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(DE94004088)

Coal-Fueled Diesel Technology Development
Fuel Injection Equipment for Coal-Fueled Diesel Engines

Topical Report

R. N. Johnson
H. L. Hayden

January 1994

Work Performed Under Contract No.: DE-AC21-88MC23174

For
U.S. Department of Energy
Office of Fossil Energy
Morgantown Energy Technology Center
Morgantown, West Virginia

By
General Electric Corporate Research and Development
Schenectady, New York

DISCLAIMER

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Distribution Category UC-111

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ABSTRACT

Because of the abrasive and corrosive nature of coal water slurries, the development of coal-fueled diesel engine technology by GE-Transportation Systems (GE-TS) required special fuel injection equipment GE-Corporate Research and Development (GE-CRD) undertook the design and development of fuel injectors, piston pumps, and check valves for this project. Components were tested at GE-CRD on a simulated engine cylinder, which included a cam-actuated "jerk" pump, prior to delivery to GE-TS for engine testing. This work was performed under DOE Contract DE-AC21-88MC23174.

KEY WORDS

coal water slurry fuel, coal-fueled diesel injection equipment, fuel injector, piston pump, check valve, "jerk" pump

CONTENTS

FIGURE LIST

1. INTRODUCTION

The development of a direct injection diesel engine by GE-Transportation Systems (GETS) using coal water slurry (CWS) fuel required special fuel injection equipment (FIE). The CWS fuel — consisting of finely ground coal with ash content reduced to 0.5 to 2%, mixed with water — is highly abrasive and corrosive to the conventional steel alloys normally used in diesel engines. Also, because of its lower specific energy, approximately twice as much CWS as diesel fuel (by volume) must be injected. To accomplish the injection with an acceptably short injection duration and achieve good fuel atomization, injection pressures of 69 to 82.7 MPa (10 to 12 kpsi) are required. A storage chamber (accumulator) adjacent to the atomizing nozzle inside each injector was required in order to achieve the required fuel delivery. Diamond atomizing orifices were used in the nozzles to provide acceptable nozzle life (Johnson, Lee, and White, 1994).

The injector, check valve, piston pump, and fuel ("jerk") pump are the main components of the fuel injection system, which is mounted on the engine (one per cylinder). (The jerk pumps were procured by GETS from Lucas Bryce Ltd, Gloucester, England; the other components were developed at the GE Corporate Research and Development Center.) These components, shown schematically in Figure 1, perform the following functions:

- The jerk pump is a cam-shaft-driven positive displacement pump that boosts the pressure of conventional diesel fuel to injection pressure levels.
- The piston pump transfers this pressure to the CWS and delivers it to the injector; an in-line check valve prevents fuel from flowing back to the piston pump
- The injector itself delivers atomized fuel to the combustion chambers.

At rated engine speed of 1050 rpm, nearly 9 injection events occur per second in a GE locomotive engine. The components were "bench" tested on a test stand at GE-CRD that simulated cylinder geometry and had a cam-driven jerk pump.

Lucas-Bryce Ltd developed a pressure-actuated fuel injector for the coal fueled diesel engine program. This injector experienced recurring internal galling, which caused needle seizure on the test stand; these injectors were not engine tested. This injector development is described in Appendix B.

2. COMPONENT DESIGN REQUIREMENTS

CWS flow rate per cylinder:	3 cc per injection
Design pressure:	104 MPa (15 kpsi)
Design Temperature:	93.3°C (200°F)
Fatigue life:	10^9 cycles
Maximum engine vibration:	± 50 g's along injector axis[1]
Injector location:	On cylinder centerline, between valve springs
Injector opening & closing time:	5.0×10^{-4} sec. (See Figure 2 for injection event timing.)
Control of injection timing:	Electronic

3. COMPONENT DESCRIPTIONS

3.1. Piston Pump

The piston pump consists of a 15.9-mm (0.625-in.) diameter free piston in a close-fitting bore with a nominal clearance of 0.0051 mm (0.0002 in.). See the drawing of the piston pump in Figure 3 and the photograph of the disassembled pump in Figure 4. The piston is relieved circumferentially to permit introduction of SAE 30 oil at 104 MPa (15 kpsi), which is approximately 20.7 MPa (3 kpsi) above fuel pressure, to prevent seizure of the piston caused by CWS particles. The purge oil flow rate is approximately 0.5% of the CWS flow rate. The cylinder length was established by the requirement of 3 cc fuel delivery per injection plus 3.175 mm (0.125 in) for cushioning the piston at the ends of the stroke. Initially, the pistons and cylinders were made of high-strength stainless alloys (17-4 PH), nitrided for wear and galling resistance. However, testing at GE-CRD indicated that it was necessary to make pistons and cylinder liners of cemented tungsten carbide for acceptable durability. The end caps are 17-4 PH S.S., age hardened to 1242 MPa (180 ksi) yield strength.

To prevent excessive fluid pressures from being developed, a pressure relief valve is incorporated in the oil end cap. A 0.254-mm (0.010-in.) hole is machined through the relief valve poppet to provide a small through-flow of oil to prevent excessive temperature rise.

[1] For GE Transportation System's single cylinder engine, lower for multicylinder engines.

A check valve (described in Section 3.3) is installed at the CWS inlet to the piston pump to prevent back-flow when fuel is delivered at high pressure to the injector.

3.2 Fuel Injector

The final fuel injector design is shown in cross-section in Figure 5. Figure 6 and Figure 7 are photographs of the assembled and unassembled injector. Figure 8 is an assembly drawing of the injector, with a parts list.

Initially the injector accumulator chamber is full of CWS at 82.7 MPa (12 kpsi): fluid pressure of 22.1 MPa (3.2 kpsi) is applied to the top of the needle piston (at the interface of the lower and upper housings); and purge oil is supplied to the needle rod at 104 MPa (15 kpsi).

With the piston of the engine on the compression stroke, an electrical signal is supplied to the servovalve, which introduces oil at 27.6 MPa (4 kpsi) to the underside of the piston located at the end of the needle rod (Figure 5). This causes the needle tip to leave the seat inside the nozzle, permitting CWS at 82.7 MPa (12 kpsi) to flow from the accumulator chamber through the atomizing orifices. The needle travels 1 mm (0.04 inch) to its fully open position, this motion being sensed by the displacement transducer (optional). When the fuel delivery is nearly complete, the electrical signal is removed from the servovalve, which rapidly relieves the 27.6-MPa (4-kpsi) oil pressure from the piston. The constant 22.1-MPa (3.2-kpsi) pressure on the other side of the piston rapidly accelerates the needle toward the seat, closing the injector in approximately 0.5 ms. The fuel in the accumulator chamber of the injector is replenished by the jerk and piston pumps, which operate at the same rate as the injector, i.e., almost 9 times per second at rated speed.

The design of the injector evolved through two generations of prototypes in which the accumulator volume doubled to 265 cc, the servovalve changed from "aerospace" to "industrial" class (same performance, one-half the cost) and the number of housings was decreased from three to two.

Several features should be noted. Both the needle tip and nozzle seat are cemented tungsten carbide. Originally, cobalt binder material was used but changed to nickel binder for improved corrosion resistance (see Appendix A). The hard tip is brazed into the metal mount at the end of the needle rod. The needle rod is 17-4 PH S.S., nitrided after grinding at its aging temperature of 482°C (900°F) for maximum wear/galling resistance. Originally, the needle rod was electroless nickel plated but severe corrosion occurred in the CWS. Nitriding was selected as a suitable alternative based upon corrosion tests performed at GE-CRD (see Appendix A) and wear tests conducted by the Materials Characterization Laboratory, Scotia, NY (see Appendix C). The piston was also nitrided.

The displacement transducer was obtained commercially (Wolff Controls, Winter Haven, FL) and is designed for use in diesel fuels at 34.5 MPa (5 kpsi).

The lower housing was made of two pieces of Mo 13-8 PH S.S. to facilitate machining the accumulator housing. The parts were electron beam (EB) welded followed by a full anneal. After finish machining, the piston and needle rod bores were nitrided (balance masked) and the entire part aged at 538°C (1000°F). In the aged condition, the yield strength is 1380 MPa (200 ksi) and the fatigue limit is 690 MPa (100 ksi) for 10^8 cycles (Carpenter, 1983). The maximum calculated tensile stress in the wall of the accumulator chamber is 449 MPa (65 ksi) at the design pressure. At the end of the lower housing adjacent to the nozzle, a hollow guide is inserted for the needle rod. The guide is nitrided 17-4 S.S. and has a 0.05-mm (0.002-inch) diametral clearance with the needle rod; this clearance has proven adequate to preclude seizure in CWS.

The upper housing contains all fluid connections and check valve connections (see Section 3.3). The servovalve mounts to the side of the upper housing and fits between two valve springs. The upper end of the housing is enlarged and circular to facilitate an O-ring seal between the housing and the rocker chamber cover.

Fasteners are alloy steels (Studs: ASTM A 193-B7, Nuts: A 194-24) with sufficient capacity and are preloaded to withstand both internal pressure forces and external acceleration loads.

3.3. Check Valves

A check valve is required between the injector and the piston pump to prevent backflow when the piston pump is on the refill stroke. This check valve — the "high pressure" check valve — attaches directly to the upper housing of the injector by means of a standard high pressure coned connection. The "low pressure" check valve is installed at the CWS inlet to the piston pump to prevent back flow when fuel is delivered at high pressure to the injector. The final check valve design is shown in Figure 9 and Figure 10.

The main parts of the check valves are the poppet (moving member with conical tip), seat, spring and housing. Figure 10 shows a two-part poppet consisting of a hard conical tip brazed into a stainless guide. Our experience with injector tips and nozzle seats suggests that a tip made of cemented tungsten carbide with nickel binder operated with a seat of the same material will perform well. Unfortunately, check valve test results were clouded for a long period of time as a result of the impact-related failure of poppets. This failure was finally traced to an excessive rate of pressure drop in the jerk pump. The solution was to produce jerk pump plungers with a shallow relief helix step of 0.2 mm (0.008 in.), which extended the pressure decay time from almost 0 to approximately 10.0 ms. The modified plunger design is shown in Figure 11.

Various other check valve poppet tip and seat materials had been tested including ceramics and Stellite 6B (one-piece poppet). Stellite performed quite well although there was visible evidence of wear after 50 hours. Unfortunately, very little running time was accumulated on the check valves fitted with carbides as they were installed in the multicylinder engine at GETS, which ran for only a few hours. However, approximately 30 trouble-free hours were accumulated on one carbide-tipped check valve on the GE-CRD test stand. The titanium nitride coating on the poppets showed no evidence of damage.

4. OPERATING EXPERIENCES AND RECOMMENDATIONS

A total of at least 500 cylinder hours was accumulated on the fuel injection equipment operating with CWS at GETS. No structural failure of pressurized components occurred. There were a few unresolved problems with some components: the brazed joint that attaches the needle tip to the holder failed in two durability test injectors; check valve poppets occasionally jammed with CWS; because of the designed-in bleed feature, pressure relief valves were very difficult to pre-set.

It seems reasonable to conclude that the fuel isolation capability of the piston pump could be incorporated into a specially designed jerk pump, thereby eliminating one major component.

5. ACKNOWLEDGMENTS

The authors wish to acknowledge the contributions of present and previous CRD personnel: Dr. Gary Leonard, for numerous inputs to the system concept-and' design and hydraulic dynamic analyses; William Longfritz for tireless drafting support spanning several design iterations; Mitchell Cohen and Mark Roos, for their excellent testing support and assistance in troubleshooting; Sid Young, for electron beam welding of the injector housings;

and David McKenney and Philip Muller of the GE-CRD Machine Shop, for excellent fabrication work, often with complex designs and difficult materials. We also wish to express our appreciation for the efforts of the GE-TS Engine Test Lab personnel headed by Dr. B. Hsu, without whose efforts the hundreds of hours of running time could not have been accumulated.

6. REFERENCES

Carpenter Technology Bulletin, "Carpenter Precipitation Hardened Stainless Steels," May 1983.

Johnson, R.N., M. Lee, and R.A. White, " Nozzle Development for Coal-Fueled Diesel Engine," Topical Report, January 1994; also published as a GE Corporate Research and Development Center TIS Report, January 1994.

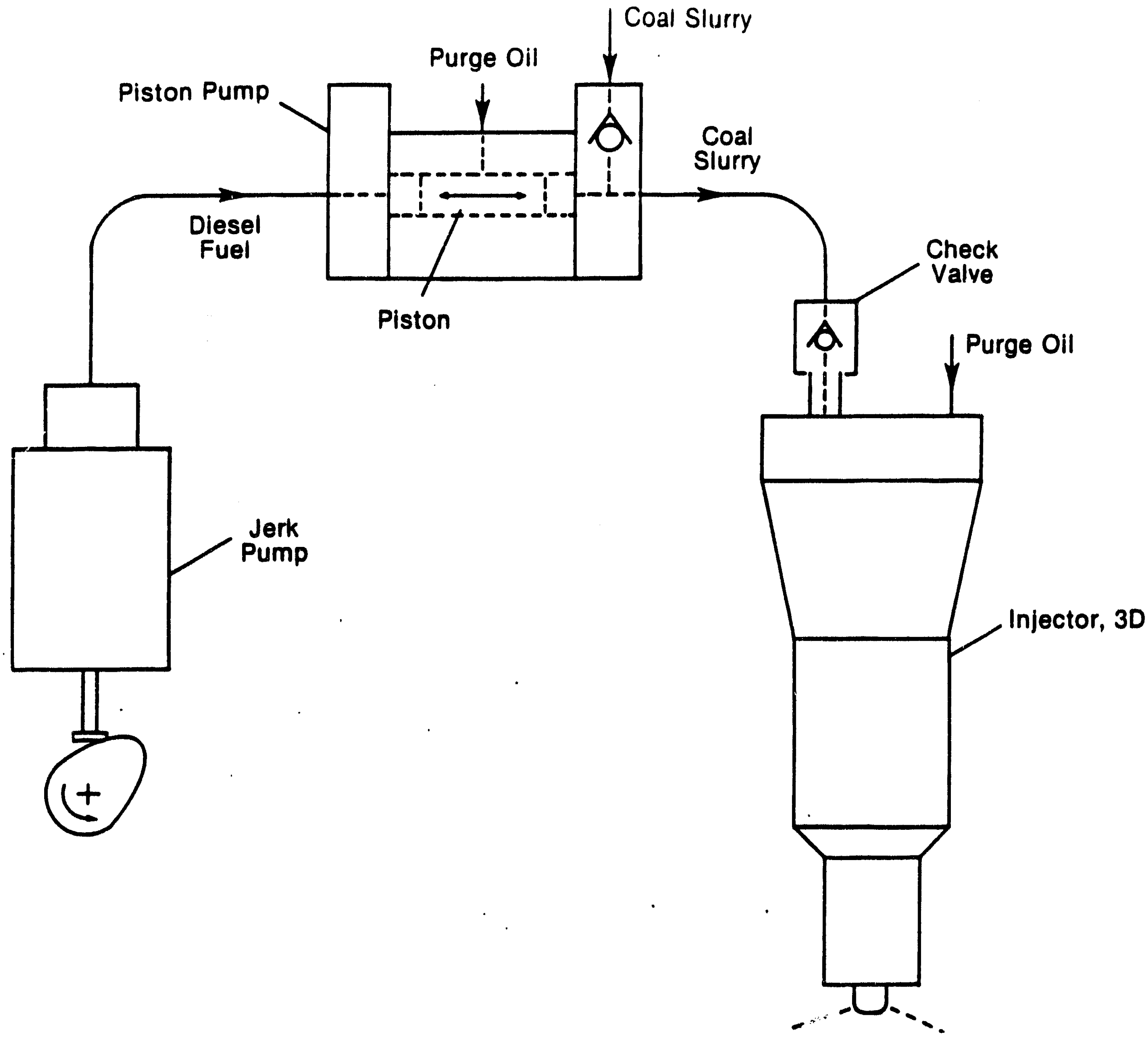


Figure 1. Final coal water slurry injection system

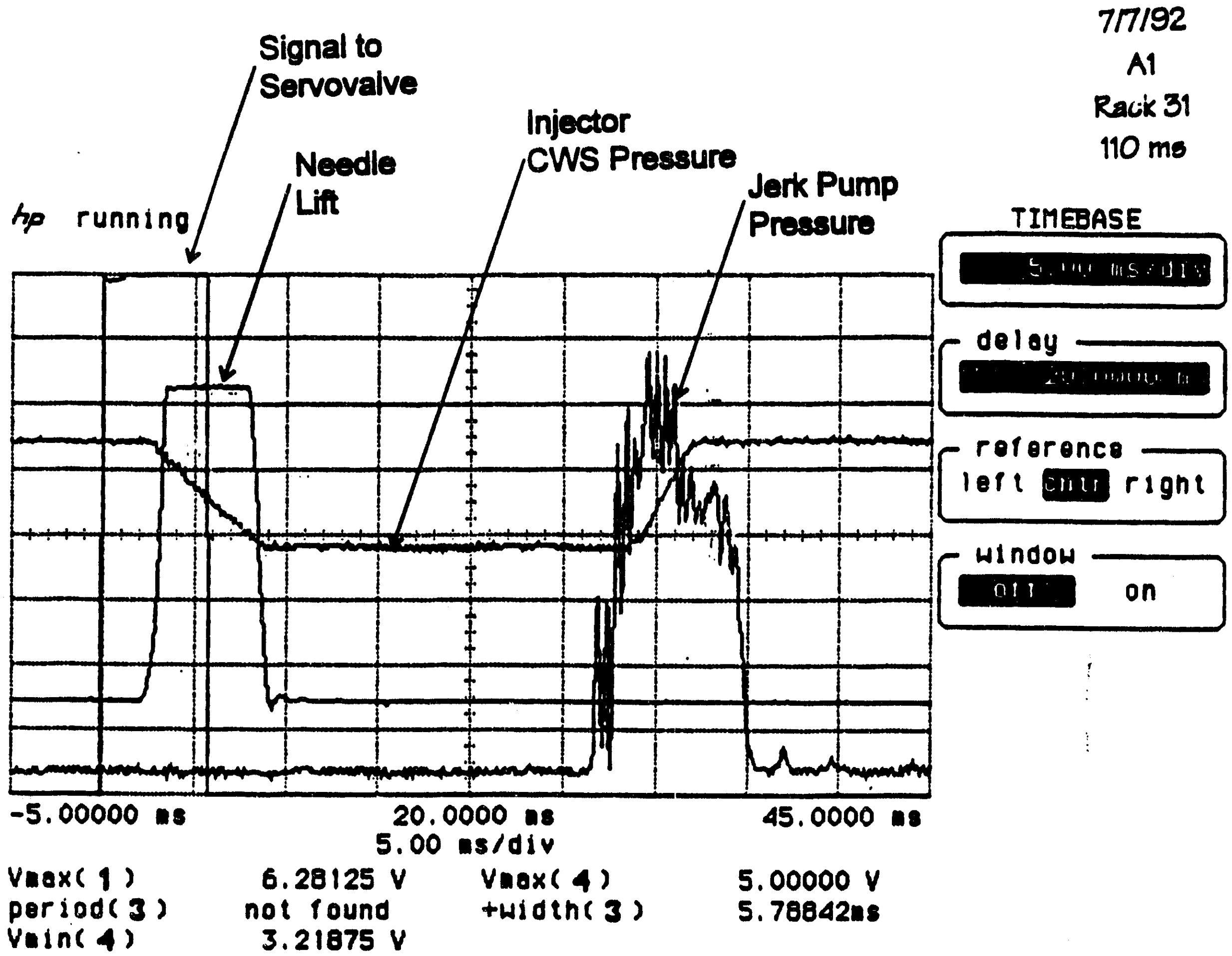
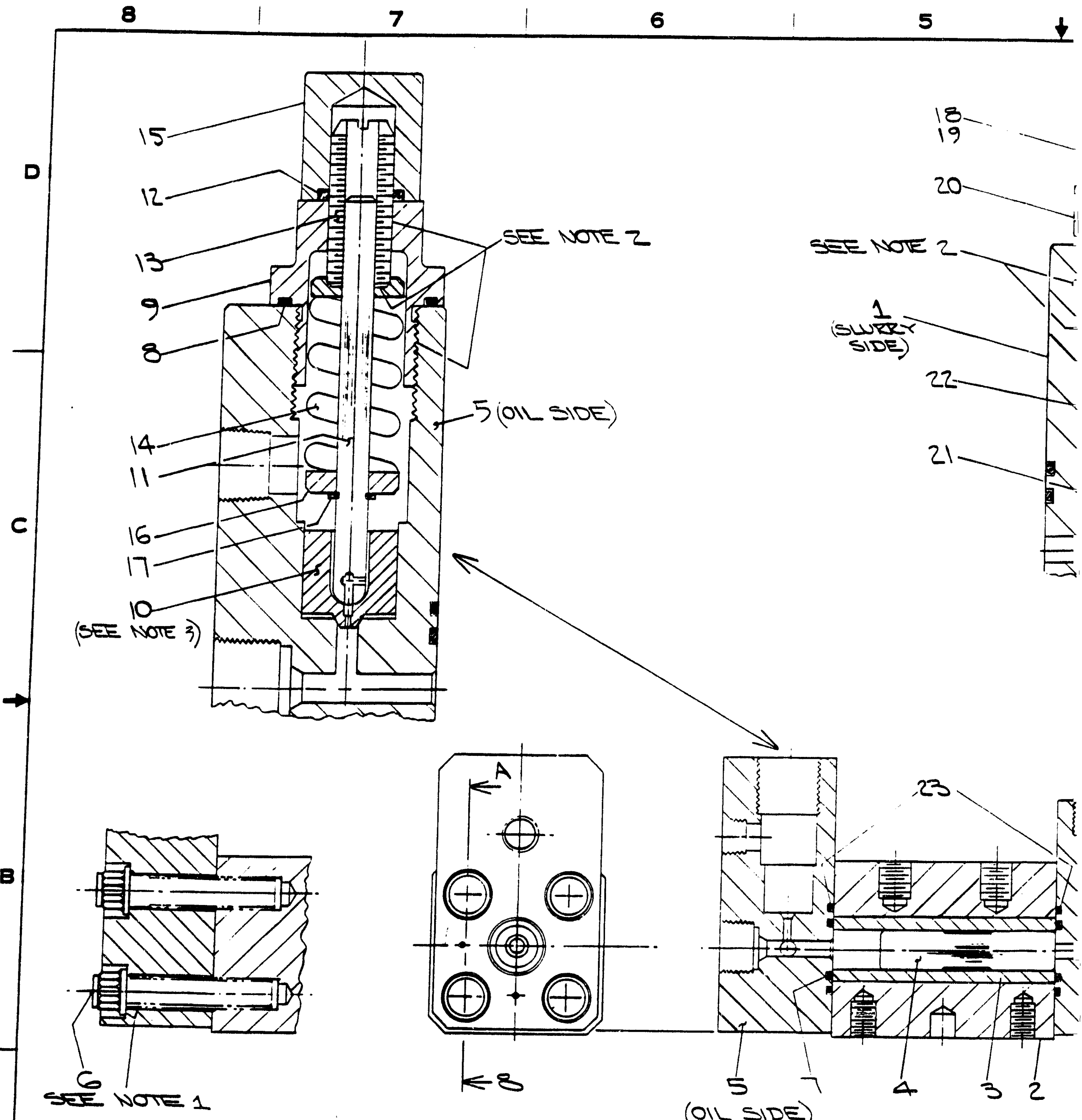


Figure 2. Injection timing and pressure



SECT. A-8

NOTES (CONT.)

4- POPPET (PT. 22) TO BE LAPPED INTO INSERT (PT. 19, MOUNTED IN RETAINER (PT. 18)) PRIOR TO ASM. INTO HOUSING, (PT. 1).

(G1) ASSEMBLY

NOTE:

1- LUBE THREADS & FACE O
"NEVERSEEZ" OR EQUIV.
130 TO 135 FT-LBS. TYP.

2- APPLY "NEVERSEEZ" L
THREADS & FACES
AND PT'S. 5, 9, 13, 15 & 1
INITIAL ASSEMBLY

3- POPPET (PT. 10) TO BE LAPPED

CONT.

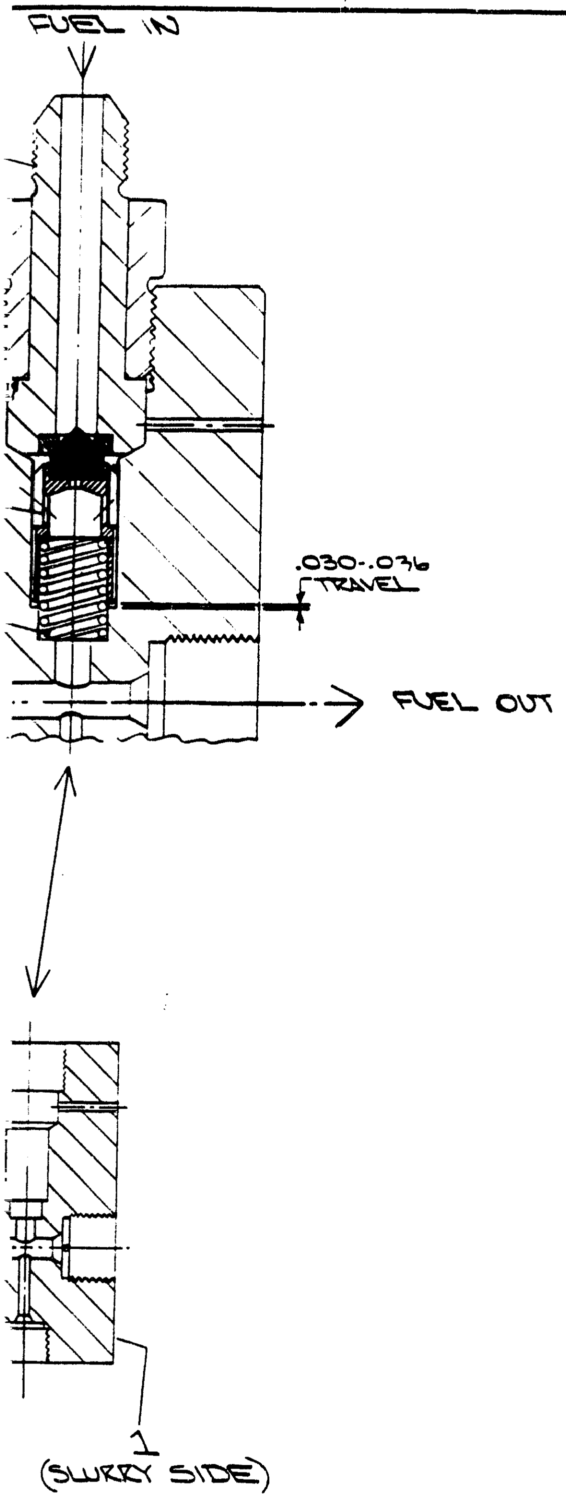
THIRD ANGLE PROJECTION

8 7 6 5

D 152D6407

REVISIONS

REV	DESCRIPTION	DATE	APPROVED
A	DELETE INSERTS PT.5, PT.6 WERE [illegible] BOLTS.	6/11/89	RNJ
3	ADDED PT.23 - PT.7 WAS # 2-019	8/2/90	RNJ
C	GEN. CHG.	12/19/90	
D	GEN. CHG.	3/29/93	



QTY.	PT.	NAME	DESCRIPTION
2	23	"O" RING	PARKER # 2-026 or EQ. MAT'L. VITON
1	22	POPPET	931E509 GR.3
1	21	SPRING	"LEE" CAT. # LC-043 EF-4 STN. STL.
1	20	NUT	931E509 PT.9
1	19	INSERT	931E509 PT. 10
1	18	RETAINER	931E509 PT. 12
1	17	RETAIN. RING	PTS. 11 THRU 17 ARE STANDARD SERIES 3800 COMPONENTS AS LISTED IN F/M SAFETY RELIEF VALVE CAT.
2	16	SPRING PLATE	
1	15	HOOD	
1	14	SPRING	
1	13	PRESS. SCREW	
1	12	SEAL	
1	11	POST	196C4385 PT.3
1	10	POPPET	196C4385 PT.2
1	9	BONNET	196C4385 PT.1
1	8	"O" RING	PARKER # 2-024 or EQ. MAT'L. BUNA N
2	7	"O" RING	PARKER # 2-018 or EQ. MAT'L. VITON
8	6	BOLT - 12 PT.	.500-13 x 2.25 LG. MAT'L. ALLOY STL.
1	5	END CAP	152D6458P1
1	4	PLUNGER	152D6448P7
1	3	CYLINDER	152D6448P5
1	2	HOUSING	152D6448P2
1	1	END CAP	152D6458P2

... BOLT HEAD WITH ... & TORQUE TO ... BOTH ENDS.

... BRICANT or EQUIV. TO ... TWEEN PTS. 1, 18, & 20 ... PRIOR TO ...

... INTO SEAT IN PT. 5.

UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN INCHES
TOLERANCES ON
2 PL DECIMALS ±
3 PL DECIMALS ±
ANGLES ±
FRACTIONS ±

SIGNATURES / DATE
DRAWN 9-15-89
CHECKED
ENGRG R.N. Johnson 10/3/89
ISSUED
R. JOHNSON
G. LEONARD

GENERAL ELECTRIC
DEPT LOC

ASSEMBLY
PISTON PUMP
COAL DIESEL PROG.

SIZE D | FSCM NO | DWG NO 152D6489
SCALE | SHEET | DISTR TO

Figure 3. Piston pump

Figure 4. Piston pump, disassembled: Relief valve(left), Check valve (right)

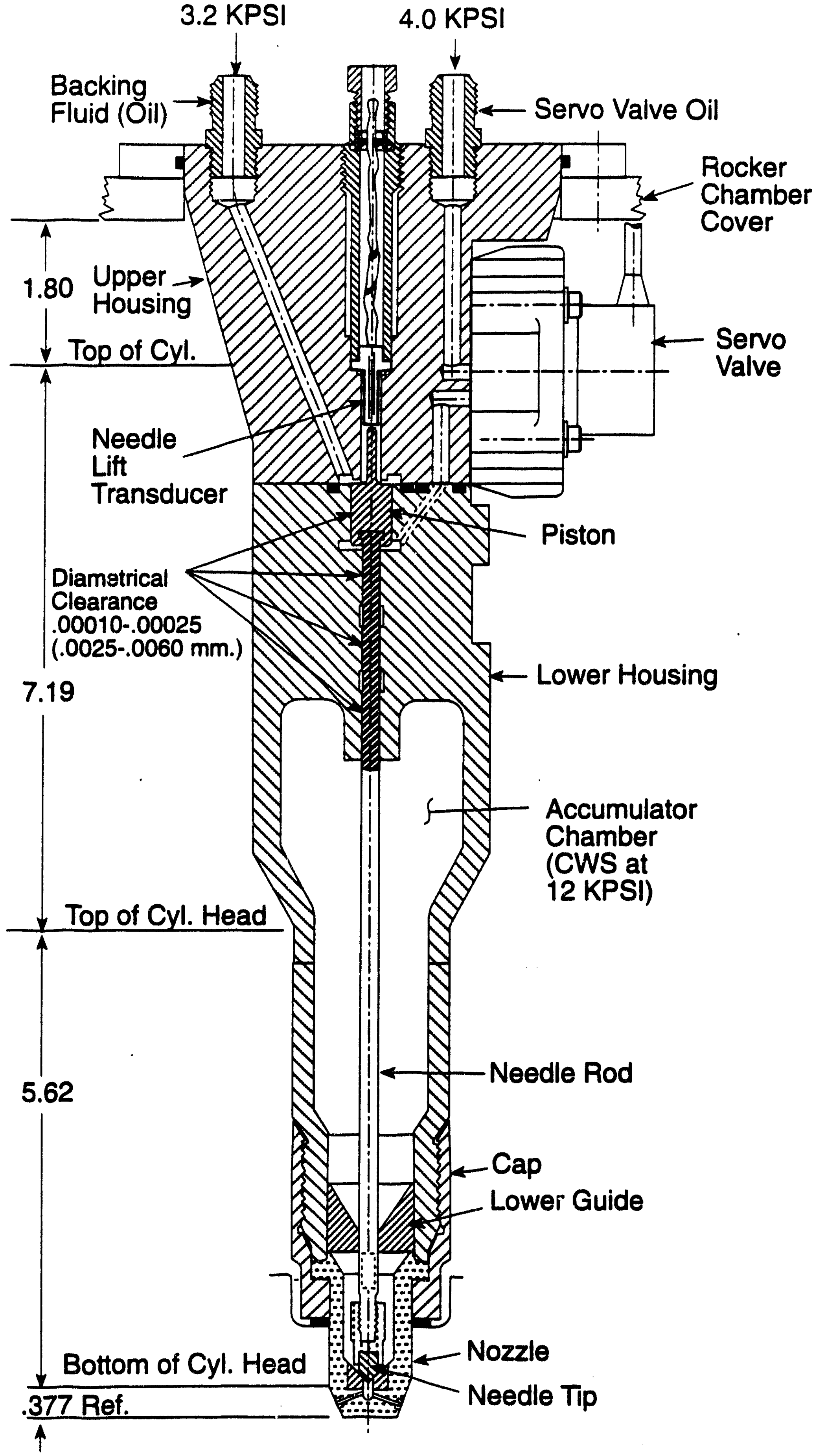


Figure 5. Final fuel injector (cross-section)

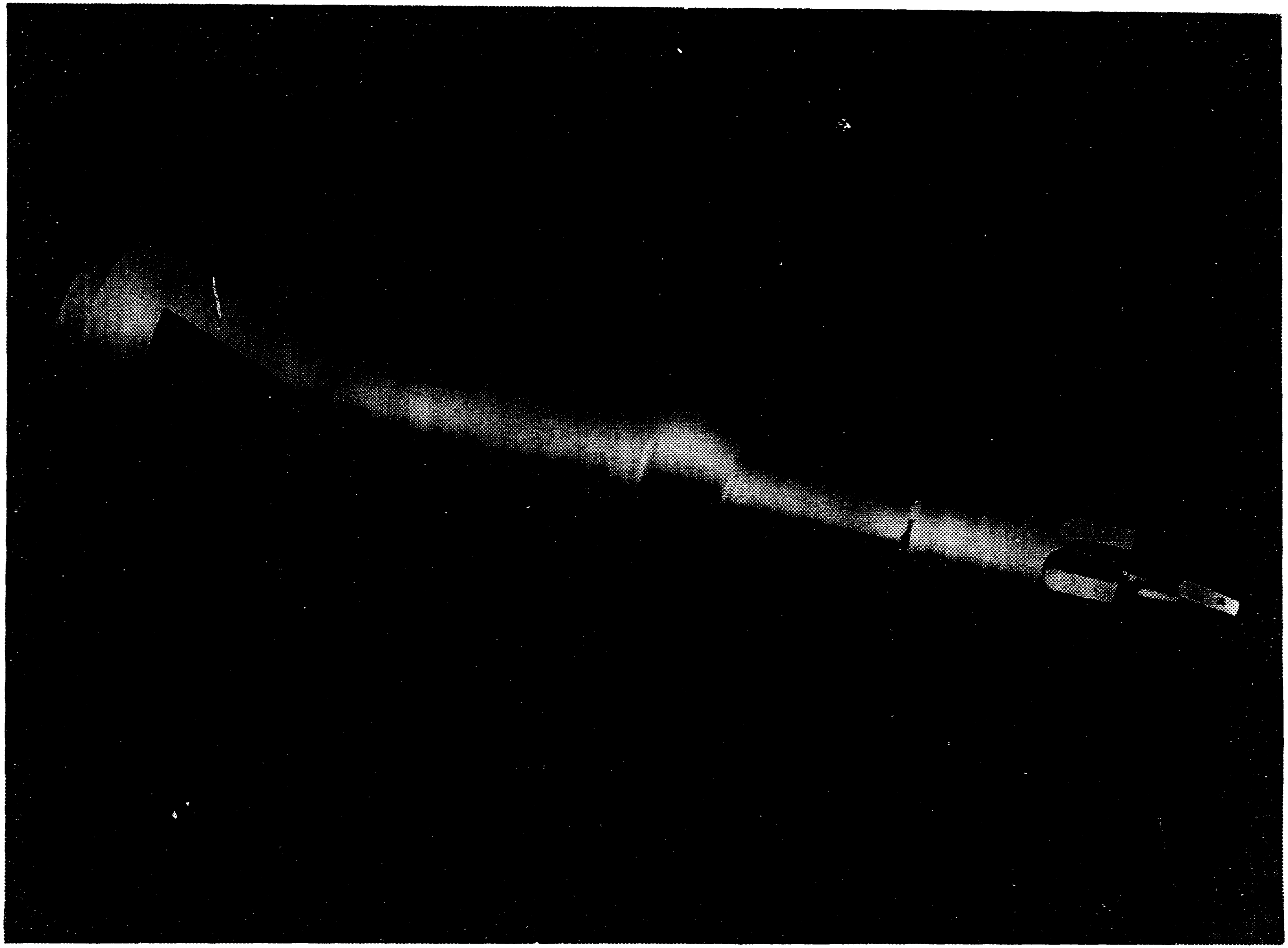


Figure 6. Final fuel injector (assembled)

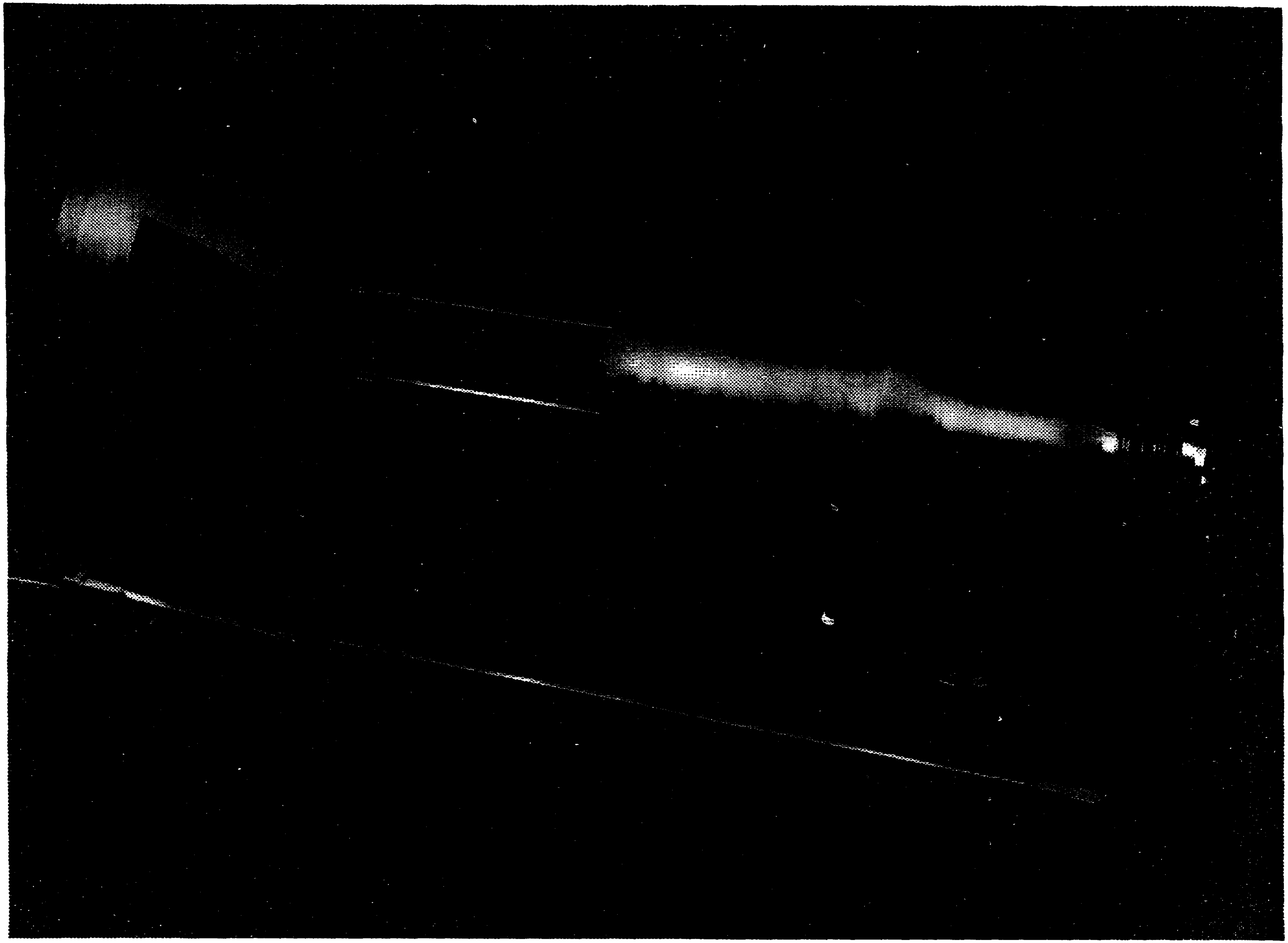
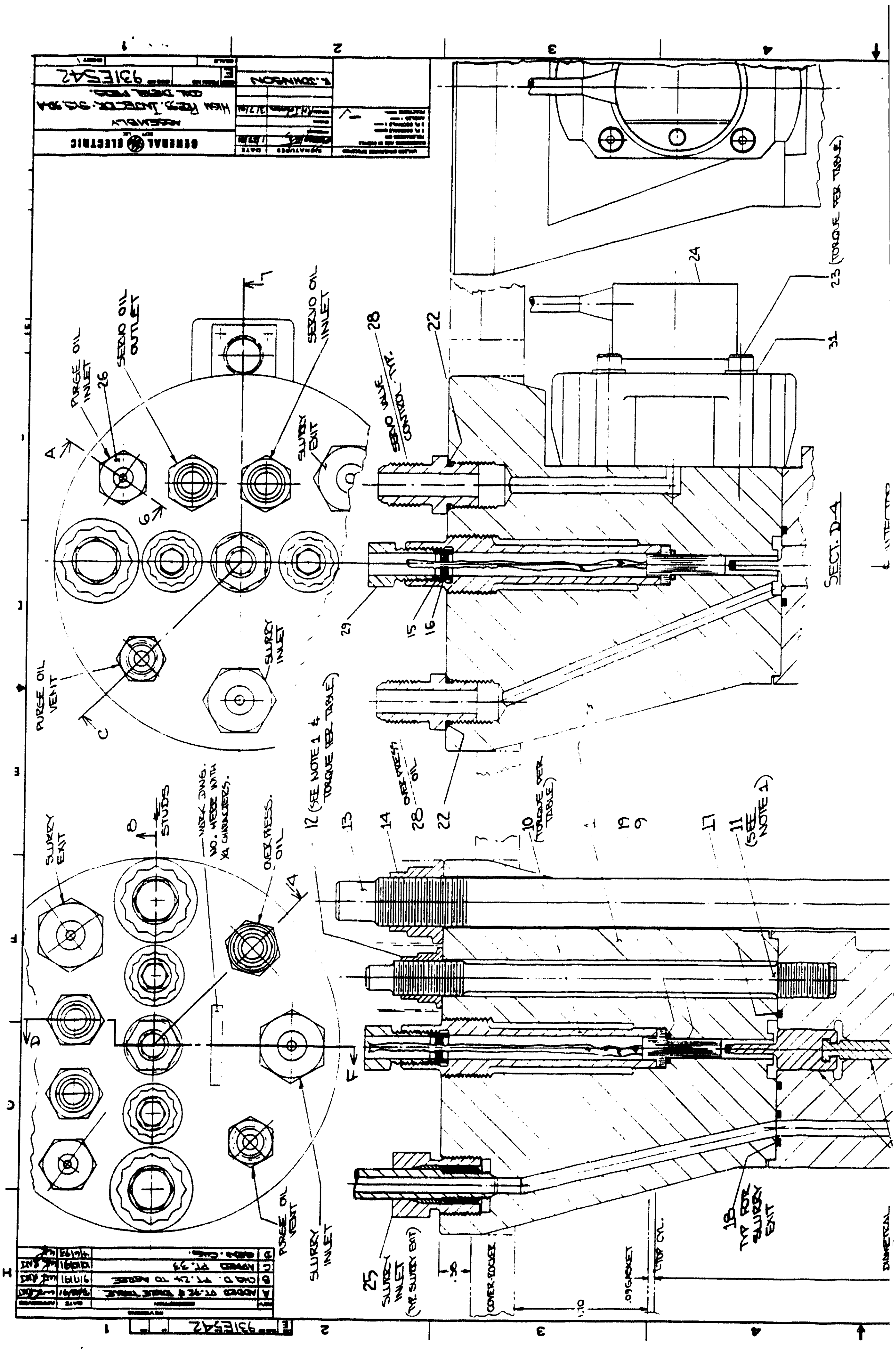


Figure 7. Final fuel injector (disassembled)


GENERAL ELECTRIC
93IE542
SLURRY INLET
SLURRY EXIT
PURGE OIL VENT
PURGE OIL INLET
SERVO OIL INLET
SERVO OIL OUTLET
OVER PRESS. OIL
STUDS
SECT. D-D

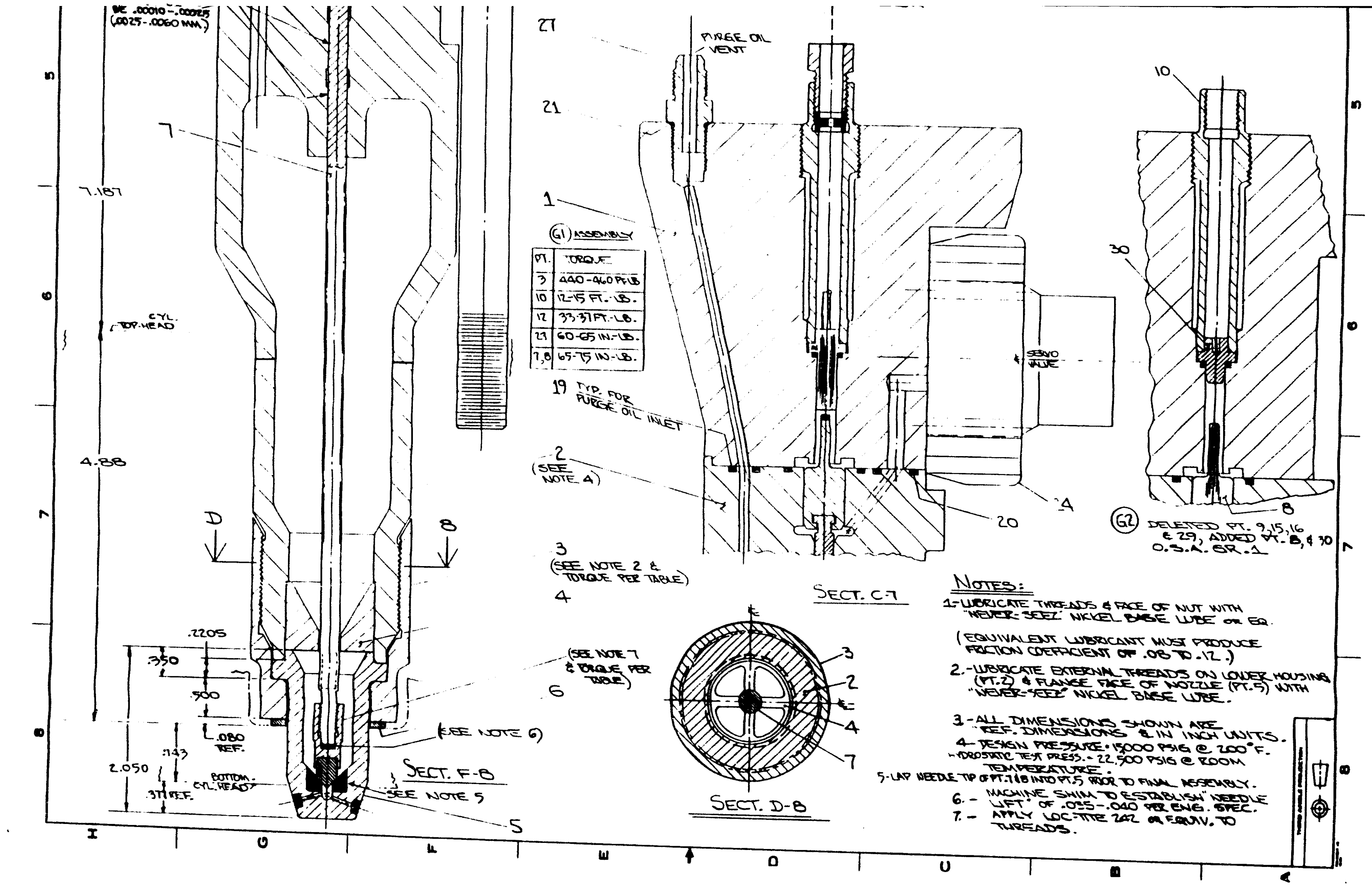


Figure 8. Assembly drawing

GENERAL ELECTRIC

PARTS LIST FOR 931E542 | CONT ON SHEET 2 | SH NO. 1

ASSEMBLY

H.P. INJECTOR -SYS. 3D-A

PARTS LIST FOR 931E542 | CONT ON SHEET 2 | SH NO. 1

FIRST MADE FOR C.D. PROG.

G2	G1	PART NO.	NAME	DRAWING NO. DESCRIPTION, MATERIAL, WEIGHT
1	1	1	UPPER HSG.	931E545 PT.1
1	1	2	LOWER HSG.	931E544 PT.1
1	1	3	NOZ. CAP	931E543 PT.2
1	1	4	LOW. GUIDE	931E543 PT.1
1	1	5	NOZ. ASM	152D6490 G1
1	1	6	GASKET	931E543 PT.4
	1	7	PISTON ASM.	931E608 G4
1		8	PISTON ASM.	931E608 G3
	1	9	DISP. TRANS.	196C4372 G1
1	1	10	PLUG	931E543 PT.6
2	2	11	STUD-INNER	931E543 PT.3
2	2	12	NUT-12 PT.	.437-14 THD. ALLOY STL.
2	2	13	STUD OUTER	SUPPLIED BY G.E.T.S.
2	2	14	NUT 12 PT.	.625-11 THD. ALLOY STL.
	2	15	WASHER	931E543 PT.8
	1	16	GROMMET	931E543 PT.9
1	1	17	"O" RING	# 2-020 MAT'L. PARKER COMP. N552-90
2	2	18	"O" RING	# 2-011 MAT'L. PARKER COMP. N552-90
3	3	19	"O" RING	# 2-010 MAT'L. PARKER COMP. N552-90
1	1	20	"O" RING	# 2-013 MAT'L. PARKER COMP. N552-90
		21	"O" RING	(INCL. WITH PT. 27)
		22	"O" RING	(INCL. WITH PT. 28)
4	4	23	SCR. SOC. HD.	#10-32X.62LG. MAT'L. ALLOY STL.
1	1	24	SERV. VALVE	"MOOG" # 774-114 WITH PIGTAIL # 07752-17
2	2	25	H.P. FITTING	(3/8) AUTOCLAVE ENG.# KCGL 60174
1	1	26	H.P. FITTING	(1/4) AUTOCLAVE ENG.# KCGL 40174
				CONT. ON SH. 2

CONT. ON SH. 2

DESCRIPTION OF GROUPS

- G2: NO TRANSDUCER
- G1: WOLFF TRANS.

REVISIONS

A	ADDED PT. 33
B	DELETED PT. 21&22
C	CHG'D. PT.7 & 8

PRINTS TO

MADE BY W. LONGFRITZ

ISSUED

APPROVALS

C R & D DIV. OR DEPT.

SCHENECTADY LOCATION

PARTS LIST FOR 931E542 | CONT ON SHEET 2 | SH NO. 1

Sheet 1 of parts list for Assembly drawing

GENERAL ELECTRIC

PARTS LIST FOR 931E542
CONT ON SHEET SH NO. 2

ASSEMBLY

PARTS LIST FOR 931E542
CONT ON SHEET SH NO. 2

H.P. INJECTOR -SYS. 3D-A

FIRST MADE FOR C.D. PROB.

			G2	G1	PART NO.	NAME	DRAWING NO., DESCRIPTION, MATERIAL, WEIGHT
			1	1	27	AN FTG. (1/4)	'AEROQUIP' CAT.#202702-4-4S (37°FLARE)
			3	3	28	AN FTG. (3/8)	'AEROQUIP' CAT.#202702-6-6S (37°FLARE)
				1	29	PLUG INNER	931E543 PT.7
			1		30	HSG. SOLID	196C4372 PT.2
			4	4	31	WASHER	FLAT, #10 SCR. .375 MAX. O.D. MAT'L. C.STL.

DESCRIPTION OF GROUPS

- NO TRANSDUCER
- WOLFF TRANS.

REVISIONS

A	ADDED PT. 33
B	DELETED PT.32 & 33 PT. 31 WAS PT. 32

PRINTS TO

MADE BY W. LONGFRITZ

ISSUED

APPROVALS

C R & D DIV. OR DEPT.

SCHENECTADY LOCATION

PARTS LIST FOR 931E542
CONT ON SHEET SH NO. 2

Sheet 2 of parts list for Assembly drawing

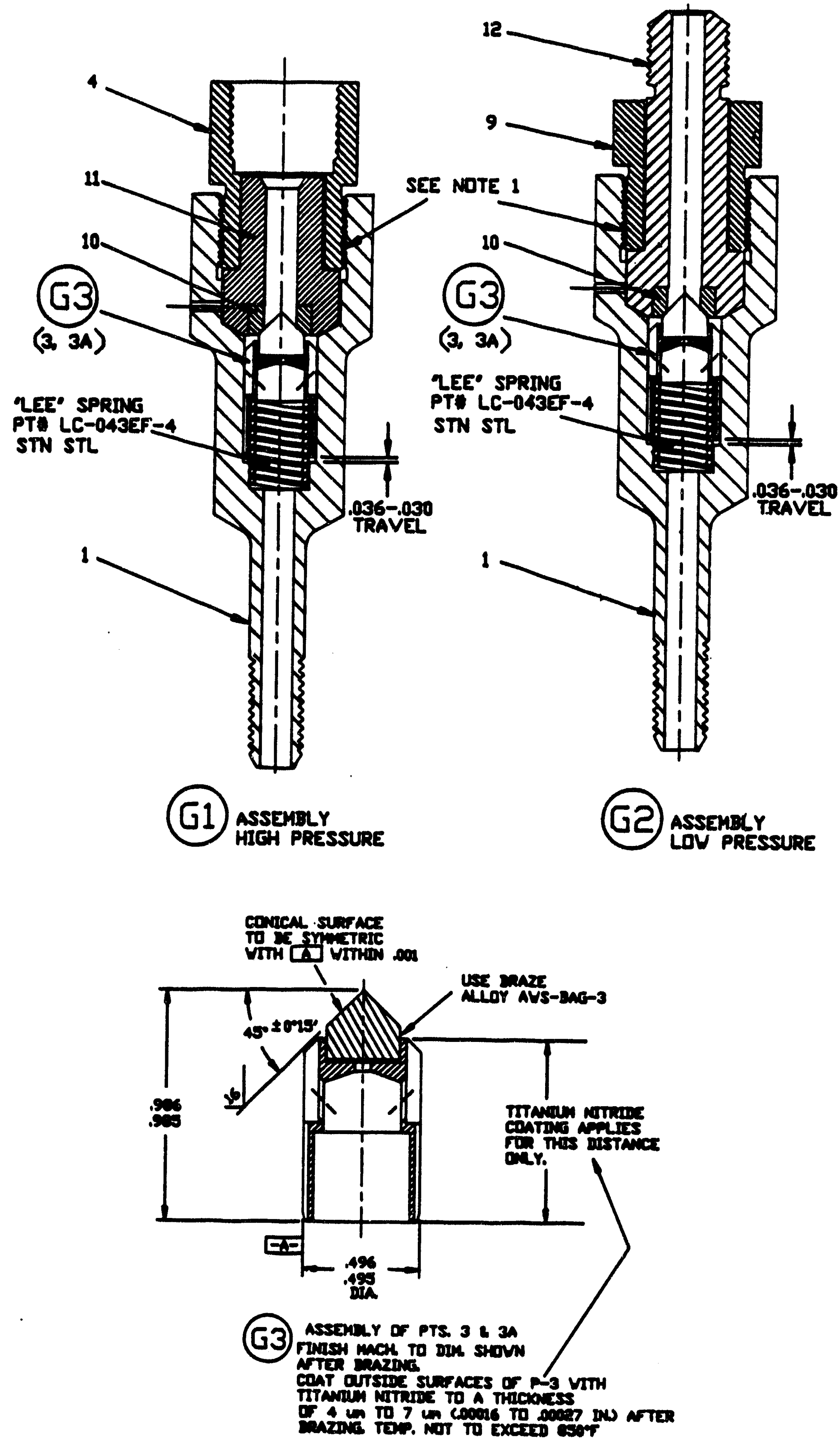


Figure 9. Check valve

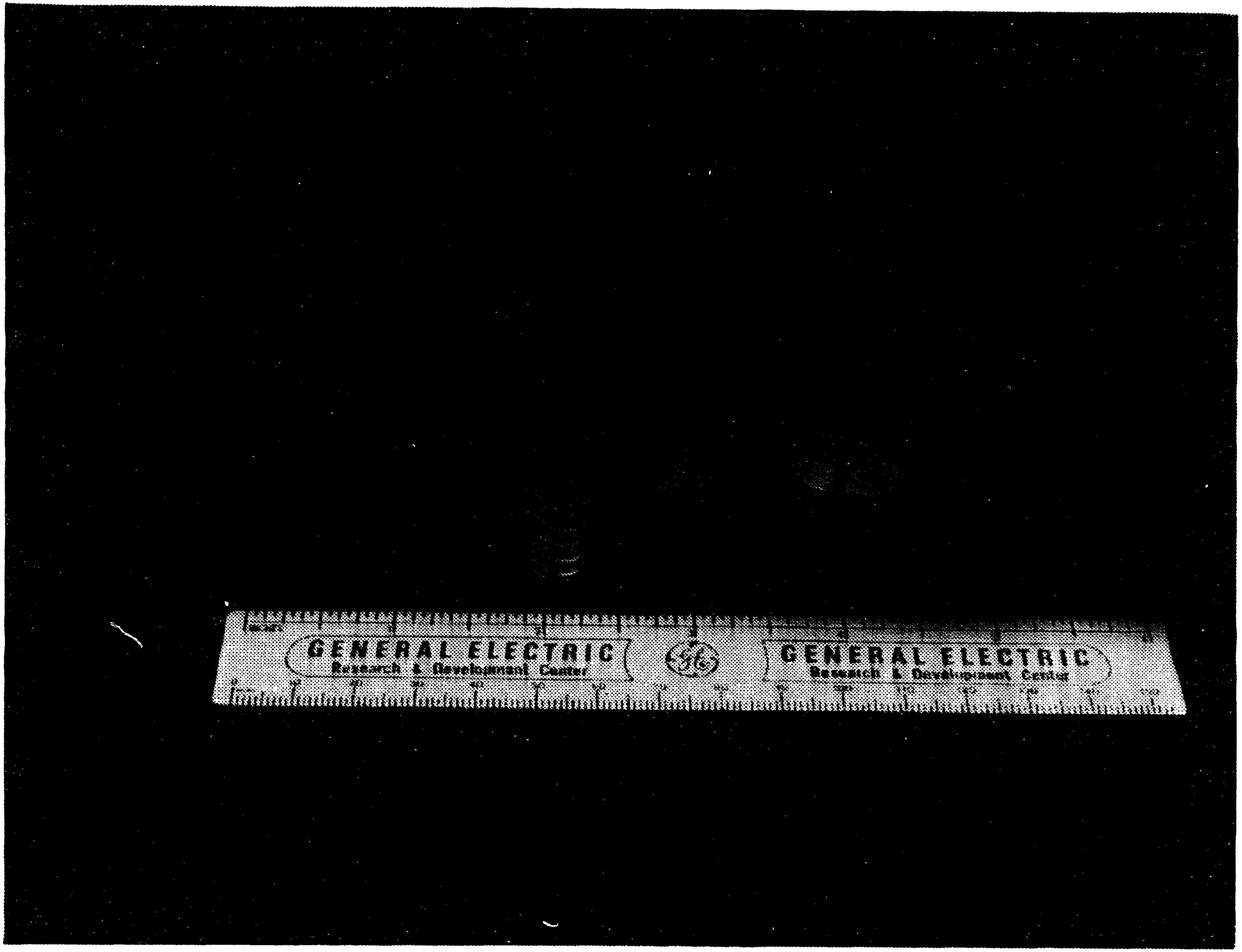


Figure 10. Check valve

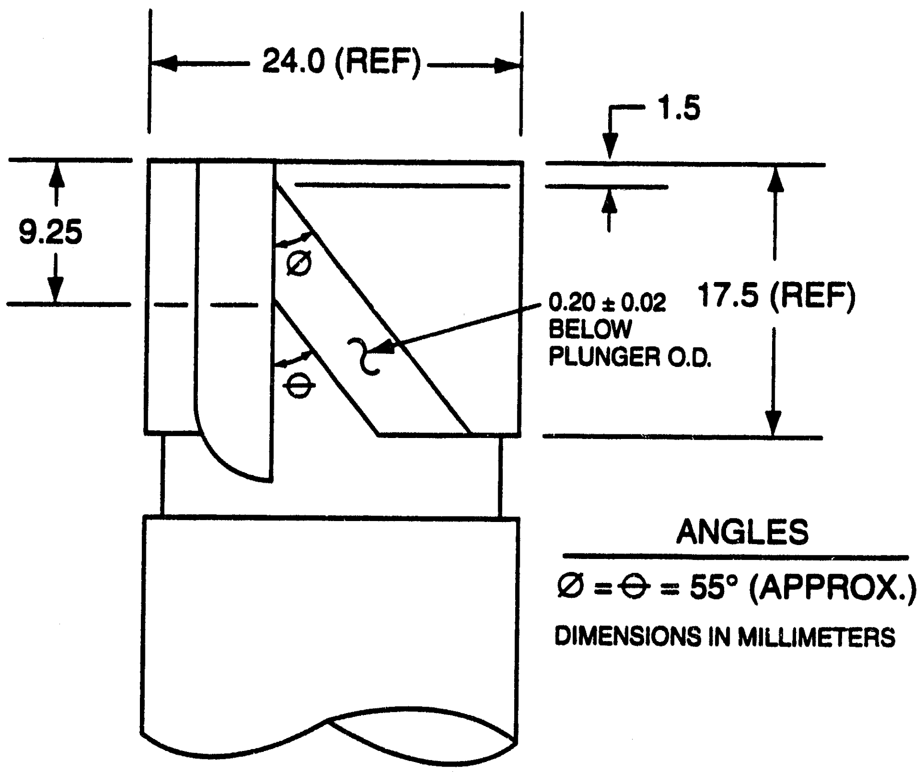


Figure 11. "Jerk" pump plunger relief helix

APPENDIX A

Corrosion of Various Injector Materials in Coal Water Slurry

APPENDIX A

CORROSION OF VARIOUS INJECTOR MATERIALS IN COAL WATER SLURRY

A.1 INTRODUCTION

Significant corrosion of the electroless nickel plating that had been applied to the surface of injector needle rods (Figure A-1) occurred in a matter of 5 hours' exposure to CWS. The purpose of the plating was to provide wear and galling resistance of the 17-4 PH stainless rod sliding against the PH 13-Mo S.S. Injector Housing and 17-4 Lower Guide. The plated surface became black in color and, under microscopic examination, penetration of the plating to the base metal had occurred in numerous locations (Figure A-1). Corrosion was also suspect, at least in part, for the pitting observed in cemented tungsten carbides-with-cobalt binder used for injector needle tips and nozzle seats. Damage to carbides was observed after 25 to 50 hours of injector operation. A test program was initiated at GE-CRD to identify alternative materials with orders of magnitude lower corrosion rates. CWS samples from two sources — Otisca, Inc. and CQ, Inc. — were provided by GE-TS.

A.2 DISCUSSION

A.2.1 Material Choice Considerations

Component life and component failure consequences were the two primary factors in candidate alternative material selection. In addition to the above observed problems, concern existed for the potential of a corrosion (or, stress corrosion) induced failure of the injector lower housing, which contains the CWS accumulator chamber. The cylindrical walls of this vessel, which includes a circumferential electron beam (EB) welded joint, experience tensile (hoop) stresses that alternate between approximately 359 and 242 MPa (52 and 35 ksi) every injection cycle. The prime candidate lower housing material for the final injector prototypes that were installed in the GE-TS multicylinder (12-cylinder) engine was precipitation hardening 13-8 Mo stainless steel (PH 13-8 Mo S.S.), age hardened at 1000°F.

For the needle rod coating (required primarily for wear and anti-galling protection where the rod slides within the injector housing), nitriding appeared to be a desirable option to the failed electroless nickel. Nitriding also seemed desirable for the injector housing bores in which the rod and piston slide. Wear tests (Appendix B) had shown nitriding to be a promising candidate.

For the needle tip and seat, literature (Kennametal Brochure, S-82) suggested that using nickel as the binder for tungsten carbide rather than cobalt should significantly reduce corrosion.

For control purposes, samples of the material to be replaced were also exposed. Sample materials and sources are given in Table A.1.

A.2.2 Test Plans

Small pieces (1.7 to 9.1 grams) of the various materials were carefully cleaned and weighed, and placed in 4-oz. glass jars containing Otisca or CQ CWS. No attempt was made to achieve a constant surface area-to-weight ratio among the samples. (This was an experiment in "engineering" rather than in "pure science.")

Initially, the jars were gently shaken twice daily to move the samples relative to the CWS. Half way through the experiment period, a low speed rolling mill was implemented to produce circulation of the CWS relative to the samples. The samples were removed and thoroughly cleaned and weighed at increasingly long time intervals. CWS was completely changed monthly. Samples were exposed to CWS for periods of 4.5 months (uncoated aged 13-8 and 17-4 S.S., and cemented carbides) to 3.5 to 1.0 month (nitrided 17-4 and 13-8 S.S.) as they became available.

A.3 TEST RESULTS

Weight change results are contained in Table A.2. A few observations can be made:

1. In nearly all cases, the percentage weight loss is significantly greater with Otisca CWS.
2. 13-8 S.S. exhibited substantially greater weight loss than 17-4, in both as-aged and aged-and-nitrided conditions.
3. Nitriding contributed to increased corrosion rates of PH S.S. However, visual examination of nitrided injector parts after engine testing revealed no corrosion damage.
4. The electroless nickel plated 17-4 samples did not exhibit significantly different weight change from nitrided material. It should be noted that phosphorus content and heat treatment can have a significant effect on the corrosion resistance of electroless nickel platings.

5. Tungsten carbide with nickel binder (VC-320) exhibited somewhat lower rates than those with cobalt binders. As with the nitrided 17-4 PH, the nickel-bindered carbides appeared significantly better than the cobalt-bindered parts they replaced in injectors and check valves after engine testing.

6. Sectioned samples of successful nitrided PH S.S. and TiN coating are shown in Figure A-2.

A.4 REFERENCE

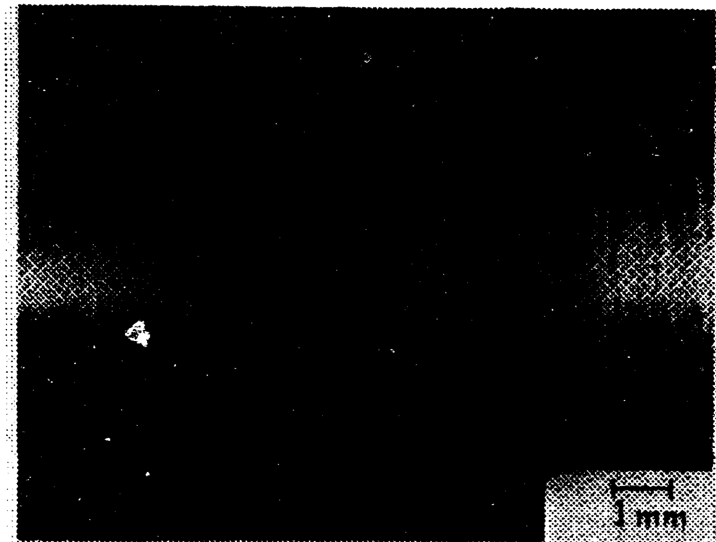
Properties and Proven Uses of Kennametal Hard Carbide Alloys, (Kennametal Brochure S-82)

Table A.1 Corrosion Test Samples

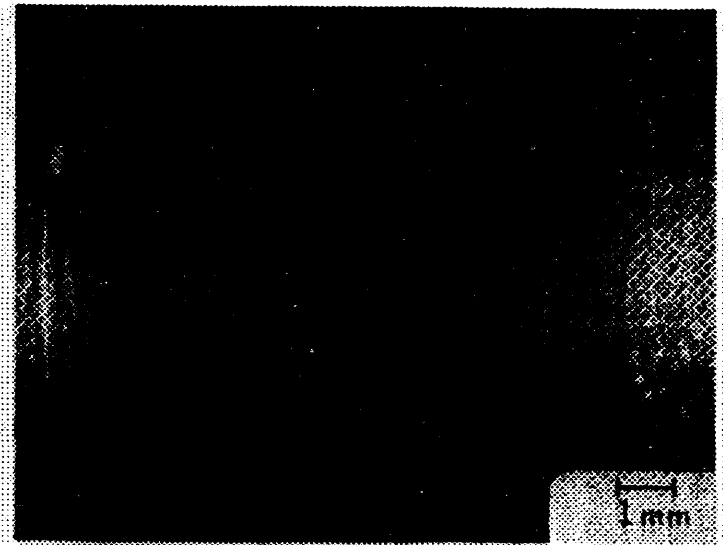
No.	Composition	Source	Preparation
1,2	PH 13-8 Mo S.S.	CRD	Aged 1000°'F
3,4	17-4 PH S.S.	CRD	Aged 900°F
5,6	Tungsten Carbide/ 6% Co binder (Grade VC- 11)	GTE Valenite Corp. Troy, MI	
7,8	Tungsten Carbide/ 14% Ni binder (Grade VC-320)	GTE Valenite	
9,10	PH 13-8 Mo S.S.	Steel Treaters, Inc. Troy, NY	Gas nitrided @ 1000°F
11,12	Tungsten Carbide/. 6.% Co.binder (Grade KF306)	Kennametal, Inc. Latrobe, PA	
13,14	17-4 PH S.S.	Sun Steel Treaters Detroit, MI	Ion nitrided after aging
15,16	17-4 PH S.S.	Metallurgical Processing New Britain, CT	Ion nitrided after aging
17,18	17-4 PH S.S.		Electroless Ni plated
19,20	PH 13-8 Mo S.S.	Steel Treaters	Gas nitrided @ 1000°F
21,22	17-4 PH S.S.	Steel Treaters	Gas nitrided @ 1000°'F
23,24	17-4 PH S.S.	Implant Sciences	N_2 ions implanted after aging
25,26	17-4 PH S.S.	Multi Arc Corp.	TiN coated after aging
27	17-4 PH S.S.	Metallurgical Processing	Plasma nitrided @ 800°F after aging @ 900°F

Table A.2 Corrosion Test Results

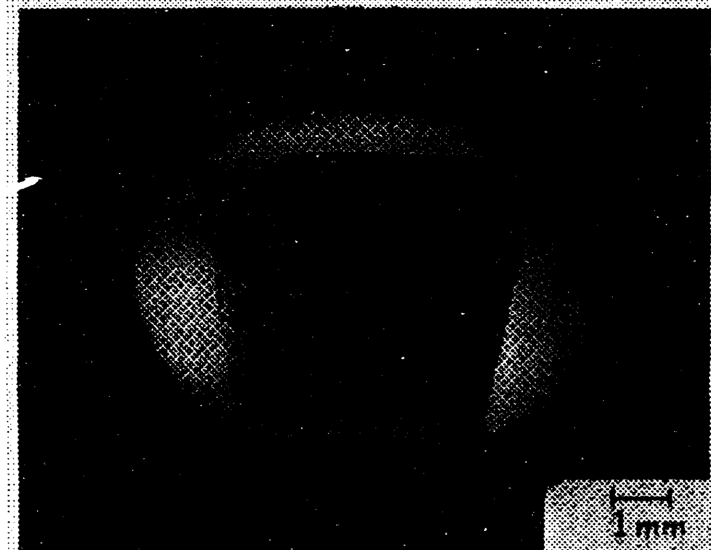
Sample	Initial Sample Wt (gm) in Otisca	Initial Sample Wt (gm) in CQ	Overall Wt Loss (gm)	% Wt Loss	Exposure Time (wks)
1	1.69042		0.00092	0.054	19
2		1.67578	0.00083	0.050	19
3	1.75945		0.00069	0.039	19
4		1,76863	0.00066	0.037	19
5	8.90540		0.02209	0.248	19
6		8.84985	0.01298	0.147	19
7	9.05175		0.01626	0.180	19
8		9.03144	0.00360	0.040	19
9	4.84549		0.05361	1.106	19
10		4.88430	0.01799	0.368	19
11	5.79889		0.01883	0.325	19
12		5.80474	0.00136	0.023	19
13	1.77080		0.03962	2.237	16
14		1.76089	0.00676	0.384	16
15	1.73936		0.00023	0.013	16
16		7.74658	0.00018	0.002	16
17	3.23035		0.00846	0.262	15
18		3.20374	0.00039	0.012	15
19	1.70524		0.05589	3.278	15
20		1.68529	0.00821	0.487	15
21	1.76618		0.02815	1.594	15
22		1.77736	0.00965	0.543	15
23	1.77713		0.00032	0.018	13
24		1.77534	0.00023	0.013	13
25	1.77614		0.00072	0.041	13
26		1.79560	0.00073	0.041	13
27	7.82112		0.02144	0.274	13



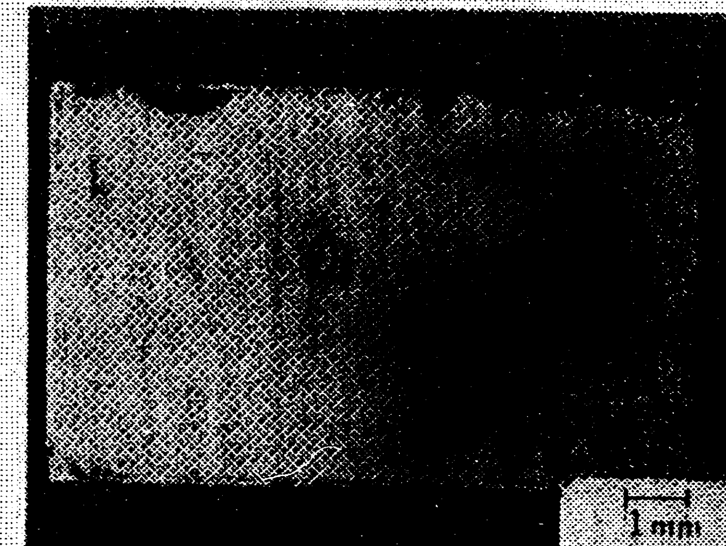
ELECTROLESS NICKEL PLATED INJECTOR NEEDLE ROD FROM LUCAS LTD., UNEXPOSED



NEEDLE ROD AFTER 1 WEEK IN OTISCA CWS (PH=5.9)



E-N BY FOUNTAIN PLATING AFTER 1 WEEK IN CWS



GAS NITRIDED PRECIPITATION HARDENING STAINLESS AFTER 1 WEEK IN OTISCA CWS

Figure A-1 Corrosion of Electroless Nickel Plating in Coal Water Slurry

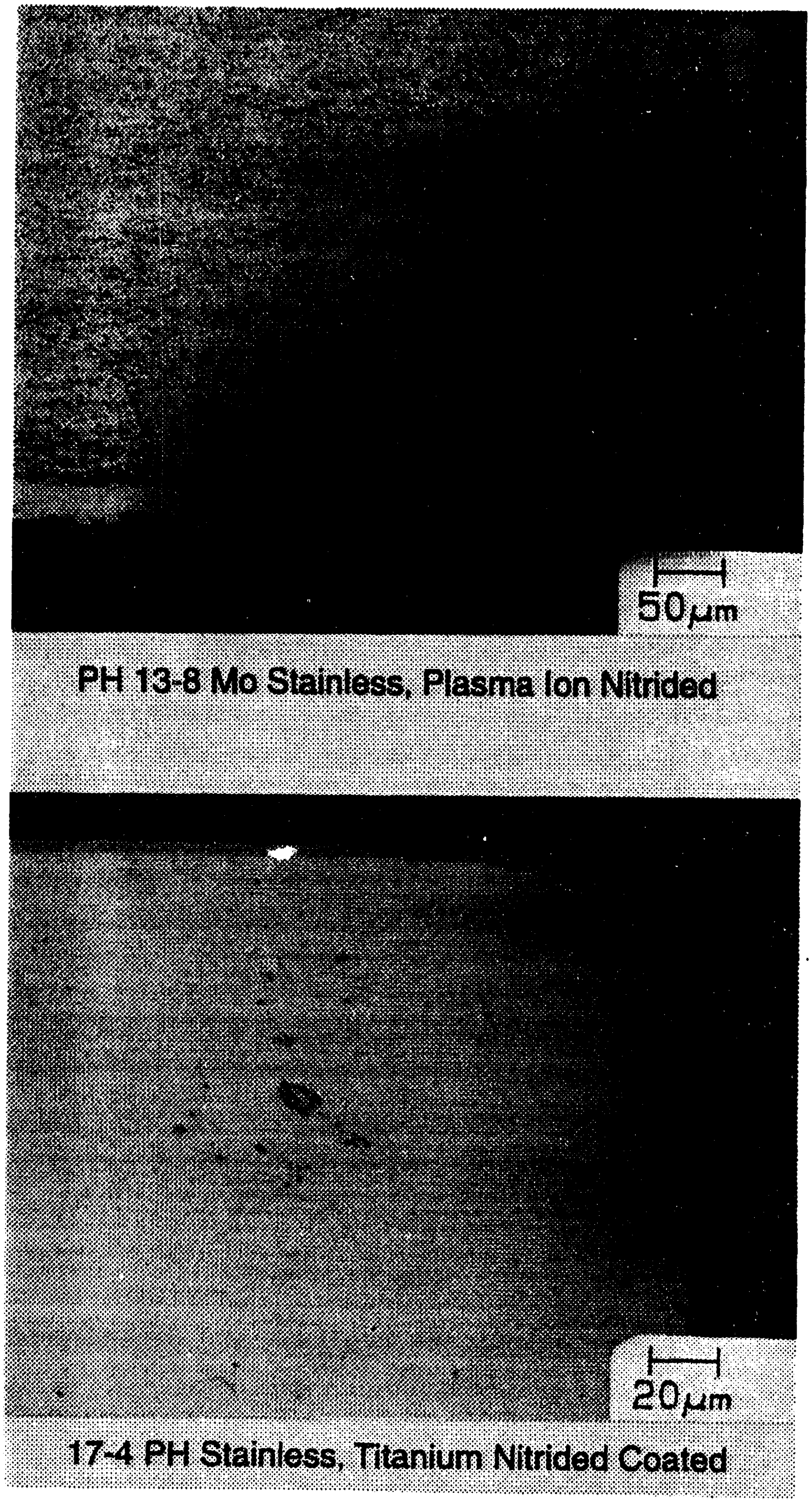


Figure A-2. Sectioned samples of successful nitrided PH S.S. and TiN coating

APPENDIX B

Assembly and Test of 6 Coal Slurry System 2C Injectors for General Electric (Lucas Bryce, Ltd)

Assembly and Test of 6
Coal Slurry System 2C
Injectors for General Electric

Report No. 90-TN-041

by A G Jones

contributions by: M Patel
R Fairs

copies to:- Mr C M D Little
Mr R Johnson
Mr A K Kalafala
Dr B D Hsu
Mr B D James
Mr J Porter

Lucas

Lucas Diesel Systems
Hucclecote
Gloucester GL3 4AB

Telephone: Gloucester (0452) 371771
Telex: 43217
Fax: Gloucester (0452) 613427

Mr R Johnson
General Electric Company
Building K1-ES 205
SCHENECTADY, NY 12345
U.S.A.

8 October 1990

WJC/PLB/G.37

Dear Mr Johnson

We have now completed the testing of the equipment for Phase 2C of the Coal Slurry programme.

The equipment is being despatched to you now, via Greenville, as requested.

Please find enclosed three copies of Report 90-TN-041 for yourself, Mr Kalafala and Dr Hsu, covering the assembly and test of the special injectors. Would you please distribute them.

We trust that you will find the goods and report satisfactory. However, we would draw your attention to Section 7 and trust that you will take the recommendations into account during your testing and any further design work.

Should you have any queries, please let us know.

Yours sincerely

P S. Best

pp W J Caveen

Technical report

Lucas Bryce Limited
Gloucester GL3 4AB

Title

Assembly and Test of 6 Coal Slurry System 2C Injectors for General Electric.

To Mr C M D Little

Job no. :

From A G Jones

Report no.: 90-TN-041

Action Mr R Johnson

Date : 26.9.90

Information Mr A K Kalafala, Mr B D James, Dr B D Hsu
Mr J Porter, Mr M Patel, Mr R Fairs,
Mr G S Thomas

File :

SUMMARY

Lucas have designed, manufactured, assembled and tested six positive displacement injectors for General Electric System 2C test programme.

These will enable G.E. to run System 3D (accumulator injector) and 2C to assess which offers the best overall design for engine performance, durability and simplicity.

Static testing was satisfactory although a higher assembly torque than designed was needed to seal the nozzle.

Oscillograms of system performance show a slow start to injection, full load period slightly shorter than System 3D. Peak pressures are lower and jerk pump rack travels are greater.

After testing, each nozzle and transfer block assembly was tighter than when first installed - no obvious reason for this has been found following various checks.

Total leakage rates have been recorded - actual purge oil loss through the nozzle sprayholes may be masked on some units by the unknown quantity of backing fluid leakage.

Various conclusions and recommendations are made.

Technical report

Lucas Bryce Limited
Gloucester GL3 4AB

Title Assembly and Test of 6 Coal Slurry System 2C Injectors for General Electric.

To Mr C M D Little

Job no. :

From A G Jones

Report no.: 90-TN-041

Action Mr R Johnson

Date : 26.9.90

Information Mr A K Kalafala, Mr B D James, Dr B D Hsu, Mr J Porter, Mr M Patel, Mr R Fairs, Mr G S Thomas

File :

1.0 INTRODUCTION

Lucas report 89-TN-049 documents our visit to General Electric Corporate Research and Development facility at Schenectady NY to discuss the next phase of their Coal Slurry test programme - a positive displacement system using the existing 24mm jerk pump, G.E. piston pump and a new 'U' size injector having the following features:

- G.E. nozzle tip having diamond sprayhole inserts, screwed onto Lucas nozzle assembly.
- purge oil feed facility to nozzle to flush CWS from clearance.
- pressure backing facility to increase N.O.P. to 10,000 lbf/in^2.

This system is being pursued by G.E. in parallel to System 3D (accumulator injector) because it is a much simpler means of providing a CWS injection than System 3D - there are potentially less problems, due to electronic timing of the injection as with 3D or maintaining consistent shot-shot output owing to inconsistent pre-charging of the accumulator. System 2C is a much simpler concept, along the lines of the previous System 2B but hopefully overcoming the problems of rapid nozzle seat wear/sprayhole wear and unsharp injection, associated with 2B.

Owing to inability to start this job at Gloucester, Lucas sourced the Design and component manufacture with their sister company, Lucas Diesel Systems at Concord Road, London.

12 A 362

This report details results of component measurements, static and dynamic tests at Lucas Diesel System, Gloucester, prior to supply to General Electric, Schenectady of the 5 injectors ordered.

2.0 EQUIPMENT SUPPLIED

5 pcs. Injector - Lucas No. 4976/4077 Iss2. (See Figure 9)

Various Injector Spares
- N.O.P. shims
- injector spring (1)
- dowels (8)
- transfer block assembly (1)

1 pc. Wolff needle lift sensor/lead
1 pc. Wolff univ. signal conditioner SSC-43001 /power supply cable

Note - 1 complete instrumented injector retained at Gloucester for backup rig tests if required.

- 1 injector supplied less nozzle assembly.

3.0 TEST FACILITY

3.1 Test Requirements

G.E. specified a functional test for each injector to prove it was working correctly, though no detail was given.

Lucas prepared the following in test schedule:-

1. Measure clearance of nozzle body/needle and transfer block/pin.
2. Flow test nozzles (sprayhole flow).
3. Identify injectors with part number and datecode.
4. H.P. test injectors to 22500 lbf/in^2 - both CWS and purge oil drillings.
5. Assemble injectors and shim for 5000±50 lbf/in^2 Nozzle Opening Pressure. Performance check for backleak rate and chatter.

- line pressure. Tapping for Kistler transducer type 6227 SN 299456 on inlet side of piston pump (GE type 196C4364)

- 3 degree cam markers were collected from the camshaft.

4.0 RESULTS

Figure 1-2

oscillograms of system performance over notches 5-8 showing nozzle needle lift, injection pressure, pumping pressure and 3 degree markers.

Figure 3

schematic of test rig circuits.

Figure 4

delivery v control rod opening curves -500, 525 rpm cam speeds.

Figure 5

clearance measurements
- nozzle body/needle
- transfer block/thrust pin
- nozzle flowtest

Figure 6

- injector component build identification
- injector handtest performance
- purge oil leak test

Figure 7

- backing pressure v nozzle opening pressure

- static high pressure test results

Figure 8

- photographs of the test stand.

Figure 9

- Cross section of System 2C injector.

5.0 DISCUSSION

5.1 Oscillograms

All the nozzle needle lift oscillograms (Figures 1 and 2) show a small pre-injection - this is probably a result of the quite large trapped volume in the total system from jerk pump to nozzle seat. Injection rate is insufficient to keep the needle lifted. This is also shown by the slow rate of needle rise in the main injection.

This is probably of little consequence to the engine as long as the timing of the main injection is correct to suit the CWS ignition delay period.

The injection period of 18 degrees cam at notch 8 (2400mm^3/ injection) compares to a period of 15 degrees for the older System 2B positive displacement system. (Lucas test stand result).

Peak pressures were somewhat lower than those obtained on the System 3D accumulator injector (Pumping pressure 20,300 lbf/in^2, Injection pressure 14760 lbf/in^2, injection period 18.4 deg. cam - notch 8). 3mm more pump rack travel was also required (full travel is 31mm).

5.2 Clearances/Dynamic Leakrates

5.2.1 Figure 5 shows the clearances in the nozzle assemblies were very close to the required 2-4 µm value. Nozzle 'B' was in fact returned to the vendor to be reneedled owing to a high clearance value.

5.2.2 Sprayhole flowrates are consistent (8% range on the mean value).

5.2.3 Of the nine transfer block assemblies produced, six were within clearance specification at 2-3 µm (Spec 2-4 µm). The two instrumented units were fitted with 7 µm clearance blocks as a result of some tightening of the pins in the bodies after test. (A spare 3 µm clearance assembly has been despatched to G.E. should they wish to change it in unit GH1).

5.2.4 On inspection of each injector after testing for purge oil leak rate and after a 2 hour 'endurance' run with one of the injectors, all the nozzle assemblies and transfer block assemblies exhibited tighter needles/pins than before test.

The transfer block thrust pins showed local polishing and the nozzle needles polish marks usually at the top and bottom of the guide diameter.

Checks were done to show that the increased nozzle nut torque was not responsible for body bore reduction (on an unused injector - the needle/pin were free after tightening to the higher torque and removing the assemblies).

One assembly was checked in the Standard Room for needle growth/bore reduction before and after test - results showed no obvious problem.

Lucas, London had commented on the needle material appearing softer than they were used to in conventional nozzles during manufacture - hardness figures were to the stellite specification.

There was never any problem attributable to needle/pin stiction on the test stand - it is probable that the oil pressures fed to both assemblies create a larger clearance when running than when measured on the bench. This problem was discussed with G.E. who agreed to accept the assemblies to this standard and monitor the problem in-house.

5.2.5 Leak Rates

Figure 6 shows the purge oil leak test results. These were taken by pressurising the purge oil cavity in the nozzle guide to 18000 lbf/in^2, running at notch 5 engine delivery and measuring both the backleakage oil flowrate (over around 20 minutes running) and the amount of test oil required to replenish the air-hydro pump tank to its full condition before test. The backleak volume measured must contain some Mobil DTE 26 fluid leaked down the transfer block/pin clearance - for the results in Figure 6, this is assumed negligible (its feed pressure is one-sixth of the purge pressure with similar clearances to the nozzle and a longer leak path).

Subtracting the two measured volumes gives an idea of the amount of test oil (distillate fuel on the engine) which would leak into the CWS fluid and be burnt. In the last column of Figure 6 this amount is expressed as a percentage of notch 5 CWS delivery - it ranges from 1.7 - 13%.

The reason for GH1 and GH2 assemblies having the lowest oil loss through the nozzle could be because the backleak volumes collected could have a relatively high amount of backing fluid in them - their transfer block clearances were quite high at 7 um. No attempt was made to measure the backing fluid supply rate (the displacement of a sealed piston in a transparent tube in the backing fluid supply line would be one means of measuring this).

5.3 Handtest Performance

General Electric had requested that the nozzle body and needle seat differential angle be minimal - previous designs of CWS injector had not had a differential and the seats were expected to wear using CWS, even with a Stellite needle and carbide seat insert, fairly rapidly, enough to lose any designed differential quite quickly. Designed differential is 0-1 degree.

The handtest results shown in Figure 6 were no surprise - it is well accepted that the 'chatter' of a nozzle on handtest is dependent on the degree of differential angle on the seats - too little and the nozzle will 'hose' or 'water-cannon' rather than atomise the oil. Handtest feed rates are very low compared with those on the engine and the test is relatively searching for seat defects on conventional nozzles.

All seats were either wet or damp after applying the standard leak test close to the opening pressure - nozzle did not drip excessively though, confirming good nozzle seat/bore concentricity.

5.4 Backing Pressure/N.O.P.

Figure 7 shows that a backing pressure around 3300-3400 lbf/in^2 was required to obtain the desired total 10,000 lbf/in^2 nozzle opening pressure - this is some 300 lbf/in^2 above the theoretical value, assuming a true seat line at the top of the needle cone. This confirms the needle actually seals part way down the cone.

5.5 Static H.P. Tests

Figure 7 lists the pressure at various nozzle nut torques at which the nozzle holder assembly, fitted with a simple lapped dummy nozzle, sealed to the normal test criterion - pressure loss less than 500 lbf/in^2 in 30 seconds, which is a relatively stringent test. Normally, this test is applied at 4500 lbf/in^2 above the working pressure and, if passed, is an adequate margin for safe use (assuming no fretting conditions exist which will reduce the ability to seal in service).

A final torque of 500 lbf-ft was chosen. Design torque was 350 ft/lbf.

If more injectors of this basic design are required by General Electric, the unit loadings on the lapped sealing faces should be increased to reduce the torque required to seal them adequately (this can be done by etching or milling away metal on the faces to increase loading particularly around the high pressure holes).

6.0 CONCLUSIONS

6.1 Five injector assemblies and one nozzle holder assembly have been manufactured, parts measured, statically and dynamically tested.

6.2 Generally, performance appears acceptable. The nozzle and transfer block assemblies become tighter after running - the reason is not yet clear. However, no stiction problems have been seen on the test stand with backing and purge oils applied.

6.3 Leak rates appear to vary quite widely though this may be a result of unknown leakage of backing fluid.

6.4 Four injectors (one instrumented) and one nozzle holder assembly have been supplied to General Electric, along with ancillary items.

7.0 RECOMMENDATIONS

7.1 G.E. should monitor the following aspects particularly on these injectors:-

- long term effects of nozzle, transfer block tightening.
- backing and purge oil leak rates on test stand and engine - this will be useful to establish future clearances if a further set of injectors is required.
- nozzle seat wear rates. N.O.P. loss with hours run on CWS - relevance to initial seat differential angle for new injector performance testing.
- any effects of initial slow start of injection on required dynamic start of injection relative to pilot injector.

ACTION: Mr R Johnson, Dr B D Hsu

7.2 Any further requirement for these injectors should reflect design changes as necessary to cover the above items, also increased high pressure face unit loadings to improve sealing.

ACTION: Mr R Johnson

Alan Jones.

A G Jones
Project Manager

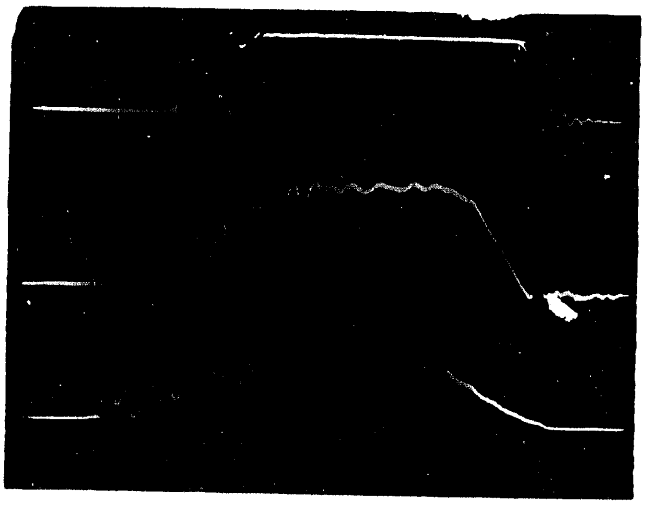
GENERAL ELECTRIC
COAL SLURRY SYSTEM 2C

REPORT No. 90-TN-41
DATE 19 SEPT. 1990

(STEEP HELIX PLUNGER)

FUEL PUMP FCVAB 240X 0830
INJECTOR 4976/4077 ISS. 2
NOZZLE HOLDER
NOZZLE 4976/4082
N.O.P. 10,000 lbf/in2
TEST RIG SPEED RPM SEE BELOW
TIMING MARKS @ 3° CAM INTERVAL
TEST OILS - CASTROL CAL 'C' - JERK PUMP & NOZZLE PURGE
- MOBIL DTE 26 - INJECTOR FEED & NOZZLE BACKING OIL

FUEL CAM 85K 11861 (CONST RATE)
'A' DIM. 6,5 mm
S.T.P.C. 4,0 mm (ON SIDE & CWS SIDE)
H.P. PIPE 9,5 mm Ø x 5,16 mm Ø x 228 mm
UNLOADING VOL. (NO VALVE) mm3
TEST RIG - HARTRIDGE 1500 PLANT #8508
PISTON PUMP - G.E. 196C4364



NOTCH 8

Fuel Delivery = 2400 mm3/inj.

Equivalent Engine Rating

525 RPM CAM = lbf/in2 BMEP

Injection Pressure from Zero

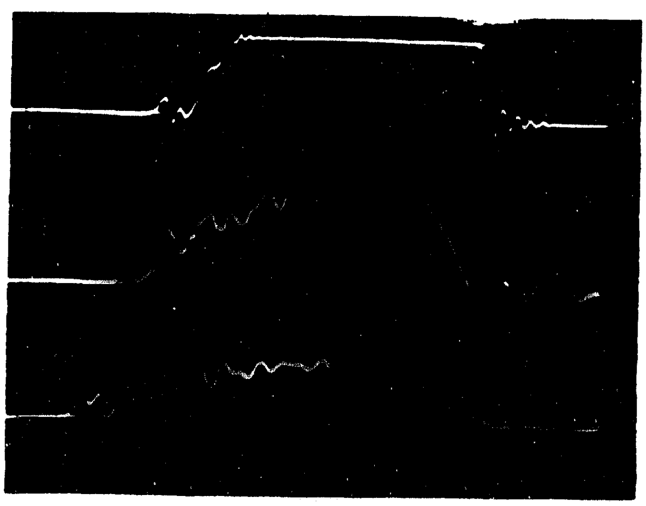
Pump = 17400 lbf/in2

Injector = 14525 lbf/in2

Injection Period = 18 °cam +1½° PRE

Residual Pressure = 1915 lbf/in2

CRO = 30 mm



NOTCH 7

Fuel Delivery = 2100 mm3/inj.

Equivalent Engine Rating

500 RPM CAM = lbf/in2 BMEP

Injection Pressure from Zero

Pump = 15950 lbf/in2

Injector = 14940 lbf/in2

Injection Period = 15,5 °cam

Residual Pressure = 2075 lbf/in2

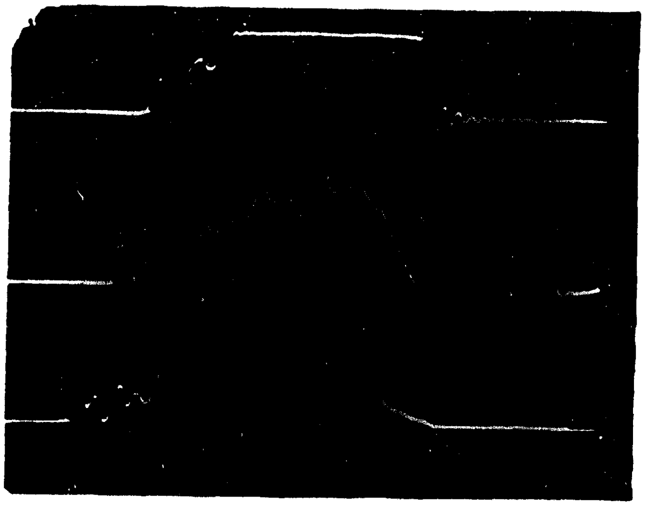
CRO = 28,5 mm

FIGURE 1

GENERAL ELECTRIC

COAL SLURRY SYSTEM 2C   STEEP HELIX JERK PUMP.   REPORT No. 90-TN-41

DETAILS AS PER FIGURE 1   DATE 19 SEPT 1990



NOTCH 6

Fuel Delivery = 1700 mm3/inj.

Equivalent Engine Rating

500 RPM CAM = lbf/in2 BMEP

Injection Pressure from Zero

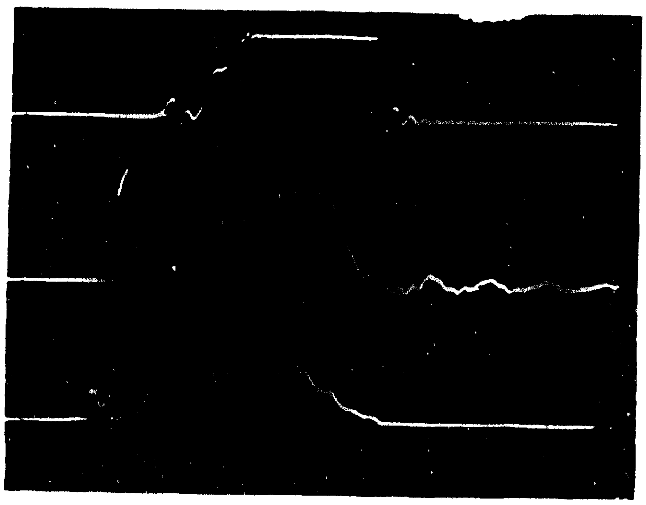
Pump = 17400 lbf/in2

Injector = 14365 lbf/in2

Injection Period = 13,3 °cam +1,2 PRE

Residual Pressure = 2715 lbf/in²

CRO = 25,5 mm



NOTCH 5

Fuel Delivery = 1200 mm3/inj.

Equivalent Engine Rating

500 RPM CAM = lbf/in2 BMEP

Injection Pressure from Zero

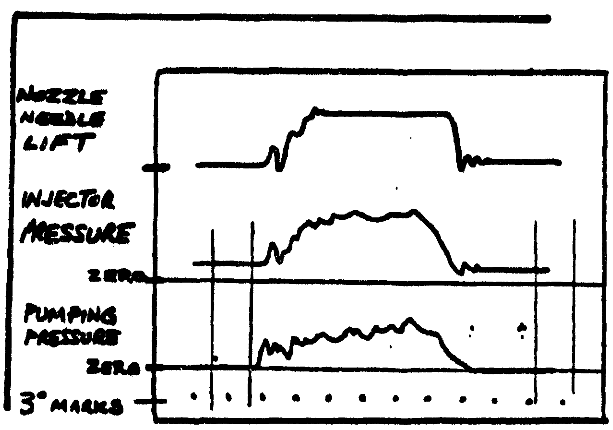
Pump = 15950 lbf/in2

Injector = 14365 lbf/in2

Injection Period = 9,6 °cam

Residual Pressure = 2715 lbf/in²

CRO = 22 mm



Fuel Delivery = mm3/inj.

Equivalent Engine Rating

= lbf/in2 BMEP

Injection Pressure from Zero

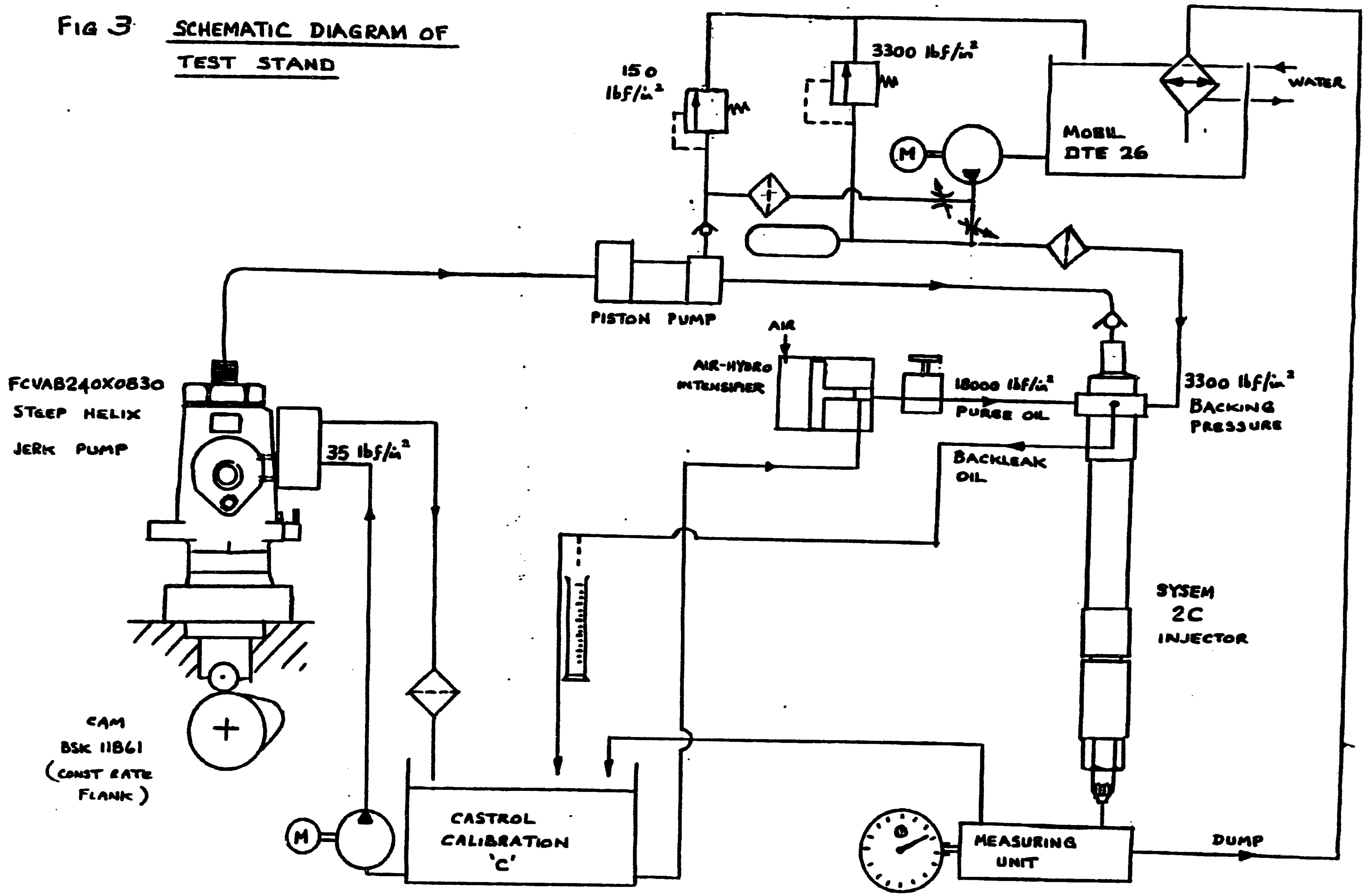
Pump = lbf/in2

Injector = lbf/in2

Injection Period = °cam

FIGURE 2

Fig 3 SCHEMATIC DIAGRAM OF TEST STAND



Coal Slurry System 2C

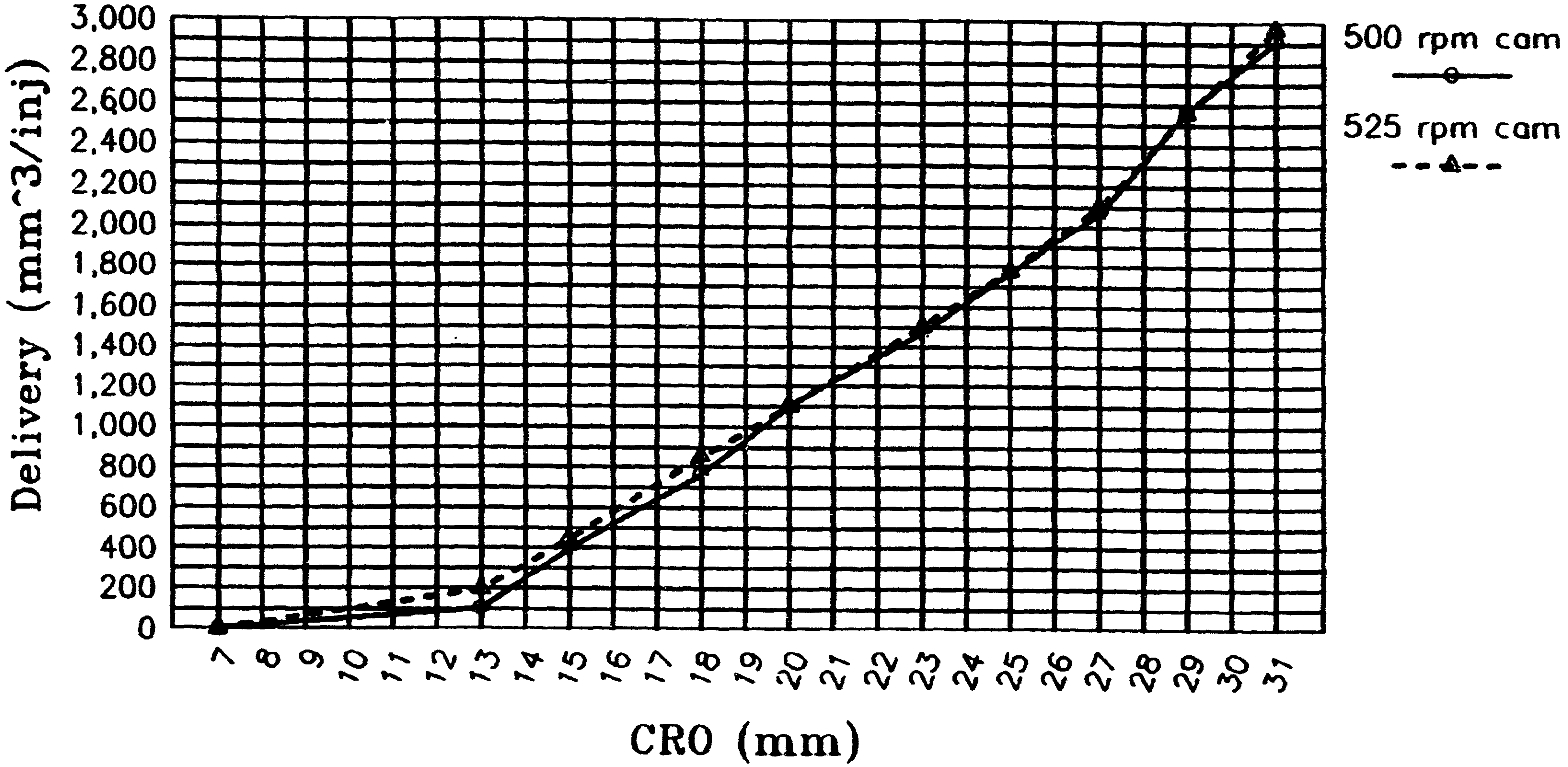
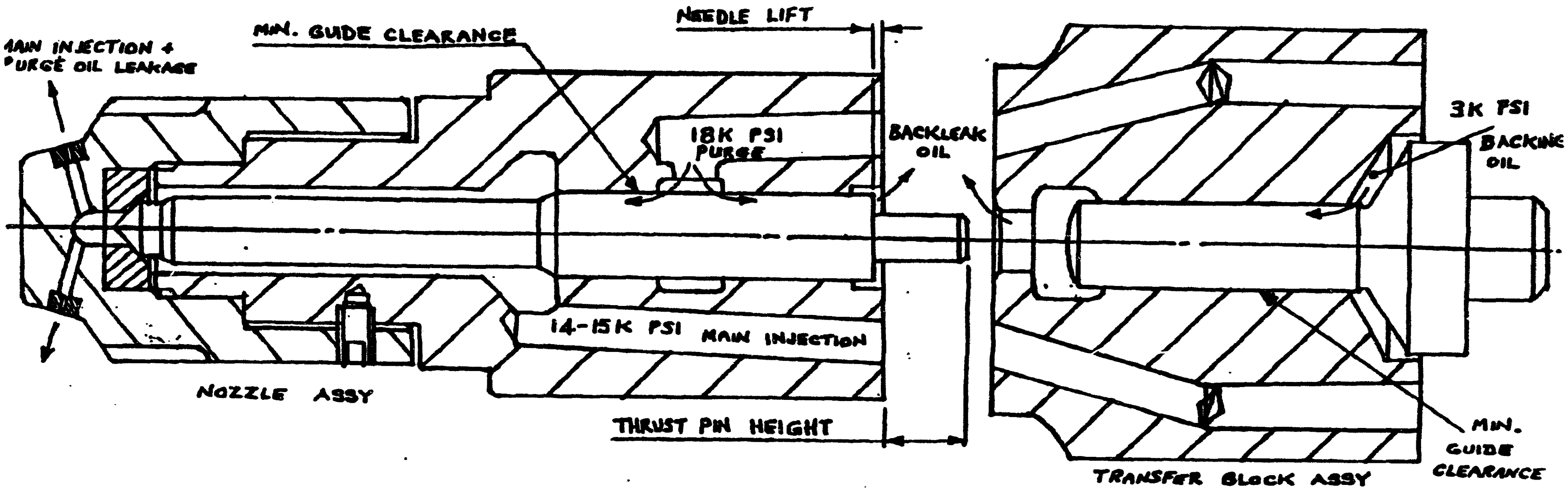


Figure 4 - Fuel delivery / CRO curve
(Steep Helix Element)
GH4 Injector

Injector 4976/4077
Fuel pump FCVAB240X0830
Test fluid Mobil DTE 26 (Inj'r only)



NOZZLE ASSEMBLY 4976/4082						
Ident.	Lift(m)	Thrust Pin Ht. (mm)	Min.Clearance (μm)	Needle Roundness (μm)	Body Bore Roundness (μm)	Flowrate L/Min#
A	0.39	8.02	4	0.4	0.5	7,27
B	0.40	7.80	3	0.3	1.0	7,56
C	0.42	8.08	4.5	0.3	0.5	7,70
D	0.40	8.88	5.5	0.2	0.4	7,10
E	0.42	8.08	3	0.3	1.2	7,60

Measurement Equipment:-
Nozzle bore - Air Gauge 19HB052/042 (Blue set)
Nozzle needle - S.O.D. Digital Micrometer NHL 1789

Transfer block bore - As above
Piston O/D - As above

Flowrate at 1000 lfb/in² feed/Castrol Cal. 'C'/40°C/Needle IN.
* Instrumented blocks

TRANSFER BLOCK - 4976/4079			
Ident.	Piston Dia (mm)	Bore Dia (mm)	Min.Clearance (μm)
A *	7.997	8.004	7
B *	7.997	8.004	7
C	8.016	8.019	3
D	8.000	8.010	10
E	8.018	8.020	2
F	8.028	8.031	3
G	8.016	8.019	3
H	8.026	8.029	3
I	8.027	8.029	2

Figure 5 - Clearances - Nozzle and Transfer Block Assemblies

Injector Ident.	Nozzle Ident ‡	Transfer Block Indent.	N.O.P. lbf/in^2 (Shim Set)	Injector Handtest Performance			Purge oil leak test (C.N-5, 21mm CRO)					
				Chatter Condition	Seat Leak Condition	Spray Condition	Volume Collected (Backleak) ML	Volume Supplied (Purge) ML	Test Time (mins)	Flow ML/Min: Total Back Leak	Flow ML/Min: Leak Thro' Nozzle	% N5 Fuel
GN 1 *	A	A	5000	Noses	Wet	Noses	1400	1650	25	66	10	1.7
GN 2 *	B	B	5000	Noses	Wet	Noses	1120	1610	32.5	49	15	2.5
GN 3	C	H	5050	Noses	Damp	Noses	1160	2340	22	106	54	9
GN 4	D	E	5000	Noses	Wet	Noses	1090	2440	20	122	67	11.2
GN 5	E	F	5000	Noses	Wet	Noses	1400	3360	25	134	78	13
GN 6	-	I	5 nozzle assemblies only available									
* Instrumented Units			No backing pressure	See 'Discussion'	NOP − 100 lbf/in^2 for 10secs -Check tip for oil		X	Y	t	$\frac{Y}{t}$	$\frac{Y-X}{t} = Z$	$\frac{Z}{600} \times 100\%$ ‡

Note - Purge oil (Castrol Cal. 'C') supplied at 14000-18000 lbf/in^2 from air-hydro unit (pulsing)

- Notch 5 = 1200 mm^3/inj @ 500 rpm cam = 600 ML/min ‡
- GN2 retained at Gloucester

Figure 6 - Injector Build Identification, N.O.P. Handtest, Purge oil leak test results

A. Backing Pressure v NOP

Backing Pressure (Mobil DTE 26) lbf/in^2	Nozzle Opening Pressure lbf/in^2
2500	8500
2600	8750
2700	9000
2800	9000
2900	9000
3000	9500
3100	9750
3200	9750
3300	10000
3400	10000
3500	10500
3700	10500

NOTE

Theoretically 3040 lbf/in^2 should produce 10000 lbf/in^2 NOP

B. High pressure static tests

Nozzle Nut Torque (ft-lbf)	CWS leak pressure lbf/in^2 *	Purge oil leak pressure lbf/in^2 *	Both passages pressurised
350	20000	-	GH1 unit
400	21500	21000	used
450	22000	22000	
500	22500	22000	

Note 1. Molybdenum paste to Moly-Panel GP50 spec. used on nozzle nut threads.
2. Final chosen torque for batch assembly - 500 ft-lbf.
3. Dummy nozzle SK14010 used.

Figure 7 - Backing Pressure v NOP and H.P. Test Results

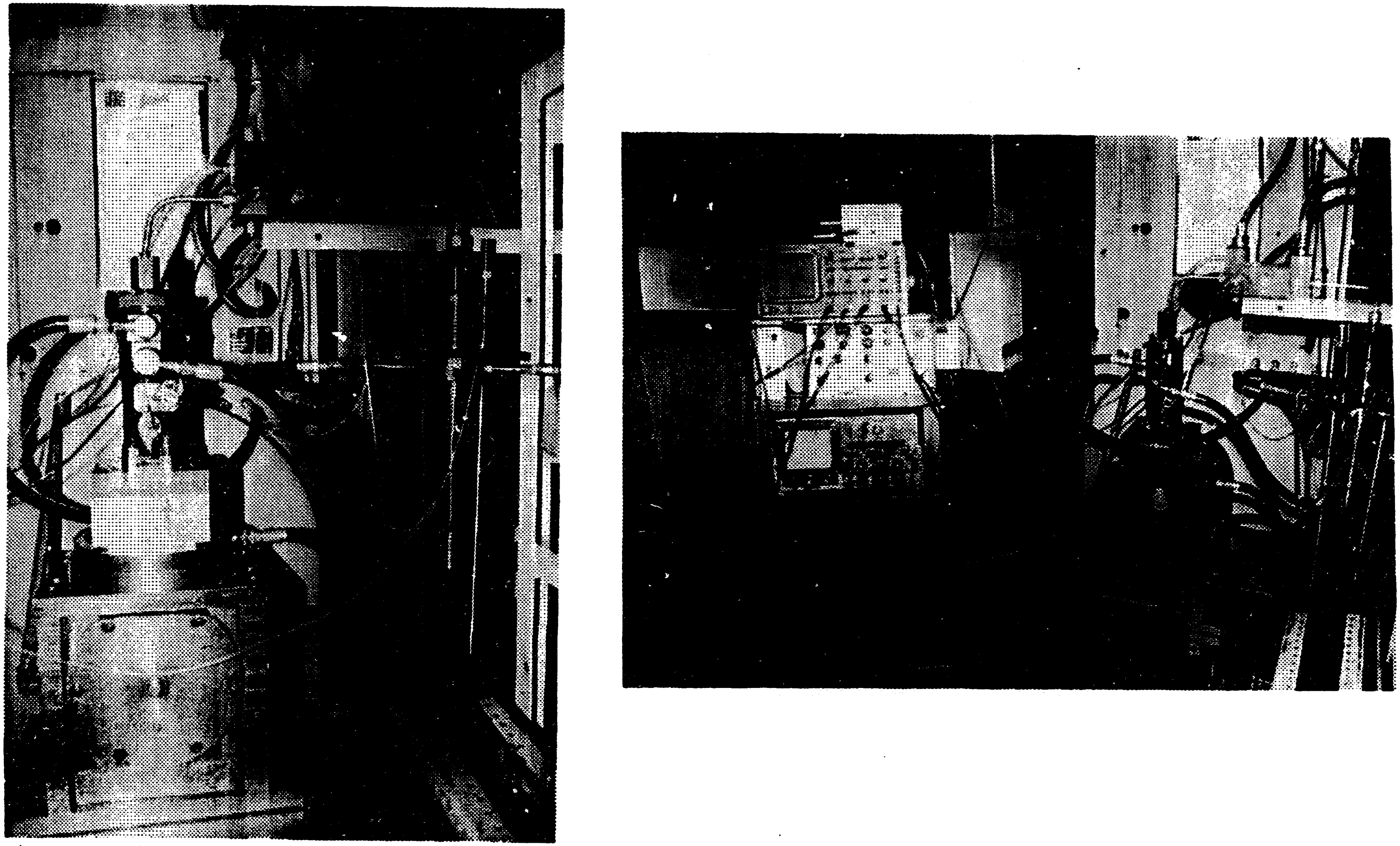


Figure 8 - System 2C - Test Stand Layout

Injector Ident.	CWS leak pressure (Purge unpressurised) lbf/in^2	CWS leak pressure (Purge pressurised) lbf/in^2	Purge oil leak pressure CWS
GH 1	23000	22500	22500
GH 2	22500	22000	22000
GH 3	23000	22500	20000
GH 4	23500	22000	23000
GH 5	23000	22000	20000
GH 6	23000	18000	20000

Figure 7 - <u>Backing pressure v NOP and H.P. test results - contd</u>

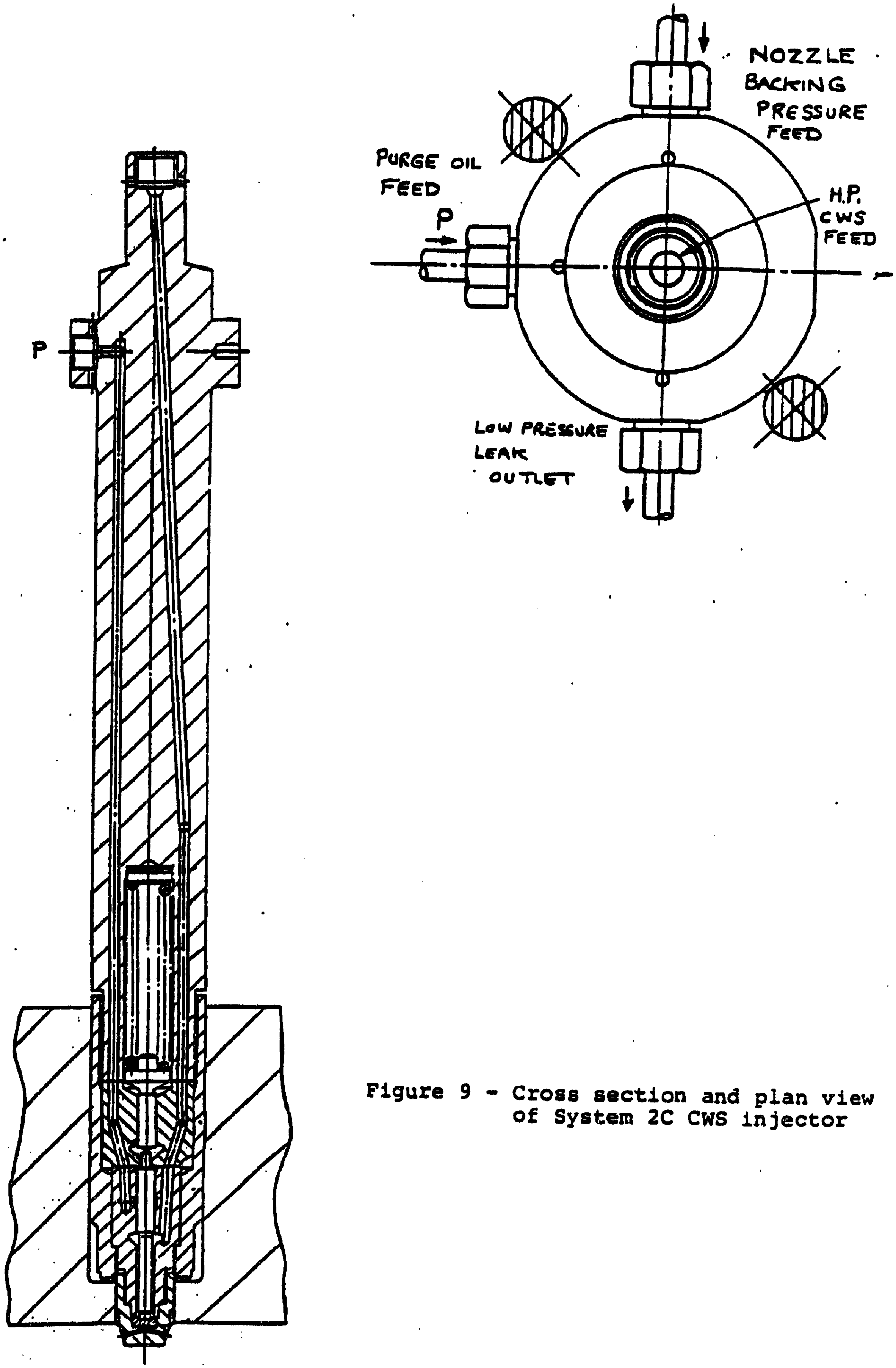


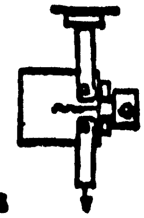
Figure 9 - Cross section and plan view of System 2C CWS injector

APPENDIX C

Coal Burning Wear Tests

(Materials Characterization Laboratory)

MATERIALS CHARACTERIZATION LABORATORY



Fracture Toughness

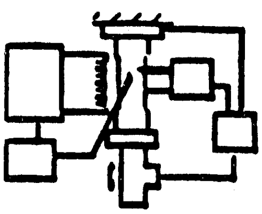
Friction and Wear

Title: COAL BURNING WEAR TESTS

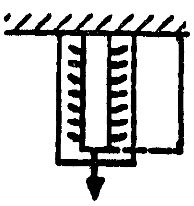
Author: R. F. Englehart, Technician
P. J. Tiberio, Manager

Report No.: 890627

Date: June 1989



Fatigue



Creep

704 CORPORATIONS PARK
SCOTIA, NEW YORK

INTRODUCTION

This test program was conducted for General Electric Corporate Research and Development Center under the direction of R. Johnson and R. Mehan. The objective of this project was to evaluate coatings and surface treatments for 13-8 and 17-4 PH steel to determine their wear properties at varying test conditions using the Faville LeValley Ring and Block Tester.

Early tests with bare 13-8 against 17-4 PH produced galling and wear at light loads resulting in the test program reported here.

CONCLUSIONS

1. A polished nitrided finish on both 13-8 and 17-4 PH gives the best test results. Polishing consisted of removing only the gray layer formed on the surface during nitriding with a 4/0 paper. The resulting surface finish was about 12 microinches.

2. A list of the coating combinations that gave improved wear resistance over bare 13-8 versus bare 17-4 PH is shown below with the best combinations at the top.

Nitrided 13-8 (polished)	vs.	Nitrided 17-4 PH (polished)
Nitrided 13-8	vs.	Nitrided 17-4 PH
Electroless nickel	vs.	Nitrided 17-4 PH
Nitrided 13-8	vs.	Hard chrome
Borided 13-8	vs.	Hard chrome

TEST EQUIPMENT AND PROCEDURES

All tests were conducted using the Falex Ring and Block Tester. A photograph of the tester is shown in Figure 1. The friction force is measured with a load cell and recorded on a strip chart recorder. Any measurable block wear was recorded on the strip chart using a LVDT on the load frame knife edge. Load is applied through a 30 to 1 load frame which is part of the test machine.

Tests were performed by oscillating the test ring through a 15° arc at 200 cycles per minute in a mineral oil bath at room temperature. The test pieces were cleaned with acetone and weighed before and after testing, and the surface was measured at this time.

The tests were started without load on the block. After running for 30 minutes with only a bail weight on the block, 2 pound weights (30# load) were added, one every 30 minutes until failure occurred or to a total load of 600 pounds. Failures were identified by erratic changes in the friction forces or LVDT signal indicating galling or severe wear.

Test sample combinations that reached maximum load were repeated to insure data reliability. Finally the most promising sample combinations were tested for 100 hours at 405 pounds load to determine their stability with time.

20/M378

Following each test the pieces were cleaned and weighed. The surface finish was measured unless the wear surface was galled. Surface finish measurements were made with a Taylor-Hobson Surtronic 3 instrument. Readings are in microinches, Ra (roughness average). The instrument was set at 0.03 in. cut-off and 0.180 stroke.

TEST RESULTS

The test results have been tabulated and are shown in Figure 2. The table shows the sample combinations, weight changes, surface finish and the maximum load and coefficient of friction.

The first sixteen tests were screening tests for all the material combinations. Tests #16-19 were repeat tests of the most promising combinations. Tests #20-22 were time extended tests run for 100 hours at a load of 405 pounds. All other test parameters were unchanged.

Figure 3 shows a bar graph of the first 19 tests indicating the highest load before failure occurred, a load of 600 pounds represents the maximum load available on this test apparatus. Figure 4 shows the coefficient of friction versus applied load for the first 16 tests. Test sample combinations that maintained a constant coefficient throughout the loading process were considered good material combinations.

Figures 5 and 6 are micrographs of four tested coatings showing the thickness and giving the coating hardness measurements. In all cases, the samples were coated with nickel for edge preservation during processing. This analysis was performed at GE CR&D by R. Mehan and is attached.

Figure 7 shows the results of the long term (100 hour) tests. Nitrided versus Nitrided has the lowest coefficient of friction while the polished pieces had a narrower wear scar.

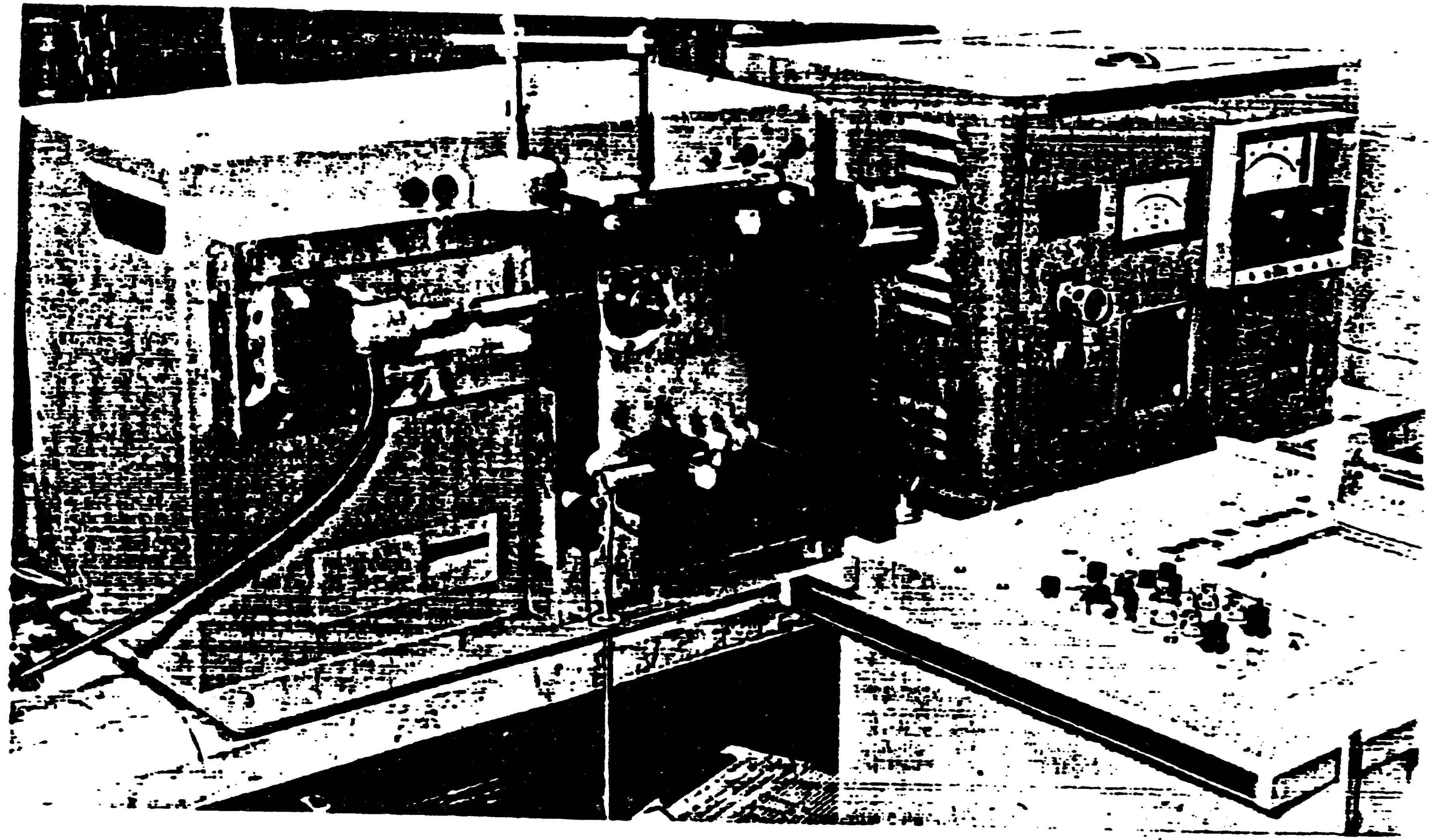
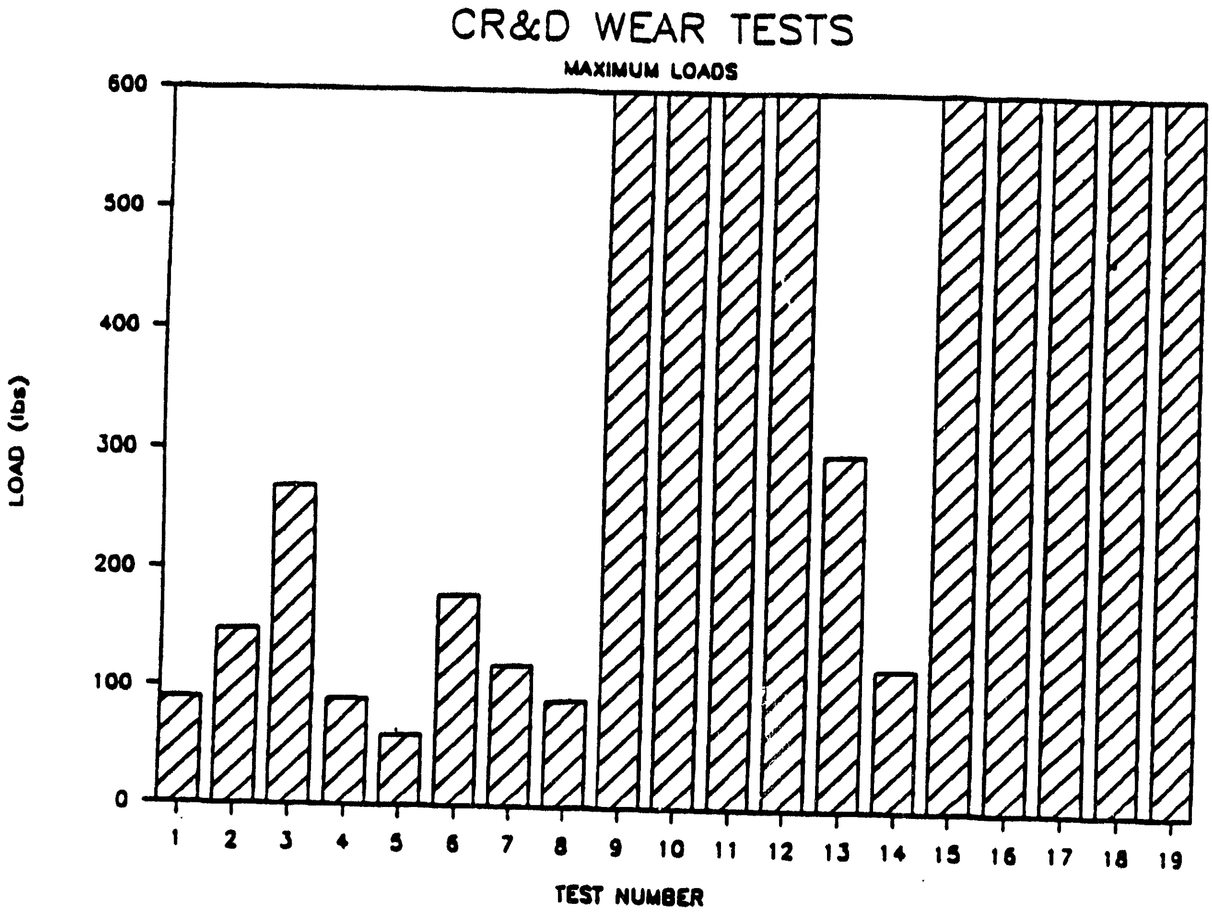


Fig. 1 ● 1214 736 LFW-1 FRICTION AND WEAR TESTING MACHINE AT LEFT, CONTROL CONSOLE AT UPPER RIGHT, RECORDING INSTRUMENTATION AT LOWER RIGHT.
E369.4 E353.2



Test No.	Ring (13-8)	Block (17-4) PH
1	bare	bare
2	bare	bare
3	bare	bare
4	bare	bare
5	bare	Hard chrome
6	Elect. nickel	Hard chrome
7	Elect. nickel	Ti Nitride
8	Elect. nickel	Ti Nitride
9	Nitrided	Hard chrome
10	Elect. nickel	Nitrided
11	Borided	Hard chrome
12	Elect. nickel	Borided
13	Elect. nickel	Borided
14	bare	Nitrided
15	Nitrided	bare
16	Nitrided	Nitrided
17	Nitrided	Hard chrome
18	Elect. nickel	Nitrided
19	Nitrided	Hard chrome

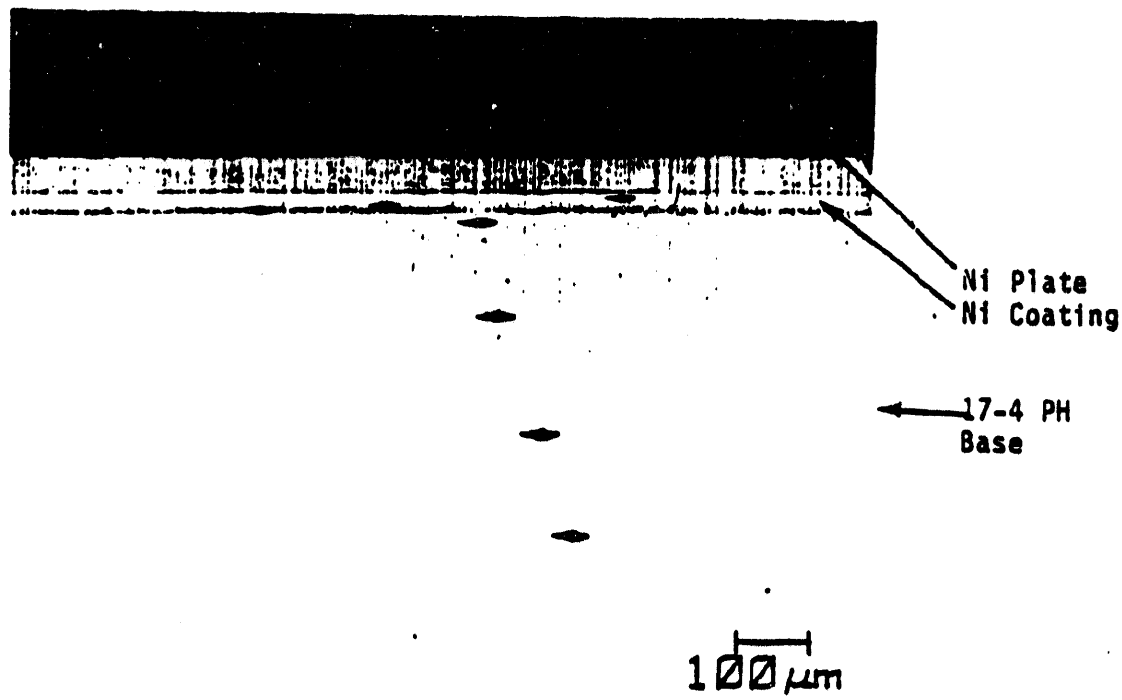
20/M378

SUMMARY SHEET

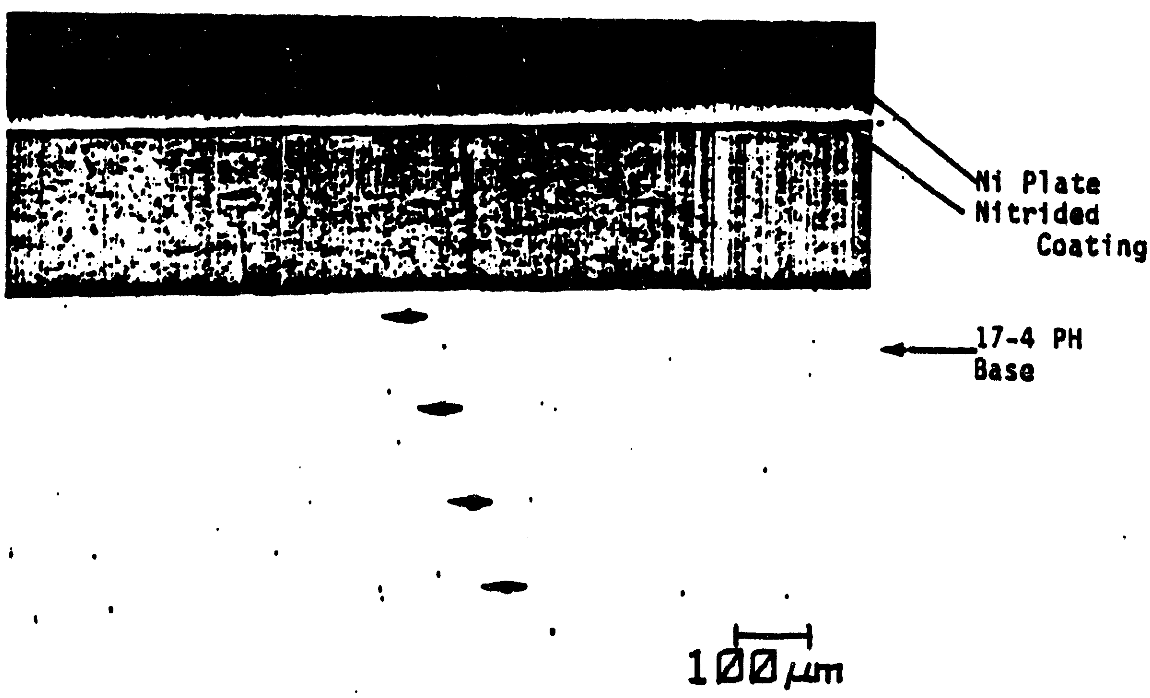
Test #	Ring Material	Block Material	Ring Weight Change	Block Weight Change	Ring Surface Finish Before	Ring Surface Finish After	Block Surface Finish Before	Block Surface Finish After	Max. Load	Max. Friction Coeff.	Comments
1	13-8 HT bare	17-4 PH bare	-.0006	-.0002	6	78	11	98	90	.40	Both ring & block deeply galled
2	13-8 HT bare	17-4 PH bare	+.0006	-.0013	6		18		150	.54	Ring & block galled
3	13-8 HT bare	17-4 PH bare	+.0003	-.0010	6		17		270	.352	Ring & block galled
4	13-8 HT bare	17-4 PH bare	-	-	6		14		90	.37	Ring & block galled
5	13-8 HT bare	Hard chrome	+.0010	+.0004	6		16		60	.30	Ring & block galled
6	Elect. nickel	Hard chrome	-.0068	-	16		16		180	.25	Ring & block galled
7	Elect. nickel	TiNi	-.0016	-	23		12		120	.35	Ring & block galled
8	Elect. nickel	TiNi	-.0005	-	26		13		90	.267	Ring & block galled
9	Nitrided 13-8	Hard chrome	-.0022	+.0002	35		19		600	.101	Final coeff. = .100 w/s 37-47 mils
10	Elect. nickel	Nitrided 17-4 PH	-.0044	-.0015	14	42	25	31	600	.121	Final coeff. = .122 w/s 68-74 mils
11	Borided nickel	Hard chrome	+.0008	-	23	18	37	40	600	.109	Final coeff. = .099
12	Elect. nickel	Borided 17-4 PH	-.0016	-.0001	22	52	24	47	600	.245	Final coeff. = .113

SUMMARY SHEET

Test #	Ring Material	Block Material	Ring Weight Change	Block Weight Change	Ring Surface Finish Before	Ring Surface Finish After	Block Surface Finish Before	Block Surface Finish After	Max. Load	Max. Friction Coeff.	Comments
13	Elect. nickel	Borided 17-4 PH	-.0001	-.0002	24	43	14	39	300	.22	Ring & Block galled
14	13-8 HT bare	Nitrided 17-4 PH	+.0006	+.0002	12	25	37	33	120	.233	Ring & Block galled
15	Nitrided 13-8	17-4 PH bare	-.0145	-	38	81	25	39	600	.113	Final coeff. = .105
16	Nitrided 13-8	Nitrided 17-4 PH	-.0056	.0006	33	15	23	22	600	.102	Final coeff. = .098 w/s 55-77 mils
17	Nitrided 13-8	Hard Cr Elect. 17-4 PH	-.0011	-	33	19	25	34	600	.103	Final coeff. = .103
18	Elect. Nickel 13-8	Nitrided 17-4 PH	-.0005	+.0002	32	21	18	26	600	.115	Final coeff. = .112
19	Nitrided 13-8	Hard Cr (fountain plating) 17-4 PH	-.0022	-.0006	34	20	17	20	600	.108	Final coeff. = .107
20	Elect. Nickel 13-8	Nitrided 17-4 PH	-.0047	-.0002	18	46	29	36	405	.136	Final coeff. = .123 w/s 76 mils, 100 hrs
21	Nitrided 13-8	Nitrided 17-4 PH	-.0027	-.0003	32	55	34	52	405	.097	Final coeff. = .081 w/s 68 mils, 100 hrs
22	Nitrided 13-8 polished	Nitrided 17-4 PH polished	-.0249	+.0001	12	18	11	15	405	.109	Final coeff. = .086 w/s 40 mils, 108 hrs

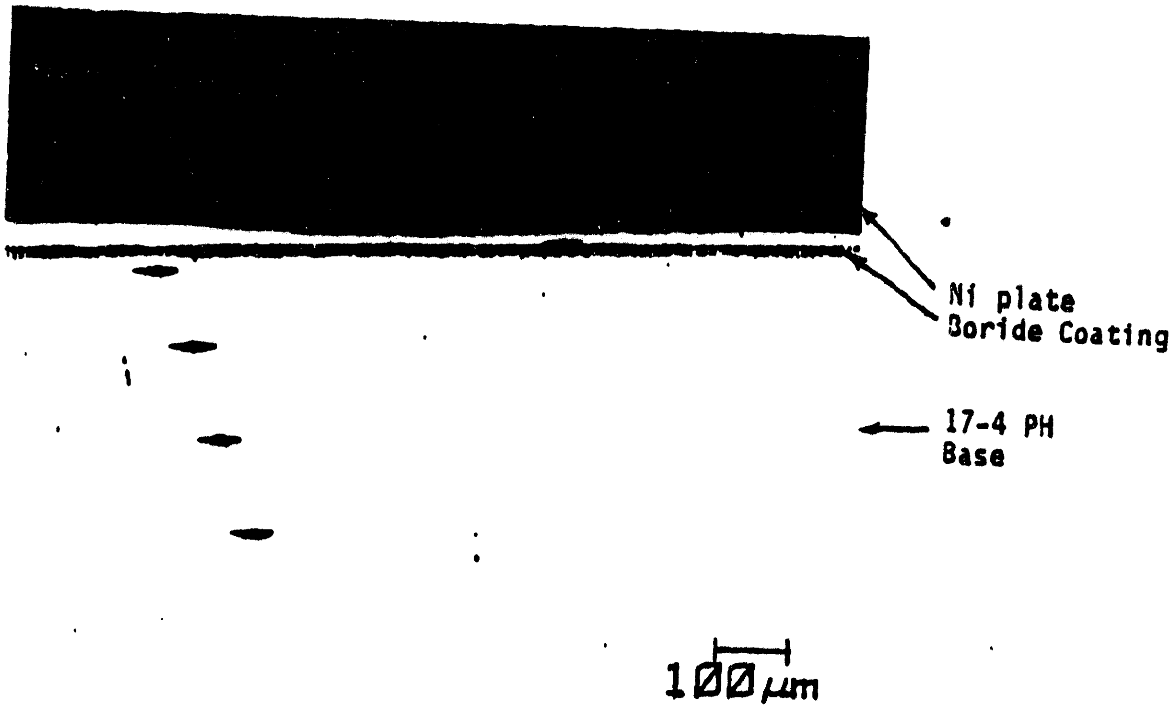


Nickel Plated - 100X
Hardness 818 Kg/mm^2

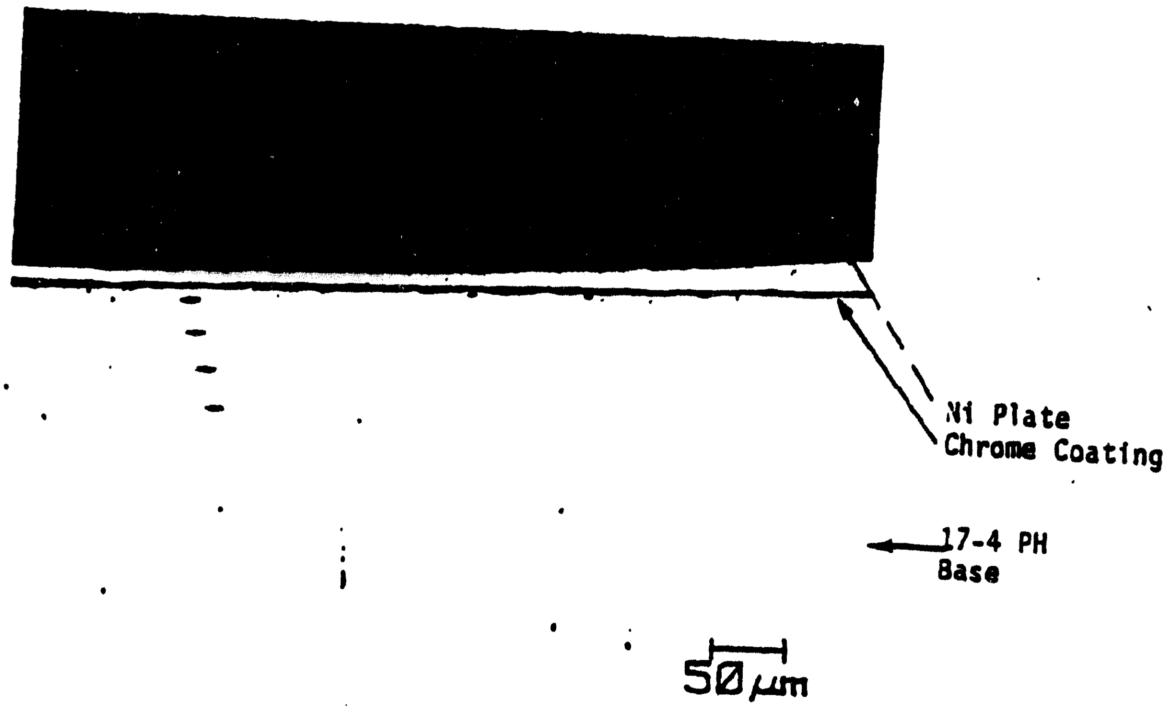


Nitrided 17-4 PH - 100X
Hardness 840 Kg/mm^2

Figure 5



Borided 17-4 PH - 100X
Hardness 1370 Kg/mm^2



Chrome Plate - 200X
Hardness 504 Kg/mm^2

Figure 6

COEFFICIENT OF FRICTION

Load	Test No. 1	2	3	4	5	6	7	8
19.5	.051	.051	.051	.051	.1	.051	.051	.051
30	.1	.083	.1	.1	.13	.1	.1	.083
60	.1	.1	.1	.1	.3	.117	.1	.117
90	.4	.094	.094	.37		.178	.144	.267
120		.1	.1			.192	.35	
150		.54	.1			.213		
180			.103			.25		
210			.105					
240			.106					
270			.352					

Load	Test No. 9	10	11	12	13	14	15	16	17	18	19
19.5	.051	.051	.051	.051	.026	.026	.026	.051	.051	.026	.051
60	.092	.1	.09		.1	.090	.1	.092	.083	.083	.092
120	.1	.1		.103	.108	.233	.108	.096	.092	.096	.1
180	.097	.109	.105		.111		.105	.1	.094	.094	.1
240	.1	.11		.12	.131		.108	.1	.096	.106	.1
300	.1	.116	.106		.22		.113	.1	.095	.1.	.1
360	.101	.113		.118			.11	.1	.097	.104	.1
420	.099	.117	.109				.11	.1	.096	.105	.105
480	.1	.115		.11			.109	.1	.1	.106	.106
540	.1	.12	.101				.106	.102	.101	.113	.106
600	.1	.122	.099	.113			.105	.098	.103	.112	.107

COAL BURNING WEAR TESTS
Supplemental Report

RF Englehart, PJ Tiberio

MCL890627, supplement
July 1992

INTRODUCTION

This report will serve to document three tests that were conducted after the data from project 89022 had been reported by MCL in report #890627. This test program was conducted for GE CR&D under the direction of R. Johnson and R. Mehan. The objective of this project was to evaluate coatings and surface treatments for 13-8 and 17-4 PH stainless steel to determine their wear properties at varying test conditions using the Faville LeValley Ring and Block Tester.

CONCLUSIONS

1. A polished gas nitrided finish on both 13-8 and 17-4 PH gives the best test results. Polishing consisted of removing only the gray layer formed on the surface during nitriding with a 4/0 paper. The resulting surface finish was as 12 μinches.

2. A list of the coating combinations that gave improved wear resistance over bare 13-8 versus bare 17-4 PH is shown below with the best combination at the top.

Nitrided 13-8 (polished)	vs.	Nitrided 17-4 PH (polished)
Nitrided 13-8	vs.	Nitrided 17-4 PH
Electroless nickel	vs.	Nitrided 17-4 PH
Nitrided 13-8	vs.	Hard chrome
Borided 13-8	vs.	Hard chrome

TEST EQUIPMENT AND PROCEDURES

All tests were conducted using the Falex Ring and Block Tester. A photograph of the tester is shown in Figure 1. The friction force is measured with a load cell and recorded on a strip chart recorder. Load is applied through a 30 to 1 load frame which is part of the test machine.

Tests were performed by oscillating the test ring through a 15° arc at 200 cycles per minute in a mineral oil bath at room temperature. The test pieces were cleaned with acetone and weighed before and after testing, and the surface was measured at this time.

The tests were started without load on the block. After running for 30 minutes with only a bail weight on the block, 2 pound weights (60# load) were added, one every 30 minutes until failure occurred or to a total load of 600 pounds. Failures were identified by erratic changes in the friction forces.

TEST RESULTS

Table 1 is a summary sheet of the data from the three tests. Coefficient of friction measurements are shown in Table 2 as in the earlier report.

R.F. Englehart

RF Englehart,
Specialist

Phillip J. Tiberio

Phillip J. Tiberio,
Mgr. Friction & Wear Div.

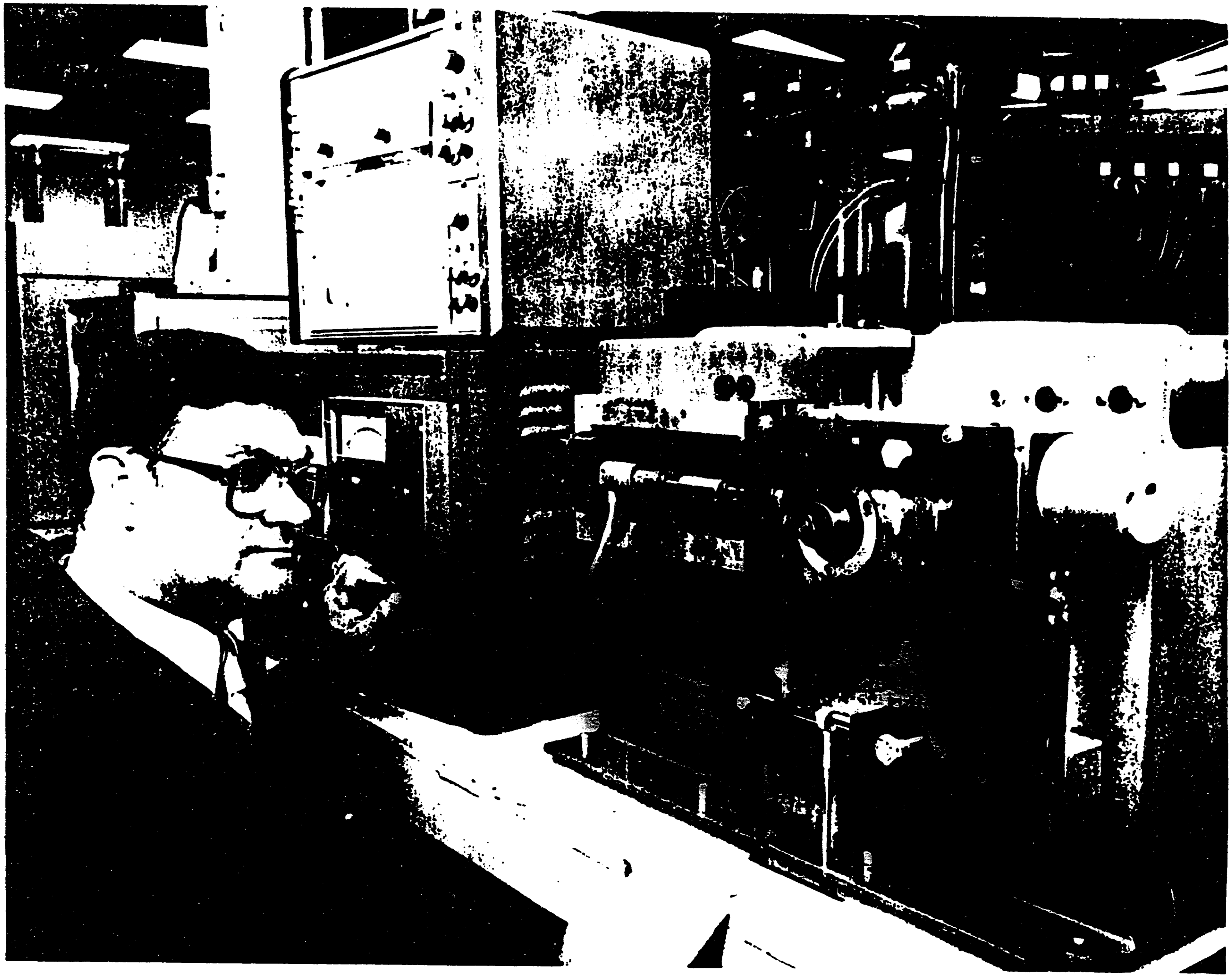
Table 1

Test No.	Ring Material	Block Material	Lube	Max. Coeff.	Max. Load	Comments
23	13-8/Poeton	17-4PH Nit. polished	Min. oil	0.113	300#	Galled - ran 14 minutes at 300 lbs. Coeff. @ failure 0.333. Step load - ½ hr.
24	Elect. Ni.	17-4PH Nit.	Min. oil	0.108	600#	w/s = 0.032". Final coeff. = 0.093. Step load - ½ hr.
25	13-8/Poeton	17-4PH Nit. polished	Min. oil	0.102	240#	Galled - ran 5 min. at 240#. Coeff. @ failure 0.35. Step load - ½ hr.

Test No.	Ring Weight Change	Block Weight Change	Ring Surface Finish		Block Surface Finish	
			Before	After	Before	After
23	-.0023g	-.0016g	32	-	10	-
24	+.0004g	-.0010g	9-12	12	19	8-10
25	-.0013g	-.0002g	30	-	10	-

Table 2

Load Lbs.	Test No. 23	24	25
30	.100	.080	.083
60	.100	.100	.100
120	.117	.094	.092
180	.111	.089	.094
240	.110	.096	.102
300	.113	.093	-
360	-	.097	-
420	-	.098	-
480	-	.096	-
540	-	.094	-
600	-	.093	-



FALEX RING & BLOCK WEAR TESTER

Figure 1

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FILMED
6/16/94

END