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LEVEL

FINAL REPORT

AERODYNAMIC HEATING OF CONVENTIONAL WEAPONS

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UNITED STATES AIR FORCE

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GRANT NO.
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Conducted by

DUPREE MAPLES

COLLEGE OF ENGINEERING
MECHANICAL ENGINEERING DEPARTMENT
LOUISIANA STATE UNIVERSITY
BATON ROUGE, LOUISIANA 70803

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A two-pronged effort in aerodynamic heating was performed. The first, and more basic requirement, was an experimental analysis of heating incurred by conventional weapons. The second effort, which was related to the first, concerned investigating heat transfer mechanisms found in and around weapons. Some of the isolated areas to be investigated were: thermal contact conductance, convective heat transfer coefficient review and analysis, thermal control methods as applied to weapons, and thermal scale modeling involving convection/conduction. The first requirement of this research program was to establish a thermal laboratory at the AFATL. This

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered) laboratory was designed to have the capabilities to experimentally investigate the effects of heating on full-scale weapons. The design included a radiant energy thermal exitation system to simulate surface heat fluxes and temperatures encountered during aerodynamic heating missions. The second requirement was accomplished by an investigation of the contact conductance of screw threads. This was selected since the fuses are normally connected to the main weapon by threads.

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SUMMARY

A research program for weapon aerodynamic heating of conventional weapons is essential for the Air Force Armament Laboratory. The development role is currently suffering in several areas due to a rapid increase in weapons performance requirements and the systems concept of weapons. The need to increase the knowledge of conventional weapons aerodynamic heating has been predicted by development of high performance aircraft capable of attaining airspeeds at which temperatures in excess of 400°F are experienced.

To begin filling the void in aerodynamic heating of weapons that exists, a two-pronged effort in aerodynamic heating was initiated under this Grant. The first, and more basic requirement, is an experimental analysis of heating incurred by conventional weapons. This effort as initially conceived was the establishment of a weapon thermal laboratory at the AFATL in DLJC experimental wing.

The second effort, which was related to the first, concerned investigating heat transfer mechanisms found in and around weapons. Some of the isolated areas to be investigated are: thermal contact conductance, convective heat transfer coefficient review and analysis, thermal control methods as applied to weapons, and thermal scale modeling involving convection/conduction.

The first requirement of this research program was to establish a thermal laboratory at the AFATL. This laboratory was designed to have the capabilities to experimentally investigate the effects of heating on full-scale weapons. The design included a radiant energy thermal exitation system to simulate surface heat fluxes and temperatures encountered during aerodynamic heating missions.

The second requirement was accomplished by an investigation of the contact conductance of screw threads. This was selected since the fuses are normally connected to the main weapon by threads. This part of the program was conducted at Louisiana State University under a modification of the original grant.

1.0 INTRODUCTION

The carriage and functional environment of weapons and related equipment carried on modern day strike aircraft is very severe, particularly with respect to the temperatures resulting from aerodynamic heating. Most conventional weapons and equipment contain explosive fillings and other components which have low temperature limitations.

1.1 BACKGROUND

Missile or aircraft flight at high speeds and high altitudes introduces many new problems to the designer. One of the more important problems that arises is caused by the skin temperatures (aerodynamic heating) that are attained at very high velocities. Adiabatic wall temperatures under these conditions can exceed temperature limitations of structural materials. The payload of explosives also has a critical temperature level which may be exceeded.

The need to increase our knowledge of conventional munition aerodynamic heating has been predicated by the development of high performance aircraft, such as the F-111 and F-15, which are capable of obtaining air speed at which temperatures in excess of 400°Fahrenheit are experienced for time durations on the order of minutes. These air speeds are obtainable with externally carried ordinances. Additionally, booster rockets are capable of obtaining air speeds at which temperature in excess of 1000°Fahrenheit are experienced for short durations on the order of seconds. Weapon components such as electronics, fuses, etc. are typically qualified to temperatures near 200°Fahrenheit. Hence, a complete understanding of aerodynamic heating incurred by high speed flight is needed in order to provide a basis for advanced weapons development.

1.2 TASKS OF GRANT

A two prong effort in weapon aerodynamic heating research was investigated. The first effort was the design of a Weapon Thermal Research Laboratory to be established at the Air Force Armament Test Laboratory (AFATL). The second effort was to conduct the necessary basic research to expand the knowledge of the convection/conduction heat transfer mechanism. The Weapons Thermal Research Laboratory was to be designed and established at Eglin initially. The Grant was modified after the laboratory was designed and the laboratory was never established. The laboratory design had the capability to determine the effects of heating on full scale weapon shapes and was designed with a radiant energy thermal exertion system to simulate surface heat fluxes and temperatures encountered during weapon carriage aerodynamic heating. Research was conducted on the conduction heat transfer mechanism which occurs through screw threads.

2.0 DESIGN OF THERMAL LABORATORY FOR AFATL

This section describes a complete Radiant Heat System which was designed for AFATL/DLJC. The system design was developed to completion as presented.

The radiant heat system was a computer based system which would provide the capability to set-up the test configuration, to run tests on the sensors and radiant arrays, control the test profile, provide the test operator with test data during the test, and store test data for post-test print-out and analysis.

2.1 GENERAL DESCRIPTION

The radiant heat system was an integrated system of hardware and software specifically designed to perform radiant heat tests on up to 10 zones on the test article.

The system provided the capability to run tests in the closed loop temperature mode. The array voltage can also be adjusted manually if the operator wishes to do so.

Prior to running the test, a test configuration must be specified. This involves specifying test article identification data, test profiles, the channels to be used for the test, and sensor information for each channel. This configuration information can then be saved on a floppy disk for later reference and modification.

After the configuration was established the system performed pre-run test on the sensors and arrays and provide pertinent information to the operator, and save test data for post-test processing.

2.1.1 HARDWARE

The hardware consisted of the computer and its peripheral equipment, input subsystem for analog and digital inputs, output sub-system for analog and digital outputs and the SCR power controllers for controlling the power into the heat lamps.

2.2 COMPUTER AND COMPUTER PERIPHERALS

The computer selected was a Digital Equipment Corporation PDP-11 with 32K words of memory, real time clock, hardware multiply/divide, automatic loader, and interface for the peripheral and input/output equipment.

The peripherals for the computer consist of a 2.5M byte cartridge disk, a dual floppy disk unit, a 165 CPS printer, an operator's console CRT, and a graphics terminal.

The disk was used by the operating software system as a storage medium for programs and data files.

The floppy disk unit was used for program and data loading and dumping. All system programs were on floppy disks, so that reloading can be accomplished easily.

The printer was used for printing out post-test reports.

The operator's console CRT provided the operator with a single control console for controlling the system and monitoring the test.

The graphics terminal was used to plot one channel's profile during the test and could be used for plotting post-test data if the necessary programs are written.

2.2.1 INPUT EQUIPMENT

The input equipment provided digital inputs and both high and low level analog inputs.

2.2.1.1 DIGITAL INPUTS

The system has 10 digital inputs; each of which is optically isolated and filtered to minimize interference from external noise.

The contact input assignments are 1 ground test input and 10 power controller on inputs.

2.2.1.2 ANALOG INPUTS

All 64 analog inputs were input via a programmable gain multiplexer - A/D converter which is expandable to 64 inputs.

Analog signals from the thermocouples (feedback sensors and monitors) were referenced by a multi-channel thermocouple reference junction compensator for any type of thermocouple. There were selected 52 spare thermocouple inputs.

2.2.2 OUTPUT EQUIPMENT

The system was designed to provide digital and analog output.

2.2.2.1 DIGITAL OUTPUTS

The system was designed to provide 40 solid state relay outputs which will be assigned the following functions: 10 each ground test, 10 each power controller power on, 1 each run, 1 each static tests complete and 6 spares. The solid state relay commands will be provided by a universal output device which also provides analog outputs.

2.2.2.2 ANALOG OUTPUTS

The system will have 10 analog outputs of 0-5VDC which will be the load voltage command to the power controllers.

2.2.3 POWER CONTROLLERS

Ten 300 ampere SCR power controllers were designed for the system. These were Research Inc. Model 651-1 or equal. These power controllers were equipped with the voltage option card for closed-loop voltage control. This voltage control option will provide automatic line voltage compensation and assure a linear control signal vs. load voltage relationship.

2.2.4 MANUAL VOLTAGE CONTROL

A manual control panel was designed which allows the operator to monitor the load voltage and current for each channel and to provide manual take-over of the load voltage if desired.

2.3 SOFTWARE

The software provided by Research, Inc. consists of a real-time disk operating system and application programs to allow test configuration, pre-run tests on the sensors and array, test control, post test data transfer and post test data log.

2.3.1 REAL-TIME DISK OPERATING SYSTEM

The real-time disk operating system was selected from a system supplied by Digital Equipment Corporation with special modifications and device handlers necessary to handle the input/output hardware.

2.3.2 TEST CONFIGURATION

The test configuration software allows the operator to create or modify a test configuration data file on the cartridge disk. This software also provided the capability to transfer the configuration file between the cartridge disk and floppy disk.

2.3.3 PRE-RUN TEST

The pre-run test software was designed to test the sensors, test the array for shorts to ground, and test to verify that all sensors in a given array zone respond when a small amount of power is applied to that zone.

2.3.4 TEST CONTROL

The test control software was designed to vary the setpoints of the assigned channels, read the feedback and monitor sensors, control the temperature, provide the test information to the operator and save test data on the cartridge disk for later transfer to floppy disk. The capability was provided to save one or more power controllers to the same closed-loop controller, thereby increasing the amount of power available for a control zone.

2.3.5 POST TEST DATA TRANSFER

The post test data transfer was designed to transfer the test data from the disk to the floppy disk for permanent storage.

2.3.6 POST TEST DATA LOG

The post test data log was designed to print out a test report containing the sensor data for each channel and monitor data for each data interval during the test.

3.0 DETAILED DESCRIPTION OF DESIGNED LABORATORY

The following sections provide a detailed description of the hardware and the software designed and specified as part of the original Grant.

3.1 HARDWARE

Most of the hardware was selected from Research, Inc.

3.1.1 COMPUTER

The computer selected was a Digital Equipment Corporation PDP-11 with 32K or 48K words of memory, real-time clock, auto-program load and interfaces for the various peripheral and input/output equipment.

3.1.2 DISK

The disk selected was a 2.5M byte cartridge disk sub-system.

3.1.3 DUAL FLOPPY DISK

The dual floppy disk selected was a DEC Model RX11 or equal.

3.1.4 PRINTER

The printer selected was a 30 cps 5 x 7 dot matrix printer with 10 characters per inch and up to 132 characters per line. It was DEC LA36 or equal.

3.1.5 GRAPHICS TERMINAL (OPTIONAL)

The graphics terminal selected was a Tektronix Model 4010-1 or 4006. The terminal has a display area 7.5 inches wide by 5.6 inches high. In the graphic display mode there are 1024x and 780y viewable points on the above mentioned display area.

3.1.6 OPERATOR'S CONSOLE CRT

The operator's console CRT will be a Research Inc. Teleray Model 3811 with a 12 inch CRT. The keyboard selected will be utilized for the following functions:

a) Test Set-up - Runs the program which allowed the creation, modification, and/or transfer of the test configuration data file.

b) Sensor Test - Runs the sensor test program and initiates the sensor test program. Since only a portion of the sensor data can be displayed at one time, a key will allow to display the next portion of the sensor data.

c) Array Test - Runs the array test program and runs the array ground test. If both the sensor test and the array test are satisfactory, 'initial test complete' message will appear on the CRT display and the 'static test complete' contact will close. This contact was used to indicate that power was applied to the power controllers.

d) Pre-Run Test - Runs the final pre-run test program and initiates the test by applying a small amount of power to the first channel used. Sensor data for that channel will be displayed on the CRT. The next channel selected was tested when requested by the operator.

e) Start - Starts the tests after verifying all utilized system channels were ready. Start control, monitoring, and data collection.

f) Hold - Stops the automatic gereration of setpoints. This holds the setpoints at their present level. All other functions continue.

g) Continue - Releases the system from hold so that it will continue on through the setpoint profile.

h) Abort - Stops the control of the test and puts all load voltages to zero. Monitoring and data collection functions continue.

i) Stop - End all testing activities and data collections. Close all data files.

j) Data Log - Initiates the post test data log.

3.1.7 INPUT HARDWARE

3.1.7.1 DIGITAL INPUTS

There were a total of 10 digital inputs. These inputs selected were periodically scanned to monitor the status of the detector contact during the initial test and the power on and auto circuit in each of the 10 power controllers.

Each input is optically isolated and filtered and will accept isolated contacts or various voltages (both AC & DC) as inputs. These isolators and filters will be mounted on the 812-CCC contact conditioning terminal strips.

3.1.7.2 ANALOG INPUTS

The 64 analog inputs will be multiplexed and digitized by a Model 812-4B ANA-PLEXER with two 32 channel FET switch cards installed.

The ANA-PLEXER will have four programmable ranges of ± 10 mv, ± 20 mv, ± 50 mv, and ± 100 mv.

The signals from the thermocouples will be conditioned by two Model 812-11-HJ UNI-BOXES.

Each of these UNI-BOXES provides 32 (plus o spare) 150°F reference junctions for any type of thermocouple. Non-thermocouple signals can also be input by these units because these signals can be connected with copper wire thereby cancelling the effects of the 150°F reference junction.

Of these 64 inputs, 10 channels are used for feed back sensors, 54 for monitors of temperatures within a given weapon.

3.1.8 OUTPUT HARDWARE

All outputs from the digital system will be provided by a Model 812-13 UNI-DRIVER with appropriate output circuit cards.

Two Model 812-13-06 four channel proportional output cards were selected. These will provide the 10 0-5VDC load voltage commands to the 10 power controllers.

One 32 channel contact driver card (Model 812-13-09) was selected. These outputs will drive solid state relays which will be assigned the following functions: 10 temperature test, 10 each power controller on, 1 each run, 1 each static tests complete, and 6 unused.

One proportional output power package (Model 812-13-07) will be required for the two proportional output cards.

3.1.9 LOAD METER AND MANUAL CONTROL PANEL

One load meter and manual control panel were selected.

This panel contains a load voltmeter and ammeter, a AUTO-MANUAL switch and a manual voltage adjust for each of the 10 power controllers.

The load voltmeter and ammeter display the RMS load voltage and current with any accuracy of $\pm$ 3%.

A power controller on condition selected was indicated by meter lights or a separate indicator light.

The AUTO-MANUAL switch selects between automatic control of the load voltage by the digital system or manual control of the voltage by the manual voltage adjust on this panel.

A section of the AUTO-MANUAL switch selected is in series with the 'power on' signal from the power controller. This combined 'power on and auto signal' will go to a digital input on the digital system, so that the status of the power controller can be monitored before and during the test.

3.1.10 POWER CONTROLLERS

The 10 power controllers selected were Research, Inc. Model 651-1-A-PA-480-100-ICT-VFB or equal.

The major components of each power controller are the SCRs, firing circuit, current detector, and various transformers and control relays.

The SCRs selected were air cooled units rated 300 ampere continous. The pead reverse voltage rating of the SCRs selected were 80 volts.

The firing circuit selected was a Model 651-1, single phase, phase angle firing circuit with the voltage and current option and a SCR gate driver card.

The voltage feedback option (-VFB) was used to linearize the output voltage with the input signal and to correct for line voltage fluctuation.

The current feedback option selected was used to provide current limiting (-CLA) at 5% to 110% of the controller rating. This current trip will be set slightly lower than the non-recurrent surge rating of the SCR thereby eliminating the need for sub-cycle fuses for the SCR's.

Both the voltage feedback and current feedback options provide a 0-5VDC signal representing the RMS load voltage and current. This signal has an accuracy of ± 1% and was selected to drive the load voltage and current meters on the load meter panel.

The current detector will close a contact whenever the current in flows to ground during the thermocouple test. This contact will be monitored by the digital system during the initial test phase of the test.

For the thermocouple test, the current limited 24VAC will be applied between the load and ground. Again, if there is a ground, there will be a current flowing and the contact will close.

3.1.11 ENCLOSURES

All components selected were mounted in equipment enclosures. The printer and graphics terminal have floor stands and will be adjacent to the equipment enclosures.

3.1.12 INTERCONNECTING CABLES

All interconnecting cables between the components selected were provided by Research Inc. along with interconnecting signal and control cables to the meter panel, and the power controllers. No power wiring was selected other than that required within the power controller enclosures. No power wiring or thermocouple wiring was selected in the initial design.

3.2 SOFTWARE

The software consisted of the real-time disk operating system, an operator's console task, and a series of programs which was loaded and run according to commands from the operator. Most programs should be written in FORTRAN IV or BASIC but some time critical routines may be written in assembly language.

3.2.1 REAL-TIME DISK OPERATING SYSTEM

The real time disk operating system selected was DEC's RSX11M or RT11 with any modifications and special device drivers required for the application.

3.2.2 OPERATOR'S CONSOLE TASK

The operator's console task was selected to provide the control functions required to operate the system. Various functions selected were interlocked with software flags and hardware to prevent the execution of a command unless the status of the system was such that the performance of that function was legal. For example, the test cannot be started until the pre-run tests were completed satisfactorily and the assigned power control channel's power was on and in the AUTO mode.

3.2.3 TEST CONFIGURATION

The system selected had the capability of creating, modifying and transferring a test configuration file which defines such things as the test article identification, type of test, channels used for test, type of sensors, etc.

The creation of a test configuration was via a dialog. The initial part of the dialog was for the entry of test identification information and other data such as how often the test data should be saved and which channel's data was to be displayed on the graphics terminal during the test. When the above was completed, the setpoint profiles were entered. Each profile was assigned a number along with the update interval, number of straight line segments in the program, type of feedback sensor, and the time and setpoint coordinates at the end of each straight line segment. The setpoint information selected was entered in degrees Celsius. When all parameters for a profile was entered, the system requested the next profile information. When a profile number of Ø was entered, the system requested data for the control channels.

Included in the control channel information was the channel number, and whether it's a master or a slave. If it was a master, the type of feedback sensor, and sensor location were entered. Then the profile number was requested. If the test mode was temperature control, the system will request the gain, rate, and reset for the control channel.

If the channel was a slave, the master channel to which it was slaved was the only entry required.

The above procedure was repeated until a channel number of Ø is entered. It then requests the monitor input assignment as to monitor number, type of sensor, and sensor location. When a monitor number of Ø was entered, the configuration process was completed.

Routines should also be provided to allow the modification of the configuration file and transfer of the file from cartridge disk to floppy disk and in the opposite direction.

3.2.4 SENSOR TEST

The sensor test selected will read all sensors assigned for the test and check for nearly equal readings from all sensors. The operator will observe the readings from the sensors and determine if the readings were proper. Since the data for only a portion of the sensors can be displayed at one time, a key on the operator's console will advance the display to the next set of sensors that can be displayed.

When all assigned channels were tested good, a system ready message was printed as output.

3.2.5 TEST CONTROL

The test control will consist of various tasks to read the analog inputs, read the contact inputs, compute setpoints, control the temperature, save the test data and update the operator displays.

Each control update interval, the feedback sensors selected was read and every data save interval, the monitors will also be read.

During the test, the status of the power on and auto contacts for the assigned channels were monitored.

Each setpoint update interval, the system will compute a new setpoint by interpolating between the end points of the current setpoint profile segment. The setpoint program will maintain a record of which segment it is currently processing and how far it has progressed through that segment.

At each data save interval, all sensor data was saved and transferred to a data file on the cartridge disk.

As the test progresses, data selected was displayed on the operator's console and the graphics terminal.

3.2.5.1 TEMPERATURE CONTROL

The test article temperature selected was controlled by a standard 3 mode control equation with proportional, derivative, and integral action. For most tests of this nature, the derivative action was not required, and perhaps the integral action was not required if the gain was run high enough. The general discrete form for the control equation is:

$$M_n = K_p e_n + K_d(e_n - e_{n-1})/\Delta t + K_i \sum_{n=0}^{n} e_n \Delta t$$

where M_n = load voltage command at sample period number n.

K_p = Gain

K_d = Rate

K_i = Reset

e_n = Error = Set point - Feedback

Δt = Sample interval

3.2.6 POST TEST DATA LOG

The post test data log will print out the test data. If desired, graphics of the test data could be displayed on the graphics terminal.

3.2.7 MISCELLANEOUS

One routine was selected to transfer both the test configuration file and the test data file to floppy disk for permanent storage and to transfer from floppy disk to disk for later data retrieval, if desired. No programs were selected to provide, however, for manipulating the test data other than the post test data log.

3.2.8 DATA CONVERSION

Data conversion routine were selected for chromel-alumel thermocouples. This routine selected was curve-fit polynomial for conversion.

4.0 AERODYNAMIC HEATING OF WEAPONS

When a body travels through the air at high speed, the air in contact with the body will have the same speed as the body. At a small distance from the surface of the body the air will be at rest and therefore a large velocity gradient will exist across a thin layer of air adjacent to the body; the boundary layer. As large shear forces exist across the boundary layer the work done by these forces is converted into heat. At some position on the body (the stagnation point) it is possible that the kinetic energy of the air flow is converted entirely into pressure and heat energy. The temperature associated with these conditions is termed the stagnation temperature (To). On other surfaces, where the air is brought to rest by the shear forces, and if the body was perfectly insulated the temperature experienced by the surface of the body is termed the recovery temperature (Tr). Apart from small areas which could experience stagnation temperatures, the recovery temperature is generally the highest temperature the body will experience.

If the temperature of the body is T, the rate of heat flow into the body (q) will be proportional to $(T_r - T)$

$$q = h(T_r - T)$$

where 'h' is the heat transfer coefficient. The heat transfer coefficient is a complex quantity and depends upon the physical properties of the air, the surface temperatures of the body and the flight conditions. A large discontinuity in the value of 'h' also occurs when the flow changes from laminar to turbulent; much higher values being associated with the turbulent flows.

To calculate the temperature distribution within the body it is necessary to compute the recovery temperature and heat transfer coefficient. A typical method of computing these parameters, for a forced convection heat transfer environment is available in the literature. A method of computing the temperature distribution in the body under these conditions is also available. In most of these conduction models only limited understanding of contact conductance is available or used. Since the fuses are attached by a very complex conduction configuration called screw threads, the Grant was modified to study contact conductance of screw threads in a laboratory at Louisiana State University in Baton Rouge, Louisiana.

5.0 CONTACT CONDUCTANCE OF SCREW THREADS

The objective of this phase of the Grant was to experimentally determine the contact conductance between two threaded surfaces. An experimental model of pipe threads was used, since pipe threads only make contact in the threaded region.

The source of heat was obtained by two ceramic radiant heaters and the heat sink established by a cold water tank. One dimensional heat flow was established by adding insulation in the proper location. The temperatures along the two mated pipe sections were measured by the use of thermocouples.

The most significant parameter for studying the heat transfer through threaded pipe sections is the resistance to heat flow (or conversely conductance) by two surfaces in contact. Engaged threads are surfaces that often constitute a resistance to heat flow between the threads. This experiment is an investigation into the heat transfer characteristics of pipe-threaded couplings. The purpose of the investigation is to experimentally determine the average contact conductance coefficient for heat transfer from the pipe to the mating coupling.

The scope of this investigation was to determine the thermal contact conductance of a model pipe coupling under the influence of various tightening torques. The specimen was constructed of stainless steel using national pipe threads. Experiments were conducted to develop a relation between the torque applied and the contact conductance for various temperature differences.

5.1 THEORY OF CONTACT CONDUCTANCE

A resistance to heat flow is produced at the interface of two metal surfaces in contact. This is a result of actual metal to metal contact occurring only at a limited number of places on the interface. Surface roughness creates gaps and voids which become occupied by air (or some other fluid medium). Heat transfer across the interface therefore, takes place at the points of metal to metal contact and through the voids occupied by the fluid medium. Since the gaps or voids are usually quite small, it is often assumed that the heat transfer through the void is by conduction and radiation with negligible convective effects. If the thermal conductivity of the fluid filling the voids is less than that of either metal surface, then a thermal resistance is developed across the interface. This resistance is referred to as the thermal contact resistance (R), the reciprocal of which is the thermal contact conductance (h_c).

The contact conductance of an interface of two metal surfaces tends to increase with increasing contact pressure. This is because the greater pressures flatten the high spots that separate the surfaces thereby increasing the area of metal to metal contact. Increased surface roughness, of course, has the opposite effect and decreases the contact conductance. Using the concept of thermal resistance the heat transfer rate through the interface has the form:

$$q = \frac{(T_2 - T_1)}{R} \qquad \text{(Eq. 1)}$$

where: q = heat transfer rate (Btu/hr - ft^2)

$(T_2 - T_1)$ = average temperature difference across the interface (°F)

R = thermal resistance (hr - ft^2 - °F/Btu)

Substituting $h_c = 1/R$ we have:

$$q = h_c(T_2 - T_1) \qquad \text{(Eq. 2)}$$

The value of h_c can now be calculated if the heat transfer rate and the temperature change are known. q is therefore determined from a similar relation:

$$q = \frac{k(T_2 - T_1)}{L} \qquad \text{(Eq. 3)}$$

where: k = thermal conductivity (Btu/hr - ft - °F)

$(T_2 - T_1)$ = temperature difference along the body (°F)

L = distance between positions 2 & 1 (ft)

Equation (3) may be applied to known temperature differences on either side of the interface (assuming no losses to the surrounding medium).

The outside and inside of the pipe and couple were well insulated, the heat was applied only on the front face of the nipple resulting in one-dimensional heat flow. Neglecting heat losses, the heat flux through the nipple was equal to the flux in the couple.

The temperature distribution was determined using thermocouples in the nipple, threads, and couple, placed at known distances in a metal of known thermal conductivity was used to determine the heat flux. The temperature distribution within the threaded contact was not assumed to be linear as in the free length. The temperature and heat flux depend on the tolerance of the threads, the number of threads in contact or metal to metal contact, and the amount of torque applied to nipple and couple.

5.2 MATERIALS AND EQUIPMENT

The experimental apparatus consist chiefly of a model of a pipe thread section, a heater for raising the temperature of one end of the pipe section and a cooling tank to act as a heat sink for the other end. The test model was constructed of stainless steel to the specifications shown in Figure 1. The design uses the male threaded section as the high temperature source with the water tank welded onto the female section. Thermocouples for temperature measurement are installed along the length of both threaded sections. The heat flow path through the model is shown in Figure 2.

As pointed out previously, the contact conductance of the threaded section should increase as the torque applied to the coupling increases. As a result of this a means for applying various torques on the coupling, which would not affect the heat flow, was devised. The device consists of two clamp-type brackets; one which clamps around the water tank and is in turn clamped in a vise (also providing a mount for the entire assembly) and another which is attached to the male pipe section for applying torque. The torque clamp is removeable and has a hex-head attachment with which any torque wrench can be adapted.

Two 2000-watt ceramic heaters, powered and controlled by a thermic temperature controller, were used to provide a constant temperature on the heater plate of the pipe section. The thermocouples were located on the model as shown in Figure 3. The thermocouples were checked for accuracy and cemented in the holes shown in Figure 3. The final thermocouple connections were made for recording the temperatures as shown in Figure 4. All temperatures were recorded continuously on a data logger.

In order to obtain accurate results, one-dimensional, steady-state heat flow must be assured. Protection against unwanted heat loss or gain is provided in two forms: fiberglass pipe insulation for the elimination of convection and conduction of heat into the atmosphere, and a water-cooled heat shield that allows the radiation from the ceramic heaters to fall only on the heater plate of the pipe test section.

The heater assembly required to mount the ceramic heaters was constructed. The brackets were made out of 1/8 inch plate of aluminum according to the dimensions and specifications given in Figure 5. The mounting structure was constructed out of 3/4 inch thick exterior plywood according to the dimensions

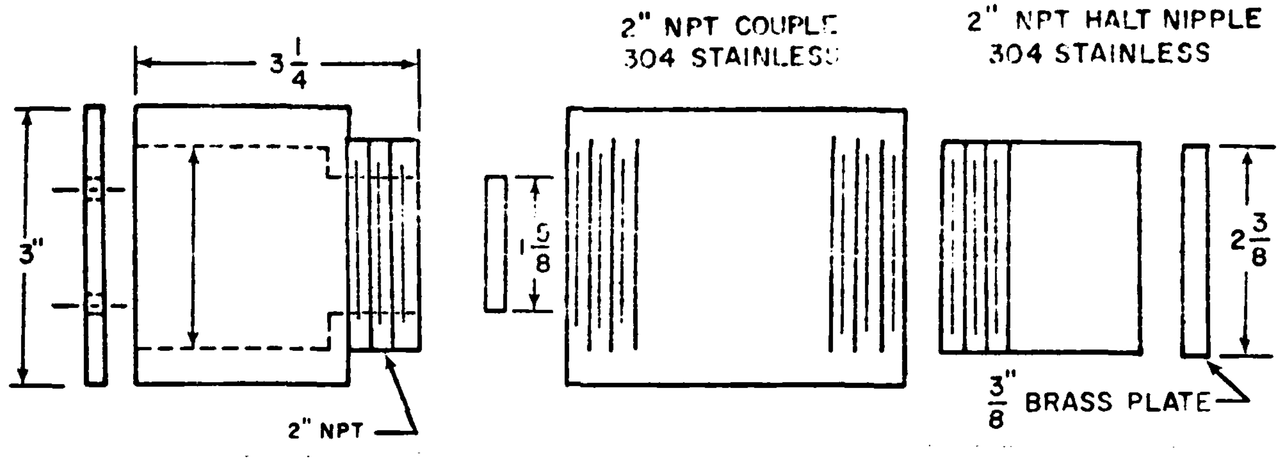

Figure 1. Specifications of Test Model

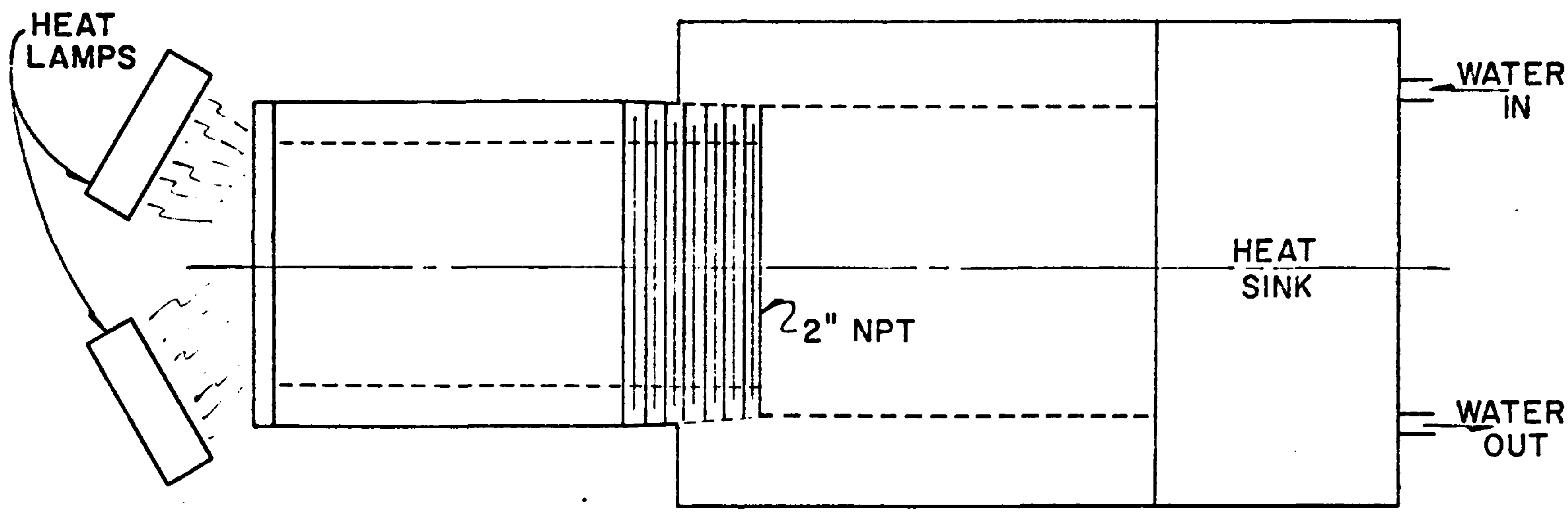

Figure 2. Heat Flow Path Through Model

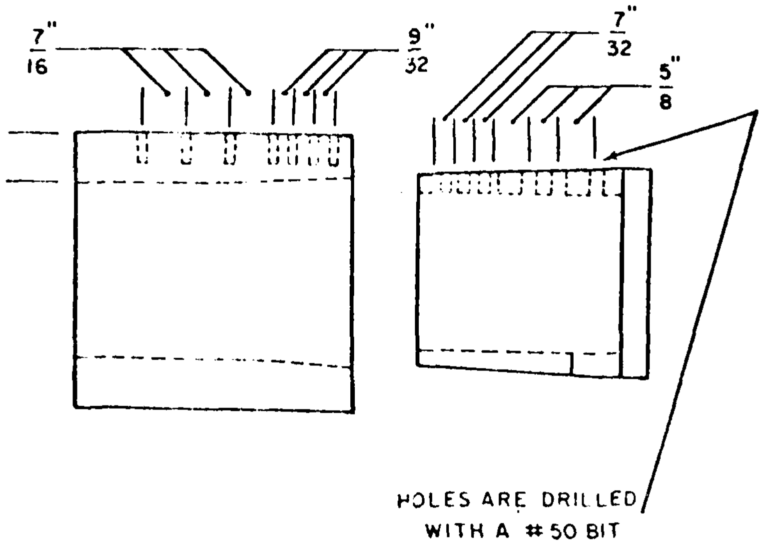

Figure 3. Location of Thermocouples on Model

and specifications given in Figure 6.

The brackets were fixed to the back of the ceramic heaters with suitable fasteners. Then the bracket-heater assembly was mounted in the mounting structure with suitable nuts, bolts and washers. This particular set-up allowed the heaters to be faced in different directions.

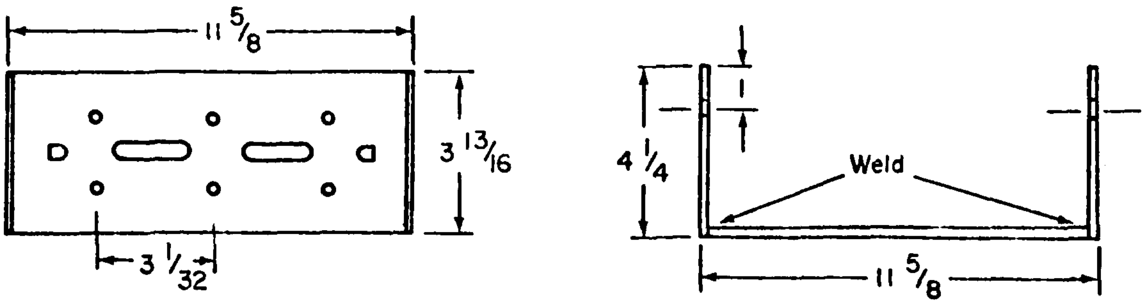

Figure 4. Specifications for Heater Mounting Bracket

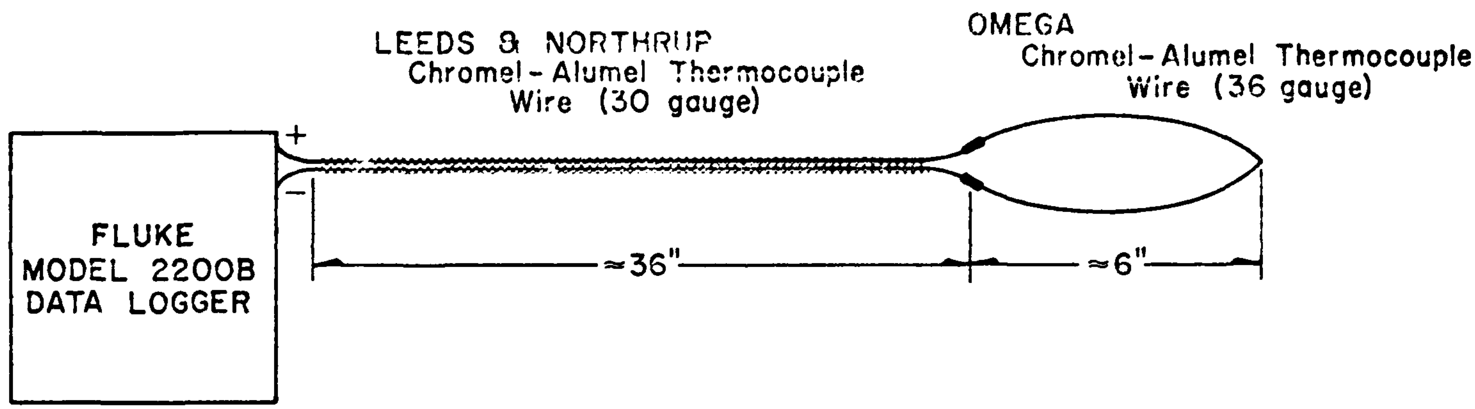

Figure 5. Temperature Recording System

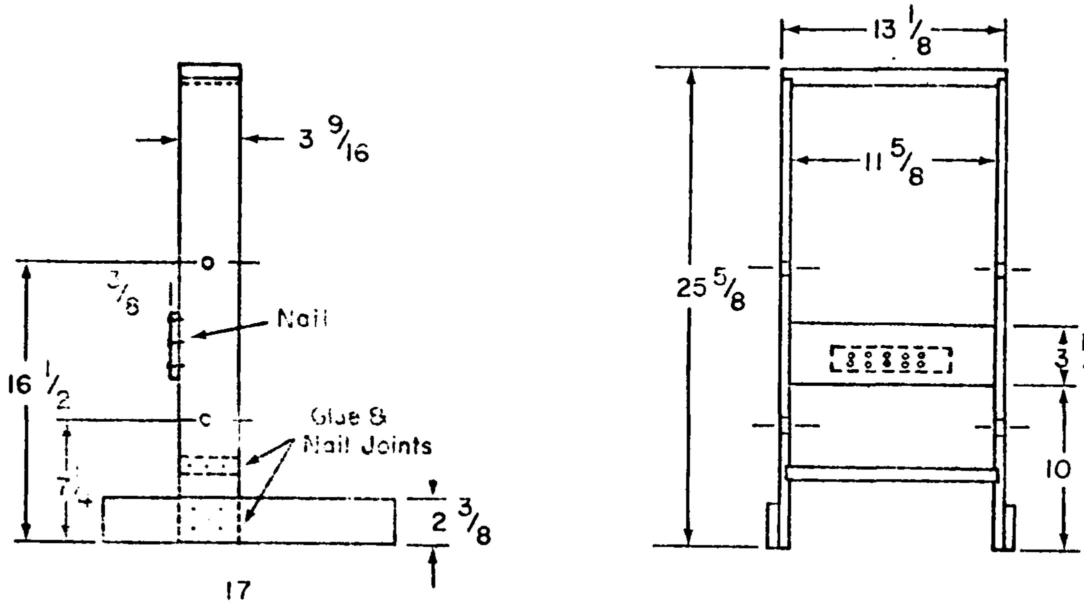

Figure 6. The Specifications for Heater Mounting Structure

A heat shield was constructed to prevent direct radiation (from the radiant heaters) from striking the entire model. The shield was constructed from a 1/16 inch thick galvanized steel sheet according to the dimensions and specifications given in Figure 7. A circular pattern of 1/4 inch copper tubing was soldered on the back of the shield, for the purpose of cooling the shield. Cold tap water was circulated through the tube.

5.3 EXPERIMENT AND PROCEDURE

The experiment was begun by placing the male threaded section into the coupling and tightening hand tight. The torpue clamp was then attached and a moment of 100 in-lb was applied with a torque wrench. The clamp was then removed, all insulation was put in place and the heat shield moved into position. The heaters were adjusted to center maximum radiation on the

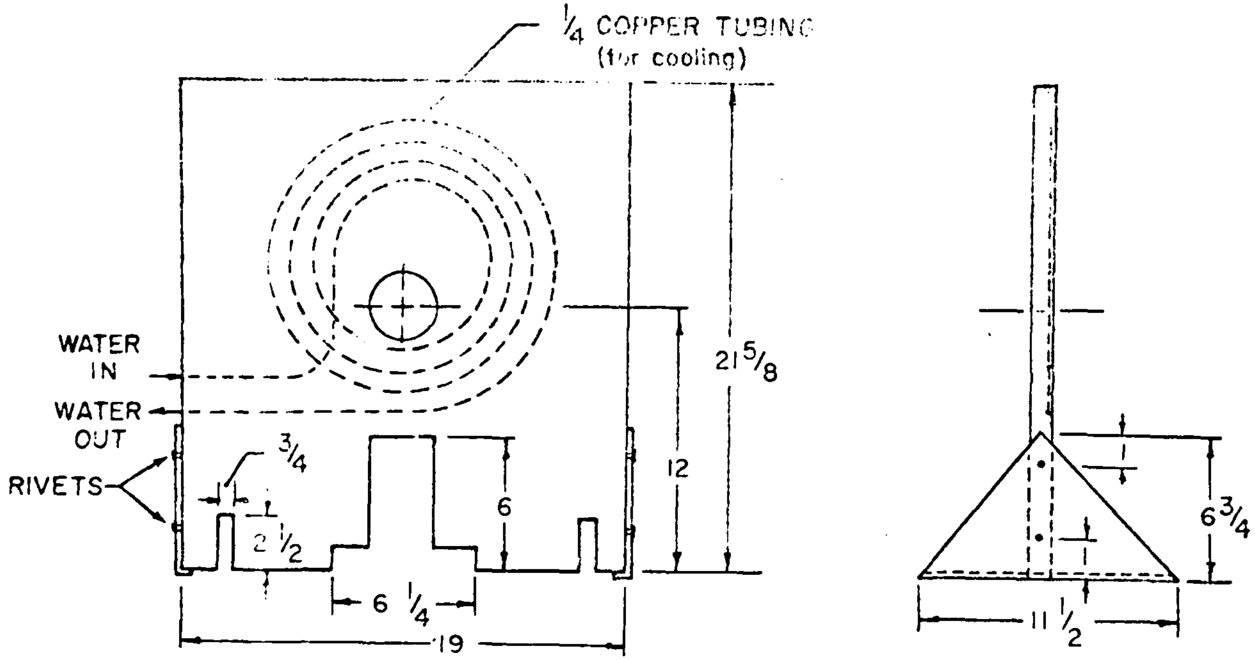

Figure 7. Specifications for Construction of Heat Shield

heater plate. The thermocouple nearest the heater plate was connected as part of the feedback loop to the temperature controller. All other thermocouples are connected to the terminals of the temperature recording data-logger.

After all systems were connected, water was circulated through the water tank and the temperature controller was set to hold the hot end of the pipe such that mean temperatures of 84, 102, 120, 139, and 157°F were obtained for different tests. Steady-state conditions were assumed after there is no change in any temperature readings for 30 minutes or more. At this time the temperature at each point along the length of the model was recorded.

The torque on the coupling was increased by 50 in-lb per test (up to a maximum of 250 in-lb) for each temperature setting of the controller. Test began at a mean temperature of 84°F and the mean temperature was incremented by approximately 170°F until the mean temperature of 157°F was reached, which was the limiting value obtainable with the heat source.

5.4 RESULTS

The temperature distributions recorded are presented in Figures 8 through 27. The one-dimensional heat flow assumption was met since the temperature distributions are linear. Figures 8 through 12 present the data obtained at a torque of 100 in-lbs. while the mean temperature varies from 84°F in Figure 8 to 157°F in Figure 12. The thermal conductivity, k, of the couple was larger than the thermal conductivity of the nipple since the slope of the temperature-distance is larger for the nipple as shown in Figures 8 through 27. Figures 13 through 17 contain the data obtained at a torque of 150 in-lbs, Figures 18 through 22 represent temperature-distances obtained at a torque of 200 in-lbs, and Figures 23 through 27 were plotted for a torque of 250 in-lbs.

Figure 28 presents the contact conductances calculated as a function of mean temperature differences at the various torque values investigated. The contact conductors presented at a torque of 250 in-lbs is a little erratic with respect ot the mean temperature. The mean temperature was established by averaging all temperatures in the contact threaded region.

5.5 CONCLUSIONS

Many parameters were shown to be significant when evaluating the heat transfer characteristics of a pipe-threaded coupling. All of which directly or indirectly affect the contact pressure and/or area between the engaged threads. Therefore, the contact pressure and the threaded area over which it is applied appear to be the main variables affecting h_c. The temperature difference across the threads did significantly affect the value of h_c, along with the tightening torque. Both the torque and mean temperature difference were influential factors governing the contact conductance, h_c, since they alone determine the contact pressure.

By a mechanical analysis of pipe thread engagement a relationship between the torque, the mean temperature, contact pressure and area of contact between engaged threads should be obtained. Utilizing this information it should be possible to determine the thermal contact conductance on a square foot basis (h_c = Btu/h-ft^2-°F). An analysis incorporating all of the above would allow prediction of the heat transfer characteristics of pipe threads of specific materials simply by knowing a few physical parameters such as diameter, torque, thread profile, temperature range, etc.

The researcher suggests that similar experiment be continued, into the affects of torque and mean temperature on h_c for pipe-threaded couplings. Additional points for consideration are listed below.

- The pipe models should be constructed of both a low and a high thermal conductivity material such as aluminum.
- The thermocouple holes should not be drilled through the threads (this may be impossible for a steel pipe with outside threading), unless they are drilled before machining of the threads.

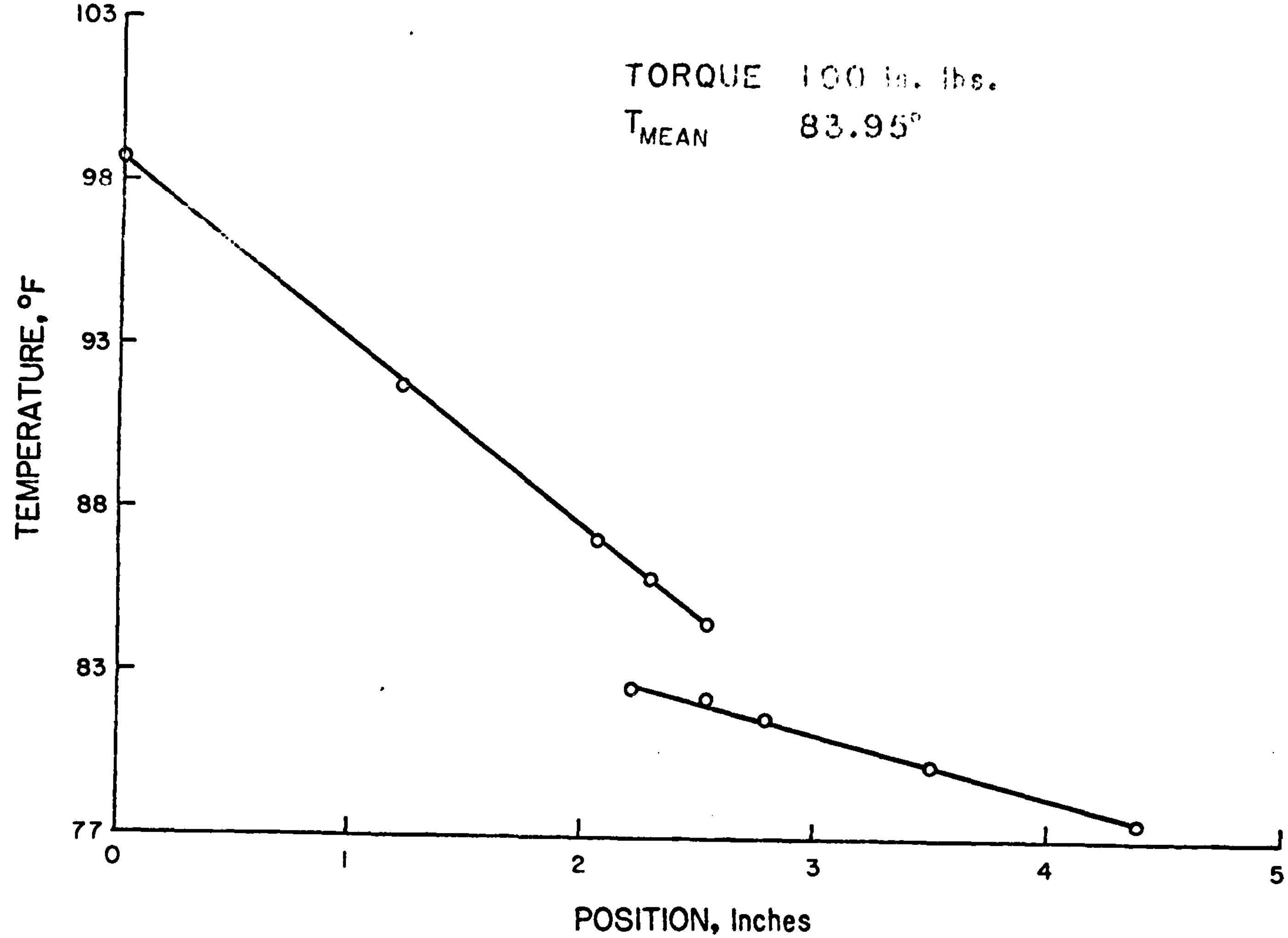

Figure 8. Temperature Distribution for: Torque = 100 in. lbs. and Mean Temperature = 83.95°F

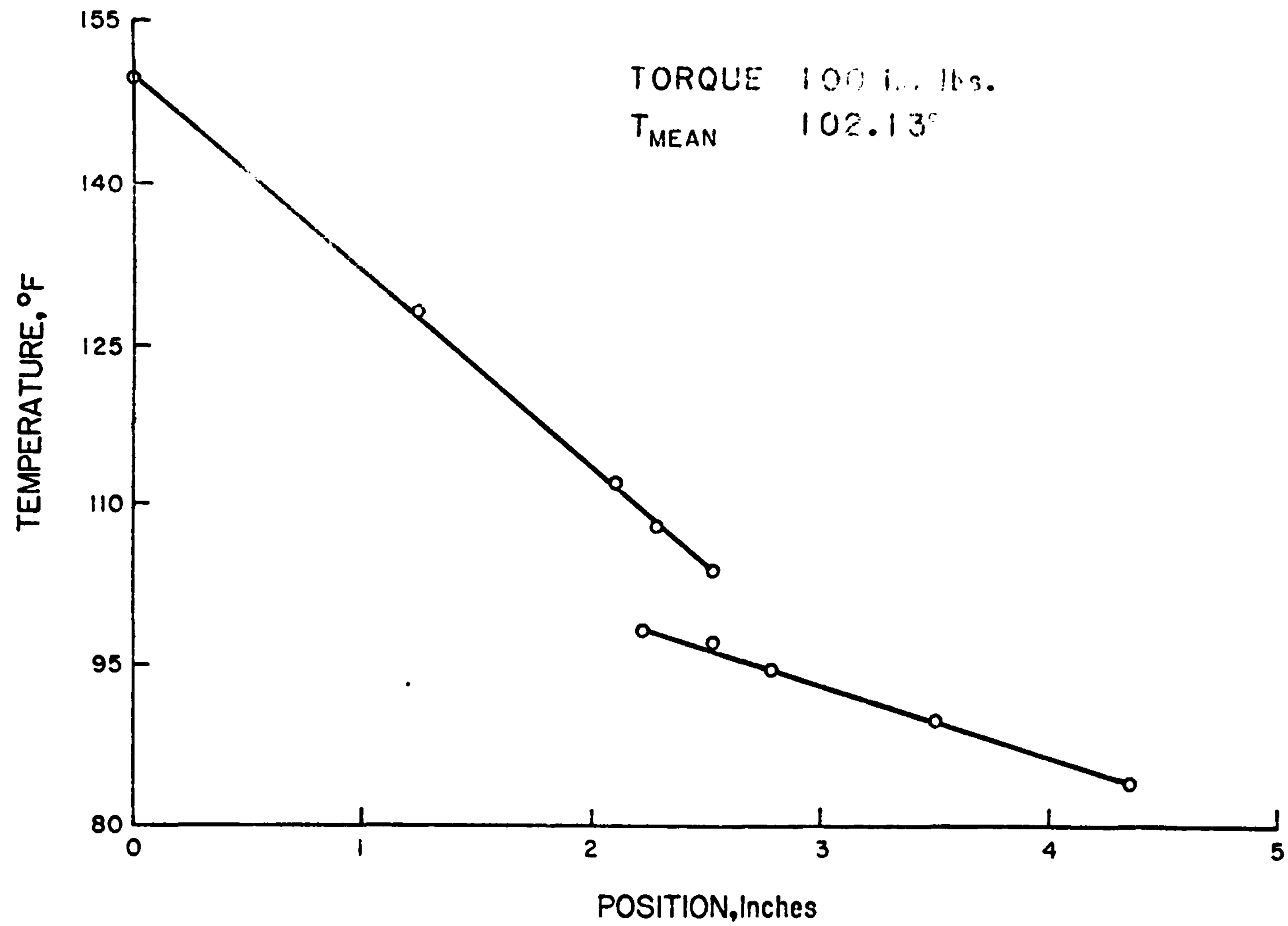

Figure 9. Temperature Distribution for: Torque = 100 in. lbs. and Mean Temperature = 102.13°

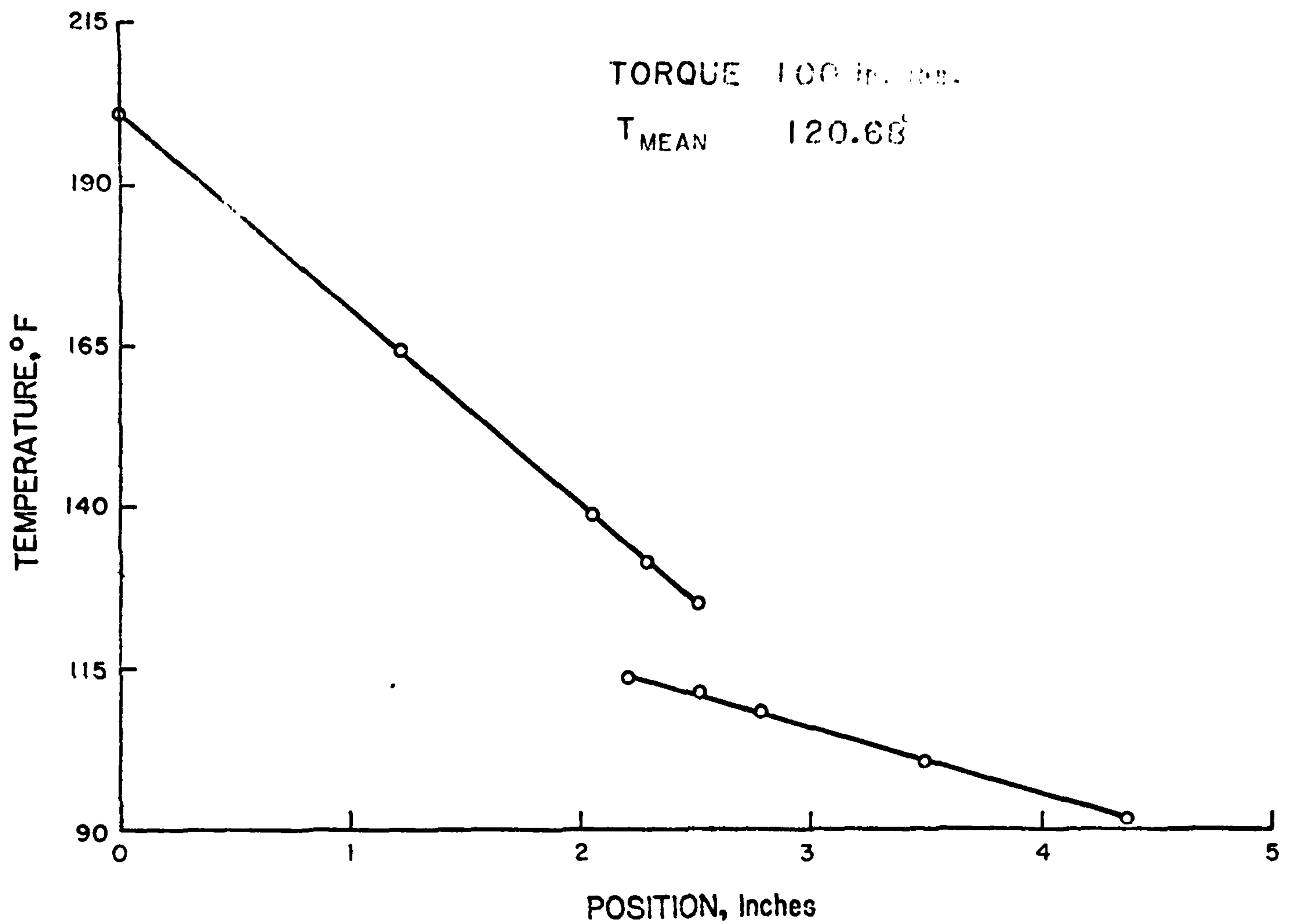

Figure 10. Temperature Distribution for: Torque = 100 in. lbs. and Mean Temperature = 120.68°F

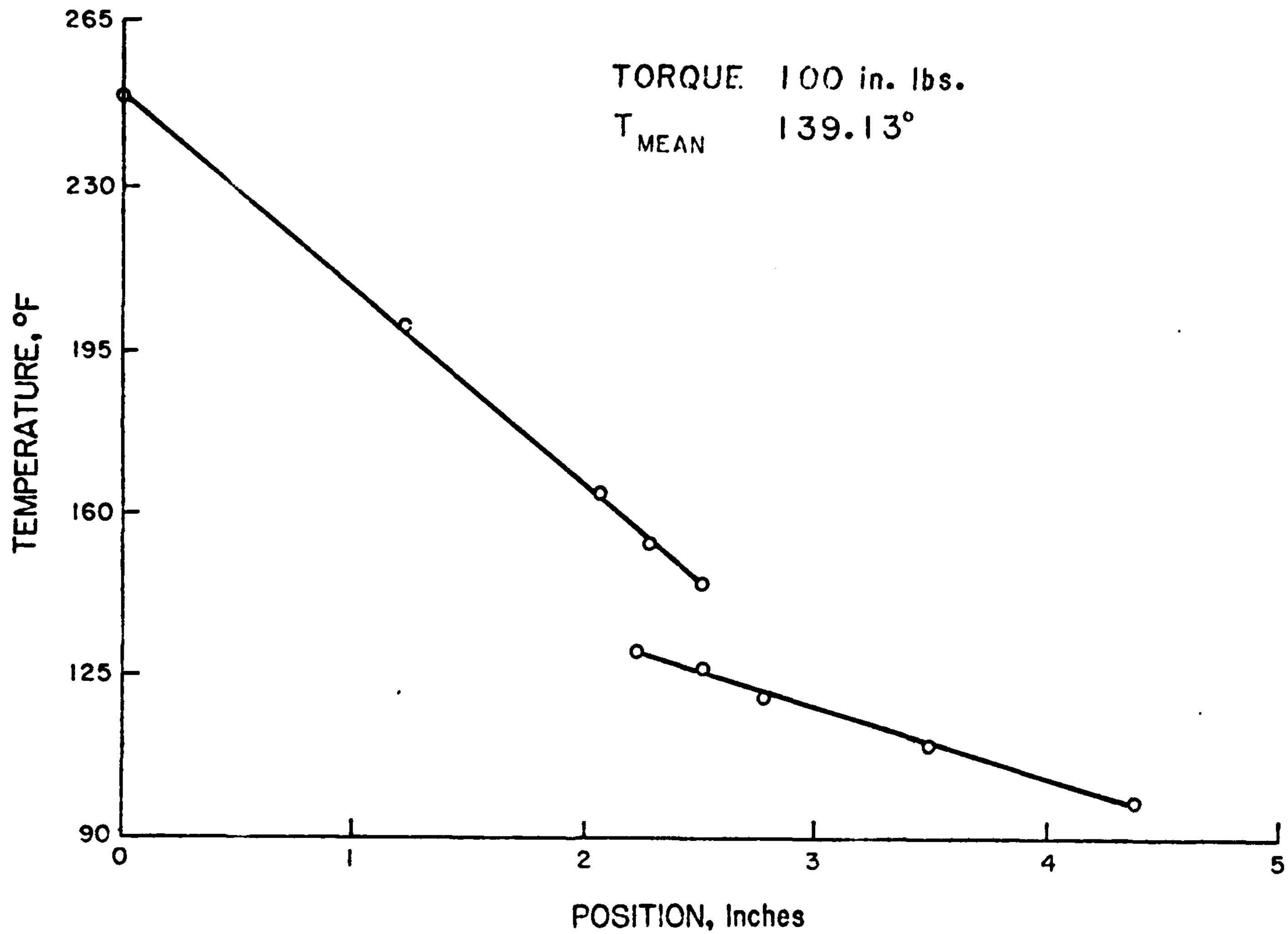

Figure 11. Temperature Distribution for: Torque = 100 in. lbs. and Mean Temperature = 139.13°

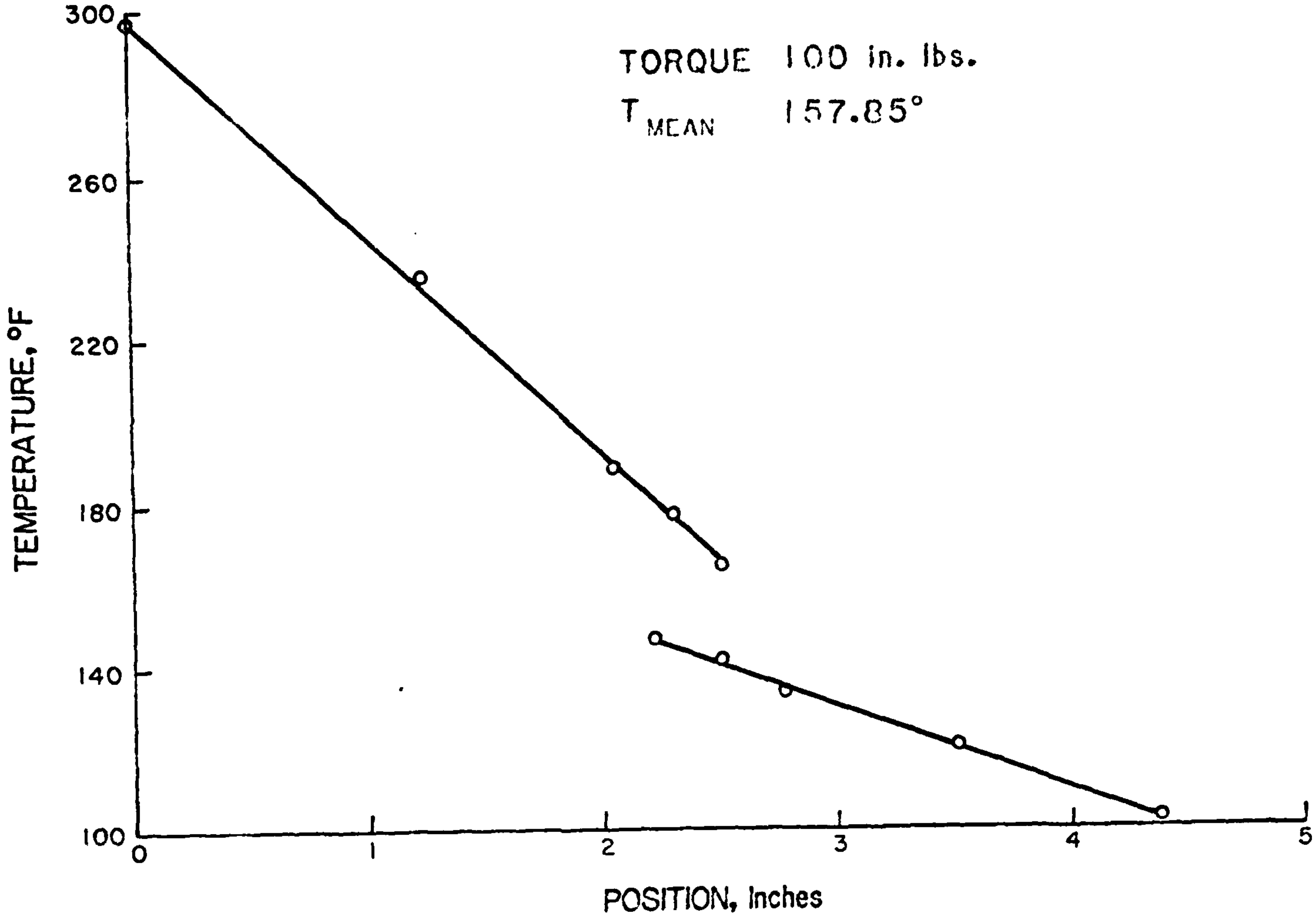

Figure 12. Temperature Distribution for: Torque = 100 in. lbs. and Mean Temperature = 157.85°F

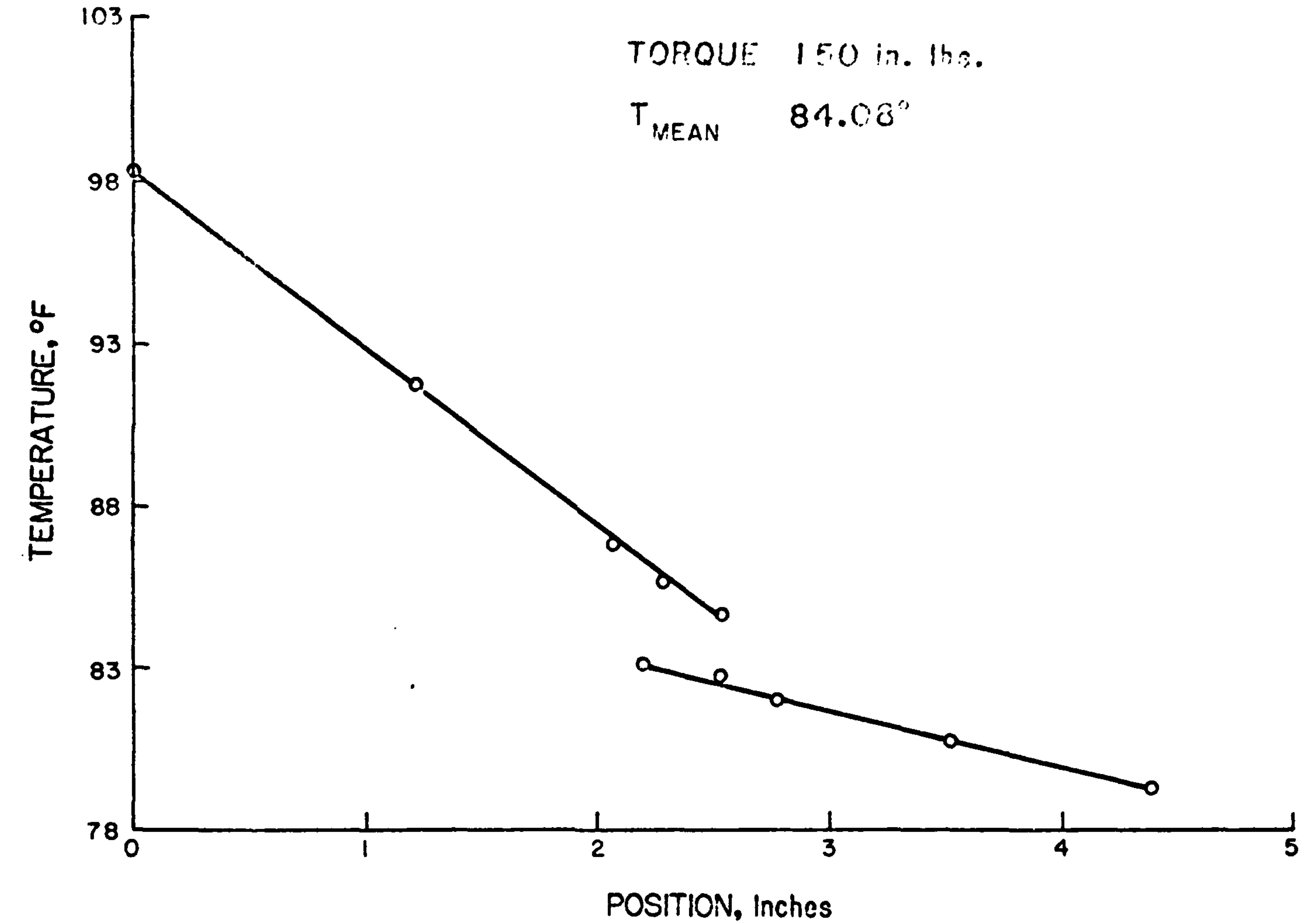

Figure 13. Temperature Distribution for: Torque = 150 in. lbs. and Mean Temperature = 84.08°F

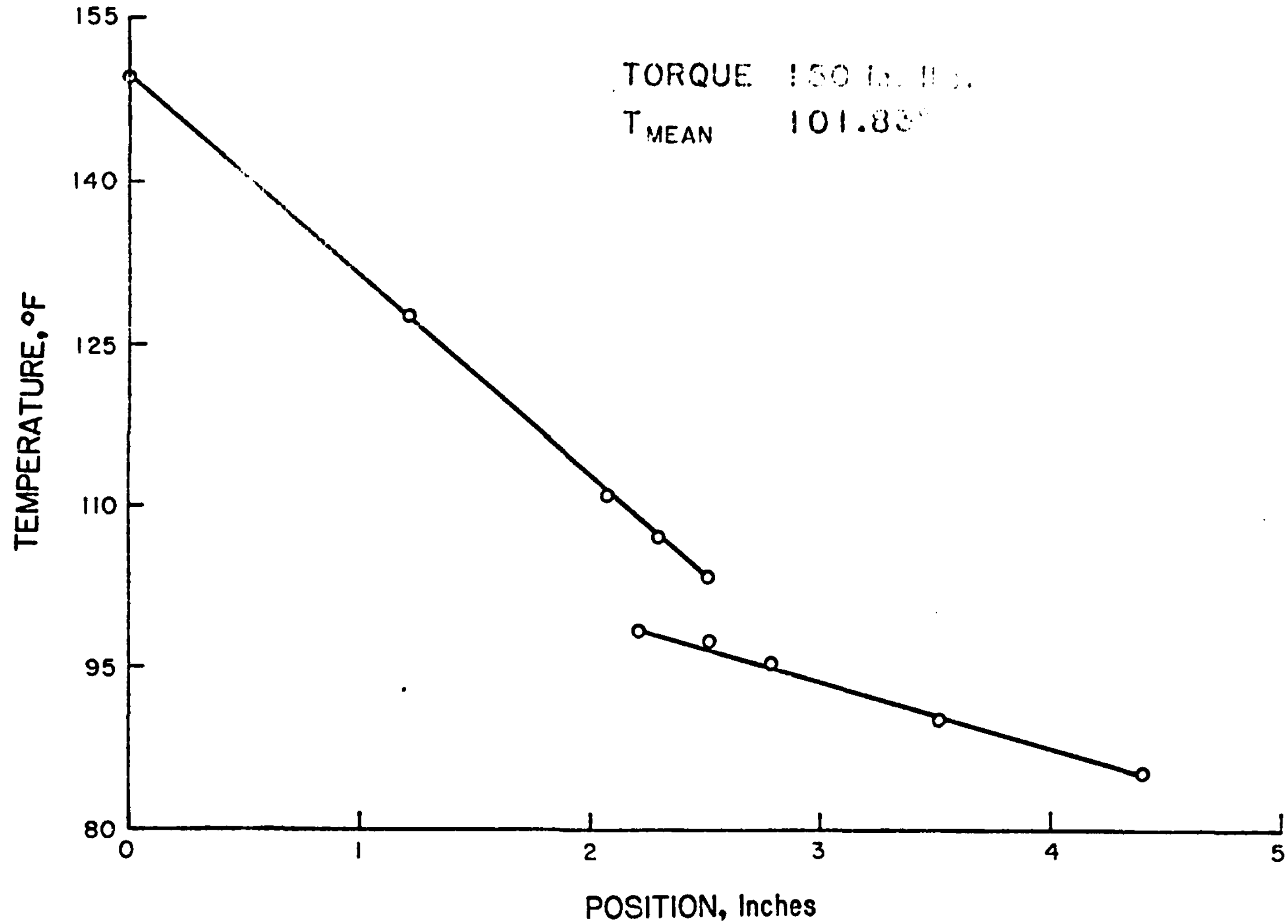

Figure 14. Temperature Distribution for: Torque = 150 in. lbs. and Mean Temperature = 101.83°F

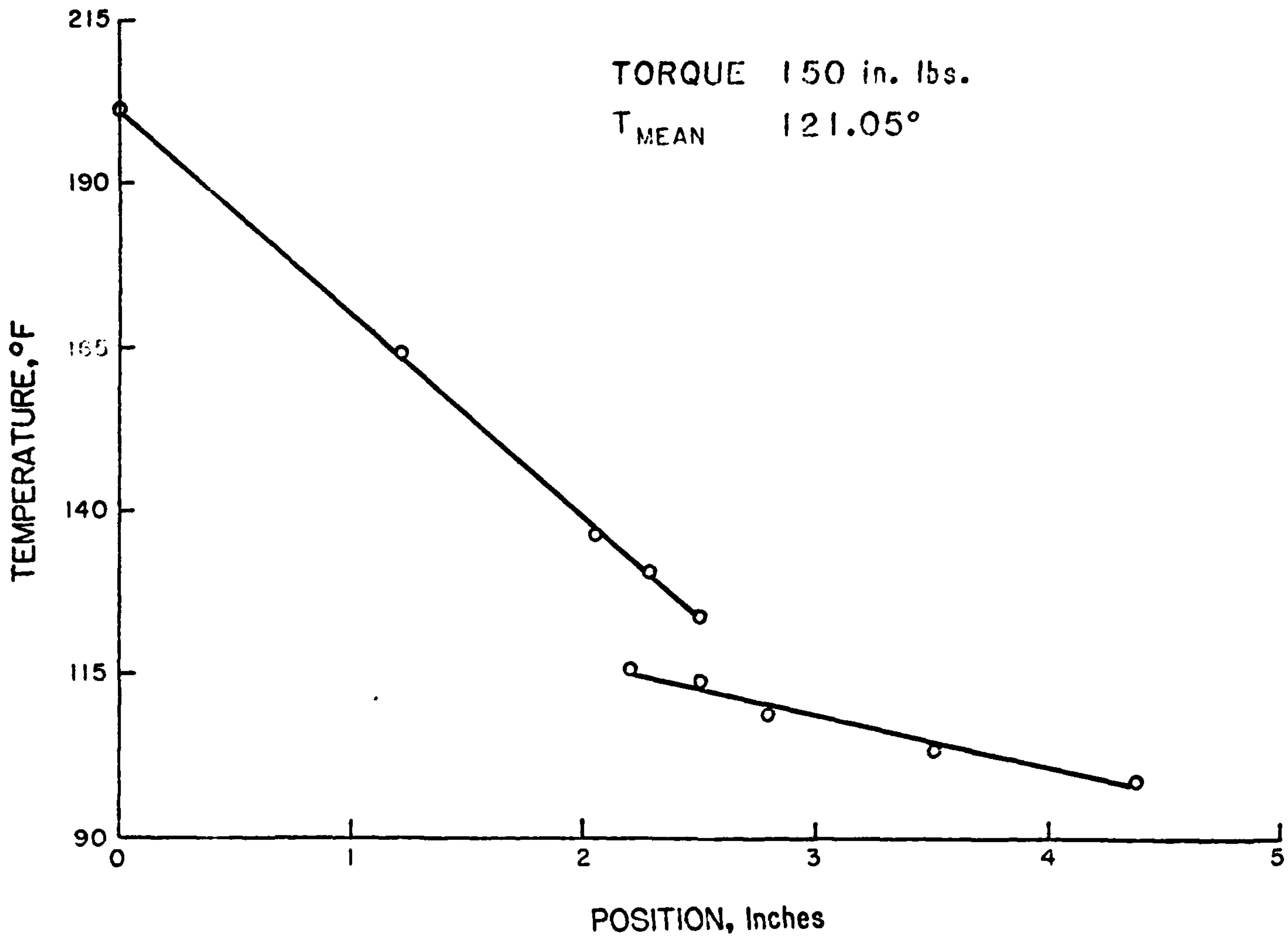

Figure 15. Temperature Distribution for: Torque = 150 in. lbs. and Mean Temperature = 121.05°F

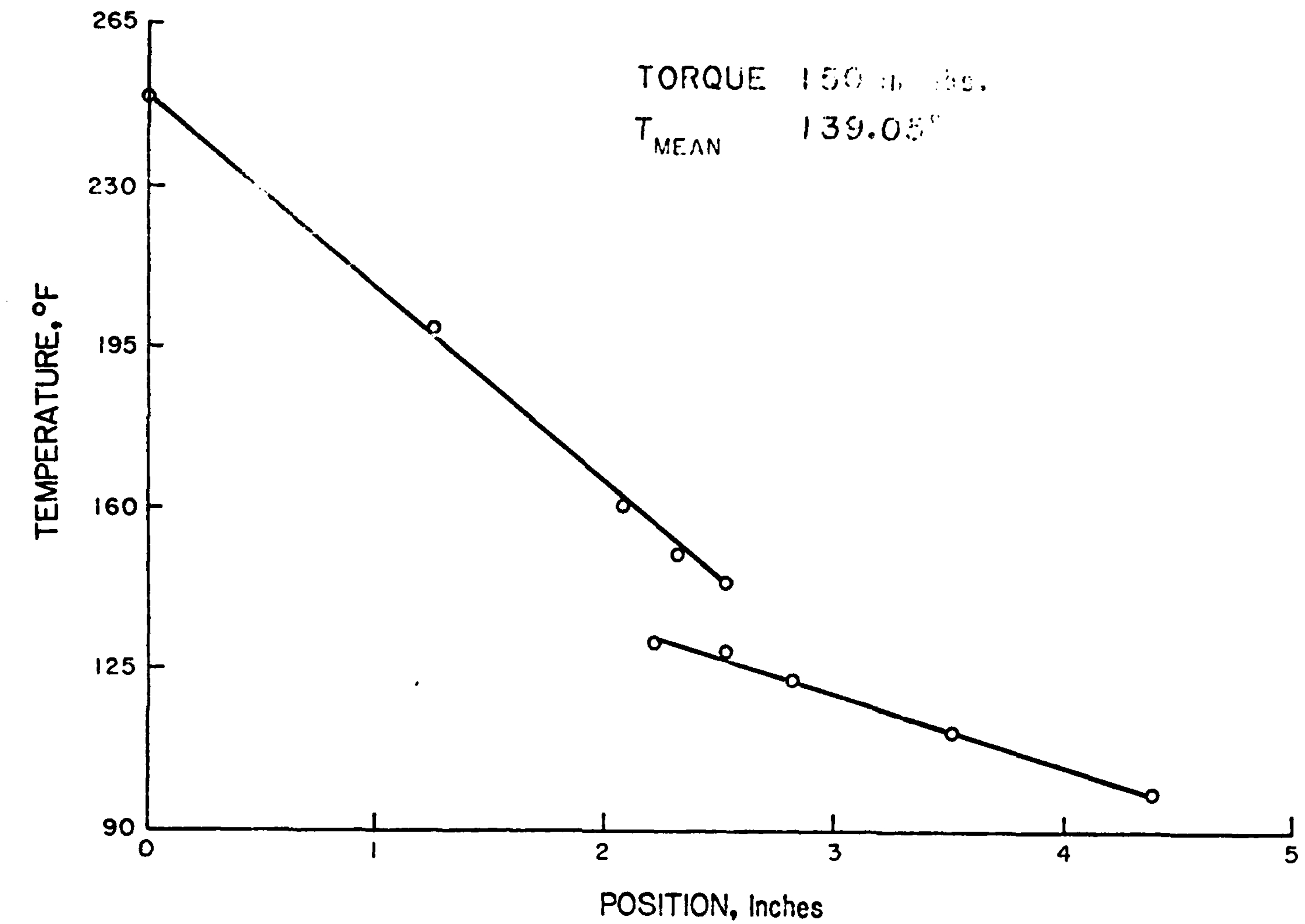

Figure 16. Temperature Distribution for: Torque = 150 in. lbs. and Mean Temperature = 139.05°F

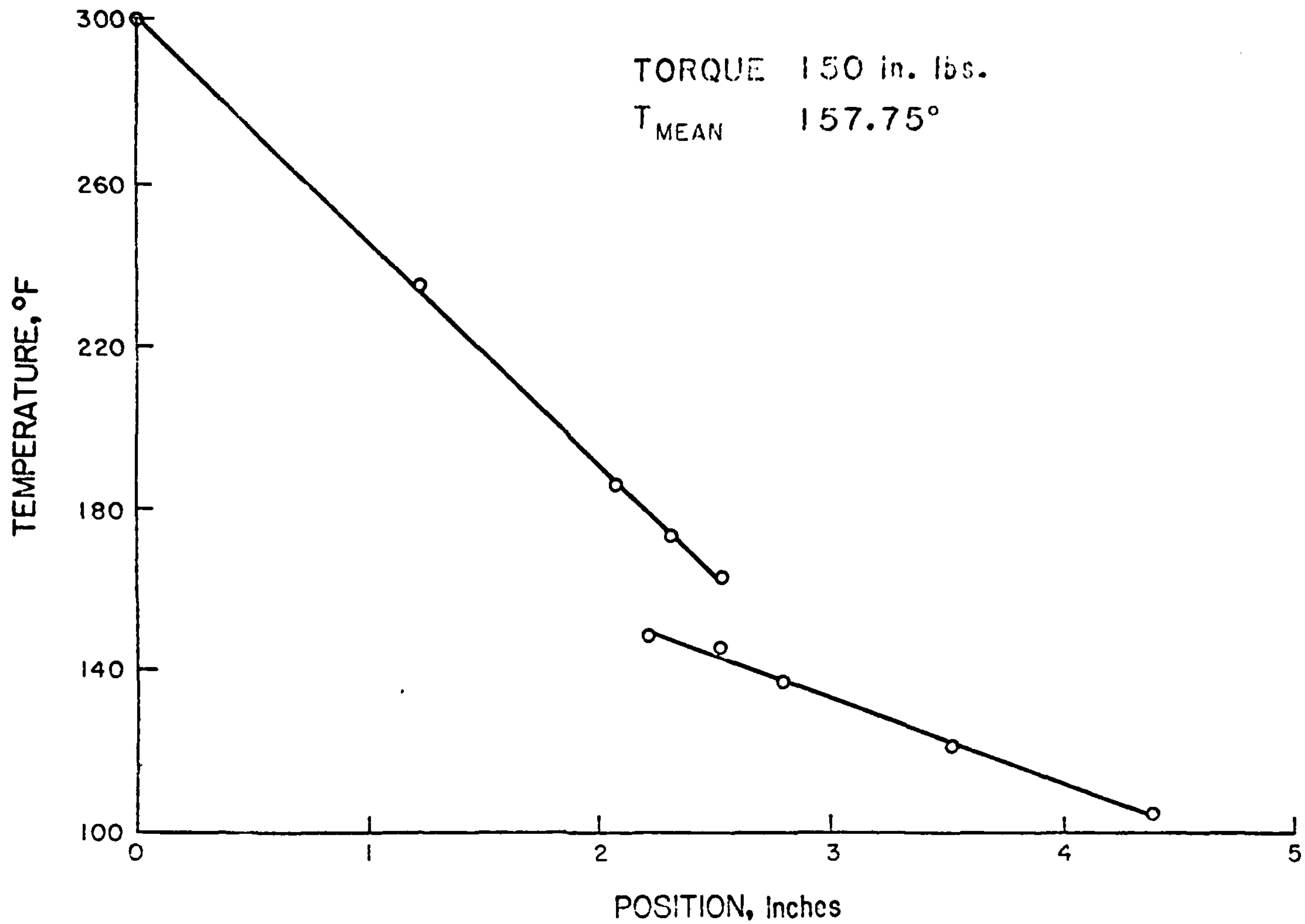

Figure 17. Temperature Distribution for: Torque = 150 in. lb. and Mean Temperature = 157.75°F

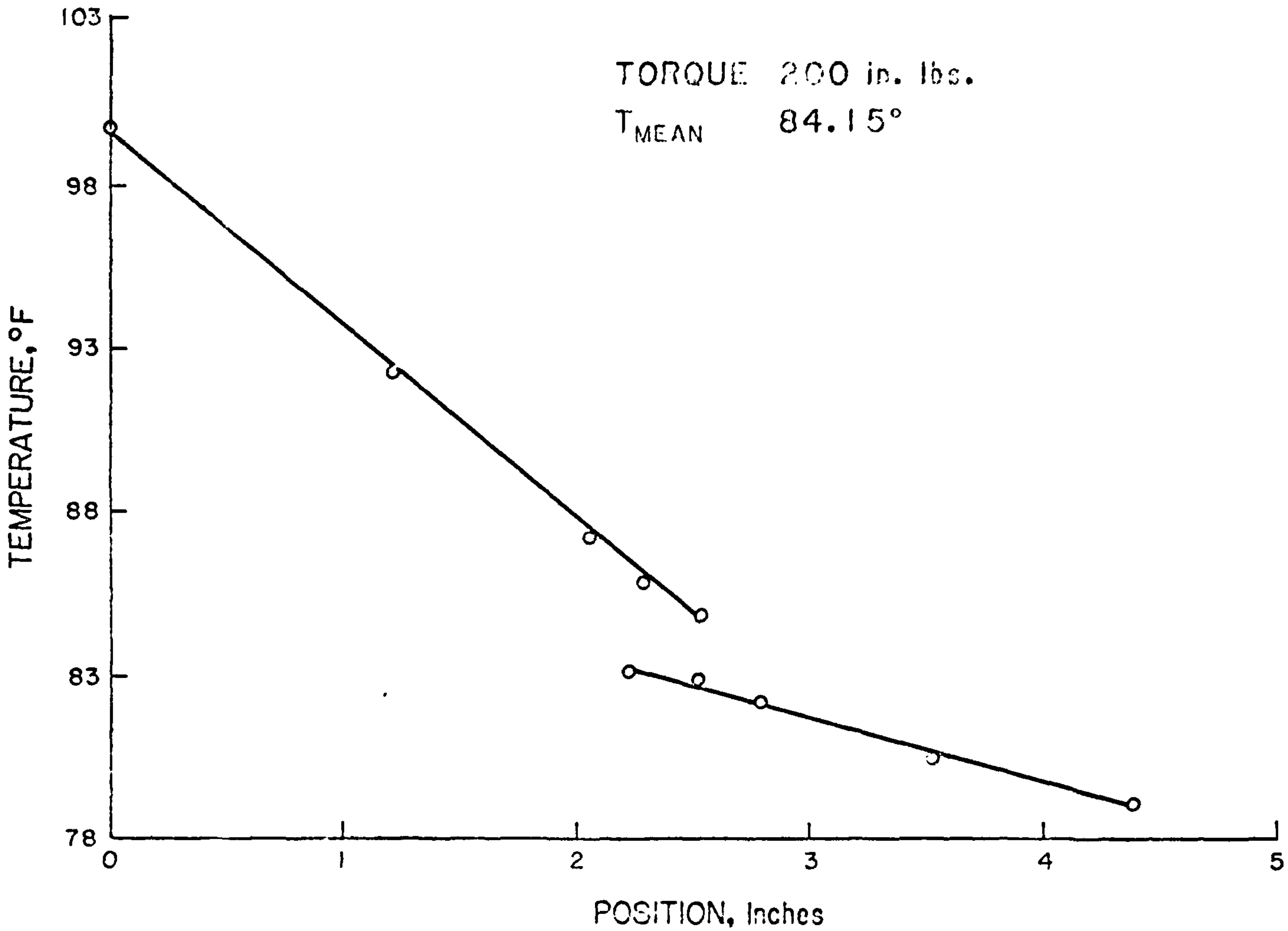

Figure 18. Temperature Distribution for: Torque = 200 in. lbs. and Mean Temperature = 84.15°F

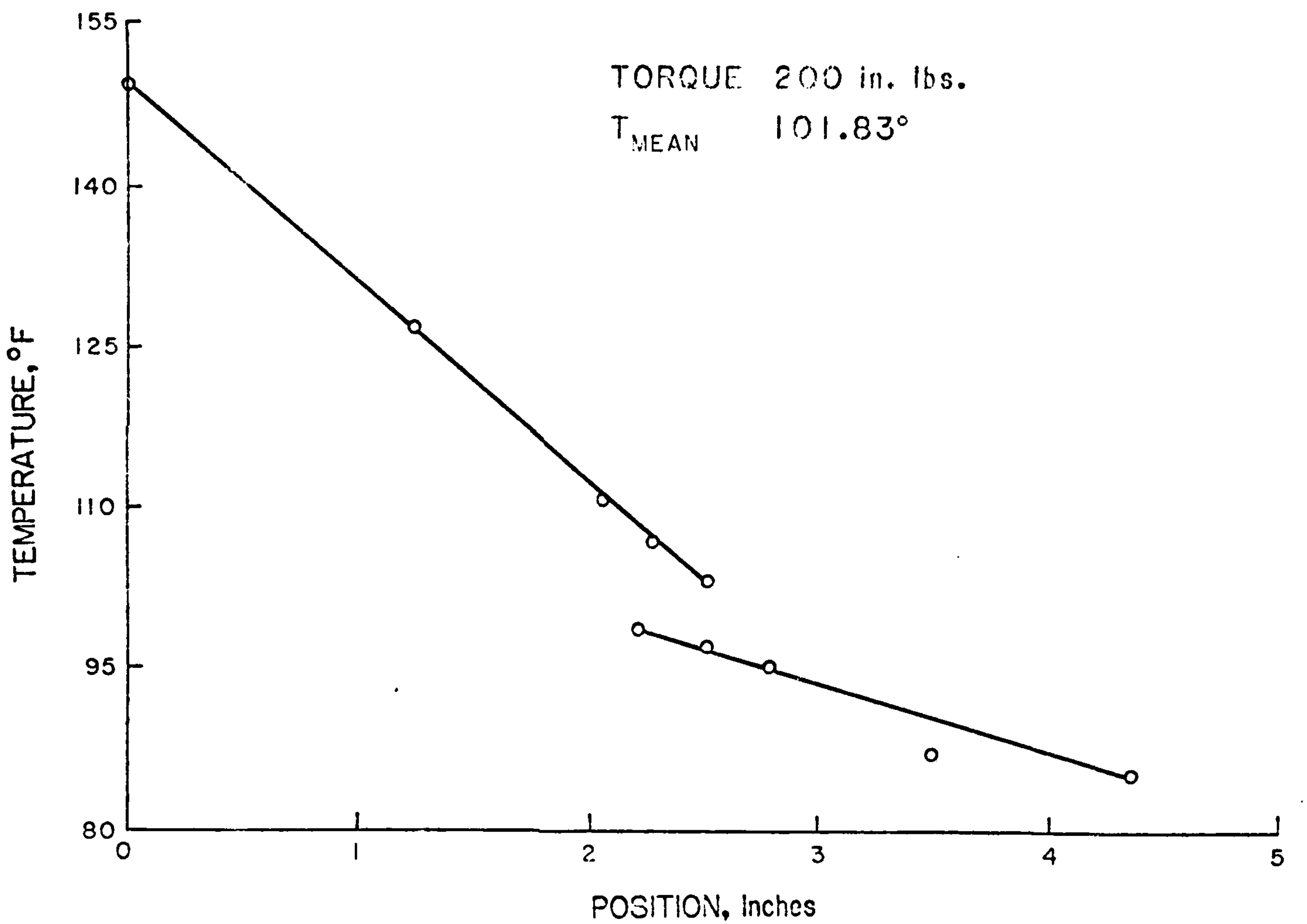

Figure 19. Temperature Distribution for: Torque = 200 in. lbs. and Mean Temperature = 101.83°F

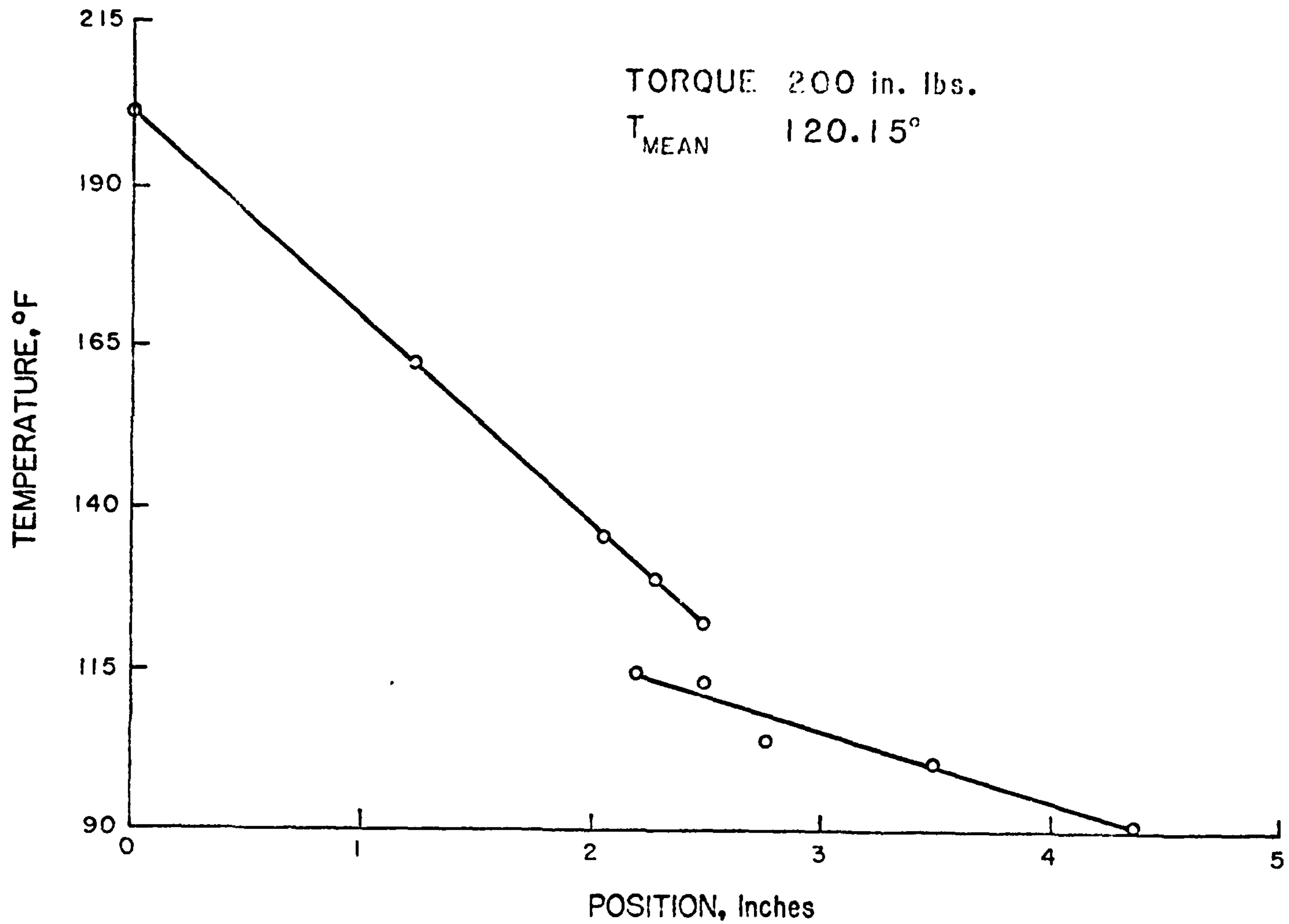

Figure 20. Temperature Distribution for: Torque = 200 in. lbs. and Mean Temperature = 120.15°F

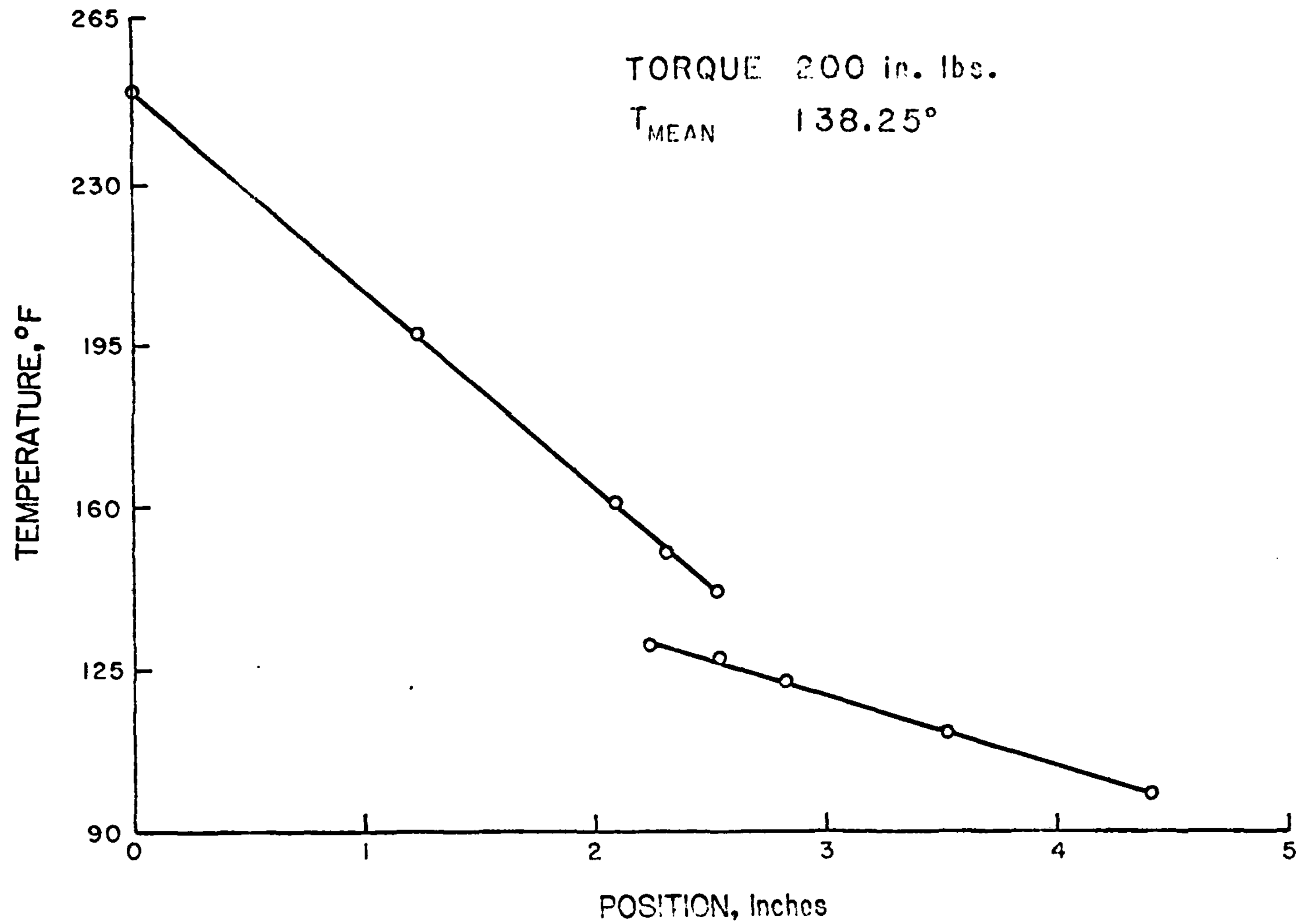

Figure 11. Temperature Distribution for: Torque = 200 in. lbs. and Mean Temperature = 138.25°F

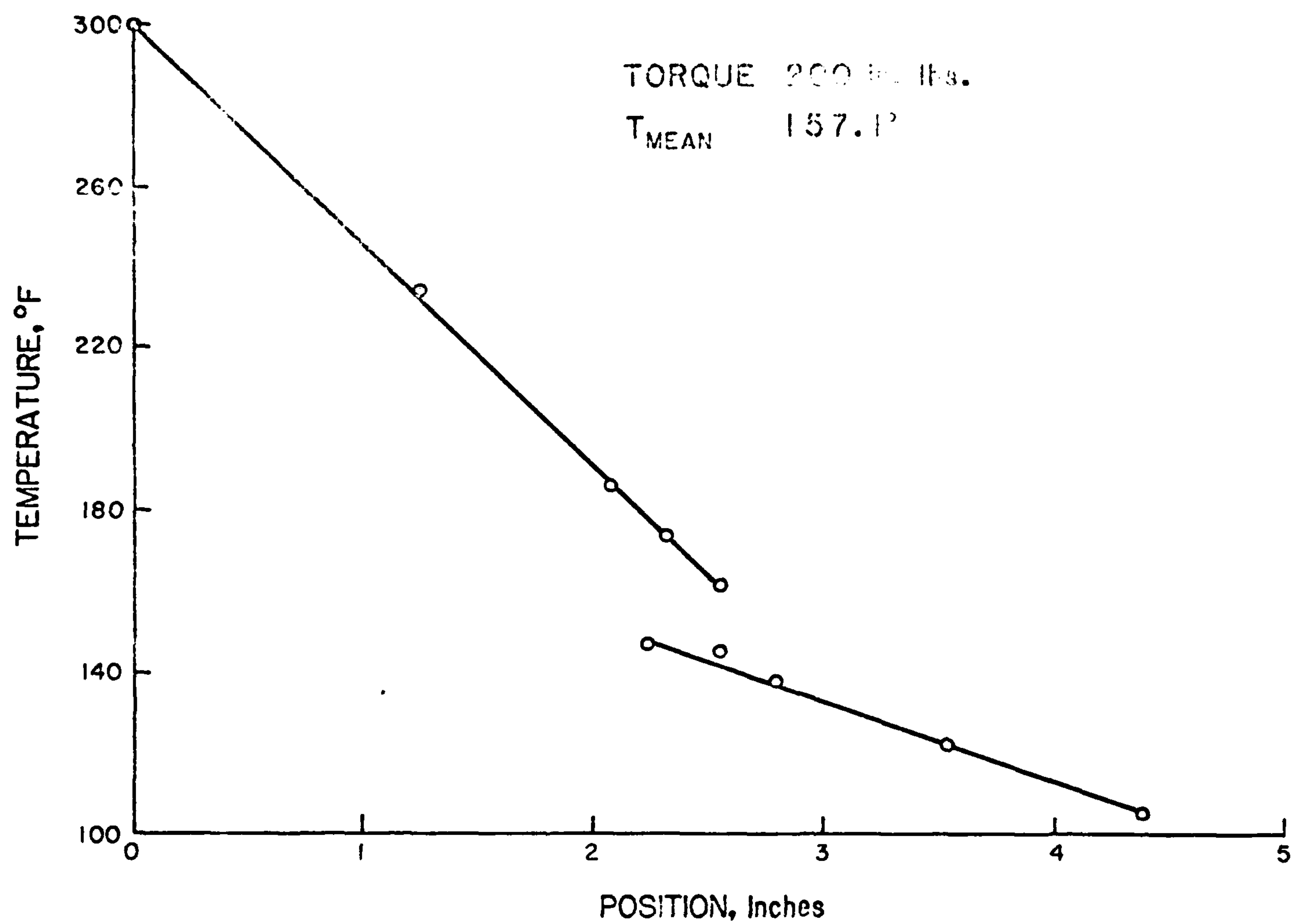

Figure 22. Temperature Distribution for: Torque = 200 in. lbs. and Mean Temperature = 157.1°F

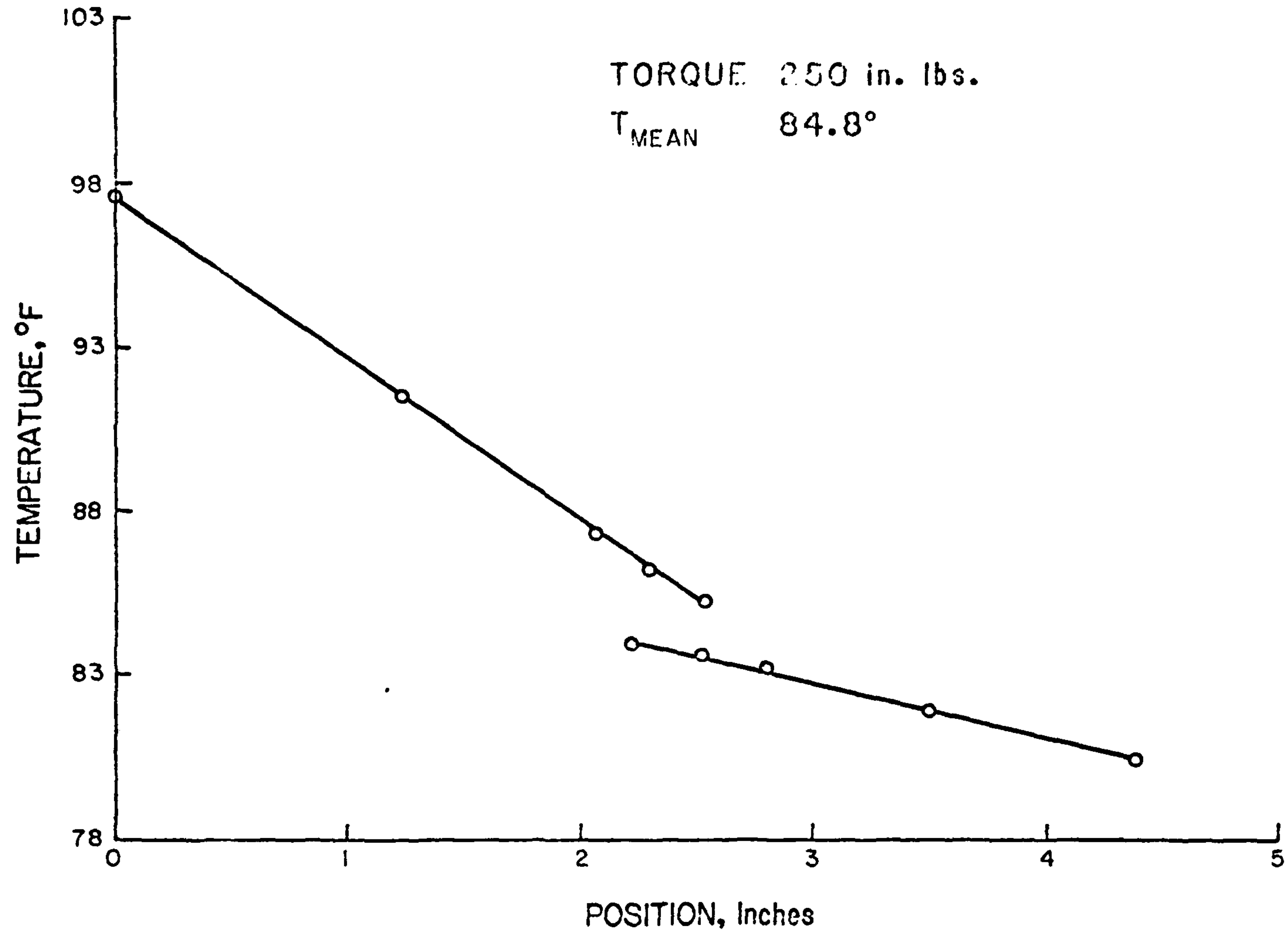

Figure 23. Temperature Distribution for: Torque = 250 in. lbs. and Mean Temperature = 84.8°F

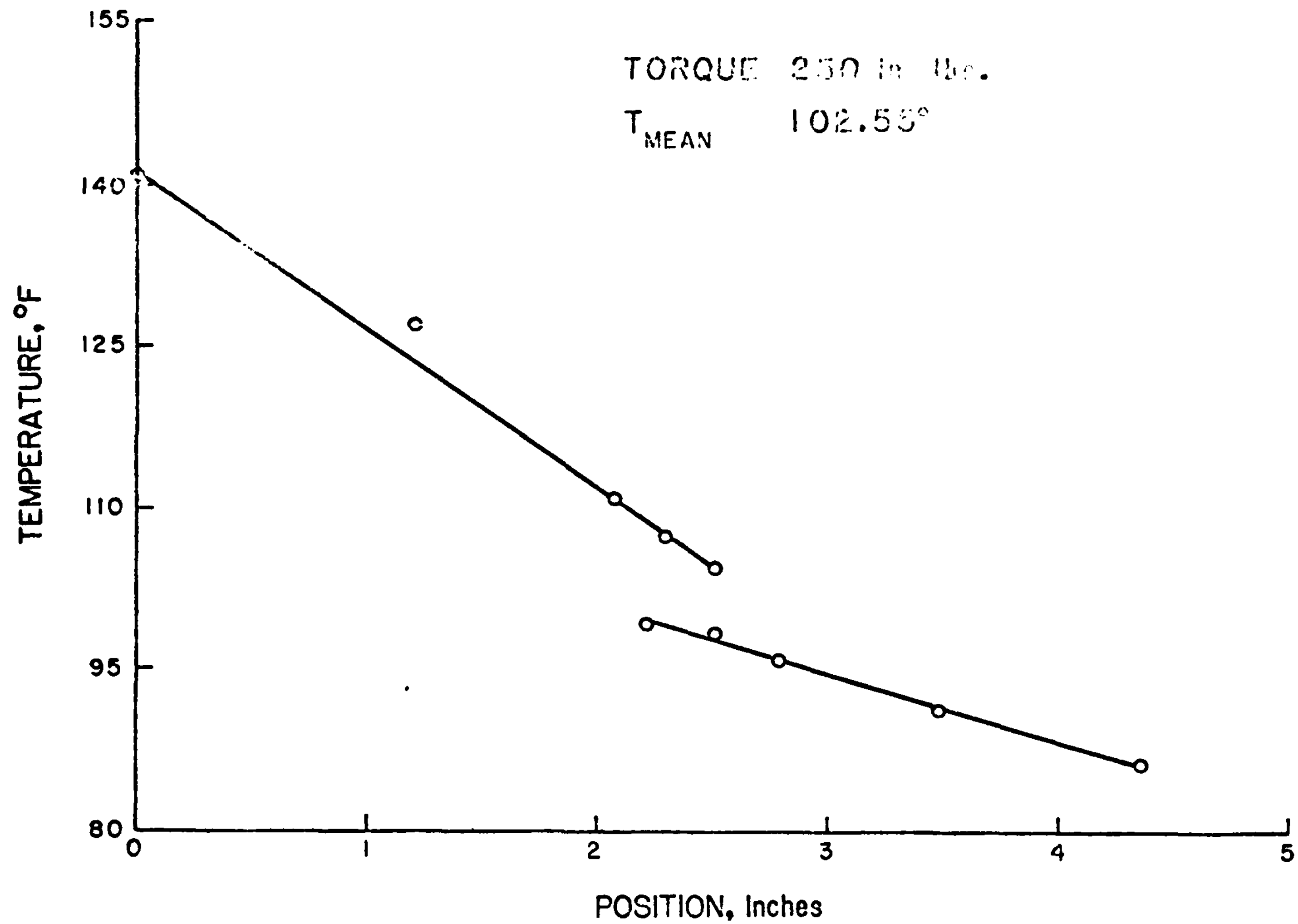

Figure 24. Temperature Distribution for: Torque = 250 in. lbs. and Mean Temperature 102.55°F

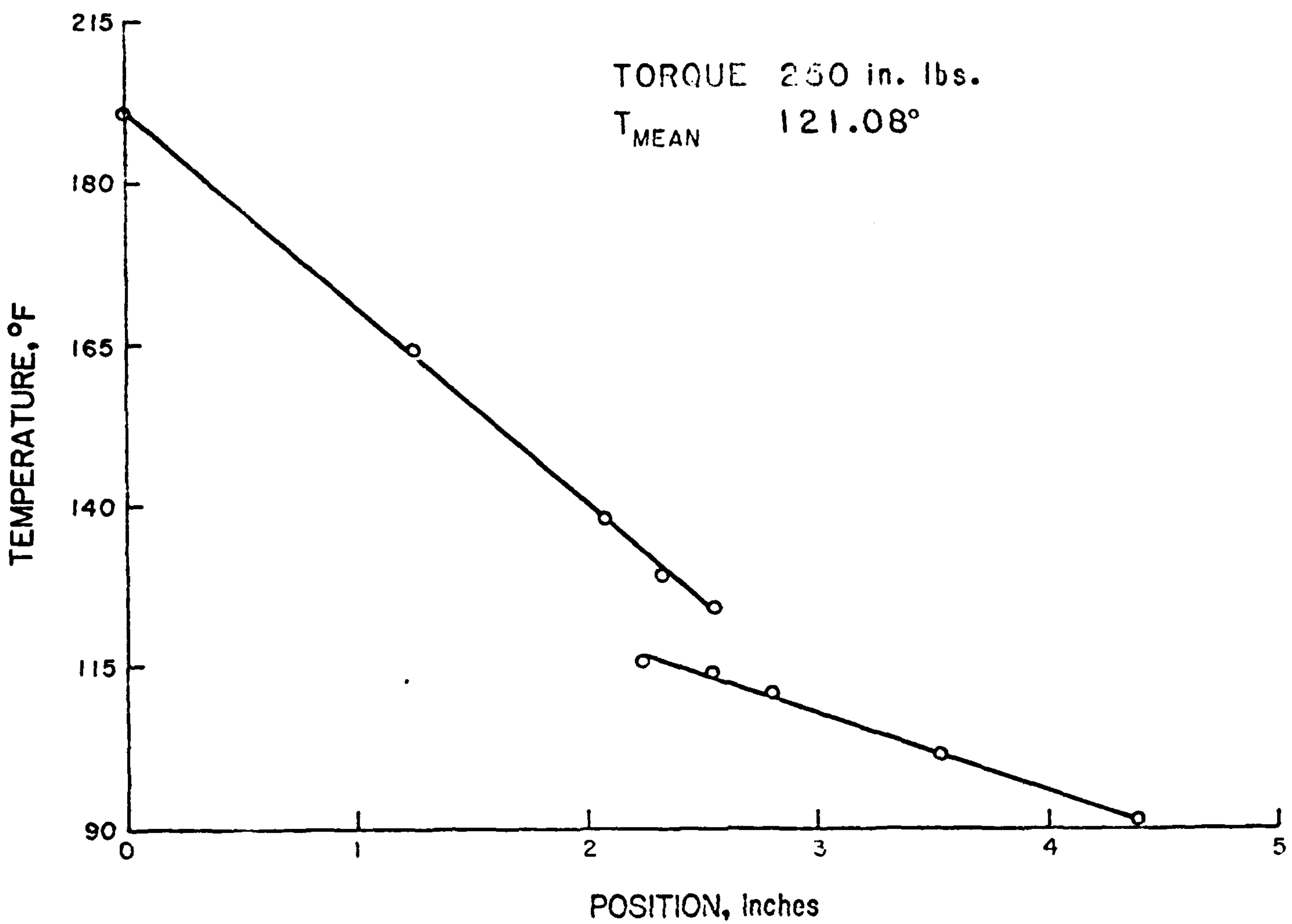

Figure 25. Temperature Distribution for: Torque = 250 in. lbs. and Mean Temperature = 121.08°F

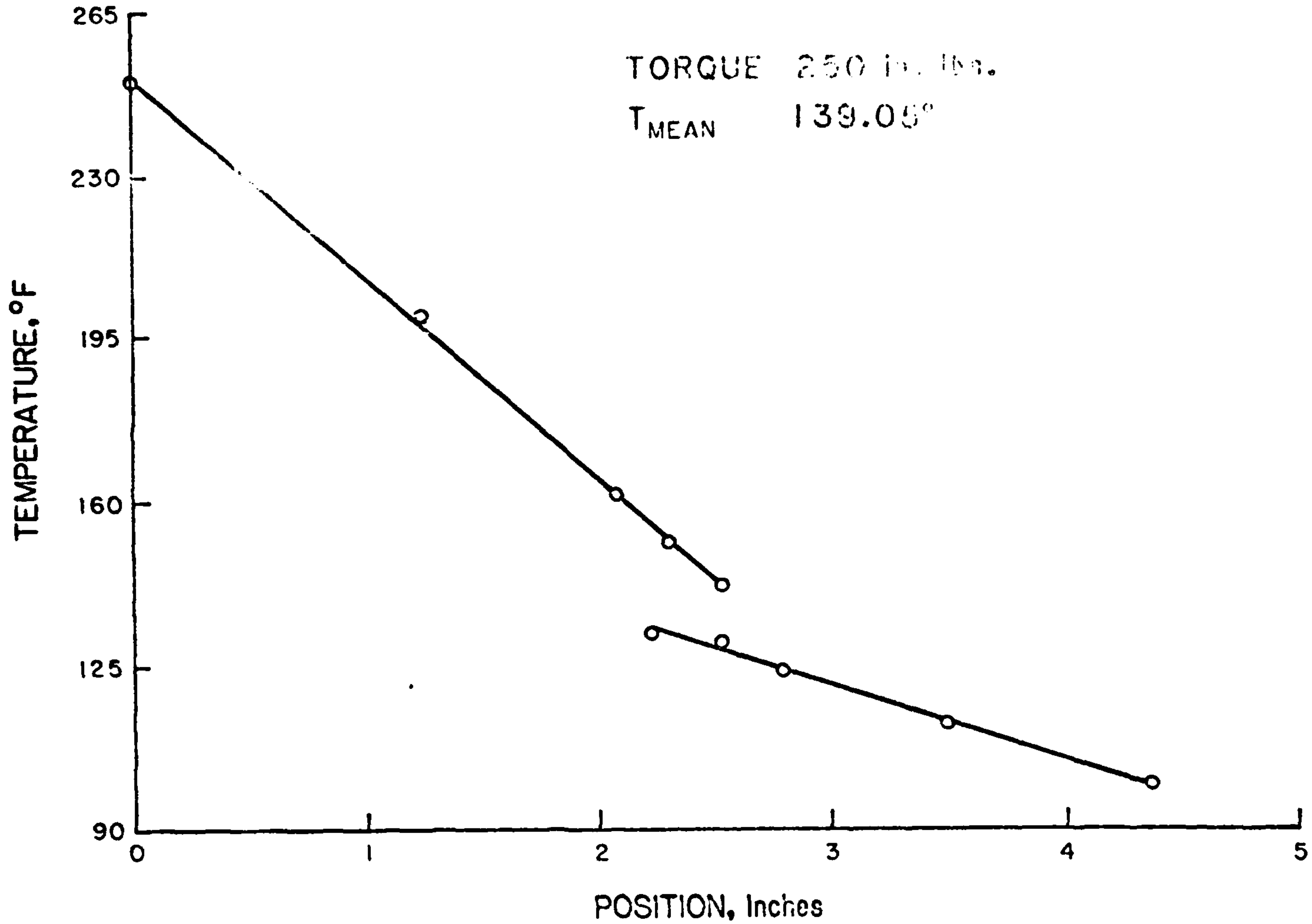

Figure 26. Temperature Distribution for: Torque = 250 in. lbs. and Mean Temperature = 139.05°F

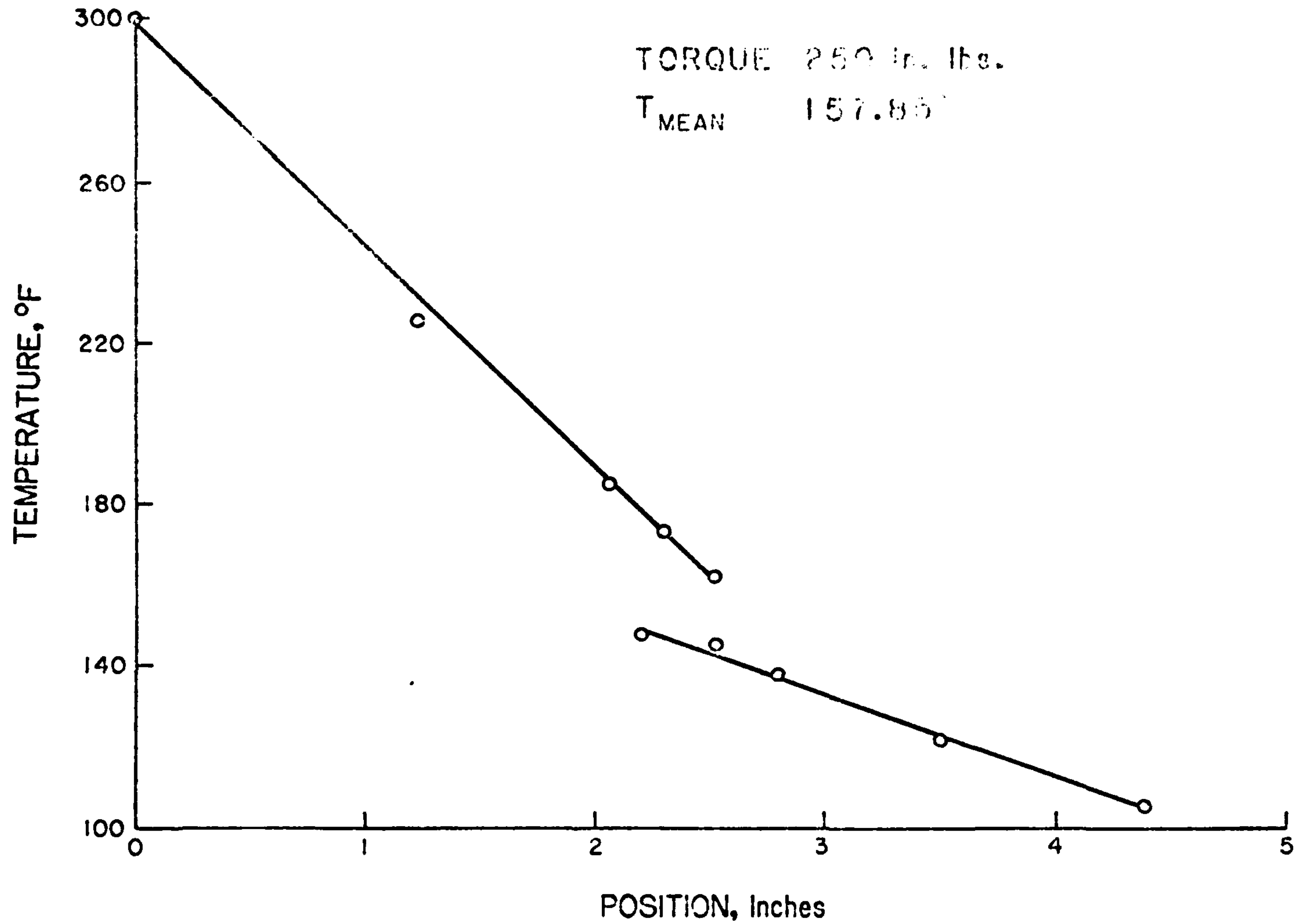

Figure 27. Temperature Distribution for: Torque = 250 in. lbs. and Mean Temperature = 157.85°F

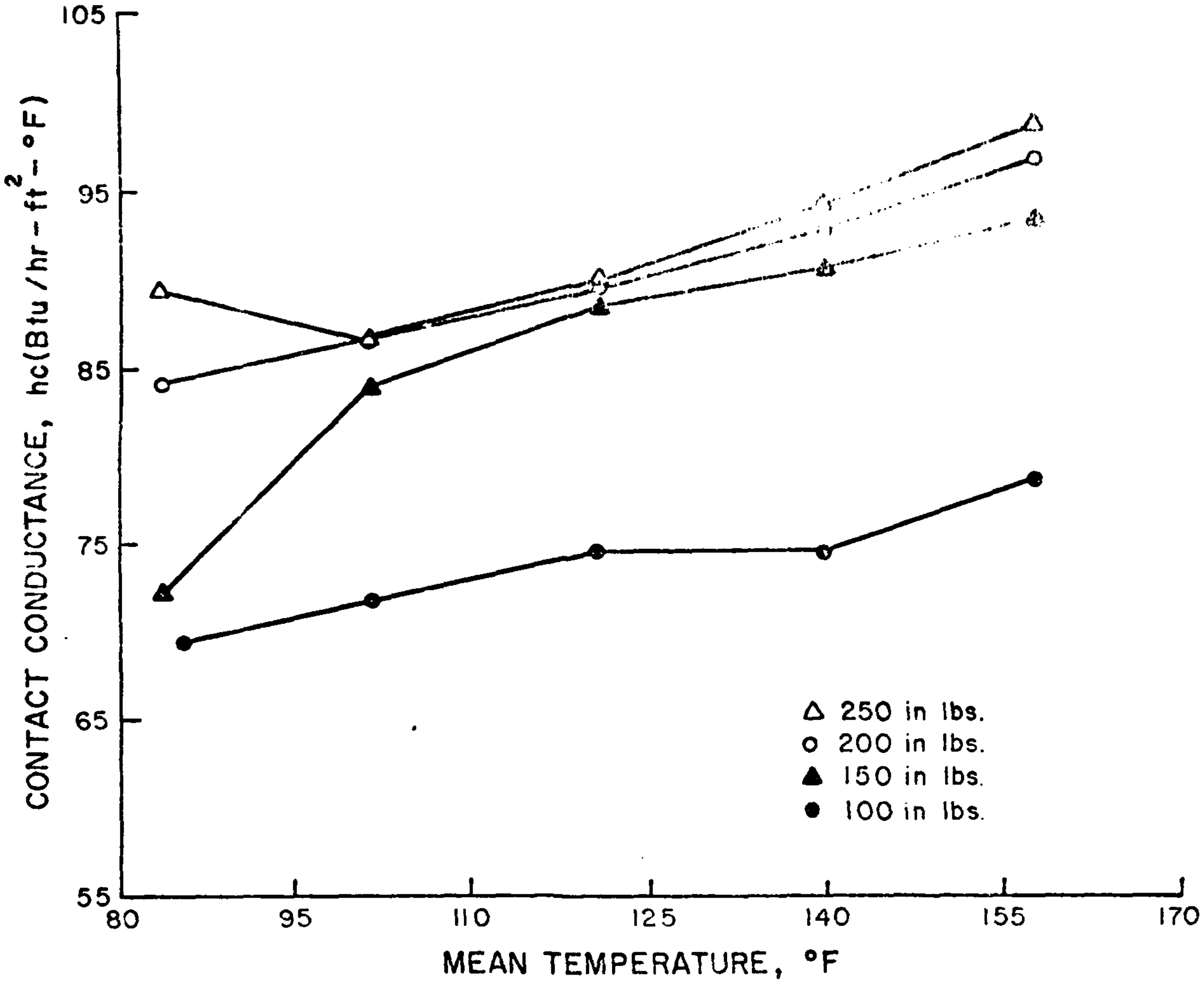

Figure 28. Contact Conductance as a Function of Torque and Mean Temperature