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DESIGN, DEVELOPMENT, FABRICATION, AND TESTING OF A SYNCHRONOUS CONDENSER FOR A HIGH-POWER THREE-PHASE TRACTION DRIVE

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16. Abstract

This report documents the synchronous machine, referred to as a synchronous condenser, which, in the tracked levitated research vehicle (TLRV), provides line commutation for the inverter and power factor correction for the linear induction motor. The machine also incorporates features permitting its use as a synchronous alternator or motor in a wide range of conventional and advanced ground transportation applications.

The machine provides a very high specific power density (1.7 kVA/lb) and voltage rating (7150 V, line-to-line, RMS), principally through the use of direct liquid cooling of both the stator and rotor windings and other elements of the machine (i.e., bearings, brushes, sliprings, etc.). Deionized water is used as the cooling liquid.

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PREFACE

This document is the historical technical record of the design, development, fabrication, and testing of a synchronous condenser prior to its installation in the tracked levitated research vehicle. Numerous photographs supplement the detailed textual descriptions to provide a clear visualization of this machine. Engineering assembly drawings are also included.

The program was accomplished under the sponsorship and guidance of the Office of Research and Development, Federal Railroad Administration, U.S. Department of Transportation, Mr. Matthew Guarino, Jr., Manager for Electrical Traction R&D.

Overall propulsion system program responsibility throughout the period of time covered by this report was vested in the Ground Transportation Group, headed by Mr. K. Chirgwin; and in the Electrical and Electromechanical Project, Chief Engineer, D. Moeller. Program guidance was provided by Mr. C. Weinstein, Program Manager; Mr. W. J. Hanlon, Program Administrator; and Mr. G. P. Kalman, Technical Manager. Significant technical contributors to the synchronous condenser work described herein were: Mr. T. E. Brown, Engineer-in-Charge; Mr. R. F. Grahl, Design and Development; Mr. F. B. McCarty, Electromagnetic Analysis; Mr. F. E. Faulkner, Thermal Analysis; and Dr. A. Hammoud, Stress and Dynamics Analysis.

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SECTION 1

INTRODUCTION

This report documents the design, development, fabrication, and testing of a wound-field, nonsalient-pole synchronous machine (hereinafter called a synchronous condenser) built to operate in the tracked levitated research vehicle (TLRV) propulsion system. The work was sponsored by the Office of Research and Development, Federal Railroad Administration, U.S. Department of Transportation, Washington, DC.

The synchronous condenser electrically parallels the linear induction motor and power conditioning unit, propulsion components of the TLRV, and is operated as an overexcited synchronous motor to provide reactive power for (1) line commutation of the power conditioning unit inverter thyristors, and (2) power factor correction of the LIM. The overall TLRV propulsion system has been documented(1)* for DOT by AiResearch.

The TLRV synchronous condenser is similar in physical size and speed rating to a wound-field, nonsalient-pole synchronous alternator developed by AiResearch for a previously produced ground transportation vehicle, the linear induction motor research vehicle (LIMRV). Detailed documentation(2) is available. The LIMRV was delivered to the DOT Transportation Test Center, Pueblo, Colorado, in early 1971, and has undergone extensive testing since that time.

Table 1-1 compares major characteristics of the TLRV condenser and the LIMRV alternator. While the LIMRV alternator is extremely lightweight and compact for its rating, it is obvious that the TLRV synchronous condenser reflects an even more significant improvement in power-to-weight ratio.

*Numbers in parentheses designate References at end of report.

The TLRV machine provides high-voltage capability with very low weight. This goal was met by incorporating direct water cooling of stator and rotor windings, and all adjunctive machine elements (bearings, brushes, sliprings, etc.).

TABLE 1-1

MAJOR CHARACTERISTICS, TLRV CONDENSER AND LIMRV ALTERNATOR

	TLRV Condenser	LIMRV Alternator
Rated speed, rpm	4950 (4-pole)	5200 (4-pole)
Rated power	7 MVA continuous, 10 MVA overload (0 power factor, 165 Hz)	3 MVA (0.6 power factor, 173 Hz)
Voltage (line-to-line), VRMS	7150	1000
Total weight, lb	4202	3600
Power density, kVA/lb	1.7 at continuous power rating 2.4 at overload power rating	0.8
Rotor diameter, in.	21.46	20.0
Mounting	Vertical	Horizontal
Cooling	Direct water-cooled	Forced air-cooled

SECTION 2

SUMMARY

The final design configuration for the synchronous condenser was a 4-pole, 3-phase, 4-wire, water-cooled, nonsalient-pole, wound-field synchronous machine with damper winding, rated at 7 MVAR continuous duty at 560 amp, 4950 rpm, and 165 Hz.

The primary design goal was an overall TLRV propulsion system with an acceptable vehicle performance factor.

To meet these objectives required the highest practical rotor speed, combined with reliable dielectric, mechanical, and temperature capabilities. To assure machine compatibility with the temperature requirements, a very effective cooling system was devised; deionized water as the coolant was pumped under relatively high pressure through the entire machine, including the rotor, bearings, brushes, and sliprings.

The design and fabrication of such a machine presented many engineering challenges in the application of materials. Where material information was nonexistent, tests were conducted to substantiate material integrity and adaptability.

The machine successfully demonstrated conformance to the design criteria at the AiResearch test facility, Torrance, California.

Upon completion of component testing, the machine was shipped to the DOT Transportation Test Center, Pueblo, Colorado, for installation in the TLRV and subsequent system checkout, test, and evaluation.

SECTION 3

SYNCHRONOUS CONDENSER CONCEPT

DESIGN REQUIREMENTS

Table 3-1 lists the major synchronous condenser (SC) design criteria, which were established from initial TLRV system studies.

As previously stated, the SC electrically parallels the LIM and the power conditioning unit (PCU), and is operated as an overexcited synchronous motor to: (1) line commutate the PCU inverter thyristors by providing a sinusoidal back-emf and leading reactive current, and (2) correct low power factor of the LIM over the range of operating frequency and thrust.

Two synchronous condensers are utilized in a full TLRV propulsion system, one for each LIM. The stator is four-wire wye-connected with neutral grounded through a high resistance. The rotor field is a conventional brush/slipring-fed series (four nonsalient poles) connection. The machine is operated at essentially constant flux density (fixed voltage per cycle) down to zero frequency and speed. The rotor is capable of safe overspeed operation to 6000 rpm.

The SC is completely water cooled, including both rotor field and damper windings, stator windings, bearings, seals, sliprings, brushes, and field protection diode. In addition, provisions for water cooling of the stator core and lower end-bell OD are also incorporated. Relatively high temperatures (up to 350°F) and high pressures (up to 450 psi) are utilized. These severe operating constraints required innovative design approaches with respect to electrical insulation, sealing, and deionized water connections.

The machine rating of 7 MVA (continuous) is the sum of the reactive power for the LIM and that required for the inverter, including phase-back and overlap considerations.

TABLE 3-1

SYNCHRONOUS CONDENSER DESIGN CRITERIA

Type	Nonsalient-pole, wound-field synchronous, with damper winding, in parallel with LIM across inverter output terminals		
Coolant	Deionized water		
Rating	Output, MVAR	7	10
	Duty	Continuous	90 sec
	Output current, amp	560	809
Speed/frequency	4950 rpm/165 Hz		
Temperature/class	356°F/IEEE Class H		
Voltage	7150 VRMS (L-L), 3ph, 4-wire (wye-connected), neutral resistance grounded		
Reactance	X (negative sequence) not to exceed 0.32 per unit (unsaturated)		
Losses	Total full load (continuous duty) losses not to exceed 500 kW		
Field power	2670 Adc at 127 Vdc (max.), 90-sec duty		
Mounting	Vertical		
Weight	Minimum		
SC/power supply relationship	Power supply is grounded to vehicle body, which is floating. The emf of the SC and the power supply voltage can be additive through the PCU, (providing an equivalent 15,900 V, line-to-line, steady-state maximum operating value of the machine; this excludes transient voltage effects, resulting in a line-to-ground voltage of approximate 8900 V)		
Excitation	From static phase delay rectifier/brush/slipring unit		
Overspeed capability	125 percent		
Field protection	Freewheeling diode		

DESIGN IMPLEMENTATION

The SC assembly (shown in Figure 3-1 after completion of component testing) was designed to meet the technical criteria specified in Table 3-1. The primary goals are: (1) low weight and volume at very high power rating, (2) combined high-voltage and high-temperature capability, and (3) minimum losses proportioned for ease of cooling.

Meeting these objectives required the use of the highest practical rotor speed, development of reliable high-dielectric, mechanical, and temperature capability, isulation systems for rotor and stator windings, and the use of extremely effective cooling techniques.

A general relationship for the machine weight, rating, and electromagnetic and mechanical factors may be expressed as:

$$\text{Weight} \quad \alpha \left(\frac{C \cdot kVA(R)}{(BQ\eta)}\right)^{0.75}$$

where
- C = a constant (relating the winding and magnetic form and distribution factors and units)
- kVA(R) = the rating (in this case specified by the propulsion system reactive power requirements)
- B = flux density (magnetic loading of the machine)
- Q = current density (electrical loading of the machine)
- η = speed (a measure of mechanical capability of the machine)

Very generally, the values for B, Q, and η are limited by the inherent capabilities of the materials used and how effectively they are handled and modified in the design (e.g., the techniques used to minimize losses, reduce heating effects, and achieve reliable and efficient electrical insulation for

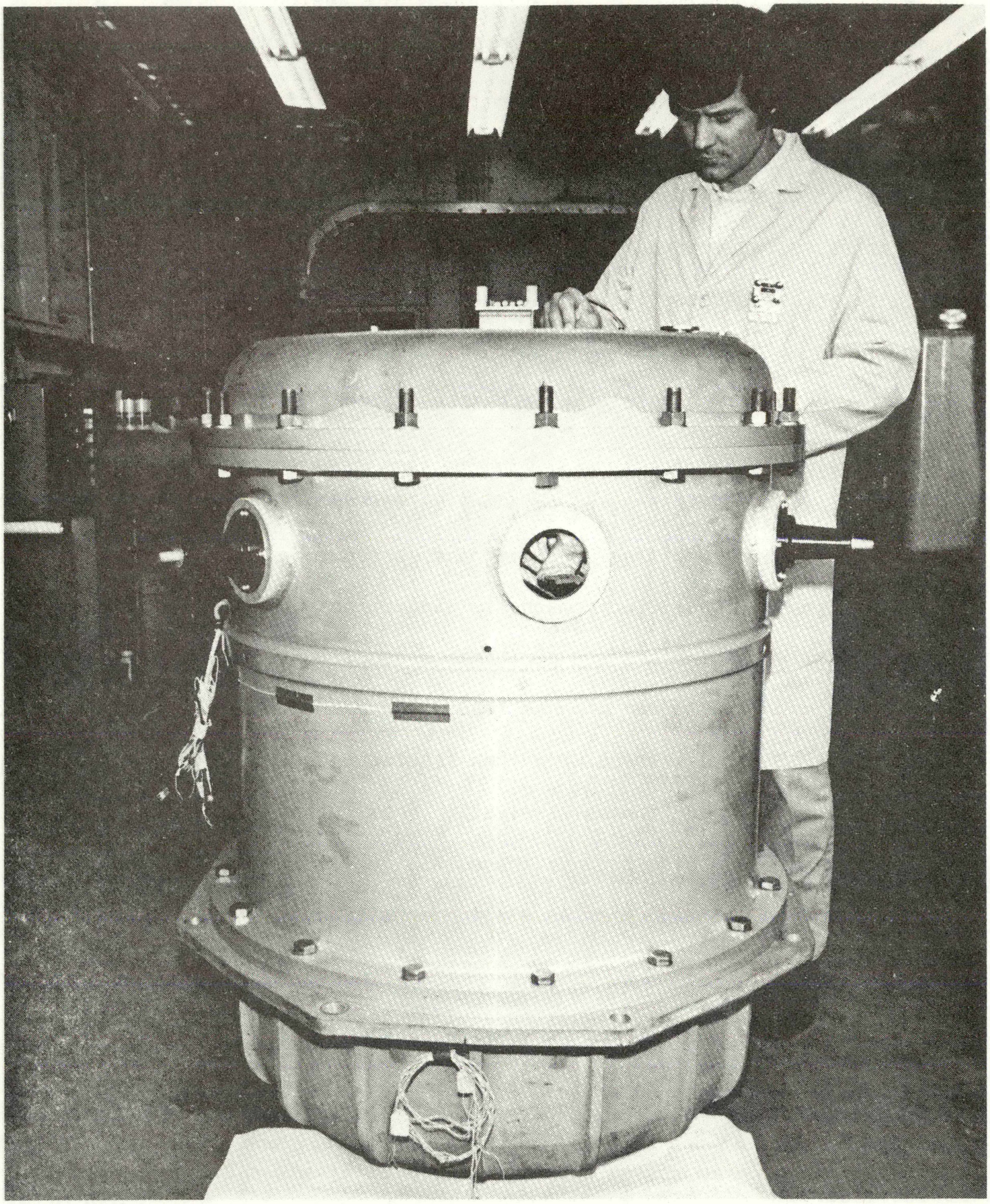


Figure 3-1. Synchronous Condenser

the windings). Also, to a degree, the manufacturing processes available modify the above considerations and must be treated by the design.

An extensive analytical development effort was made, consisting of separate, detailed electromagnetic, thermal, and mechanical (stress) analyses. The design process relied heavily upon existing and proven digital computer programs and was iterative, using successive results from the separate analyses made in the above three areas. Supporting manual calculations were also made to develop certain of the machine losses and mechanical factors. Table 3-2 presents the major parameter description of the machine as calculated in the final design iteration.

The digital computer program used may be set up either to develop a machine geometry and resulting parameter and performance conditions based upon selected major input electromagnetic assumptions, or to develop electromagnetic and other parameters and performance conditions based upon a selected machine geometry. The former program input mode was used initially to develop trial machine geometries, which were then treated and successively modified by supporting mechanical and thermal analyses. From these iterations and material selection and manufacturing process tradeoffs, the final machine geometry was developed and used to calculate the electromagnetic and performance results shown in Figure 3-2.

A detailed weight analysis was made after design completion. The computed total dry weight for the machine is 4221 lb. The machine's center of gravity is approximately 2 in. lower than its physical center.

During the program design phase, formal preliminary and final design review meetings were attended by AiResearch design team members, outside consultants, and representatives of the contracting (DOT) office. Pertinent action items resulting from these two reviews were incorporated in the SC design.

TABLE 3-2

SYNCHRONOUS CONDENSER DESIGN PARAMETERS (CALCULATED)

	Value	
System Rating Factors		
Thrust, lbf	0 to 10,000	0 to 15,000
Vehicle speed, mph	0 to 250	0 to 300
Load condition	Nominal	Maximum
Load duty cycle	Continuous	90 sec (max.)
Total operating life (goal), hr	1000	
Electromagnetic Specifications		
Rating, MVA	6.94	10
Power factor	0	
Armature voltage, VRMS	4130/7150	
Field voltage, Vdc	85	128
Armature current, ARMS	560	809
Field current, Adc	1795	2664
Armature phases	3	
Rotor poles	4	
Speed, rpm	4950	
Frequency, Hz	165	
Total weight, lb	4202	
Outside diameter, in. (excluding flanges)	33	
Overall length, in.	45.5	
Total volume, cu ft	22.5	
Total losses, kW	495.4	932.6
Rotor diameter, in.	21.46	
Active (magnetic) length, in.	13.60	
Radial airgap length, in.	0.40	
Specific weight, lb/kVAR	0.605	0.420
Specific volume, cu ft/kVAR	0.00537	0.00225
Mechanical Specifications		
Overspeed, rpm (percent)	5940 (120)	
First critical speed, rpm (includes vehicle data)	2700	
Peripheral velocity, ft/sec at 4950 rpm:		
Rotor core	465	
Slipring	135	
Outer water seal	75.5	
Inner water seal	46	

TABLE 3-2 (Continued)

	Value
Rotor unbalance limit, in.-oz	16
Rotor angular momentum, in.-lb-sec	158,000
Rotor mass moment of inertia, in.-lb-sec^2	297
Rotor acceleration limit, sec (0 to 4950 rpm)	1.5
Gyroscopic load, lb	
At mounts	476
At bearings	190
Gyroscopic moment, in.-lb	6070
Weight, lb	
Rotor assembly	1745
Stator assembly	1950
Lower end-bell assembly	288
Upper end-bell assembly	202
Included water	22
Thermal Specifications	
Coolant	Triple-distilled deionized water
Coolant electrical resistivity limit, megohm-cm at 70°F	1.0
Inlet pressure, psi	
Stator (max.)	450
Rotor (max.)	360
Water flow, gpm	
Stator, total	37.5
Armature conductors	36.0
Backiron (closed for 6.2 mile duty)	0
End-bell and diode	1.0
Brushes and mounts	0.5
Rotor, total	36.0
Field conductors	24.0
Damper bars and rings	10.0
Sliprings	1.0
Bearings	1.0
Temperature (max. for 3 min, 6.2-mile duty, 110°F start), °F	
Stator	
Copper (armature)	322
Tooth	378
Backiron	204
Housing	260
Diode	255
End-bell	255

TABLE 3-2 (Continued)

	Value
Internal ambient	300
Brush	346
Water inlet	224
Water outlet	320
Rotor	
Copper (field)	349
Damper	303
Core	293
Tooth	313
Top bearing	286
Bottom bearing	252
Slipring	335
Internal ambient	300
Water inlet	224
Water outlet	342

Supporting mechanical and thermal analyses were performed for the final design iteration.

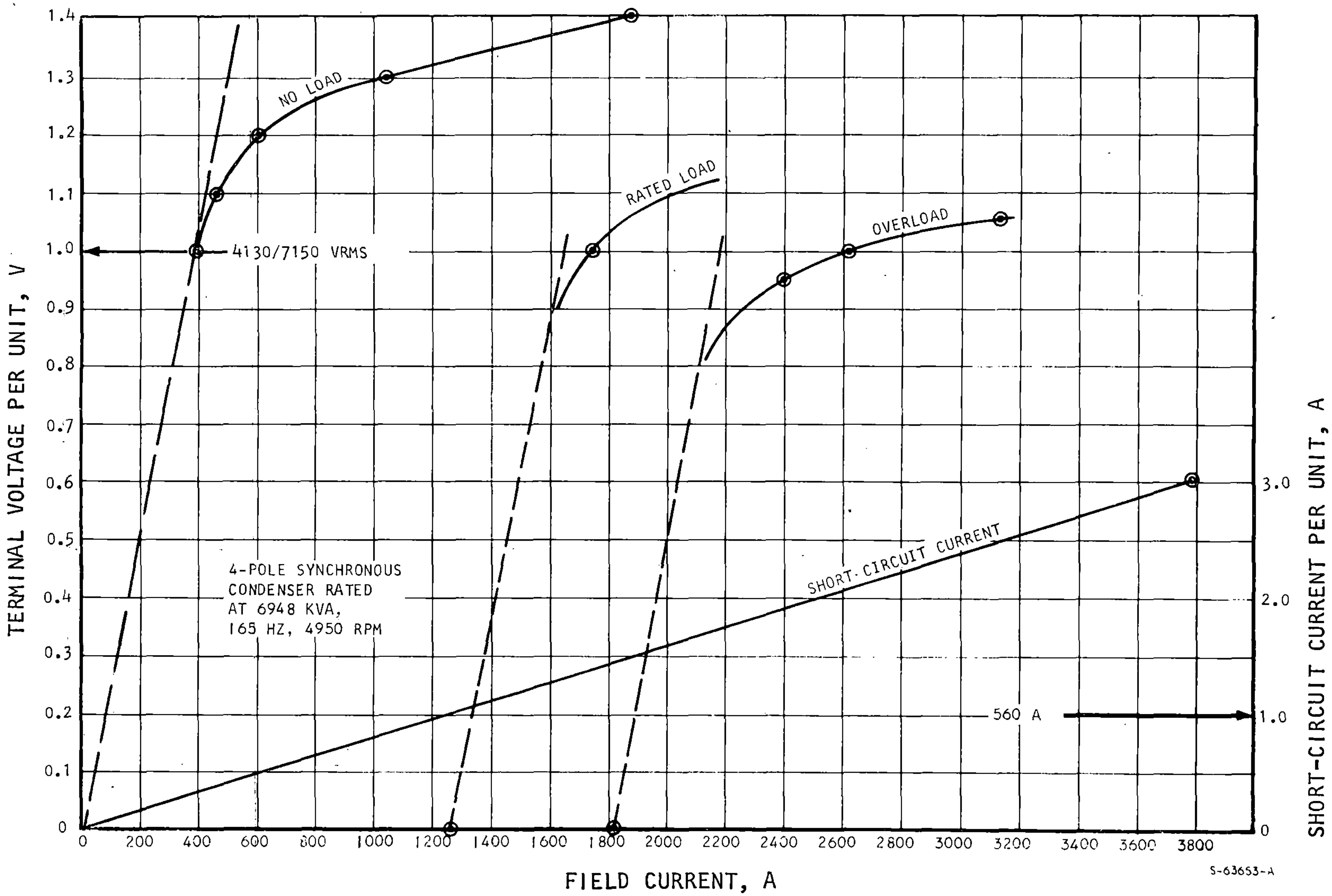


Figure 3-2. Load/No-Load Saturation and Short-Circuit Current Performance (Calculated)

11.04

Linear
Induction
Motor

Stator Winding Reactance

Provision of a low-reactance machine is of direct benefit to the input source, overall propulsion system, and inverter sizing. An amortisseur winding was incorporated in the design to aid in reducing machine reactance values (e.g., negative sequence). For the same reason, stator winding design was emphasized to minimize reactance values. Table 3-3 lists calculated data on the electrical windings.

Rotor Mechanical Strength

Obtaining a mechanically rugged rotor was a major design consideration, since this allows confident selection of a high rotor speed with attendant weight benefit. For this reason, use of a high-strength machine-steel forging was most attractive. Section 4 provides details on material selection.

Rotor Winding Excitation

The machine utilizes a lightweight, compact brush and slipring for rotor field winding excitation. This approach allows full field excitation (forcing) during system startup and avoids additional design and manufacturing complexity associated with an integrated or companion rotating exciter machine by making use of a more readily available low-voltage, high-current, static power supply technology.

Stator Lamination Design

A conventional single-piece concentric stator lamination concept was adopted. This approach has several advantages over a segmented (multiple-piece) approach, including:

- Greater mechanical strenth and rigidity
- Tighter dimensional control possible
- Better stacking factors and control

TABLE 3-3

ELECTRICAL WINDING DATA (CALCULATED)

Parameter	Value	
Load Condition	Nominal	Maximum
Armature density, A/in.^{2}	18,667	26,973
Field current density, A/in.^{2}	15,885	23,578
Armature		
Phase resistance, ohms (356 F)		0.218
Base impedance, ohms		7.38
Synchronous reactance, per unit (unsaturated)		3.44
Transient reactance, per unit (unsaturated)		0.496
Subtransient reactance, per unit (unsaturated)		0.316
Negative sequence (X_2) reactance, per unit		0.316
Stator leakage reactance, per unit		0.174
Field leakage reactance, per unit		0.358
Zero sequence reactance, per unit		0.102
Damper leakage reactance, per unit		0.142
Mean turn length, in.		82.56
Strands per turn		2
Turns per phase		72
Turn per slot		3
Field		
Resistance, ohms (356°F)		0.0481
Inductance mH (unsaturated)		16.9
Mean turn length, in.		61.43
Strands per turn		1
Turns per pole		20
Turns per slot		5

- Improved electrical and weight characteristics due to elimination of parasitic airgaps between segments (refer to Section 4 for additional information on material selection)

Conductors and Windings

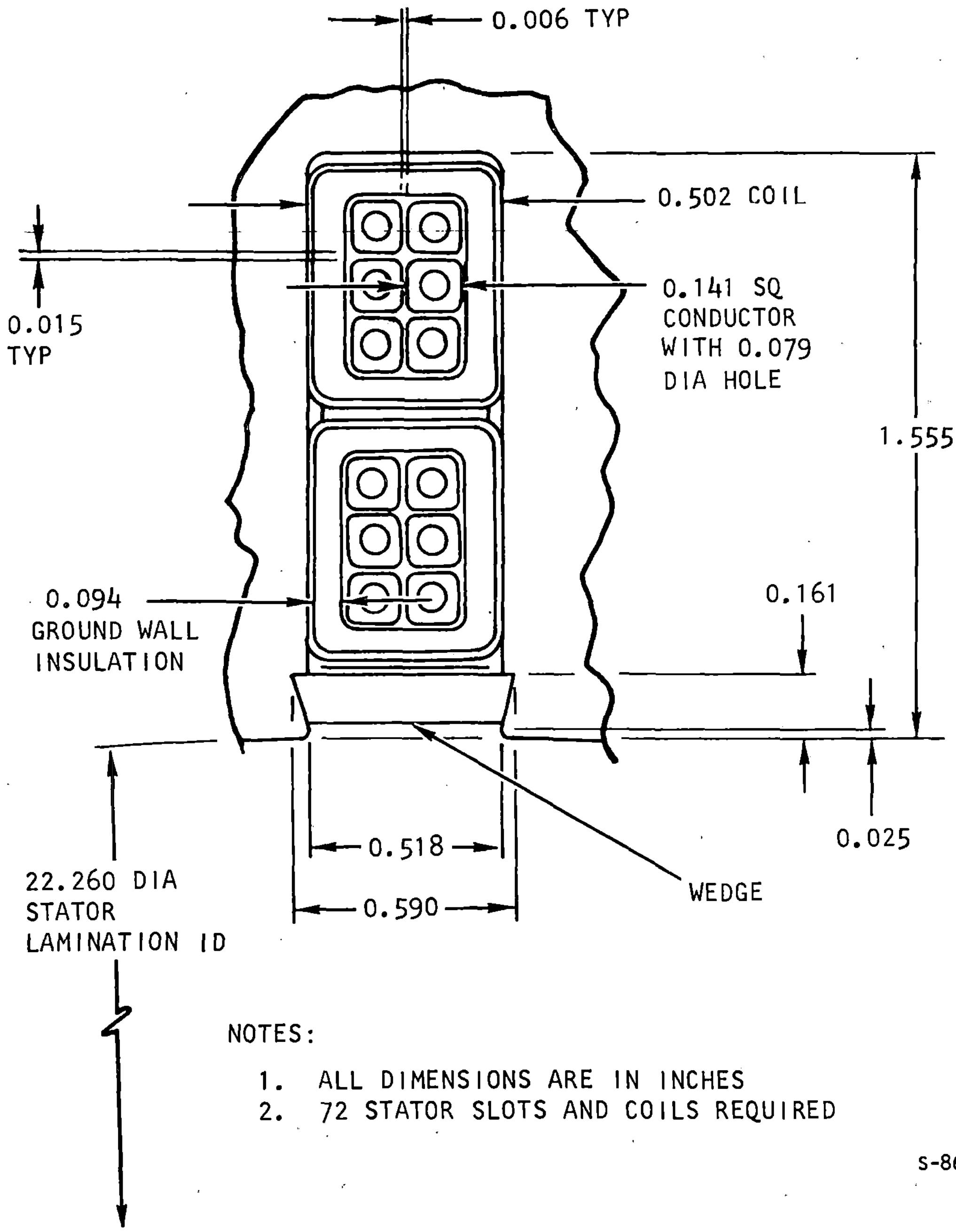
Use of hollow copper conductors directly cooled by deionized water is the single most advantageous weight factor of the design. By further proportioning the design so that most of the machine losses are produced in the windings (i.e., in the area most attractive from a heat transfer and cooling standpoint) the maximum benefits of this approach are achieved.

1. Stator

Selected stator conductor size results from various tradeoffs made in the design, including stranding requirements to minimize eddy current losses, number of turns required to meet the specified voltage, insulation thickness requirements, and maintenance of reasonable cooling passage size. The resulting conductor sizing is shown in Figure 3-3 with the corresponding stator slot sizing. Figure 3-4 provides stator winding design data. Design parameters are specified and connection details shown. The connection was arranged to provide minimum length buses that did not require active internal cooling and also to permit minimum size terminations for the winding.

2. Rotor

The rotor conductor selection was heavily influenced by the need to provide a rugged construction capable of high-speed operation that required relative minimum of cooling connections. These considerations generally lead to a low number of winding turns and the largest practical conductor size. Figures 3-5 and 3-6 show the selected rotor conductor and slot sizing. Figure 3-7



NOTES:

1. ALL DIMENSIONS ARE IN INCHES
2. 72 STATOR SLOTS AND COILS REQUIRED

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Figure 3-3. Stator Slot and Coil

POSITIONS OF COIL GROUPS, JUMPERS, AND INTERCONNECTIONS BY SLOT NUMBERS

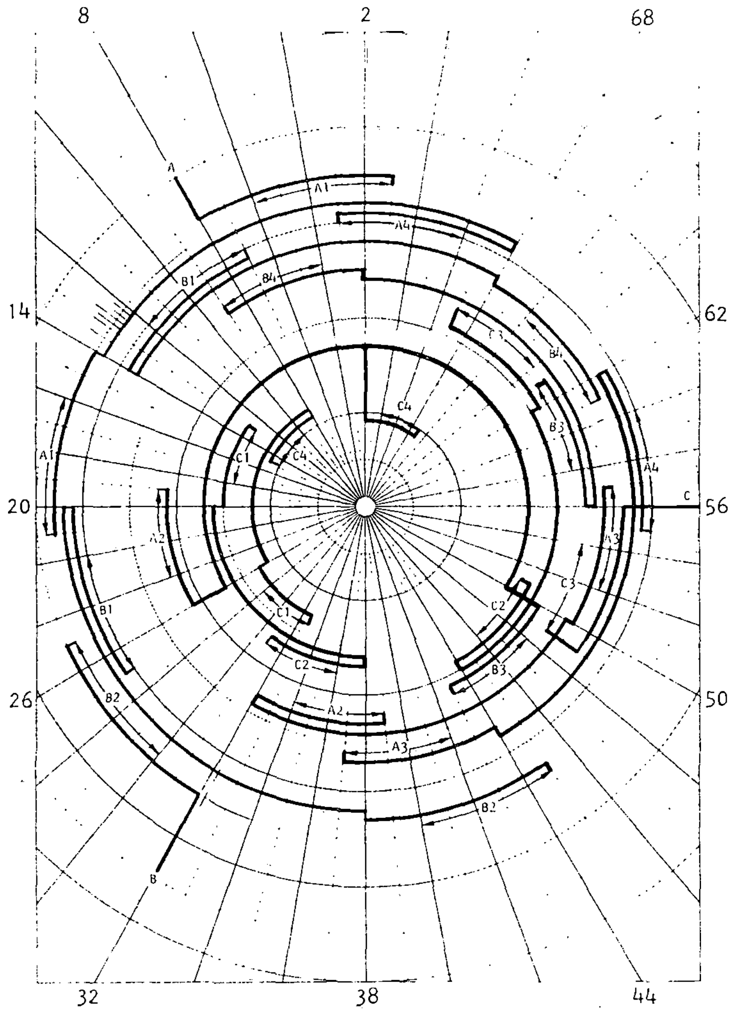

Figure 3-4.

OPERATIONAL DATA

RATING	0-7000 KVAR (CONTINUOUS)
VOLTAGE	0-4130/7150 VRMS (8900 VRMS LINE-TO-GROUND)
CURRENT	0-565 A PER PHASE (RATED)
FREQUENCY	0-165 Hz
TEMPERATURE	÷32 TO 350°F (COIL AVERAGE)
WATER INLET PRESS	450 PSI
WATER FLOW RATE	36 GPM (TOTAL)
LIFE	1000 HR

WINDING DATA

COILS AND SLOTS	72
POLES	4
PHASES	3
COIL GROUPS	12
COIL GROUPS PER PHASE	4
COILS PER COIL GROUP, 6 REQD (REF: DWG 2045175)	-1 PN: 1 EA, -2 PN: 3 EA, -3 PN: 2 EA
COIL GROUPS PER POLE	1
TURNS PER COIL	3
SERIES COILS PER PHASE	24
PARALLEL COILS PER PHASE	1
WINDING CONNECTION	WYE (FOUR WYE)
PHASE BELT	60°
COIL THROW	SLOT 1-16 (15 SLOT OR 5/6 PITCH)
NUMBER OF STRANDS PER TURN	2
PHASE/ROTATION (LOOKING AT LEAD END)	ABC FOR CCW
SLOTS PER POLE	18
SLOTS PER POLE PER PHASE	6 (INTEGRAL)
SKEW	NONE
JUMPER BARS	10 (INCLUDING NEUTRAL)
SERIES ELECTRICAL CONNECTIONS AND QUADRUPLE-BRAZE WATER FITTINGS	60
END ELECTRICAL CONNECTIONS AND DOUBLE-BRAZE WATER FITTINGS	24

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Stator Winding Design Data

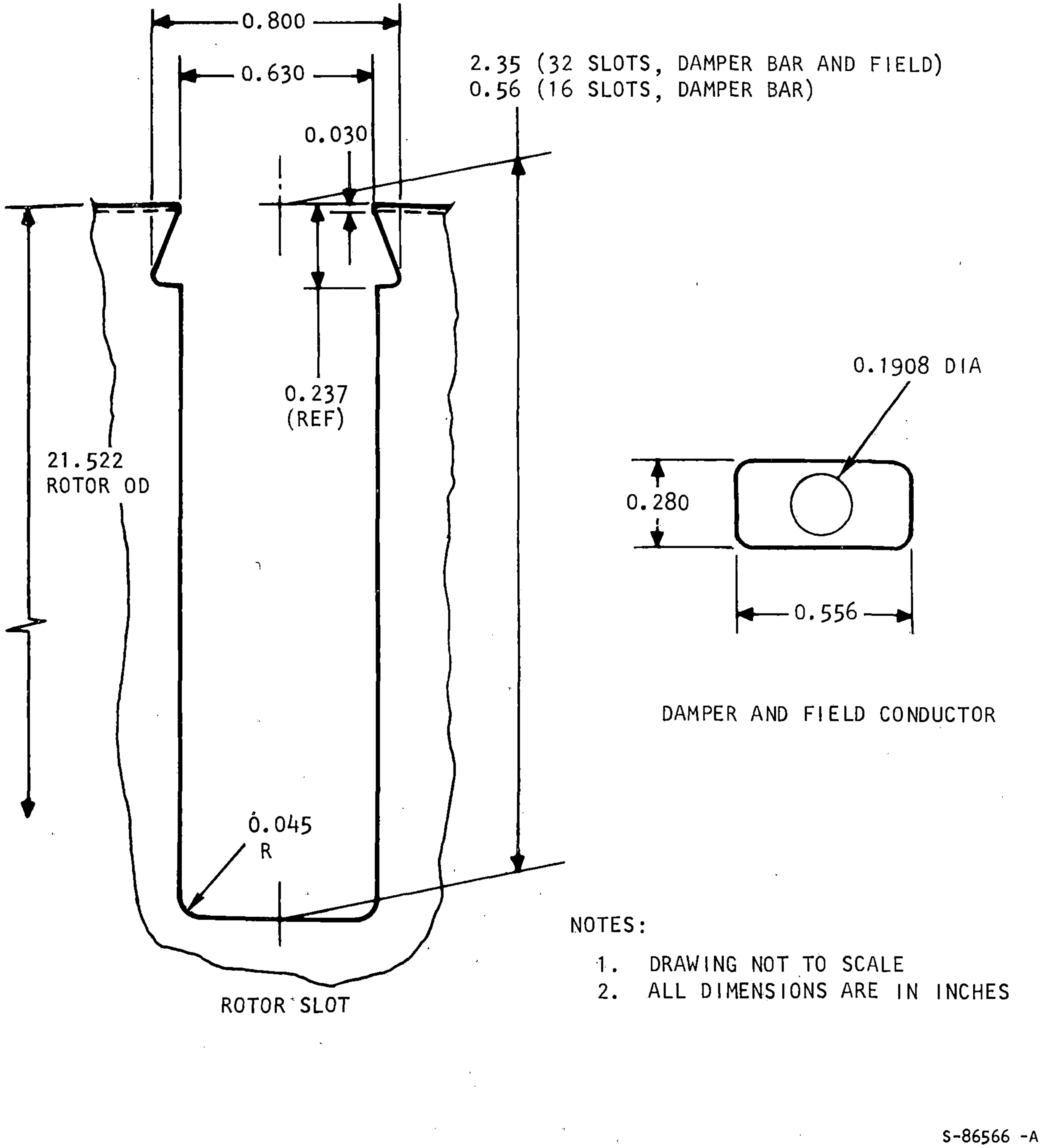
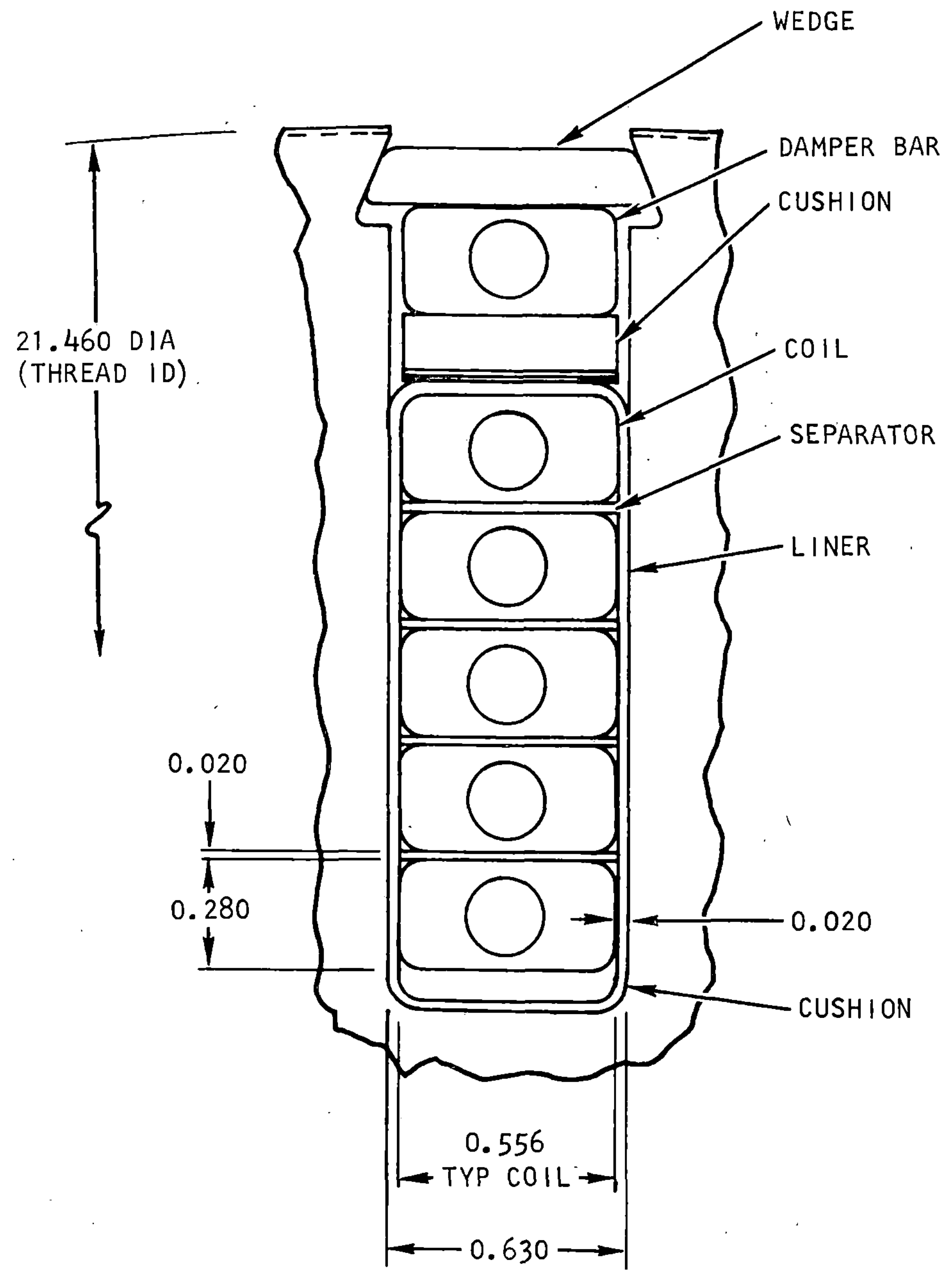


Figure 3-5. Rotor Slot and Damper and Field Conductor Configuration



NOTES:

1. DRAWING NOT TO SCALE
2. ALL DIMENSIONS ARE IN INCHES

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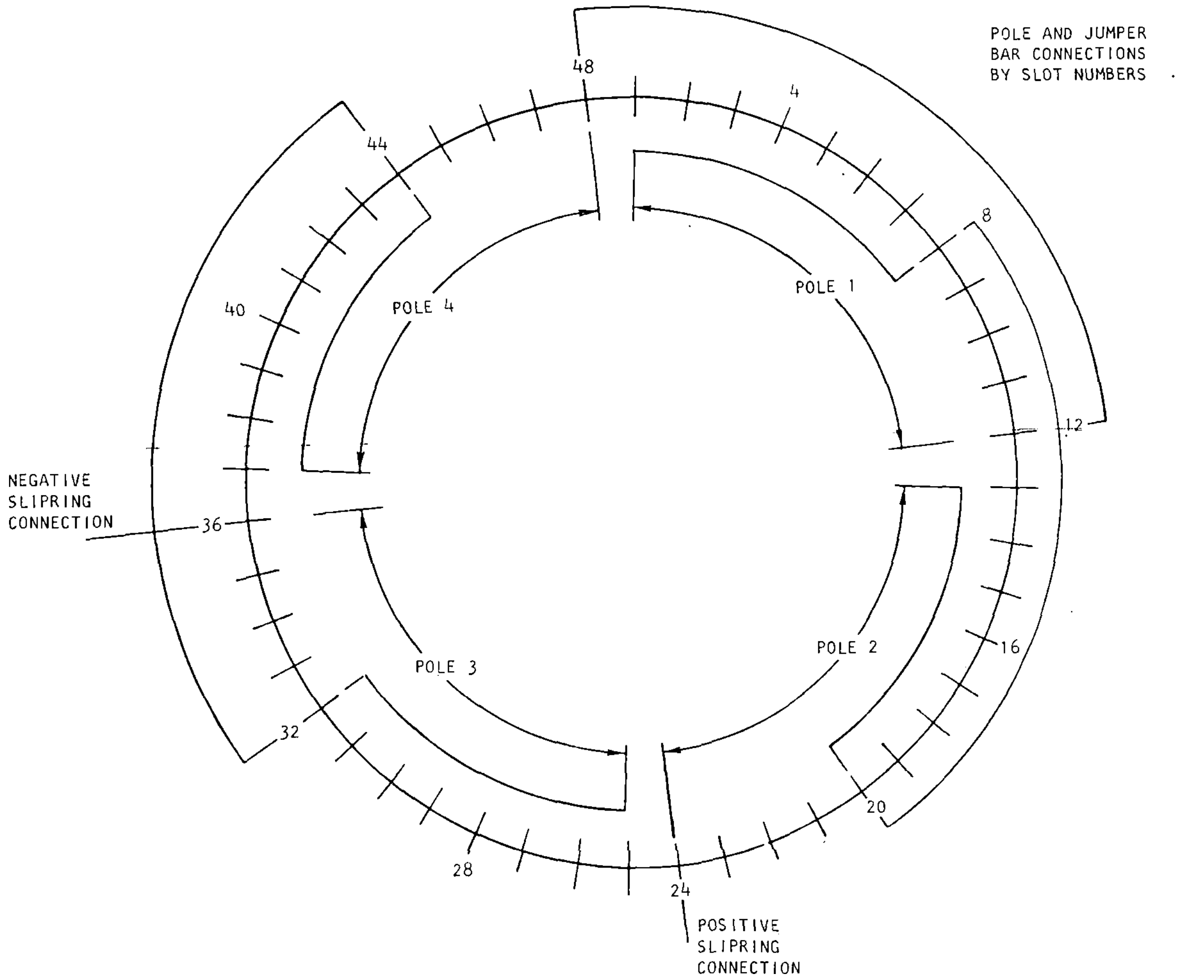
Figure 3-6. Rotor Core Slot and Coil Configuration



OPERATIONAL DATA

VOLTAGE	0-140 VDC
CURRENT	0-1750 AMP DC (CONTINUOUS)
TEMPERATURE	320 TO 350°F (CONTINUOUS)
WATER INLET PRESSURE	360 PSI (AT SHAFT INLET)
WATER FLOW RATER	36 GPM (TOTAL)
LIFE	1000 HR

WINDING DATA

FIELD COILS	16
DAMPER BARS	48
SLOTS	48
POLES (NONSALIENT)	4
COIL AND POLE GROUPS	4
COILS PER POLE OR COIL GROUP	4
TURNS PER COIL	5
SERIES COILS PER POLE	4
PARALLEL COILS PER POLE	1
SERIES COILS TOTAL	16
STRANDS PER TURN	1
JUMPER BARS	3
FIELD WINDING	CONCENTRIC COIL
DAMPER WINDING	SQUIRREL CAGE
COOLANT (COILS, DAMPER BARS, SLIPRING)	LIQUID (DEIONIZED WATER)

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Figure 3-7. Rotor Winding Design Data

rotor winding design data. Design parameters are specified and connection details shown. Rotor bus bars are solid conductor style to obviate the need for cooling connections.

Cooling Water Connections

Both the stator and rotor windings are series-connected electrically and parallel-connected hydraulically. The connections to the water system must accordingly be electrically nonconductive. The number of such connections was kept to the practical minimum. The connections are made in both cases by special design, high-strength sections.

Stator and Rotor Insulation

Rather high stator voltage requirements (i.e., above normal corona producing levels) and the desirability of operating at fairly high temperature obviously necessitated careful attention to the area of stator-winding electrical insulation selection and coordination. The problem was further complicated by the requirement for a very compact machine and the resulting need for precise dimensional control. During the late design and early manufacturing phases of the program, the selected insulation was successfully endurance tested at maximum anticipated operating temperature and in excess of both the maximum operating voltage and life. The basic need was a very rugged rotor insulation system with low creep properties under mechanical loading due to high-speed operation.

Machine Losses

Table 3-4 lists machine losses under rated load and overload conditions. It is evident that the winding losses represent a high portion of the total machine losses.

TABLE 3-4

MACHINE LOSSES

Source	Rated Load, kW	Overload, kW
Stator copper	192.2	401.4
Rotor copper	155.1	341.7
Stray	69.4	100.3
Pole surface	48.0	46.0
Friction and windage	10.5	10.5
Stator core	9.5	10.8
Stator teeth	4.2	4.7
Brush friction	4.9	4.9
Brush (electrical)	1.4	2.1
Seal friction	0.2	0.2
Total	495.4	922.6

Damper Windings

In the TLRV application, the SC operates in parallel with the LIM at the terminals of the variable-voltage/variable-frequency inverter. Six times per cycle, during inverter commutation, overlap occurs, which in effect is a line-to-line short circuit. The damper windings compensate for the negative sequence current and resulting mmf developed during such asymmetrical operation.

A conservative approach was used to predict the magnitude of this mmf. The SC was assumed to be single-phasing during such operation. On this basis, the mmf that must be compensated is equal to one-half of the single-phase mmf. Under this assumption, the current in each damper bar will be two and one-half times the SC current. At the overload condition, with 800-A armature current, the damper bar carries 2000 A. This corresponds to a damper bar current density of 15,000 A/sq in.

SECTION 4

MATERIALS

APPLICATION AND SELECTION

Evolution of the SC presented many unique, rigorous challenges in the area of materials application. In addition to high-voltage requirements and compact size with low weight criteria, it was also necessary to devise a reliable cooling system using deionized water as the coolant at 225 F inlet temperature. Selection of materials was a very important part of the SC design, involving considerable tradeoff in candidate materials, careful description of material properties, and close comparison and evaluation of material treatments and processes. Where sufficient information was not available to evaluate a material with respect to the requirement of the machine, tests were initiated to provide data for selection.

Selection Criteria

Table 4-1 lists critical materials used, identifies pertinent specifications, and describes special handling requirements. Each listed component or material is discussed in detail below. Paragraph numbers are keyed to Table 4-1.

1. Stator Laminations

Stator laminations were fabricated from 0.014-in.-thick M-19 silicon steel with C4 surface insulation. Use of this electrical grade steel was based upon its proven electromagnetic capability and manufacturing technology. The material has excellent and reliable properties for both magnetic induction and mechanical capability. In addition, its superior high-resistance surface coating provides a high interlaminar resistance that aids in minimizing losses of

TABLE 4-1

SYNCHRONOUS CONDENSER MATERIALS

Component/Item	Description	Specification	Special Handling	Selection Basis	Remarks
1. Stator lamination	29 gage (0.014 sheet) silicon steel (fully processed, single-piece core plated	AISI M-19-C4	Heattreat per AiResearch HT59	1) Noncritical heat treatment 2) Mechanical and electrical properties 3) Available in large sizes 4) Proven technology	Vanadium permendur considered
2. Stator housing	Aluminum alloy forging	6061-T6 per QQ-A-367 comp 6061 cond T651	Heattreat to T6 per AiResearch HT3	1) High strength 2) Low weight	Lower cost than weld fabrication
3. Stator conductor	Boron deoxidized copper 0.0548-0.0594 lb/ft 0.141 x 0.141 cross section (hollow)	CDA No. 109	Add 7 to 10 oz silver per ton	1) High conductivity 2) Excellent braze properties	
4. Stator conductor insulation	1 layer Kapton, 2 layers Dacron-glass (ground wall: 5 layers loaded epoxy mica paper with glass cloth and Dacron mat)		Hot-pressed, vacuum impregnation	1) High-temp capability 2) Good dielectric	Life tested (accel) at 150 VRMS/mil, 60 Hz, 356°F, for 2500 hr
5. Stator coolant transfer tube	Thermoplastic (polyarylsulfone)	Astrel 360 plastic	Machined from round stock	1) Water compatibility 2) Temp capability 3) Good dielectric 4) High strength	Test-proved over Teflon Nomex at rated conditions
6. Rotor core	High-strength alloy steel forging	HP 9-4-20	Heattreat to Rc 41-45 per dwg	1) High strength 2) Magnetic properties 3) Previous experience 4) Good thick section properties after heat treatment	Three pieces E-beam welded together
7. Rotor conductor 8. Damper bar	Boron deoxidized copper 0.483-0.495 lb/ft 0.28 x 0.56 cross section (hollow)	CDA No. 109	Add 7 to 10 oz silver per ton	1) High conductivity 2) Excellent braze properties	
9. Rotor coil insulation shroud	Mica ring layup 15 percent fiber glass, 14-17 percent epoxy resin, balance mica			1) Minimum deflection and creep 2) Good dielectric	
10. Winding support ring	Forged ring, nickel base alloy	AMS 5663 (INCO 718)	Heattreat to Rc 38 (min) per AiResearch HT71 treatment B	1) High strength 2) Low thermal expansion 3) Previous use	
11. End-bell	Cast aluminum alloy	MIL-A-21180 comp A356-T61	Lower end-bell has cast-in-place CRES coolant line	1) Low weight, high strength 2) Good thick-section properties	
12. Brush	Copper graphite (75 percent copper by weight)			1) High conductivity 2) Low specific resistance 3) Low contact drop 4) Low friction	
13. Collector ring	Forged ring, chromium-copper	RWMA, Class 2 (Mallory 3)	Age 2-4 hr at 875°-925°F in a protective atmosphere	High conductivity and strength	
14. Damper bar manifold	Forged ring, chromium-copper	RWMA, Class 2 (Mallory 3)	Age 2-4 hr at 875°-925°F in a protective atmosphere	High conductivity and strength	
15. Rotor winding coolant manifold	Stainless steel	AMS 5643 (17-4 PH)	Heattreat per AiResearch HP38	1) Strength 2) Low thermal expansion 3) Minimum distortion after weld	
16. Rotor insulation	0.020 sheet hard mica splitting			1) Strength under compression 2) Good dielectric 3) High-temp capability	
17. Coil blocking and bracing	Glass mat polyester laminate	Glastic 200		High-temp strength	Fabrication ease
18.1 Stator tape inner layer	0.006-in.-thick mica mat (polyester film, non-woven glass, polyester film)	G.E. 77956	1/2 lap wrap 4 layers minimum	1) Good dielectric 2) High-temp capability 3) Conforms easily	
18.2 Stator tape outer layer	0.0075-thk, B-staged, epoxy-coated polyester glass	G.E. 76593	1/2 lap wrap 8 layers minimum, cure at 170°C for 1 hour	1) Good dielectric 2) Low dissipation factor 3) High-temp capability	Shrinkage and resin flow insures sealing; use to wrap rotor coil end turns

TABLE 4-1 (CONTINUED)

Component/Item	Description	Specification	Special Handling	Selection Basis	Remarks
19. Stator jumper bar	Electrolytic tough-pitch copper	CDA No. 110 (QQ-C-502)		1) High conductivity 2) Availability	Wrapped with Items 18.1 and 18.2
20. Rotor jumper bar	Oxygen-free, high-conductivity copper	CDA No. 102 (QQ-C-502)		1) No residual deoxidant 2) High conductivity	Wrapped with Item 18.2
21. Stator stack tie bolt	Stainless steel	A286 (AMS 5737)	Insulation is overwrapped with stretch Mylar, cured, and machined to size	1) High strength 2) Low thermal expansion	Insulated with epoxy-glass tape 1012-36 cross ply (3M)
22. Collector ring Insulation (slip-ring assy)	Alumina ceramic (99 percent Al_2O_3)	Coors AD-99	Fits 0.012 tight (OD)	1) Thermal conductivity 2) Compressive strength 3) Good dielectric	

the assembled laminations. The material is available in wide-strip widths, permitting single, concentric lamination construction in the size desired and has proven punching technology and noncritical heat treatment requirements.

Due to slightly superior ideal electromagnetic properties, the use of vanadium permendur was also considered for stator laminations, but rejected because of technological limitations. A primary disadvantage of vanadium permendur is its need for a critical and very precisely controlled inert atmosphere heat treatment to attain full electromagnetic properties. Furthermore, the material is not available in wide strips, or with a suitable high-resistance surface coating. Its cost is considerably greater. These factors result in compromises of the SC design and construction that rule out vanadium permendur despite its potentially attainable superior electromagnetic properties.

2. Stator Housing

Consideration was given to machining the housing from (1) a rolled and welded plate with welded flanges, or (2) a cylindrical forging. Approach (2) was used as it proved more predictable and economical.

3. Stator Conductor

Stator conductor material is boron deoxidized copper No. 109 with 7 to 10 ounces of silver added per ton to ensure high-temperature strength properties of conductors above 300°F. The use of oxygen-free copper is necessary to avoid embrittlement problems associated with brazing. The stator conductor form chosen (i.e., square with a round hole) is consistent with standard conductor production technology, although smaller than standard size. In fact, this is one of the smallest size hollow conductors that has been produced (see Figure 3-3).

4. Stator Conductor Insulation

The mica insulation system for this machine was developed especially for this unit, and to the best of our knowledge, has not been used by other manufacturers. It qualifies for Class H (356°F continuous) rating and consists of a fused Kapton tape and glass sleeving, followed by five sealed half-lap tape layers of epoxy mica, and a final corona shield of asbestos/graphite. The coil is hot pressed to ensure a sealed, void-free insulation. Test bars made with the stator conductor and its insulation system were subjected to an accelerated life test at 150 VRMS per mil, 60 Hz, at a temperature of 356°F, and successfully withstood more than 2500 hours.

5. Stator Coolant Transfer Tube

Selection of high-strength and high-temperature thermoplastic used for the electrically nonconductive stator coolant tube was based upon results of development tests. Tests were conducted on a variety of materials and configurations, with deionized water, at temperature and pressure in excess of 350°F and 450 psig, with both temperature and pressure cycled up and down. Alternate coolant connections based upon use of a flexible Teflon hose with outer Nomex cloth did not withstand the thermal cycling tests.

6. Rotor Core

Rotor core material selection was based on the need for a mechanically strong and electromagnetically efficient steel. Republic Steel Co. material HP 9-4-20 offers the advantage of through hardening in thick sections, combined with good retention of electromagnetic properties after heat treatment. Previous use of this material on a similar program (LIMRV) provided a basis for evaluating post-manufacture properties. Test bars cut from the rotor core forgings and heat treated with the rotor assembly were used for material and process sampling to provide data on material characteristics, including tensile strength, hardness, electromagnetic properties, plating effectiveness, hardness, and machinability. See Figure 4-1 for magnetic test data.

7. and 8. Rotor Conductor and Damper Bar

The rotor field and damper conductor material selection criteria parallel those for the stator conductor. Its full-slot width, rectangular cross section establishes a good footprint. A strong and simple ~~cell insulation system~~ can be used due to low voltage (see Figures 3-5 and 3-6).

9. Rotor Coil Insulation Shroud

The mica material selected for the insulating shroud ring provides a dielectric separation of field and damper windings with high compressive strength and low deflection and creep, which results in very low balance shift.

10. Winding Support Ring

The winding support ring material must have high strength and minimum thermal growth. This ring must support all rotor field end turns and damper bar extensions. Previous experience in similar applications was the reason that a nickel-based alloy forging was selected.

11. End-Bell

The 356-T61 cast aluminum is a commonly used material with good thick-section properties and very high strength, which provides the capability to support the vertically mounted machine (see Figure 4-2).

12. Brush

The brushes must operate at a maximum rated speed of 1634 in./sec. Brush loading is about 2 lb with constant-tension springs. The metal/graphite brushes, with a 75 percent copper content, provide high conductivity with low friction

LIMRV ALTERNATOR																	
Rotor Ring 2		Rotor Ring 3		Rotor Ring 4		Rotor Ring 2		Rotor Ring 3		Rotor Ring 4		Rotor Ring 4		Rotor Ring 3		Rotor Ring 2	
H	B	H	B	H	B	H	B	H	B	H	B	H	B	H	B	H	B
						293	74										
						263	72							268	92.4		
269	120	286	112	283	108	258	72	280	73.1	289	73	254	93	252	90.4		
224	118.2	266	110	251	105.5	252	72	248	72.4	260	72.8	221	92.5	234	89.5	258	11C.5
193	116.0	238	107	212	104	226	70	214	69.0	231	72.5	183	88	202	88.6	243	109.6
149	112	206	105	178	97.5	212	69	182	66.7	202	69.0	143	84	173	86.2	211	108.0
104	104	180	101	148	93	185	68	150	63.0	173	65.0	98.4	72.5	140	82.0	155	106.0
87	101	150	97	114	85	161	64	113	55.7	144	61	86	66	117	77.2	108	97.0
56	87	121	91	89	77	140	64	95.4	49.6	116	54.5	58	48.5	84	68.0	64	84.0
45	75	91	81	57	55	120	60	63.5	34.6	87	48.9	38	30	61	53.7	41	55
35	57	61	61	44	42	94	56	34.7	15.0	58	34.5			43	40	9	8
25	40	47	48	30	23	63	48			32	16.4			29	26.5		
● Not same batch as LIM rotor		Specimen to deter- [illegible] heat treat cycle		■ Test run for rotor heat treat determination													

TLRV SYNCHRONOUS CONDENSER									
Rotor Ring 1		Rotor Ring 1 500°F		Rotor Ring 2		Rotor Ring 2 500°F		Rotor Final Temper	
H	B	H	B	H	B	H	B	H	B
356	111.8	360	103	352	111.1	349	103	350	111.5
319	109.2	325	101.5	309	109.8	320	101	318	108.2
290	108.0	290	99.5	291	108.9	291	99.5	272	108.0
264	106.5	264	98	262	106.0	262	98.5	258	105.5
232	105.5	234	96	239	103.9	230	96	230	102.9
203	102.0	203	94	207	101.0	204	94.6	198	99.5
168	98.5	174	89	178	99.0	163	91.0	172	96.1
112	89.0	145	87	137	92.6	140	87.0	144	92.5
90	79.0	116	83.2	116	87.5	116	81.0	117	88.2
58	59	90	75	87	79.1	87	74.8	86	79.0
32	36	58	60.2	52	56.1	61	59.5	57	62.9
		32	34	32	38.8			29	35.6
Specimen 1 after initial heat treat				Specimen 2 after initial heat treat				◆ After final temper	

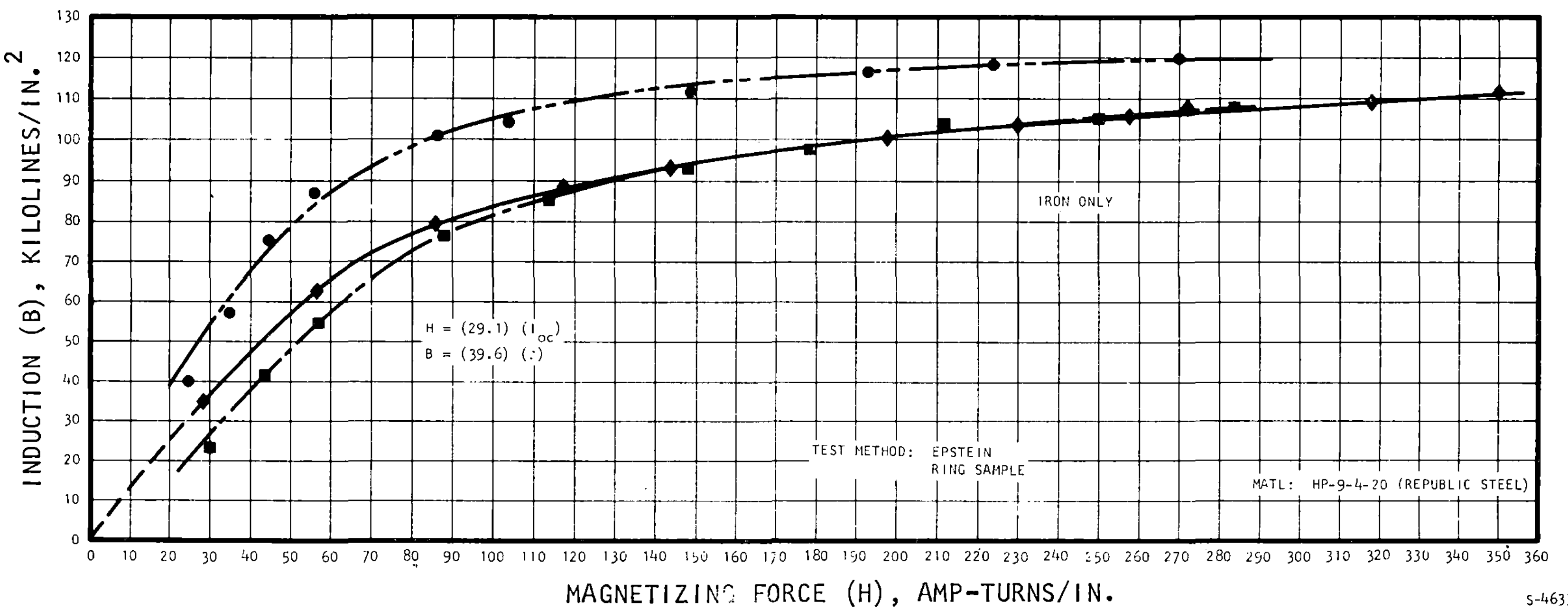

Figure 4-1. Rotor Core Material Magnetic Properties, LIMRV vs TLRV

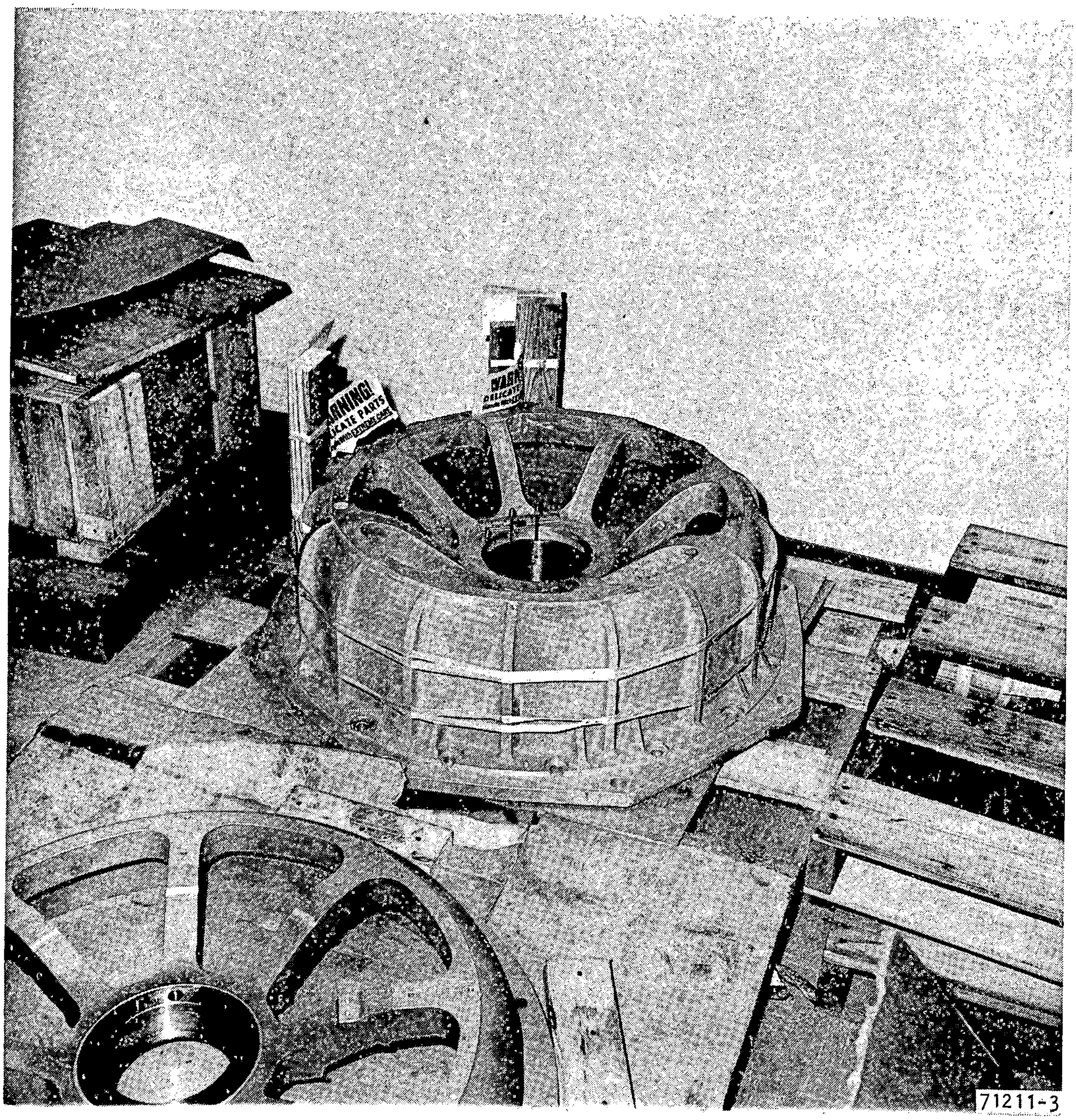

Figure 4-2. Lower End-Bell Casting with Cast-in-Place Coolant Line

and contact drop. Thus, a maximum rated continuous current of 123 A is carried with relatively low losses, minimizing the cooling requirements.

13. Collector Ring

The bolted-together collector rings, due to operating temperature and centrifugal loads, must be fabricated from a high-strength material that is also a good electrical conductor. The chromium-copper forging provided a heat-treatable material with uniform properties in addition to the necessary good conductivity.

14. Damper Bar Manifold

For the damper bar manifold, selection of the chromium-copper forging was again based on the requirements for a very high-strength (must withstand 2000 psi) material with good electrical conductivity. It is also an easy material to braze and reheat-treat to acceptable strength characteristics.

15. Rotor Winding Coolant Manifold

The rotor winding coolant manifold (Figure 4-3) is subjected to high centrifugal loading. It requires corrosion resistance and a minimum of thermal expansion. The material not only is acceptable for these reasons but can be easily welded with a minimum of distortion and is fairly free machining. A cast version was initially considered to eliminate complex weldment, but fabrication schedules could not be met under the then existing pattern-shop work loads.

16. Rotor Insulation

The rotor insulation must be able to withstand Class H (356°F) temperatures. This material provides that capability and it has the characteristics of a very high dielectric. It can also stand high compressive loads.

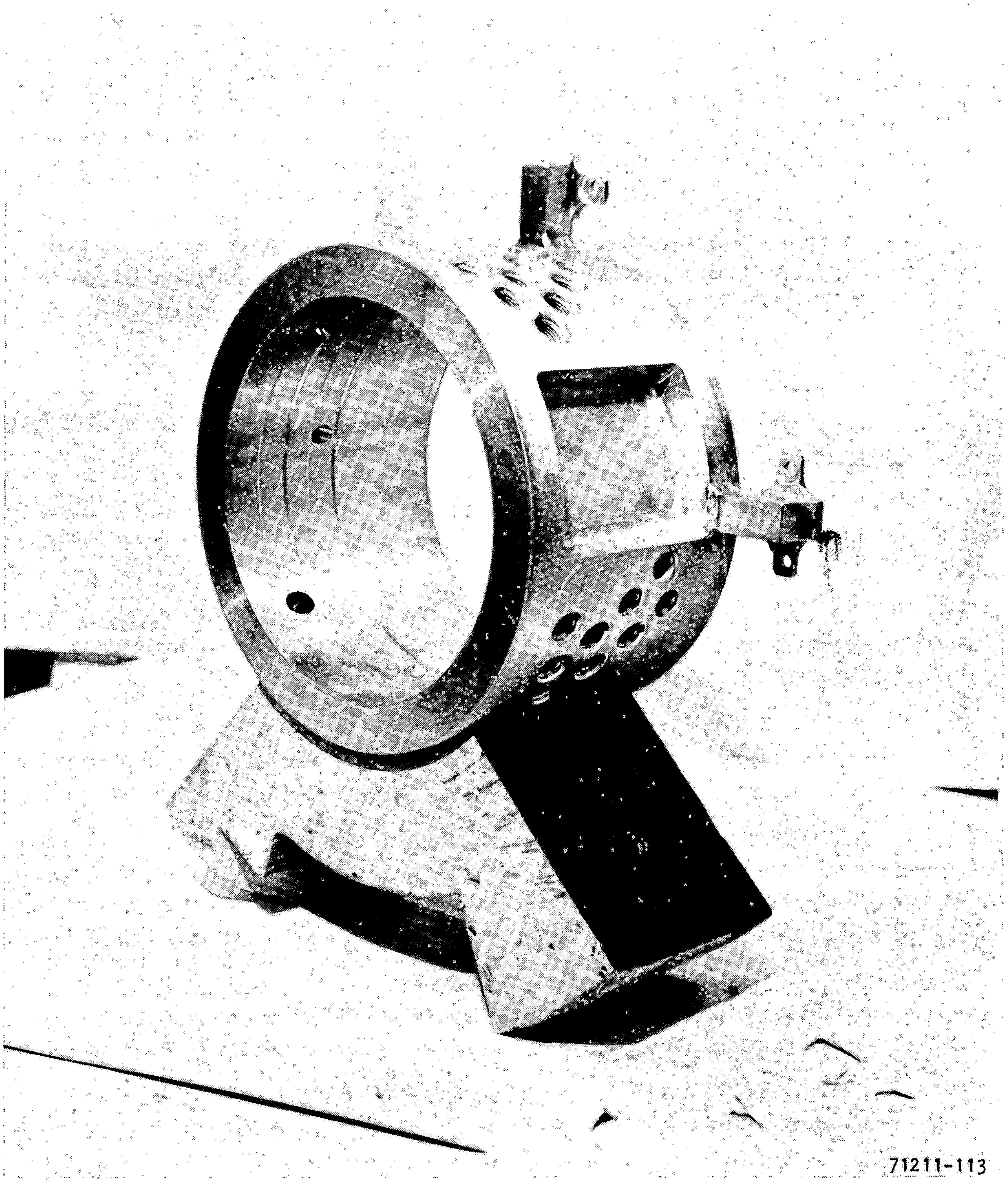

Figure 4-3. Rotor Coil Coolant Manifold

17. Coil Blocking and Bracing

The comparison of various insulating materials resulted in the selection of Glastic 200 as the superior material for this Class H (356 F) temperature application. It has good high-temperature strength, high dielectric strength, and low moisture absorption. It can be easily fabricated.

18.1 Stator Tape Inner Layer

Choice of high mica content tape is based on excellent electrical strength at the Class H temperature and proven application at the voltage level.

18.2 Stator Tape Outer Layer

This B-staged tape provides very high electrical strength (2100 V/mil avg), effectively withstands the Class H temperatures, and is fast curing at 388 F. During cure, the flow of resin plus shrinkage of the polyester thread wrap ensures a moisture-tight wrap and a rugged, damage-resistant final casting.

19. Stator Jumper Bar

Stator jumper bar material consideration was primarily based on high conductivity and ease of fabrication. The selected copper was immediately available, and fabrication posed no problem.

20. Rotor Jumper Bar

High conductivity and ability to withstand brazing operations were the requirements for this material. The selected oxygen-free, high-conductivity copper is without residual deoxidant, assuring excellent braze characteristics.

21. Stator Stack Tie Bolt

Stainless steel (A286) was selected primarily because it is a common, high-strength bolt material, and in relation to the stack has low thermal expansion. It is also nonmagnetic.

22. Collector Ring Insulation

Ring insulation criteria dictated a good thermal conducting material able to withstand very high compressive loads and provide good electrical insulation. A tight interference fit between the collector rings and collector hub through the alumina ceramic permits indirect cooling of the collector rings while effectively isolating them electrically.

BEARINGS AND SEALS

Bearings

The upper bearing for the SC is a Class 5 roller bearing with a bronze cage for high-temperature operation. The lower bearings are duplex, 40 angular contact, with bronze cages. They are installed back-to-back but precisely separated. These bearings are machined to provide a medium preload (785 lb per set) when clamped up. The bearing lubricant is a high-speed, high-temperature grease, a mixture of synthetic (nonsilicon) type oil, high molecular weight organic compound, and sodium soap.

Seals

All O-ring seals are Viton for high-temperature service. Three types of rotating seals are used. The upper bearing cavity grease seal is a segmented carbon ring with an outer garter spring exerting radial pressure inward. The seal rides on a hard-chromed ring. The grease seals for the lower bearing cavity are standard multileaf (two rotating, two stationary) labyrinth seals. For water separation, two carbon-faced seals are used. The seal for the lower cover is designed for 5 gpm leakage with a pressure differential of about 150 psi (inlet to discharge). A larger seal isolates the water flow chamber from the bearing cavity. This seal must exclude water and steam (coolant water at 225°F) from the bearing cavity with the rotor stationary under maximum pressure. A pressure differential as high as 300 psi could develop here. This seal was initially assembled with a wavy spring washer, but changing to coil springs with a higher spring rate provided more uniform and higher face loading.

COOLANT FLOW PATH CONFIGURATION

Precision machinery was necessary in many areas to efficiently provide adequate coolant flow. Problems and solutions are discussed below.

Bearing Housing

The bearing housing, of two-piece construction, provides water flow around the bearings. It consists of a sleeve with a machined, circumferential, helical groove welded into a housing for the upper bearing and pressed in place with O-rings at the lower end.

Rotor/Brush Holder

Another helical groove is machined in the rotor to provide the coolant flowpath for the bore of the slip rings. The brush holder heat exchanger is a copper plate with a circular groove about 0.62-in. wide, furnace-brazed to a cover plate to form an annular flowpath for the coolant.

Stator Coils

Water for the stator coils is distributed through two fabricated, log-type manifolds. Machined fittings are welded to a 0.75-in.-OD tube after the tube ends are welded together, forming a ring. The fittings are oriented so that the connected transfer tubes form a tangent to the mean centerline of the manifold tube. This configuration provides a very compact assembly at minimum expense of axial length.

STATOR AND ROTOR COILS

Both the stator and rotor coils are shaped to very tight bend radii, with a large pitch that must fit into deep slots: 72 deg for stator coils (see Figure 4-4), and 82-1/2 deg for the largest rotor coil. The coils fit together within a minimum of space and require unusually close control of tolerances. The coils are filled with wax, wound, and formed with fixturing and tooling to meet the required size and shape. The stator coils are then insulated with the micaceous material and tested to meet applicable design criteria. The rotor coils, though not insulated, have fittings brazed to them. Rotor coils have four configurations for the four poles. The stator coil has three different coil end configurations. The stator conductor is 0.14-in. sq (see Figure 3-3), while the rectangular damper and field conductor measures 0.280 by 0.556 in. (see Figure 3-5).

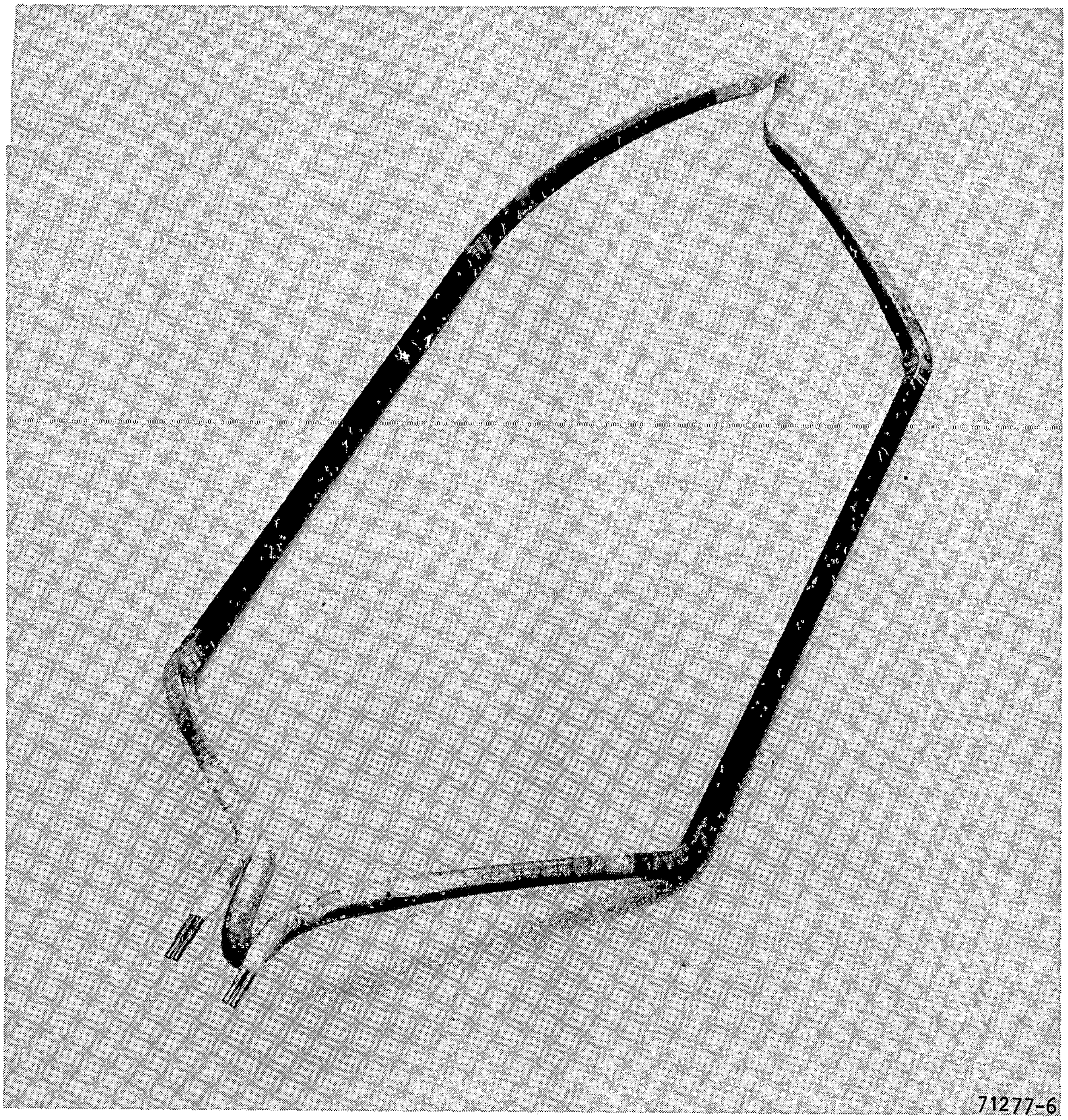

Figure 4-4. Typical Stator Coil as Installed

SECTION 5

FABRICATION AND ASSEMBLY

Synchronous condenser fabrication and assembly were completed in three major stages: (1) rotor core fabrication and final assembly, (2) stator stack and housing assembly, and (3) unit final assembly. Procedures were established for each operation and inspection to insure tight control of fabrication. Three multiuse fixtures were fabricated to provide accurate tooling and special handling characteristics capability. Complementing the three main stages of fabrication and assembly were several subassembly operations such as the top end-bell assembly and the brush holder assembly.

Throughout design and final assembly, the need for maximum ease of maintainability was stressed. The intended objective was achieved, as evidenced by the fact that all seals and bearings are removable with rotor disassembly, all coolant lines are replaceable without major disassembly, and all brushes can be inspected or removed by removing nothing but the top cover plates. The entire rotor assembly can be removed by two men in less than three hours, thus making the machine totally accessible.

Discussed below are the stages of fabrication, assembly, and major subassembly necessary to complete the synchronous condenser.

ROTOR FABRICATION

The rotor core comprises three forgings, electron-beam welded together to two 45-deg conical joints, at an approximate 9.25-in. mean diameter and 1.50-in. thickness. The initial operation is premachining the forgings for weldment. Rotor configuration necessitated that the first weld be inspected while accessible, prior to completing the second weld. To expedite fabrication, determine potential distortion, and define the electron-beam welding schedule, samples of identical thickness were welded at the same angle. Pull samples were also tested to establish weld properties. Both welds were separately fluorescent-penetrant and ultrasonically inspected. After welding, the internal cavity was cleaned with a slurry, flushed with water, and dried at a temperature of 250 F.

Following rough machining operations to semifinish the bearing journals, the coil slots were cut to their final depth. The rotor was then heattreated (Rockwell C41-45) and final-machined prior to nickel plating. The rotor centerline was reestablished by using four slot bottoms at each end for indication and location. Diameters, including bearing journals, were then machined with an allowance made for the final plating. The internal bore was honed to provide the critical surface finish required for internal sealing. Final operations consisted of thread cutting, boring of various holes, and cutting of an internal spline at the top end. The slot wedge grooves were then milled into the slots, and grinding of the critical winding support ring diameters and bearing journals was completed. The final machining operation was cutting of a thread on the core OD to minimize eddy current losses.

Plating allowance of 0.0025 in. per surface was provided for all internal and external surfaces except the bearing nut threads and internally threaded holes. These areas were masked and the whole rotor was then electroless nickel plated to a thickness of 0.0025 in. Critical thickness control was maintained at the bearing journals to provide the close tolerance required for bearing fits. No further machining was necessary to ensure proper clearances. (Prior test samples were plated to insure the compatibility of the HP9-4-20 steel with the electroless nickel.)

After installation of various plugs, the finished rotor core was dynamically biplanar balanced by removing material from the core sides for correction. Final balance was within 2 oz-in. (see Figures 5-1 and 5-2).

ROTOR ASSEMBLY

Prior to assembly into the rotor, the rotor coils were inspected, flow-checked, and orificed for flow-control criteria. The four coils were then installed one pole at a time with the turn-to-turn insulation (sheet mica) inserted and trimmed as required. Axial blocking positioned the coils and end turns were taped. With axial alignment and blocking established, steel bars with clamp rings were positioned in place of the damper bars, using 48 threaded rods to clamp down on the bars (see Figure 5-3). The coils were clamped radially inward and compressed and the entire assembly was oven-cured for four hours. Hardwood forming blocks were installed under the end turns to ensure the proper radial dimensions. After the clamping bars and rings were disassembled, the mica coil support ring was added along with the damper bars. The clamping fixture was then reassembled to provide compression, and the assembly was reheated for four hours to cure the insulating mica ring. The Inconel slot wedges were installed. To assemble the damper bar manifold, the damper bars were slightly deformed radially, and clamped in position for torch brazing to the manifold (see Figure 5-4). To prevent damage to the coil insulation and blocking, wet asbestos was packed around each bar as a heat barrier. The damper bars and both manifolds were then hydrostatically pressure tested to 2000 psig with water. Additional filler blocks were added prior to assembling the coil support rings.

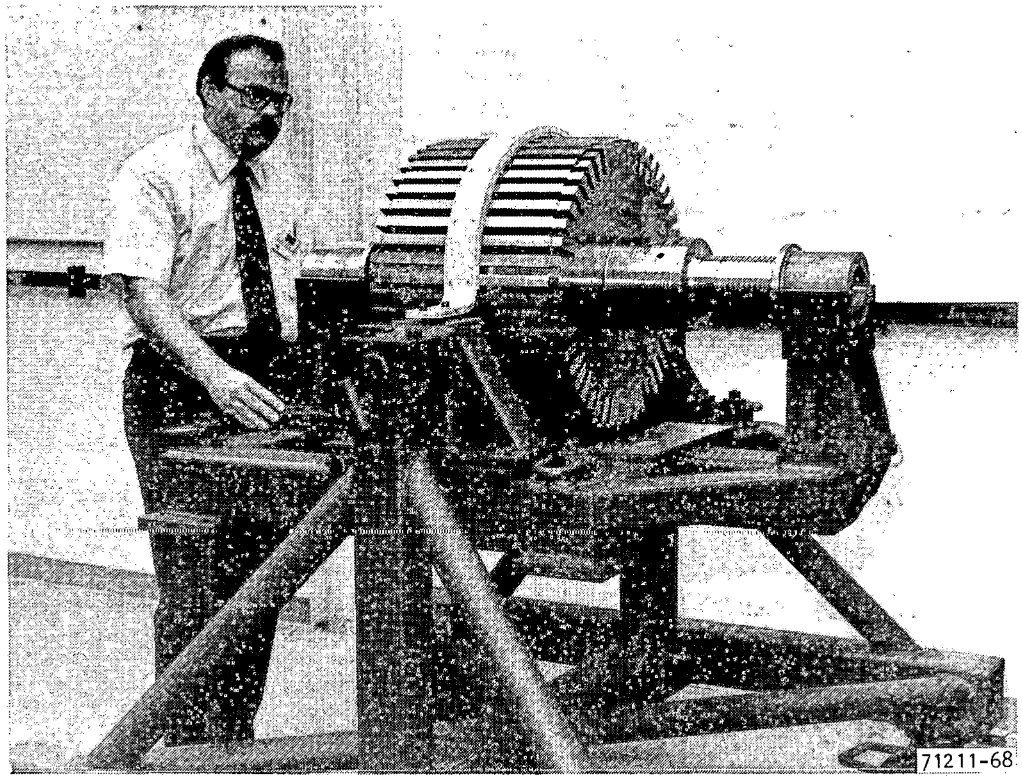

Figure 5-1. Rotor Core in Holding Fixture

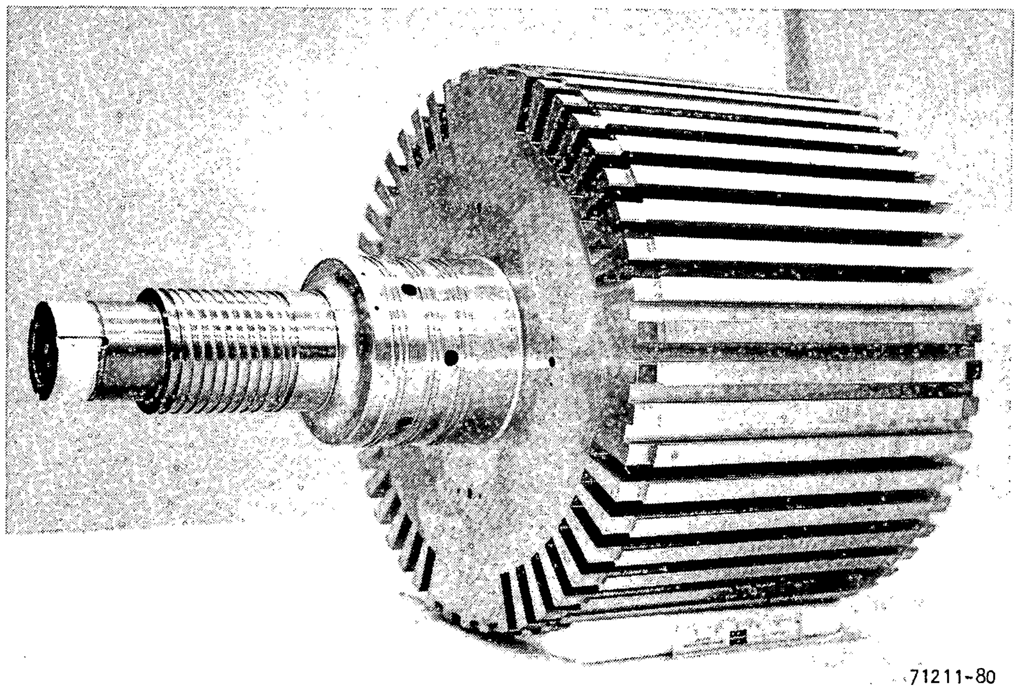

Figure 5-2. Finished Machined Rotor Core

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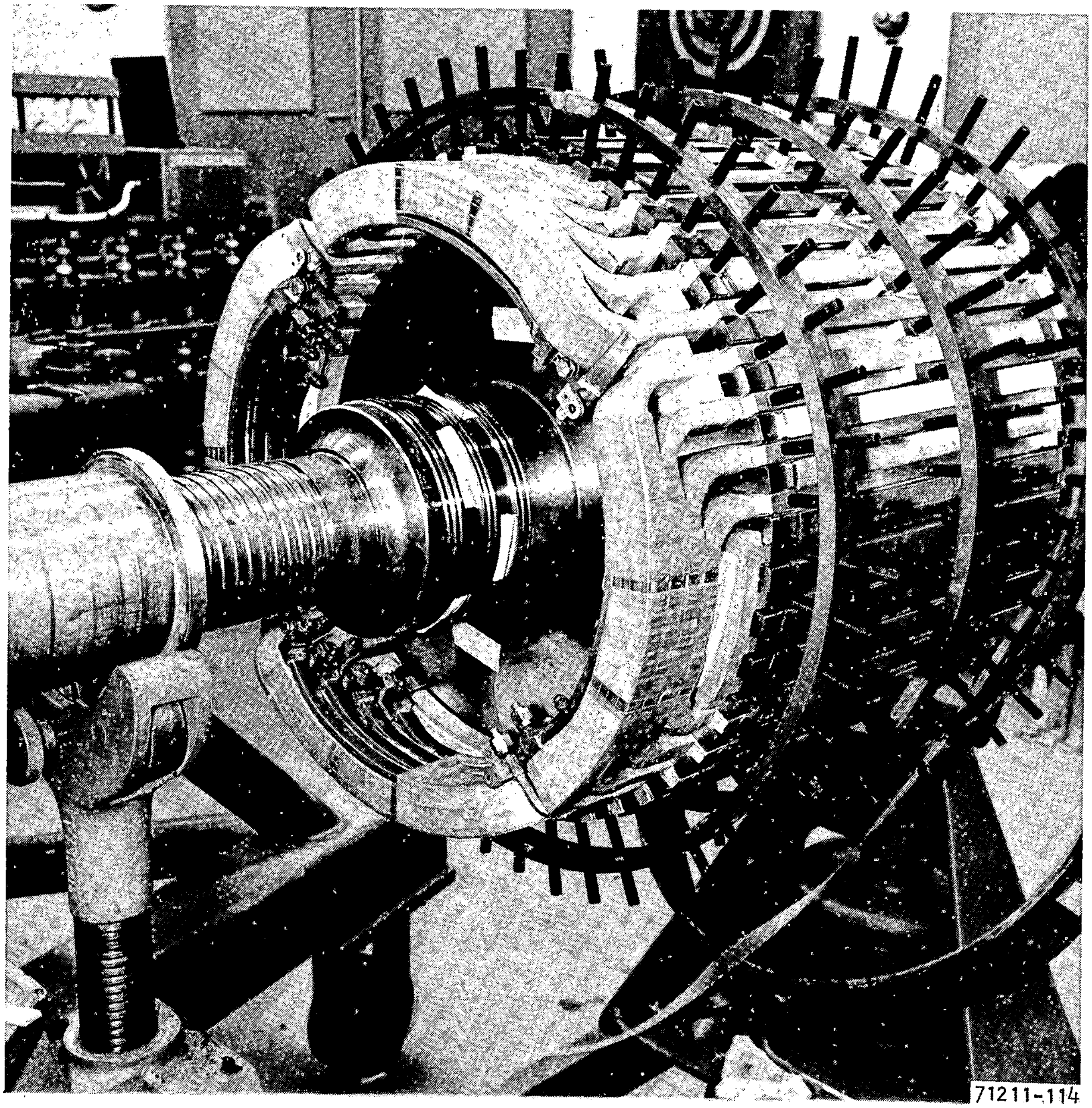

Figure 5-3. Clamp Rings

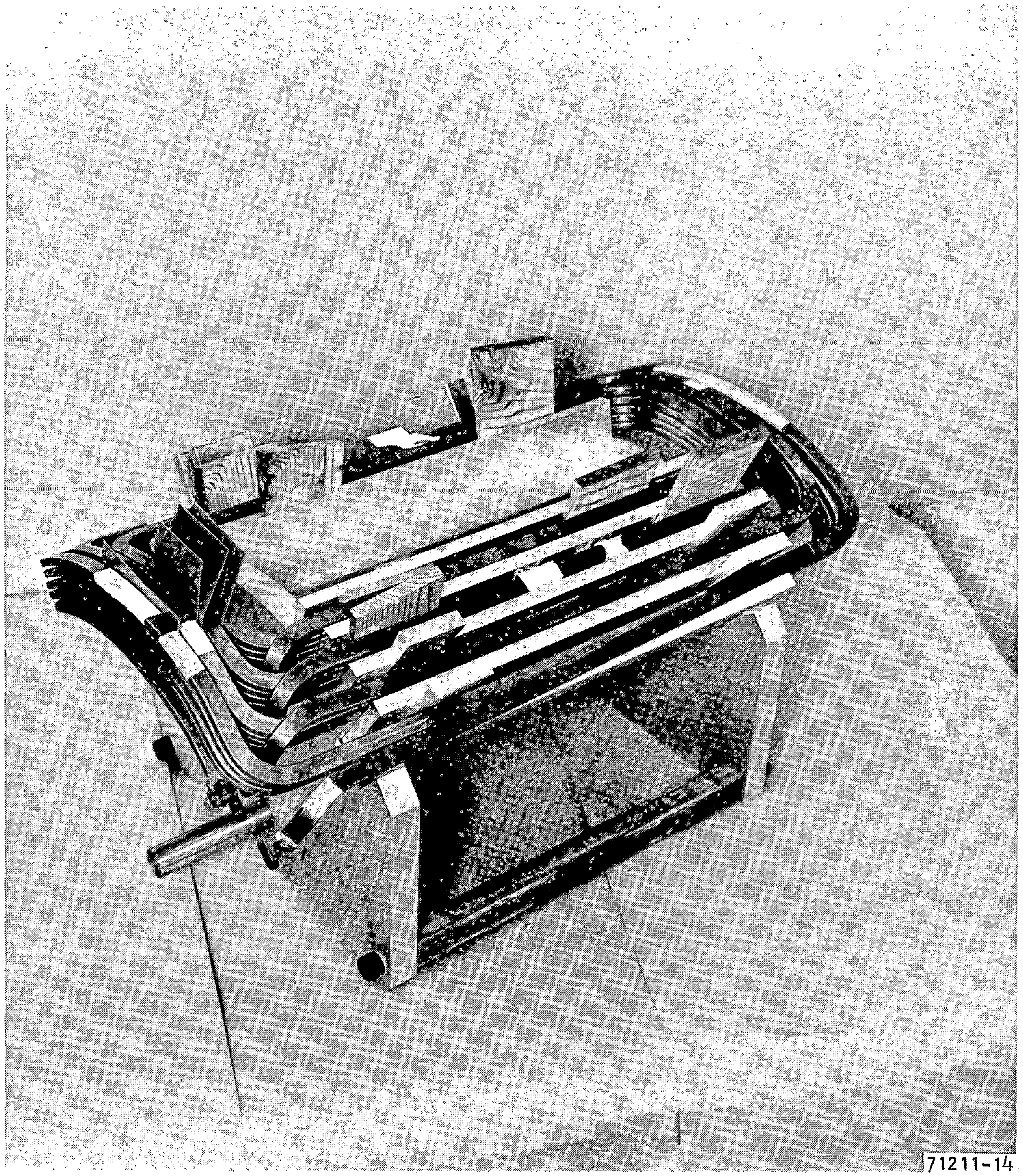

Figure 5-4. Rotor Coils in Inspection Fixture

The as-assembled cold fit of the support rings diameter is 0.062 to 0.070 in. tight. The rings were heated to 1100 F minimum to attain the radial thermal expansion necessary for assembly. A time limit of 2 min was established to prevent a hangup of the 65-lb rings due to cooldown.

The rotor manifold was completely assembled and the winding jumper bars were installed. The rotor transfer tubes (Figures 5-5 and 5-6) were then installed, each individually fitted. In some instances, this operation required slight adjustment of the coil connections to provide proper alignment. With the final blocking and supports secure, the slipring assembly and the internal manifold were installed. The rotor assembly was hydrostatically pressure tested to 450 psig with water to check transfer tube seals. As described in Section 8, the rotor was balanced and spin tested prior to assembly in the machine (See Figure 5-7).

STATOR STACK ASSEMBLY

The stator stack assembly (shown in Figure 5-8) is a 72-slot stator lamination stacked to form a conventional hollow cylindrical stator core. Laminations 0.014-in. thick were coated and bonded with Chrysler cycle weld K183 to provide a high interlaminar resistance. This two-step process creates an initial nominal coating thickness of 0.003 in. per side and a final average thickness of 0.0003 in. per side when stacked. Prior to being cured as a stack, the assembly was retained and clamped by nonmagnetic thru-bolts and end support plates that prevent lamination flaring. The stack was then post-cured at 400°F for one hour. The outside diameter of the stack was machined while still in the fixture to provide a fit to the housing ID of 0.032 to 0.042 in. tight. (This ensures good thermal conductivity and tightness at the elevated operating temperatures.)

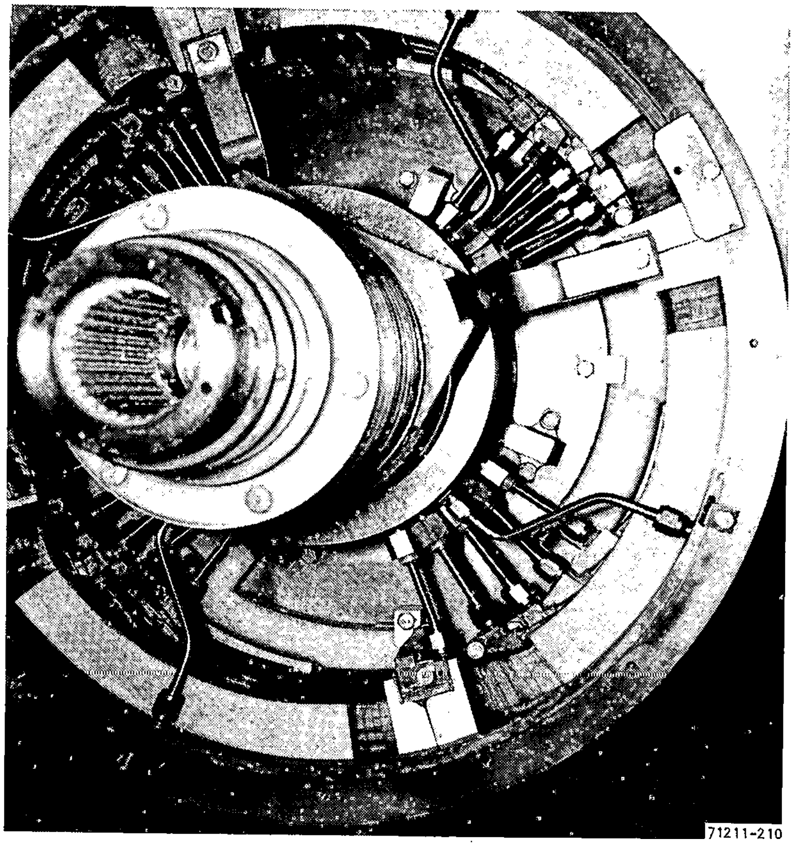

Figure 5-5. Upper End of Final Rotor Core

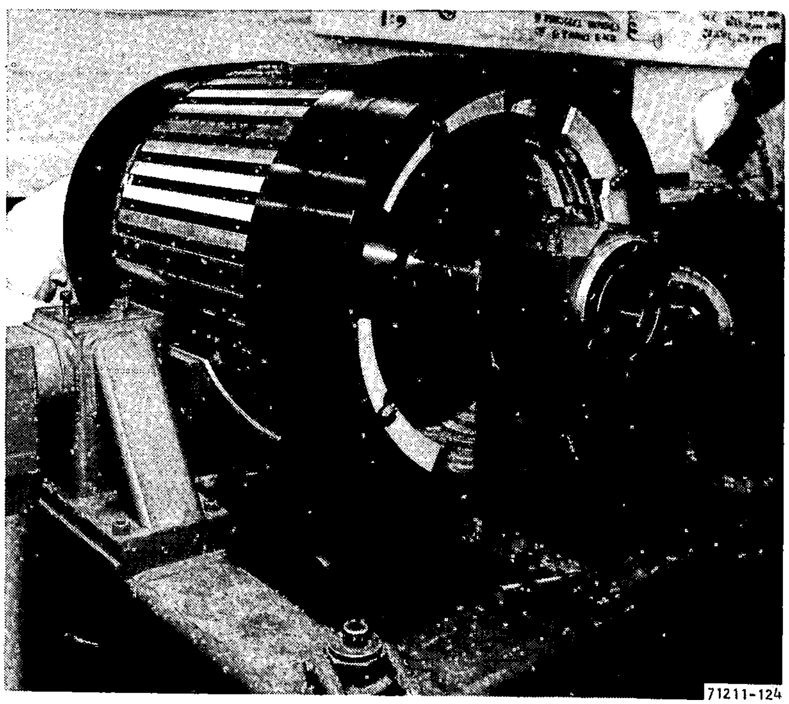

Figure 5-6. Lower End of Final Rotor Assembly

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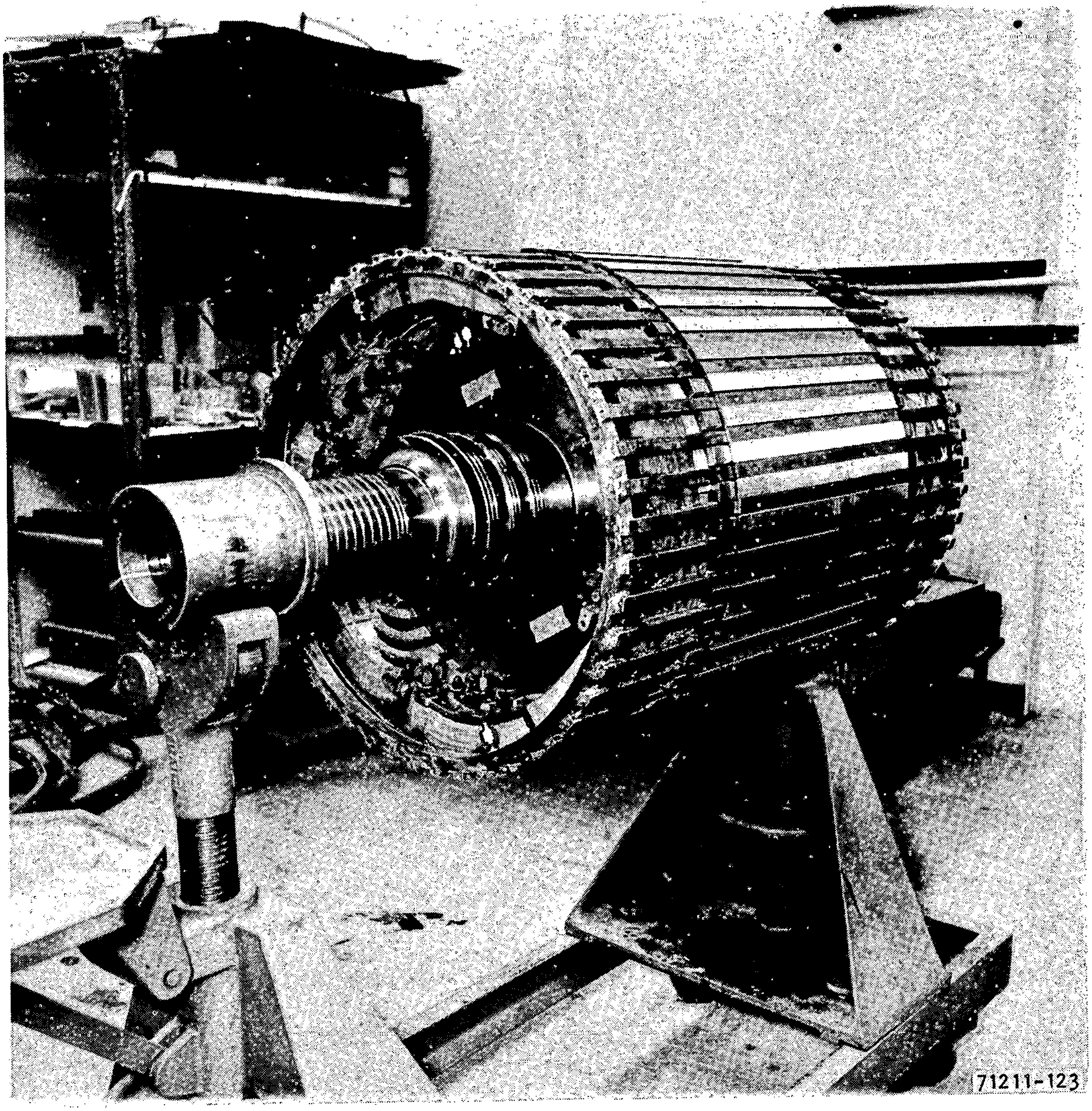

Figure 5-7. Completed Damper Bar Installation

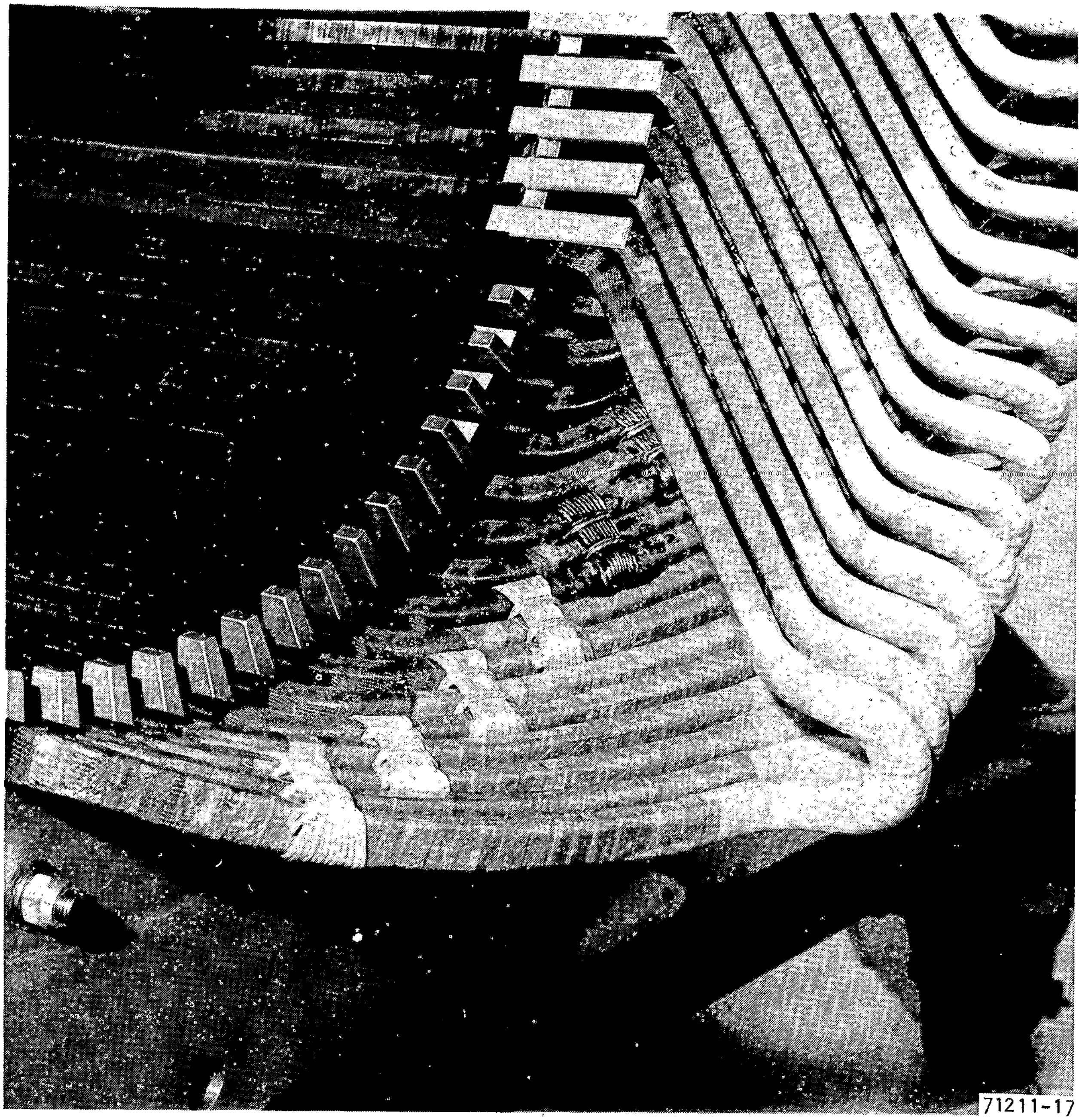

Figure 5-8. Stator Stack and Coil Assembly

STATOR HOUSING ASSEMBLY

The stator housing is a single, machined, aluminum forging. It was heated to 340°F for four hours to permit assembly over the stack. A plate was attached to the top flange and a guide rod used to lower the stator housing over the stack to the proper position. (Temperatures and dimensions were monitored, with time to cool recorded to ensure that a hangup did not occur.) The stack and housing assembly was then connected to the lower end-bell. The lower bearing housing bore was machined relative to the ID of the laminations. With the same machine setup, the top end-bell was lowered onto the housing and the top bearing bore machined relative to the lower bore to minimize bearing eccentricity. After locating pins were installed, the end-bells were removed and the stack placed in a special fixture for coil assembly.

STATOR COIL INSTALLATION

Tne 72 coils install into a stack with fairly deep slots. This, combined with the long coil pitch (due to four-pole configuration), made careful handling important, particularly during installation of the last 15 coils. By inserting a rod through the center of the stack for support, one side of the first 15 coils was lifted to facilitate assembly and tying of the final 15 coils. As each coil of the last 15 was installed, one of those tied up was released and positioned. The coil insulation is hot-pressed and nonflexible throughout, except for the knuckles, which are flexible and allow some deformation. This provided sufficient coil displacement to fit the coils (see Figure 5-9). Coils were periodically hi-potted during installation. With all slot sticks in, the entire assembly was hi-potted again. With final checks completed, the next operation was the brazing of special fittings to the coils.

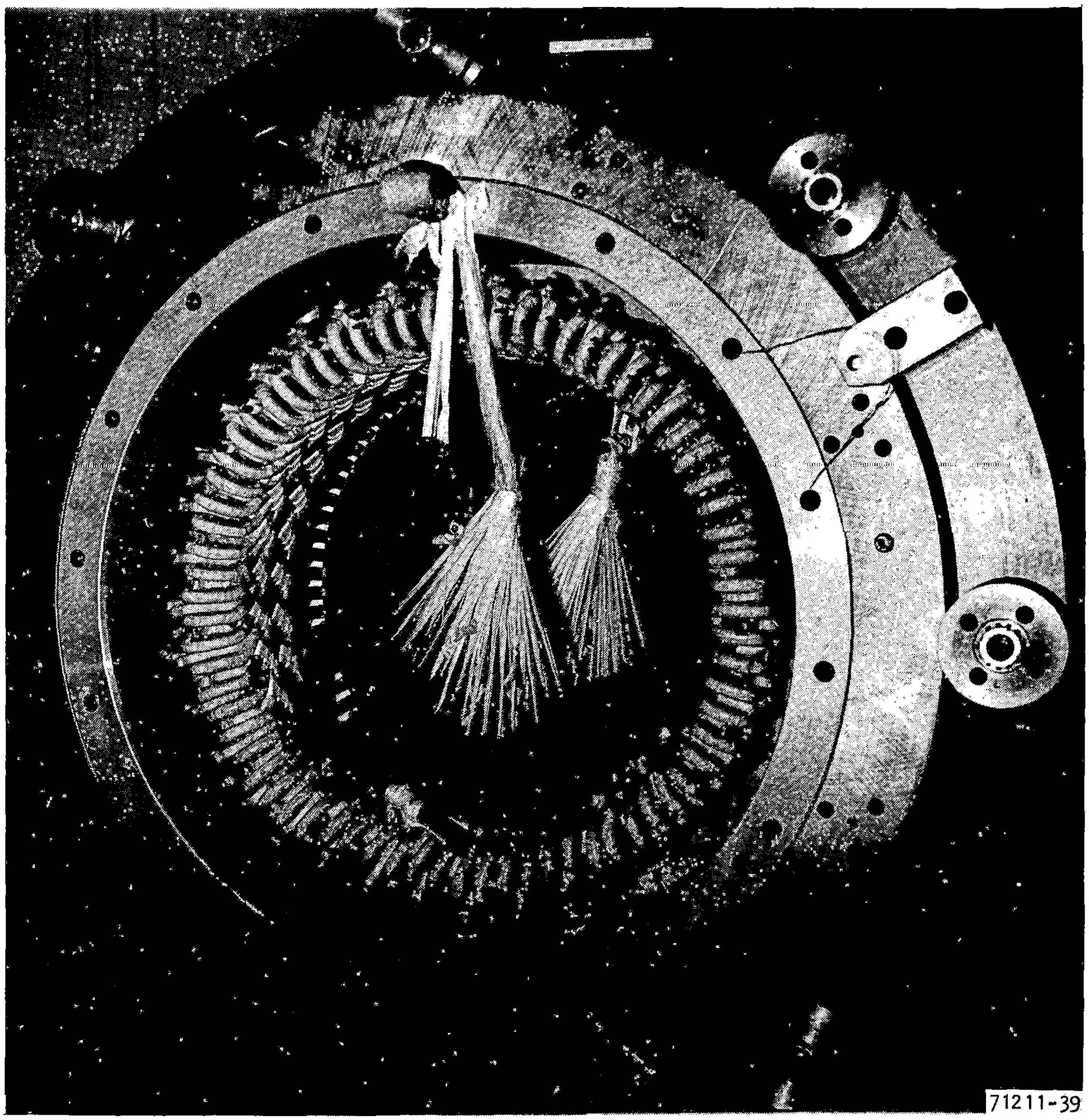

Figure 5-9. Support Arrangement for Installation of Last 15 Coils

Although series-connected electrically, the coils are parallel-connected hydraulically. This required the brazing of 84 fittings, 72 with four conductor-cooling passages and the remainder with two. An investigation was conducted to determine the most effective way to braze without damaging the coil insulation. After a comparison of various methods, including induction-brazed joints, the final decision was to use a torch with silver braze alloy (Bag No. 3). This alloy does not flow until heated to 1270°F, but with wet asbestos packed around the fittings several inches deep, an acceptable temperature of 450°F within 1 in. of the braze joint was maintained.

The coils, while being installed, were also partially blocked and secured to prevent movement. The jumper bars, except neutral, cover a span of about 90 deg and the arrangement is such that they are on 120-deg centers. The bars overlap phase-to-phase and with blocking and tying, provide a builtup support for the end turns (see Figure 5-10).

Blocking material used for the stator coils is glass mat polyester laminate, selected for its Class H (356°F) temperature capability, strength, and low moisture-absorption rate. Two pieces of the material were installed between three adjacent coils and the coils tied together with epoxy surge cable. A symmetrical pattern was established such that all coils were tied in two places at the inner and outer sides of both ends. In addition, epoxy surge cable (0.50-in.-dia) was tied to each coil at the knuckles, jumper bars, and twice around the outside of the lower end coils. After the blocking ties and cord were coated with Epoxolite 6107 to provide corona protection, the stator stack was oven cured at 135°F for 4 hours.

The SC machine external terminations are commercial 15 kV terminals with the inner end modified to fit within the confined envelope of coils and external housing. The modified end and the connecting jumper bars were taped. Each terminal assembly was then hi-potted to a minimum of 26 kV, providing an external standard terminal with quick attachment and high-voltage capability (see Figure 5-11).

FINAL ASSEMBLY

The stator assembly was bolted onto the lower end-bell. The lower bearings, with a dummy spacer, were assembled and used as a guide for installation of the rotor assembly. the rotor was lifted with special tools and lowered into place. Four spacers were installed between the rotor core and bearing carrier, which positioned the rotor about 0.25 in. from the lower bearing carrier.

A special fixture was fabricated to simulate the stator coolant manifold mounted to the upper end-bell. This was necessary to provide accurate sizing of the stator coolant lines (see Figure 5-12). These lines had to be sized and then brazed. Some realignment of fittings was necessary, both on the coils and the manifolds. Prior to final tightening, the B-nuts were tightened. Shrink tubing was then shrunk in place over the tube, providing additional creep distance between metal fittings of the close proximity coolant lines as shown in Figure 5-12.

Assembly of the end-bell with the brushes provides a compact subassembly that permits easy handling, inspection, and testing. The end-bell, a single-piece aluminum casting, also has the top bearing and seal installed.

Brushes were installed into 24 holders arranged in two rows. The pattern is staggered, one side to the other, to make use of a common mount that is water cooled and serves as a heat sink for the brush holders. Beryllia-ceramic plates between the brush holders and heat exchangers provide thermal conductivity and the required electrical isolation. The heat exchanger is, in turn, isolated from its support by a machined glass-reinforced ring. This ring supports and separates two bus rings that provide the terminations for the brush leads. (See Figure 5-13). Bus bars connect the bus rings to each side of the diode on the top of the end-bell.

Three lift screws and guide pins were used to install the top end-bell, to lessen the possibility of damaging the top seal and provide a controlled and guided descent onto the machine. The stator manifolds were then secured and machine flanges bolted together. Assembled to the top end-bell is a water-cooled, free-wheeling (clamping) diode connected across the field winding to provide transient protection.

With the upper bearing locating the rotor axis, the lower bearings were disassembled and the complete bearing and seal assembly installed. By installing the cover or final lower piece, the rotor was lifted approximately 0.015 in. off the spacers. This then permitted hand rotation of the rotor and with the installation of the resolver assembly (i.e., shaft position sensor) at the upper end of the shaft, the machine was ready for system connection and follow-on tests. The shaft position sensor, connected via a flexible shaft to the top of the SC shaft, is electrically and positionally phased with the rotor windings to provide propulsion system control.

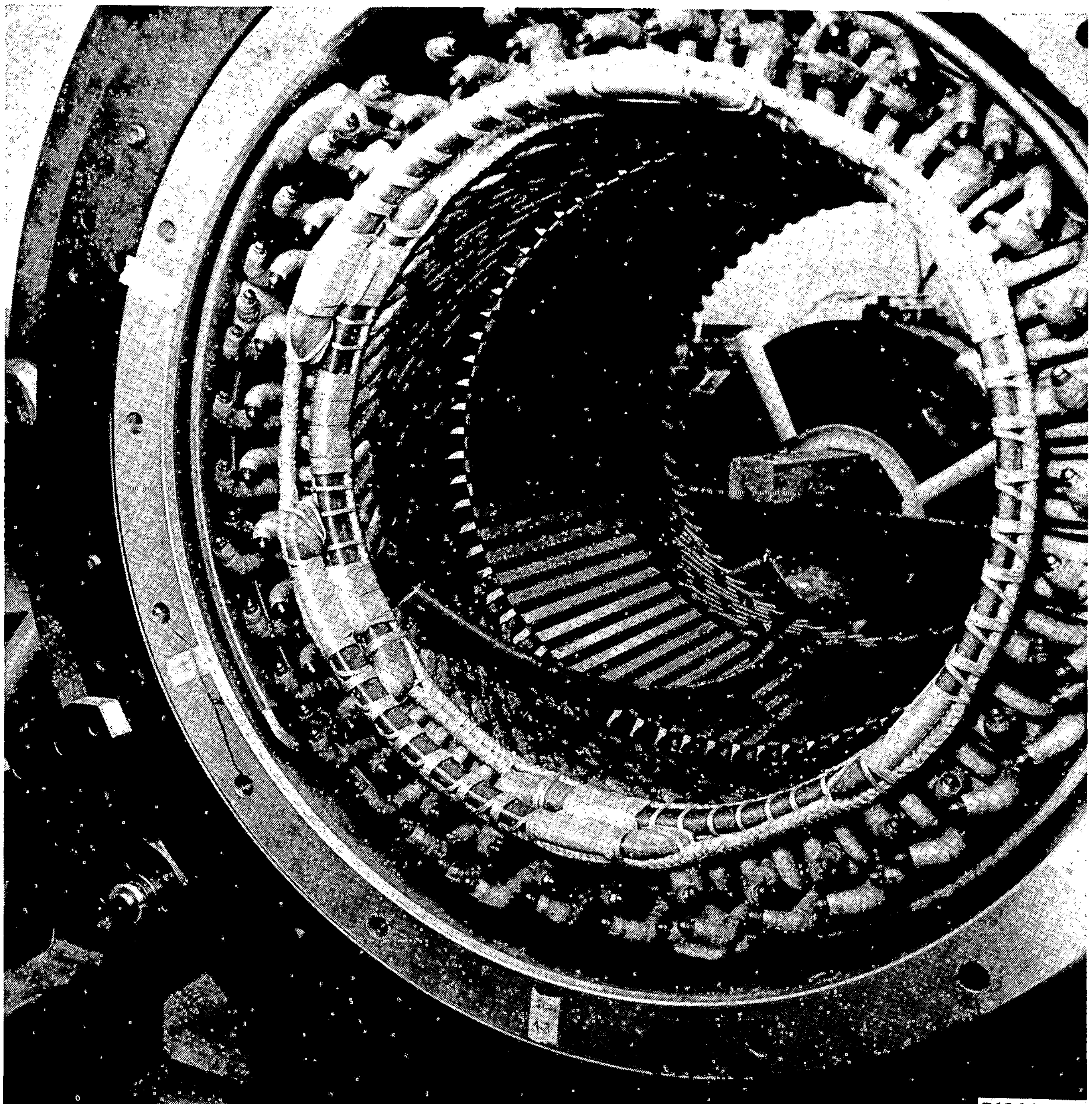

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Figure 5-10. Jumper Bar Installation with Coil Support Cord and Ties

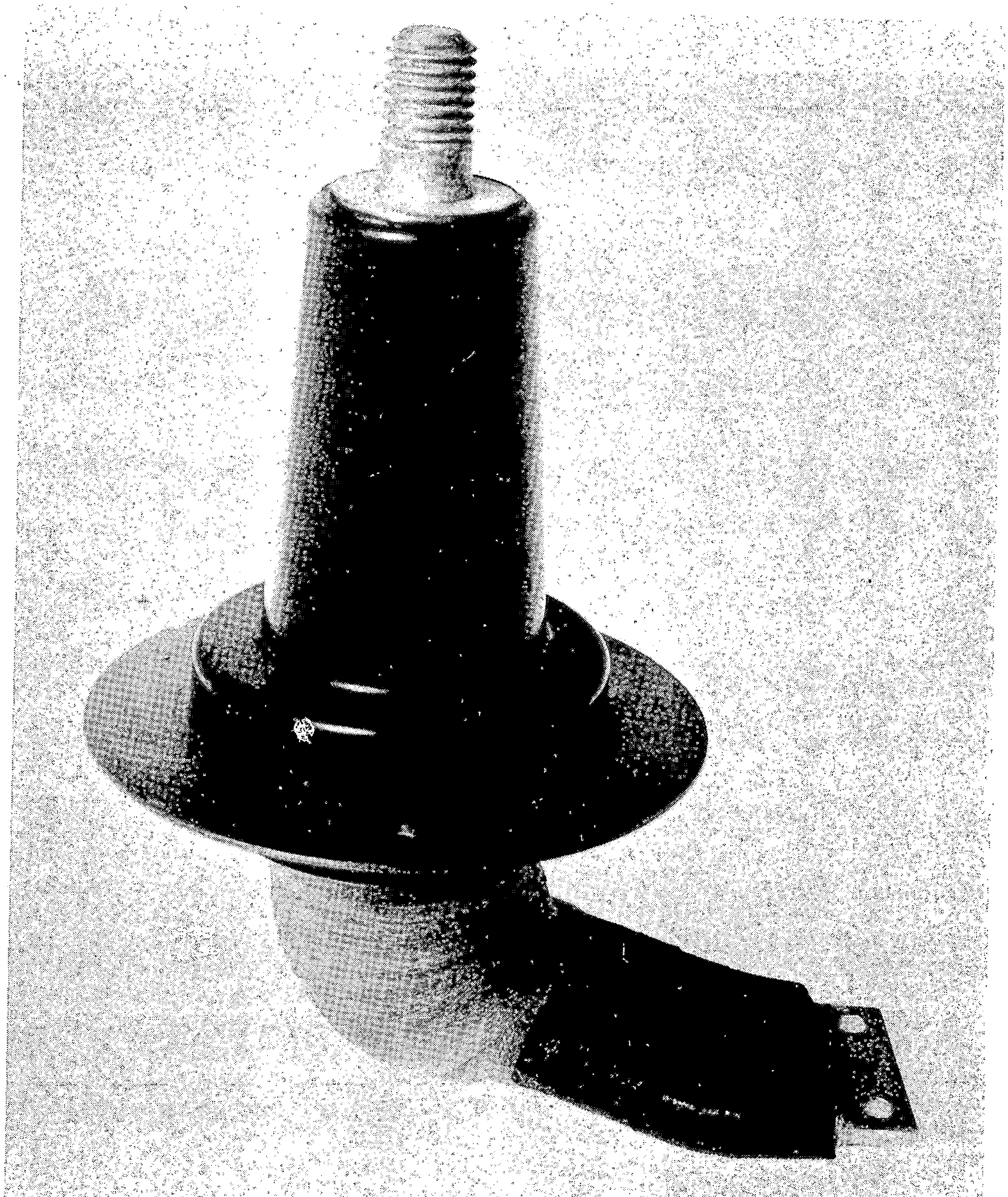


Figure 5-11. Typical Stator Terminal Assembly

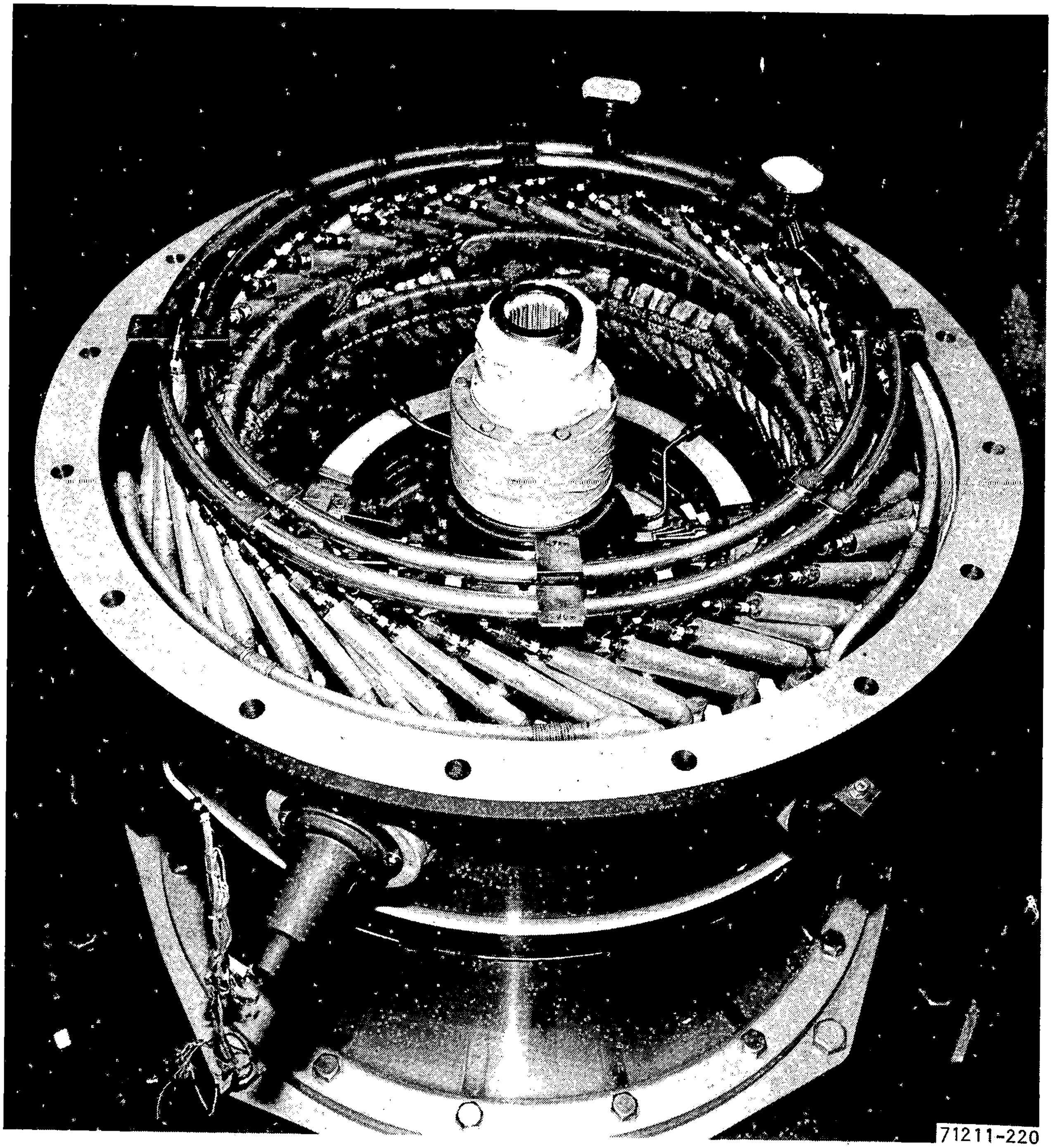


Figure 5-12. Stator Coil Coolant Transfer Tube and Manifold Assembly (Prior to Shrinking Installation)

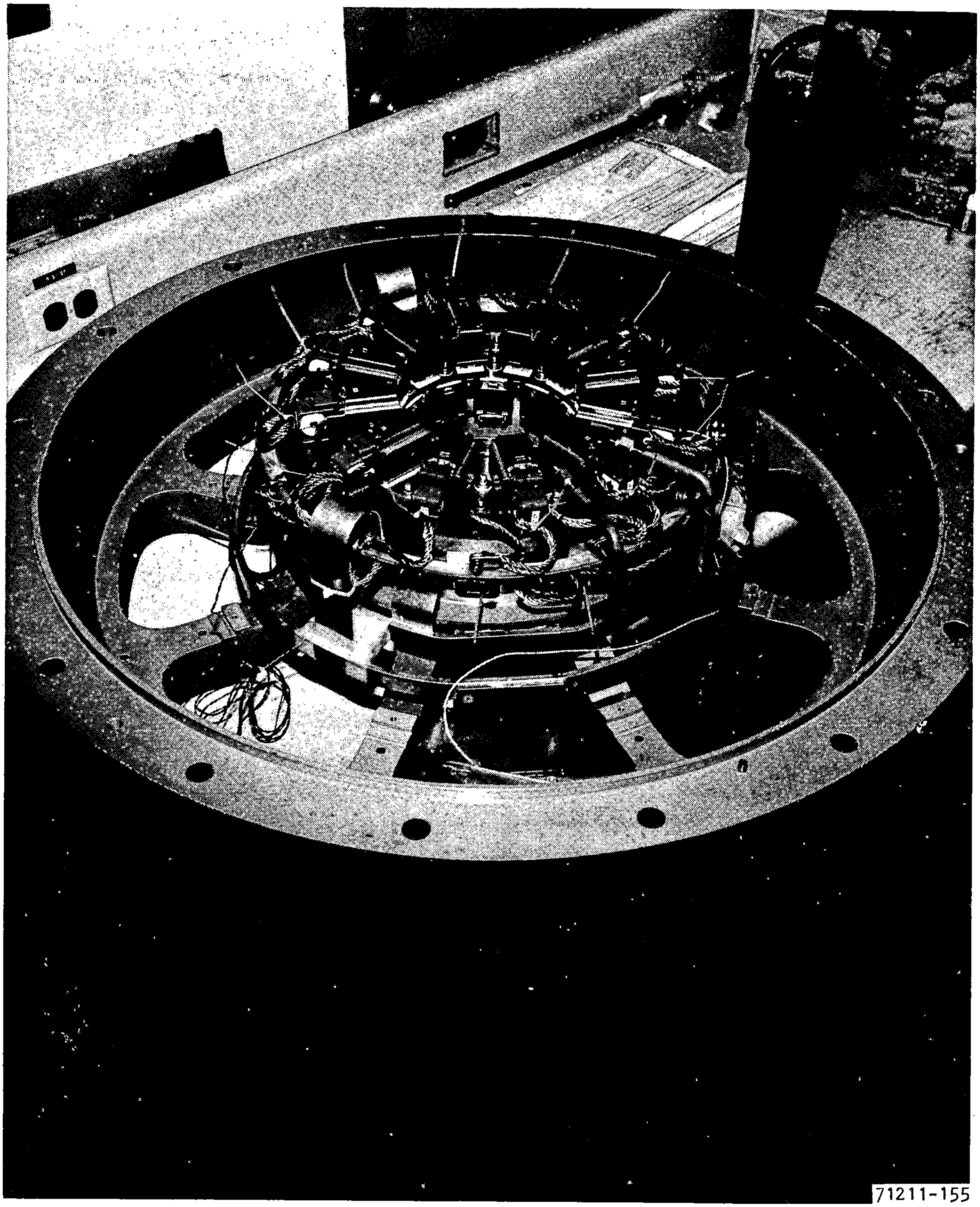


Figure 5-13. Top End-Bell Assembly

SECTION 6

DEVELOPMENT TESTING

Several construction aspects of the synchronous condenser required development testing to evolve and validate fabrication and assembly methods. Some of the unique tests conducted to meet inspection requirements are described below.

~~BRAZING TECHNIQUES~~

One of the design problems involved brazing the fittings to the coils in close proximity to the Class H, high-voltage insulation system. In addition, joints were (1) copper to stainless steel, (2) subjected to a 1000-psig water pressure test, and (3) usually required larger clearances then preferred for an ideal braze joint.

The high-strength requirement, compatibility criteria, and previous experience favored use of AMS 4771 or Bag No. 3 with B-1 flux. This material begins to flow at 1250°F, is compatible with most materials, and is widely used and readily available.

Numerous braze fitting configurations were investigated. Furnace and induction brazing with several different types of induction coils were evaluated. Various techniques with a contact induction brazing machine (similar to spot welding) aimed at localizing heat did not yield reliable or predictable joints. The technique found to be most consistent, repeatable, and least additive of heat to the insulation system was torch brazing, using wet asbestos (about 3 in. thick) packed around coil groups as a heat sink. Insulation susceptible to damage was covered in this manner and the temperature monitored by thermocouples 0.75 in. from the weld joint. Temperatures ranging from of 490° to 540°F were recorded while the braze alloy was melting at 1270°F. The appearance of the insulation on the coil test samples ranged from no indication of scorching to faint burn traces. All test joints were micro-sectioned after pressure tests to permit evaluation of the brazed joint.

Along with brazing, consideration was given to preventing flux contamination. After brazing, hot water and sodium dichromate (0.1 percent by weight) was power-flushed through the coils for two hours. Next, tap water was flushed through the coils and this was followed by a final flushing of distilled water. A resistivity reading was then taken to assure low contamination. The minimum criteria for acceptability was 200,000 ohms. Actual recorded values were 600,000 to 900,000 ohms.

Other braze samples were made to duplicate the type of joint between the rotor damper bar and its manifold. Using a hole size 0.04-in. larger than required, these samples were brazed and pressure tested. This larger hole permitted reasonable tolerance for positioning holes in the manifold. The joint successfully withstood 2800 psig water pressure. The proof pressure requirement for these connections is 2500 psig.

WATER CONNECTION

Four methods of transferring the water from a manifold to the rotor and stator coils via nonconductive hose or tube were investigated. Test specimens were: (1) a flexible nonconductive hose, (2) a nonconductive manifold, (3) nonconductive fittings, and (4) nonconductive, nonflexible transfer tubes. Configuration (4) was selected, a transfer tube made of Astrel 360, a thermoplastic (polyarysulfone) manufactured by the 3M Company. Astrel 360 has good high-strength properties at elevated temperatures, is an excellent dielectric, and has good machining characteristics.

The transfer tube configuration (Figure 6-1) is 3.10 in. long and uses standard 37-1/2 deg AN fittings (dash 4 size) for connections. Astrel 360 was also used as the dielectric in the rotor coolant transfer tube assembly as shown in Figure 6-2. This low-voltage winding required very small dielectric standoff distances (less than 0.10 in.) but was required to sustain higher water pressure due to dynamic pumping forces. Thermal and mechanical factors are also of more concern for these items. As shown in Figure 6-2, an O-ring provides a seal for thermal and dynamic radial movements and also compensates for the radial location of the rotor coil fittings due to assembly tolerances.

Another candidate material that showed excellent properties was a polyimide resin. The latter passed all critical tests, but there was some question of degradation due to prolonged exposure to hot deionized water.

Prior to transfer tube selection, all four configurations were subjected to a 24-hour thermal/pressure cycle test. A special fixture was fabricated to hold the test specimen ends during oven aging. Inlet pressure to each specimen was cycled from 0 to 450 to 0 psig with water, while the ambient temperature was cycled from room temperature to 225°F to room temperature. Other than requiring a slight retightening after the initial cycle or two, specimen (4) completed the test without leakage. Thermal/pressure cycle test results for the other three test specimens and criteria for their nonselection are described below.

<u>Specimen (1)</u>

The first approach involved use of flexible hoses to minimize misalignment problems and reduce possible thermal expansion effects. A test program for hoses was initiated, including resistance readings, pressure tests, and

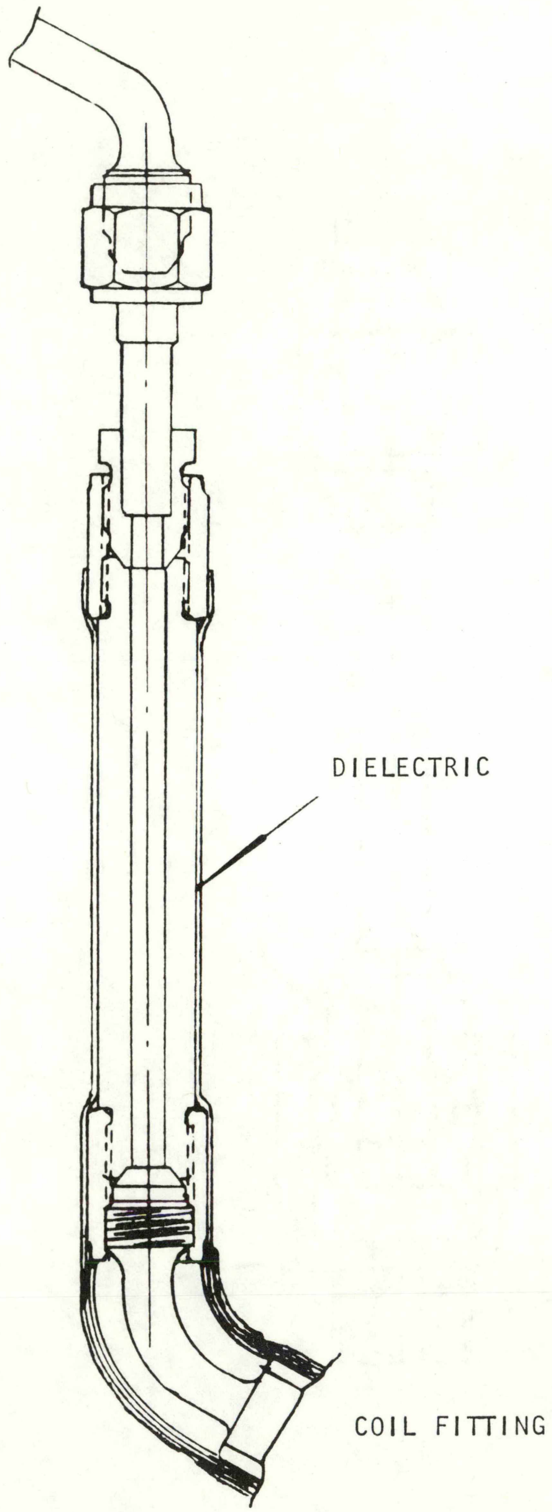


Figure 6-1. Stator Coil Coolant Transfer Tube

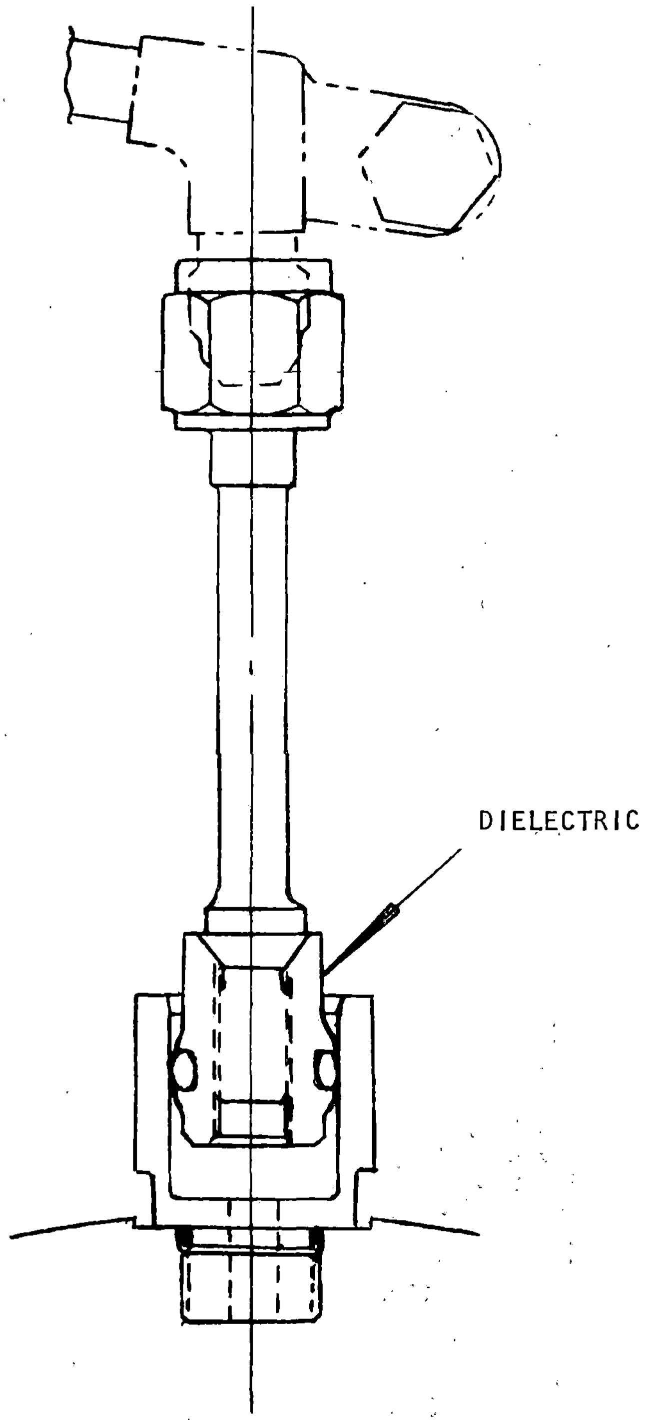


Figure 6-2. Rotor Coil Coolant Transfer Tube

thermal cycling. The hose that apparently met all criteria was a convoluted Teflon tube with an outer wrap of Nomex braid. The Teflon was swaged to the AN fittings. Samples furnished for tests passed all preliminary requirement criteria for two different sizes, 1/4- and 3/8-in. However, in the process of production testing, the hoses failed thermal cycling tests. Initial testing at 800 psig and elevated temperature indicated no leakage; although, after cooling and repressurizing/reheating, leakage occurred at the swaged joints. (This hose is used sucessfully in other applications, but it proved unsuitable under the prevailing high-temperature, high-pressure conditions of this application.)

Specimen (2)

Initial results were promising. A small thermoplastic manifold with thick walls was tested. However, a fairly complex, small, compact configuration was needed. An extremely high cost of tooling, plus a fairly high risk factor in developing a small single-piece configuration made this approach unattractive.

Specimen (3)

Attempts were made to construct a suitable union for the rotor based on an AN-5 fitting. Various plastics were used, including some with glass fiber reinforcements. the thermoplastic and polyimides proved superior with respect to mechanical properties and machinability in small size. Although these specimens functioned satisfactorily, they lacked the strength to carry the required load.

LOWER END-BELL CASTING

Development testing was also conducted on the lower end-bell. This casting has deep, thin webs and struts. Compared with the majority of the mass, these webs and struts have very small cross section. Since the flange is the sole support of the SC, maximum cast properties were a must. Also cast integrally was a coolant coil of 1/4-in. stainless steel tubing. The intent was for only one pour, as there was only one cooling coil available. To anticipate the chill problem for the large cross sections and to analyze material properties, three separate pours of aluminum were made of a section one-eighth of the configuration or one strut. After each pour, the casting was X-rayed and checked for porosity. Chills were modified after each cast with the second and third casts sectioned at the strut, pull bars made, and the material properties checked. The 356-T61 aluminum alloy satisfied MIL-A-21180 Class I (Table IV) spec requirements, and the entire end-bell was poured with the 65-ft stainless steel coolant coil cast in place.

ROTOR CORE

Rotor fabrication involved a three-piece forging joined by means of electron beam welding. All previous AiResearch history with the Republic HP9-4-20 steel alloy was based on TIG welding. Specimens of the forgings were cut to duplicate length and angle of the finished weld and welded together to set up the proper weld schedule. They were then machined into pull bars to check post-weld mechanical properties.

Plating

Additional parts of the rotor forging samples were used for the electroless nickel plate process and to establish some of the machining specifications. Several pieces were used to compare the magnetic properties before and after welding.

Testing

The primary test for the low-voltage, noninsulated rotor coil was pressurization to 2800 psig. The coils were also calibrated by enlarging an orifice to establish a 1.5-gpm water flow at 105 psig.

Insulation

The stator coil mica insulation system was a critical development item. It must withstand an operational voltage of 7150 V line-to-line in a Class H (356°F) temperature environment. Test bars made with the stator conductor and the insulation system were given accelerated life tests at 356°F, 150 VRMS per mil, and 60 Hz. The test specimens successfully met the insulation requirements for an endurance period in excess of 2500 hours.

Each coil consists of six hollow conductors individually insulated with one layer half-lap wrap, of 0.001-in.-thick Kapton tape with double Dacron-glass. The coil is wound as two parallel conductors, three-turn configuration. The turns were separated by one layer of 0.00545-in.-thick Dacron tape, which is then single-layer wrapped around the six conductors. Covering this are five and one-half layers of B-stage epoxy mica papers with glass cloth and 0.008-in.-thick Dacron mat backing applied with half-lap wrap. Final outside insulation is one layer of asbestos tape. The coil regions that fit into the slot were then painted with a conducting (graphilic) air-drying paint, and the remaining coil was coated with a nonsilicone, air-drying varnish. This insulation system provides a Class H (356°F) temperature capability and operates at 90 V per mil in the actual application, which is approximately 1.8 times the normal commercial rating (See Figure 6-3).

In addition to the test bar sample, drawing requirements call for a turn-to-turn insulation test at room temperature at 40 to 50 VRMS/mil (1800 VRMS for 15 sec at 60 Hz), and a ground insulation test-conductor-to-ground (metallic sheath) at 20,000 VRMS and 60 Hz for one minute at room temperature. Coils are pressure tested to 900 psig while restrained and flow tested at 0.25 gpm flow, 220 psig pressure, and 168°F temperature.

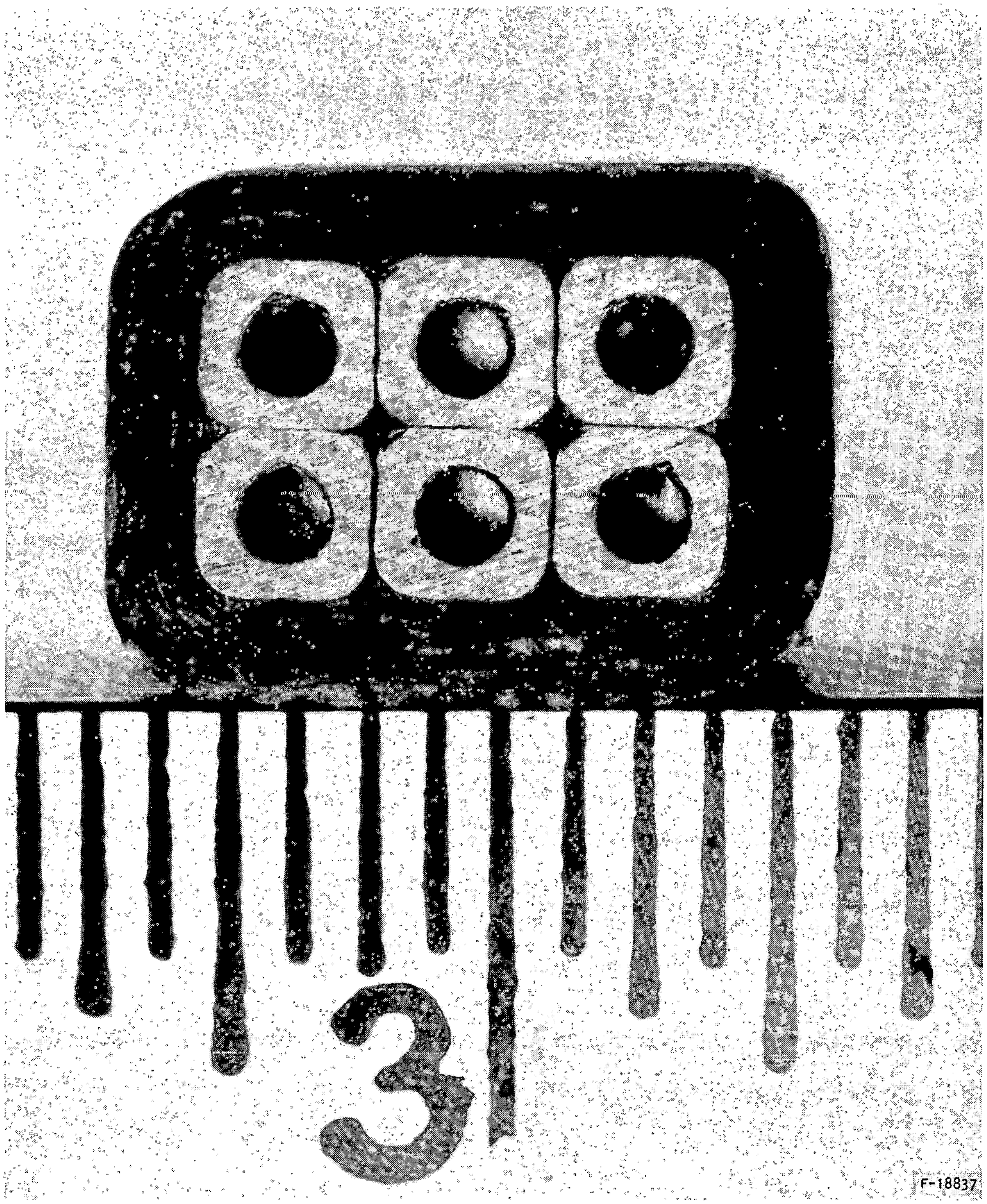


Figure 6-3. Typical Stator Coil Hollow Conductor Configuration

SECTION 7

FUNCTIONAL TESTING

TEST RIG

A dynamic model of the synchronous condenser was constructed to simulate actual operating conditions for brushes, sliprings, bearings, seals, and water manifolds. Among the achieved goals were:

At rated speed, current, and temperature, brush wear was 0.0001 in. per hour with no apparent slipring wear.

SC design intent was verified during operation at rated field current (2750 A), voltage (128 V), and speed (5000 rpm).

The SC was operated more than 17 hours under electrical power with 14 hours at rated speed. Total running time was 43.5 hours.

Data was taken at various speeds and ratings, providing assessment at other than rated conditions.

No visible wear or leakage was noted at the upper shaft lubrication seal.

The brush assembly was successfully operated with and without water coolant.

Rotating manifolds (inner shaft water transfer and blanked-off rotor coil) proved leak-free and created no balance problems with water flow.

Bearing and seal maintainability without disturbing the basic assembly was confirmed.

Testing was conducted on various lower face seal rotor and bearing nut combinations. Total sealing of the lower bearing face seal needed to be accomplished, although slight leakage did not impair the operating performance of the other components.

The model was a vertical machine, driven by a 25-hp, 0-to-6000 rpm hydraulic motor. A dummy rotor was used (See Figure 7-1), and actual rotor weight was simulated by a preload created by coil springs, making it possible to increase or decrease the load as desired. Actual component hardware, except rotor and support structure, was used (See Figure 7-2).

With the preload based on the calculated weight of the rotor (1750 lb), the bearings and seals were subjected to rated speed and temperature operating conditions. Coolant flowpaths for bearings, slipring assembly, and brush holders were identical to the final configuration, and provided a means of evaluating the seals as well as the heat transfer capabilities of various cooled components.

Instrumentation was the same configuration as that to be used in the final unit. Thermocouples were inserted in six brushes for temperature monitoring; the respective supporting holders were similarly instrumented. The upper roller bearing and the two lower duplex bearings were monitored for temperature on their OD. In addition, temperatures for the lower bearing cavity face seal and the coolant water were recorded. Water flow and pressure measurements were taken for each of the major coolant flowpaths (i.e., rotor in and out, bearing housing, and brush heat exchanger). Accelerometers measured vibration in three axes at both the upper and lower bearings.

For additional data, various designs were evaluated with the same bearings but different seal configurations. Specimens included a high-speed

Figure 7-1. Test Rig Dummy Rotor, Rotor Manifold, and Lower Duplex Bearing

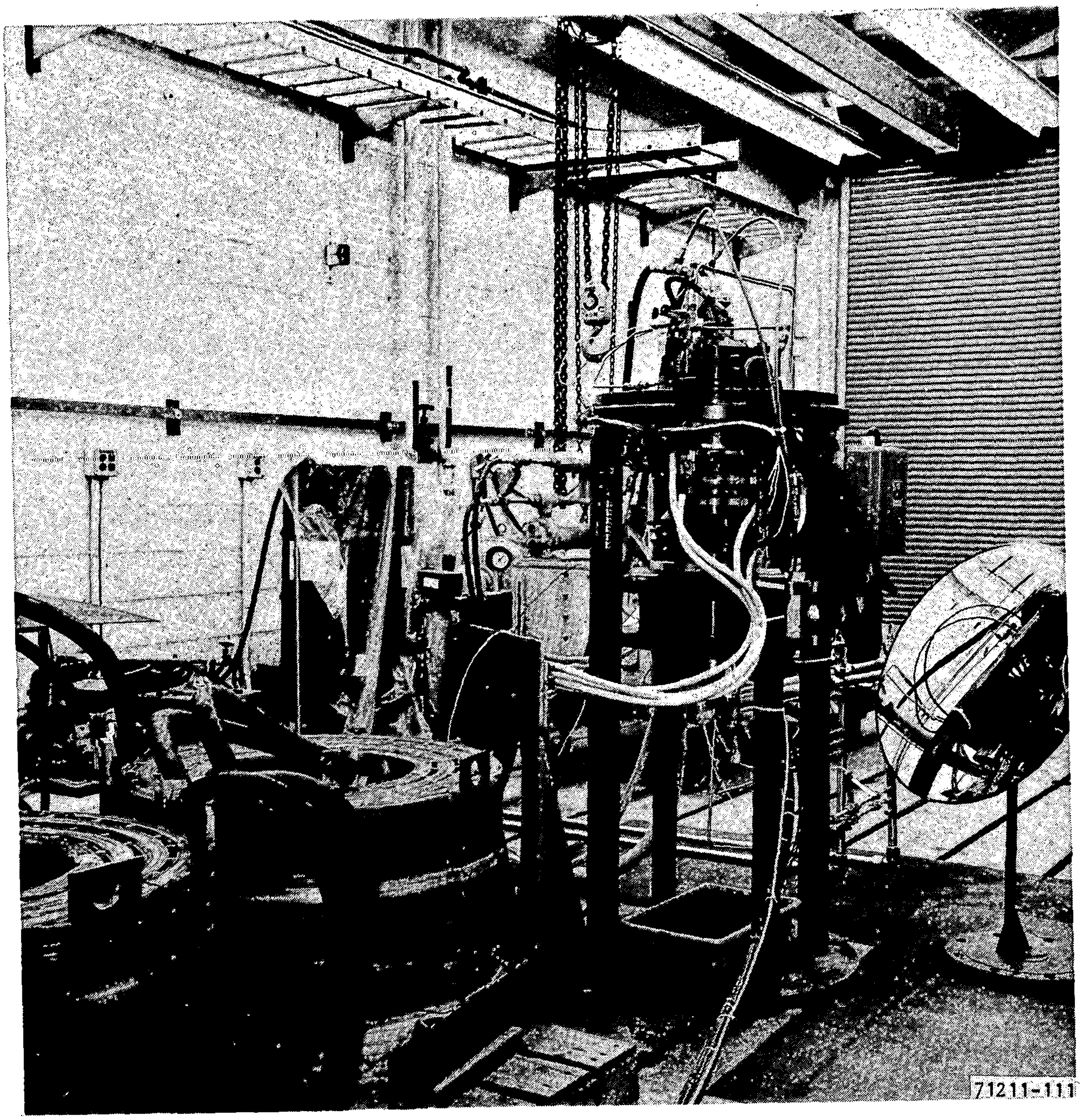


Figure 7-2. Synchronous Condenser Test Rig

lip seal, reversed face seal installation, a dual labyrinth, refloating seal rotor, and the existing face seal with various springs to provide different loading conditions on the carbon. Twenty-one tests were completed with 16 different configurations, including an 8-hour endurance test with a single lower bearing configuration. These tests provided a comparison of sealing capability and running characteristics for future consideration.

FUNCTIONAL TESTS

The facility test capability (torque and hp) was limited so that only partial load testing could be employed. The drive for the machine was powered by two side-by-side dc motors mounted vertically above the SC. Capable of a combined 500 hp, these motors were each connected by drive chains to a center drive shaft that transmitted torque through a crowned spline coupling to a drive spline on top of the SC shaft, as shown in Figure 7-3.

SC operational procedures during test stages were based on IEEE publication No. 115, "Test Procedures for Synchronous Machines." Short circuit tests were performed at reduced speed. Zero power factor tests, although desirable, were precluded due to the unavailability of time and funds necessary to complete testing within the allotted period. SC electrical characteristics, cooling system capability, and mechanical integrity were tested to establish conformance with acceptance criteria. No-load saturation tests were performed at speeds of 1250, 3050, 3200, and 4950 rpm (rated speed), and short-circuit and negative sequence tests at one-half rated speed. Additional tests also were conducted to collect thermal data samplings, recheck rotor balance, investigate overspeed, verify instrumentation adequacy, check out the TLRV system field power supply, and research critical speed resonant frequencies.

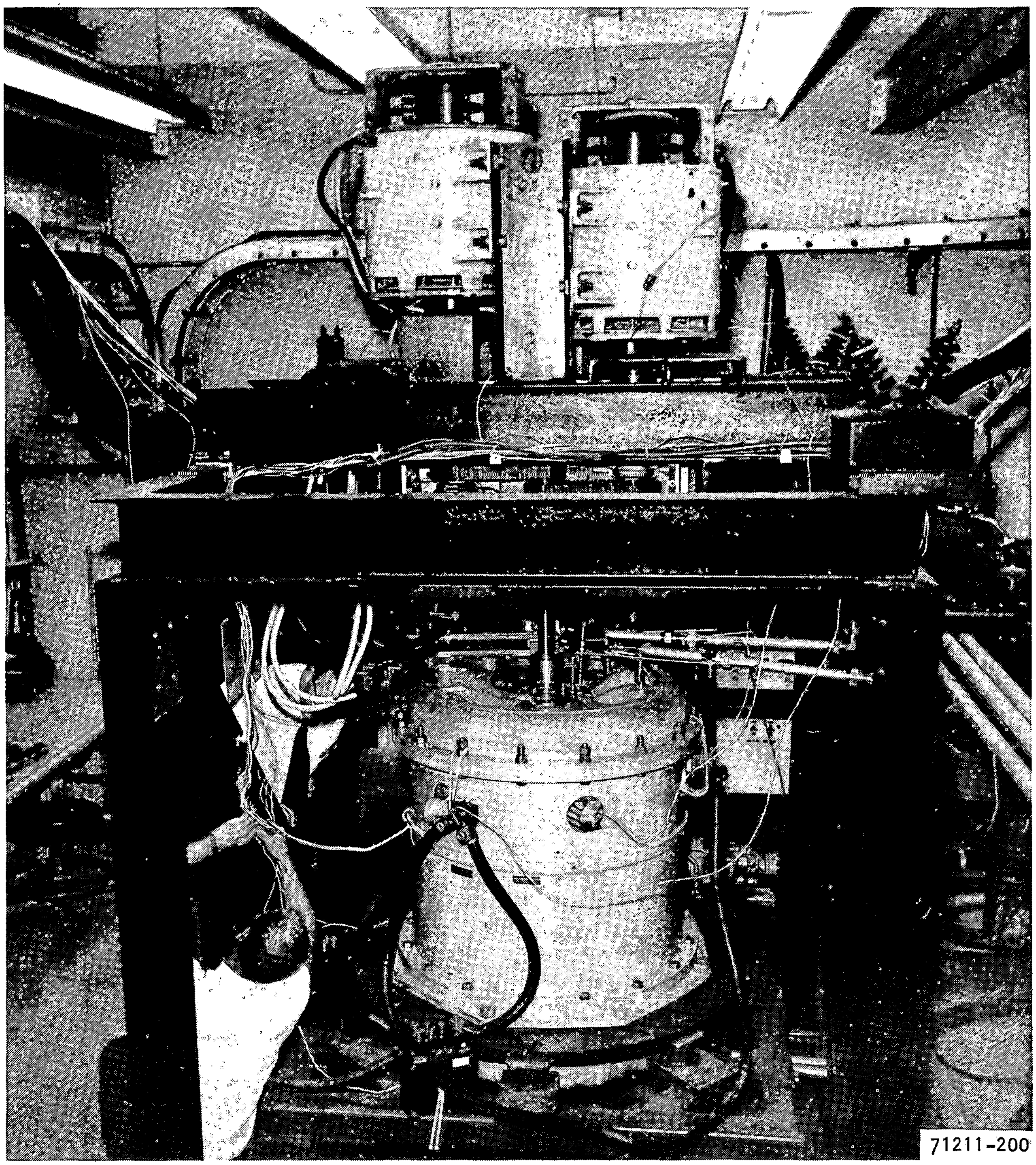


Figure 7-3. Functional Test Setup

Initial runs were made to determine the test facility drive characteristics, and vibration peculiarities, and to determine a bearing temperature profile. The first rated speed run was conducted after 4.2 hours of running at reduced speeds without cooling water or current applied to the SC. With the cooling system fully operational, current was applied after 7.2 hours of preliminary testing.

On the final run, the SC was satisfactorily operated at rated speed (4950 to 5050 rpm) with various levels of output voltage up to 110 percent of the rated 7150 VRMS L-L. A 13-minute portion of this test was performed at rated voltage with a total run time of 30 minutes. (Coolant water conductivity was 4.6 megohm-cm.) Test results are presented in curve form in Figures 7-4 through 7-15. Additional information on various runs is provided below.

The first no-load saturation run was conducted at a speed of 1100 rpm followed by a 2500 rpm no-load saturation run using the final TLRV system phase delay rectifier field supply. Data was recorded at current levels up to 2000 A at a speed of 1100 rpm (see Figure 7-4). At 2500 rpm (one-half rated speed), no-load saturation characteristics were measured with field current up to 1500 A and line-to-neutral voltage of 3300 V (see Figure 7-5). Thermal tests under short-circuit conditions were conducted at one-half rated speed, followed by negative sequence reactance tests at one-half rated speed (see Figures 7-6 and 7-7). With a line-to-line short circuit continuously applied, values for negative sequence reactance were verified as 0.31 per unit at 200-A field current and 0.27 per unit at 600-A field current (Reference: IEEE Publication 115, method 26.3, para 7.40.30). Various runs were made to check balance characteristics. Included in this testing phase was a thermal check at various speeds under no-load saturated conditions, for recording

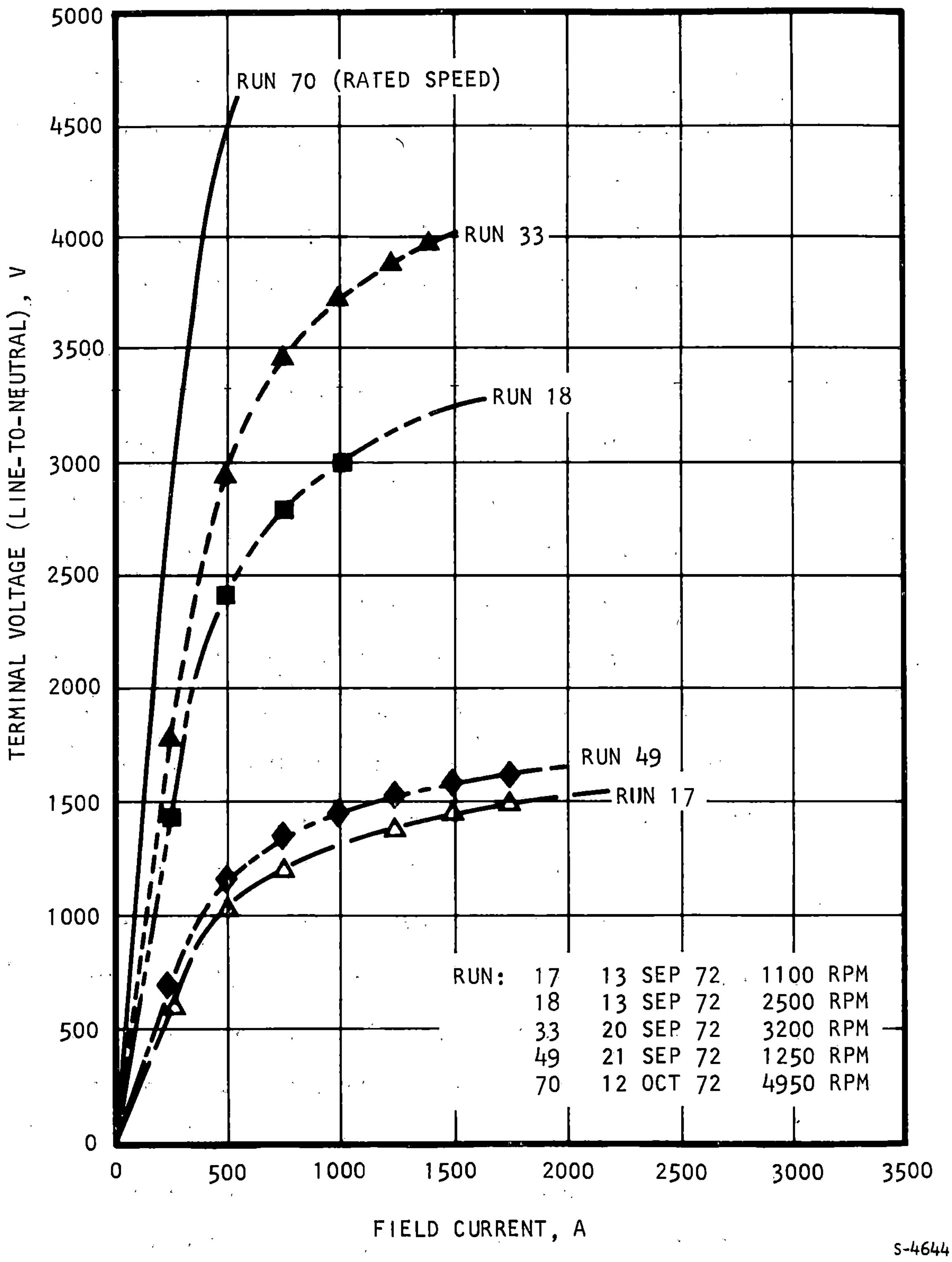


Figure 7-4. No-Load Saturation Tests

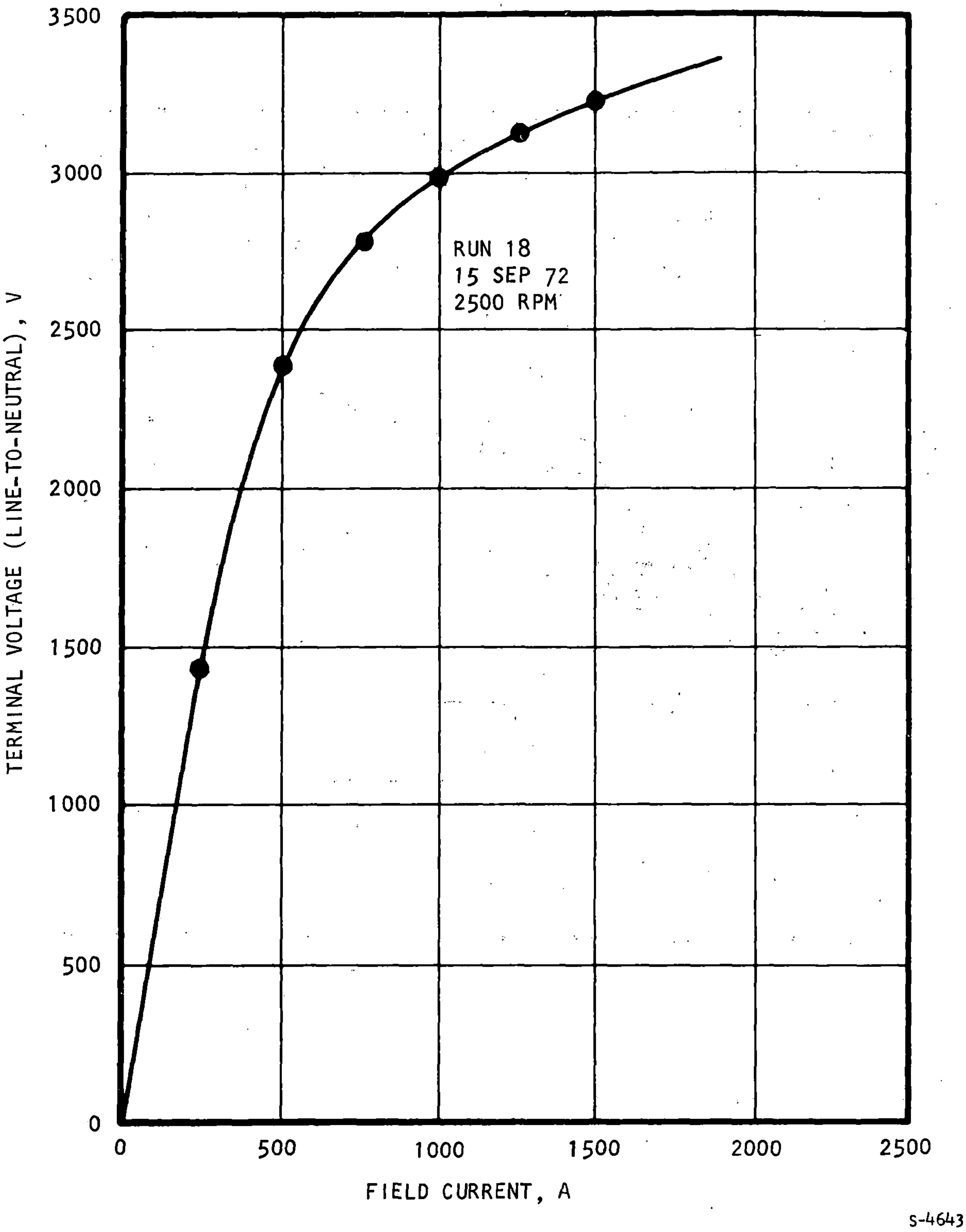


Figure 7-5. No-Load Saturation Test at One-Half Rated Speed

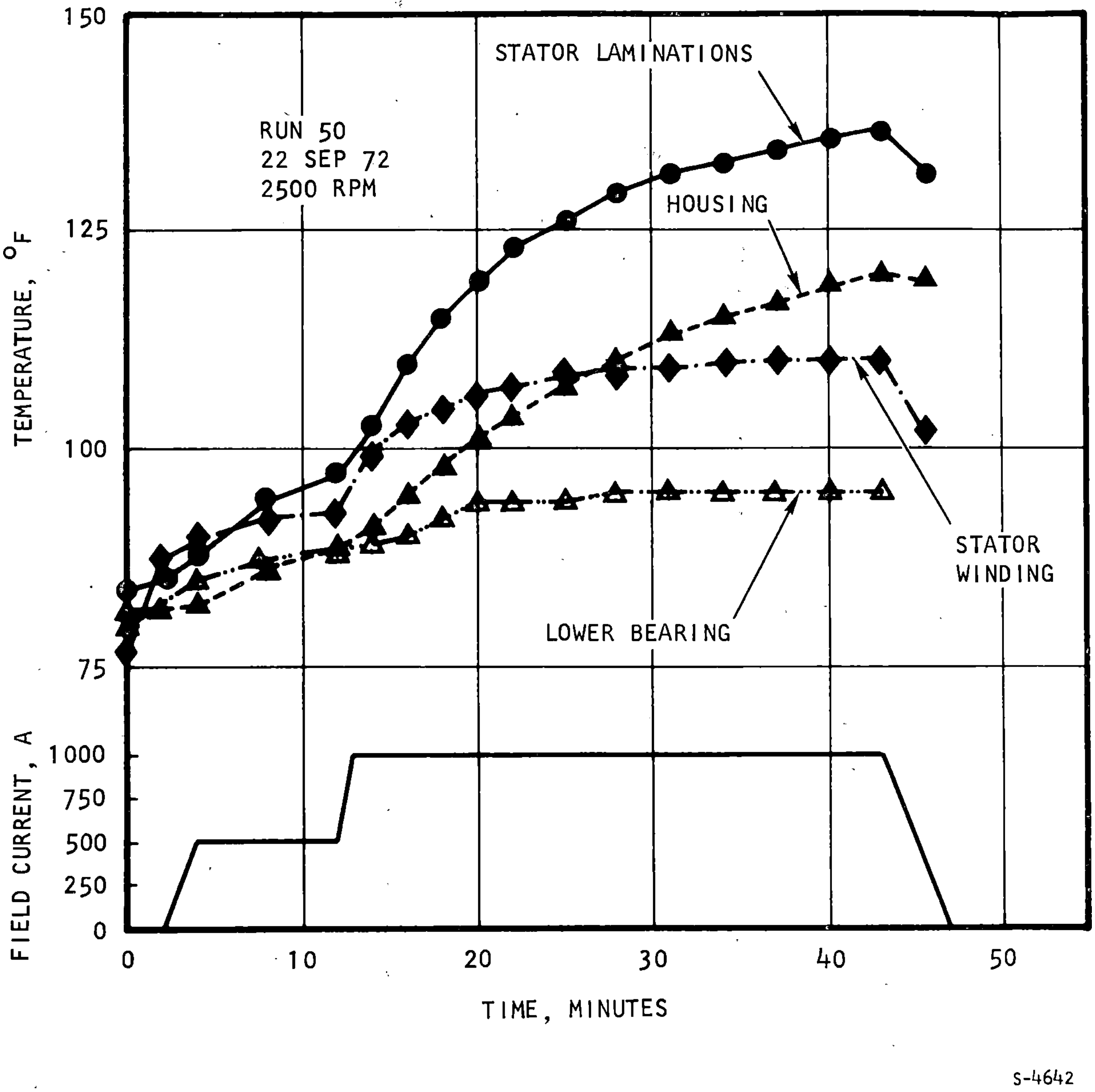


Figure 7-6. Short-Circuit Terminal Test at One-Half Rated Speed

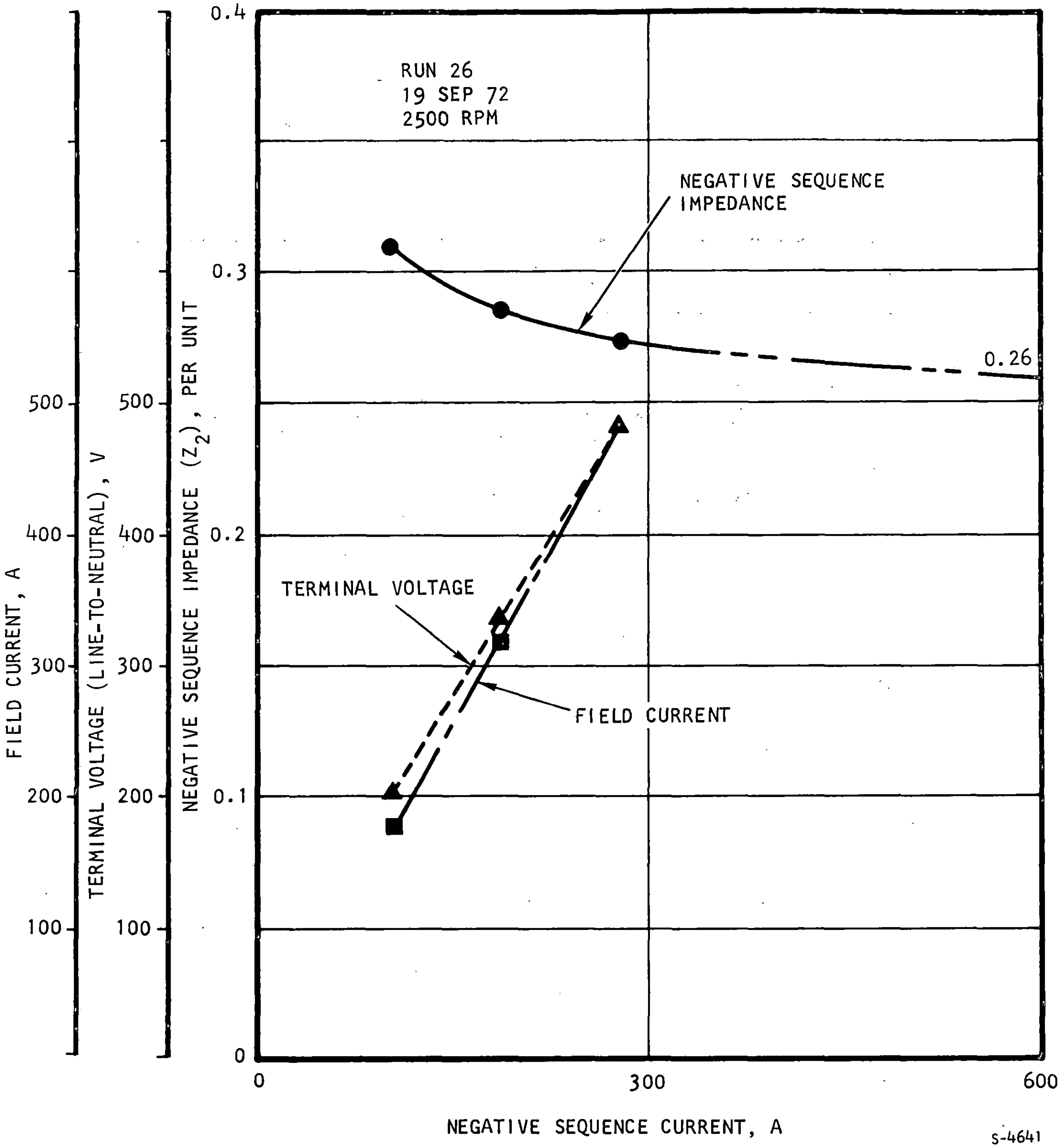


Figure 7-7. Negative Sequence Impedance Test at One-Half Rated Speed

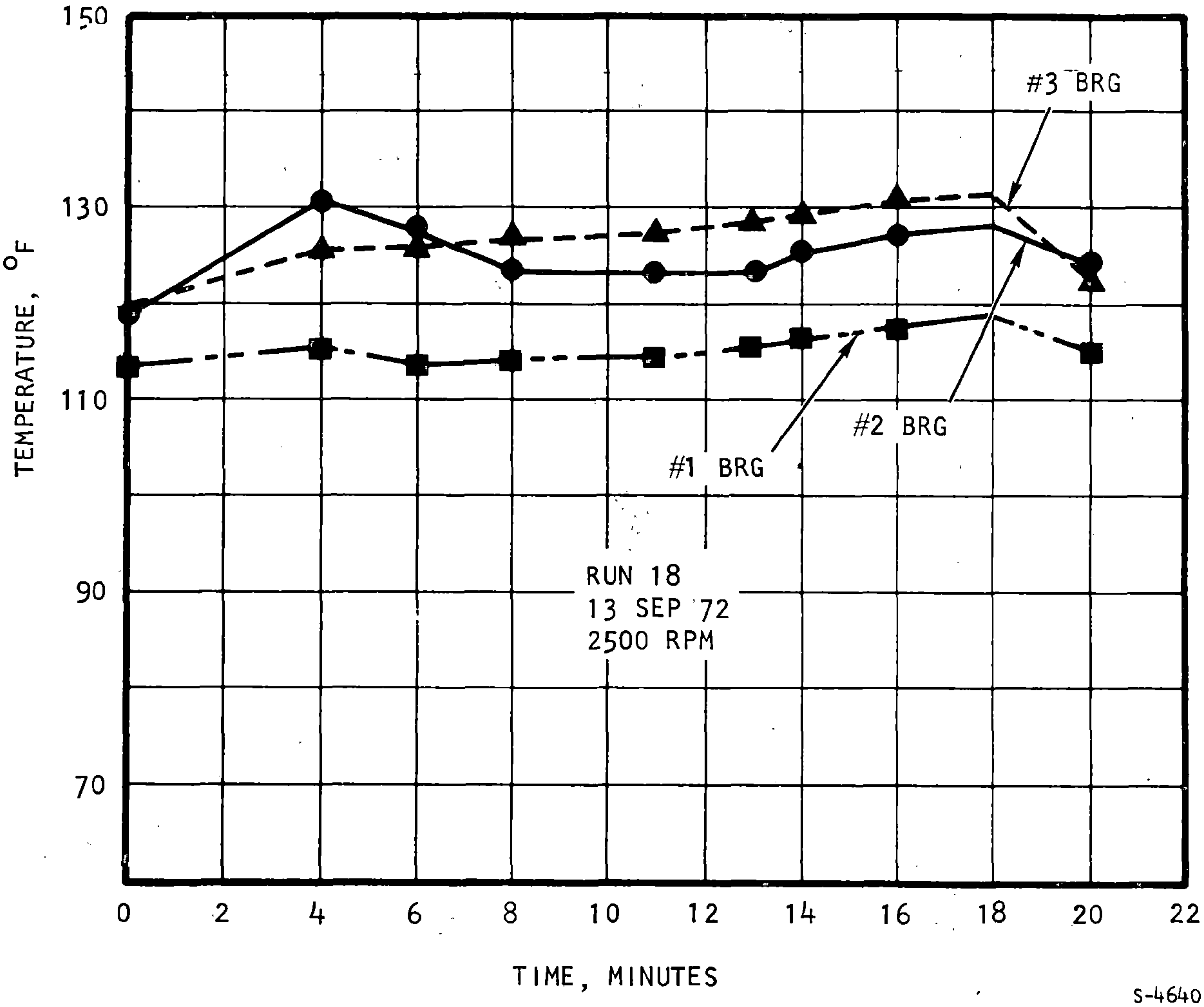


Figure 7-8. Bearing Temperatures at End of Test Run

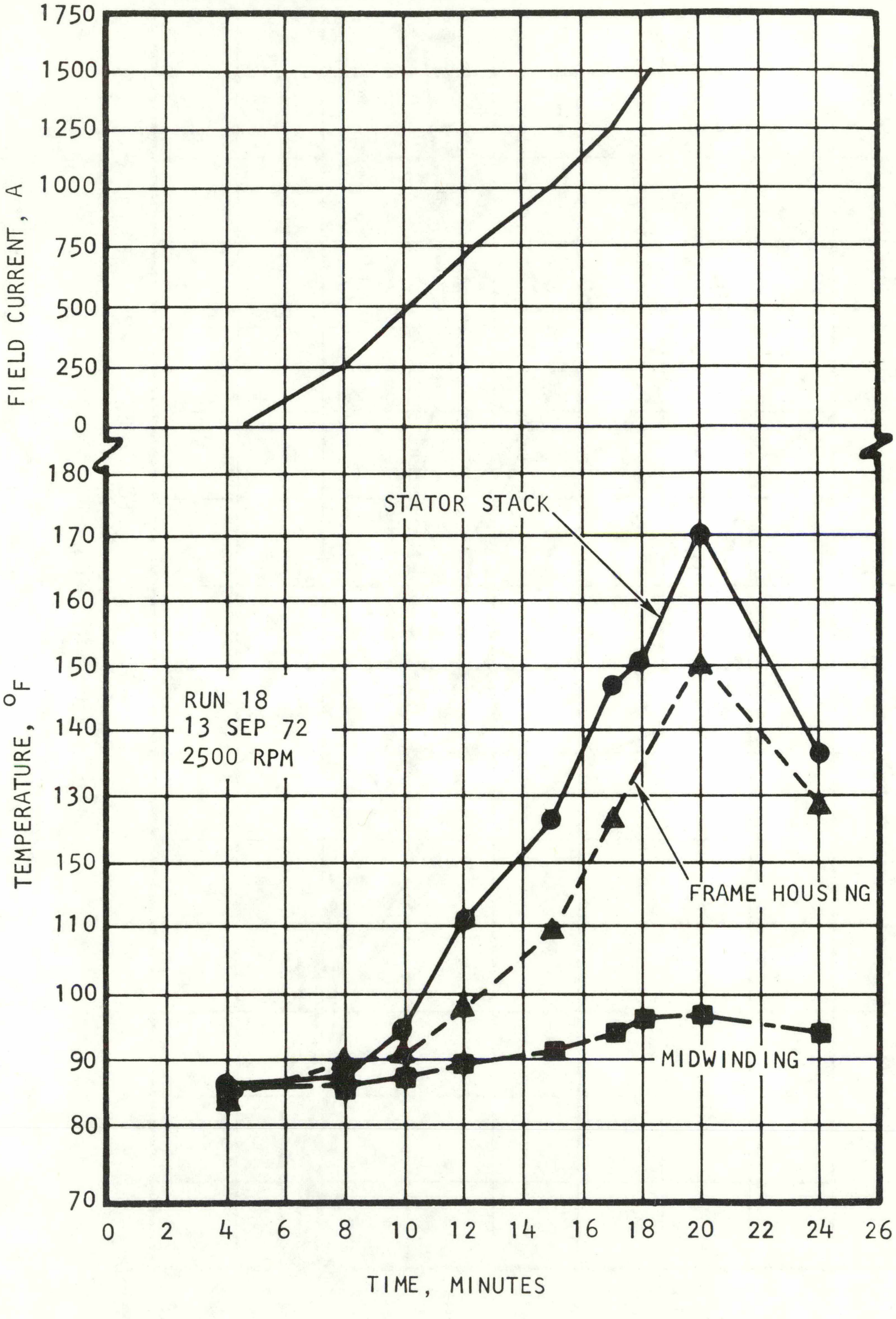


Figure 7-9. Stator Winding Temperature during No-Load Saturation Test

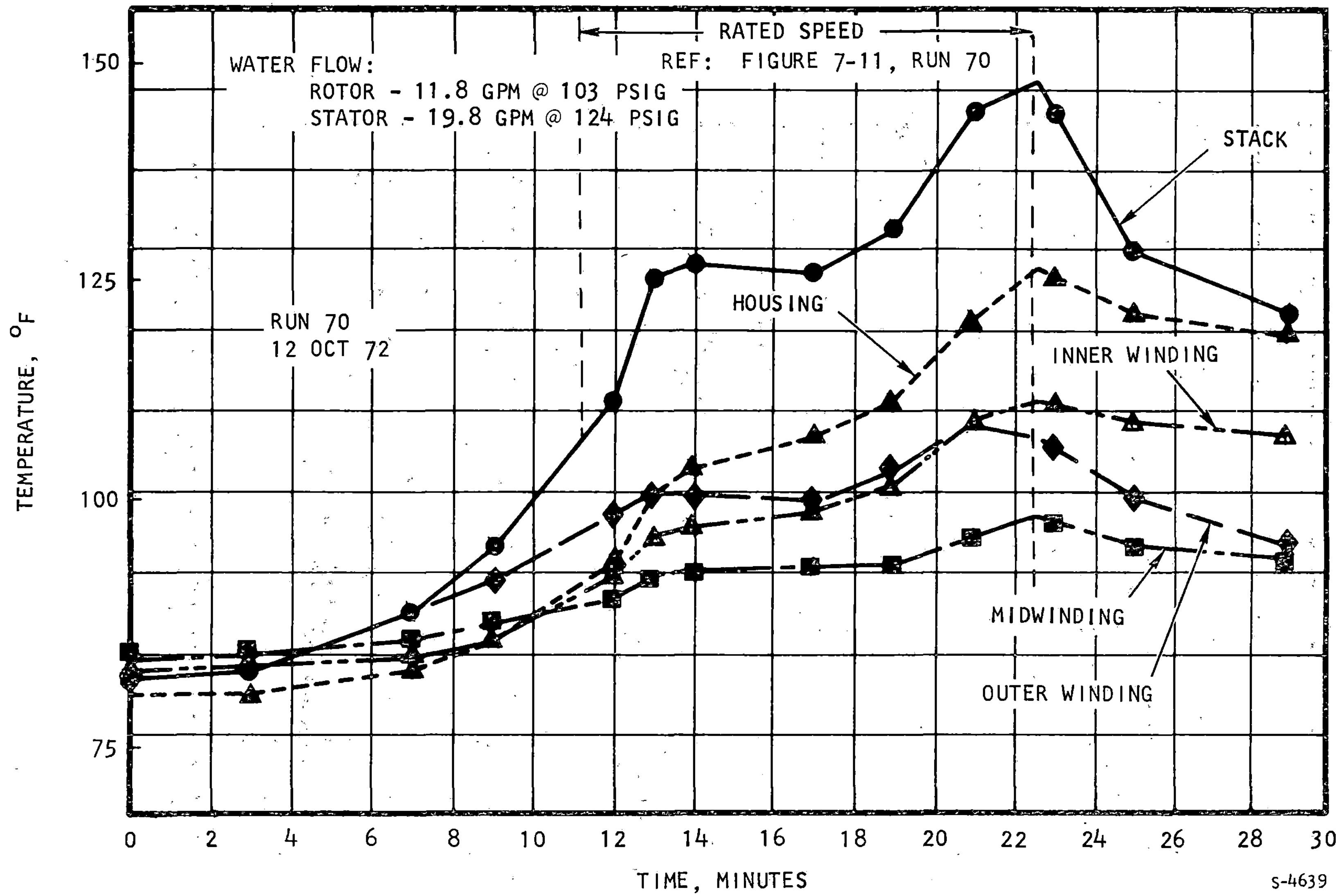


Figure 7-10. Coolant Water Temperature vs Running Time

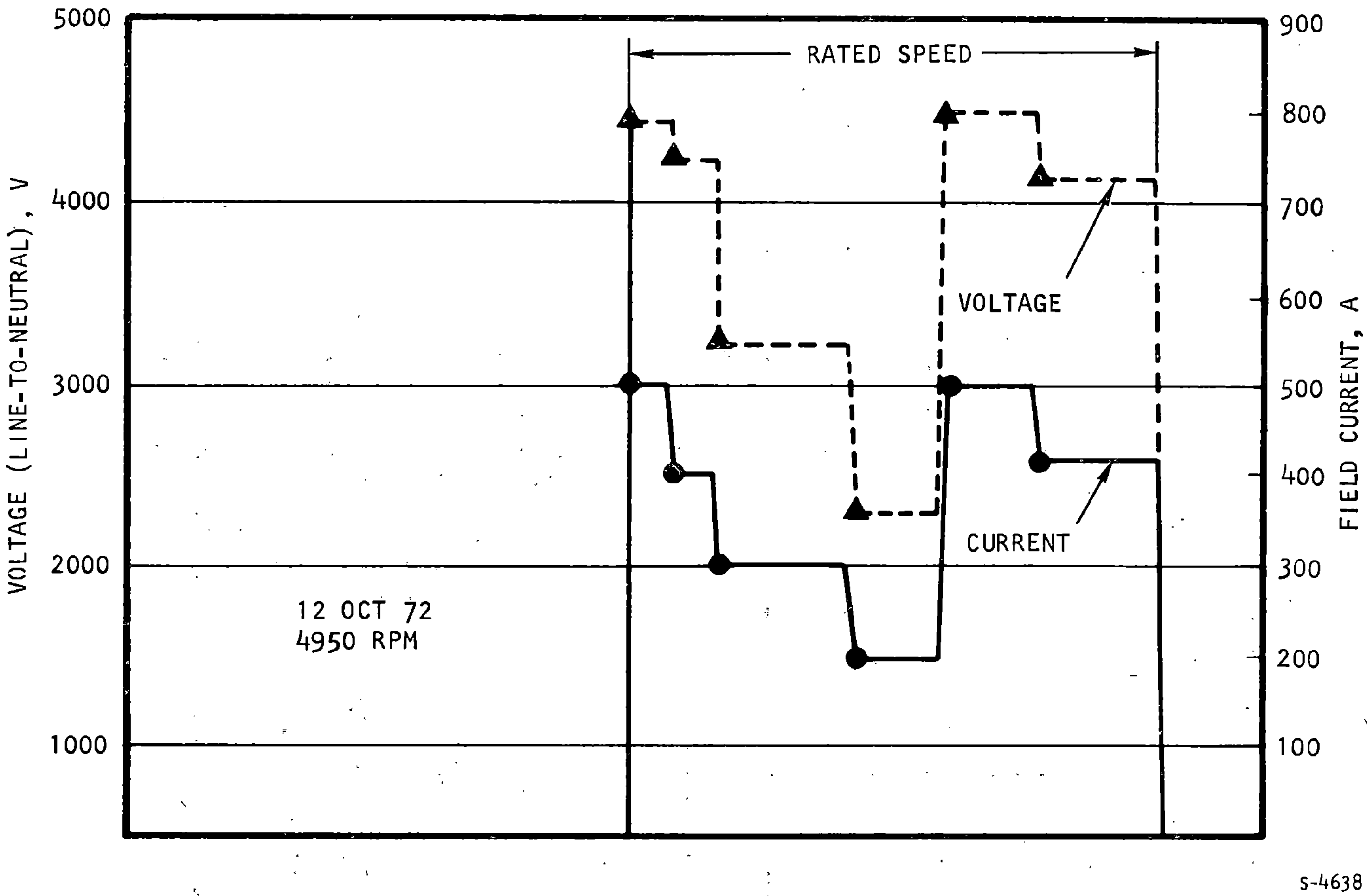


Figure 7-11. No-Load Saturation Test, Run 70

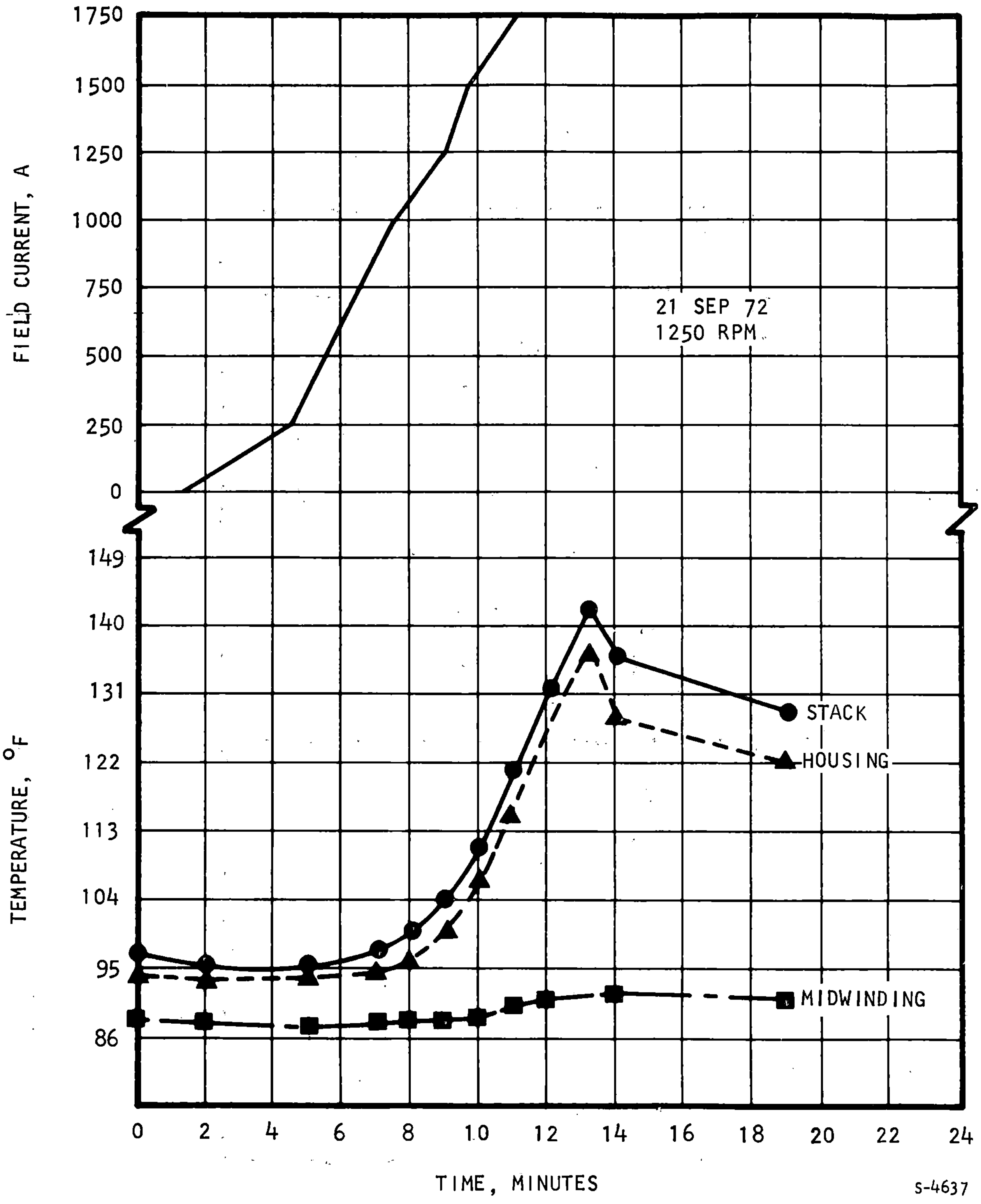


Figure 7-12. No-Load Saturation Test, Run 49

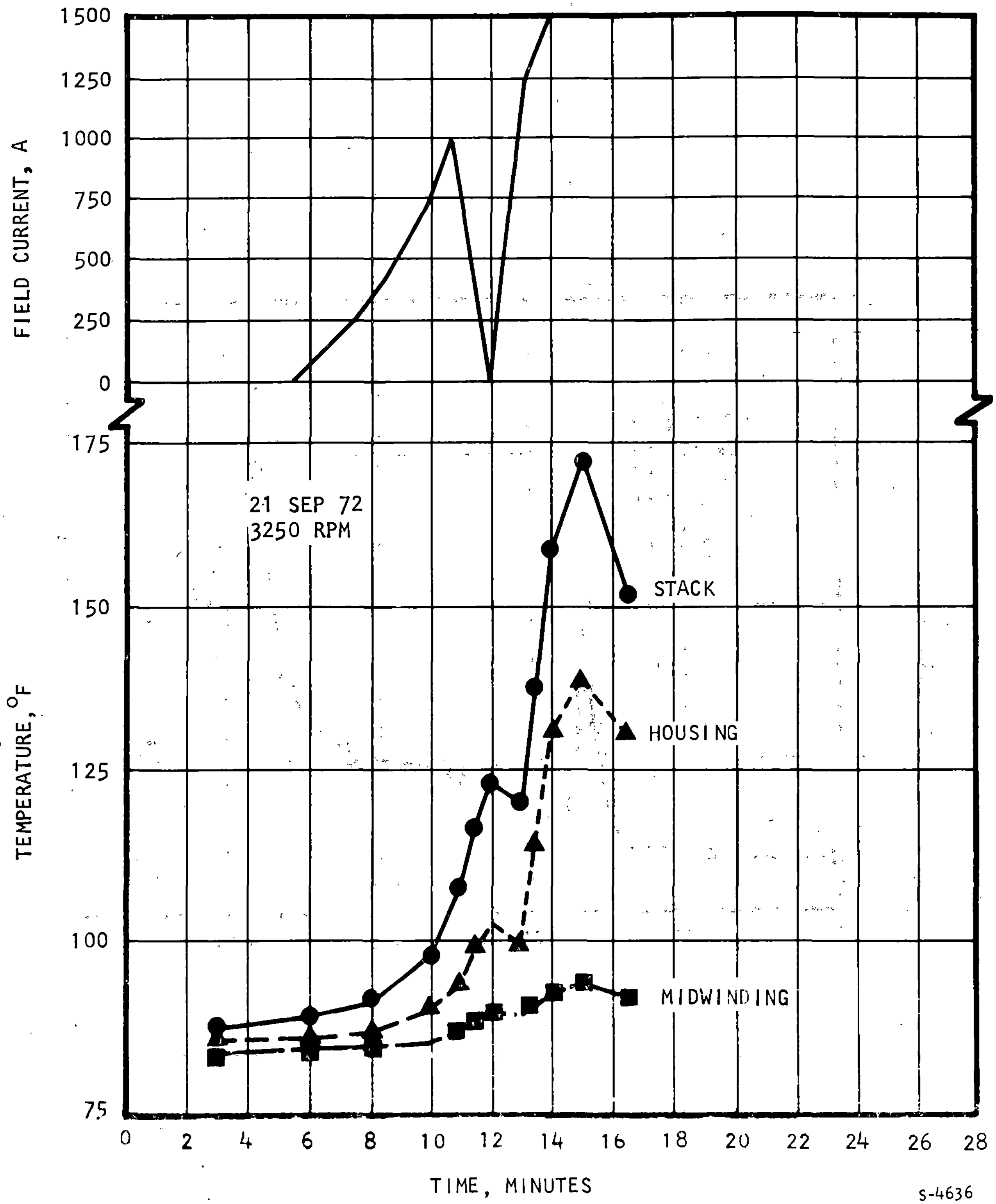


Figure 7-13. No-Load Saturation Test, Run 48

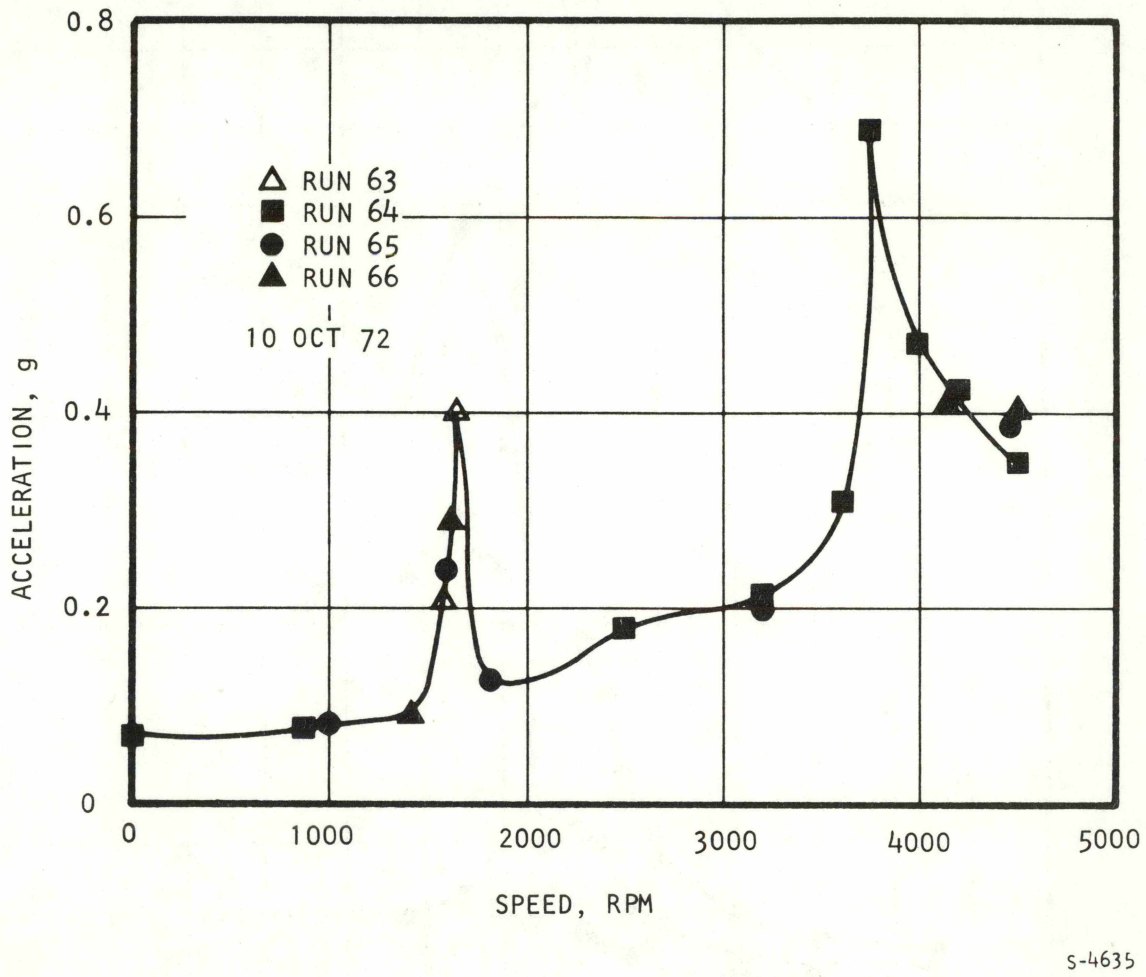


Figure 7-14. Critical Speed Search

NOTE: FULL-LOAD SATURATION DATA CALCULATED BY USING REACTANCES DERIVED IN ACCORDANCE WITH IEEE NO. 115 SYNCHRONOUS TEST CODE

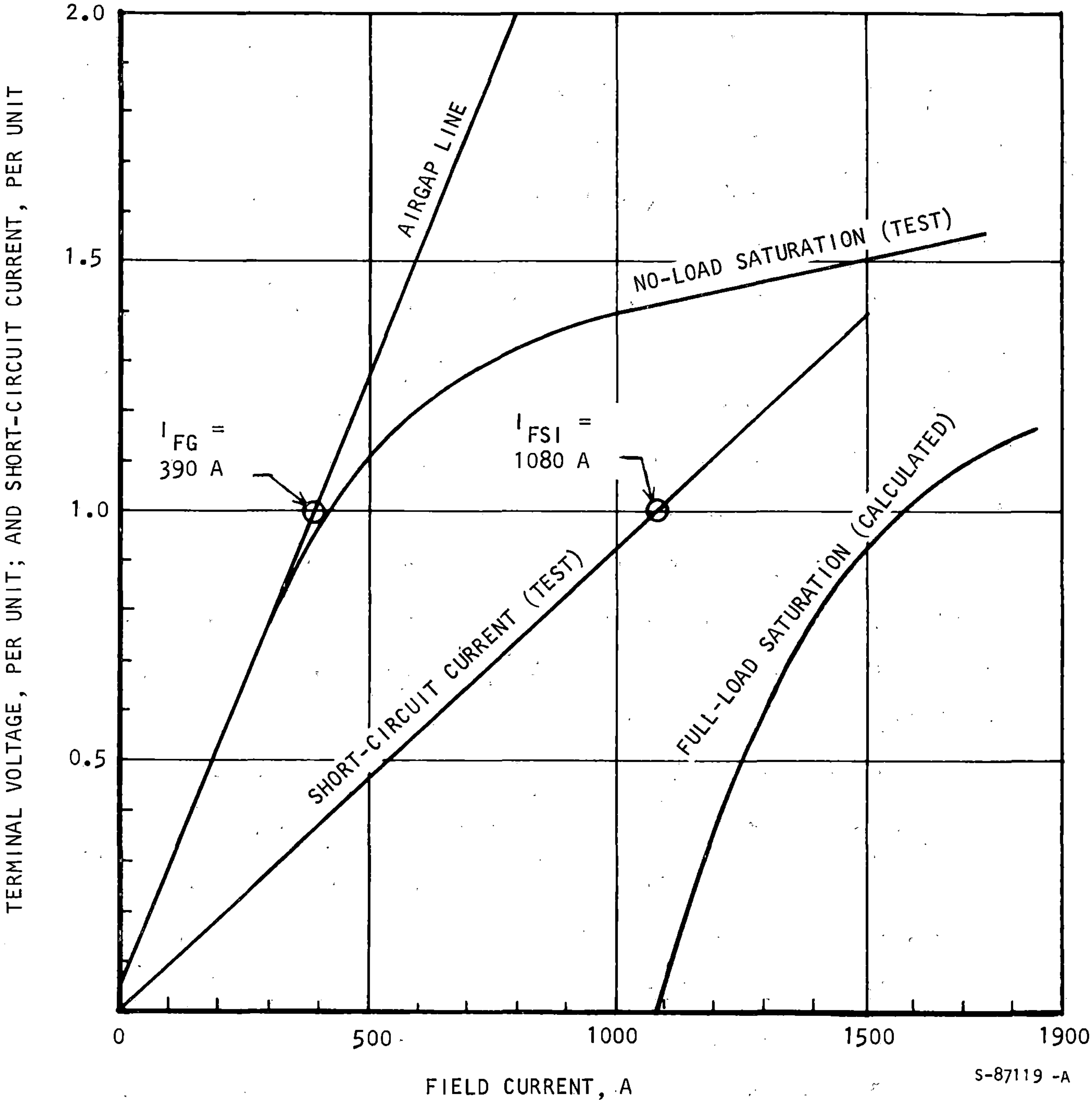


Figure 7-15. No-Load Saturation, Short-Circuit Current, and Full-Load Saturation Tests

maximum temperature effects with lower coolant flow rates (see Figures 7-8 through 7-13). Prior to running at maximum rated speed, the SC was searched for critical speeds (resonant frequencies). Vibration levels were checked at various speeds (see Figure 7-14). The critical speeds were identified as 1640 rpm and about 3760 rpm with test stand support (mounting stiffness and fixture are different than on the actual vehicle). The machine operated through critical speeds with a maximum accelerometer reading of about 0.69 g.

Short-Circuit Operation

Figure 7-15 shows calculated reactance and actual test results for no-load and short-circuit performance. This data indicates field requirements slightly lower than those predicted by the electromagnetic analyses.

Synchronous condenser testing was limited by available facilities and equipment. As a result, the machine was operated at combined full speed and full voltage and at combined full current and partial temperature, but it was not possible to conduct load testing. Hence, zero power factor data, load regulation tests, and full thermal evaluation could only be estimated.

Cooling System

The facility water system was a limiting factor for rated speed testing. The SC was designed to flow 37.5 gpm through the stator coils and 36 gpm through the rotor. With a flow rate of 20.4 gpm through the stator coils and 12.5 gpm through the rotor, machine temperatures were still below design temperatures. Also, pressures were well below system requirements. To prevent possible boiling within coils, it was desirable to maintain water inlet pressure at 300 psi minimum. Actual water pressures were 140 psi (stator) and 103 psi (rotor). Figure 7-16 shows the cooling water system. Figure 7-17 is a system schematic.

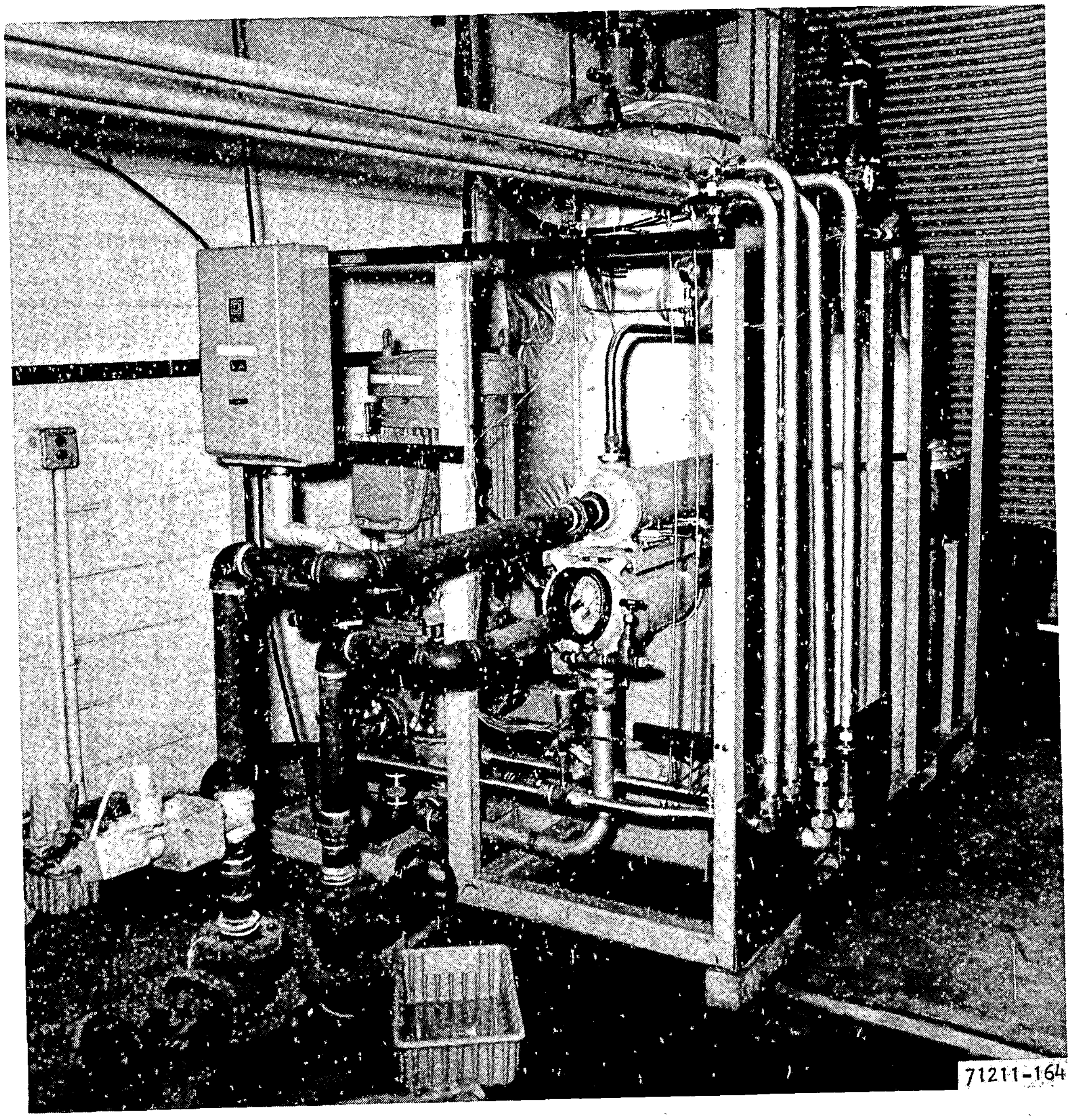


Figure 7-16. Cooling Water System

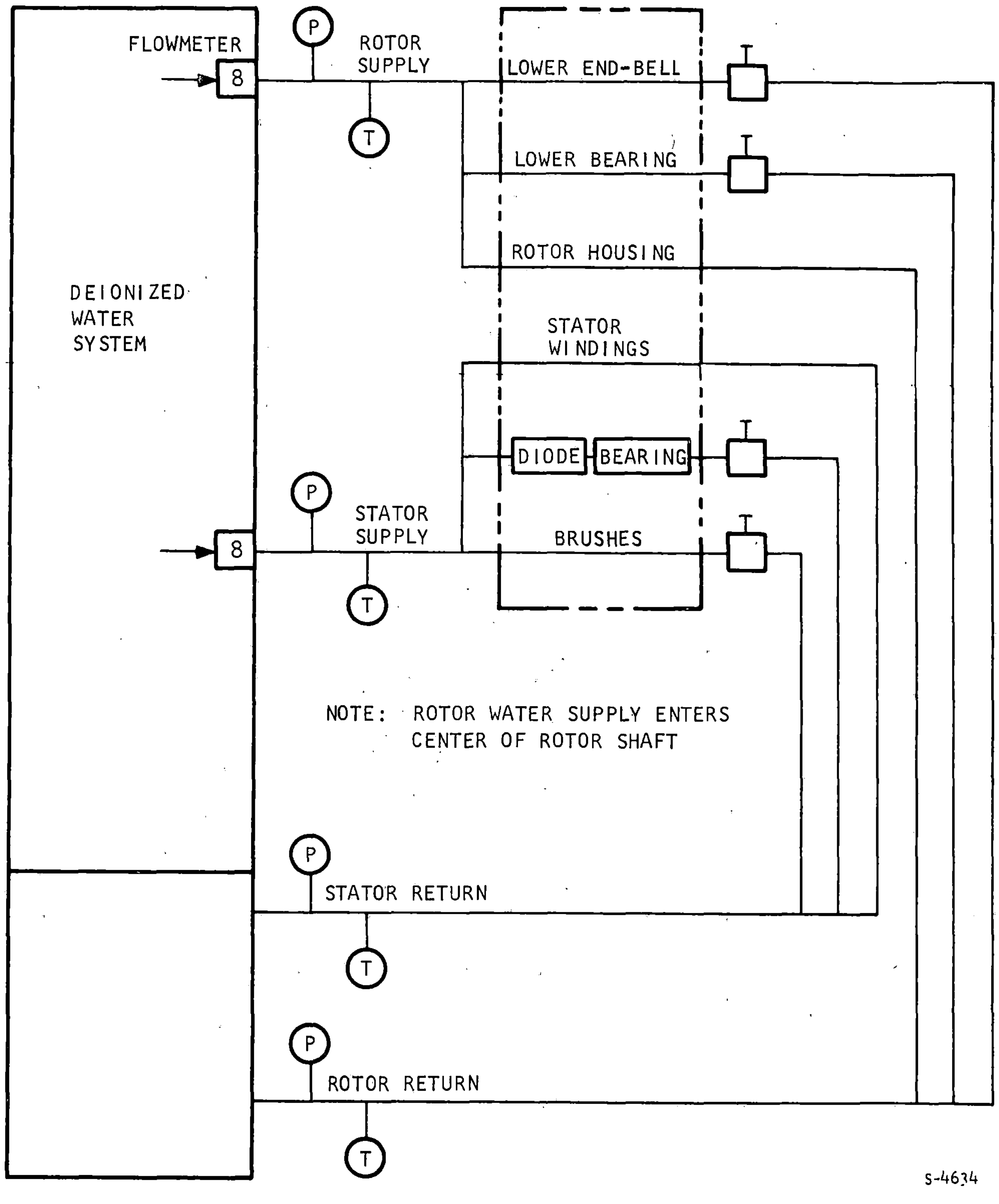


Figure 7-17. Cooling Water System Schematic

Coolant water used was provided by a remote deionization system that recirculated the water. Water was cooled, filtered, and chemically deionized at a rate of approximately 35 gpm.

High voltages were not applied unless the deionized water conductivity reading was 2.0 megohm-cm minimum. The rotor coil-to-ground resistance reading was 100 kilohms with a water conductivity of 2.6 megohm-cm. By operating the deionization system for one hour, water conductivity was raised to 3.6 megohm-cm and the rotor resistance to ground increased to 140 kilohms. Whenever the water was left stagnant for 8 hours or more, the conductivity dropped below the 2.0 megohm-cm reading and it was necessary to deionize for at least an hour to achieve acceptable water purity.

Test Stand

The test stand support was actually the fabrication holding fixture for the vertically operated machine. This initially provided a soft mount, but after lower speed runs, the mounts were shimmed solid, closely duplicating the final support condition.

Chain Drive

A chain drive was selected rather than a conventional gearbox to curtail the development effort for a drive train (i.e., special gear design and fabrication) and to minimize the leadtime involved in hardware procurement. Further, this method of power transmission was attractive because the compact size rendered future maintenance easier and less time consuming.

Chains used were approximately 5-in. wide and ran on convoluted gear teeth, forming a precision fit that showed little tendency to wander or produce backlash. The chains were mounted vertically on edge and run through a splash lubrication system. The chains ran faultlessly with or without SC load, not only at rated speed (4950 rpm), but also when the drive motors were used for SC braking.

Instrumentation

Instrumentation included equipment for monitoring temperatures of the bearing OD's, lower dynamic seal, laminations, stator coils, stator housing, and brush holder heat exchanger. The instrumented test rig brushes were used to compile a record of brush temperatures. The stator coils had special sensors installed within slots between the wedge and coil, between coils, and between coil and bottom of slot. In addition, data recorded included characteristics of water flow, pressure and conductivity, machine vibration (three axes at top and bottom), current and voltage at various times, and rotational speed settings as dictated by individual test.

1. Temperature Sensors

All temperature sensors except those associated with the brushes and stator coils are button-type, platinum-resistance devices. The stator coil temperature sensing element is a platinum strip approximately 13.5 in. long. The brush temperature sensors are thermocouples epoxied in holes drilled at the shunt ends of the brushes.

2. Vibration Sensors

Vibration was monitored by piezoelectric accelerometers, three at the top end and three at the lower end. They were mounted on a common block attached to the end-bell directly outside the bearing. In addition to installation along the X, Y, and Z axes, accelerometers were attached to the drive motors and their supporting frames to confirm that no vibration was contributed by the drive units.

SECTION 8

ROTOR BALANCING

BALANCING PROCEDURES

Although the rotor core configuration is symmetrical, precision balancing is mandatory to minimize vibration. Both the core and final rotor assembly were dynamically biplanar balanced at 500 rpm (increased to 800 rpm for a final check). Special Class 7 bearings, ball at the lower end and roller at the upper end, were used for all balance operations. Both the rotor core and rotor assembly were balanced horizontally.

Maximum allowed unbalance for the rotor core was 8 oz-in. (at a mean radius of approx 8.0 in.) at either plane with the planes about 15 in. apart. Material can be removed at each end of the rotor core for balance correction. Actual unbalance at this stage was only 2 oz-in.

Sequential balance operations were necessary for the final rotor assembly. The complete rotor assembly was balanced with all rotating parts except the bearings. The bearings were not considered proper class for an accurate balancing operation. With the installation of coils, blocking, manifolds, and slipring assembly, unbalance was expected to increase considerably. Using the extreme ends of the winding support rings, weights were to be added for balance adjustment. Balance weights are copper, nominally weigh 280 gm, and are attached with two bolts. Modification to the balance weight was permitted as long as bolt retention to the support ring was not impaired. NOTE: Bolts are never loaded, as the weights are centrifugally loaded to the ring during rotation.

As before, the balance operation was biplanar with the planes approximately 27.5 in. apart. Allowable unbalance was 5 oz-in. (141 gm-in.) at a 10-in.-radius. After the initial correction, the assembly had to be installed into a special spin test fixture to seat the coils and blocking before the final balance was possible. The final unbalance was 0.50 oz-in. (15 gm-in.) in the upper plane and 0.75 oz-in. (22 gm-in.) in the lower plane.

SPIN TEST

The complexity and one-of-a-kind nature of the SC precluded its use for overspeed testing of the rotor after the initial assembly. The test objective was to spin the rotor at overspeed (125 percent of rated speed) to seat the coils and blocking.

A special test fixture (Figure 8-1) was fabricated to facilitate use of the spin pit. This fixture permitted the use of actual bearings while the rotor was installed in the designed vertical position. By testing in a vacuum, the lack of air friction permitted use of a small 7-hp air turbine motor to spin the rotor to a maximum speed of 4370 rpm (speed limitation was due to the time for the drive turbine to attain speed, resulting in excessive bearing temperatures). The only variance between tested design and final design was the use of turbine oil instead of grease for bearing lubrication, because the grease could not withstand sustained operation in a vacuum.

At the end of this test the total radial outward movement of the coil ends was 0.09 in. This movement was the result of insulation compression between the damper windings and coil endturns, combined with a slight reseating of the endturns; compensation was made during the final blocking.

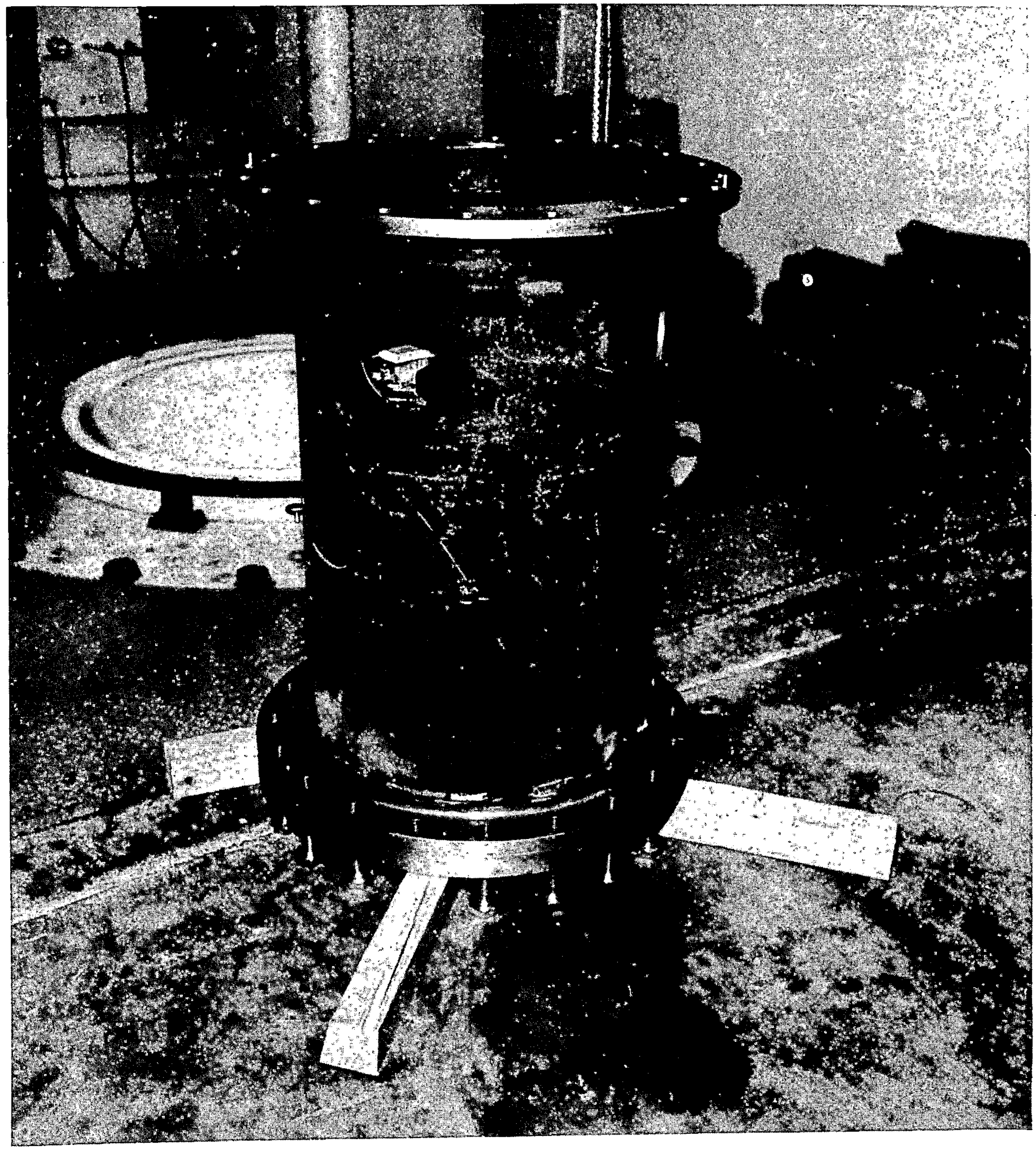


Figure 8-1. Rotor Test Fixture Removed from Spin Pit

SECTION 9

ASSEMBLY DRAWINGS

This section contains the following synchronous condenser assembly drawings:

Figure	Drawing	Description
9-1	2000942	Synchronous condenser outline drawing
9-2	2045175	Stator coil assembly
9-3	2045162	Stator stack assembly
9-4	2045177	Rotor coil assembly
9-5	2045166	Rotor core assembly (2 pages)

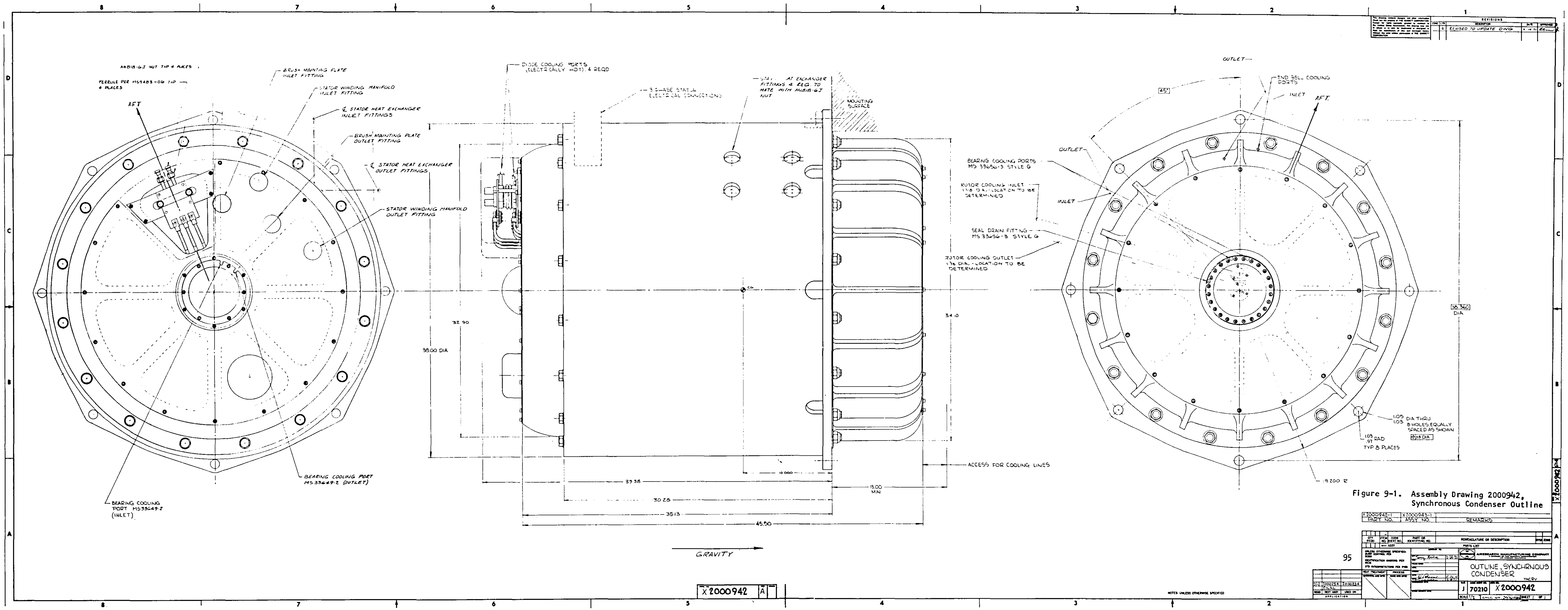


Figure 9-1. Assembly Drawing 2000942, Synchronous Condenser Outline

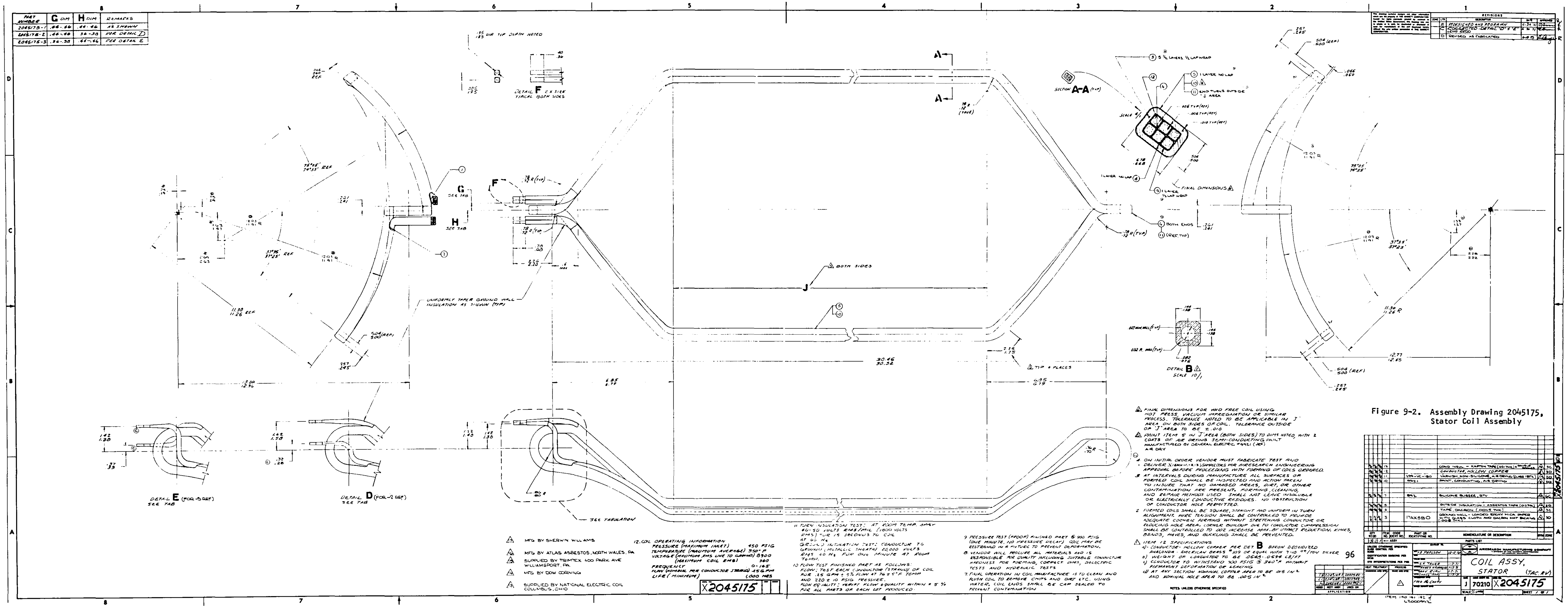


Figure 9-2. Assembly Drawing 2045175, Stator Coil Assembly

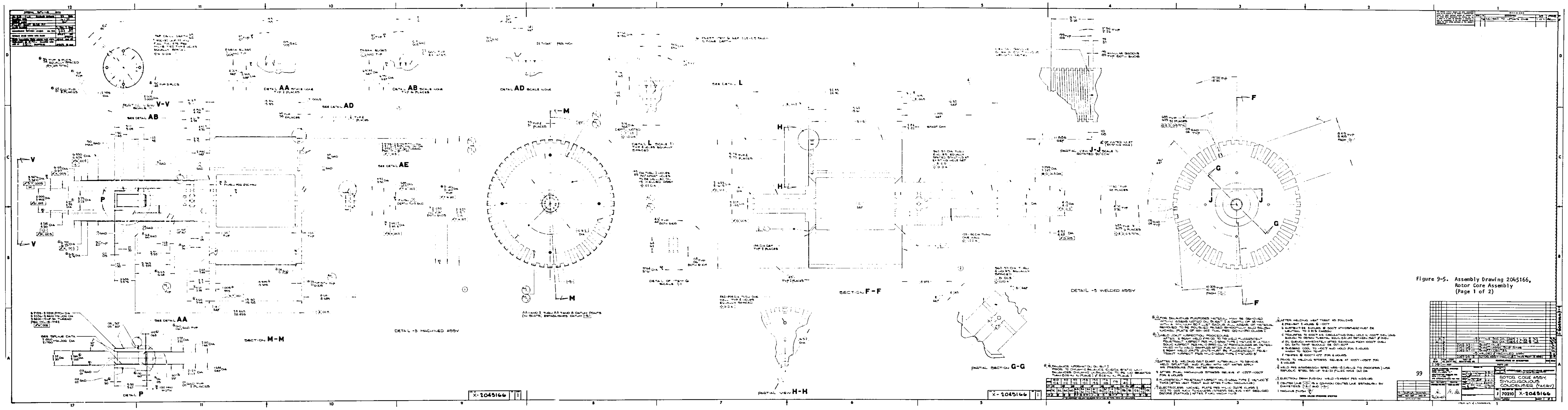


Figure 9-5. Assembly Drawing 2045166, Rotor Core Assembly (Page 1 of 2)

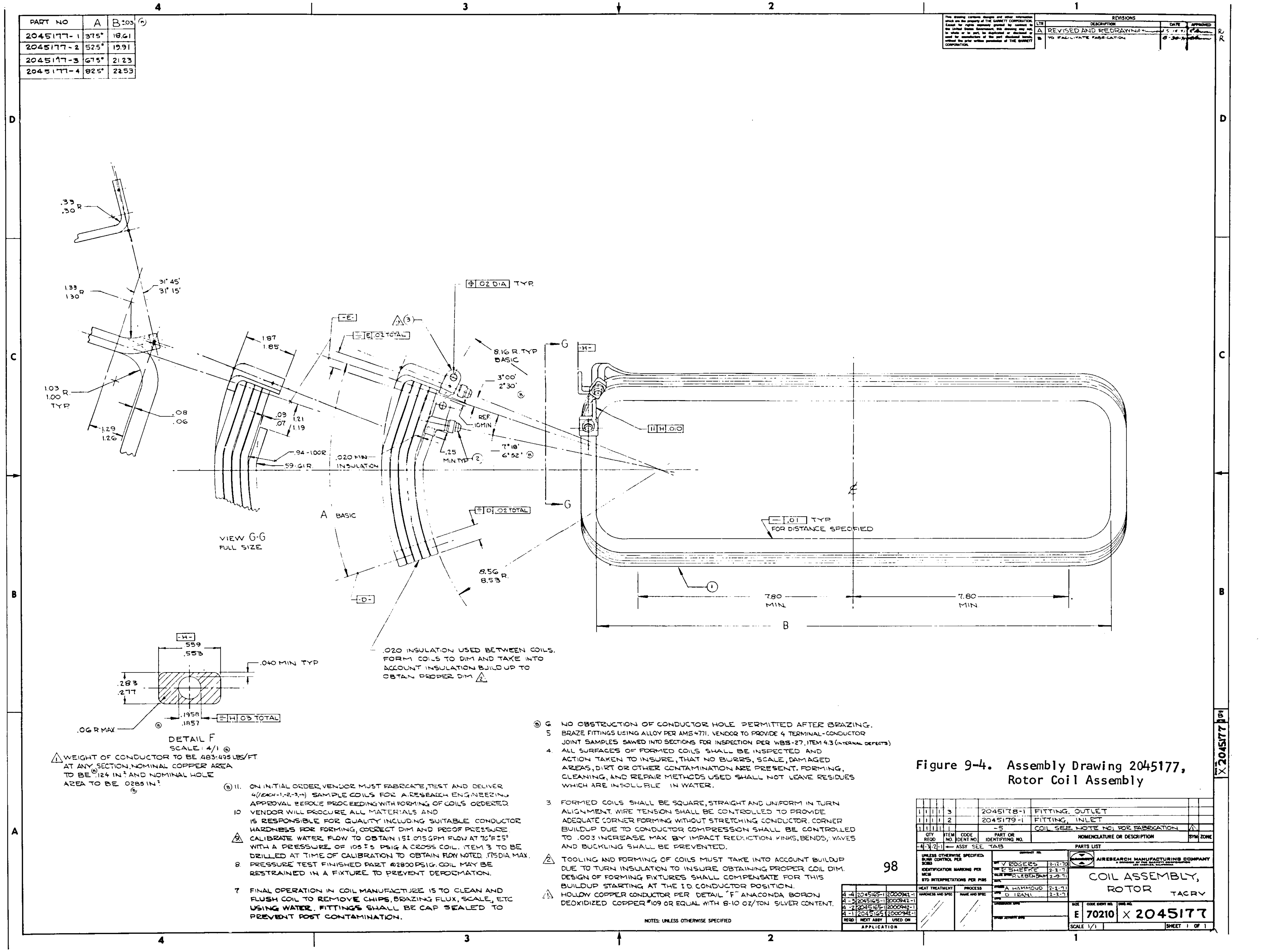
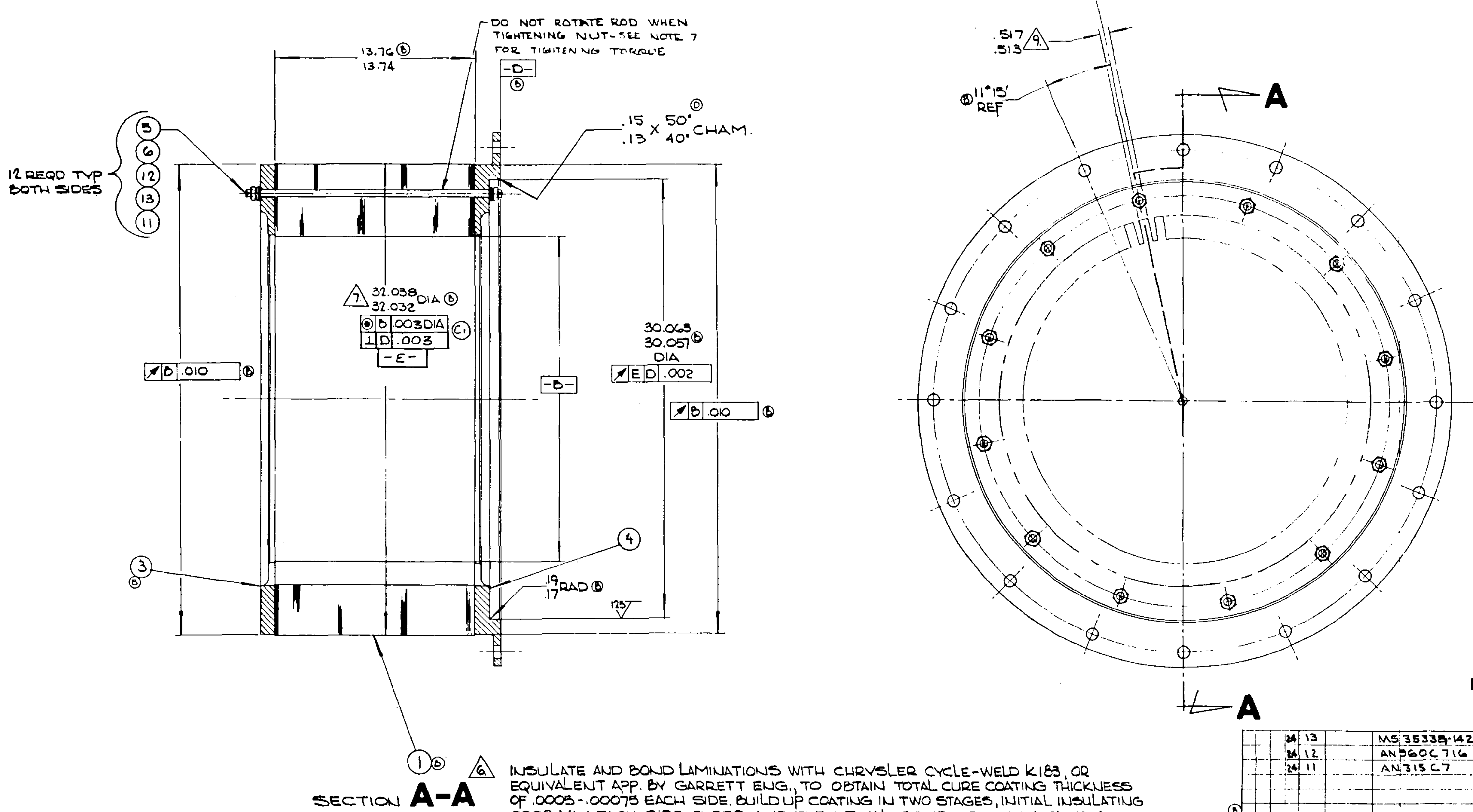


Figure 9-4. Assembly Drawing 2045177, Rotor Coil Assembly

LTR	REVISIONS DESCRIPTION	DATE	APPROVED
A	REVISED WITH CHANGES	8-22-7?	
B	REVISED WITH CHANGES	4/9/71	
C	REVISED WITH CHANGES	5/13/71	
D	REVISED WITH CHANGES	8-1-71	



9. SLOT OF ITEM 1 AS ..ACK TO BE NORMAL TO -B- WITHIN TOLERANCE NOTED FOR ASSEMBLED WIDTH.

8. SLOTS AND RINGS TO BE FREE OF BONDING MATERIAL. FILING OR GRINDING OF SLOTS NOT PERMITTED.

7. AFTER POST-CURE, COOL STACK TO ROOM TEMP- MACHINE STACK O.D. TORQUE RING BOLTS TO 40-50 LB-FT. OF TORQUE.

6. INSULATE AND BOND LAMINATIONS WITH CHRYSLER CYCLE-WELD K183, OR EQUIVALENT APP. BY GARRETT ENG., TO OBTAIN TOTAL CURE COATING THICKNESS OF .0005-.00075 EACH SIDE. BUILD UP COATING IN TWO STAGES, INITIAL INSULATING .0003 MIN EACH SIDE, CURED, AND THEN FINAL BONDING COAT APPLIED AND CURED AFTER STACKING, PER MANUFACTURE'S INSTRUCTIONS, PLUS POST CURE WITH IRON STABILIZED AT 400°F FOR ONE HOUR

5. BEFORE COATING OR STACKING, 1291 LBS OF LAMINATIONS SHALL BE WEIGHED-OUT FOR ASSEMBLY. VENDOR TO CERTIFY THAT THIS WEIGHT WAS USED. IF NECESSARY TO OBTAIN SPECIFIED CORE LENGTH UNDER FULL CLAMPING PRESSURE, UP TO 14 POUNDS OF LAMINATIONS MAY BE ADDED. VENDOR TO CERTIFY IRON WEIGHT OF ADDED LAMINATIONS.

4. MEGGER TEST ITEM 5 ROD, TO FRAME AFTER INSTALLATION AND AFTER BONDING. RESISTANCE SHALL EXCEED 100 MEG OHMS AT 500 VDC

3. MUST BE STACKED ON A 22.250-22.254 DIA MANDREL AND NORMAL TO -D- WITHIN .005. APPLY RELEASE COMPOUND TO ONE CLAMP RING.

2. WEIGHT OF FINISHED ASSY TO BE RECORDED.

1. STACK ITEM 1 WITH BURRS ALL IN SAME DIRECTION.

NOTES: UNLESS OTHERWISE SPECIFIED

Figure 9-3. Assembly Drawing 2045162, Stator Stack Assembly

QTY REQD	ITEM NO.	CODE IDENT NO.	PART OR IDENTIFYING NO.	NOMENCLATURE OR DESCRIPTION	SYM
24	13		MS35338-142	WASHER, LOCK	
24	12		AN960C716	WASHER, PLAIN	
24	11		AN315C7	NUT	
AR	7		K183	ADHESIVE	
24	6		519344-1	WASHER, INSULATION	
12	5		2045195-1	ROD, THREADED INSULATED.	
1	4		2045193-1	RING, CLAMP, BOTTOM	
1	3		2045192-1	RING, CLAMP, TOP	
AR	1		2045161-1	LAMINATION	
-1	← ASSY			PARTS LIST	

REQD	NEXT ASSY	USED ON
1(-1)	2045164-1	2005942-1
APPLICATION		

UNLESS OTHERWISE SPECIFIED: BURR CONTROL PER SC653
IDENTIFICATION MARKING PER MC16
STD INTERPRETATIONS PER PIBS

HEAT TREATMENT — HARDNESS AND SPEC | PROCESS — NAME AND SPEC

DFT 12-18-70; CHK 1-5-70; VALUE ENGR 1-5-71; MATL 1-12-71; 1-6-70; APPD 1-13-71

AIRESEARCH MANUFACTURING COMPANY
A DIVISION OF THE GARRETT CORPORATION
LOS ANGELES, CALIFORNIA

STACK ASSY. STATOR

SIZE D | CODE IDENT NO. 70210 | DWG NO. X 2045162

SCALE 1/4"=1" | SHEET 1 OF

RECORD CENTER

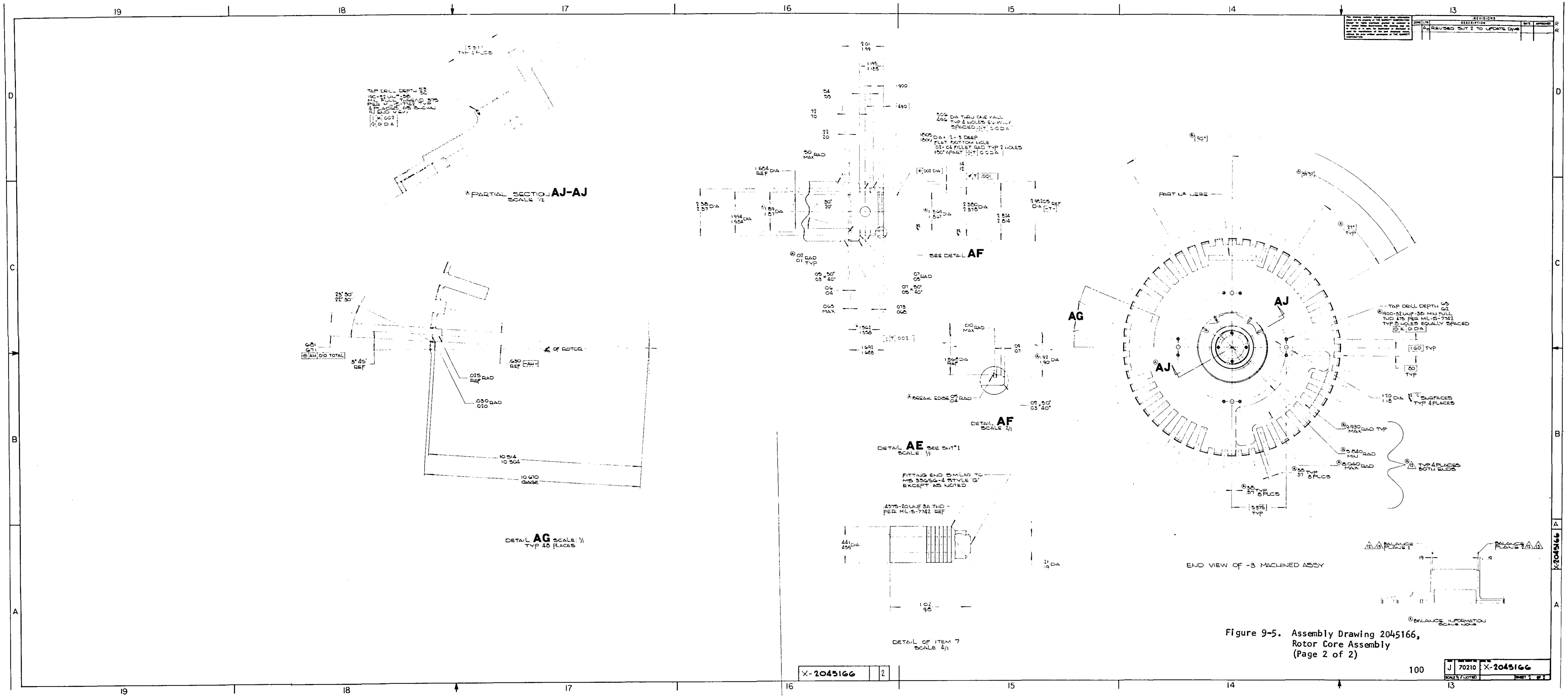


Figure 9-5. Assembly Drawing 2045166, Rotor Core Assembly (Page 2 of 2)

REFERENCES

1. "Development and Manufacture of a Linear Induction Motor Propulsion System for the Tracked Air Cushion Research Vehicle," Report FRA-RT-72-35, April 1971.

2. "Linear Induction Motor Research," Report FRA-RT-73-2, -3, -4, and -5, October 1971.