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AVRADCOM REPORT NO. 76-45

PRODUCTION ENGINEERING MEASURES PROGRAM
MANUFACTURING METHODS AND TECHNOLOGY

Engineering Services to Conduct Qualification Testing of Precision Forged Spiral Bevel Gears

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October 1977

Final Report Contract Number DAAJ01-74-C-1052 (P1G)

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St. Louis, Missouri 63166

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Conventional production gears	Equivalent
Precision integrally forged gears	

20. ABSTRACT *(Continue on reverse side if necessary and identify by block number)*

This report presents the results of a program to evaluate the relative surface-load capacity of CH-47C transmission spiral bevel gears manufactured by the integrally forged method (forged and ground) as compared to conventional current production gears (cut and ground). A three-phase test program was conducted. Phase I included the deflection test of one set of conventional baseline gears and rotating-load tests of two sets each of the integrally forged and conventional baseline gears. All gears were run at torque levels equivalent to 50, 100, and 150 percent of the CH-47C single-engine rating. Phase II included rotating-load tests of two additional conventional baseline and five additional integrally forged gear sets in the Boeing Vertol test stand at loads of 100 to 130 percent of single-engine rating for 340 hours. Phase III involved extended surface-fatigue testing of four precision integrally forged gear sets in the test stand at 100 percent of single-engine rating for 800 hours. The results of this testing indicate that the surface-load capacity of the integrally forged gear sets is at least equivalent to that of the conventional baseline gears.

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SUMMARY

This report presents the results of an experimental program conducted to evaluate the relative surface-load capacity of CH-47C helicopter engine-transmission spiral bevel gears manufactured by the integrally forged method (forged and ground) as compared to conventional current production gears (cut and ground).

A three-phase test program was conducted. Phase I testing included the deflection test of one set (pair) of conventional baseline gears and rotating-load tests of two sets each of the integrally forged and conventional baseline gears. All gears were run at torque levels equivalent to 50, 100, and 150 percent of the CH-47C single-engine rating. Phase II included rotating-load tests of two additional conventional baseline and five additional integrally forged gear sets in the Boeing Vertol engine-transmission test stand at loads of 100 to 130 percent of single-engine rating for a total of 340 hours. Phase III involved extended surface-fatigue testing of four precision integrally forged gear sets in the engine-transmission test stand at 100 percent of single-engine rating for a total of 800 hours (200 hours per set).

The results of this testing indicated that the surface-load capacity of the integrally forged gear sets was at least equivalent to that of the conventional baseline gears.

FOREWORD

This report compiles and summarizes the work accomplished under U.S. Army Aviation Research and Development Command (AVRADCOM) contract DAAJ01-74-C-1052 (P1G), "Engineering Services to Conduct Qualification Testing of Precision Forged Spiral Bevel Gears," by the Advanced Power Train Technology department of the Boeing Vertol Company.

Technical direction from AVRADCOM for this program was provided by Ronald Evers, Richard Tierce, James Bunyard, Bernestine Page, and Daniel Haugan.

The effort reported here was performed between July 1974 and October 1977. The Phase I screening tests were conducted at the Boeing Vertol Gear Research Test Facility which is located on the campus of Villanova University. Professors William Murphy and James Currie provided assistance in the successful completion of this phase of the program. The full-scale transmission testing (Phases II and III) was accomplished in the CH-47 engine-transmission engineering test facility under the supervision of Boeing Vertol test engineers Joseph Janson, Jim Nonemaker, and John Weischedel. The interest and assistance provided by Dr. Roger Skrocki, TRW Inc., Armen Coppe, Litton Precision Gear, and Robert W. Howells, Boeing Vertol, are also gratefully acknowledged. Raymond J. Drago was Project Engineer with A. J. Lemanski serving as Program Manager.

The government-furnished equipment integrally forged spiral bevel gear test specimens were produced under contract DAAJ01-69-C-0614 (1G) issued to TRW Inc. The purpose of this program was to evaluate the technical and economic feasibility of integrally forging spiral bevel gears. The report from this program is entitled, "Spiral Bevel Gear and Pinion Forging Development Program", ER 7389-F, February 29, 1972. The gears integrally forged as a part of that program were ground to the standard CH-47C engine box configuration by Litton Precision Gear, Chicago, Illinois. The EDM electrodes used in the fabrication of the forging dies were also manufactured by Litton.

This project was conducted as part of the U.S. Army Aviation Research and Development Command manufacturing technology program. The primary objective of this program is to develop, on a timely basis, manufacturing processes, techniques, and equipment for use in production of Army materiel. Comments are solicited on the potential utilization of the information contained herein as applied to present and future production programs. Such comments should be sent to: U.S. Army Aviation Research and Development Command, ATTN: DRDAV-EXT, P.O. Box 209, St. Louis, Missouri, 63166.

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INTRODUCTION

High-speed, high-capacity gear systems generally tend to be relatively expensive, especially in the case of helicopter transmissions, with their added requirements for light weight and high reliability. A substantial part of this cost is in the fabrication of the gears, particularly spiral bevel gears. The current technology employed in the manufacture of spiral bevel gears has reached a limit in that only minimal improvements in unit costs have been achieved recently. Apparently a new approach to the basic manufacturing process is required to provide a significant improvement in direct labor and material costs, without sacrificing quality or load capacity.

Current integral precision forging technology can reduce the cost of bevel gear manufacturing by eliminating or reducing a number of machining operations. By directly preforming the teeth and the major sections of the blank, dual benefits can be obtained. First, the grain flow in the tooth flank and root area can be more conforming, thus providing the potential for strength; and second, the need for specialized machine cutting tools and high-skill-level operators can be reduced.

This report summarizes the results of a three-phase test program conducted by Boeing Vertol Company to determine if the surface-load capacity of integral forged spiral bevel gears is at least equivalent to that of identical (geometry and material) gears made by conventional methods. Although it is likely that the strength of the integral forged teeth may be greater than that of the conventional cut teeth, this test effort was not designed to determine the magnitude of this improvement, if any. Rather, since the apparent economic benefits of the integral forging process have already been established, it was the objective of this effort to establish whether or not the integral forged gear teeth met the minimum standards required of equivalent conventional gear teeth with regard to surface-load capacity.

TECHNICAL APPROACH

BACKGROUND

The manufacturing and processing techniques used in the fabrication of current high-power, high-speed precision aircraft gearing have achieved a high degree of sophistication through technological improvements in machine tool developments and advancements in the use of associated equipment. The analytical methods used for rating the performance of this gearing have also been refined to keep pace with the fabrication developments. In spite of these efforts, the cost of precision aircraft-quality gearing, especially spiral bevel gearing, has remained relatively high. This is largely the result of placing major emphasis on improving load capacity and reliability while decreasing weight, with only secondary regard for cost. Until recently, this was the only course possible, since significant cost reduction could only be obtained by sacrificing load capacity or quality; this is certainly unacceptable for an aircraft transmission application.

The substantial cost reductions inherent in the chipless fabrication of gear teeth have been demonstrated in numerous applications using materials (metal powders, plastics, etc) and processes (sintering, extrusion, die casting, etc) which are markedly different from those typically employed in the manufacture of aircraft-quality power gearing. Unfortunately, these alternatives are lacking in one or more critical characteristics required for aircraft power applications. The integral precision gear tooth/blank forging process, however, has demonstrated a potential for producing semifinished high-capacity gears of aircraft quality and strength using conventional aircraft materials (e.g., AISI 9310 steel). Advances in forging die materials, die sinking techniques, and forging equipment make integral precision gear forging a potential production process.

The potential feasibility of integrally forged semifinished gear fabrication has been demonstrated. It now remains to refine the process for production and to further evaluate the load capacity and performance of gears made by this technique.

STATEMENT OF PROBLEM

The technical feasibility and potential economic advantage of precision integral forging CH-47C engine-transmission-type spiral bevel gears have been demonstrated by TRW. This effort, however, does not of itself provide sufficient justification to qualify this method for the production of aircraft transmission gearing. The TRW program considered the forging process itself with limited single-tooth bending-fatigue tests using finish-ground integrally forged and conventional baseline gears. The results of this testing, though somewhat clouded by large data scatter, did indicate an advantage for the integral forged gears. Although cost is a major factor in the design of an aircraft system, the load capacity and reliability of critical dynamic components cannot be compromised. It is thus apparent that before the precision integral forging process can be considered for flight hardware, extensive bench testing must be accomplished.

This testing may logically be divided into two distinct areas of investigation. First, considering the apparent economic advantages of the forging process, if it can be established that in a given application the forged gears have load capacity equal to those of conventional manufacture, they provide an advantage because they are more cost-effective. Second, because of the conforming nature of the grain flow in the fillet/root region, an improvement in bending fatigue may be an additional benefit. Only the first test objective is addressed in this effort. The second is rightly the province of a specific separate program with a substantially different test method.

The current contracted program evaluates the relative (not absolute) surface-load capacity of typical precision integral forged spiral bevel gears as compared to conventional baseline gears. As a result of previous testing, it has been established that the CH-47C production engine-box gears are capable of withstanding substantial overloads without significant distress. With this in mind, the testing reported herein has been divided into three phases. The first phase involves relatively short-term (6 million cycles), high-load (150 percent single-engine rating), sudden-death-type tests. The purpose of these Phase I tests was to determine, early in the program, if some critical deficiency in the integral forged gears substantially affects their performance. Should this have been the case (it was not!), a cost savings to the Army would have been made by not proceeding with further testing. The testing defined in Phase II is of longer term with larger sample size and varying load, designed to establish the load equivalence of the forged and baseline configurations in an actual aircraft transmission. Phase III is longer term, endurance-type running with constant load designed to confirm load equivalence and reliability.

In addition to the load-capacity evaluation, it was necessary to examine both the forged and baseline gears metallurgically to determine if the forging process introduced some unforeseen condition which could affect the long-term reliability of the gears. The conformity of the grain flow, particularly in the fillet/root area, is also of special interest because of the potential improvement in bending fatigue which may be obtained.

GEAR FABRICATION

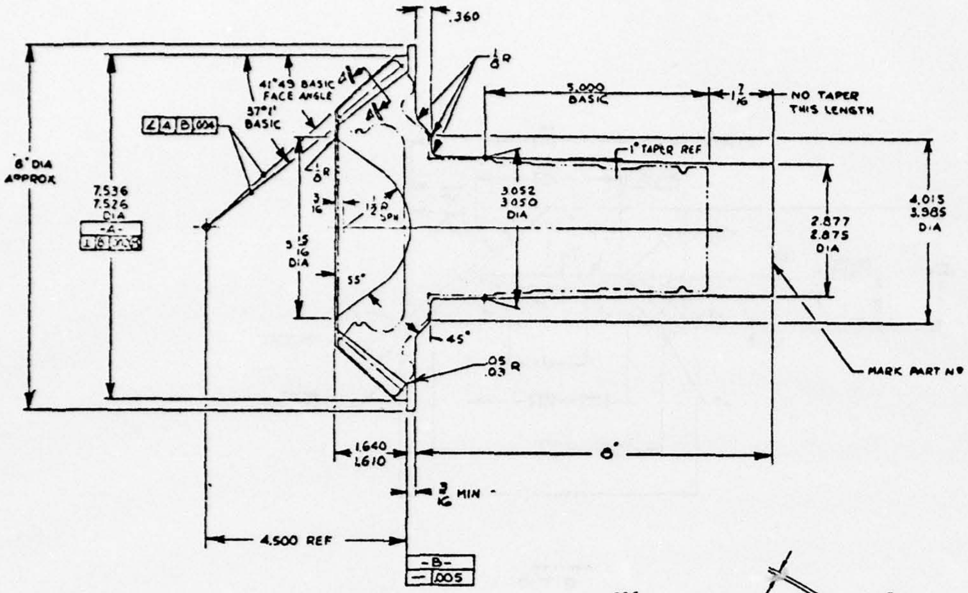
The conventional baseline test gears were manufactured in a manner exactly identical to the equivalent current production engine-box gears; in fact, the baseline gears were fabricated as part of a normal production run. The raw materials used for the baseline gears were rough forgings which were then rough-machined and prepared for tooth generation (cutting). The precision integral forged gears were forged from a billet directly to the rough-machined state, including teeth. The precision integral forged pinion and gear blanks were manufactured as shown in Figures 1 and 2.

The test gears with integral teeth were forged using a modified crank press. The Maxipress (Figure 3), a product of National Machinery Company, is a conventional design, single-action mechanical crank press which has been used for precision production forging for over 30 years and is widely available in industry. This machine is capable, with the use of proper dies, of holding production tolerances of a few thousandths of an inch. The test gears were forged using two successive press blows, Figure 4, in order to provide an end product with optimum properties.

The sequences followed in the manufacture of both the baseline and the precision forged test gears are roughly outlined in Figure 5. The projected main benefit is obtained by completely eliminating the "generate semifinished gear teeth" step through the use of the integral tooth forging technique. A detailed description of the forging process used and its development is provided in the TRW report ER 7389-F and will not be repeated here; however, a brief synopsis follows.

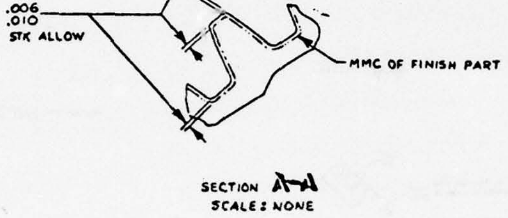
In order to produce precisely the tooth form desired, it is necessary to produce very accurate forging dies. This was accomplished by using electrical-discharge machining (EDM) to fabricate the die cavities. Conventional Gleason spiral bevel gear tooth-cutting equipment was used to manufacture EDM electrodes, which were then used to transfer (by the EDM process) the gear tooth form to the forging die cavities. The EDM electrode materials were carbon and brass. The carbon electrodes provided good wear (erosion) resistance and were used for rough cutting the dies while the brass electrodes, which exhibit a much higher wear rate but produce a finer finish on the die, were used for finish cutting the dies. Since some distortion always occurs in the forging and heat-treating processes, it was necessary to develop the die configuration such that the final ground teeth were within tolerance and all surfaces fully cleaned up with uniform stock removal. This was accomplished by cutting new electrodes, again using conventional Gleason machinery, to incorporate changes identified by the initial development. This process was repeated until an acceptable die configuration was obtained. These dies were then used for hot-coining the teeth on preforms which were themselves forged from billets, as shown in Figures 6 and 7. The coined gears and pinions were then subjected to process machining, heat treatments, and final grinding.

From the point of the carburizing-hardening operations on through final grind, the manufacturing sequence and operations are identical for both the conventional and the precision forged gears. These operations were in fact carried out by the subcontractor (Litton) currently supplying production CH-47C gears for Boeing Vertol.



SPIRAL BEVEL GEAR DATA	
NUMBER OF TEETH	35
PITCH	4.930
PRESSURE ANGLE	22° 30'
SPIRAL ANGLE (MEAN)	25° 0' LH
PITCH DIAMETER	7.099
SHAFT ANGLE BASIC	90°
PITCH ANGLE BASIC	39° 9'
ROOT ANGLE BASIC	37° 1'
FILLET RADIUS	.045 - .055
PITCH TOLERANCE	.0003
TOTAL INDEX TOLERANCE	.0015
BACKLASH CONTRIBUTION OF GEAR WITH ZERO BACKLASH MASTER (NORMAL)	.003 - .006
WHOLE DEPTH	.383 - .393

REFERENCE DATA	
CIRCULAR TOOTH THK @ P D	.334 - .337
ADDENDUM	.199
DEDENDUM	.184
NORMAL CHORDAL THK @ P D	.287
NORMAL CHORDAL ADDENDUM	.197
BACKLASH WITH MATING GEAR ON STANDARD MOUNTING DISTANCE (NORMAL)	.006 - .012
NUMBER OF TEETH IN MATING GEAR	43
LOAD SIDE OF TOOTH	CONCAVE



NOTES UNLESS OTHERWISE SPECIFIED

1. MATERIAL: AMS 6265
   AISI 9310 CVM-BMS 7-6

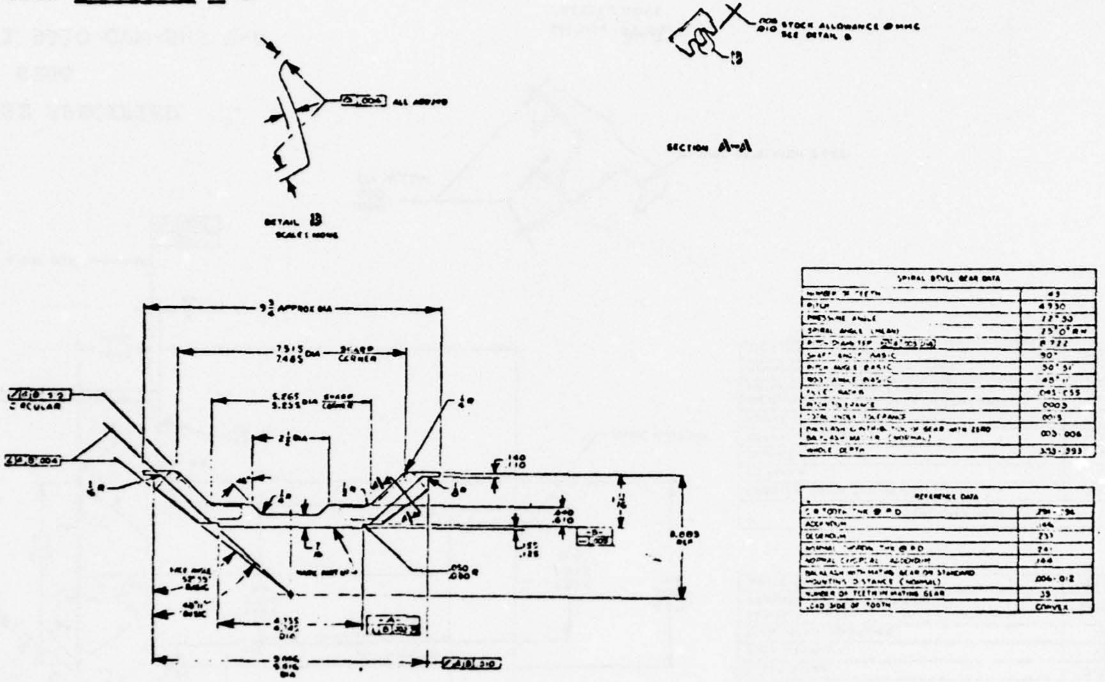
2. TOLERANCES: FRACTIONS ——— ± 1/32
   ANGLES ——— ± 2°

Figure 1. Pinion Forging Design.

NOTES UNLESS OTHERWISE SPECIFIED

1. MATERIAL: AMS 6265
   AISI 9310 CVM-BMS 7-6

2. TOLERANCES: FRACTIONS ____ ± 1/32
   ANGLES ____ ± 2°



SPIRAL BEVEL GEAR DATA	
NUMBER OF TEETH	43
PITCH	4.930
PRESSURE ANGLE	22°30'
SPIRAL ANGLE (MEAN)	25°0' RH
PITCH DIAMETER [illegible]	8.722
SHAFT ANGLE BASIC	90°
PITCH ANGLE BASIC	50°51'
ROOT ANGLE BASIC	45°11'
FILLET RADIUS	.045-.055
PITCH TOLERANCE	.0003
TOTAL INDEX TOLERANCE	.0015
BACKLASH CONTROL [illegible] OF GEAR WITH ZERO BACKLASH MASTER (NORMAL)	.003-.006
WHOLE DEPTH	.353-.393

REFERENCE DATA	
C.R. TOOTH THK @ P.D	[illegible]
ADDENDUM	.144
DEDENDUM	.231
NORMAL CHORDAL THK @ P.D	.241
NORMAL CHORDAL ADDENDUM	.144
BACKLASH WITH MATING GEAR ON STANDARD MOUNTING DISTANCE (NORMAL)	.006-.012
NUMBER OF TEETH IN MATING GEAR	35
LOAD SIDE OF TOOTH	CONVEX

Figure 2. Gear Forging Design.

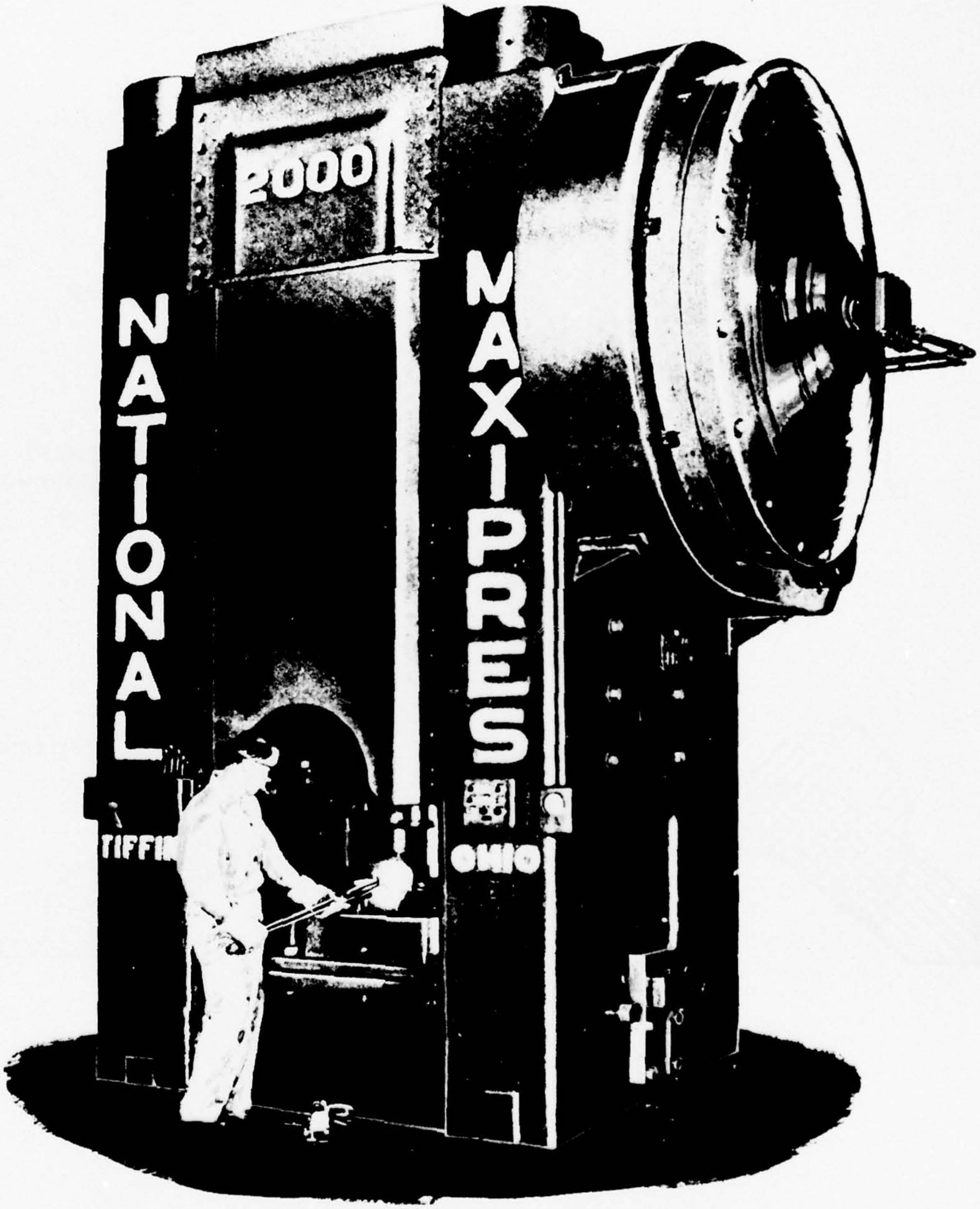


Figure 3. Rigid-Frame Single-Crank-Type Mechanical Press Used for Close-Tolerance Forging of Spiral Bevel Gears.

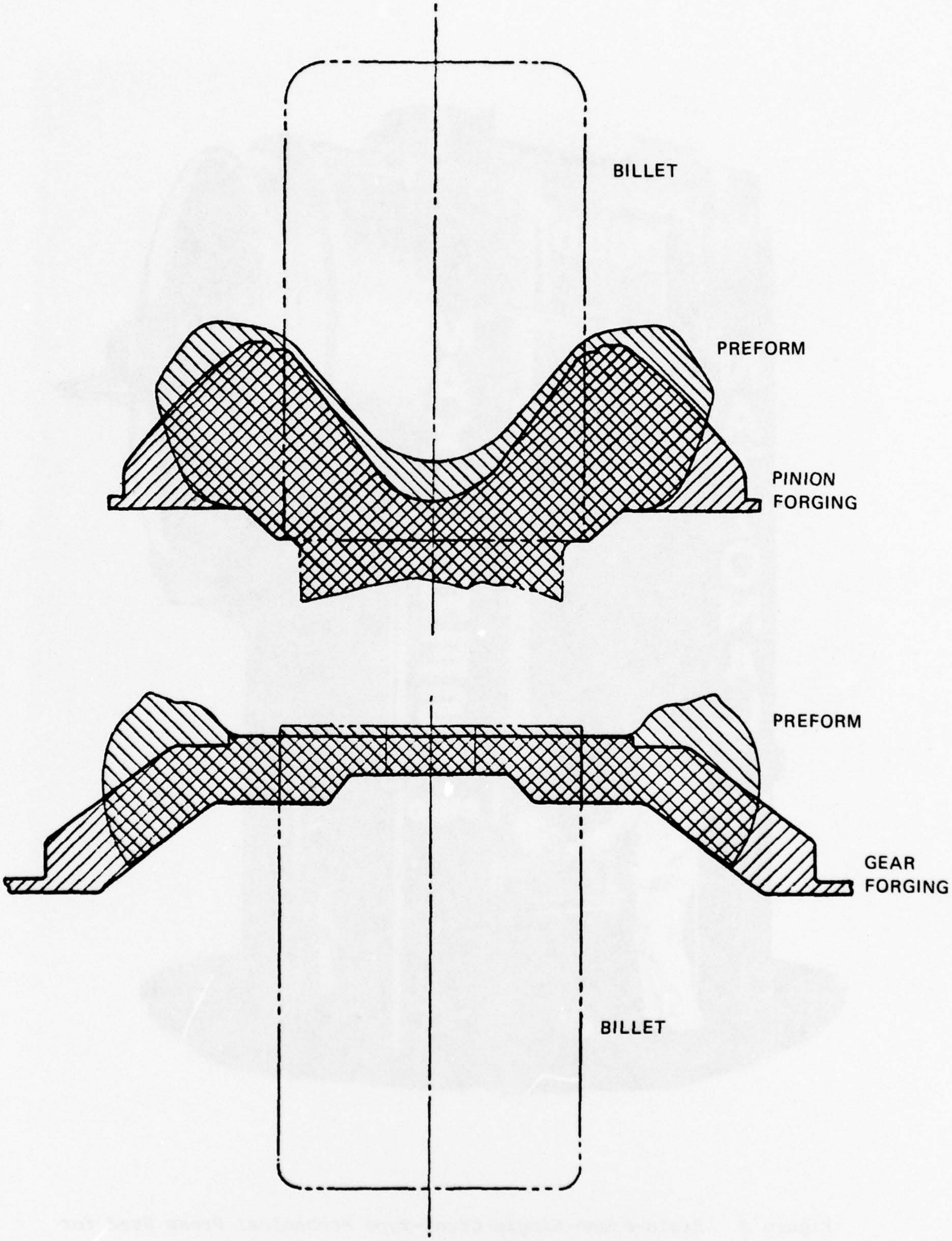


Figure 4. Billet and Preform Layouts.

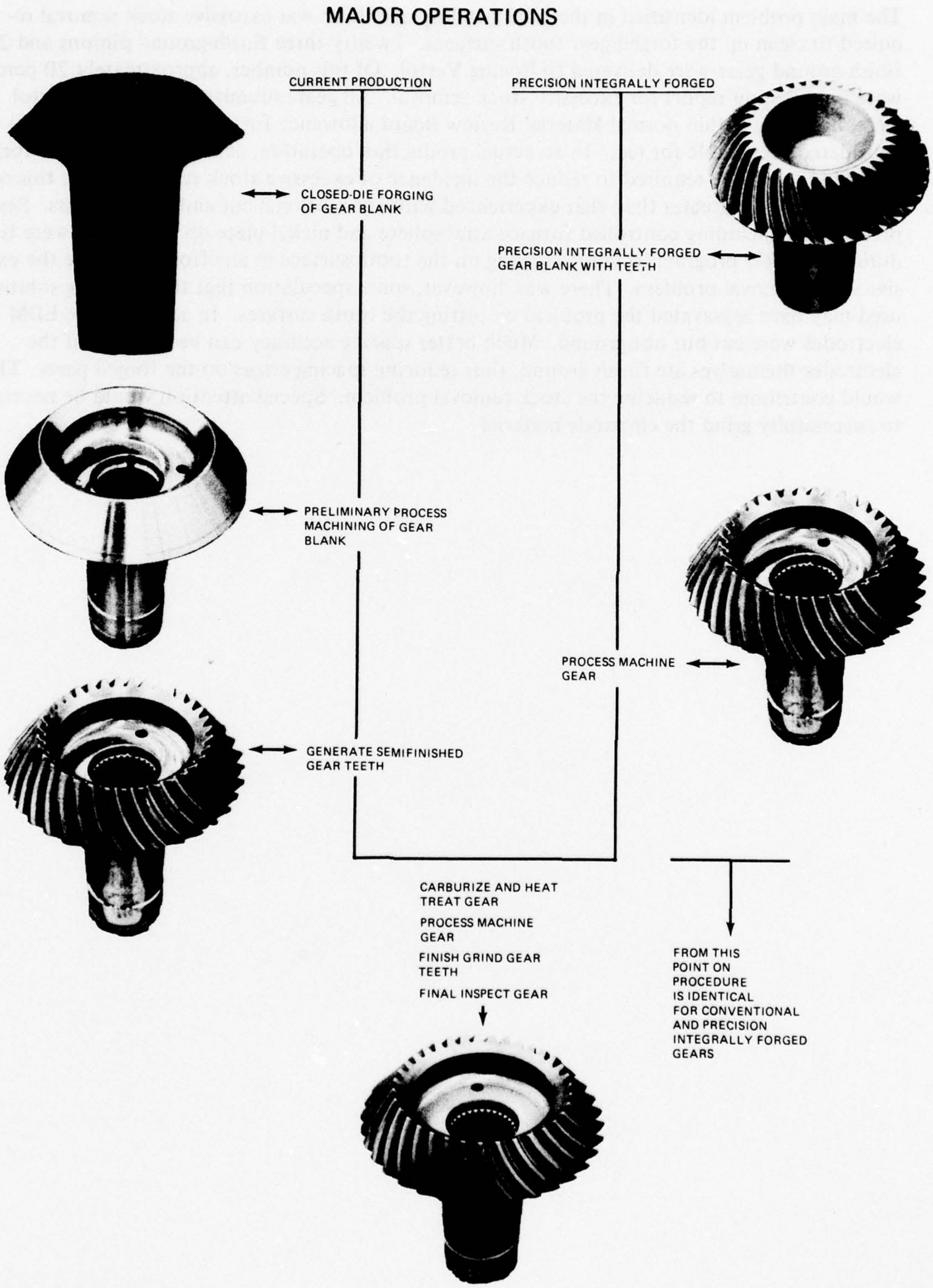


Figure 5. Comparison of Production Methods for Spiral Bevel Gears.

The main problem identified in the final grinding operation was excessive stock removal required to clean up the forged gear tooth surfaces. Twenty-three finish-ground pinions and 26 finish-ground gears were delivered to Boeing Vertol. Of this number, approximately 20 percent were on rejection report for excessive stock removal. All gears submitted to Boeing Vertol were, however, within normal Material Review Board allowance for stock removal and thus were considered acceptable for test. In an actual production operation, additional care in the forging operation would be required to reduce the incidence of excessive stock removal, since this rejection rate is far greater than that experienced with conventional cut and ground gears. Several precautions, including controlled furnace atmosphere and nickel plate on the billets, were tried during the TRW program to reduce scaling on the tooth surface in an effort to reduce the excessive stock removal problem. There was, however, some speculation that the stripping solution used may have aggravated the problem by pitting the tooth surfaces. In addition, the EDM electrodes were cut but not ground. Much better spacing accuracy can be obtained if the electrodes themselves are finish ground, thus reducing spacing errors on the forged parts. This would contribute to reducing the stock removal problem. Special attention would be necessary to successfully grind the electrode material.

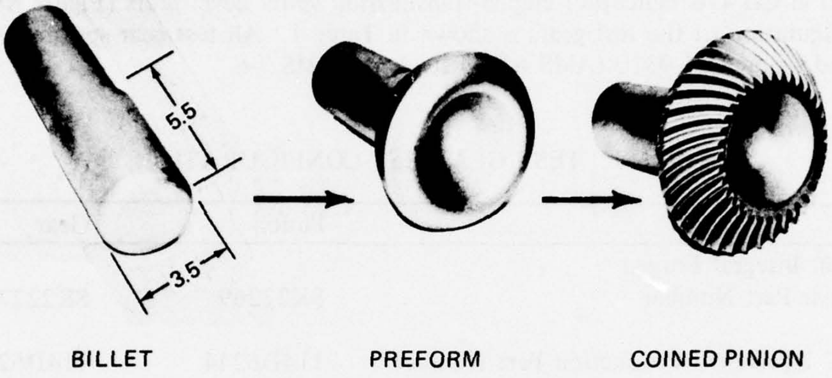


Figure 6. Pinion Forging Sequence.

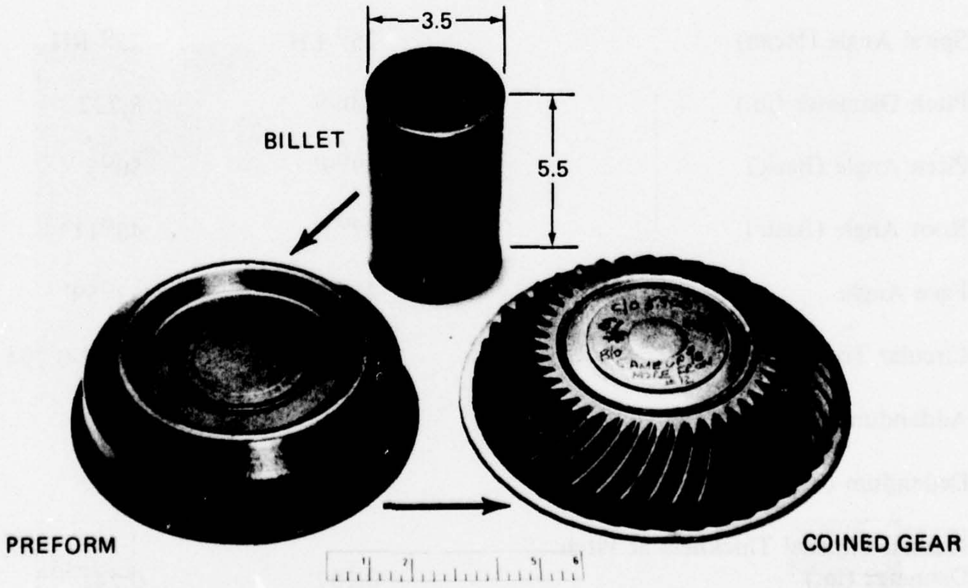


Figure 7. Gear Forging Sequence.

TEST METHOD

TEST SPECIMEN DESIGN

The GFE test gears used in this program were identical in geometry and material to the current production CH-47C helicopter engine-transmission spiral bevel gears (Figure 8). The general configuration of the test gears is shown in Table 1. All test gear specimens were manufactured from AISI 9310 (AMS 6265) steel, per BMS 7-6.

TABLE 1. TEST GEAR SET CONFIGURATION

	Pinion	Gear
Precision Integral Forged Test Gear Part Number	SK22269	SK22270
CH-47C Equivalent Production Part Number	114D6244	114D6245
Number of Teeth	35	43
Pitch	4.930	4.930
Pressure Angle	22°30'	22°30'
Spiral Angle (Mean)	25° LH	25° RH
Pitch Diameter (in.)	7.099	8.722
Pitch Angle (Basic)	39°9'	50°5'
Root Angle (Basic)	37°1'	48°11'
Face Angle	41°49'	52°59'
Circular Tooth Thickness (in.)	0.344-0.337	0.291-0.294
Addendum (in.)	0.199	0.146
Dedendum (in.)	0.184	0.237
Normal Chordal Thickness at Pitch Diameter (in.)	0.287	0.241
Load Side of Tooth	Concave	Convex

Both conventional baseline and precision integral forged bevel pinion and gear test specimens were final machined per drawings SK22269 (Figure 9) and SK22270 (Figure 10), respectively. These drawings represent the current production parts. New part numbers were assigned to preclude any possible misuse of these test gears.

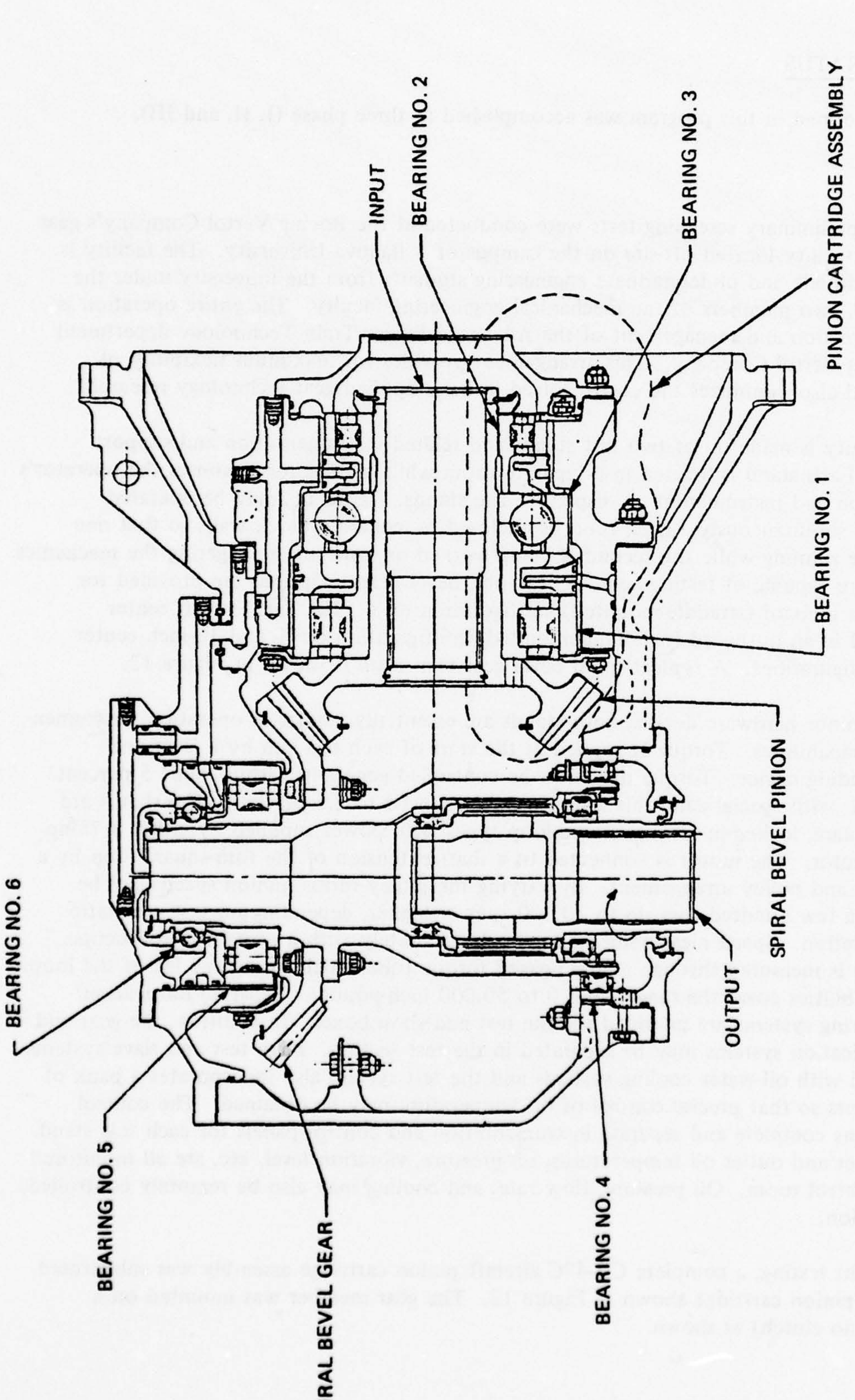


Figure 8. Cross Section of the CH-47 Engine Nose Gearbox.

TEST APPARATUS

The testing defined in this program was accomplished in three phase (I, II, and III).

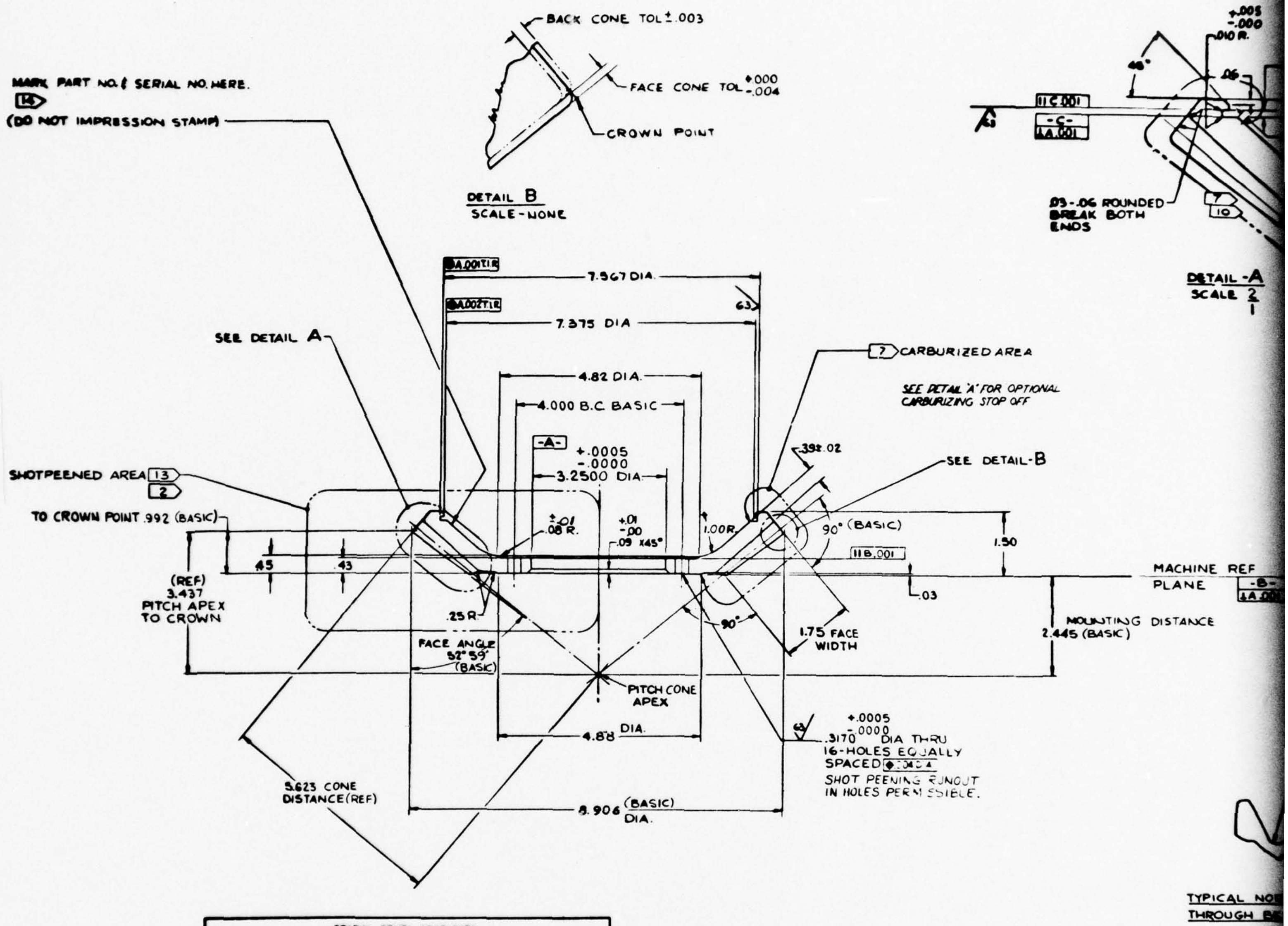
Phase I

The Phase I preliminary screening tests were conducted at the Boeing Vertol Company's gear research test facility located off-site on the campus of Villanova University. The facility is staffed by graduate and undergraduate engineering students from the university under the supervision of two members of the mechanical engineering faculty. The entire operation is under the direction and management of the Advanced Power Train Technology department of the Boeing Vertol Company. This arrangement provides for maximum flexibility of operation and also minimizes the cost involved in basic applied gear technology research.

The test facility is made up of two test stands and related instrumentation and support equipment. Each stand is located in a separate room while a third room houses the operator's control station and instrumentation displays. The stands, Figure 11, may be operated separately or simultaneously. Each room is enclosed by concrete block walls so that one stand may be running while the second is being worked on without endangering the mechanics. The stands are capable of testing spur, helical, and bevel gears. Options are provided for running in an inboard (straddle-mounted) configuration on 6-, 10-, and 15-inch center distances and in an outboard (overhung-mounted) configuration on 6- and 10-inch center distance configurations. A typical spiral bevel gear test setup is shown in Figure 12.

Except for minor hardware details, both stands are essentially similar in operation, instrumentation, and capabilities. Torque is applied at the start of each test run by a lever and hydraulic loading device. Torque may thus be controlled generally within about 5 percent of target and, with special care, this range may be reduced to 2.5 percent. The stands are both four-square, locked-in-torque, closed-loop types with power supplied by either a 75-hp or 100-hp motor. The motor is connected to a shaft extension of the four-square loop by a toothed belt and pulley arrangement. By varying the pulley ratios, pinion speed may be varied from a few hundred rpm up to 10,000 rpm or higher, depending on test gear ratio and configuration. Speed measurements are made accurately with a portable stroboscope. Shaft torque is measured through a strain-gaged torque tube which forms one leg of the loop. Torque capabilities cover the range from 0 to 50,000 inch-pounds. Separate lubrication/cooling/filtering systems are provided for the test and slave boxes. In addition, the gear and bearing lubrication systems may be separated in the test section. Both test and slave systems are equipped with oil-water cooling systems and the test system also incorporates a bank of electric heaters so that precise control of oil temperature may be obtained. The control room contains complete and separate instrumentation and control panels for each test stand. Oil flow, inlet and outlet oil temperatures, oil pressure, vibration level, etc, are all monitored from the control room. Oil pressure, flow rate. and cooling may also be remotely controlled at this location.

In the present testing, a complete CH-47C aircraft pinion cartridge assembly was substituted for the test pinion cartridge shown in Figure 12. The gear member was mounted on a solid shaft (no clutch) as shown.



SPIRAL BEVEL GEAR DATA	
NUMBER OF TEETH	43
PITCH	4.930
PRESSURE ANGLE	22° 30'
SPIRAL ANGLE (MEAN)	25° 0' RH
PITCH DIAMETER [● A .001 TIR]	8.722
SHAFT ANGLE (BASIC)	90°
PITCH ANGLE (BASIC)	50° 51'
ROOT ANGLE (BASIC)	48° 11'
FILLET RADIUS	.045 — .055
PITCH TOLERANCE	.0003
TOTAL INDEX TOLERANCE	.0015
BACKLASH CONTRIBUTION OF GEAR WITH ZERO BACKLASH MASTER (NORMAL) 14	.003 TO .006
WHOLE DEPTH	.383 — .393

REFERENCE DATA	
CIRCULAR TOOTH THICKNESS AT PITCH DIAMETER	.291 — .294
ADDENDUM	.146
DEDENDUM	.237
NORMAL CHORDAL THICKNESS AT PITCH DIAMETER	.241
NORMAL CHORDAL ADDENDUM	.144
BACKLASH WITH MATING GEAR ON STANDARD MOUNTING DISTANCE (NORMAL)	.006 — .012
NUMBER OF TEETH IN MATING GEAR	35
LOAD SIDE OF TOOTH	CONVEX
GLEASON SUMMARY NO. 16 HYPOID GENERATOR	130.039
GLEASON SUMMARY NO 26 GENERATOR	129.946

Figure 9. Test Gear Final Machine Drawing.

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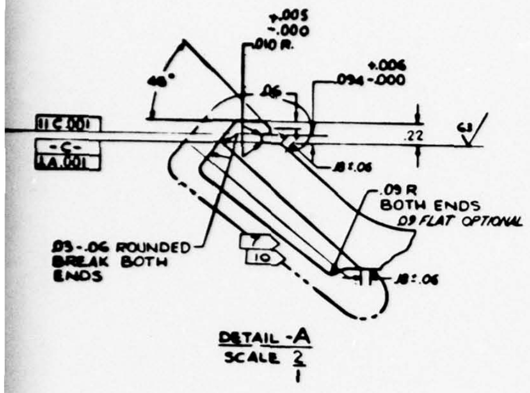


DETAIL -A
SCALE 2/1

NOTES

1. ALL DIAMETERS ON A COMMON CENTERLINE TO BE CONCENTRIC TO EACH OTHER WITHIN .003 TIR UNLESS OTHERWISE NOTED

2. SHOT PEENING IS PERMISSIBLE IN GROOVE BUT NOT MANDATORY. DO NOT MASK.

3. MAXIMUM SURFACE ROUGHNESS 125 EXCEPT AS NOTED

4. FINISH ON GEAR TEETH 25 FLANKS AND 32 FILLETS. SURFACE FINISH REQUIREMENTS TO BE MET AFTER FINAL PROCESSING

5. BEVEL GEAR TEETH TO BE GROUND TO MATCH MASTER.

6. RELATIVE AZIMUTH POSITION OF GEAR TEETH, AND HOLES OPTIONAL UNLESS SPECIFIED

7. HEAT TREATMENT
   - A. CARBURIZE ENCLOSED AREAS PER BOEING PROCESS SPECIFICATION MS 12.02
   - B. CARBURIZED CASE HARDNESS ROCKWELL C
   - C. EFFECTIVE CASE DEPTH AFTER GRINDING
   - D. CORE HARDNESS ROCKWELL C
   - E. CORE STRENGTH PSI (REF)
   - F. DRAW AT 300°F - 325°F FOR FOUR HOURS AFTER FINAL GRIND

	AREA 'A'	AREA 'B'
A		
B	59-64	
C	.030 TO .050	
D	32 -42	
E	142000 - 194000	

8. BREAK ALL SHARP EDGES NOT SPECIFIED TO A RADIUS OR A CHAMFER OF .010 TO .025.

9. FINISH BLACK OXIDE TREATMENT PER BOEING PROCESS SPECIFICATION MS 8.17.

10. OPTIONAL CARBURIZED AREA.

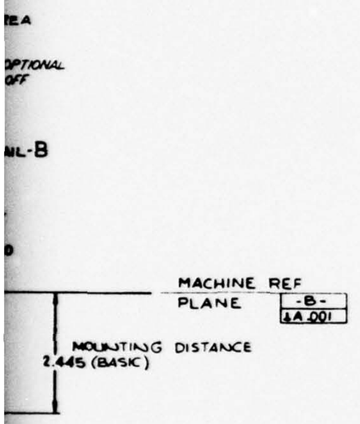
11. NITAL ETCH INSPECTION PER BOEING PROCESS SPECIFICATION BAC 5436 PRIOR TO SHOT PEENING.

12. FLUORESCENT MAGNETIC PARTICLE INSPECTION PER BOEING PROCESS SPECIFICATION BAC 5424 CLASS A.

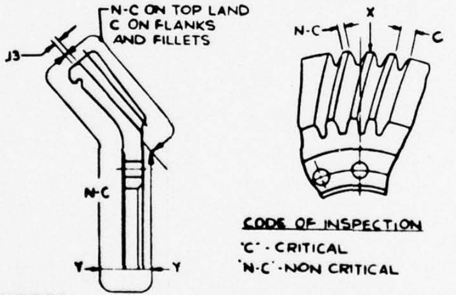
13. SHOT PEEN ENCLOSED AREA PER BOEING PROCESS SPECIFICATION BAC 5730 AFTER GRINDING AND PRIOR TO BLACK OXIDE TREATMENT EXCEPT AS NOTED.
   - A. SHOT SIZE 110
   - B. ARC HEIGHT .008-.012 A2
   - C. COVERAGE 200%

14. MARK ACTUAL MOUNTING DISTANCE AND BACKLASH HERE

15. HANDLE PART SK 22270-1 PER BOEING VERTOL SPEC. PS-122

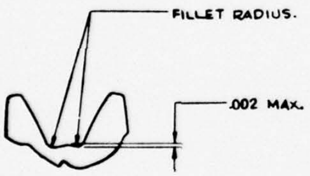


12. FLUORESCENT MAGNETIC PARTICLE INSPECTION PER BOEING SPEC BAC 5424 CLASS A. (SK 22270-1)



CODE OF INSPECTION
'C' - CRITICAL
'N-C' - NON CRITICAL

MAGNETISM
1- AXIS X-X ACROSS TEETH - TURN 90° FOR SECOND SHOT 1800-2200 AMPS.
2- AXIS Y-Y CENTRAL CONDUCTOR FOR TEETH 2000-2400 AMPS FOR SHAFT 1800-2000 AMPS.
3- COIL 500-800 AMPS.



TYPICAL NORMAL SECTION
THROUGH BEVEL GEAR TEETH

.294
.012
EX
39
46

PART OR IDENTIFYING NUMBER	NOMENCLATURE OR DESCRIPTION	MATERIAL AND SPECIFICATION	HT TR	FINISH	PT MK	REV LTR
SK 22270-1	GEAR	FORGING STEEL AMS 6265 AISI 9310 CVM - BMS7-6 HDN & TEMP	7	9	VE	

RELEASE
LIST OF MATERIAL

PART MARKING PER BAC 5307
SEE BAC D 2097 FOR SURFACE ROUGHNESS
MATERIAL SUBSTITUTION & EQUIVALENTS PER D8-0127
FOR FINISH CODE SEE Doc. PS-362
DWG ORIG BY (GROUP) ADV DRIVE SYS TECH. CHANGE NO

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DIMENSIONING & TOLERANCING PER MIL-STD-8
UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES
TOLERANCES
ANGLES ± .5°
.X ± .1
.XX ± .01
.XXX ± .005

CONTR
DR V. PERILLO DATE 3-12-76
CHK J LEEDS 5-6-76
STRUCT
WTS
GS J.R. Wheat 4-13-76
PROJ [illegible] 4/1/76

THE BOEING COMPANY
VERTOL DIVISION MORTON, PENNSYLVANIA

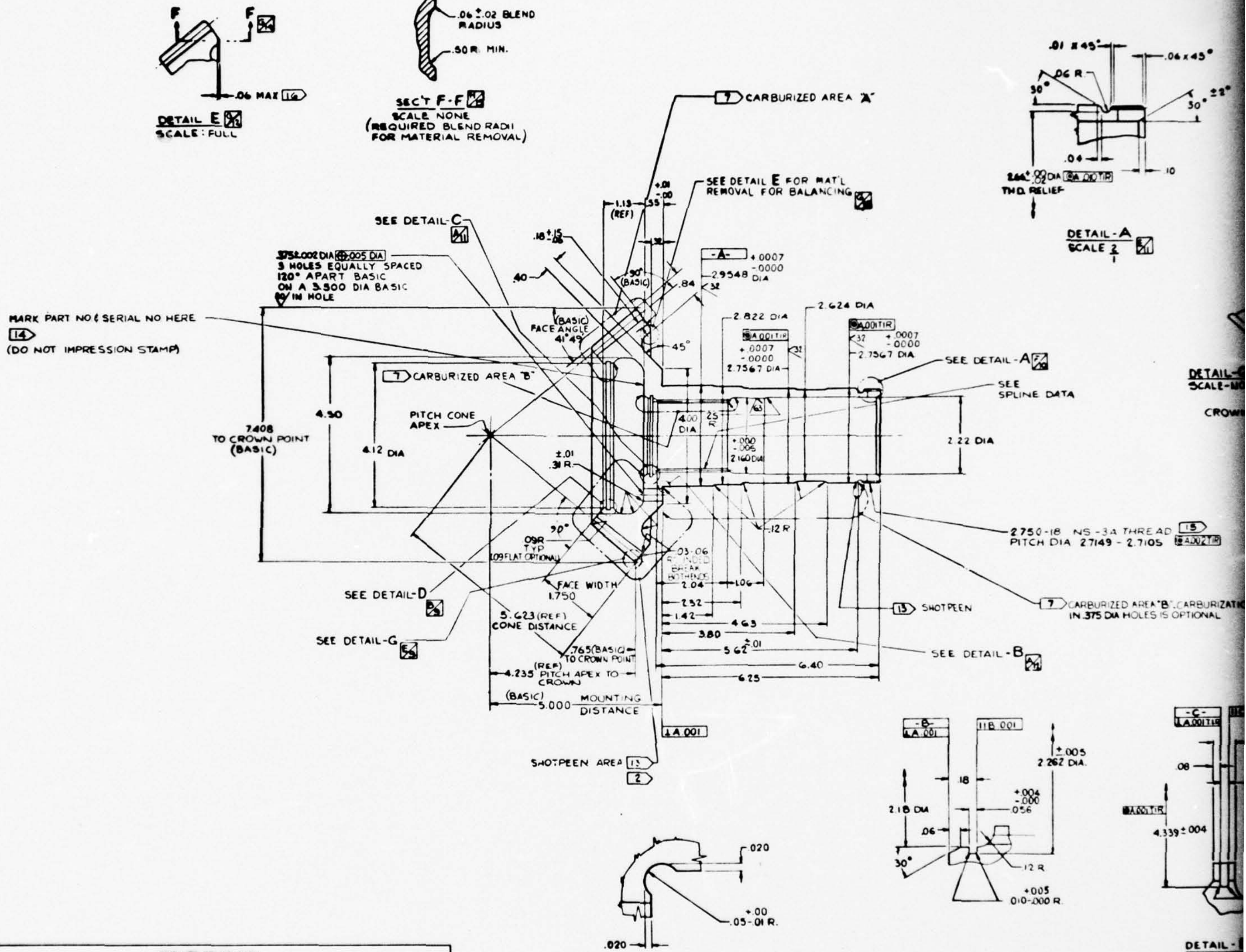
BASELINE SPIRAL BEVEL GEAR

SIZE J CODE IDENT NO 77272 SK 22270
SCALE FULL SH 1 OF 1

BEST AVAILABLE COPY

2

BEST AVAILABLE COPY

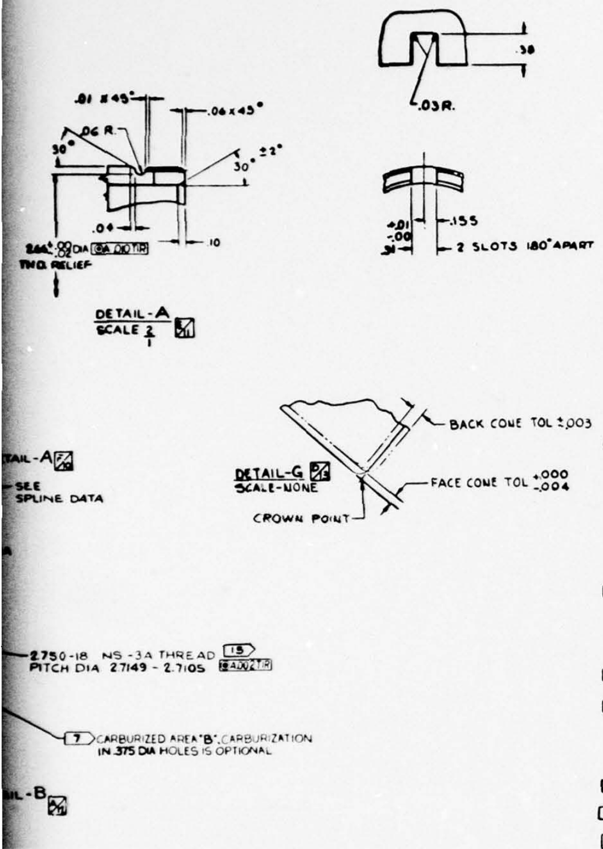


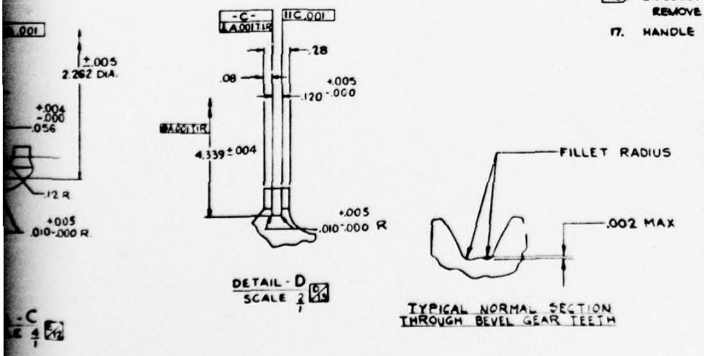
INVOLUTE SPLINE DATA			
TYPE FILLET ROOT SIDE FIT		EXTERNAL	INTERNAL
NUMBER OF TEETH			32
PITCH			16/32
PRESSURE ANGLE			30°
PITCH DIAMETER [illegible]			2.0000
MAJOR DIAMETER		—	2.125 — 2.1235
MINOR DIAMETER		—	1.9375 — 1.9425
[illegible] DIAMETER			2.0665
BASE CIRCLE DIAMETER REF			1.7321
CIRCULAR TOOTH THICKNESS	MINIMUM ACTUAL		
	MAXIMUM EFFECTIVE		
CIRCULAR SPACE WIDTH	MAXIMUM ACTUAL	—	[illegible]
	MINIMUM EFFECTIVE	—	[illegible]
MEASUREMENT BETWEEN TWO PINS		MIN	[illegible] MAX
PIN DIAMETER			[illegible]
TOTAL INDEX TOLERANCE			[illegible]
[illegible]			[illegible]
[illegible] TOLERANCE		[illegible]	[illegible]
[illegible]			[illegible]

SPIRAL BEVEL GEAR DATA	
NUMBER OF TEETH	35
PITCH	4.930
PRESSURE ANGLE	22°30'
SPIRAL ANGLE (MEAN)	25°0' LH
PITCH DIAMETER [illegible]	7.099
SHAFT ANGLE (BASIC)	90°
PITCH ANGLE (BASIC)	39°9'
ROOT ANGLE (BASIC)	37°1'
FILLET RADIUS	.045 — .055
PITCH TOLERANCE	.0003
TOTAL INDEX TOLERANCE	.0015
BACKLASH CONTRIBUTION OF GEAR WITH ZERO BACKLASH MASTER (NORMAL) 14	.005 TO .006
WHOLE DEPTH	.383 — .393

REFERENCE DATA	
CIRCULAR TOOTH THICKNESS AT PITCH DIAMETER	.334 — .337
ADDENDUM	.199
DEDENDUM	.184
NORMAL CHORDAL THICKNESS AT PITCH DIAMETER	.287
NORMAL CHORDAL ADDENDUM	.197
BACKLASH WITH MATING GEAR ON STANDARD MOUNTING DISTANCE (NORMAL)	.006 — .012
NUMBER OF TEETH IN MATING GEAR	43
LOAD SIDE OF TOOTH	CONCAVE
GLEASON SUMMARY NO 16 HYPOID GENERATOR	150.053
GLEASON SUMMARY NO 26 GENERATOR	129.946

Figure 10. Test Pinion Final Machine Drawing.





TYPICAL NORMAL SECTION THROUGH BEVEL GEAR TEETH

NOTES

1. ALL DIAMETERS EXCEPT TAPERS AND CHAMFERS ON A COMMON CENTER LINE TO BE CONCENTRIC TO EACH OTHER WITHIN .002 TIR UNLESS OTHERWISE NOTED TAPERS AND CHAMFERS TO BE CONCENTRIC TO OTHER DIAMETERS ON COMMON CENTER LINE WITHIN .010 TIR

2. SHOT PEENING IS PERMISSIBLE IN GROOVES, .51R UNDER TOE OF GEAR TEETH & .375 DIA. HOLES, BUT NOT MANDATORY. DO NOT MASK.

3. MAXIMUM SURFACE ROUGHNESS 125 EXCEPT AS NOTED

4. FINISH ON GEAR TEETH 25 FLANKS AND 32 FILLETS. SURFACE FINISH REQUIREMENTS TO BE MET AFTER FINAL PROCESSING.

5. FINISH ON SPLINE TEETH 63 FLANKS AND FILLETS

6. RELATIVE AZIMUTH POSITION OF GEAR TEETH, SPLINE TEETH AND HOLES OPTIONAL UNLESS SPECIFIED

7. HEAT TREATMENT

	AREA 'A'	AREA 'B'
A. CARBURIZE ENCLOSED AREAS PER BOEING PROCESS SPECIFICATION MS 12.02		
B. CARBURIZED CASE HARDNESS ROCKWELL C	59-64	59-64
C. EFFECTIVE CASE DEPTH AFTER GRINDING	.030 TO .050	.010-.020
D. CORE HARDNESS ROCKWELL C	32-42	32-42
E. CORE STRENGTH PSI (REF)	142 TO 194 KSI	142 TO 194 KSI

F. DRAW AT 300°F - 325°F FOR FOUR HOURS AFTER FINAL GRIND

8. BREAK ALL SHARP EDGES NOT SPECIFIED TO A RADIUS OR A CHAMFER OF .010 TO .025

9. FINISH BLACK OXIDE TREATMENT PER BOEING PROCESS SPECIFICATION MS 8.17.

10. BEVEL GEAR TEETH TO BE GROUND TO MATCH MASTER.

11. NITAL ETCH INSPECTION PER BOEING PROCESS SPECIFICATION BAC 5436 PRIOR TO SHOT PEENING.

12. FLUORESCENT MAGNETIC PARTICLE INSPECTION PER BOEING PROCESS SPECIFICATION BAC 5424 CLASS A

13. SHOT PEEN ENCLOSED AREA PER BOEING PROCESS SPECIFICATION BAC 5730 AFTER GRINDING AND PRIOR TO BLACK OXIDE TREATMENT EXCEPT AS NOTED
   - A. SHOT SIZE 110
   - B. ARC HEIGHT .008-.012 A2
   - C. COVERAGE 200%

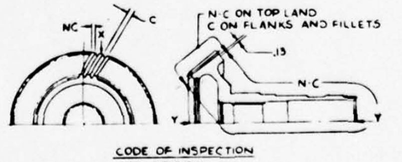
14. MARK ACTUAL MOUNTING DISTANCE AND BACKLASH HERE

15. THREADS PER FEDERAL HANDBOOK H-28.

16. SK 22269 GEAR TO BE STATICALLY BALANCED TO .01 INCH-OUNCES. REMOVE MATERIAL FROM INDICATED AREAS.

17. HANDLE PART SK22269 PER BOEING VERTOL SPEC PS-122

12 FLUORESCENT MAGNETIC PARTICLE INSPECTION PER BOEING SPEC BAC 5424 CLASS A. (SK22269-1)



CODE OF INSPECTION
"C" = CRITICAL
"N-C" = NON CRITICAL

MAGNETISM
1- AXIS X-X ACROSS TEETH. TURN 90° FOR SECOND SHOT 1800-2200 AMPS.
2- AXIS Y-Y CENTRAL CONDUCTOR FOR TEETH 2000-2400 AMPS FOR SHAFT 1800-2000 AMPS.
3- COIL 500-800 AMPS.

REFERENCE DATA	
ESS AT PITCH DIAMETER	.334 — .337
	.199
	.184
SS AT PITCH DIAMETER	.287
ENDUM	.197
EAR ON STANDARD MOUNTING	.006 — .012
ING GEAR	43
	CONCAVE
ON HYPOID GENERATOR	150.051
NO 26 GENERATOR	129.946

PART OR IDENTIFYING NUMBER	NOMENCLATURE OR DESCRIPTION	ZONE	MATERIAL AND SPECIFICATION	HT TR	FINISH	ST NO	REV LTR
SK 22269-1	PINION		FORGING STEEL AMS 6265 AISI 9310 CVM-BMS 7-[illegible] HPN & TEMP	7	9	VB	

RELEASE

LIST OF MATERIAL

PART MARKING PER BAC 5307

SEE BAC D 2097 FOR SURFACE ROUGHNESS

MATERIAL SUBSTITUTION & EQUIVALENTS PER D6-017
FOR FINISH CODE SEE DOC PS 568

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UNLESS OTHERWISE STATED DIMENSIONS ARE IN INCHES
TOLERANCES
ANGLES ±.5° .X ±.1
.XX ±.01
.XXX ±.005

ADV DRIVE
DWG ORIG BY (GROUP) SYS TECH CHANGE NO

CONTR
DR [illegible]
CHK J. LEEDS
STRESS
WT
[illegible]
PROJ [illegible]
APP

THE BOEING COMPANY
VERTOL DIVISION MORTON, PENNSYLVANIA

BASELINE SPIRAL BEVEL PINION

SIZE J
CODE IDENT NO 77272
SK 22269
SCALE FULL
SH 1 OF 1

BEST AVAILABLE COPY

2

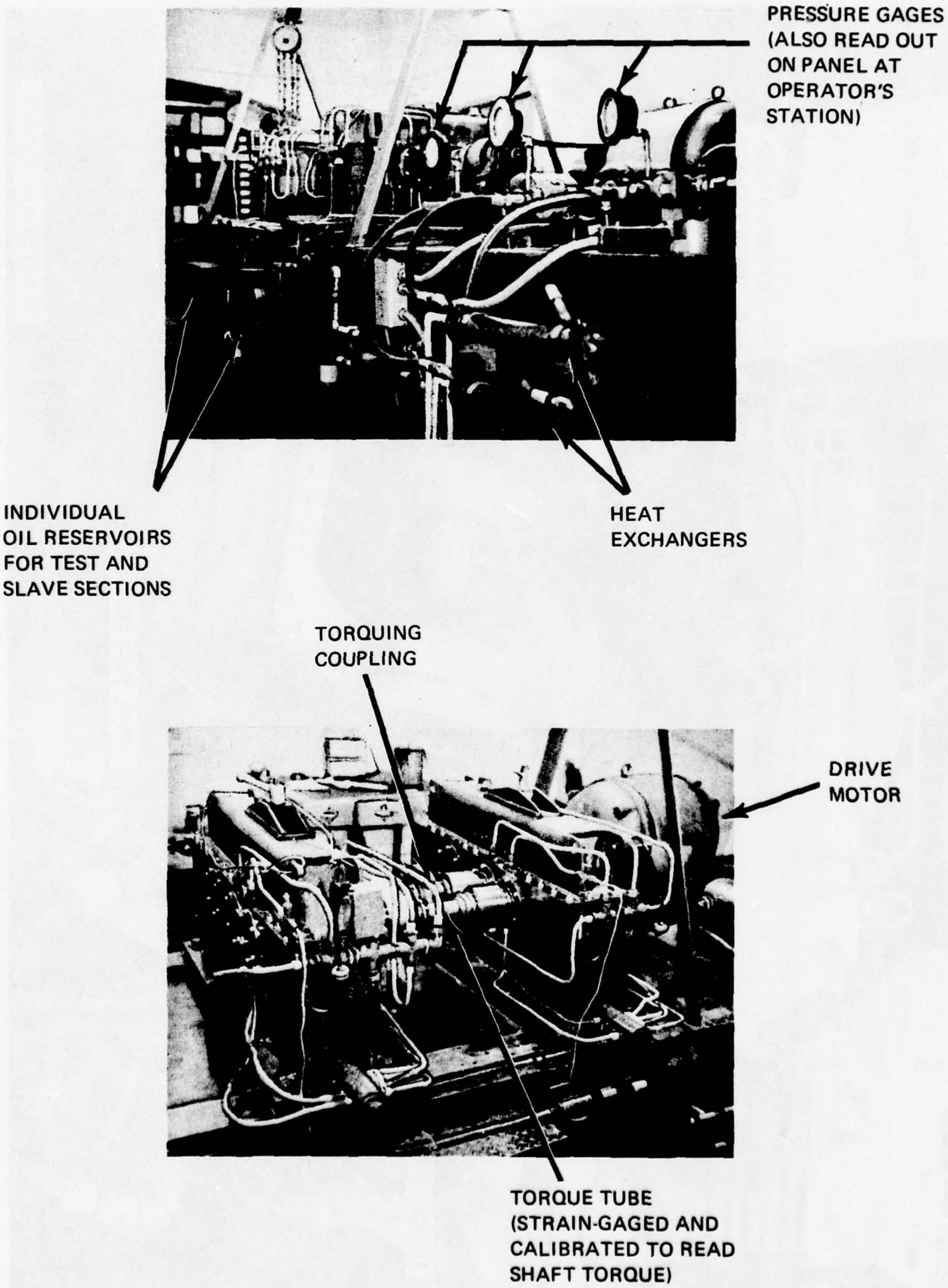

Figure 11. Details of the Gear Research Test Stands.

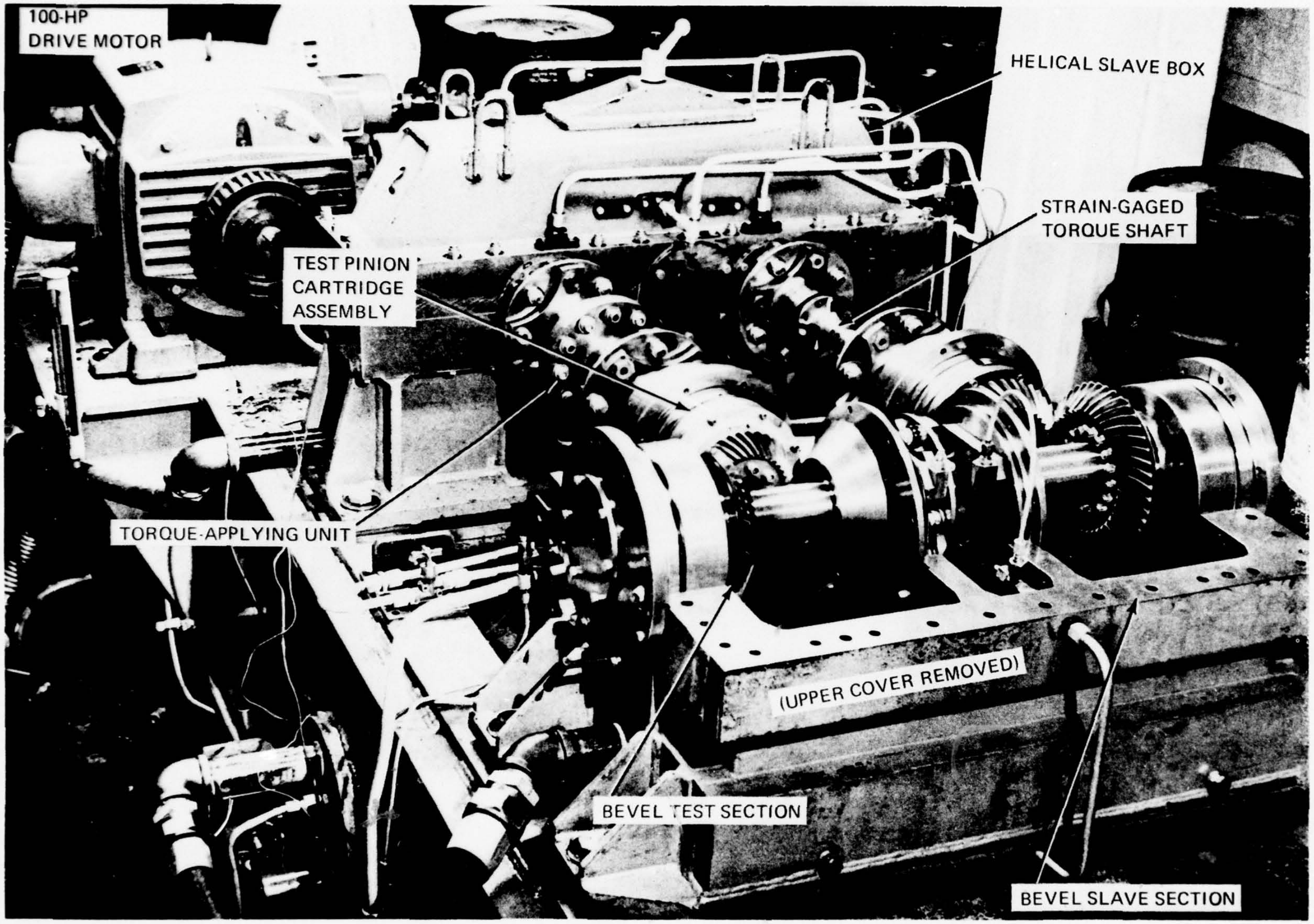

Figure 12. Closed-Loop Bevel Gear Research Test Stand.

Phases II and III

All Phase II and III testing was conducted on the CH-47C closed-loop engine-combiner test stand. This rig is of the four-square, locked-in-torque type with variable speed and torque capabilities. Two engine boxes and a combining transmission, as shown in Figure 13, may be run simultaneously. For purposes of this test program, a slave combiner was used with two test engine boxes. Control over temperature is maintained by use of special oil-water heat exchangers with condition monitoring provided by the standard aircraft instrumentation. All operations are controlled from a remote panel setup outside the cell. The standard aircraft oil system (oil, filter, pumps, etc) is used on the test boxes; however, the aircraft cooler is not used. Oil-water heat exchangers are substituted for the aircraft cooler to simplify the test system.

The test rig as configured will accept two engine boxes (and a combiner) in their exact aircraft configuration except for a shortened cross-shaft. The standard cross-shafts are replaced with much shorter, strain-gaged aluminum adapter/shafts (integral) which are used to monitor torque. The test stand is capable of testing either engine transmission up to 130 percent of maximum single-engine torque, but not both simultaneously. With all gearboxes installed in the stand, it is possible to remove the gear member from any test box for internal inspection without removing the engine box from the stand (a valuable time-saving feature for step-load runs as used in this program).

The use of this stand simulates actual aircraft conditions.

TESTING TECHNIQUE

Phase I

The primary test variable was shaft torque. The test conditions maintained for each run are shown in Table 2. Four gear sets, two conventional baseline and two precision integral forged, were tested with each set being subjected to the complete load spectrum shown in Table 3.

TABLE 2. PHASE I TEST CONDITIONS

Input Pinion Speed	3,450 ± 50 rpm
Inlet Oil Temperature	195^{o}F ± 5^{o}F
Inlet Oil Pressure	55 ± 5 psi
Oil Type	MIL-L-23699

Gear tooth load was a function of shaft torque which was applied through a lever system at the beginning of each test run. Torque levels were observed on a Strainsert SR2 instrument at the beginning and conclusion of each test run. Deviation from the initial target torque was controlled within 5 percent at test startup.

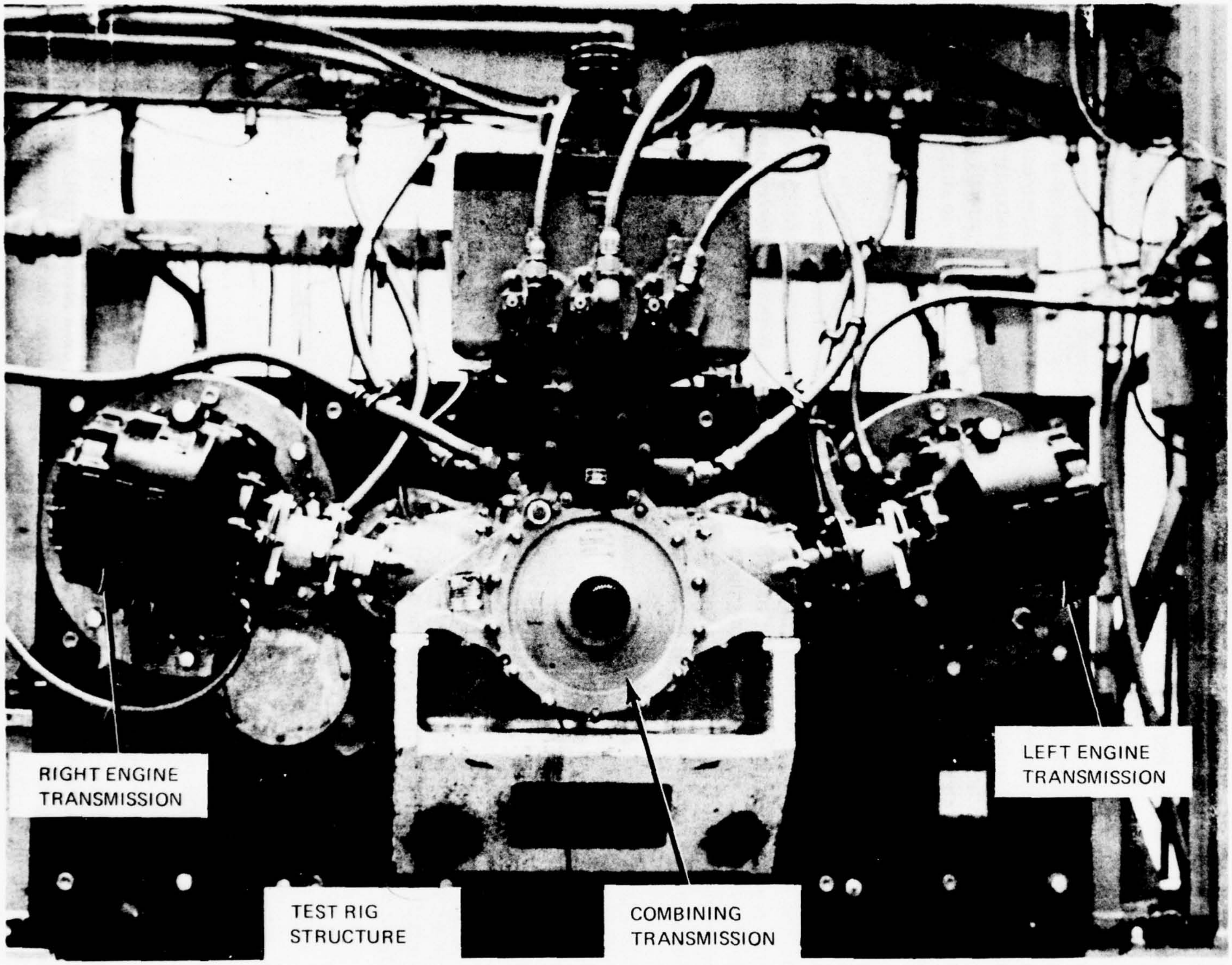

Figure 13. CH-47C Closed-Loop Engine-Combiner Test Stand.

TABLE 3. PHASE I TEST LOADING

Run Number	Percent Load*	Pinion Torque (in.-lb)	Cycles	Time (hr)
1	50	8,000	4×10^5	2
2	100	16,000	6×10^6	29.3
3	150	24,000	6×10^6	29.3
*Based on maximum aircraft single-engine torque				

The torquemeter was calibrated before and at the conclusion of the test program. Calibration was conducted on a Riehle deadweight torsion test machine (Figure 14). Recalibration curves agreed with the initial curve within 2 percent. Test time (cycles) was determined by a log record of running time on an elapsed-time meter in the test stand console. Power was supplied by a 100-hp electric motor driving the input shaft through a toothed belt arrangement.

Prior to conducting the test program, deflection tests were conducted by mounting the test gears in the test box, applying specified loads, and rotating the mesh by hand. This effort was conducted to evaluate the contact patterns and to finalize the grinding summaries.

The test procedure used for all test gears in this program was the same and consisted of the following sequence:

Test runs were conducted for specified times at the specified load levels. During the test runs, vibration surveillance was provided by visual observation of the oscilloscope traces (see Figure 15). Visual inspections were made at 30-minute intervals during the first hour's running and at 4-hour intervals thereafter until completion of the run.

Since comparison of the relative load capacity, regardless of failure mode, is the prime objective of this program, the testing was conducted under conditions which simulate aircraft operations rather than under conditions aimed at producing certain types of failures. Under these circumstances, each gear set was run for the specified period of time regardless of condition except, of course, if a catastrophic failure occurred (none did), and the condition of all teeth monitored as noted above. Relative load capacity may then be determined by comparing time/condition records for each gear set.

Phase II

As was the case with Phase I testing, the primary variable for Phase II was shaft torque. The test conditions maintained for each Phase II test run are summarized in Table 4. The oil inlet temperature and pressure vary somewhat from the Phase I testing. Since the Phase I tests were designed to be severe preliminary tests, the conditions used represented worst-case operation. The Phase II tests were designed to simulate long-term, high-load aircraft operation; thus the test conditions represent nominal aircraft operation.

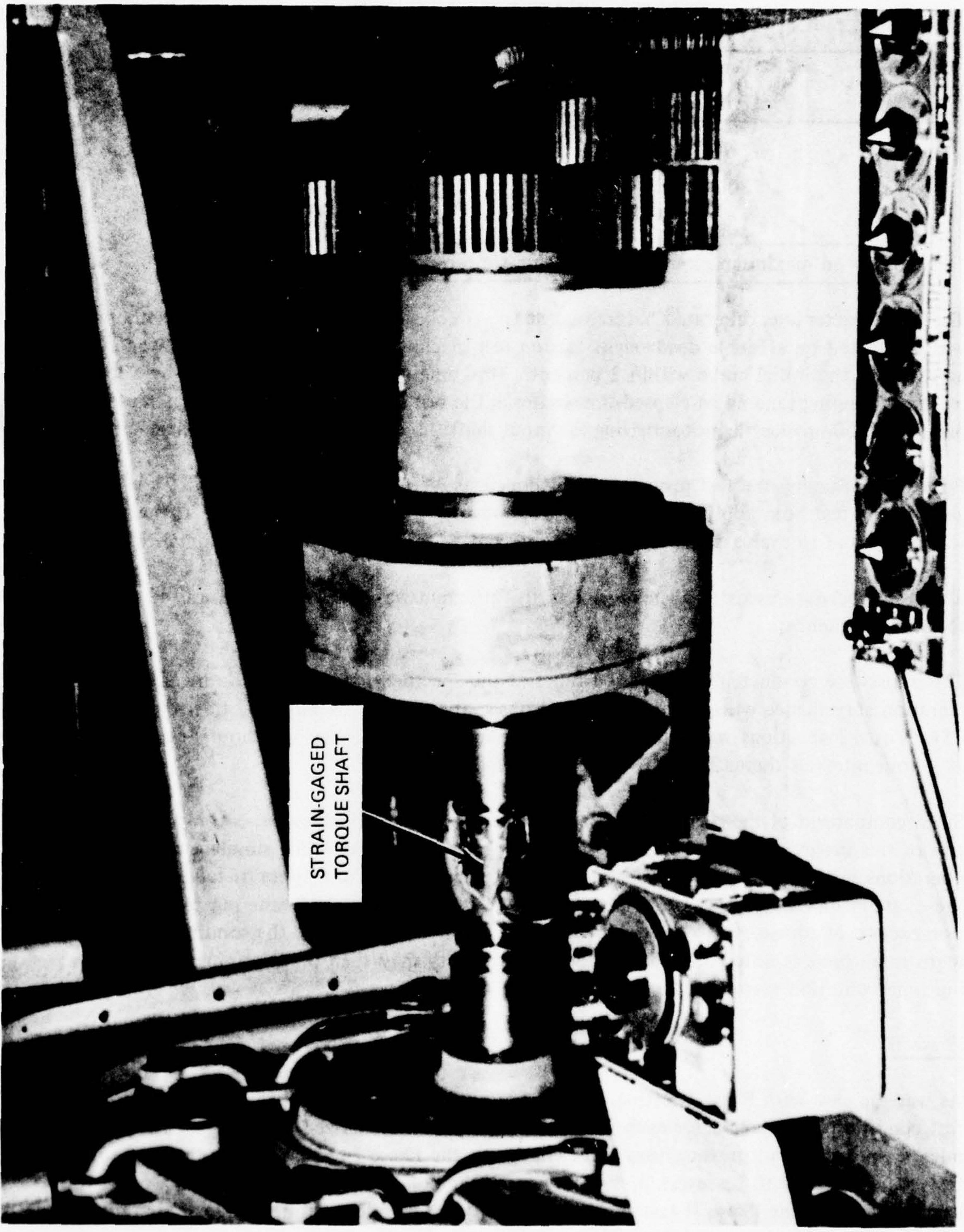

Figure 14. Deadweight Torsion Test Machine.

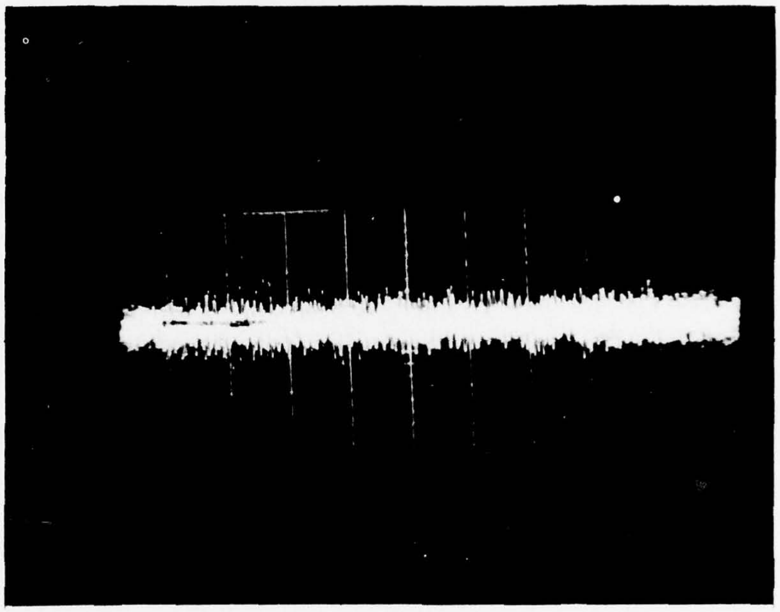

Figure 15. Typical Oscillograph Trace of Spiral Bevel Test Gearbox During Run; the Response of the Accelerometer Mounted on the Test Gearbox was Monitored During Running to Preclude Possible Catastrophic Failure.

TABLE 4. PHASE II AND III TEST CONDITIONS

Input Pinion Speed	14,720 ± 5%
Inlet Oil Temperature	$140^{\circ}F \pm 5^{\circ}F$
Inlet Oil Pressure	40 ± 5 psi
Oil Type	MIL-L-23699

Prior to initiating the test program, deflection tests were conducted by mounting the test gears in the test box, applying specified loads, and rotating the system by hand. This effort was conducted to insure that the gear pattern motion, within the aircraft system, was acceptable at the high overload conditions to be run.

All aircraft transmissions are subjected to a specific run-in procedure before being released either for production or test. This run-in procedure was also followed with each test box used in this program. Each box was built according to normal aircraft procedures with the usual backlash and pattern checks. The boxes are then installed in the test rig and run at the load levels shown in Table 5. The run-in procedure is based on twin-engine loading, which is somewhat lower than the test loads. After the run-in is completed, the gear cartridge is removed so that the gears may be visually inspected. If no discrepancies are discovered, the box is reassembled and is then ready for testing.

TABLE 5. STANDARD CH-47 PRODUCTION BOX RUN-IN LOADING

Run Number	Percent Load*	Pinion Torque (in.-lb)	Cycles	Time (hr)
1	10	1,212	4.7×10^5	0.5
2	50	6,060	4.7×10^5	0.5
3	100	12,120	9.4×10^5	1.0

*Based on maximum twin-engine torque

Two sets each (a total of 4 sets) of the standard baseline and the precision forged bevel gears were subjected to a screening test run as defined in Table 6. In these and all subsequent tests, both right and left engine box configurations were used to avoid any bias which might occur due to location. The purpose of these screening tests was to identify any major problem or defect, particularly those which may be speed-dependent, before embarking on the extended endurance runs. Each test gear set was examined visually at the completion of its 20-hour run. Because of the very high loads applied, each box was loaded individually rather than in pairs. This effectively reduced the load on the slave combining transmission without compromising the test results.

TABLE 6. PHASE II SCREENING TEST LOADING

Percent Load*	130
Pinion Torque (in.-lb)	20,800
Cycles	1.8×10^7
Time (hr)	20

*Based on maximum aircraft single-engine torque

Upon the successful completion of the screening tests, the test engine boxes were prepared for the endurance testing. Visual examination of all components revealed no discrepancies. In order to provide for minimum overall test costs, two engine transmissions were built up and installed in the test rig, as shown in Figure 13, for each run. In order to reduce the effective load on the slave, each box was loaded individually; that is, the full load was applied to one box while the other was idled at about 15-percent load. The role of load and idle boxes was then reversed so that each box was run at the specified load for the specified time. At the completion of each load level, the gear cartridge was removed from each box to permit visual inspection of the gears. The condition of the teeth was noted, after which the cartridges were reinstalled and the same procedure was repeated for the next load level. Each of three precision forged bevel gear sets was subjected to 100-hour endurance runs by this procedure in accordance with the load schedule shown in Table 7.

TABLE 7. PHASE II 100-HOUR ENDURANCE TEST RUNS

Run Number	Percent Load*	Pinion Torque (in.-lb)	Cycles	Time (hr)
1	100	16,000	2.2×10^7	25
2	110	17,600	2.2×10^7	25
3	120	19,200	2.2×10^7	25
4	130	20,800	2.2×10^7	25
		Totals:	8.8×10^7	100

*Based on maximum aircraft single-engine torque rating (3,750 hp at 14,720 rpm)

Phase III

This testing was conducted to evaluate the surface durability characteristics of the precision forged gears over a relatively long timespan (1.8×10^8 cycles per gear set). It provided some indication of the relative reliability of the forged gears.

As was the case with the gear sets run in Phase II, all Phase III gear sets were subjected to the standard production run-in procedure (as shown in Table 5) prior to the start of each test. After the run-in was completed the gear cartridge on each engine box was removed for visual inspection.

A total of four precision, integrally forged gear sets were run simultaneously with a slave combining transmission in the test rig shown in Figure 13. The test conditions were as shown in Table 4.

Unlike the Phase II testing, however, this testing was accomplished for 200 hours at constant torque and speed (both maintained within ±5 percent). Testing was halted at approximately 25-hour intervals at which time the gear cartridges were removed to permit visual inspection of the gears.

Patterning Procedure

Prior to running, each bevel gear set must be bench-patterned to insure that proper mounting has been achieved. Generally, this involves several trial combinations of pinion and gear shims to produce a satisfactory pattern. The patterning procedure used for production CH-47C engine boxes was used in this program for both the baseline and forged gears, in Phases I and II. The bench-patterning effort required for both baseline and forged test gears closely paralleled that of standard production parts. Likewise, the backlash checking procedure and typical results were similar to production experience.

GEAR STRESS AND FLASH TEMPERATURE CALCULATIONS

To maintain a consistent and accurate rating practice, most of the major aircraft companies and engine manufacturers use the American Gear Manufacturer's (AGMA) Standards for Strength and Durability rating. Although AGMA rating formulas for strength and durability provide for the use of modifying factors to account for misalignment, dynamic conditions, overload conditions, size effect, etc, specific values for these factors as applicable to helicopter transmission gears do not exist. This requires a comparison of gear stresses with operational and test experience gained in previous design efforts.

Conducting gear load capacity investigations in a research and development test stand presents different conditions for forecasting stress allowables as compared to testing in an aircraft transmission mounted in a test stand. The alignment, rigidity, dynamics, etc, of an R&D test stand act to improve the load capacity of the actual test specimens. Past experience with the Boeing Vertol R&D test stand used for this program has indicated increased load capacity for test gears (depending on gear type) in the range of 1.5 to 3.0 times the design allowables established for aircraft power gears. Consequently it is not practical to establish a basic load level for test gears in the design stage for R&D operation in a test stand environment without relating these loads to standard design practice. Therefore, it must be expected that baseline configuration test gears will operate in an R&D test stand at stress levels above the 100-percent load level which has been established for operation in an aircraft transmission without failure. For these reasons, the maximum load level in the Phase I testing has been chosen as 150 percent of the single-engine rating while that in the Phase II testing is limited to 130 percent.

The 100-percent baseline design load for the test gear configurations used in this test program was established as 100 percent of the CH-47C helicopter single-engine rating. This is 3,750 horsepower at 14,720 rpm for a pinion torque of 16,056 in.-lb, resulting in a tangential tooth load of 4,523 pounds.

Bending Stress (Bending Fatigue)

The test gear stress levels presented in this report were calculated by an existing Boeing Vertol computer program based on the Gleason method and the following AGMA Standards:

216.01 – Surface Durability (Pitting) Formulas for Spiral Bevel Gear Teeth

223.01 – Rating the Strength of Spiral Bevel Gear Teeth

AGMA Standard 223.01 rates the bending strength of spiral bevel gear teeth as follows:

$$S_t = \frac{W_t K_o}{K_v} \frac{P_d}{F} \frac{K_s K_m}{J} ,$$

where S_t = calculated tensile stress at root of tooth in pounds per square inch

W_t = transmitted tangential load in pounds

K_o = overload factor

K_v = dynamic factor

P_d = diametral pitch at heel end

F = face width in inches

K_s = size factor

K_m = load distribution factor

J = geometry factor.

For the test specimens in this program, assume

$K_o, K_v = 1.0$

and $F = 1.750$

$P_d = 4.930$

$J = 0.3289$ pinion (calculated by Boeing Vertol computer program)

$= 0.3276$ gear (calculated by Boeing Vertol computer program)

$K_s = 0.6711$

$K_m = 1.1.$

Therefore the test specimen root fillet bending stress at 100-percent torque is

$$S_{tp} = \frac{4523\,(1)}{1}\;\frac{4.93}{1.75}\;\frac{0.6711\,(1.1)}{0.3289} = 28.6 \text{ ksi pinion,}$$

$$S_{tg} = \frac{4523\,(1)}{1}\;\frac{4.93}{1.75}\;\frac{0.6711\,(1.1)}{0.3276} = 28.7 \text{ ksi gear.}$$

Since the pinion and gear bending stresses are almost equal (a desirable condition for an infinite-life design), they are plotted as a single line in Figure 16.

Contact Stress (Surface Durability)

AGMA Standard 216.01 rates the contact stress of spiral bevel gears as follows:

$$S_c = C_p \sqrt{\frac{W_t\,C_o}{C_v}\;\frac{C_s}{dF}\;\frac{C_m\,C_f}{I}}\;,$$

where S_c = calculated maximum contact stress in pounds per square inch

C_p = elastic coefficient (2,800 for steel)

W_t = transmitted tangential load at operating pitch diameter in pounds

C_o = overload factor

C_v = dynamic factor

d = pinion operating pitch diameter, inches

F = face width, inches

C_s = size factor

C_m = load distribution factor

I = geometry factor

C_f = surface condition factor.

For the test specimens used in this program, assume

$C_o, C_v, C_s, C_f = 1.0$

and $C_m = 1.1$

I = 0.0726 (calculated by Boeing Vertol computer program)

d = 7.099.

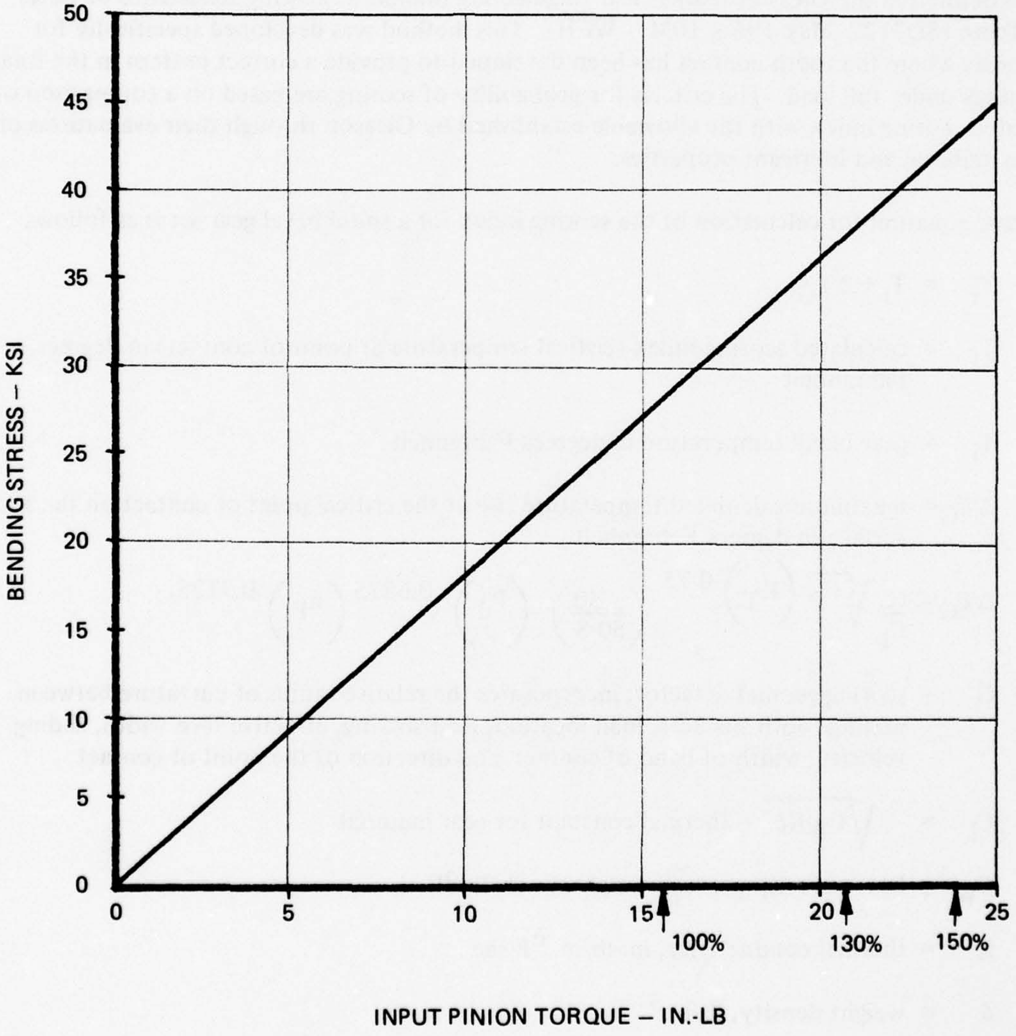

Figure 16. Tooth Bending Stress Versus Input Pinion Torque.

Then the contact stress at 100-percent torque is

$$S_c = 2800 \sqrt{\frac{4523\,(1)}{1} \; \frac{1}{7.099 \times 1.750} \; \frac{1.1\,(1)}{0.0726}}\ ,$$

$$S_c = 208 \text{ ksi (see Figure 17).}$$

Flash Temperature (Scoring Hazard)

The accepted method for prediction of the scoring probability or scoring hazard of spiral bevel gears is defined in the Gleason Works Gear Engineering Standard, Scoring Resistance of Bevel Gear Teeth (SD3122, May 1966, 10M – WFH). This method was developed specifically for bevel gears where the tooth contact has been developed to provide a correct pattern in the final mountings under full load. The criteria for probability of scoring are based on a comparison of the calculated scoring index with the allowable established by Gleason through their evaluations of various material and lubricant properties.

The basic equation for calculation of the scoring index for a spiral bevel gear set is as follows:

$$T_f = T_i + \Delta T_G,$$

where T_f = calculated scoring index (critical temperature at point of contact) in degrees Fahrenheit

T_i = gear blank temperature in degrees Fahrenheit

ΔT_G = maximum calculated temperature rise at the critical point of contact on the tooth surface in degrees Fahrenheit.

$$\Delta T_G = \frac{G}{C_l} \sqrt{C_P} \left(K_T\right)^{0.75} \left(\frac{50}{50\text{-}S}\right) \left(P_d\right)^{0.6875} \left(n_P\right)^{0.3125},$$

where G = scoring geometry factor; incorporates the relative radius of curvature between mating tooth surfaces, load location, load sharing, effective face width, sliding velocity, width of band of contact, and direction of the point of contact

$C_l = \sqrt{C_W K \delta}$ = thermal constant for gear material

C_W = heat capacity per unit weight, in.-lb/lb °F

K = thermal conductivity, in.-lb/in. °F sec

δ = weight density, lb/in.^{3}

C_P = elastic coefficient

$K_T = \dfrac{T_P\, L_O\, L_M}{L_V\, F}$ = load factor

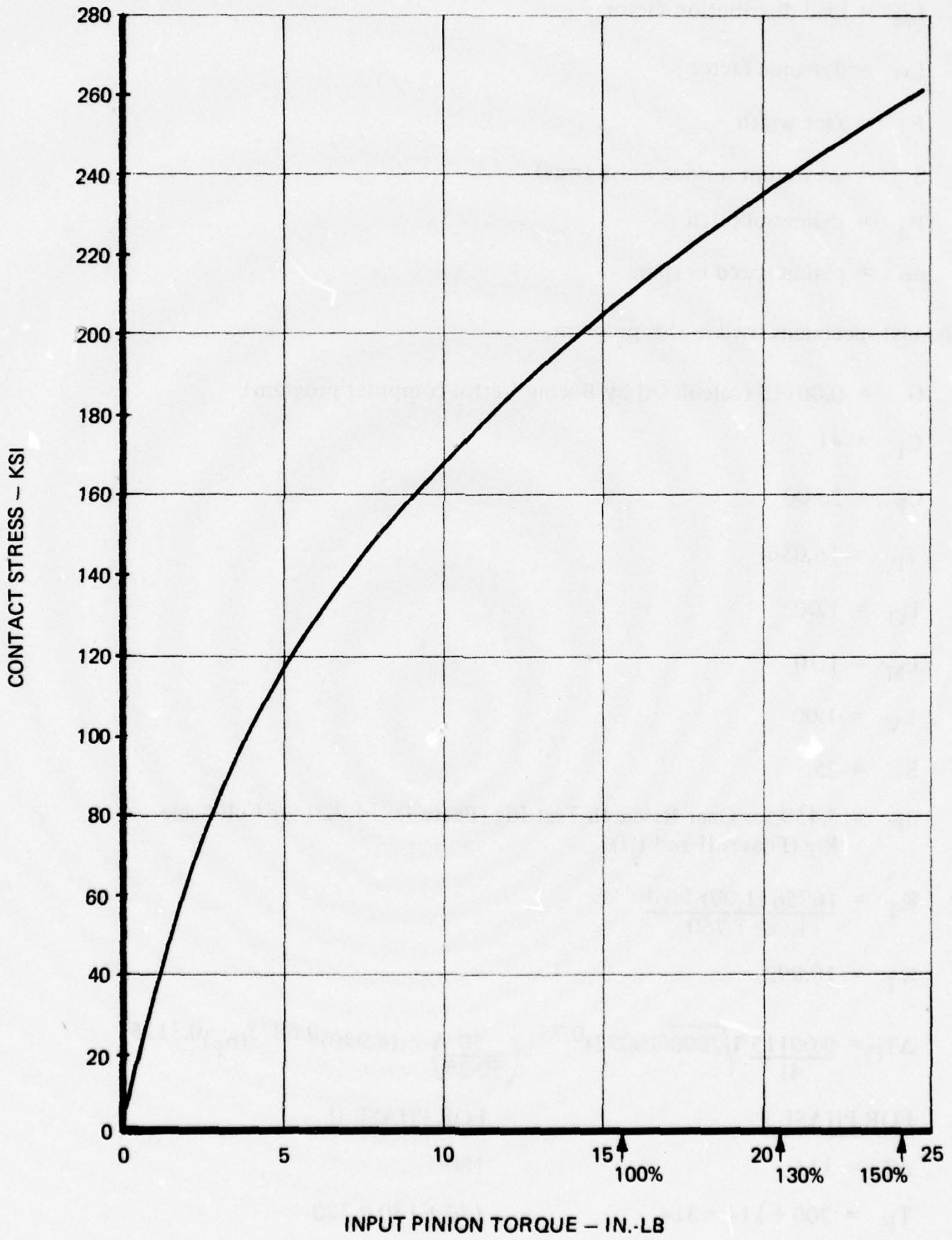

Figure 17. Contact Stress Versus Input Pinion Torque.

T_P = pinion torque in pound-inches

L_O = overload factor

L_M = load distribution factor

L_V = dynamic factor

F = face width

S = maximum surface finish (rms)

P_d = diametral pitch

n_P = pinion speed in rpm.

For the test specimens used in this program,

G = 0.00115 (calculated by Boeing Vertol computer program)

C_1 = 41

C_P = 2,800

T_P = 16,056

L_O = 1.00

L_M = 1.10

L_V = 1.00

S = 25

n_P = 3,450 for Gear Research Test Rig (Phase I), 14,720 for Full-Scale Rig (Phases II and III)

$$K_T = \frac{16056\,(1.00)\;1.10}{(1.00)\;1.750}$$

$$K_T = 10{,}092$$

$$\Delta T_G = \frac{0.00115}{41}\sqrt{2800}\,(10092)^{0.75}\left(\frac{50}{50\text{-}25}\right)(4.930)^{0.6875}(n_P)^{0.3125}$$

	FOR PHASE I	FOR PHASE II
$\Delta T_G =$	114	180
$T_F =$	200 + 114 = 314	140 + 180 = 320

The flash temperature variation with shaft torque is shown in Figure 18.

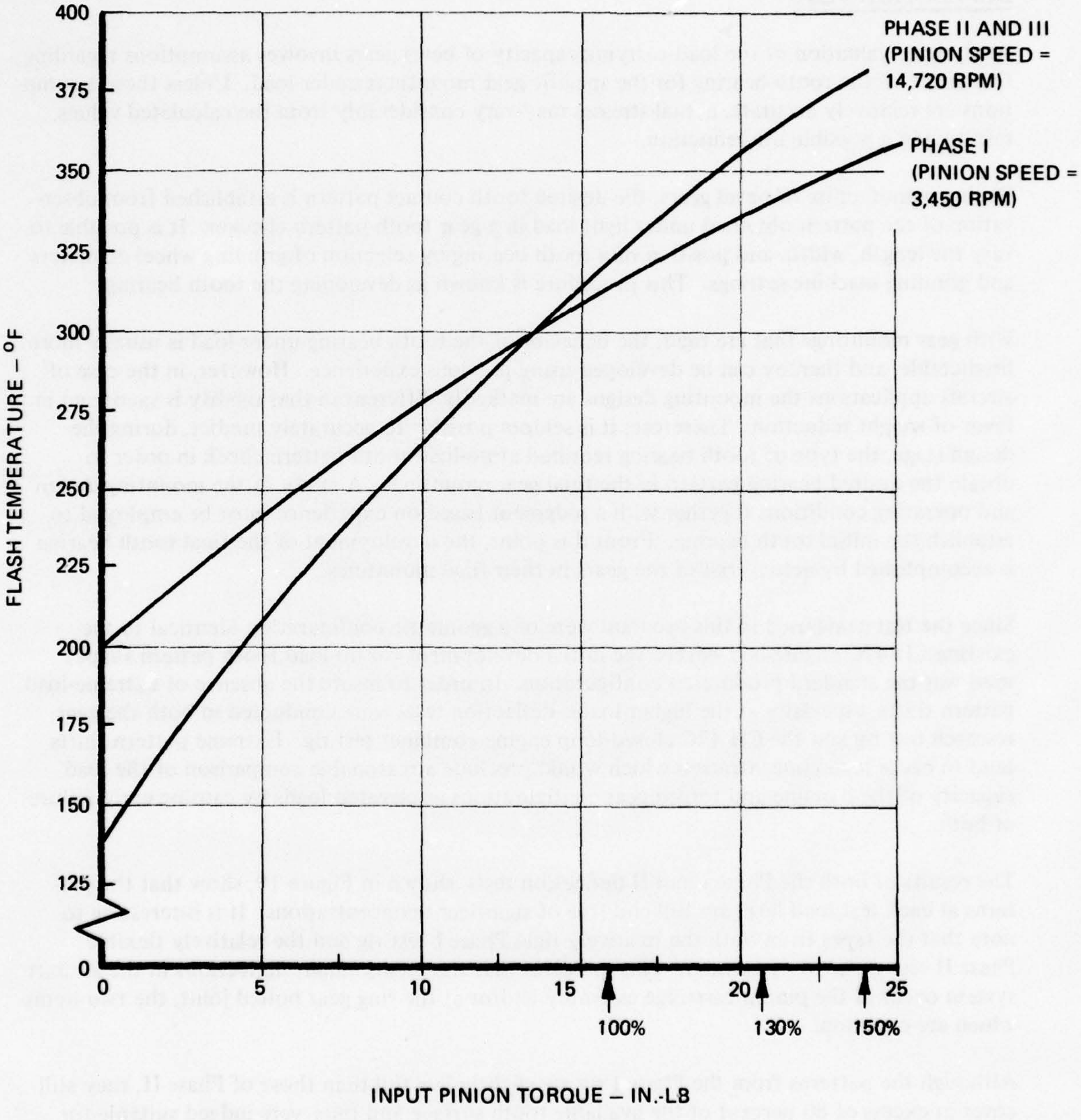

Figure 18. Flash Temperature Versus Input Pinion Torque.

TEST RESULTS

DEFLECTION TEST

Analytical evaluation of the load-carrying capacity of bevel gears involves assumptions regarding the nature of the tooth bearing for the specific gear mountings under load. Unless these assumptions are relatively accurate, actual stresses may vary considerably from the calculated values, resulting in a possible life reduction.

During manufacture of bevel gears, the desired tooth contact pattern is established from observation of the pattern obtained under light load in a gear tooth pattern checker. It is possible to vary the length, width, and position of a tooth bearing by selection of grinding wheel diameters and grinding machine settings. This procedure is known as developing the tooth bearing.

With gear mountings that are rigid, the behavior of the tooth bearing under load is usually more predictable, and thereby can be developed using previous experience. However, in the case of aircraft applications the mounting designs are markedly different in that rigidity is sacrificed in favor of weight reduction. Therefore, it is seldom possible to accurately predict, during the design stage, the type of tooth bearing required at no-load tooth pattern check in order to obtain the desired bearing pattern in the final gear mountings. A study of the mounting design and operating conditions together with a judgment based on experience must be employed to establish the initial tooth bearing. From this point, the development of the final tooth bearing is accomplished by actual trial of the gears in their final mountings.

Since the test gears used in this program were of a geometric configuration identical to the existing CH-47C engine-box bevels, the initial development (or no-load tooth pattern shape) used was the standard production configuration. In order to insure the absence of extreme-load pattern shifts, especially at the higher loads, deflection tests were conducted in both the gear research test rig and the CH-47C closed-loop engine-combiner test rig. Extreme pattern shifts tend to cause load concentration which would preclude a reasonable comparison of the load capacity of the baseline and forged gear configurations at elevated loads by causing early failure of both.

The results of both the Phase I and II deflection tests, shown in Figure 19, show that the patterns at each test load level are full and free of significant concentrations. It is interesting to note that the tapes from both the relatively rigid Phase I test rig and the relatively flexible Phase II test rig are quite similar. This indicates that the predominant deflections in the aircraft system occur in the pinion cartridge assembly and/or at the ring gear bolted joint, the two items which are common.

Although the patterns from the Phase I rig are slightly less full than those of Phase II, they still cover in excess of 80 percent of the available tooth surface and thus were judged suitable for load running.

The results of the deflection tests indicated that the standard production tooth contact pattern was suitable for the high loads to be encountered in the Phase I and II testing. This being the case, no grinding development was required, thus resulting in a substantial cost savings.

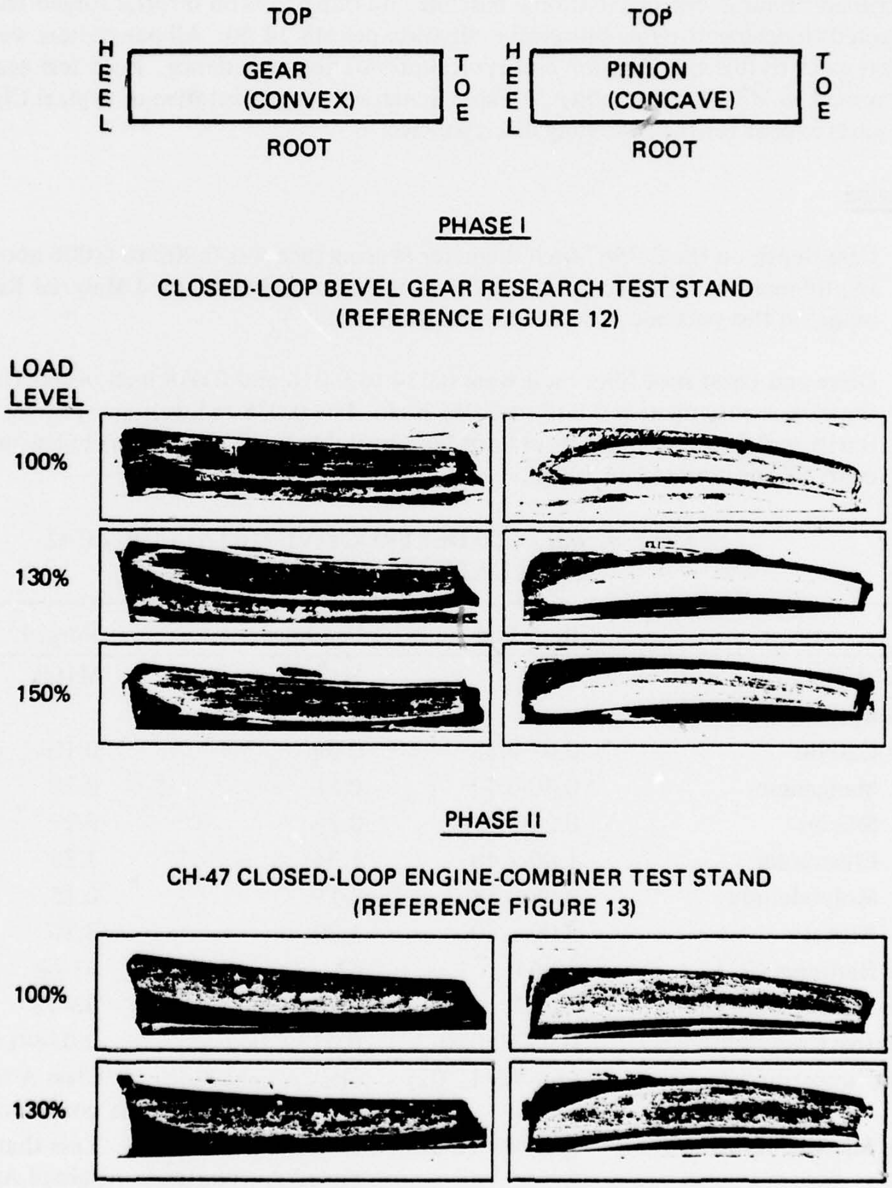

Figure 19. Deflection Test Patterns.

The Phase III test setup was identical to that used in Phase II; thus no additional deflection testing was required.

METALLURGICAL EVALUATION

After load running, one conventional baseline and one precision integral forged test pinion were subjected to destructive metallurgical evaluation per MS 14.00. All parameters were evaluated with respect to this specification and typical production experience. Both test gears generally conformed to MS 14.00 as shown in Table 8 and were representative of typical CH-47C engine-box parts except for the following discrepancies:

Baseline

1. Case depth on the 2.7567-inch-diameter bearing race was 0.002 to 0.006 above the drawing requirement of 0.010 to 0.020. This is within normally accepted Material Review Board range on this part and is considered insignificant.
2. Drive and coast root fillet radii were 0.014 to 0.016 and 0.058 inch, respectively. The drawing requirement is 0.045 to 0.055 inch. The 0.058 radius is acceptable; however, the 0.014 to 0.016 fillet radii would not be acceptable for flight aircraft but would be acceptable for limited bench test.

TABLE 8. MS 14.00 DESTRUCTIVE METALLURGICAL EVALUATION TEST RESULTS

	Required	Baseline	Forged
Serial Number	–	M1115	M108
Chemical Composition (%)			
Carbon	0.07-0.13	0.09	0.10
Manganese	0.40-0.70	0.51	0.70
Silicon	0.20-0.35	0.27	0.27
Chromium	1.00-1.40	1.34	1.35
Molybdenum	0.08-0.18	0.11	0.15
Nickel	3.00-3.50	3.00	3.30
Case Hardness (R_c)	59-64	63	61-64
Core Hardness (R_c)	32-42	34	38-42
Effective Case Depth (in.)	0.030-0.050	0.033-0.047	0.038-0.051
Case Microstructure	(per MS 12.02)	Class A light discontinuous acceptable	Class A light discontinuous acceptable
Core Microstructure	(per MS 12.02)	Less than 10% retained Austenite acceptable	Less than 10% retained Austenite acceptable
Grain Flow	N/A	Does not conform to tooth shape	Roughly conforms to tooth shape

Precision Integrally Forged

1. Drawing requirements for effective case depths (ECD) in the tooth area and the spline area were 0.030 to 0.050 inch and 0.010 to 0.020 inch respectively. The actual effective case depths ranged from 0.038 to 0.056 inch in the tooth area and 0.020 to 0.032 inch in the spline area. The slightly higher ECD is acceptable for flight aircraft parts.

2. Drive and coast root fillet radii were 0.020 to 0.063 (lowest on drive side). The blueprint requirement is 0.045 to 0.055 inch. The 0.063 radius (coast side) is acceptable; however, the 0.020 fillet radius would not be considered acceptable for a flight aircraft but would be acceptable for a limited bench test.

The forged bevel pinion (serial number M108) used in this evaluation is the one which experienced a pitting fatigue failure in the Phase I testing. No metallurgical discrepancy was identified which would account for the failure.

Figures 20 through 24 present typical results of the MS 14.00 investigation. Figure 21 shows an etched cross-section of a conventional baseline gear while 22 shows a similar view of a precision integral forged gear. Careful inspection of the root areas of each picture will reveal the conformity of the grain flow for the forged teeth and a lack of conformity for the baseline teeth. For clarity, an enlarged photo of the precision forged cross section is shown in Figure 25.

All forged pinions used in this program (Phases I, II and III) were from a single heat lot (No. L610); thus only one forged specimen was evaluated.

TEST DATA AND DISCUSSION

Summaries of the test data for Phases I, II and III are shown in Tables 9, 10 and 11 respectively. A typical pretest pinion is shown in Figure 26. For ease of comparison, the results are presented only in terms of percent load and time. Generally (with the exception of the number M 108 forged pinion), the condition of all test specimens at the conclusion of each run was excellent. All exhibited full, well-developed load patterns for all runs.

Virtually all Phase I and II test pinions (forged and baseline) had a light hard line in the root at the toe end as shown in Figure 27. This is due to the very high loading applied in these tests. This condition in no way affected the test results or the basis for comparison. The line shown in Figure 27 represents the area of highest unit surface loading and thus, if a surface failure is to occur, this high load area is the most likely origin. It is not surprising, then, to note that the single surface failure which did occur originated, as shown in Figure 29, in this area. Figure 30 presents a map of the failed teeth. No metallurgical reason was found for this failure and a double check of the applied loads revealed no discrepancy. Since no other failures occurred and in view of the good and consistent condition of all other teeth on all other gears, the only logical alternative appears to be to regard this failure as statistical rather than characteristic of the forging process.

The condition of the Phase III test gears was uniformly excellent, with no evidence of distress of any kind. In fact, the hard line in the root of all the Phase I and II test pinions was absent on the Phase III pinions, as shown in Figure 28.

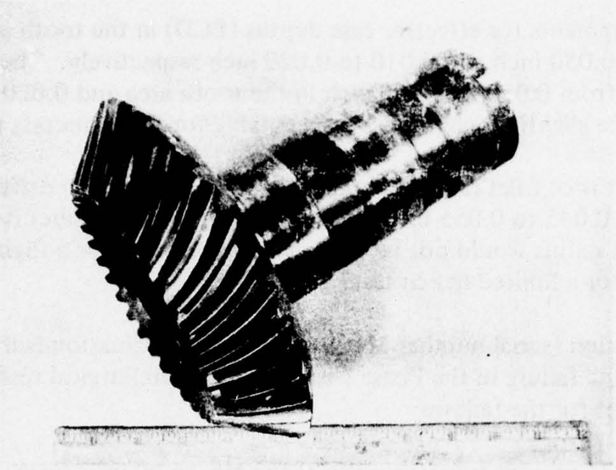

Figure 20. A Typical As-Received Spiral Bevel Pinion Gear, Part Number SK22269.

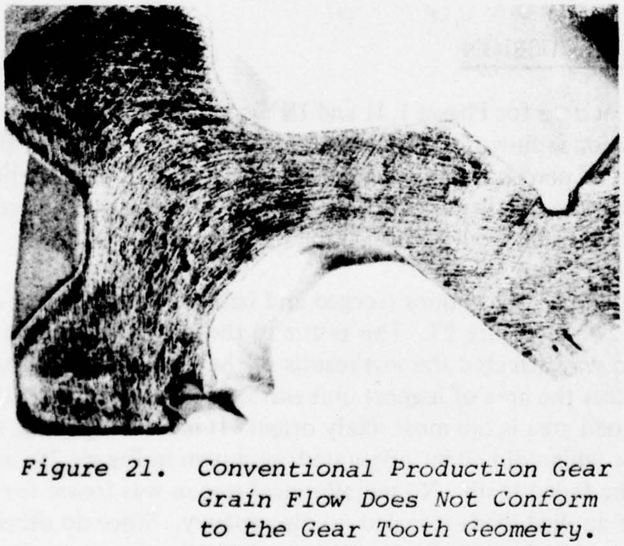

Figure 21. Conventional Production Gear Grain Flow Does Not Conform to the Gear Tooth Geometry. This Gear is Representative of a Production Pinion Gear, Part Number 114D6244. Etch With Hot Hydrochloric Acid.

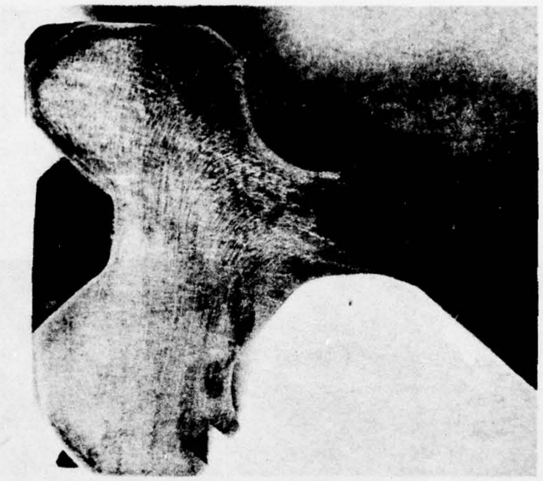

Figure 22. *The Grain Flow for Precision Integrally Forged Gear M108 Roughly Conforms to the Gear Tooth Geometry; Etch With Hot Hydrochloric Acid.*

Figure 23. *Alkaline Sodium Picrate-Etched Case Microstructure Shows Light Discontinuous Class A Carbides.*

Figure 24. *Nital-Etched Core Microstructure has Tempered Martensite and Bainite.*

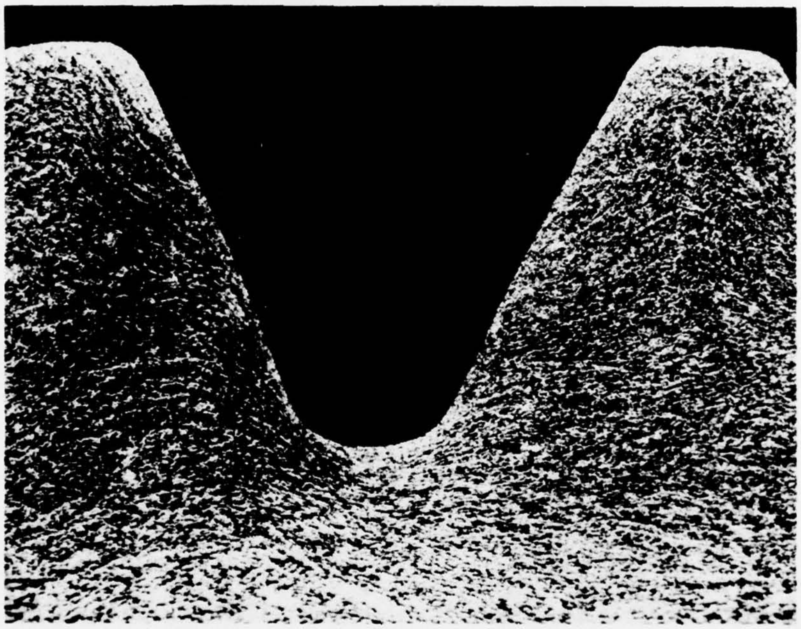

Figure 25. Precision Integrally Forged Gear Tooth Profile Showing Forging Flow Lines; Etch With Hot Hydrochloric Acid.

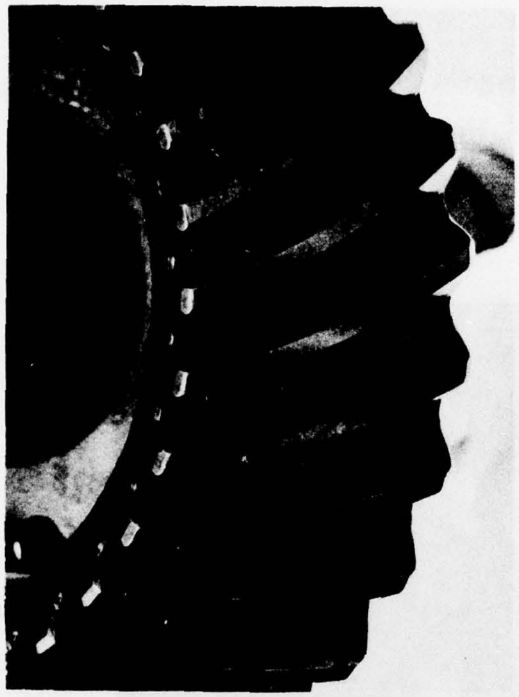

Figure 26.

Typical As-Received Pinion Tooth Condition, Phases I, II, and III.

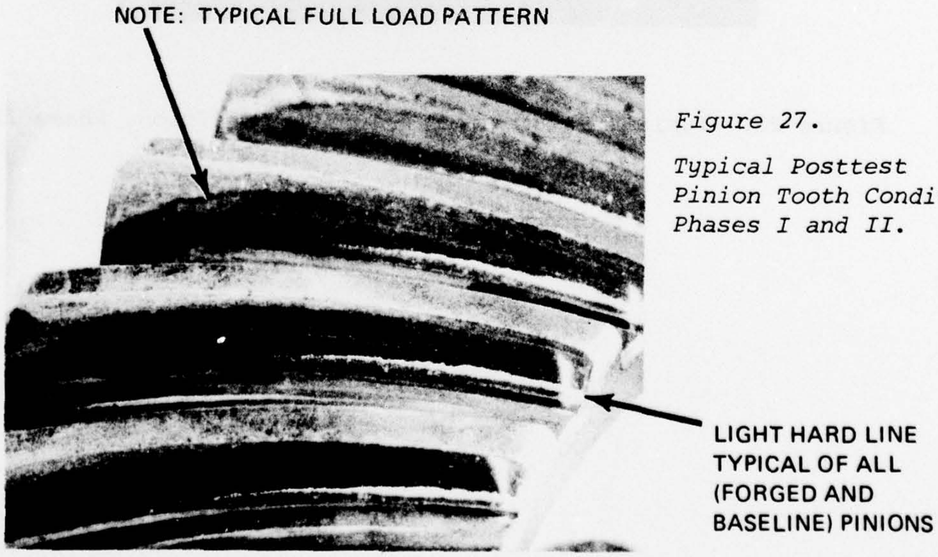

Figure 27.

Typical Posttest Pinion Tooth Condition, Phases I and II.

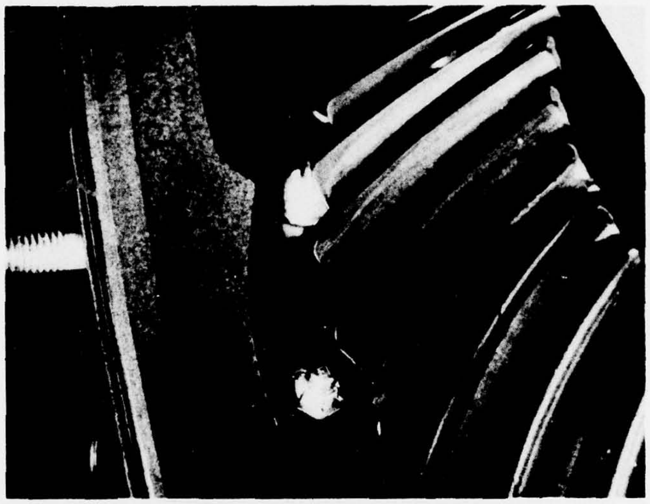

Figure 28. Typical Posttest Pinion Tooth Condition, Phase III.

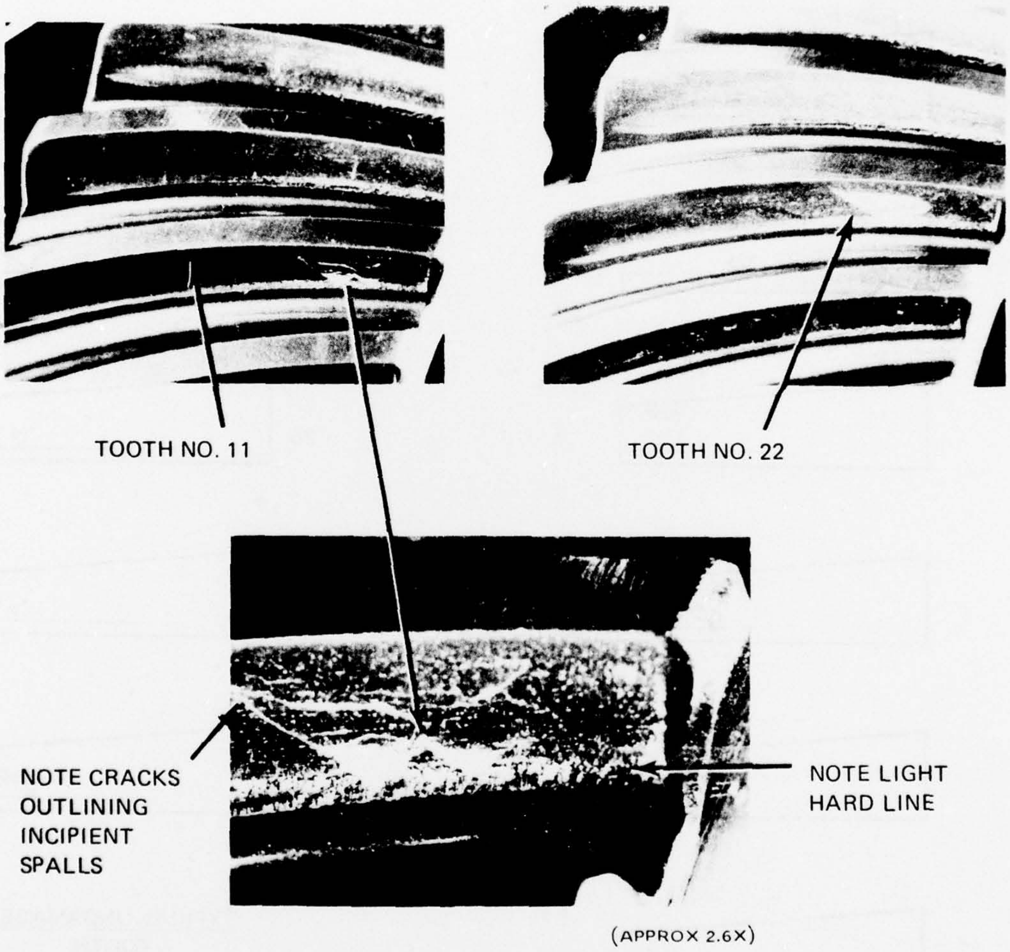

Figure 29. Typical Spalled Teeth, Forged Pinion Serial Number M108.

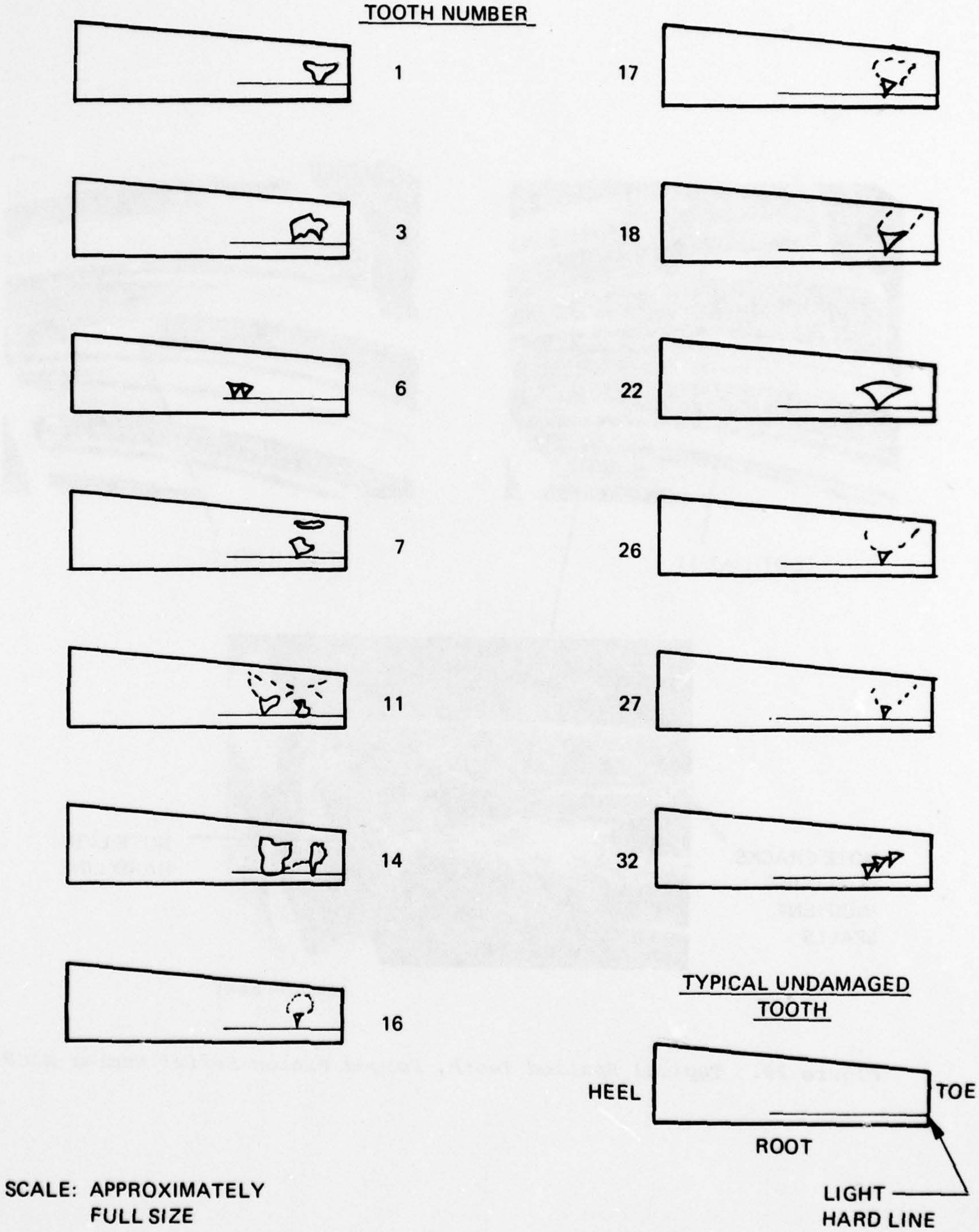

Figure 30. Map of Spalled Teeth on Serial Number M108 Forged Pinion.

Examination of the test data reveals the fact that the forged bevel gears (except as noted above) accommodated the overload conditions as well as the standard baseline gears. Although drawing extensive conclusions regarding precision forged gears in general is somewhat premature, it is safe to say that, based on these typical samples, the precision forging process is capable of producing spiral bevel gears with sufficient load capacity for some current aircraft applications.

TABLE 9. PHASE I TEST DATA SUMMARY

Run Number	Type*	Serial Number (pinion/gear)	Load (percent)	Time (hours)	Time (cycles)	Comments
1	B	M1203/M1050	50	2.5	5.2×10^5	Light load pattern visible
2	B	M1203/M1050	101	29.3	6.0×10^6	Light hard line visible in root at toe end – no distress
3	B	M1203/M1050	153	29.3	6.0×10^6	Light hard line still visible – no progression – tooth surface in good condition
4	B	M1115/M1186	47	2.0	4.1×10^5	Good – no distress – good load pattern
5	B	M1115/M1186	106	29.3	6.0×10^6	Light hard line – no distress
6	B	M1115/M1186	153	29.3	6.0×10^6	No change – load pattern very good
7	F	M108/M123	56	2.0	4.1×10^5	Partial load pattern visible – appears good
8	F	M108/M123	103	29.3	6.0×10^6	At 4 hours pinion showed light frosting in dedendum toe end – no change by end of run
9	F	M108/M123	153	29.3	6.0×10^6	All checks up to 16 hours showed no change in gear tooth condition. At 16 hours 2 teeth showed small (1/16 x 1/16) spalls. At 24 hours 3 teeth spalled (1/8 x 1/8). At 28 hours 5 teeth spalled (vary from 1/16 x 1/8 to 1/8 x 1/4). At test completion, 13 teeth spalled.
10	F	M109/M133	47	2.0	4.1×10^6	Light hard line visible similar to Run 1
11	F	M109/M133	101	29.3	6.0×10^6	Gear surface condition excellent
12	F	M109/M133	155	29.3	6.0×10^6	Light hard line similar to Run 2 visible – no distress

*B = Baseline test gears
F = Precision integral forged test specimens

TABLE 10. PHASE II TEST DATA SUMMARY

Run Number	Time (hours)	Time (cycles)	Left Engine Transmission Type*	Serial Number (pinion/gear)	Load (percent)	Comments	Right Engine Transmission Type*	Serial Number (pinion/gear)	Load (percent)	Comments
1	20	1.8×10^7	B	M1068/M1190	10	**	F	M117/M103	125	Light hard line as noted in Phase I Testing – no distress
2	20	1.8×10^7	B	M1068/M1190	125	Light hard line as noted in Phase I testing – no distress	F	M117/M103	10	**
3	20	1.8×10^7	F	M104/M110	130	Light hard line but no distress	B	M1116/M1183	13	**
4	20	1.8×10^7	F	M104/M110	15	**	B	M1116/M1183	127	Light hard line – no distress
5	25	2.2×10^7	F	M103/M112	105	No distress	F	M110/M115	15	**
6	25	2.2×10^7	F	M103/M112	18	**	F	M110/M115	102	Load pattern good
7	25	2.2×10^7	F	M103/M112	112	No distress	F	M110/M115	17	**
8	25	2.2×10^7	F	M103/M112	18	**	F	M110/M115	112	No distress
9	25	2.2×10^7	F	M103/M112	115	No distress	F	M110/M115	13	**
10	25	2.2×10^7	F	M103/M112	19	**	F	M110/M115	121	No distress
11	25	2.2×10^7	F	M103/M112	131	No distress	F	M110/M115	19	**
12	25	2.2×10^7	F	M103/M112	15	**	F	M110/M115	130	Flank condition good
13	25	2.2×10^7	F	M111/M117	98	Load pattern good			10	Engineering test slave engine box used for Runs 13–16 as right slave
14	25	2.2×10^7	F	M111/M117	109	No distress			10	
15	25	2.2×10^7	F	M111/M117	124	No distress – light hard line			10	
16	22.5	2.0×10^7	F	M111/M117	129	Slave combiner housing failed – gears look good			10	
17	2.5	2.2×10^6	F	M111/M117	129	Light hard line did not progress – gear teeth look good	F	M110/M115	10	** Slave combiner housing failed necessitating use of this test gearbox for timely program completion

*B = Baseline test gears
F = Precision integral forged test gears
**Test boxes functioned as slaves for these runs to complete loop.

TABLE 11. PHASE III TEST DATA SUMMARY

Run Number	Time		Left Engine Transmission			Right Engine Transmission		
	(hours)	(cycles)	Serial Number (pinion/gear)	Load (percent)	Comments	Serial Number (pinion/gear)	Load (percent)	Comments
1	25	2.2×10^7	M101/M104	100		M106/M106	100	
2	25	2.2×10^7	M101/M104	100		M106/M106	100	
3	25	2.2×10^7	M101/M104	100		M106/M106	100	
4	25	2.2×10^7	M101/M104	100	Load pattern and condition of teeth at every inspection excellent	M106/M106	100	Load pattern and condition of teeth at every inspection excellent
5	25	2.2×10^7	M101/M104	100		M106/M106	100	
6	25	2.2×10^7	M101/M104	100		M106/M106	100	
7	25	2.2×10^7	M101/M104	100		M106/M106	100	
8	25	2.2×10^7	M101/M104	100		M106/M106	100	
Totals	200	1.76×10^8						
9	25	2.2×10^7	M107/M109	100		M112/M108	100	
10	25	2.2×10^7	M107/M109	100		M112/M108	100	
11	25	2.2×10^7	M107/M109	100		M112/M108	100	
12	25	2.2×10^7	M107/M109	100	Load pattern and condition of teeth at every inspection excellent	M112/M108	100	Load pattern and condition of teeth at every inspection excellent
13	25	2.2×10^7	M107/M109	100		M112/M108	100	
14	25	2.2×10^7	M107/M109	100		M112/M108	100	
15	25	2.2×10^7	M107/M109	100		M112/M108	100	
16	25	2.2×10^7	M107/M109	100		M112/M108	100	
Totals	200	1.76×10^8						

CONCLUSIONS

Based on the testing reported herein, the following conclusions relating specifically to CH-47C engine-transmission bevel gears have been reached:

1. The precision integral forged gears demonstrated overload capacity equal to that demonstrated by the conventional baseline gears.

2. Grain flow in the tooth fillet/root area of the precision integral forged gears generally conformed to the tooth shape while that of the conventional baseline gears did not.

3. Other than grain flow, the precision integral forged gears exhibited metallurgical properties identical to those of the baseline conventional gears.

4. Excessive stock removal required for the full cleanup of tooth flanks is a significant manufacturing problem that should be resolved for production of precision integral forged gears.

RECOMMENDATIONS

The results of this program have indicated the need for further development and testing. Specifically, the following items either singly or in combination should be considered:

1. Generally, machine elements with discontinuities such as fillets, shoulders, etc, exhibit better fatigue characteristics if the grain flow follows the contour of the discontinuity. Since the grain flow in the integral forged gear tooth roots conforms to the contour of the fillet, it follows that a substantial improvement in bending fatigue may be obtained. Preliminary, limited single-tooth bending fatigue testing conducted by TRW gave added credence to this projected improvement. The large scatter in the TRW tests would probably be reduced if rotating rather than single-tooth fatigue testing were accomplished. An experimental program (preferably rotating) to evaluate the bending fatigue life of the forged gear teeth in comparison with conventional baseline teeth will establish the magnitude of this improvement and allow future designs to take full advantage of it either in terms of decreased weight or increased reliability, or both.

2. The integral precision forged CH-47C engine-transmission bevel gears have demonstrated equal performance at projected reduced unit cost over a range of loading which extends well beyond normal aircraft operation; thus, the next step is, logically, qualification for flight testing. This test program would involve substantial testing on several gear sets in the closed-loop engineering test stand at normal aircraft loading. Successful completion of this program may qualify the forged gear method for flight testing.

A total of 23 SK22269 precision forged test pinions and 26 SK22270 precision forged test gears were delivered to Boeing Vertol as GFE. Seven gear sets were consumed in the testing reported here, leaving 16 gear sets available for further testing as noted above.

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2	Sikorsky Aircraft Division; United Aircraft Corporation; ATTN: Mr. Stan Silverstein; Section Supv, Manufacturing Tech.; Stratford, Connecticut 06497
2	Bell Helicopter Textron; Division of Textron Inc.; ATTN: Mr. P. Baumgartner, Chief, Manufacturing Technology; PO Box 482; Ft. Worth, Texas 76101
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