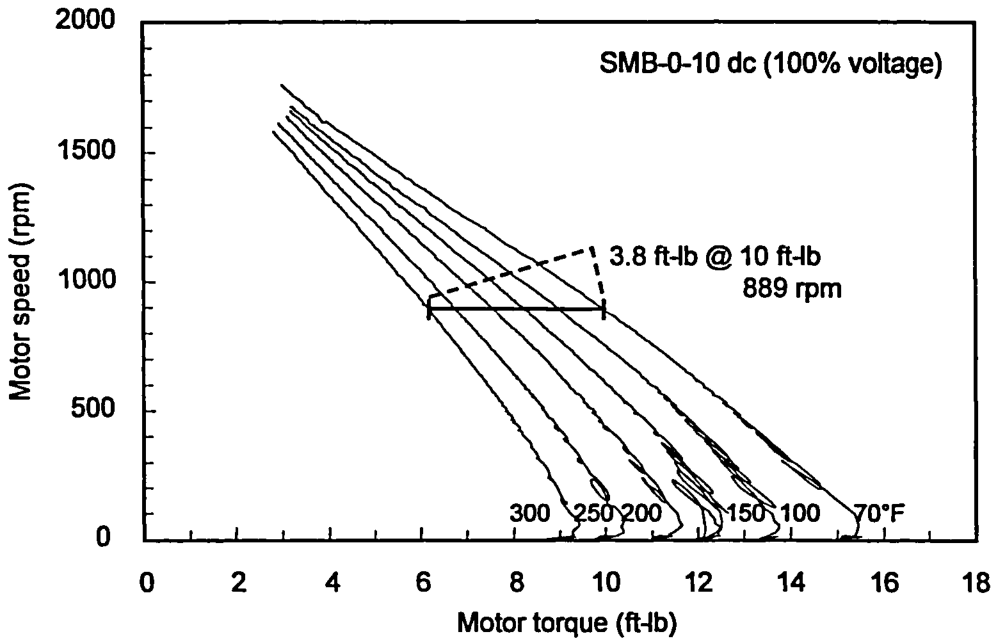


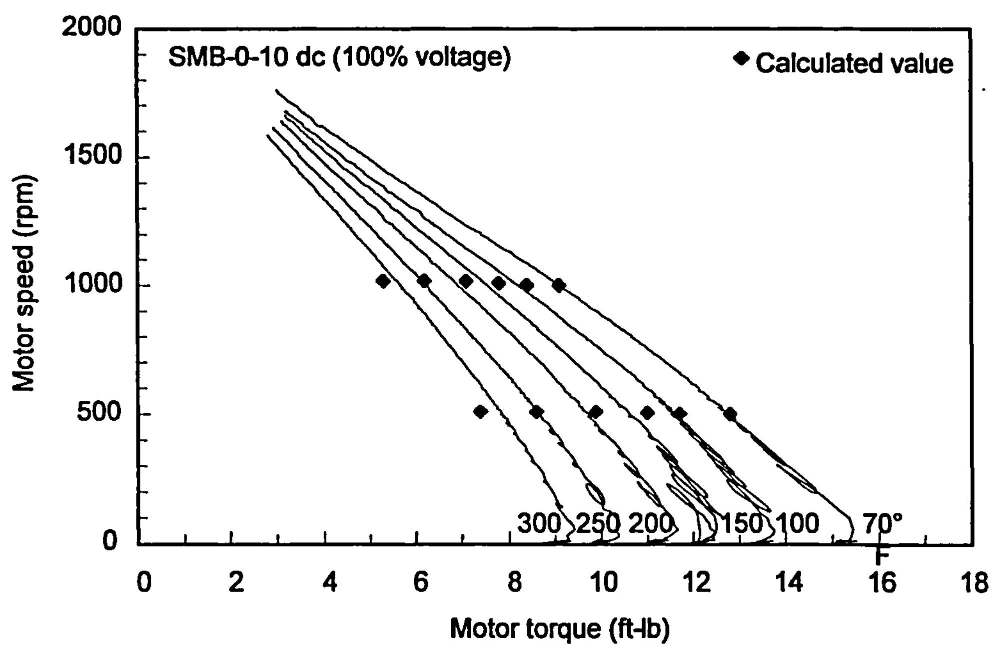


Reduced voltage tests.

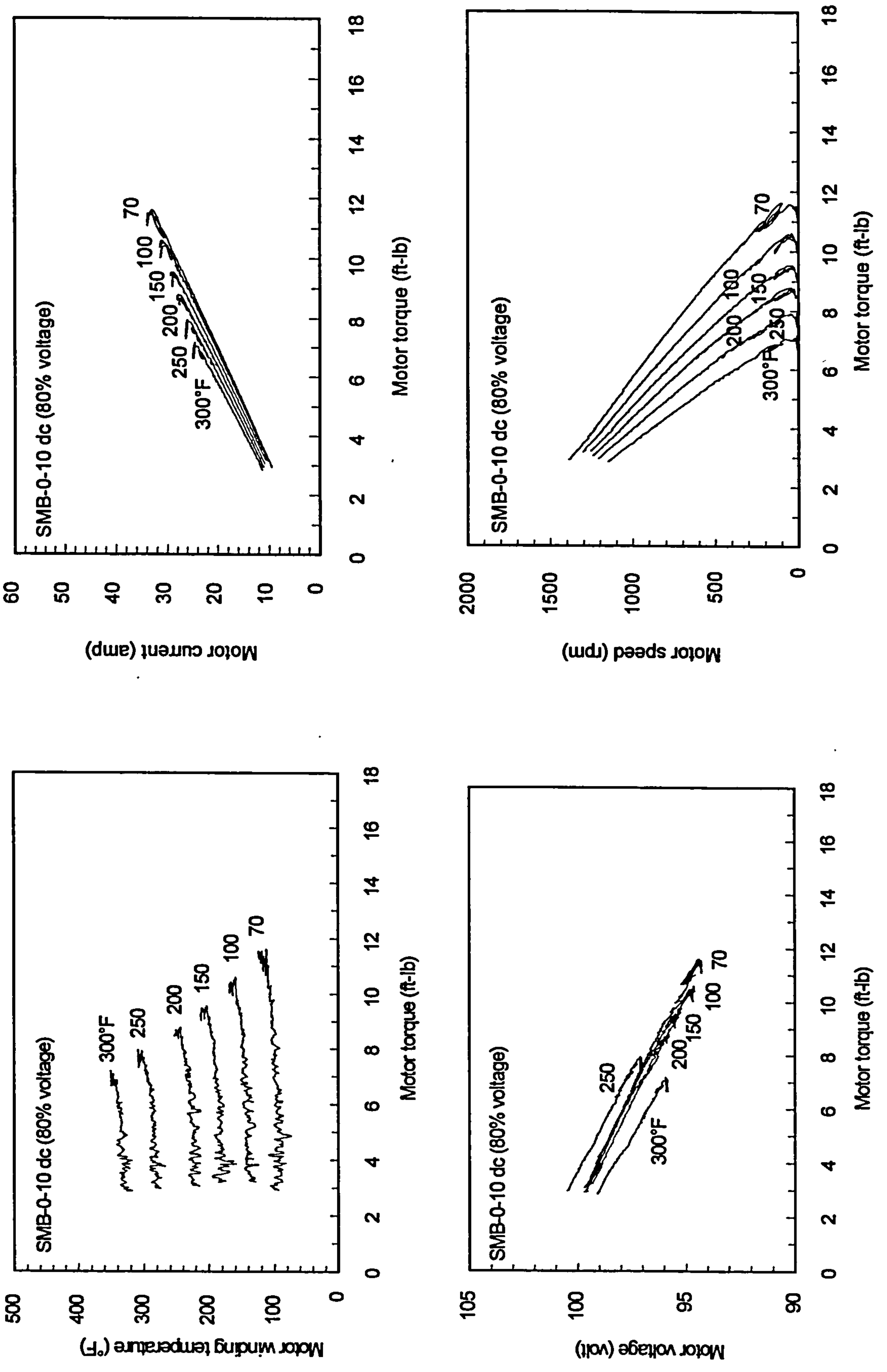


Elevated temperature tests.

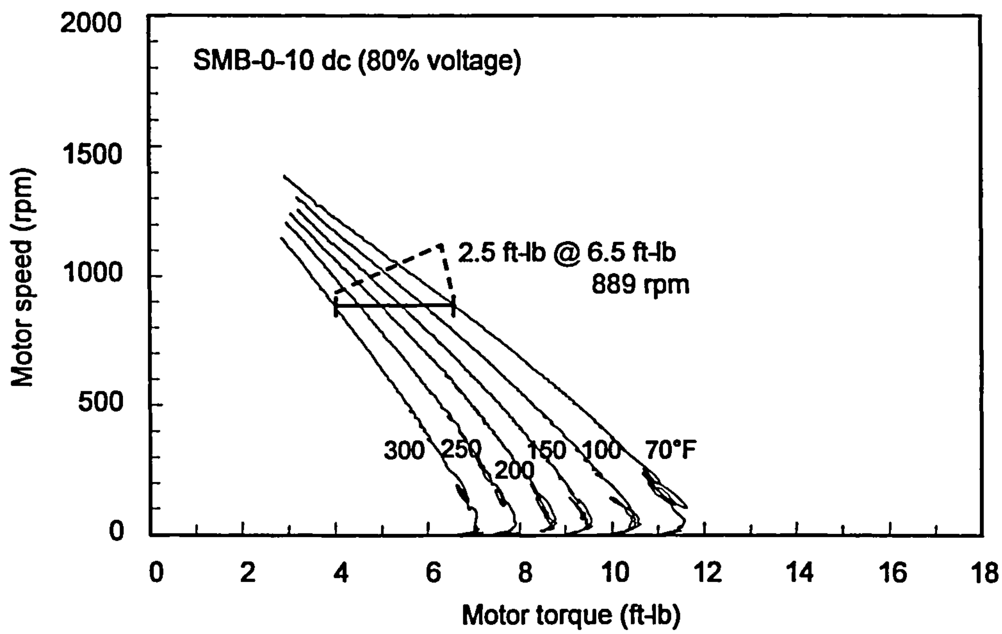


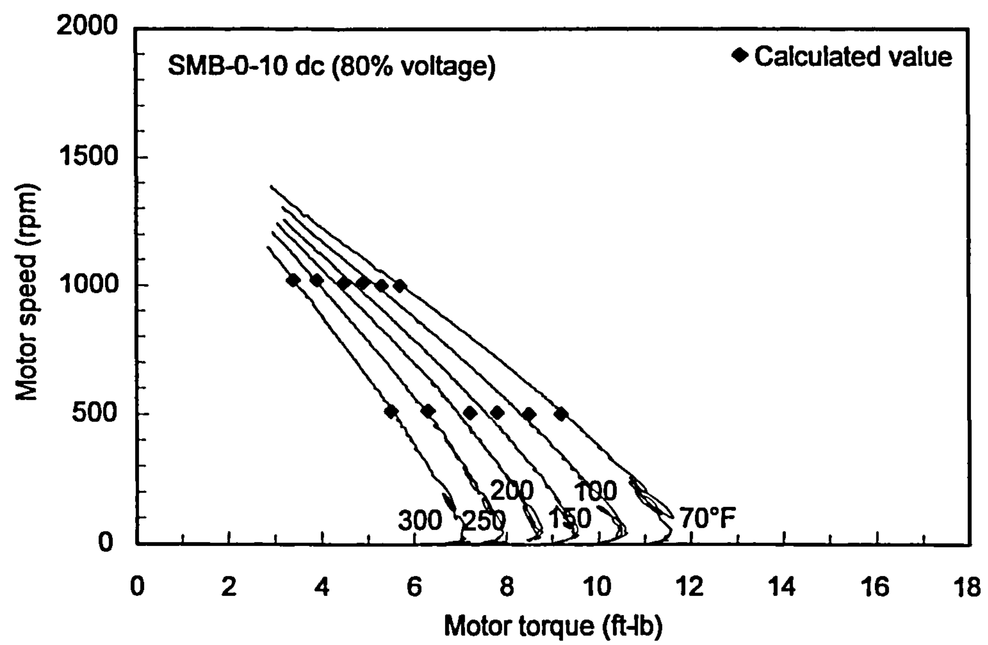


Elevated temperature tests.

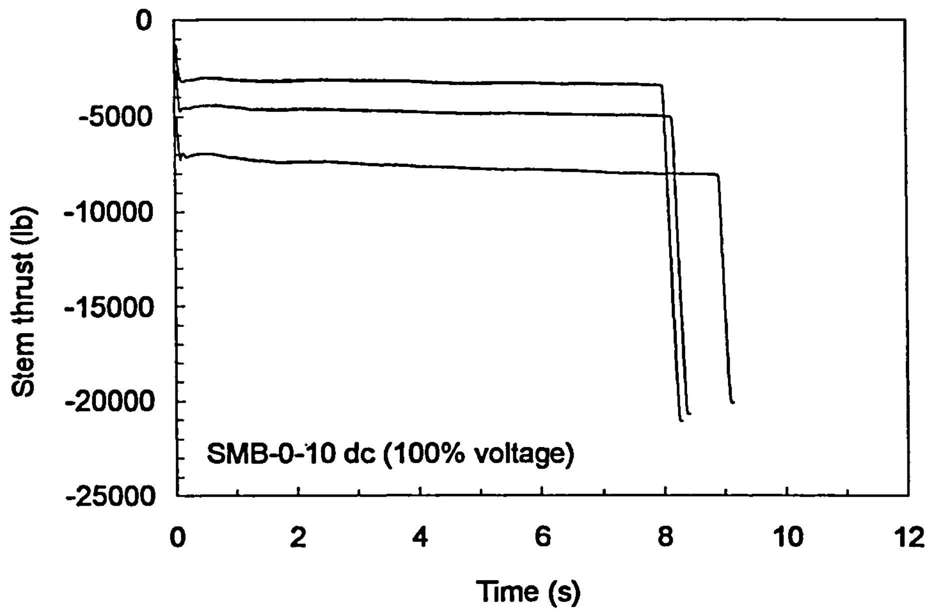


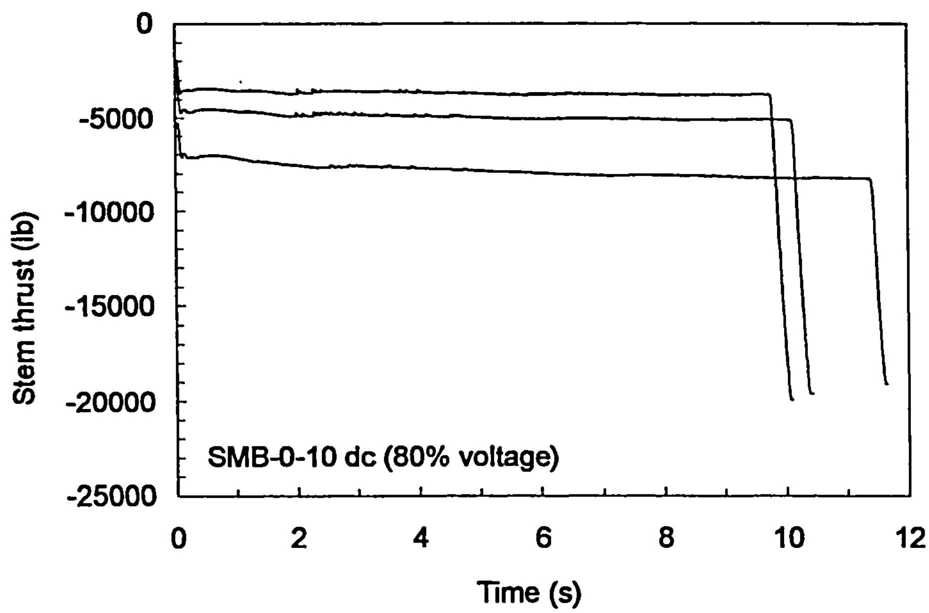
Elevated temperature tests.



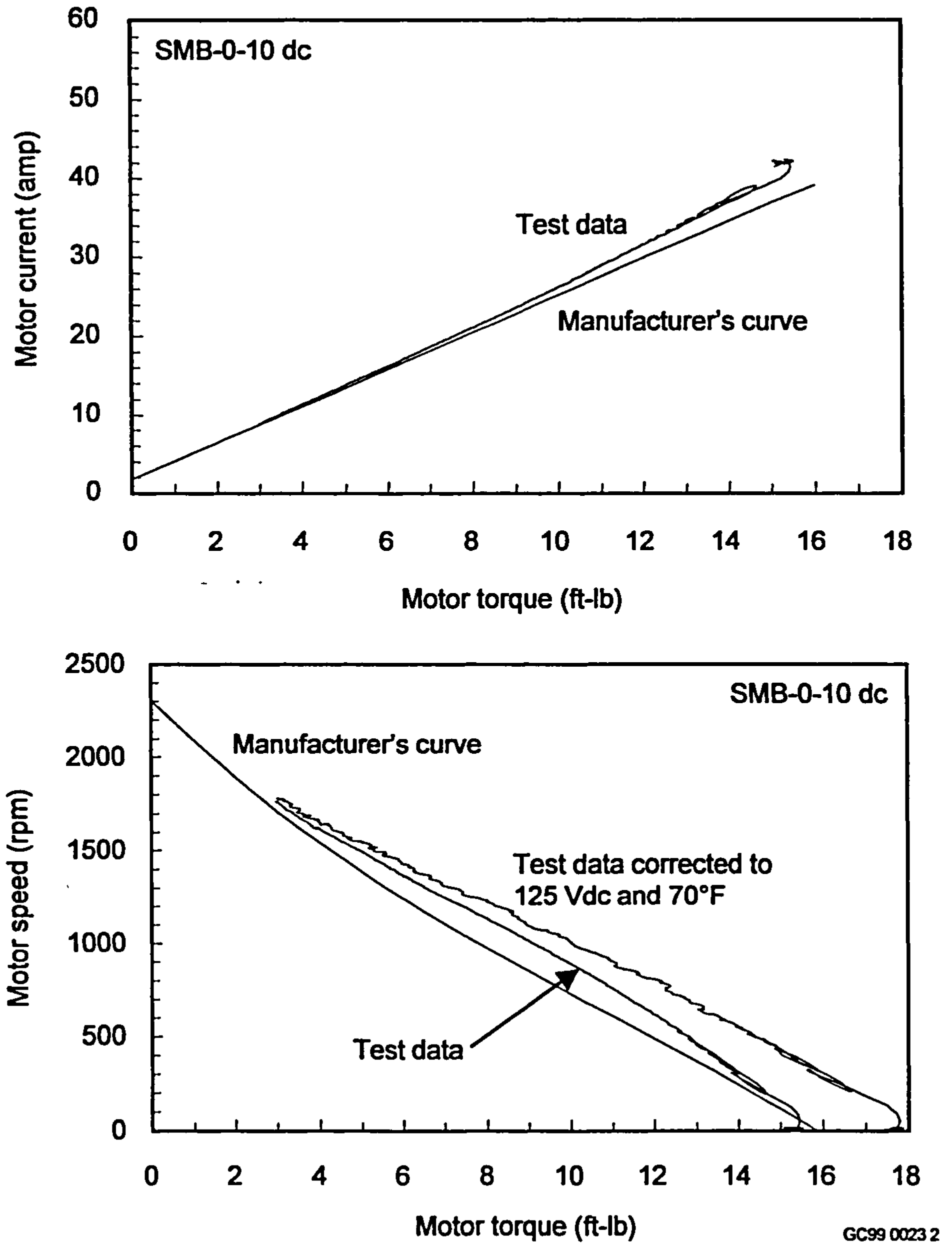


Elevated temperature tests.

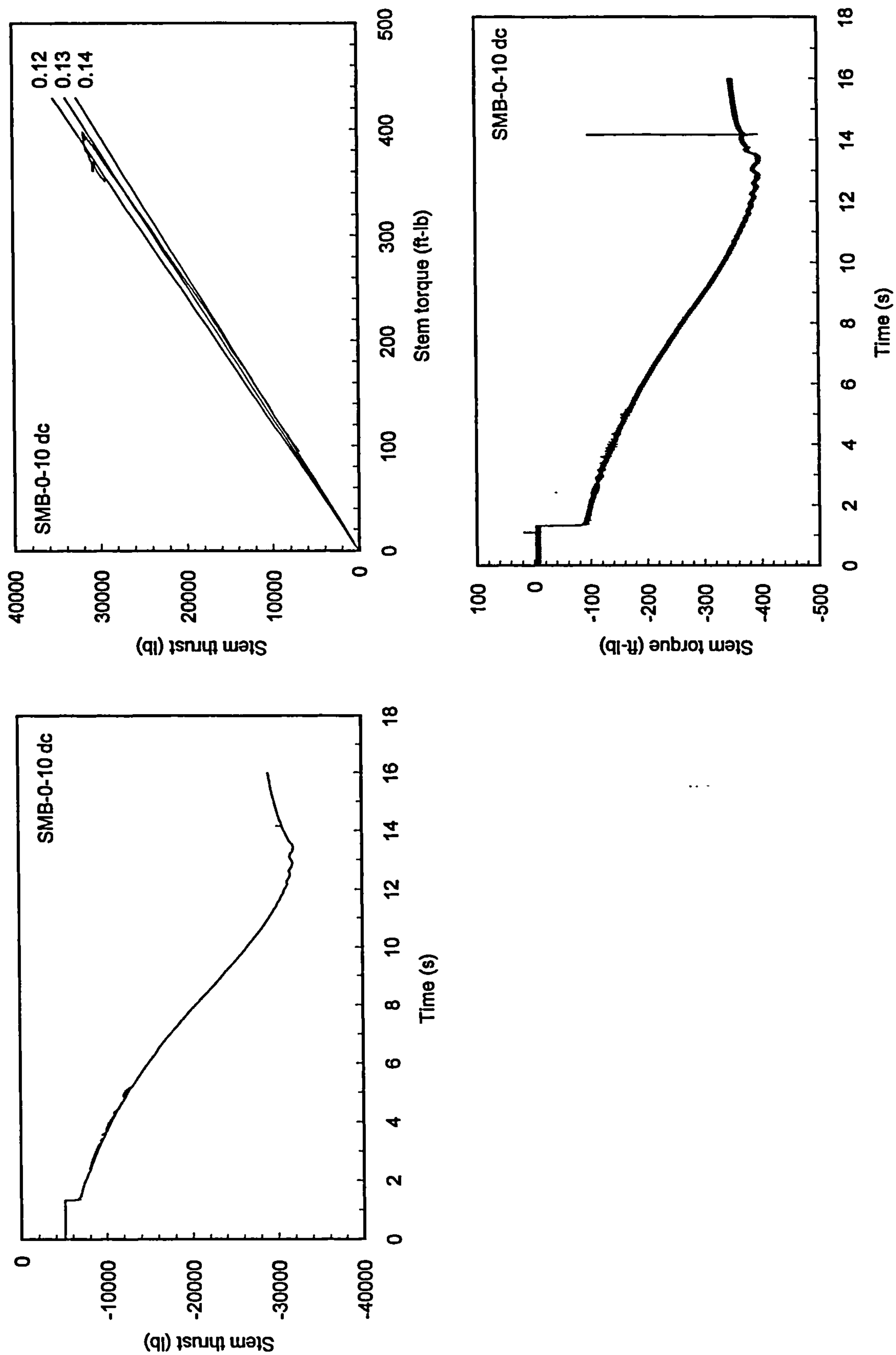




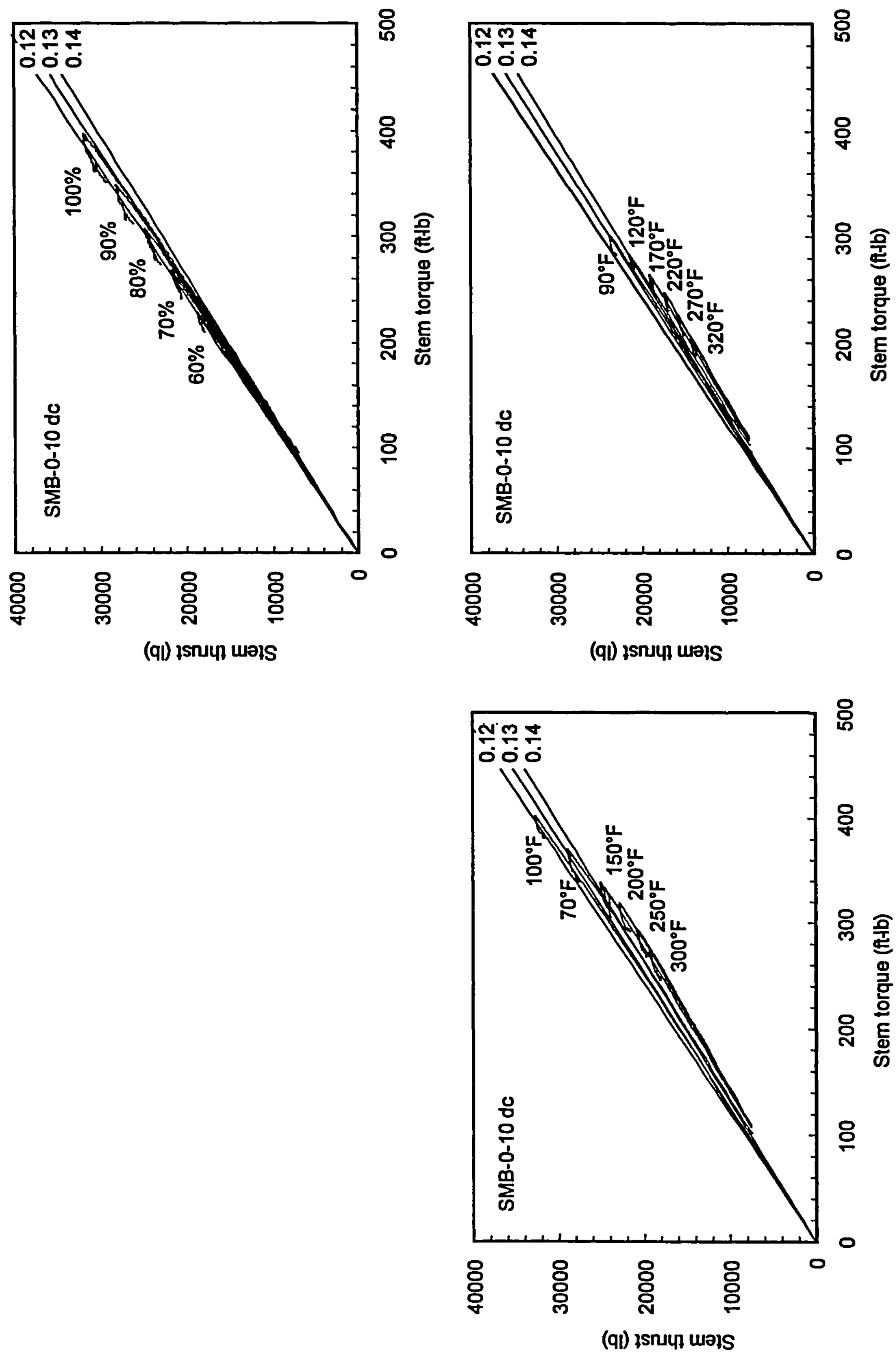
Stroke times.



Performance curves.

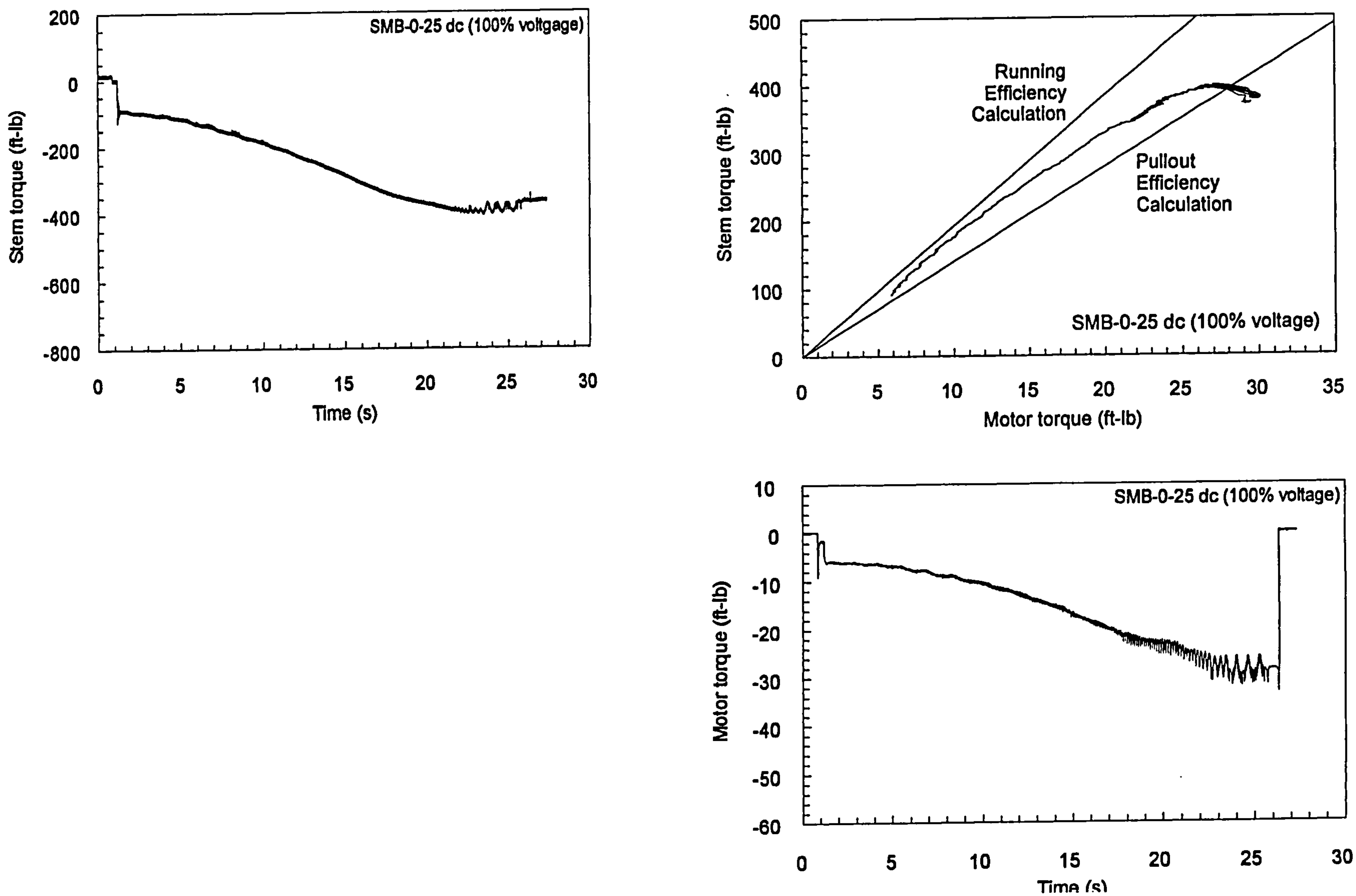


Stem/stem-nut friction.

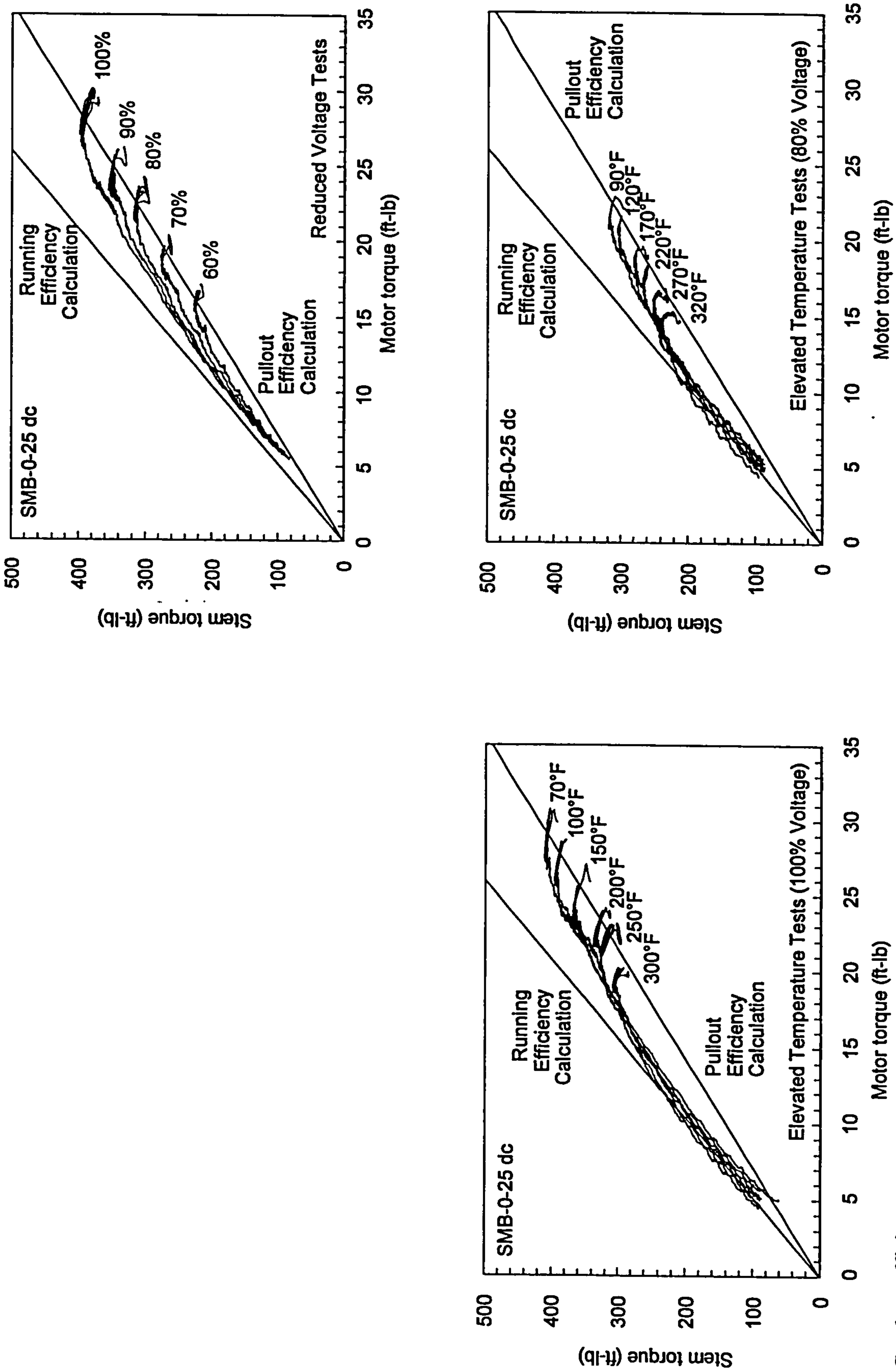


Stem/stem-nut friction.

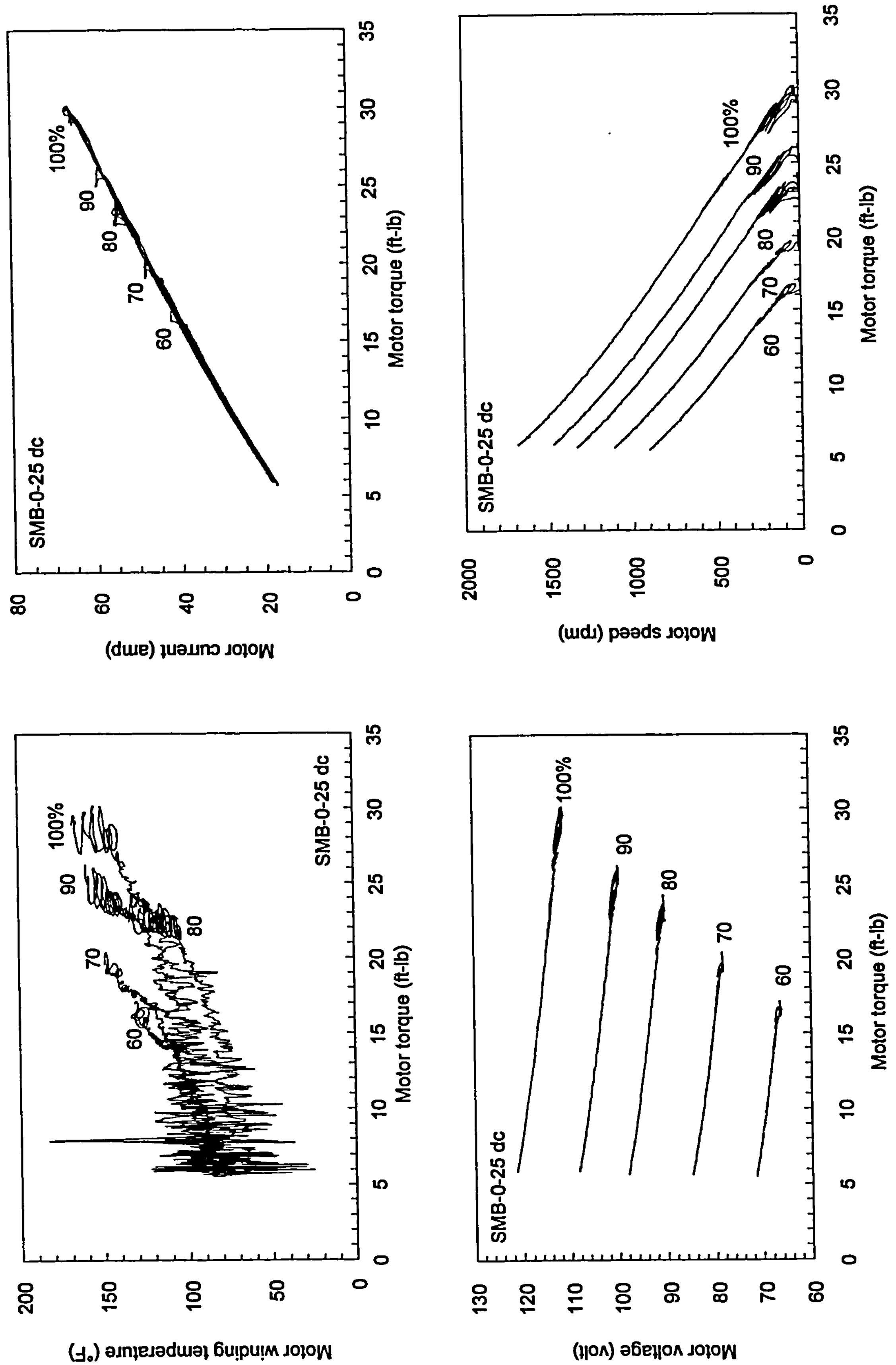
A-2. DATA PLOTS, SMB-0-25



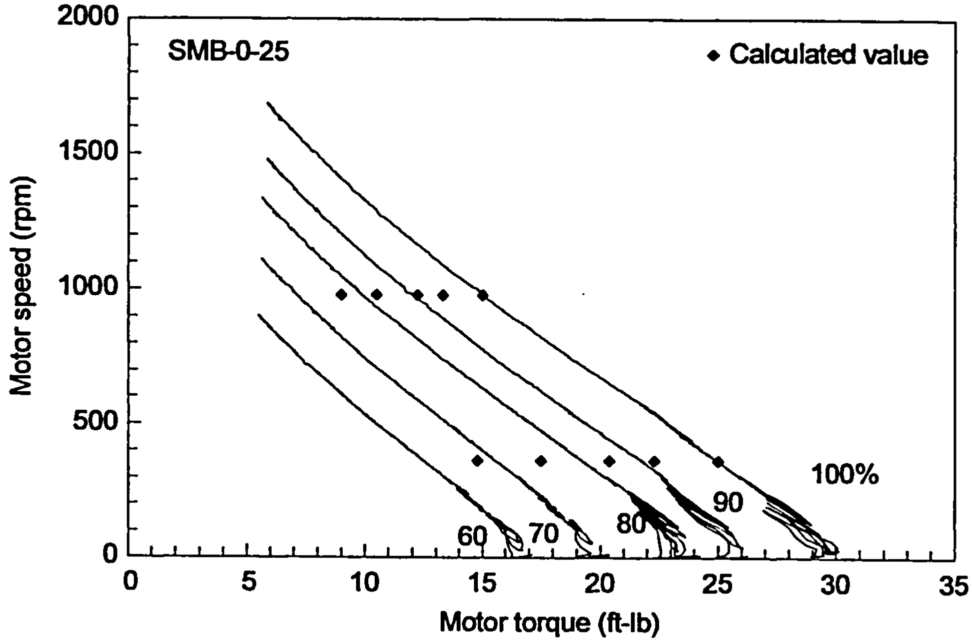
Gearbox efficiency.

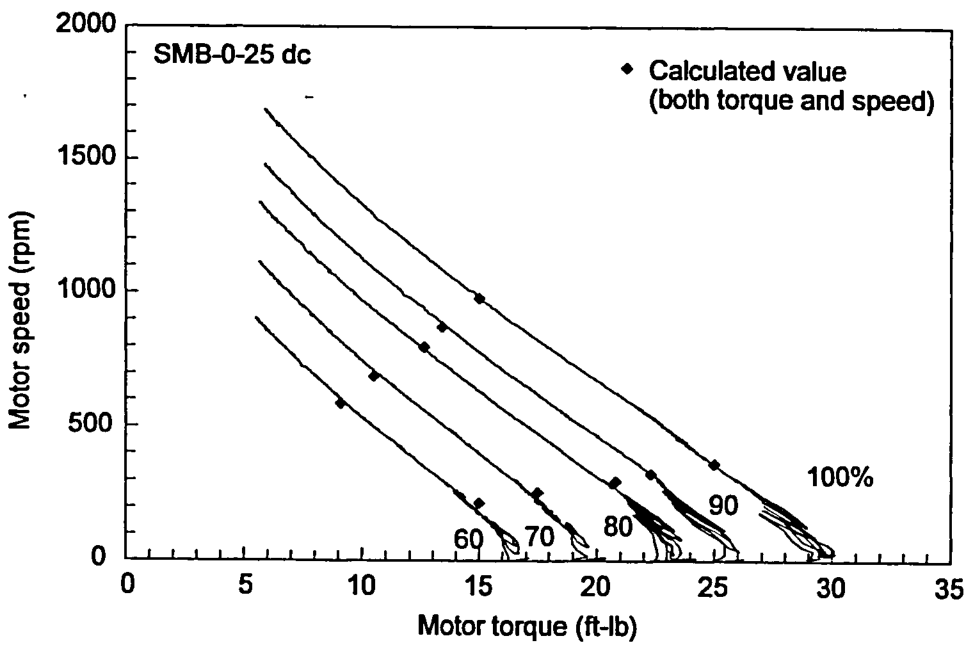


Gearbox efficiency.

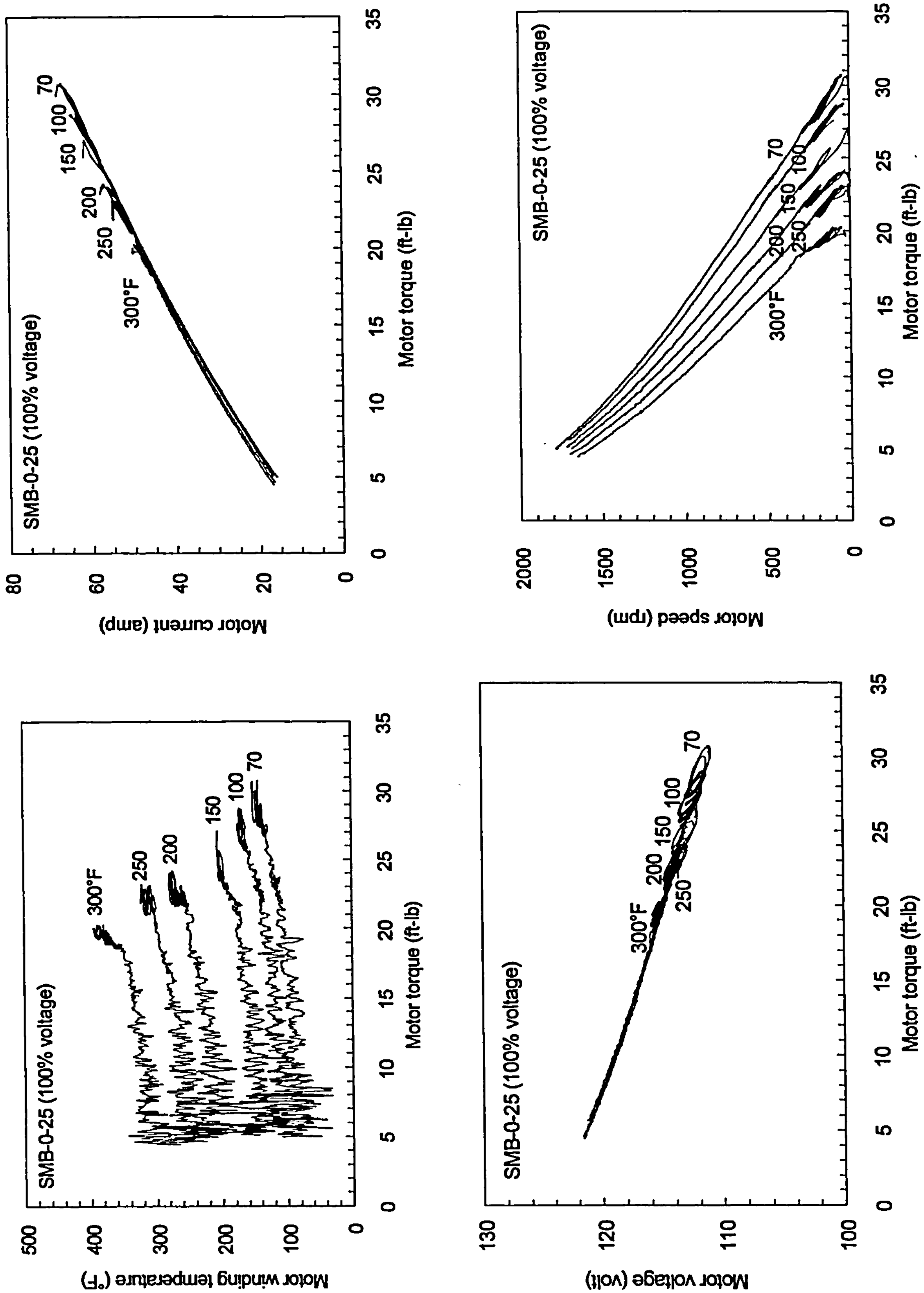


Reduced voltage tests.

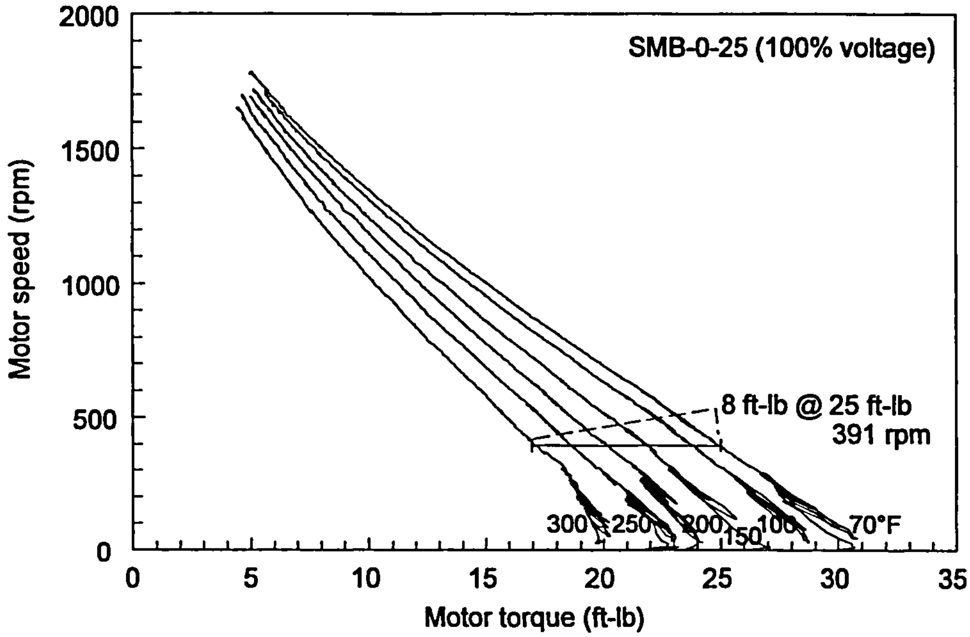


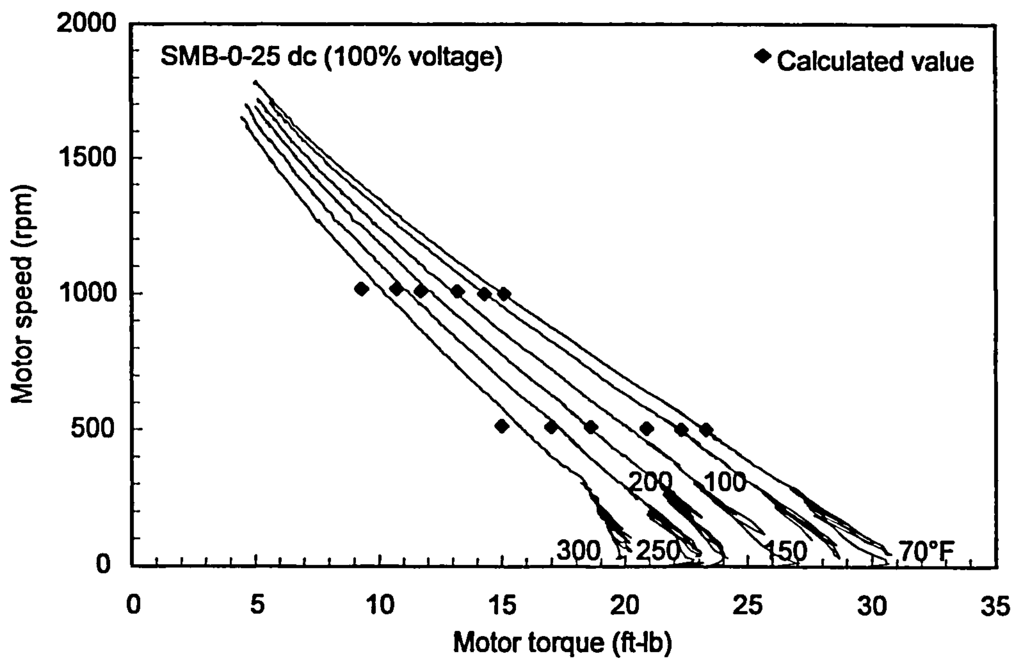


Reduced voltage tests.



Elevated temperature tests.





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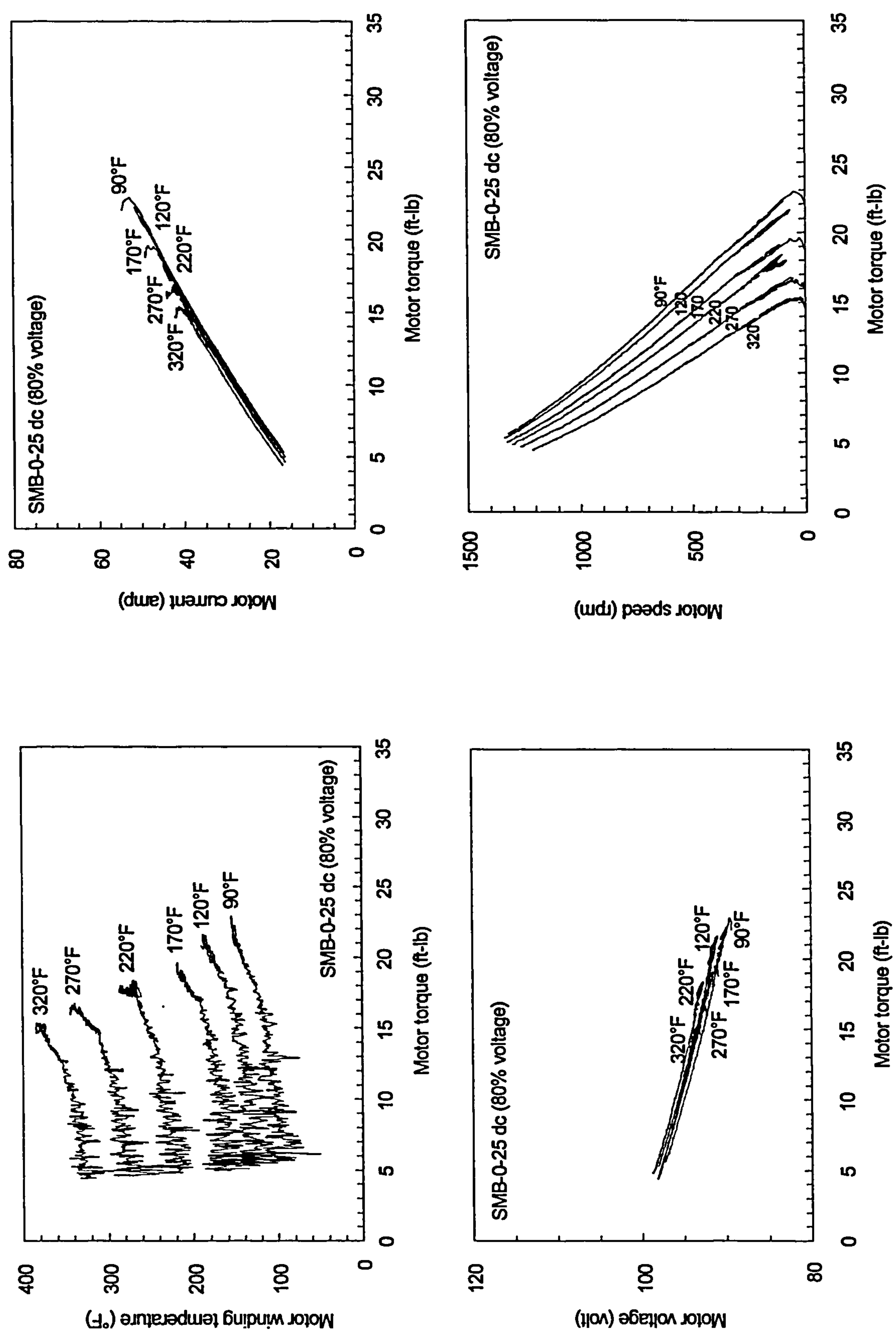

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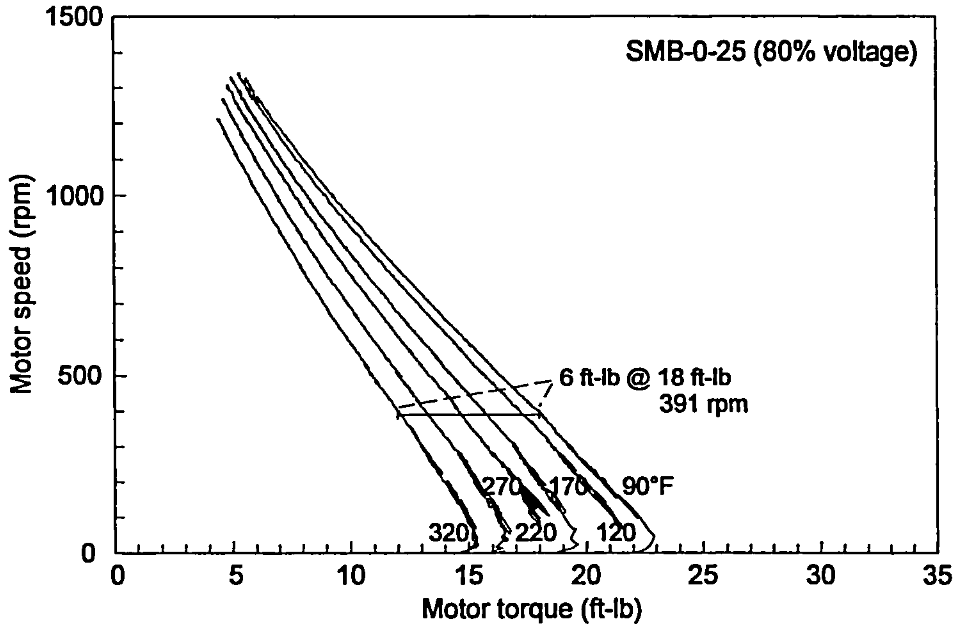

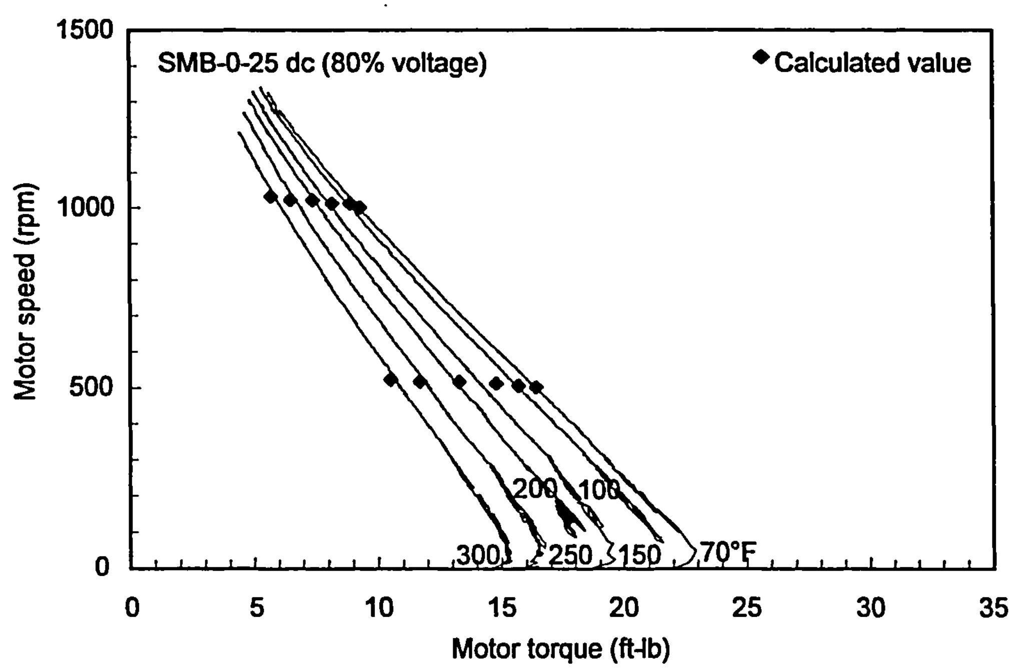

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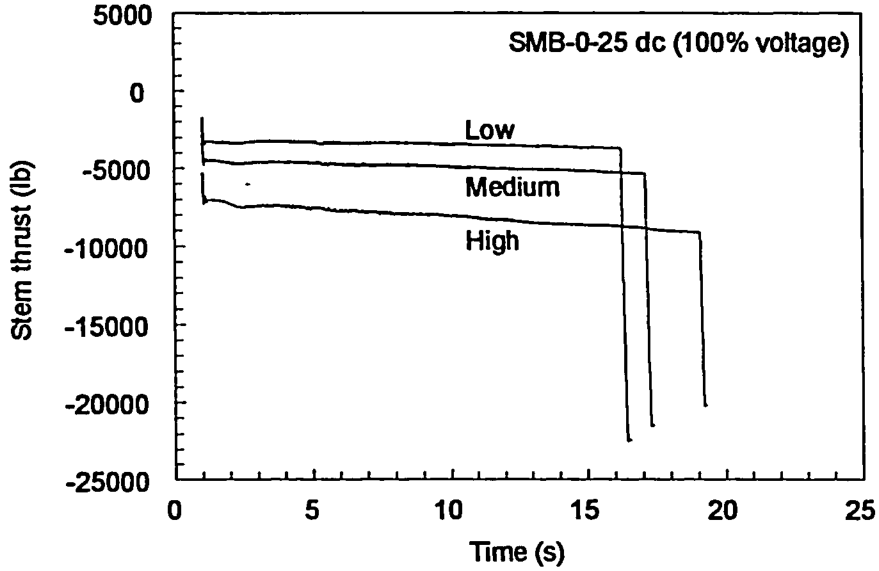
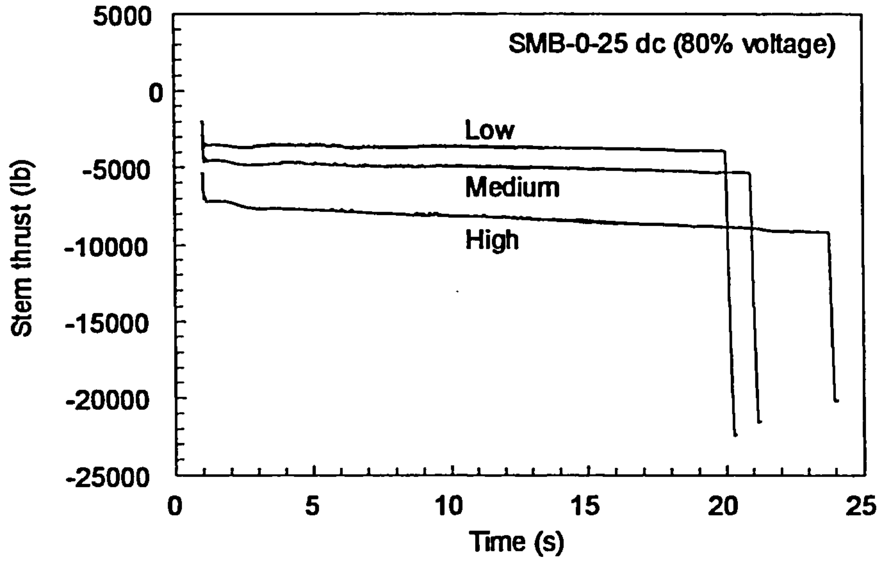
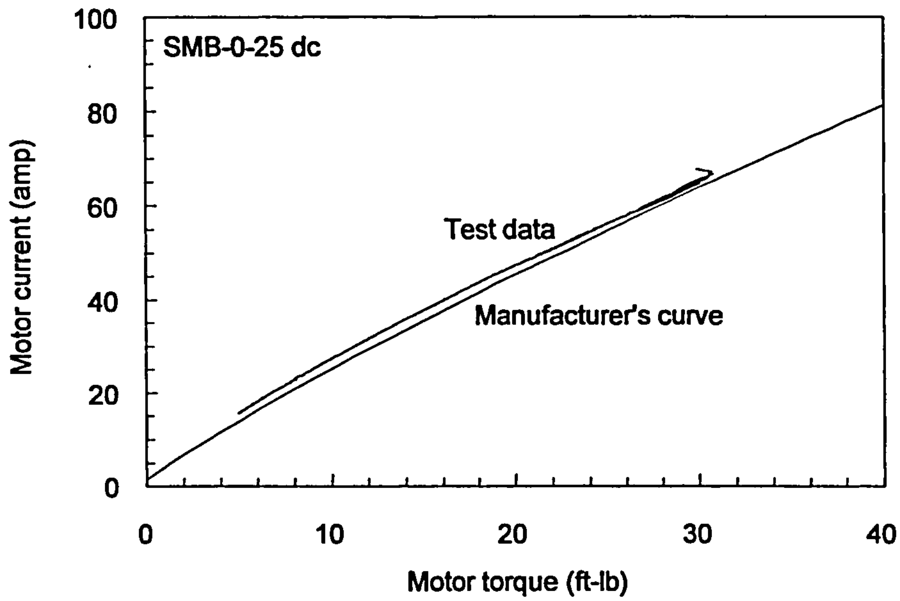
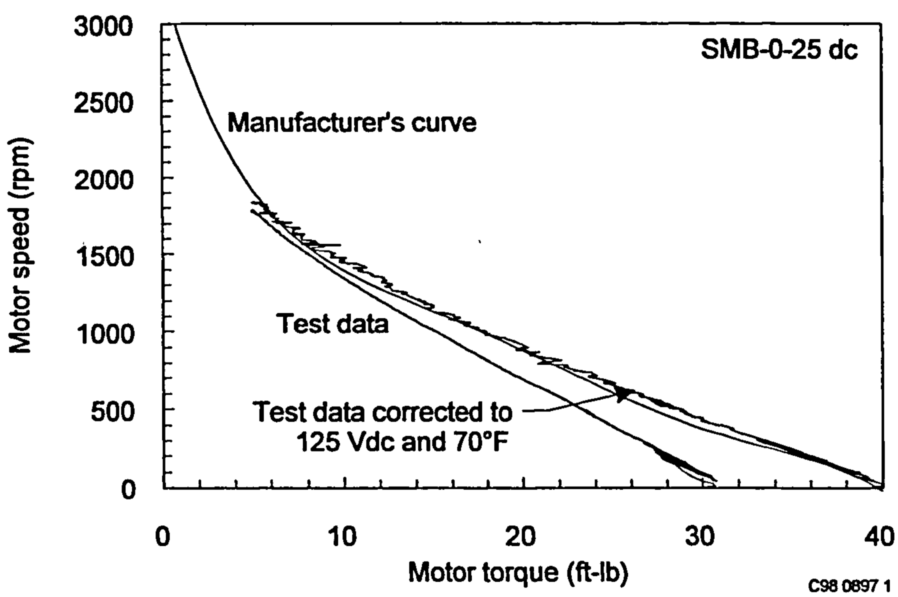


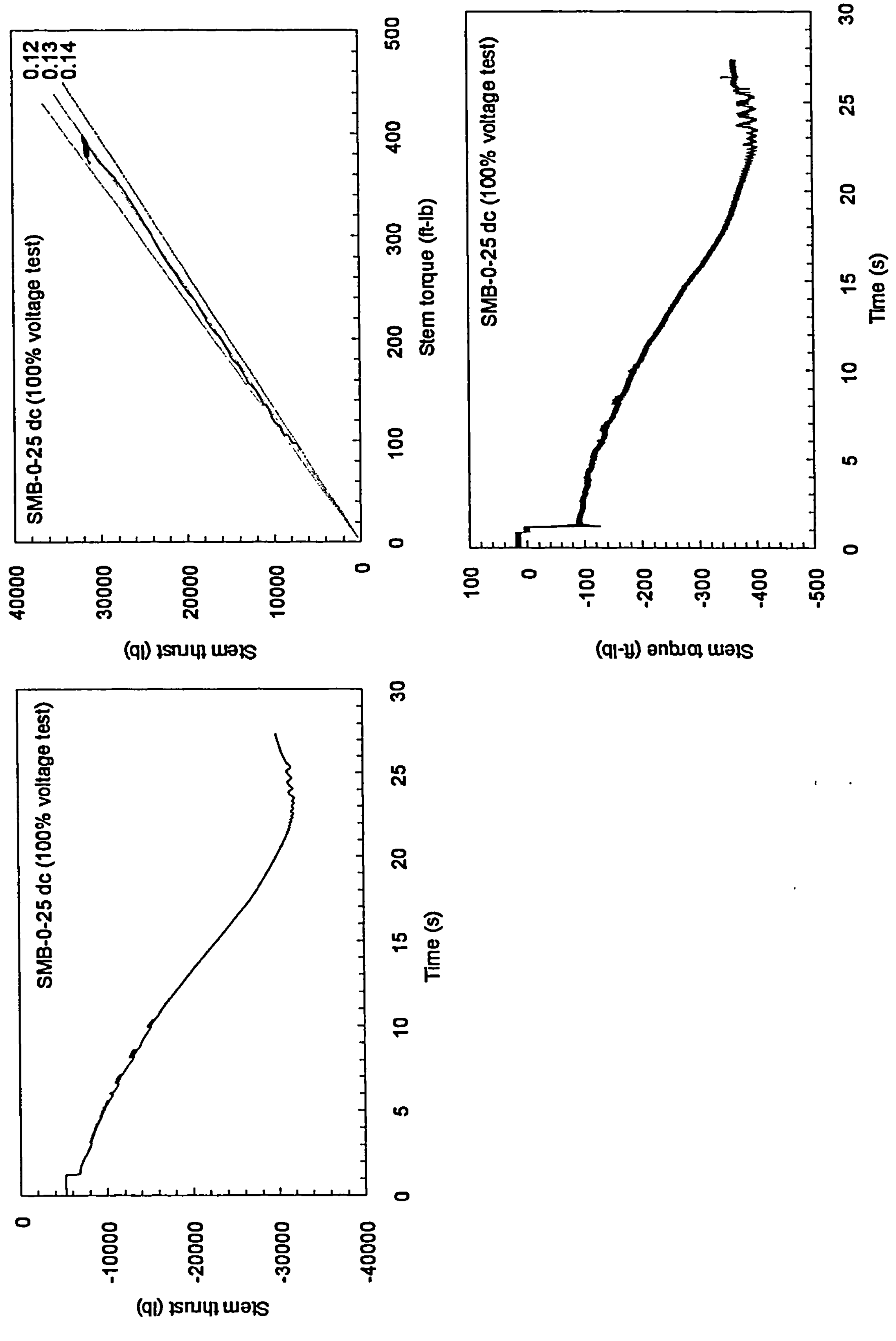


Stroke times.

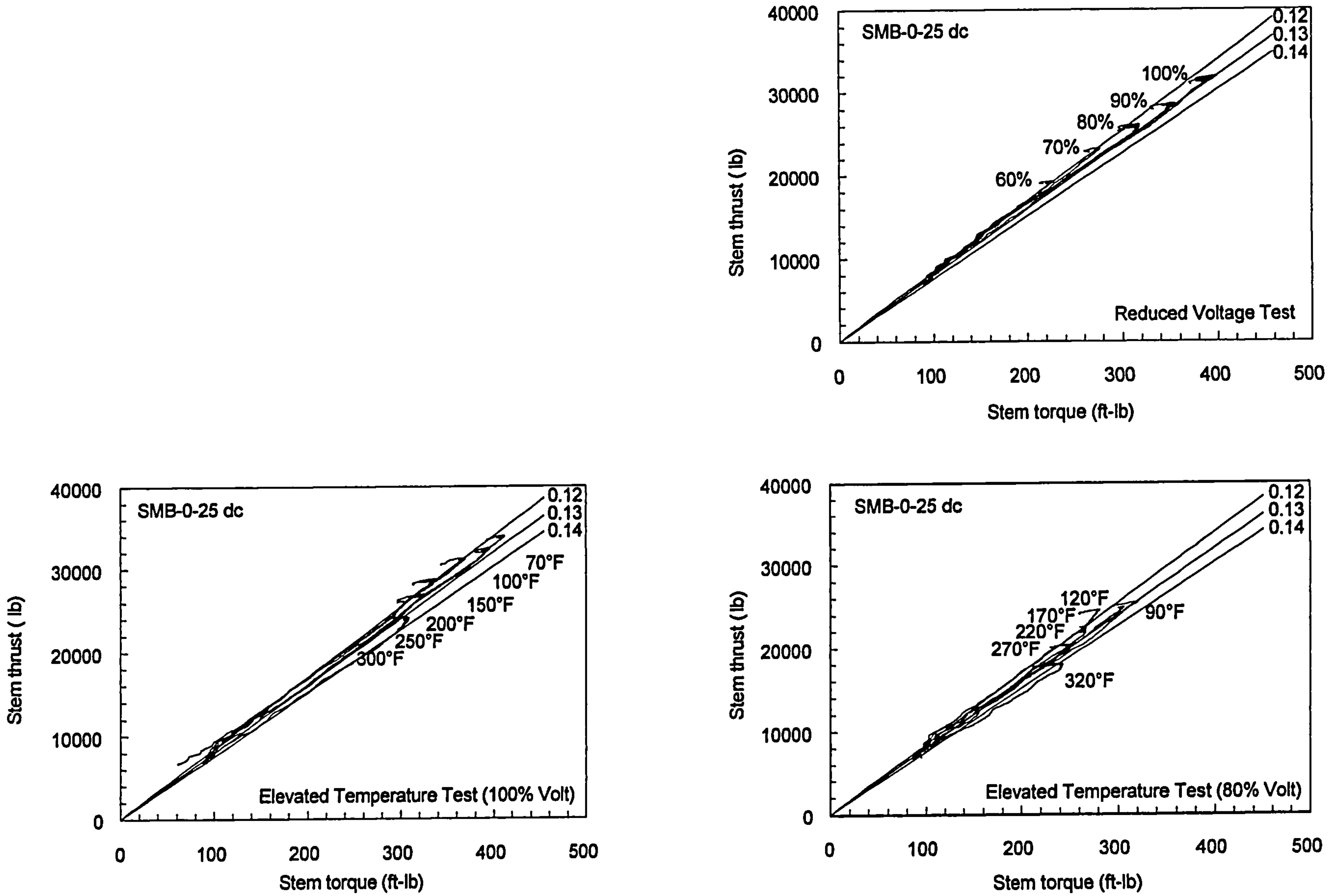




Performance curves.

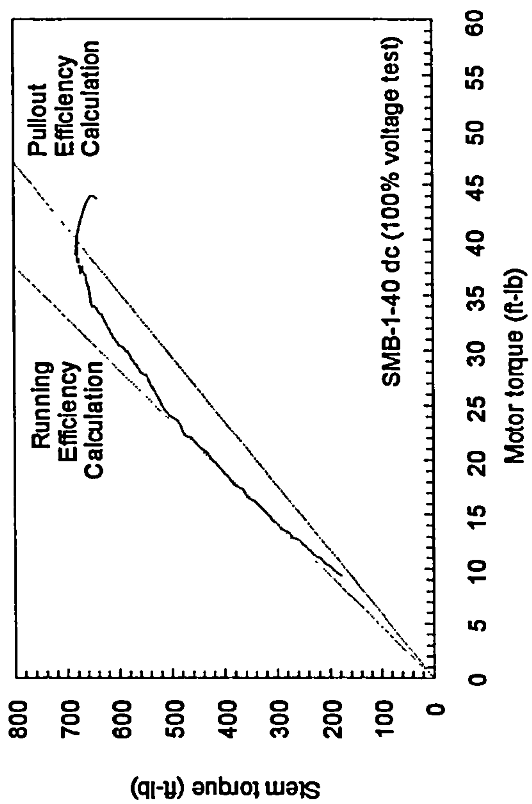


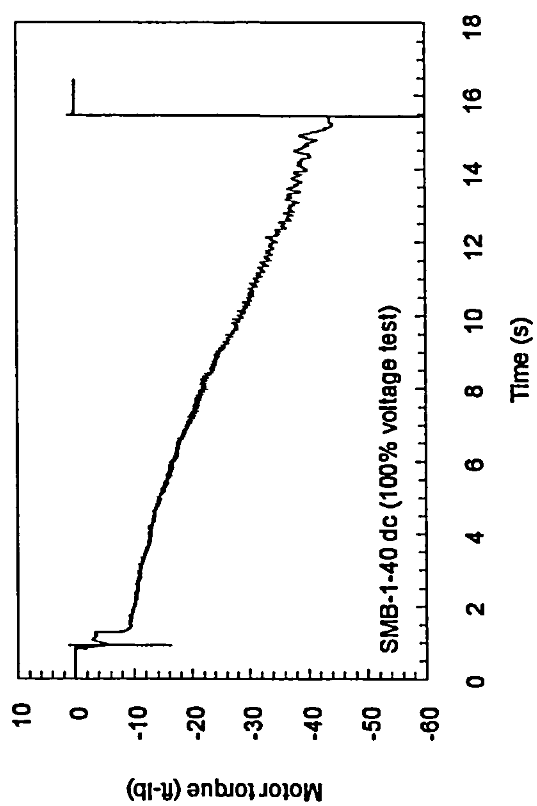
Stem/stem-nut friction.

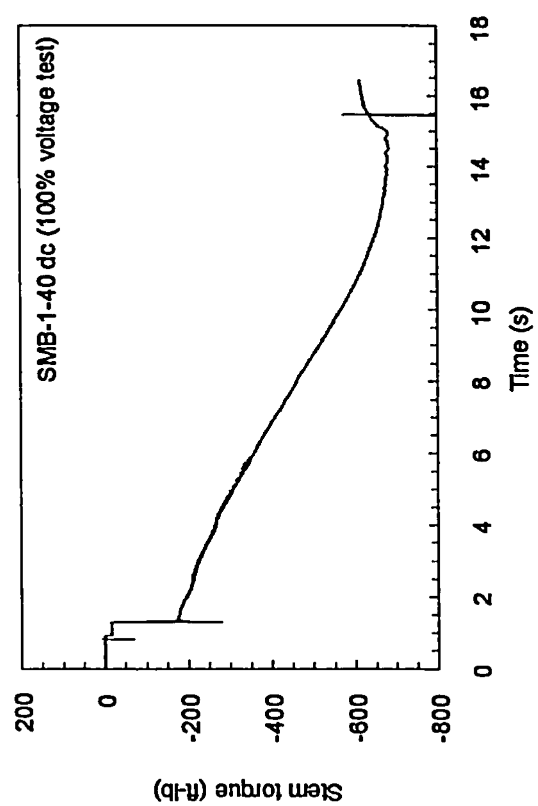


Stem/stem-nut friction.

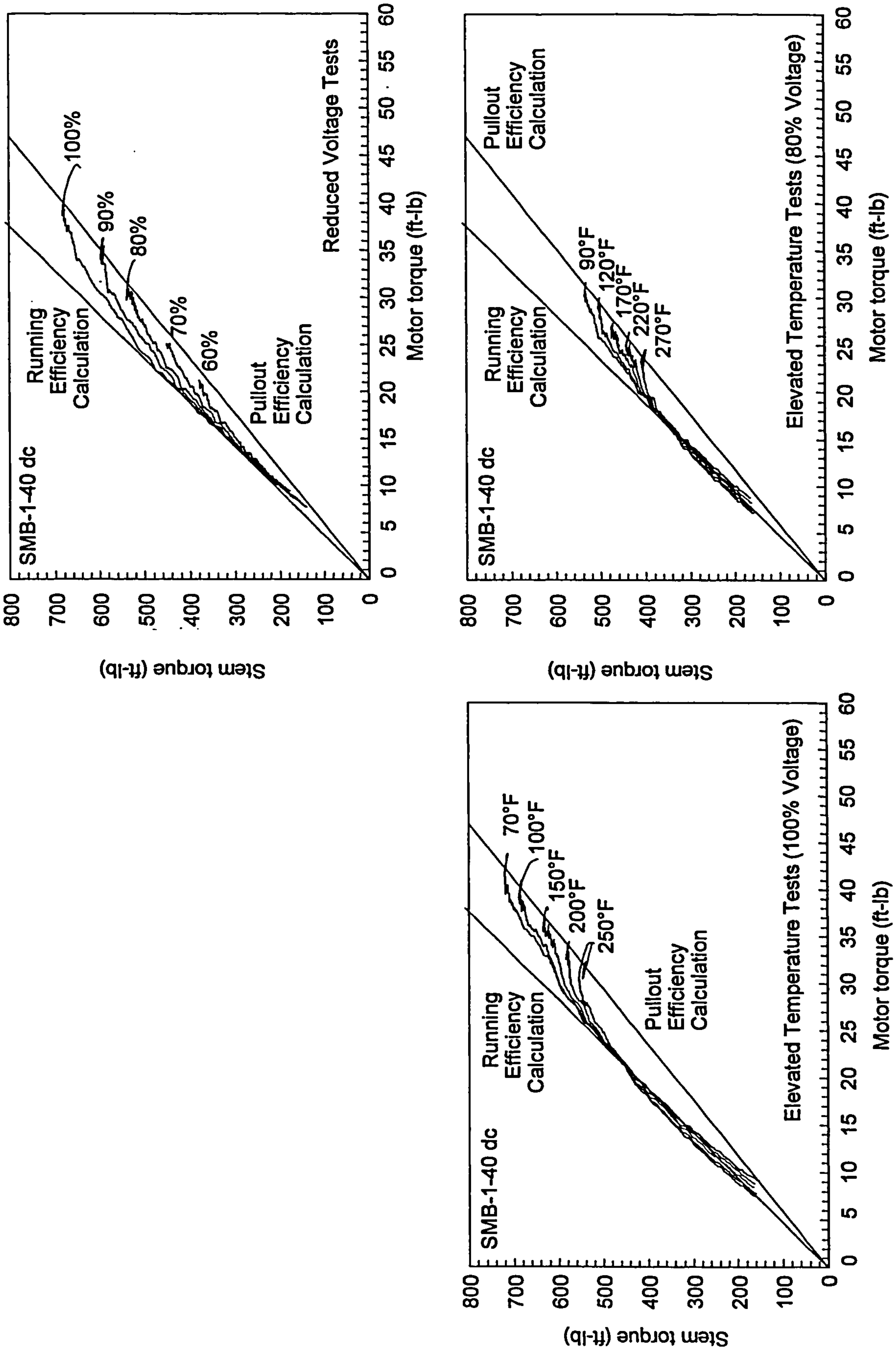
A-3. DATA PLOTS, SMB-1-40



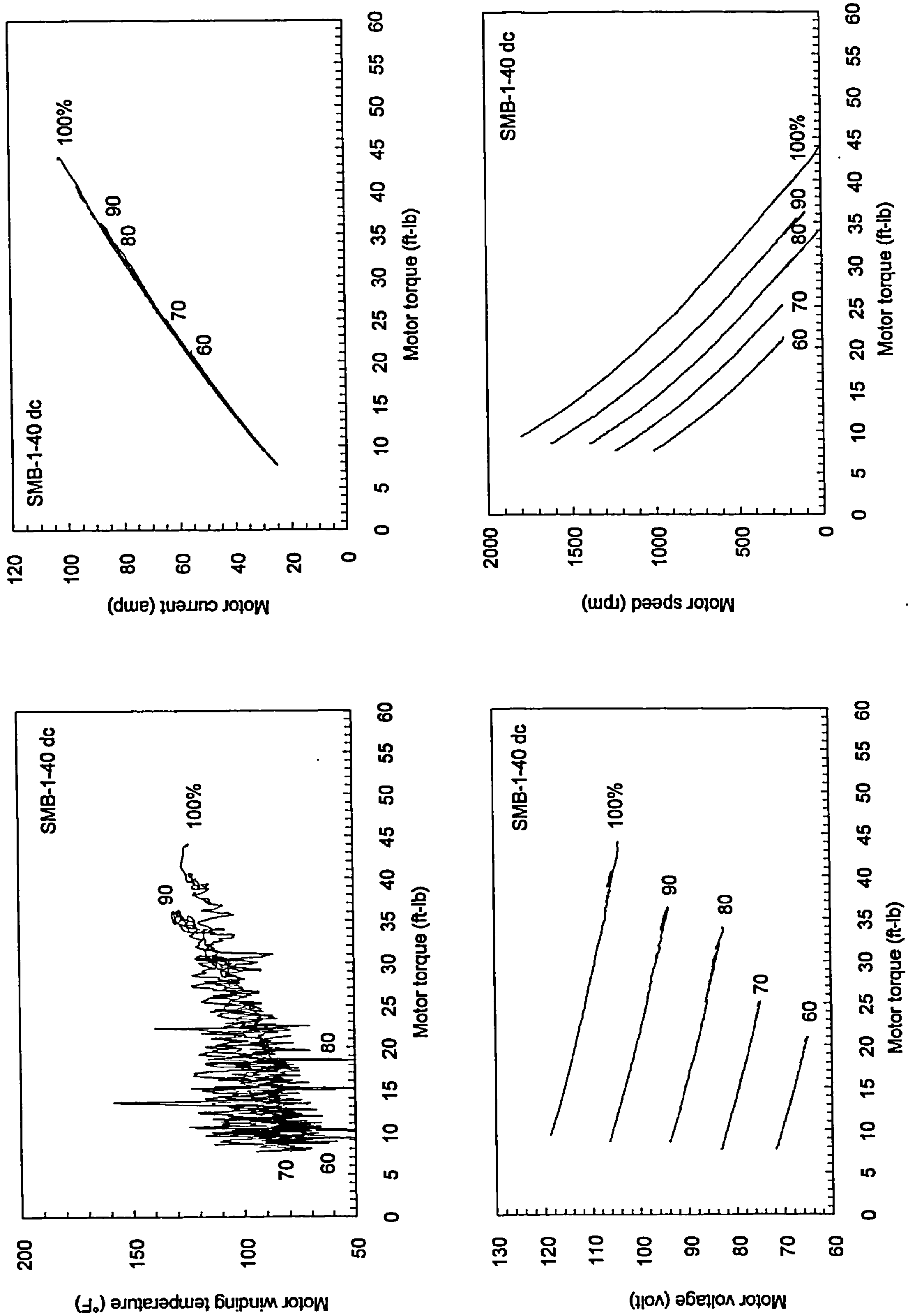




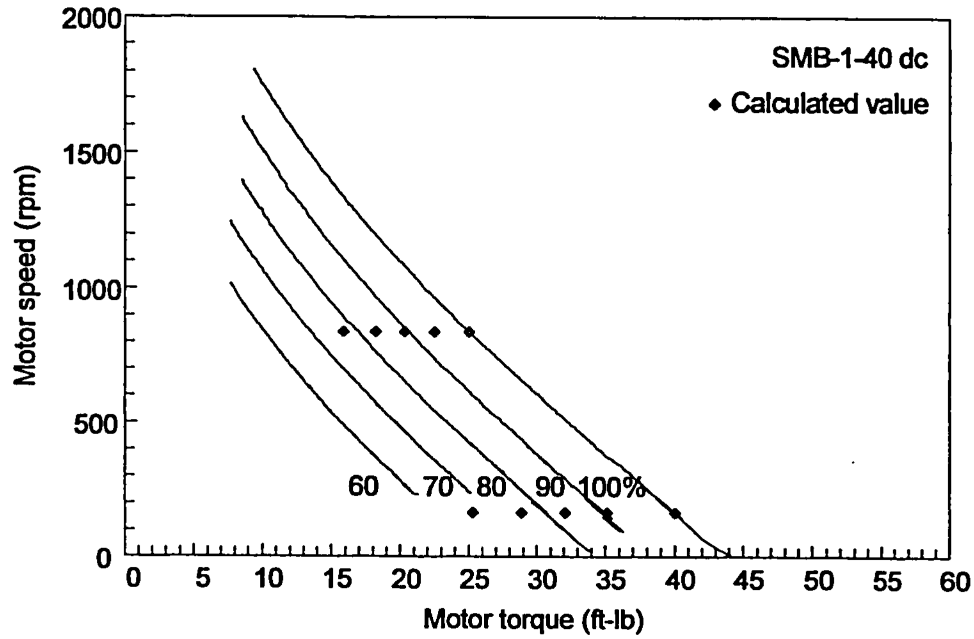
Gearbox efficiency.

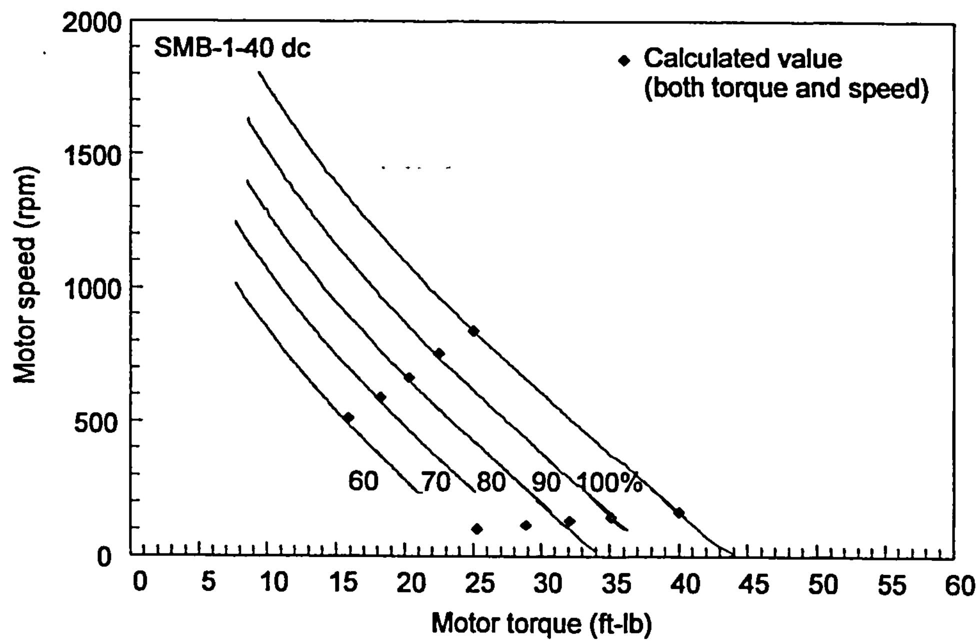


Gearbox efficiency.

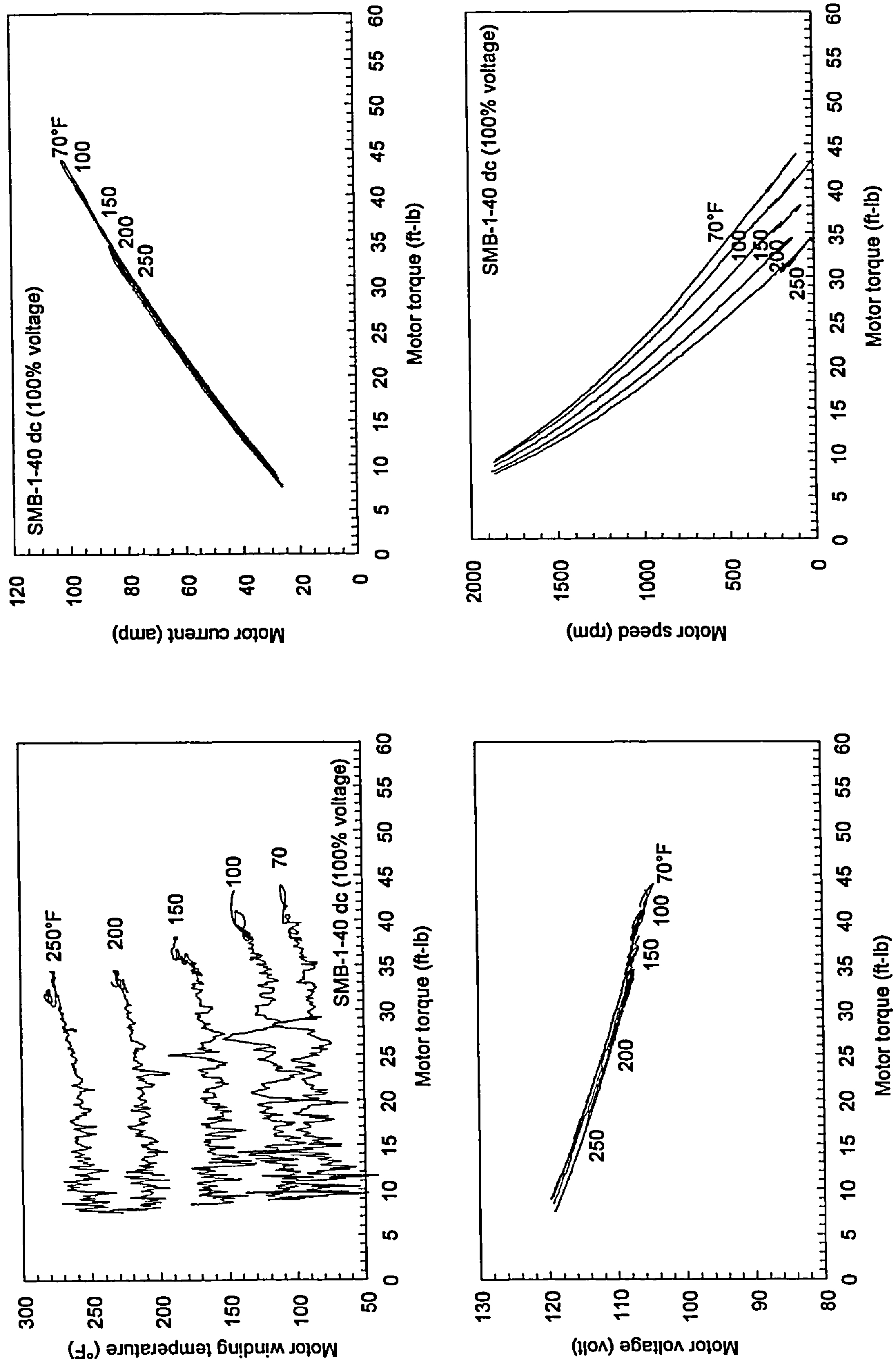


Degraded voltage tests.

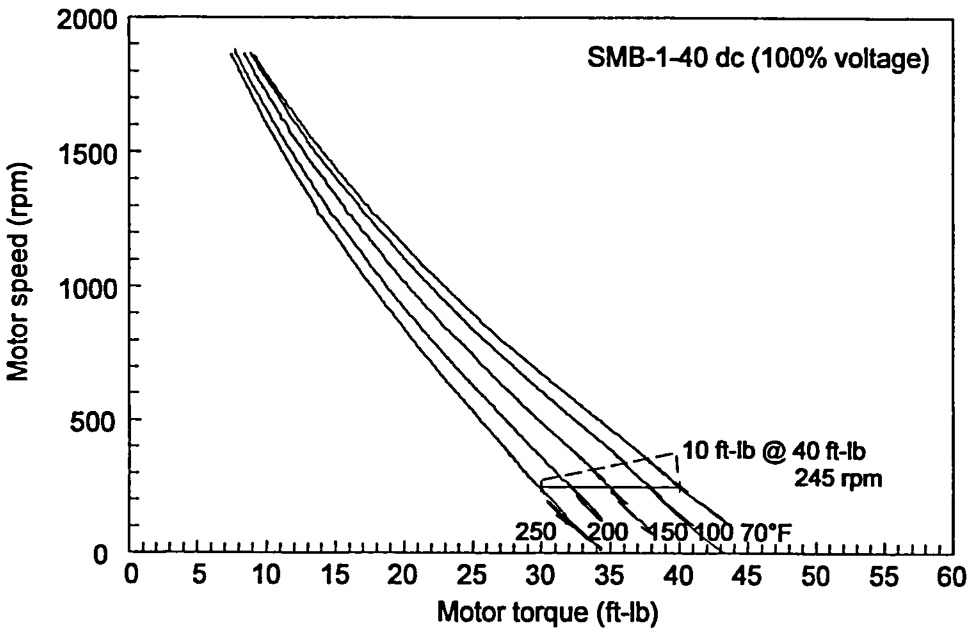


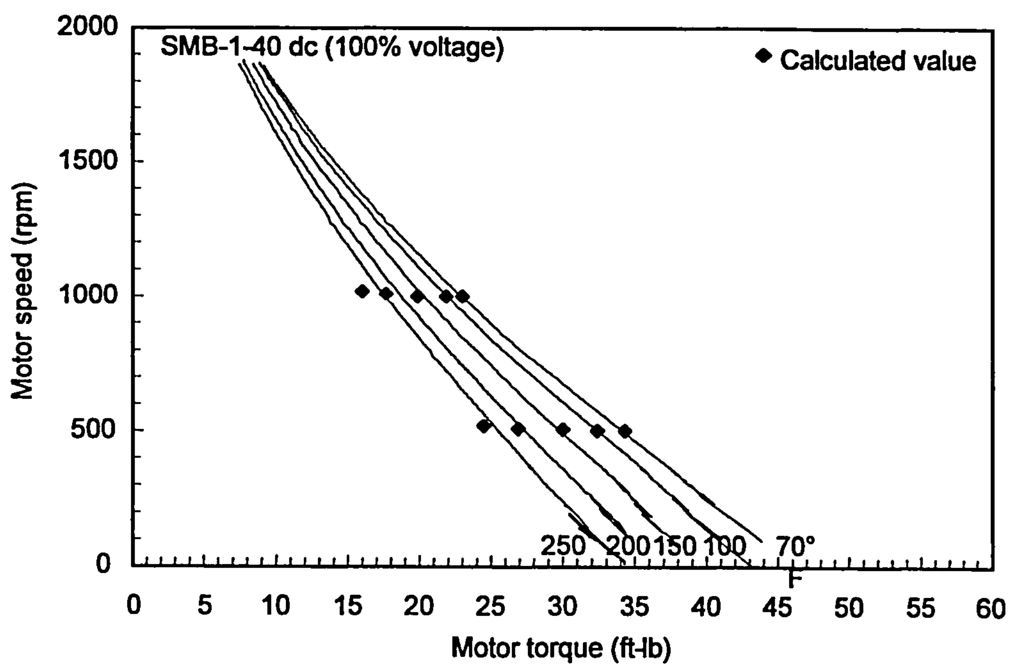


Degraded voltage tests.

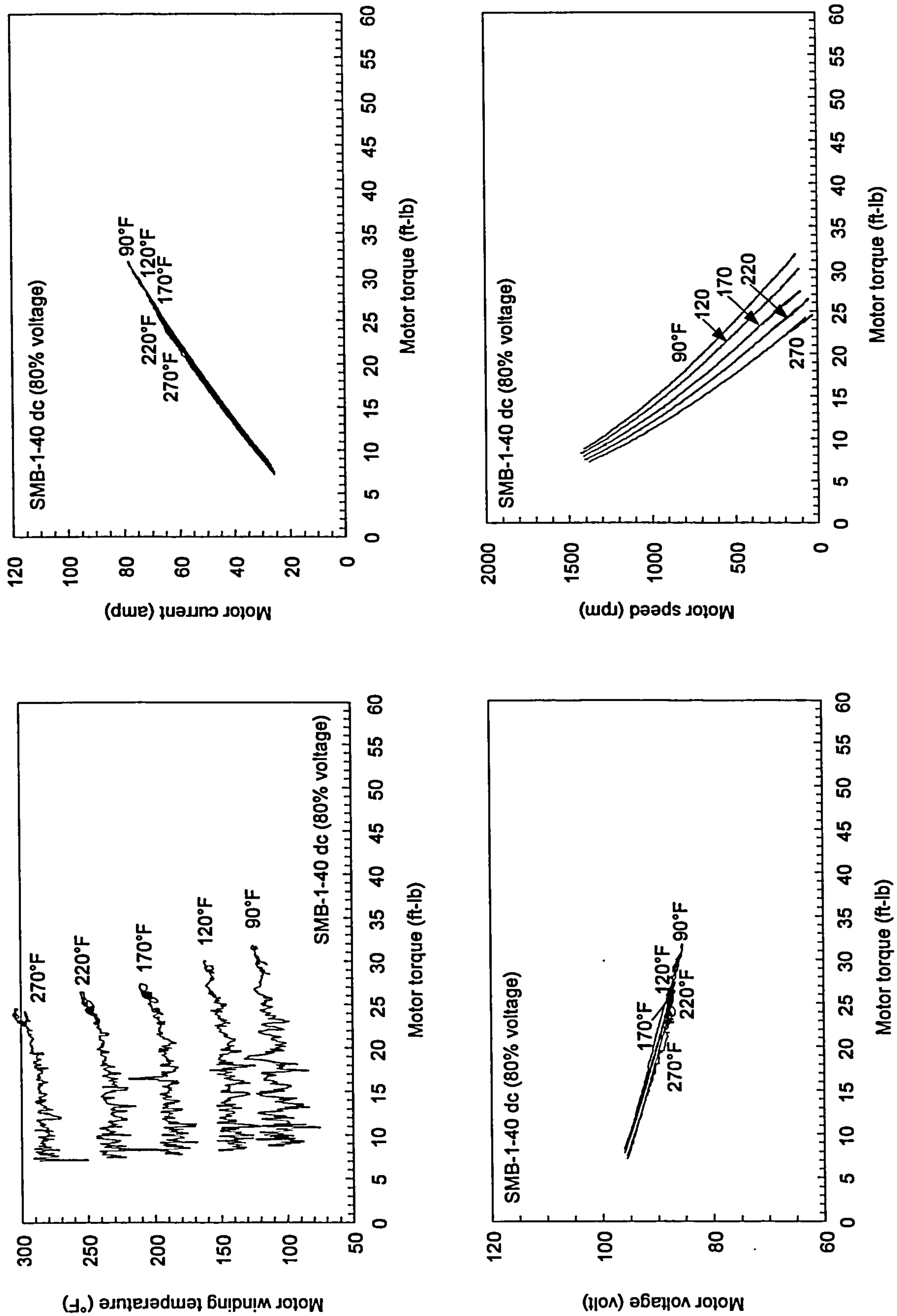


Elevated temperature tests.

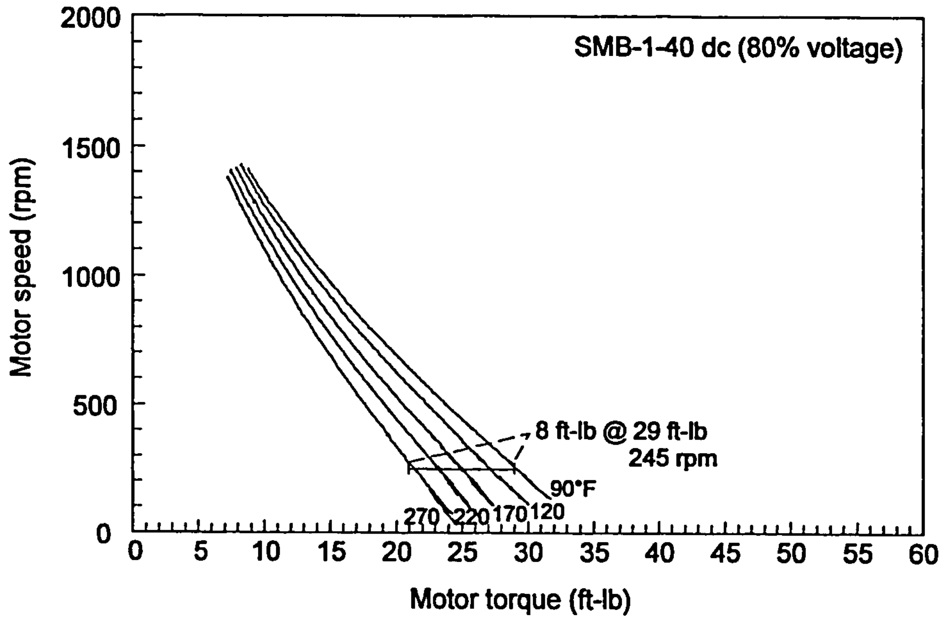


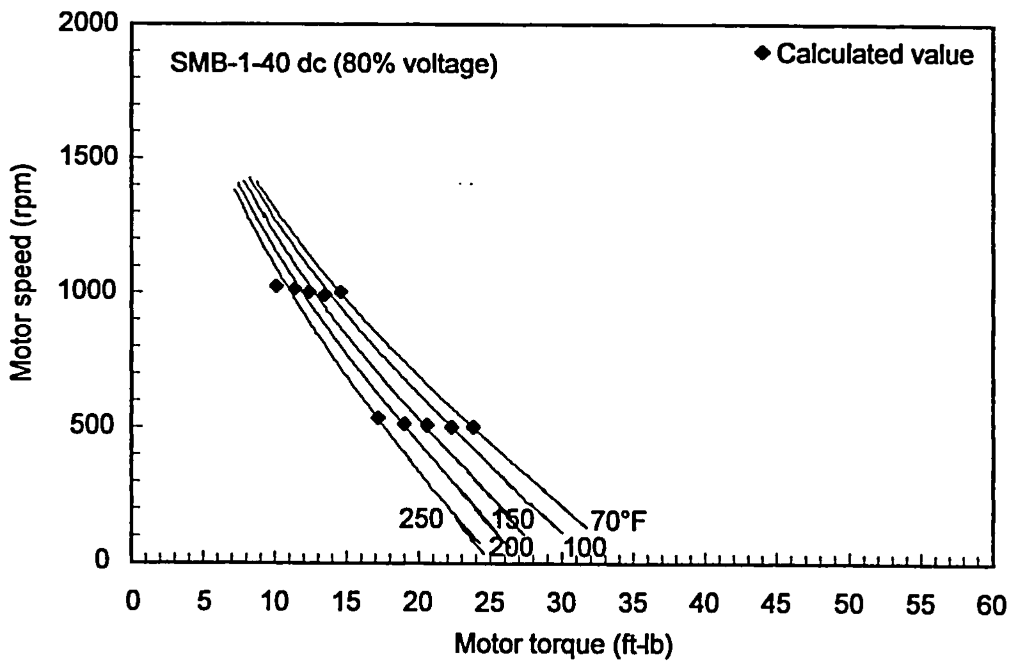


Elevated temperature tests.

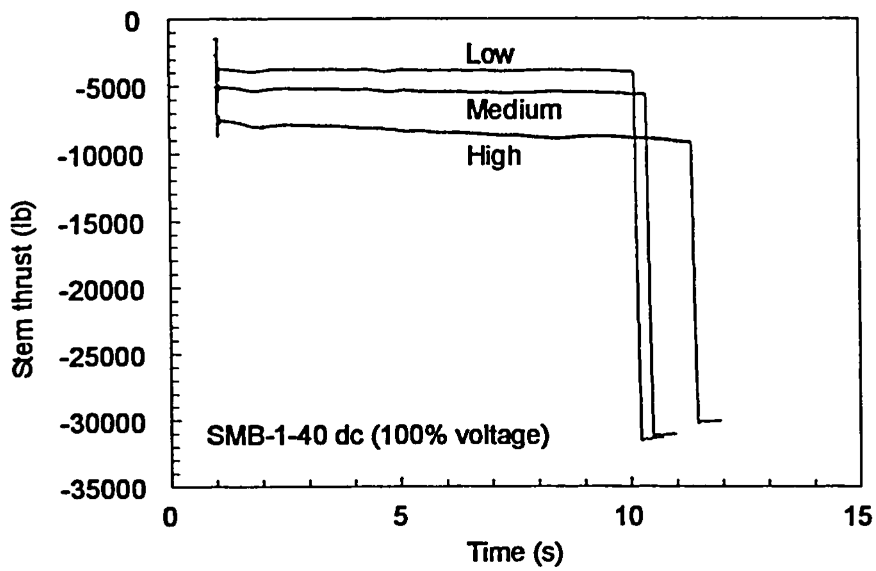


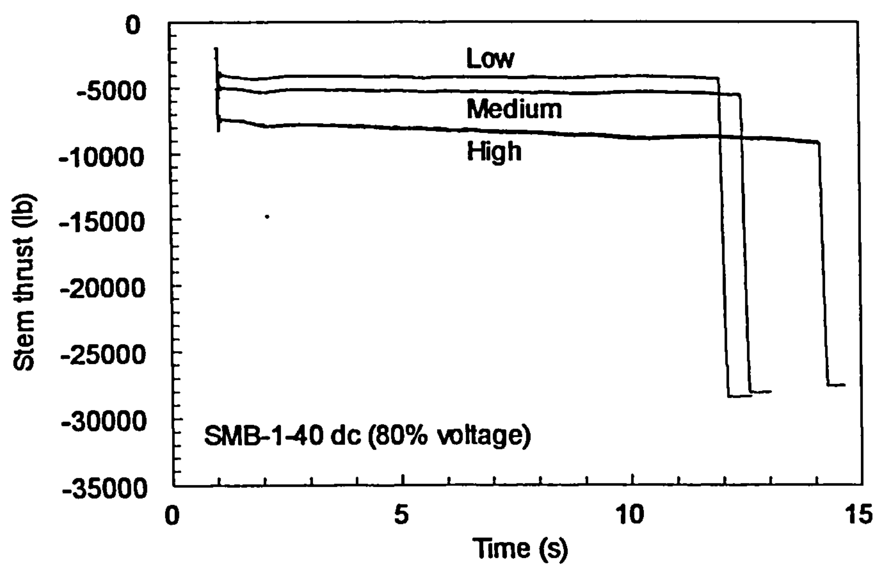
Elevated temperature tests.



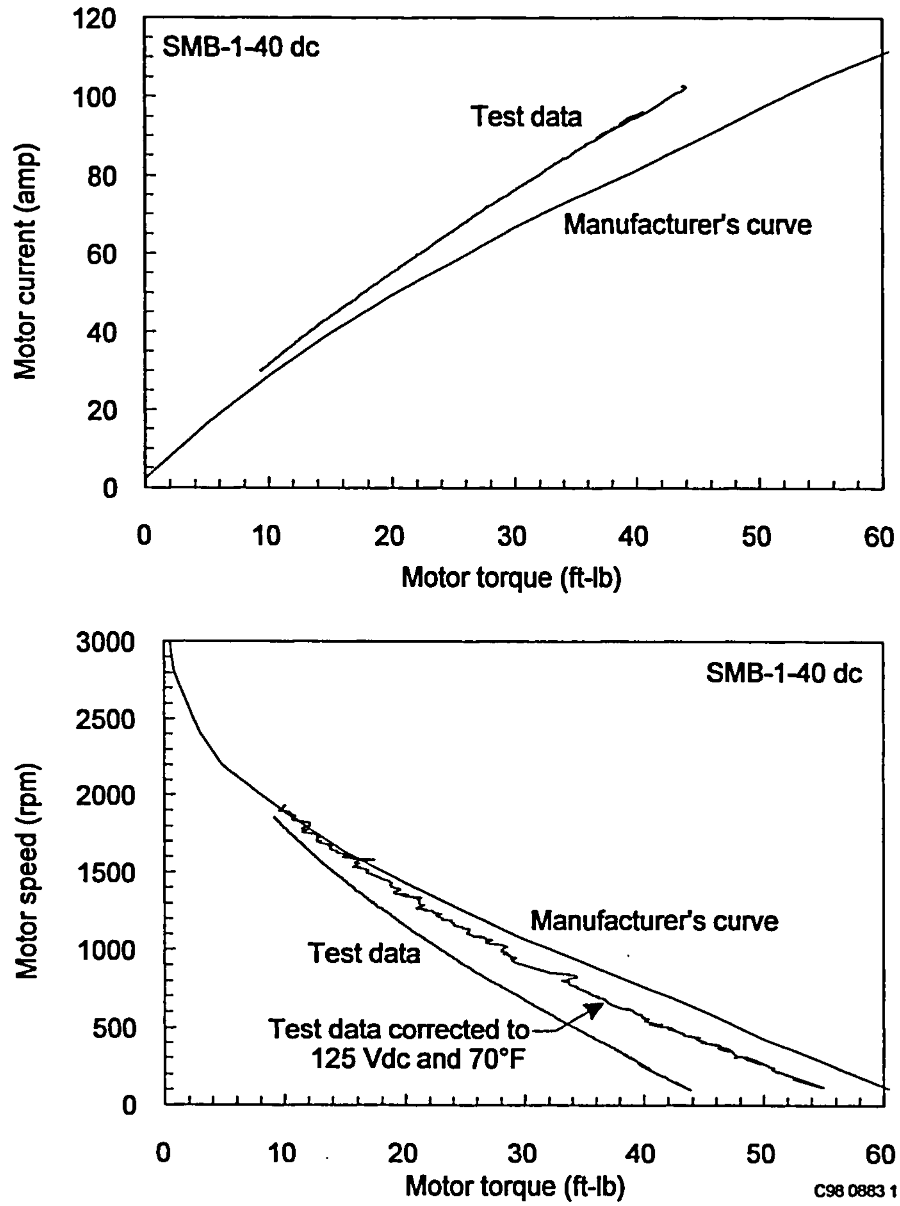


Elevated temperature tests.

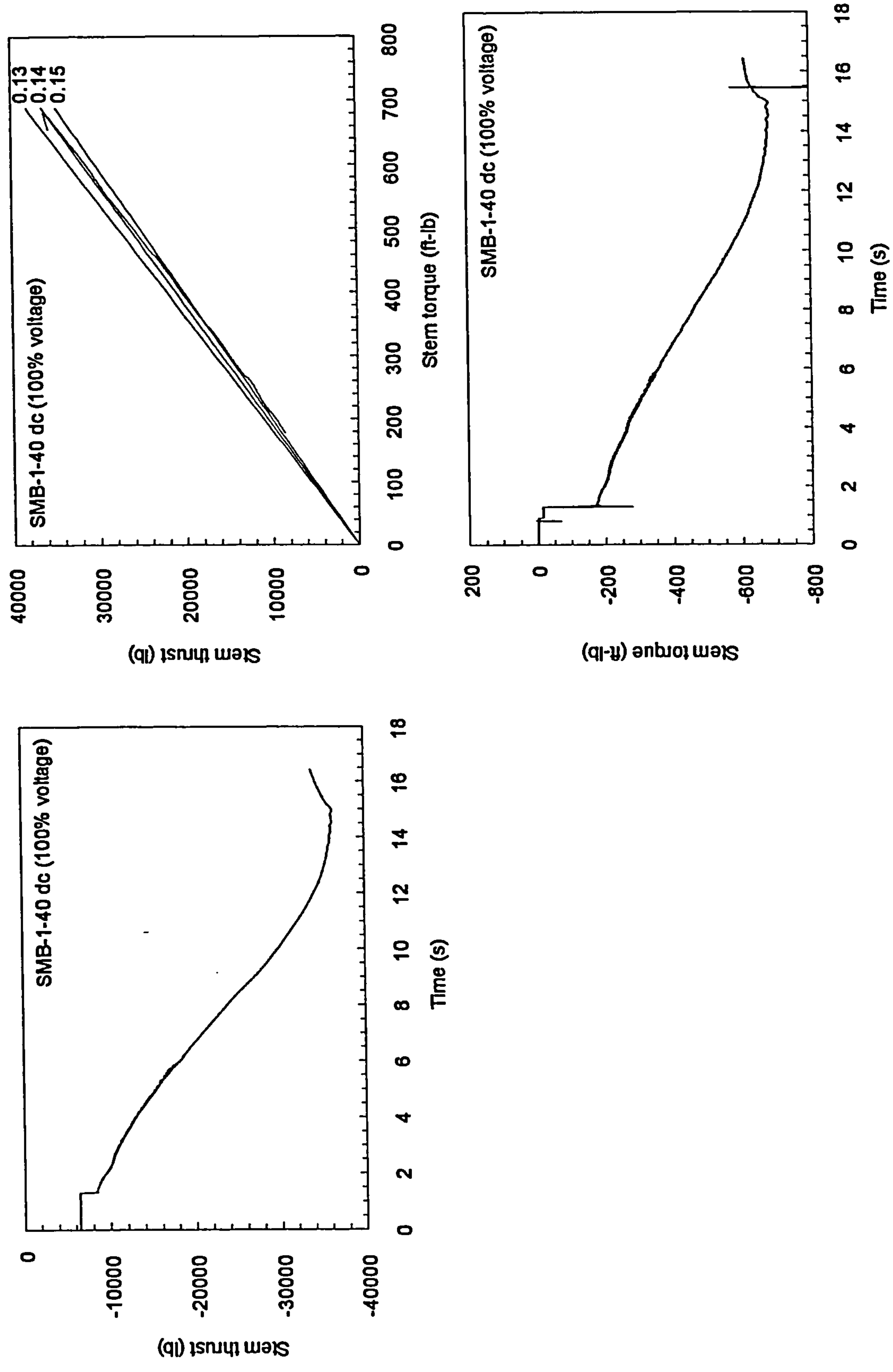




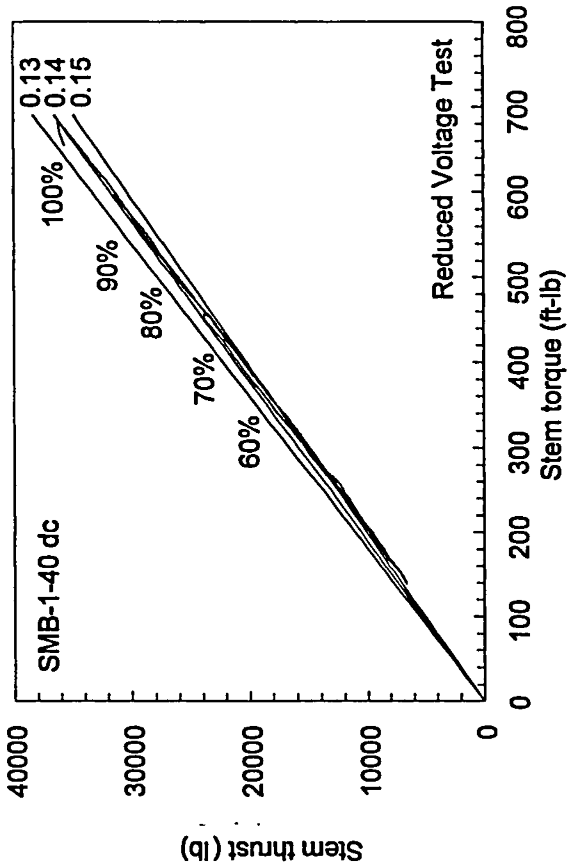
Stroke times.

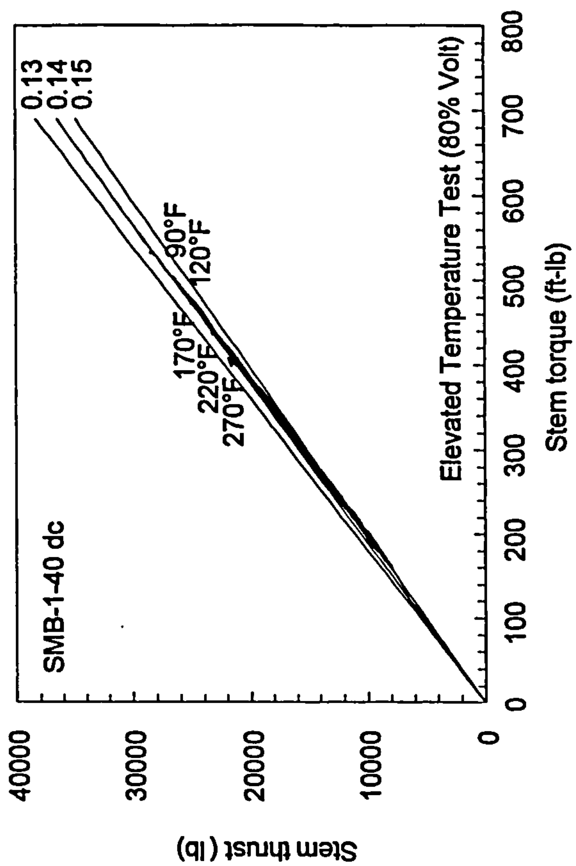


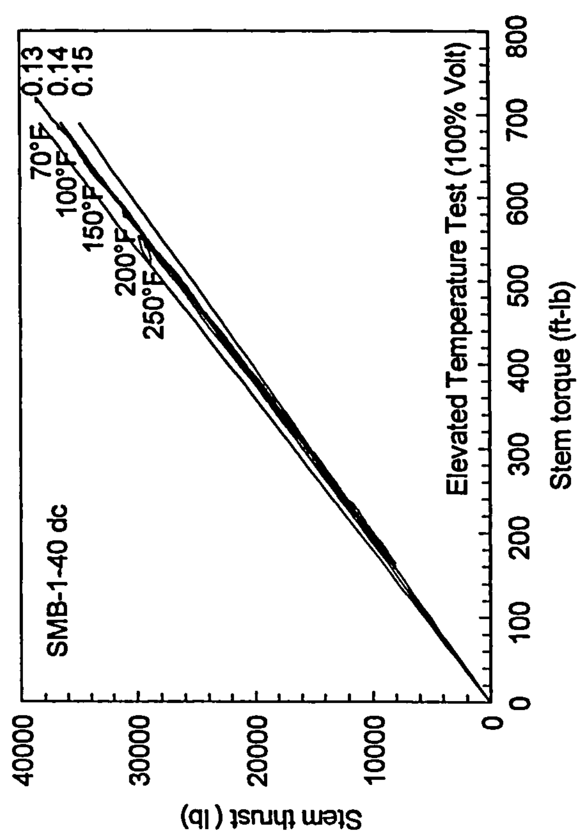
Performance curves.



Stem/stem-nut friction.

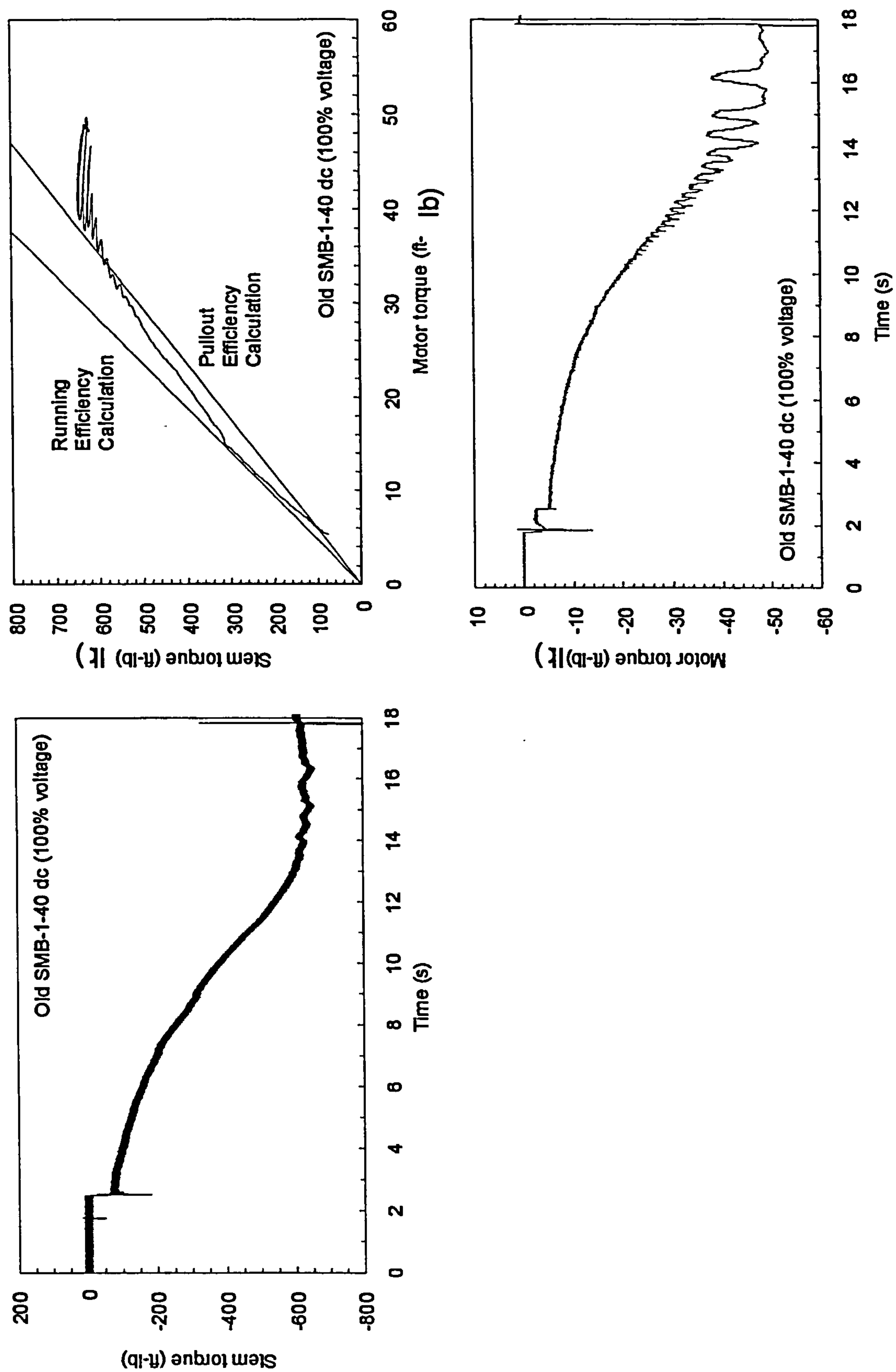




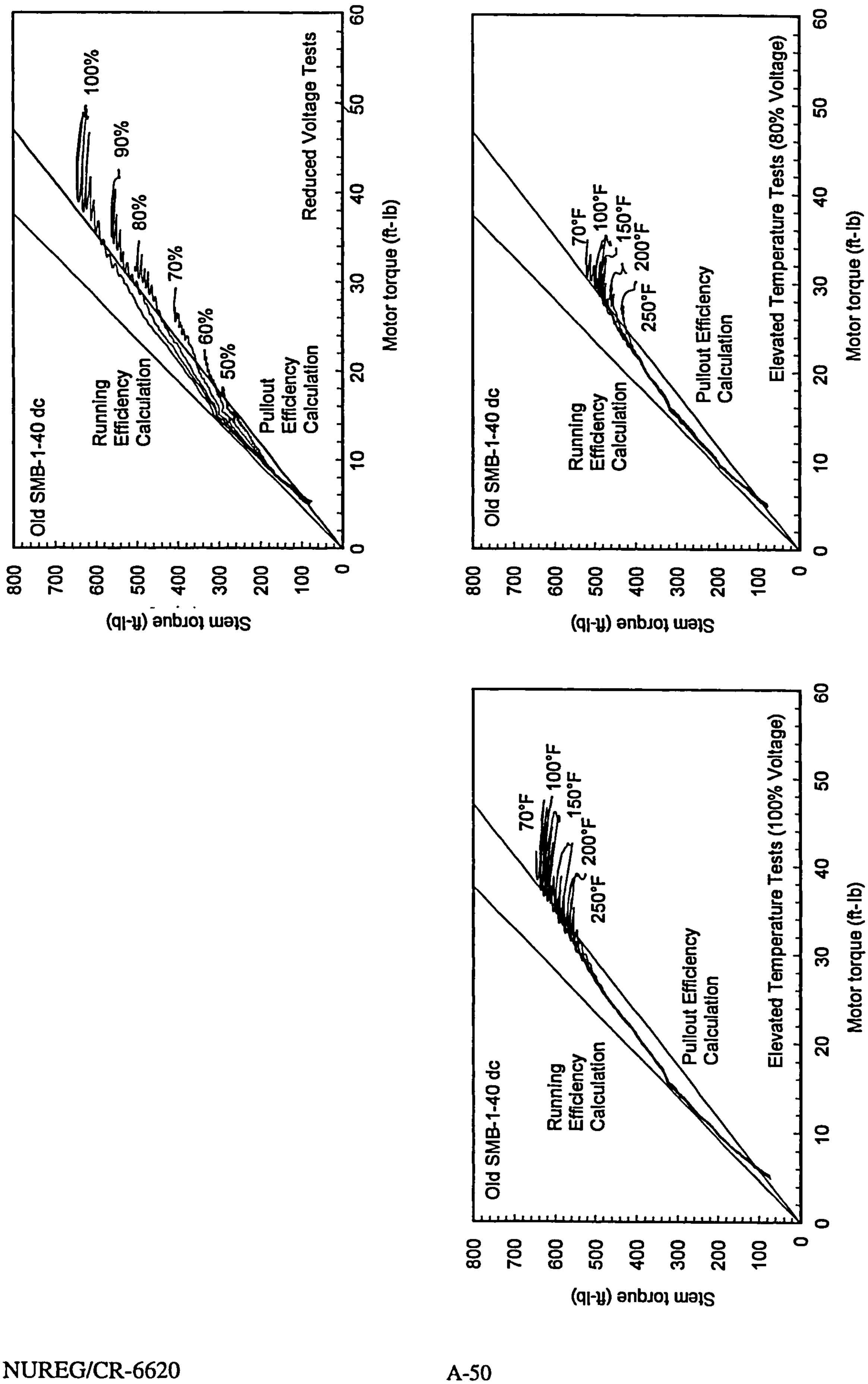


Stem/stem-nut friction.

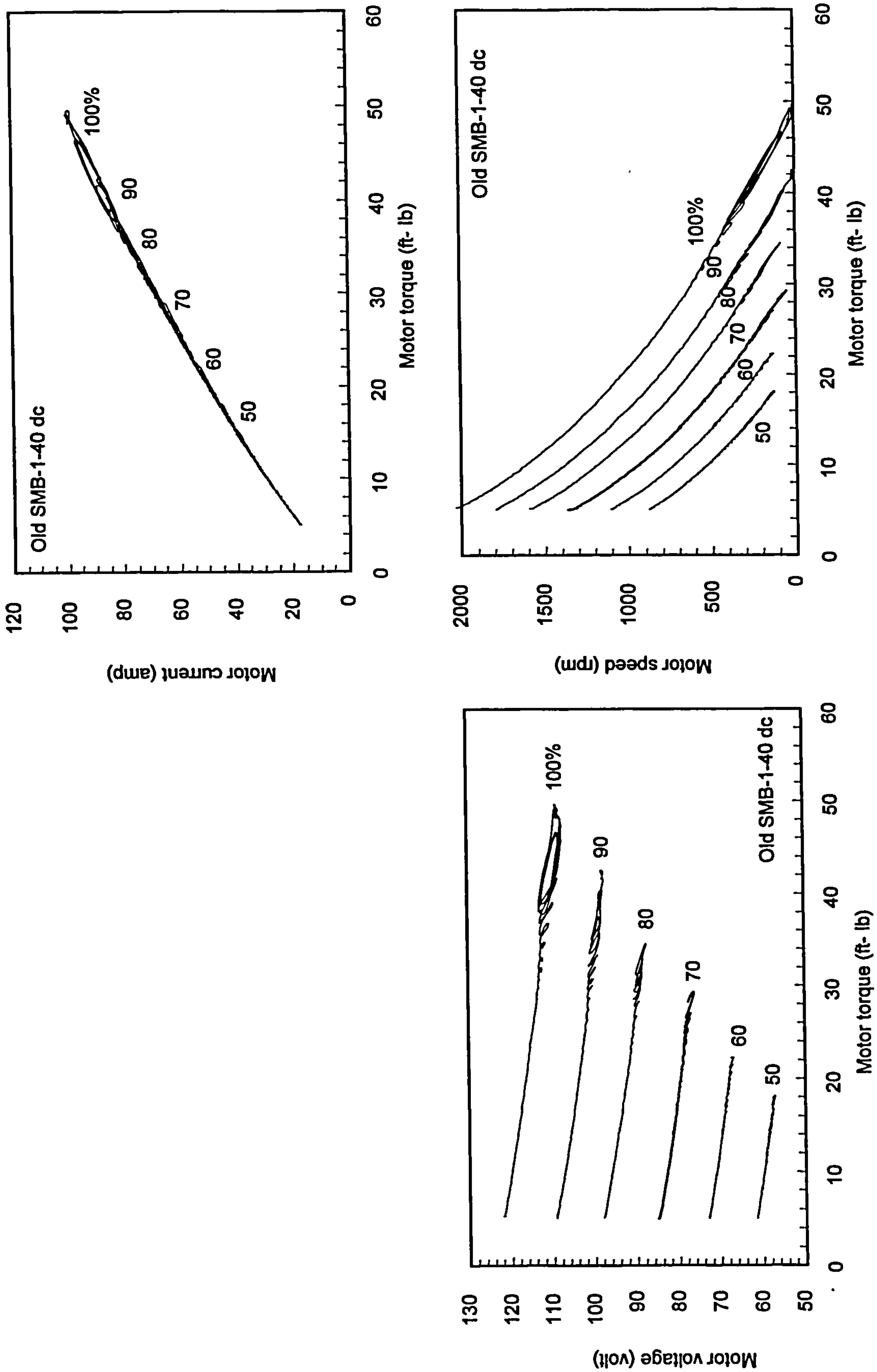
A-4. DATA PLOTS, OLD SMB-1-40



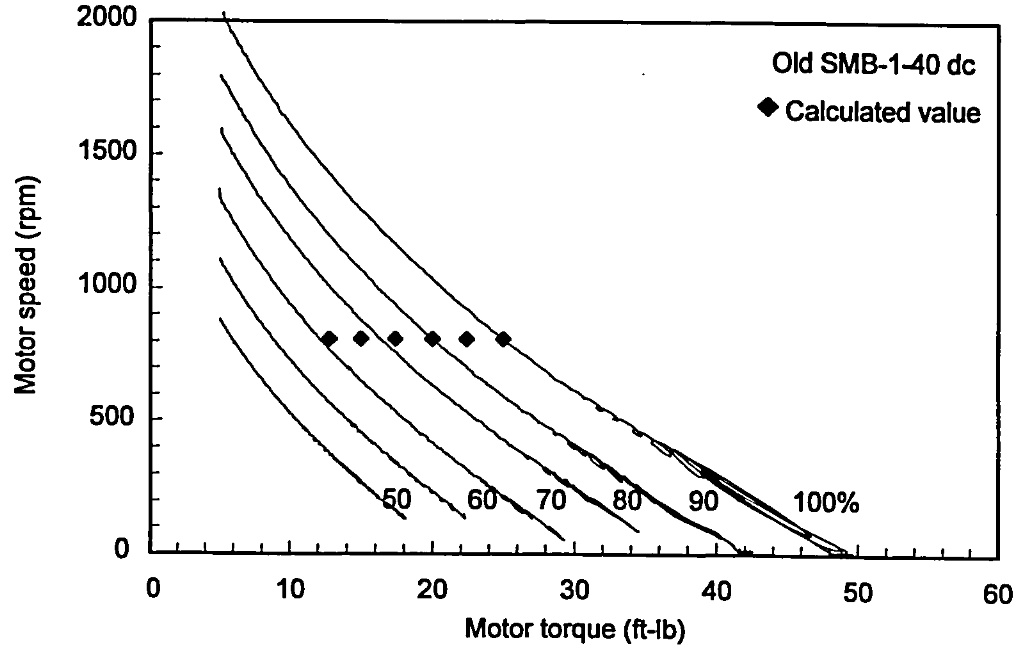
Gearbox efficiency.

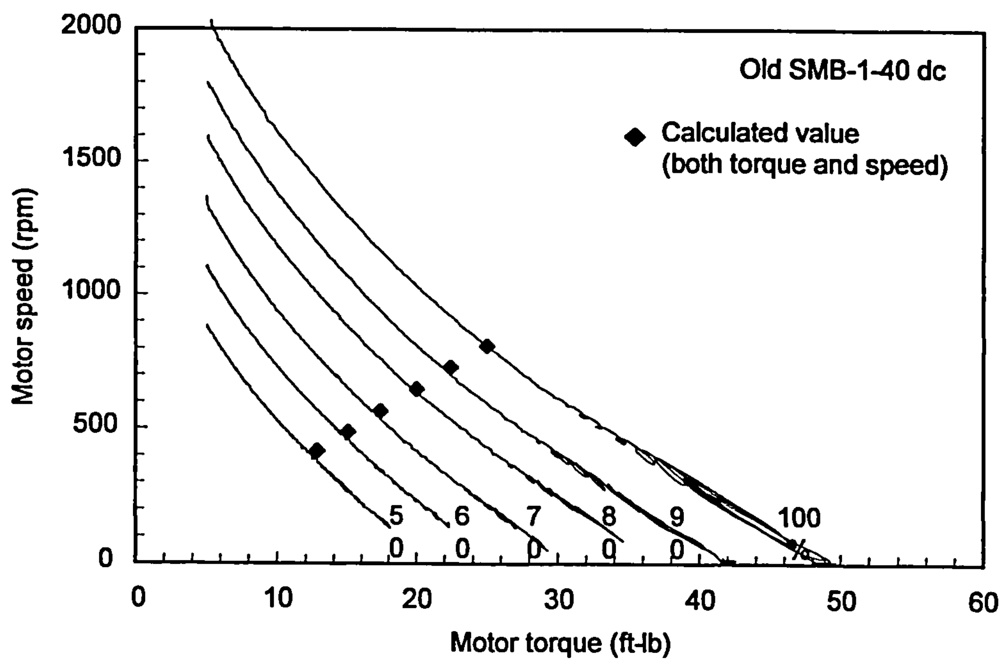


Gearbox efficiency.

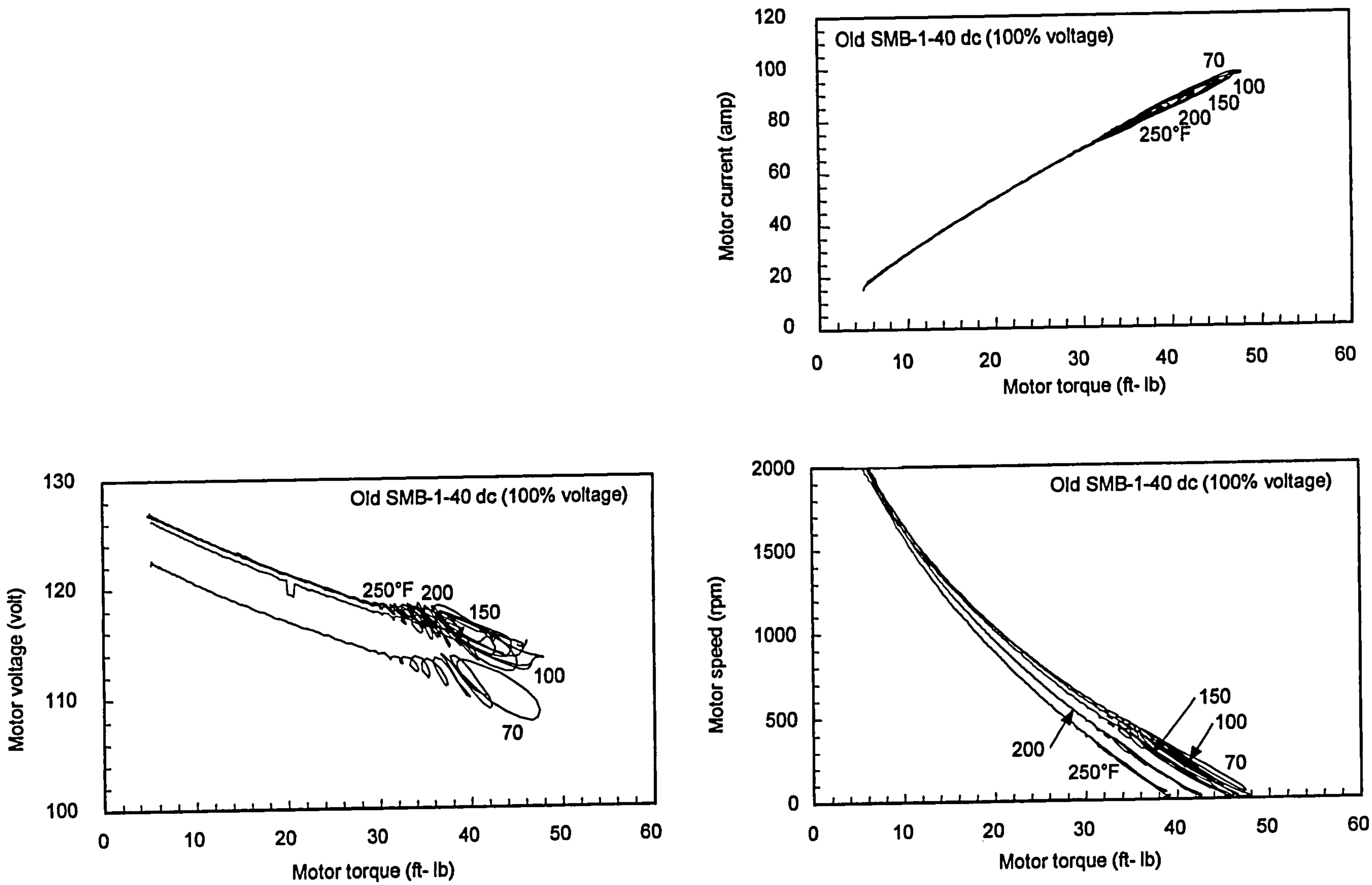


Degraded voltage testing.

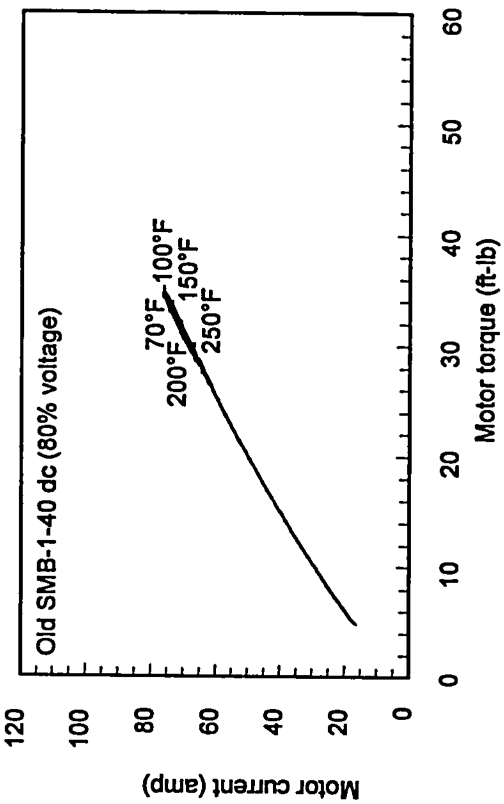


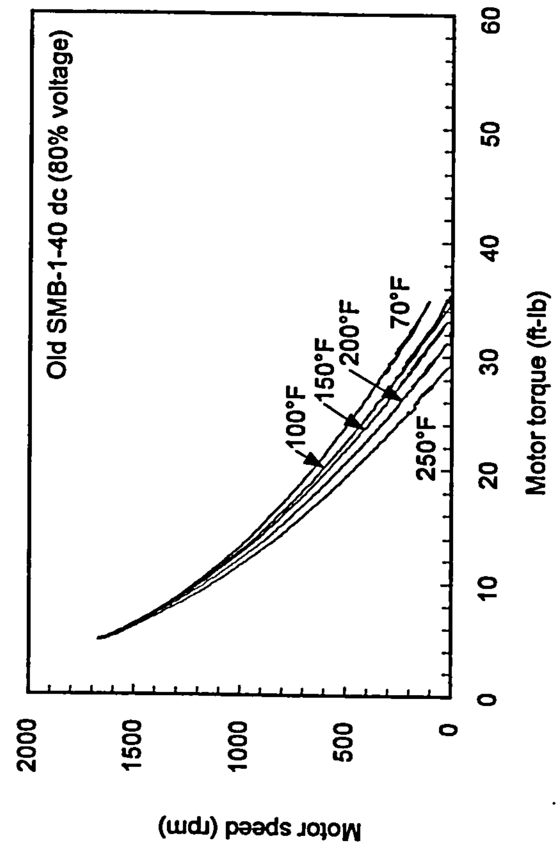


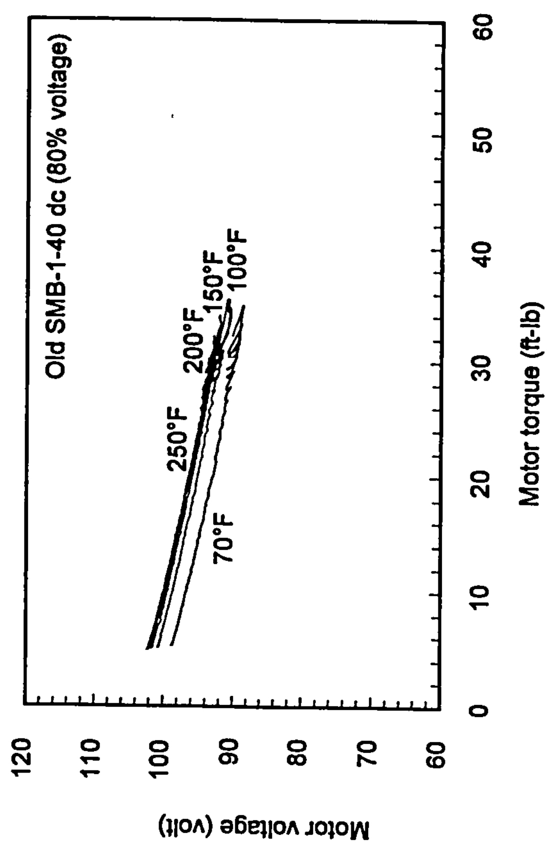
Degraded voltage tests.



Elevated temperature testing.







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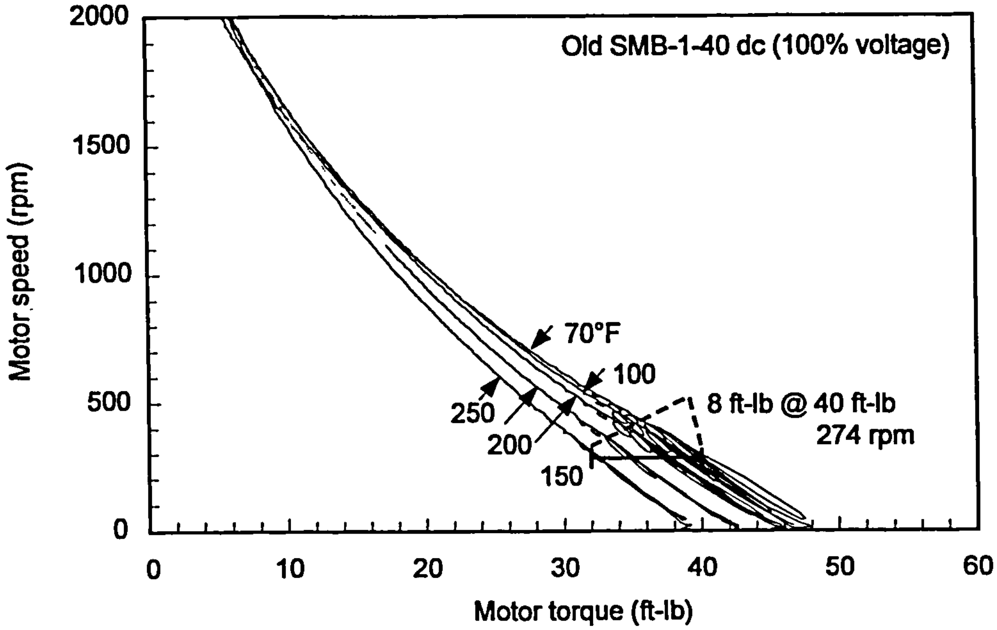
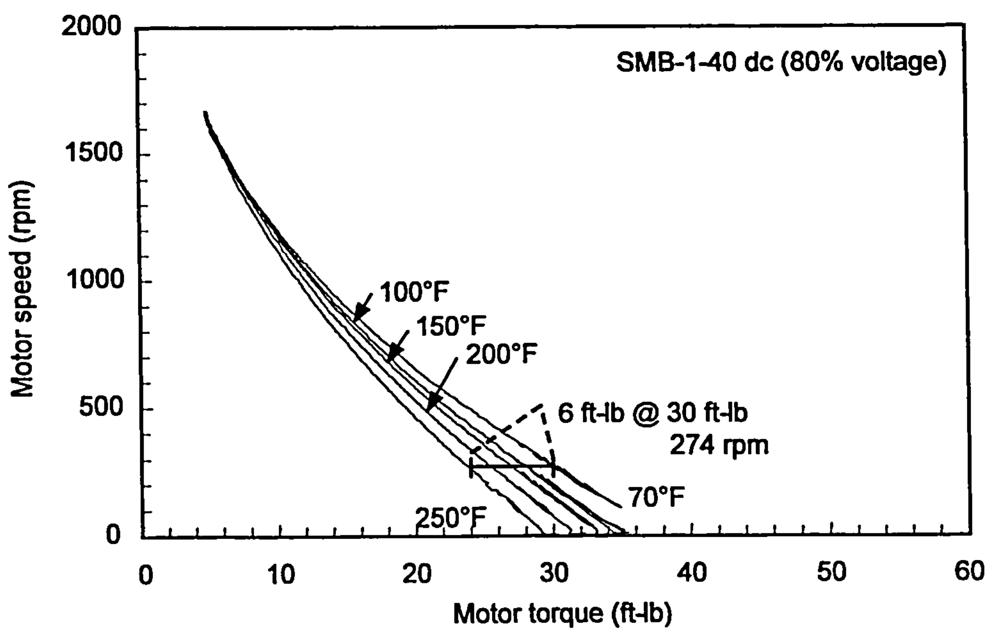
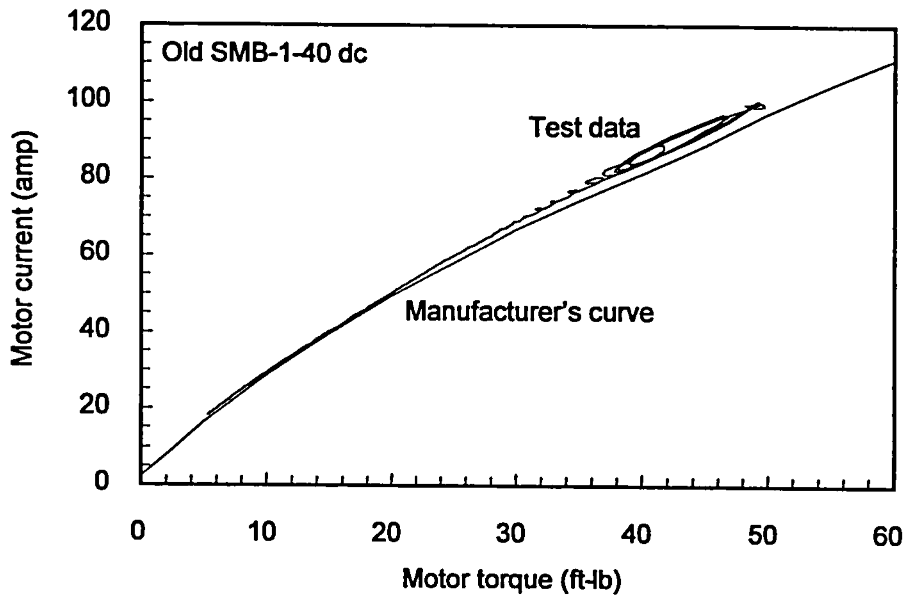
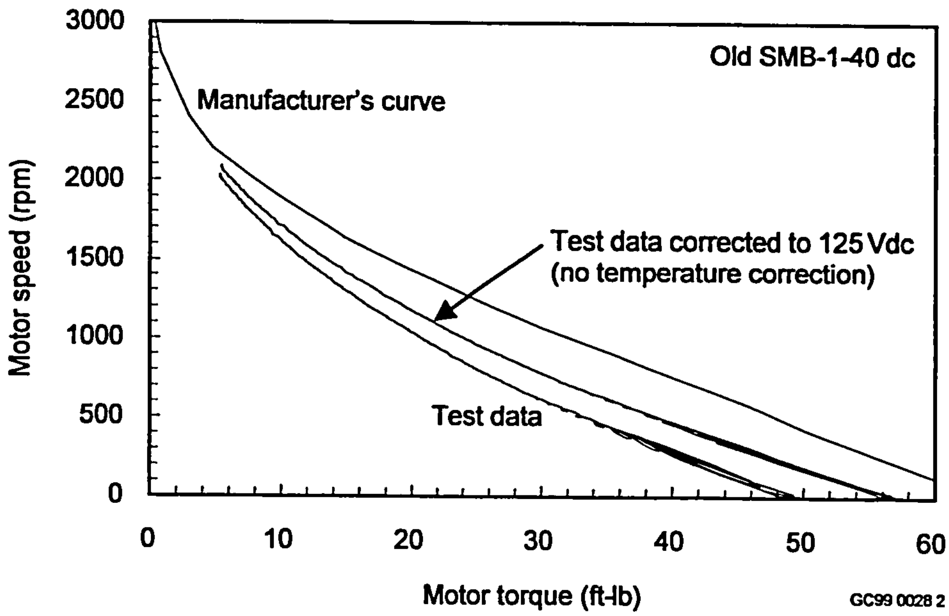


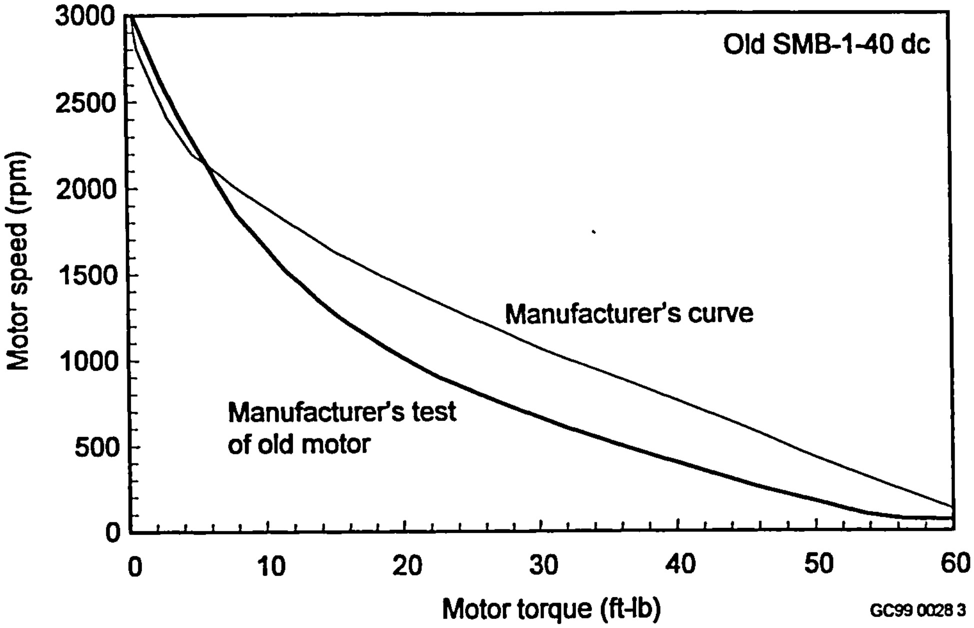


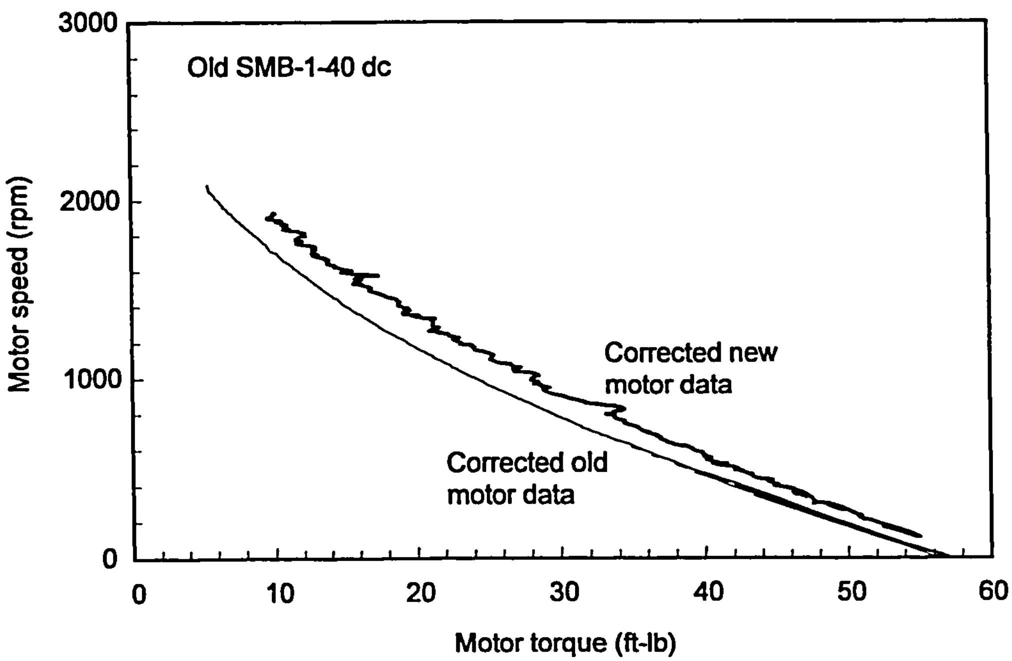
Elevated temperature tests.





Performance curves.





Performance curves.

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10. SUPPLEMENTARY NOTES

J.E. Jackson, NRC Project Manager

11. ABSTRACT *(200 words or less)*

This reports documents results of dc-powered motor-operated valve (MOV) research sponsored by the U.S. Nuclear Regulatory Commission (NRC) and conducted at the Idaho National Engineering and Environmental Laboratory (INEEL). We tested four typical dc electric motors and two gearboxes at conditions a motor might experience while closing a valve in a nuclear power plant, including such off-normal conditions as operations at high temperature and reduced voltage. We also monitored gearbox efficiency and stem nut coefficient of friction. Results showed that actual gearbox efficiencies were lower than efficiency valves published by the manufacturer. Because of the decrease in gearbox efficiency at low-speed, high-torque operation, increases in motor torque at motor speeds lower than a threshold of about 200 to 300 rpm failed to produce a corresponding increase in actuator output torque. Results of tests reduced voltage fell very close to predictions that anticipated linear reductions in both motor torque and motor speed. However, in some instances actual and predicted performance fell below the motor speed threshold identified above. Actual motor torque losses due to elevated temperature conditions were significantly greater than anticipated by the manufacturer's published data. Changes in running load had significant effects on valve stroke times and motor heating.

12. KEY WORDS/DESCRIPTORS *(List words or phrases that will assist researchers in locating the report.)*

motor-operated valve (MOV)
dc motor
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