ENGINE REBUILD REPORT

Motor Vessel Columbia

for

State of Alaska
Division of Marine Transportation
Department of Public Works

by

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INTRODUCTION

The engines of the Motor Vessel Columbia were examined in late January, 1981 and a preliminary report describing their condition was prepared. (1)

The present report is the continuation of the earlier work and describes the condition of the engines during rebuilding through March, 1981.

Assessment of the initial data, tests performed, and conclusions drawn are the content of this report.

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I

ENGINE BLOCKS

The Enterprise engine has 16 cylinders in a V (vee) configuration with two separate 8-cylinder blocks bolted to the base. Individual cylinder liners are held in place by the clamping force of the head installation and are sealed at the bottom with multiple o-ring seals. The top of the liner is held in the block with a lip (.250 x 1.5 inch) that is clamped by the head. The block is counterbored to accept this lip.

A major concern of engine block examination was the deformation in the counterbore and the landing surface for the liner lip when compared to the original or design dimensions. Data recorded during December, 1980 and shown in Tables 1 to 4 (pp. I-2 to I-5) indicated the need for an in-depth look at the blocks. Also, one of the tie-bolts holding the blocks to the base had broken on ~~December~~ Sept 26, 1980. Upon replacement, all the tie-bolts had simply been retorqued to factory levels and a record kept of when the nuts had broken free. (2)

The areas of the engine block examined, measured, and reported in this section are the following: 1) the diameters of the bore and counterbore, 2) the counterbore lip holding the cylinder liner, and 3) the torque levels of the bolts holding the blocks to the base.

Bore and Counterbore Diameters

The firing surface of the block and bore and counterbore dimensions are shown in Figure 1 (p. I-6). The corresponding dimensions for the cylinder liners are shown in Figure 2 (p. I-7). Measurements of the diameter of the bore of the blocks were taken at perpendicular directions to show the degree to which the openings had deformed, symmetrically and non-symmetrically. These values are plotted in Figure 3 (p. I-8) for both main engines.

The 3-9 o'clock direction shown in Figure 3 is in the longitudinal

Table 1. Port Main Engine, M/V Columbia

Cyl	Pos	Crush	Counter-bore Depth	Liner Flange Thick	Counter-bore ID	Liner Fl. OD	Block ID	Liner OD	12-78 Crush	12-78 Workbook
1	12	.003	1.5055	1.506	19.523	19.494	19.008	18.995		
	3	.0022	1.505	1.506	19.516	19.494	19.008	18.994		.0055
	6	.002	1.505	1.506						
	9	.0013	1.504	1.503						
2	12	.005	1.5055	1.505	19.522	19.504	19.009	18.997		
	3	.0035	1.504	1.504	19.514	19.495	19.006	18.997		
	6	.003	1.504	1.507					.006	.0055
	9	.0025	1.504	1.505						
3	12	.006	1.513	1.506	19.522	19.499	19.010		.0059	
	3	.006	1.513	1.505	19.514	19.497	19.004		.0059	.0025
	6	.005	1.515	1.505					.0025	.006
	9	.006	1.514	1.505					.0025	
4	12	.003	1.503	1.505	19.518	19.497	19.010	18.998	.0053	
	3	.0045	1.5035	1.505	19.509	19.490	19.002	18.995	.0095	.005
	6	.002	1.5045	1.506					.006	.009
	9	.0035	1.503	1.504					.007	
5	12	.003	1.504	1.504	19.524	19.495	19.012	18.997	.0075	
	3	.0027	1.5035	1.503	19.511	19.494	19.003	18.996	.005	.005
	6	.002	1.5035	1.5035					.006	.0080
	9	.0023	1.504	1.504					.0075	
6	12	.0025	1.504	1.507	19.525	19.497	19.011	18.995	.0075	
	3	.0025	1.505	1.503	19.512	19.496	19.008	18.991	.0072	.005
	6	.002	1.5045	1.506					.005	.008
	9	.0027	1.505	1.506					.008	
7	12	.002	1.503	1.506	19.522	19.495	19.008	18.998	.007	.006
	3	.0017	1.5045	1.505	19.515	19.494	19.005	18.997	.008	.0085
	6	.002	1.505	1.506					.007	
	9	.0017	1.5055	1.507					.0075	
8	12	.001	1.505	1.504	19.521	19.494	19.008	18.997	.004	.0035
	3	.0015	1.505	1.504	19.514	19.493	19.006	18.994	.0105	.0105
	6	.001	1.5055	1.504					.007	
	9	.001	1.506	1.505					.005	

Table 2. Port Main Engine, M/V Columbia

Cyl	Pos	Crush	Counter-bore Depth	Liner Flange Thick	Counter-bore ID	Liner Fl. OD	Block ID	Liner OD	Crush	12-78 Workbook
9	12	.004	1.505	1.505	19.520	19.494	19.006	18.997		
	3	.0027	1.504	1.505	19.516	19.495	19.005	18.997		.003
	[illegible]	.003	1.504	1.505						.0035
	9	.0017	1.504	1.505						
10	12	.0025	1.503	1.505	19.520	19.495	19.008	18.998	.005	
	3	.0028	1.502	1.505	19.516	19.494	19.005	18.996		.005
	6	.0025	1.5025	1.503					.0065	.008
	9	.0025	1.5025	1.503						
11	12	.005	1.5035	1.504	19.523	19.498	19.009	18.997	.005	
	3	.0037	1.5055	1.504	19.512	19.497	19.004	18.998	.006	.0035
	6	-.001	1.509	1.504					.0065	.0065
	9	.000	1.506	1.505					.006	
12	12	-.001	1.503	1.505	19.528	19.495	19.013	18.997	.006	
	3	-.0025	1.503	1.505	19.512	19.496	19.002	18.997	.0055	.0055
	6	-.002	1.502	1.505					.0055	.007
	9	-.0018	1.504	1.505					.0055	
13	12	-.001	1.5065	1.502	19.526	19.493	19.012	18.997	.005	
	3	-.0007	1.507	1.503	19.512	19.493	19.003	18.997	.005	.004
	6	-.002	1.505	1.502					.0075	.008
	9	.0007	1.505	1.503					.0071	
14	12	.002	1.505	1.505	19.525	19.495	19.010	18.999	.0055	
	3	.0015	1.507	1.505	19.515	19.493	19.004	18.997		.004
	6	.001	1.505	1.505					.004	.0065
	9	.001	1.507	1.505					.004	
15	12	.002	1.505	1.505	9.523	19.495	19.010	18.998	.005	
	3	.0025	1.504	1.505	19.515	19.494	19.005	18.997	.0055	.004
	6	.002	1.505	1.505					.004	.005
	9	.0022	1.505	1.505					.0042	
16	12	.002	1.505	1.507	19.525	19.496	19.011	18.999	.005	
	3	.0017	1.505	1.506	19.516	19.494	19.005	18.997	.006	.0045
	6	.001	1.507	1.506					.006	.006
	9	.002	1.507	1.506					.0095	

Table 3. Starboard Main Engine, M/V Columbia

Cyl	Pos	Crush	Counter-bore Depth	Liner Flange Thick	Counter-bore ID	Liner Fl. OD	Block ID	Liner OD	Crush	12-78 Workbook
1	12	.005	1.502	1.505	19.520	19.499	19.007	19.001		
	3	.0045	.504	.503	.517	19.497	.008	18.995		
	6	.004	.501	.506					.009	.007
	9	.0045	.502	.504						
2	12	.005	1.503	1.504	19.522	19.501	19.009	18.997		
	3	.0035	.500	.504	.514	19.500	.002	18.995		
	6	.003	.504	.504					.018	.0055
	9	.0045	.504	.504						
3	12	.004	1.503	1.505	19.526		19.010			
	3	.004	.503	.504	.513		.003	18.996		
	6	.004	.503	.506					.006	.007
	9	.004	.504	.505						
4	12	.004	1.504	1.506	19.525		19.012	18.997		
	3	.0035	.502	.506	.510			18.996		
	6	.004	.503	.507			19.001		.006	.0055
	9	.004	.503	.506						
5	12	.004	1.503	1.504	19.520	19.509	19.011	19.006		
	3	.005	.503	.503	.509		.002			
	6	.004	.501	.504					.021	.045
	9	.006	.504	.506						
6	12	.006	1.501	1.506	19.522	19.498	19.009	19.001		
	3	.005	.501	.506	.512	19.443	.003	18.995		
	6	.005	.501	.505					.008	.0065
	9	.006	.502	.506						
7	12	.006	1.503	1.506	19.521	19.496	19.009	19.000		
	3	.005	.501	.506	.514	19.496	.004	18.999		
	6	.006	.502	.506					.001	.005
	9	.0055	.503	.506						
8	12	.006	1.503	1.507	19.519	19.500	19.008	19.002		
	3	.006	.501	.503	.516	19.492	.006	18.992		
	6	.005	.503	.506					.009	.0055
	9	.0055	.503	.506						

Table 4. Starboard Main Engine, M/V Columbia

Cyl	Pos	Crush	Counter-bore Depth	Liner Flange Thick	Counter-bore ID	Liner Fl. OD	Block ID	Liner OD	Crush	12-78 Workbook
9	12	.009	1.504	1.506	19.519		19.006			
	3	.0075	.502	.506	.516		.006			
	6	.010	.503	.507						.006
	9	.0095	.502						.0025	.0800
10	12	.005	1.502	1.506	19.523		19.009			
	3	.005	.503	.505	.515		.004	18.999		
	6	.006	.504						.006	.005
	9	.005	.503							
11	12	.005	1.503	1.506	19.528		19.011			
	3	.0045	.503	.506	.513		.001			
	6	.003	.505						.007	.0055
	9	.0035	.502							
12	12	.004	1.503	1.505	19.526		19.015			
	3	.005	.504	.505	.511		.003			
	6	.004	.505						.005	.0055
	9	.004	.504	.506						
13	12	.004	1.503	1.506	19.526		19.012			
	3	.004	.502	.505	.516		.002			
	6	.004	.503	.506					.009	.0045
	9	.004	.502	.505						
14	12	.004	1.503	1.506	19.528		19.009			
	3	.0045	.502	1.504	.516		.001			
	6	.004	.504						.006	.0045
	9	.003	.502	.506						
15	12	.004	1.503		19.524		19.009			
	3	.004	.502		.515		.006			
	6	.004	.503						.005	.005
	9	.0035	.500	.504						
16	13	.005	1.504	1.504	19.523		19.007			
	3	.0035	.502	.504	.524		.006			
	6	.003	.503	.504					.004	.004
	9	.0035	.503	.503						

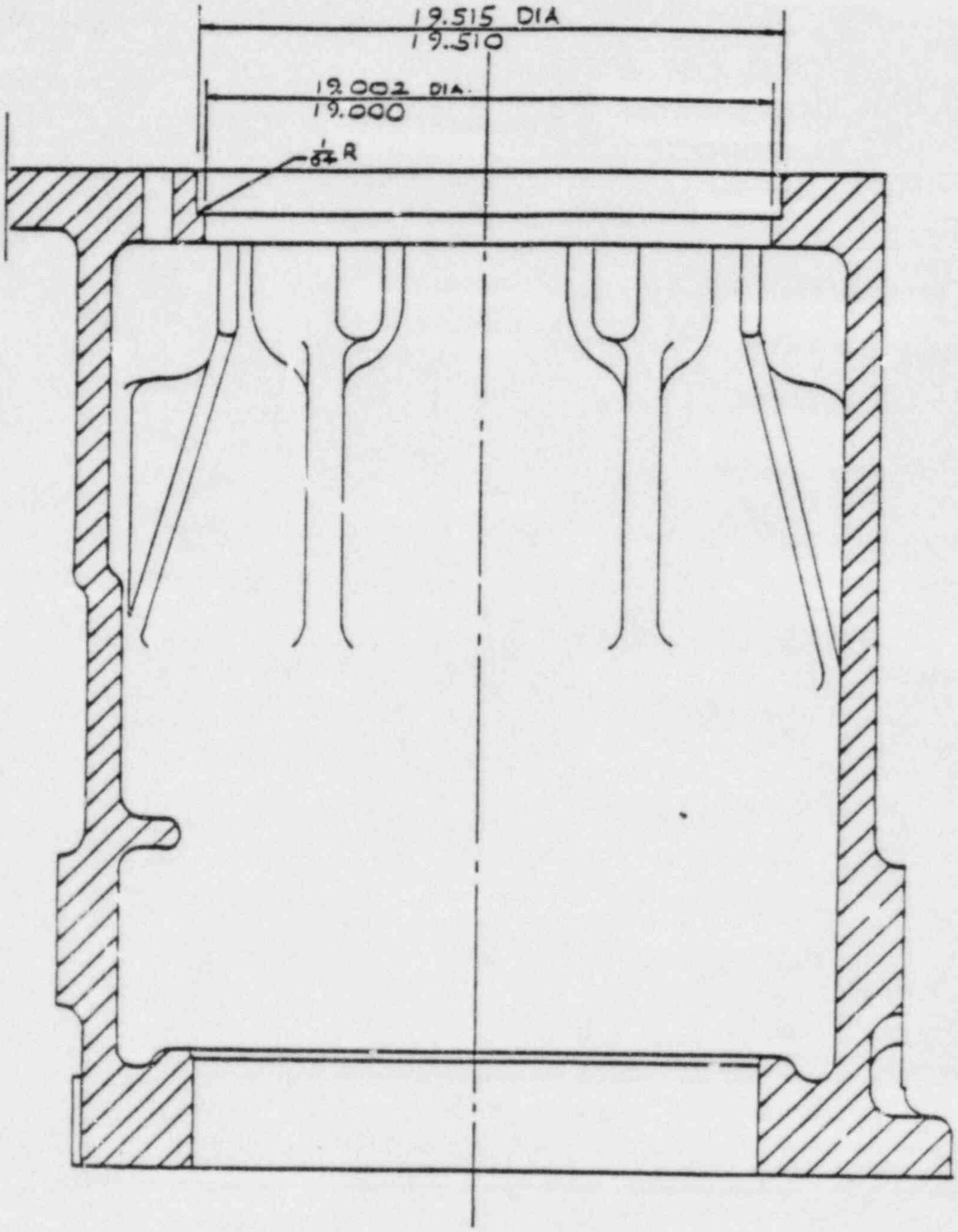


Figure 1. Cylinder Configuration, Engine Block

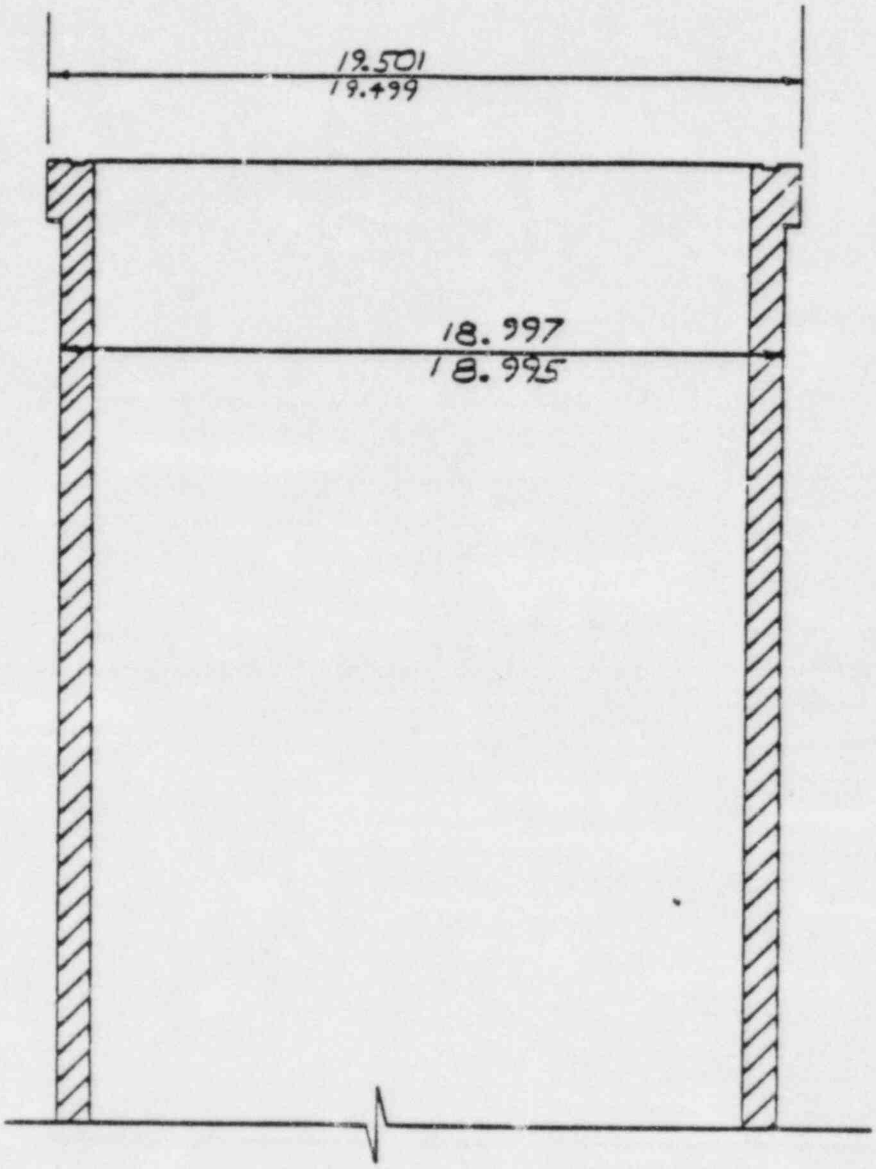


Figure 2. Upper Cylinder Liner

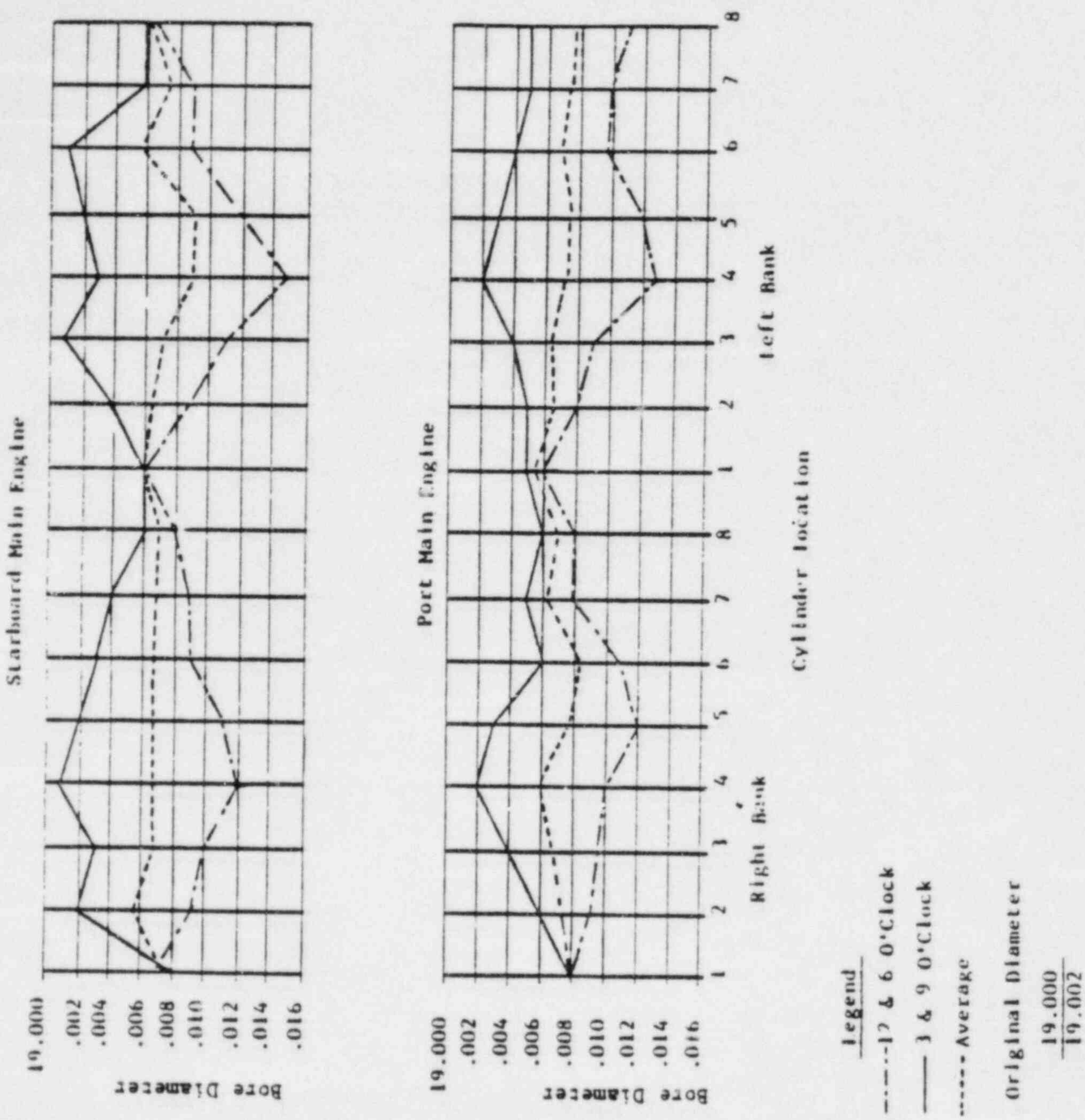


Figure 3. Bore Diameter, Engine Blocks, M/V Columbia, December 19, 1980

direction of the block and the 6 - 12 o'clock direction is perpendicular to this. These directions are as if one is standing beside the engine to view the dimensions.

Figure 3 data show a gradual increase in all cylinder diameters and a pattern of non-symmetrical change similar for all four blocks. All the bore diameters have grown uniformly between .006 and .007 inch over the lifetime of the engine. This increase indicates an interstitial flow within the metallic structure of the block that has allowed a permanent change in dimensions.

Interstitial flow is an effect of creep whereby metal changes slowly in dimension in response to a stress below the yield point. Effects of creep occur under several conditions. The conditions present in the Enterprise engine are increased temperatures associated with operating stresses to produce a permanent strain on the interior surface of the block bore. Although the strain for uniform deformation--368 micro-inches corresponding to a stress of 11,000 psi--is within acceptable limits for the cast iron material of the block, when combined with other deformations, its effects contribute to specific forms of metallic failure. TDI 1

In additi n to the uniform increase in all bore diameters, there is a pattern of non-uniform deformation. While the cylinders at the ends of the blocks remain essentially circular the cylinders at the center show a gradual change to a maximum ovalness of .012 to .015 inch. This ovalness is a result of dimensional changes beyond the uniform increase in diameter to which all the cylinders are subject. It indicates that the structural webs between the cylinders are subject to the effects of creep.

Because the center webs are heated during operation while the outer portion of the end cylinders remain at room temperature, the effects of creep will be seen more in the hotter than in the cooler regions. Creep has produced a maximum of approximately 1,000 micro-inch of strain with a corresponding stress TDI 2 of 30,000 psi. A visual concept of this is to imagine adding an external clamp applied to the blocks to produce an equal but opposite stress on the engine in order to restore the cylinders to their circular shape.

Both uniform diameter increase and ovalness have resulted from metallic creep. Because the combined stresses (41,000 psi) are well above design limits for cast iron, metallic failure was expected in the intercylinder web areas and around the cylinder circumferences where the proximity of holes for cooling water and studs produce stress concentrations. Metallic failure was found and is discussed in Section V, Nondestructive Testing.

Counterbore Lip

The second major concern was the block's counterbore lip which holds the cylinder liner. Excessively high stress due to liner clamping had caused metallic failure. The bore of the block is nominally 19.000 inches and the counterbore, 19.500 inches. The counterbore lip, with a width of .250 inch, must resist the force from prestressing the cylinder head studs. When the total force generated by the studs is calculated, the compressive stress on the counterbore lip is in excess of 76,000 psi. This value assumes the following: 1) the threads are well lubricated, 2) all forces are uniformly distributed, and 3) no out-of-trueness or other artifacts are present to increase this value. Because compressive stress occurred at an inside corner under tension, the corner was a prime area for inspection for metallic failure.

Additional stress on the counterbore lip was caused by the near presence of the termination of threads for the cylinder head studs as shown in Figure 4 (p. I-11). Both counterbore depth and the beginning of the threads in the block are 1.500 inches below the block surface leaving only a .625 inch space between the two. Because this space experiences extremely high stress concentration it was examined for the possibility of metal failure. Various types were found.

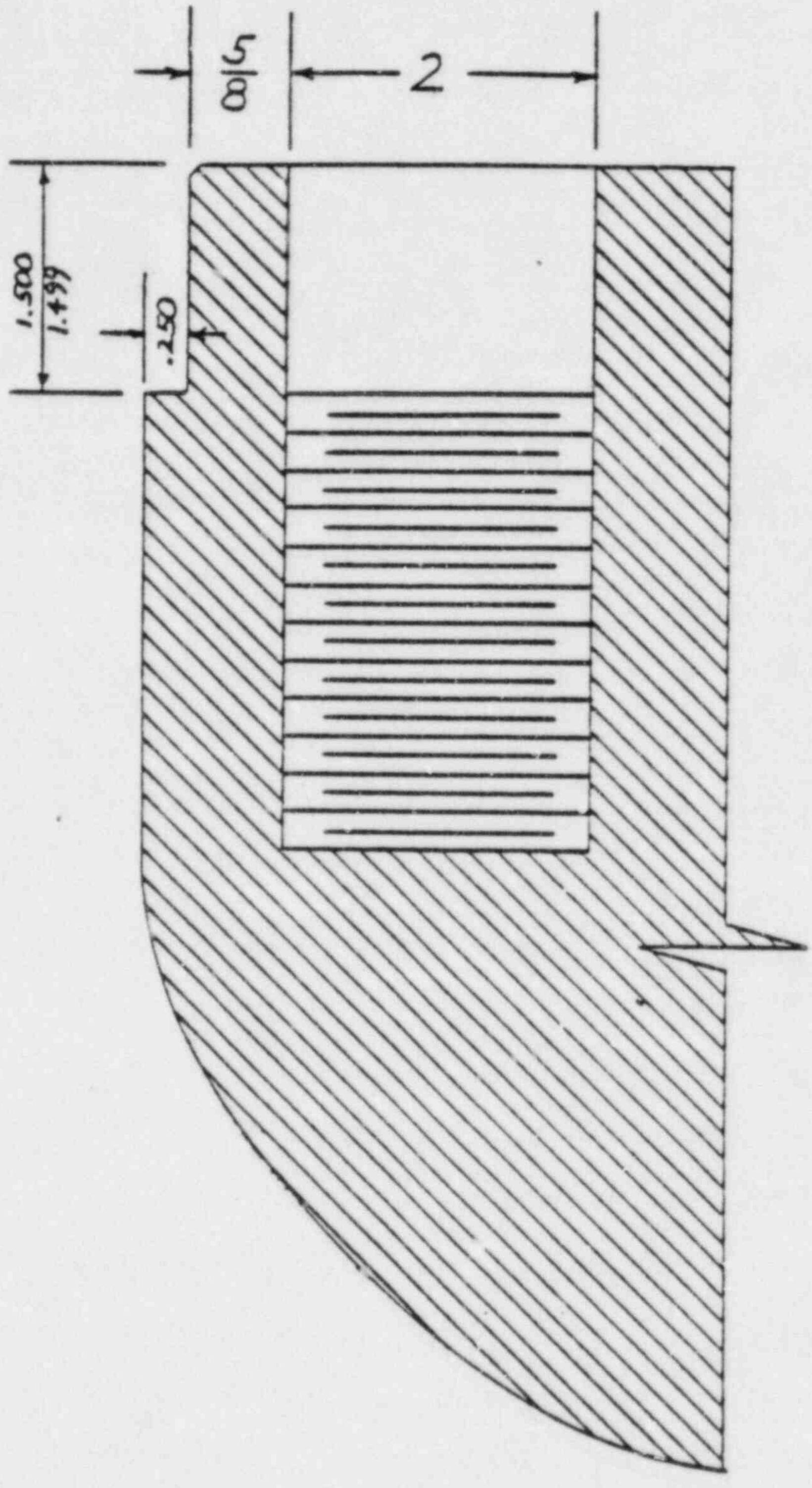


Figure 4. Counterbore and Stud Configuration

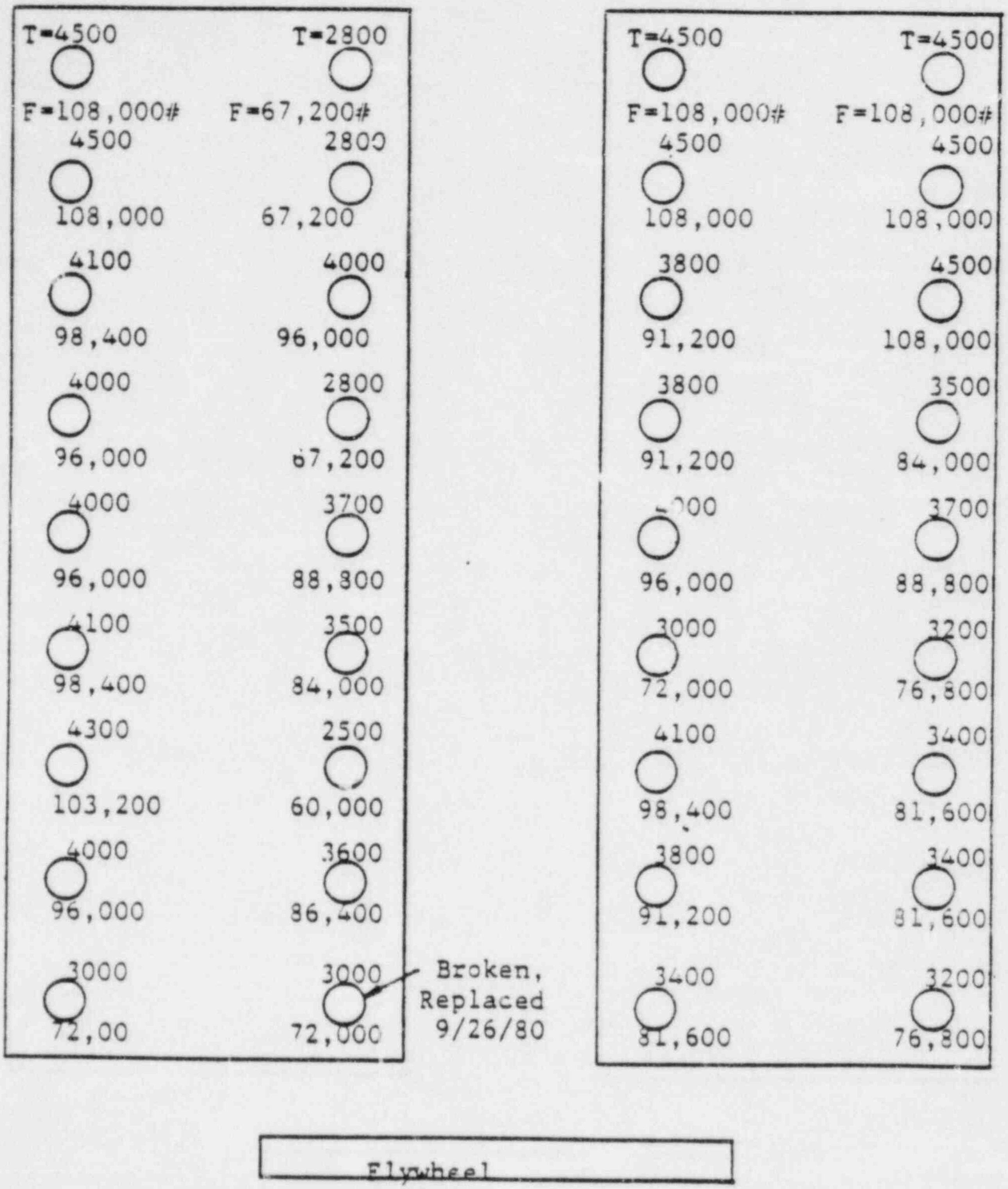
Torque Level of Bolts Holding the Blocks to the Base

On September 26, 1980, a bolt broke on the left rear block of the starboard main engine. Temporary repairs were made and the bolt was replaced on return to Seattle. During installation of the new bolt, the torque levels of all block bolts were checked by noting when the nuts moved during a retorquing procedure. The procedure used was to begin at one corner of the block and proceed down one side and back up the other. Figures 5 and 6 (pp. I-13 and I-14) show the recorded break-loose torque levels observed during this procedure and the force levels of preload in the bolts. (3)

In Figure 7 (p. I-15), the force from the calculated preload by the four bolts surrounding each cylinder is compared to the maximum force generated by the firing pressure. The question is whether or not, in the partially torqued condition observed, there was sufficient structural integrity in the preload forces to keep the engine properly together. The data show that for several cylinders on the starboard engine, preload force was inadequate, while on the port engine preload force was sufficient but not optimum.

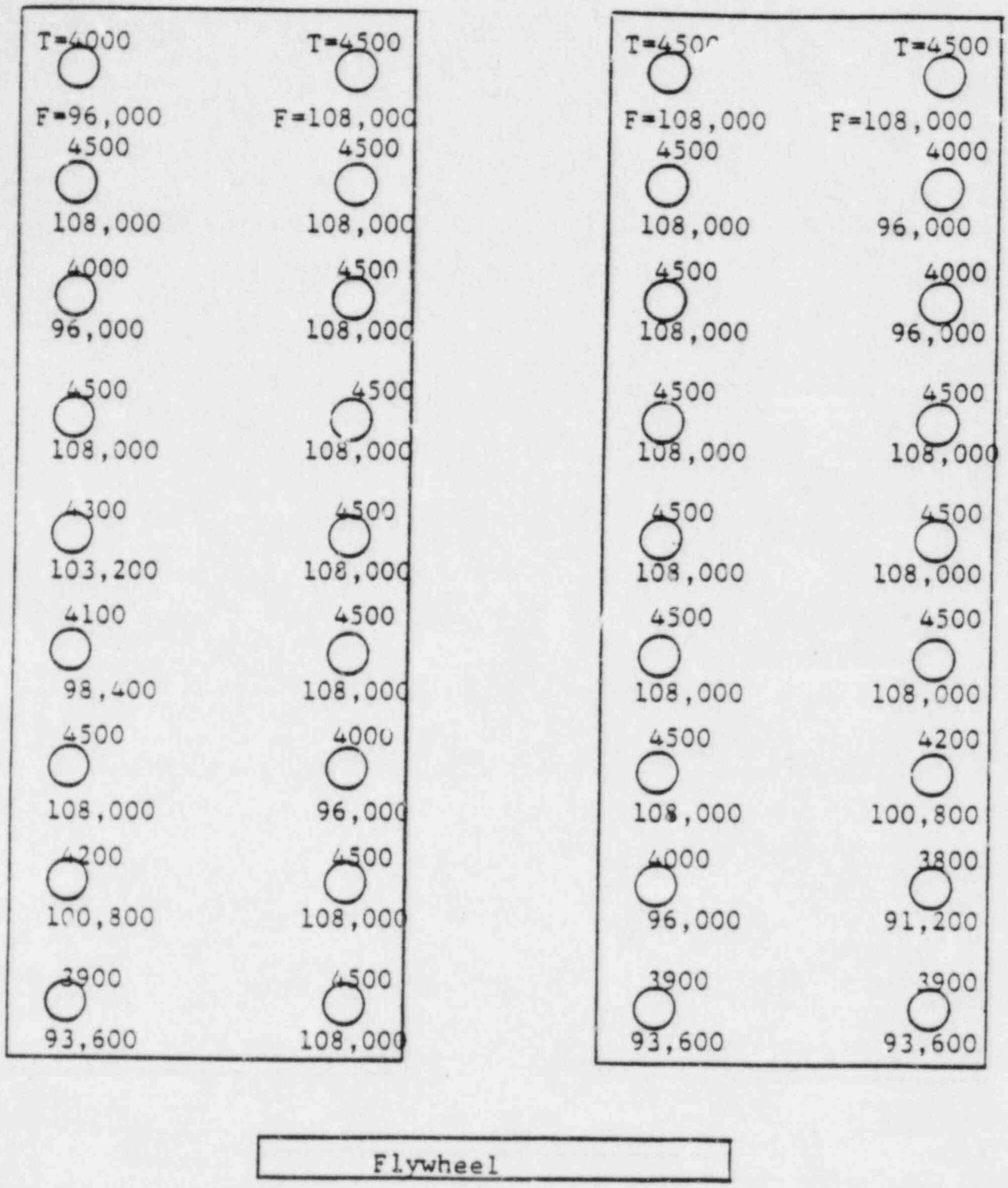
The blocks were removed from the base of the engine because of failures detected during nondestructive testing. After the blocks were removed from both engines and the face of the base where they had been resting could be seen, the surface characteristics of the metal showed differences across the face. Looking at the engine from the side, the top of the base beneath the blocks near the center of the engine showed a surface characteristic called fretting. Contiguous surfaces on the blocks showed similar fretting, like a corrosive etching. Where the previous surface had been smooth, it was now rugged and irregular. No measurements were made but the deepest groves were estimated at a millimeter (.040 inch). TO 7

Fretting is a corrosion-like wear of metal occurring when there is a small cyclic motion between two mating surfaces under load. In the case of



T = Torque (ft-lb)
F = Force (ft)

Figure 5. Block to Crankcase Bolts, Starboard Main Engine, December 31, 1980



T = Torque (ft-lb)
F = Force (ft)

Figure 6. Block to Crankcase Bolts, Port Main Engine, December 31, 1980

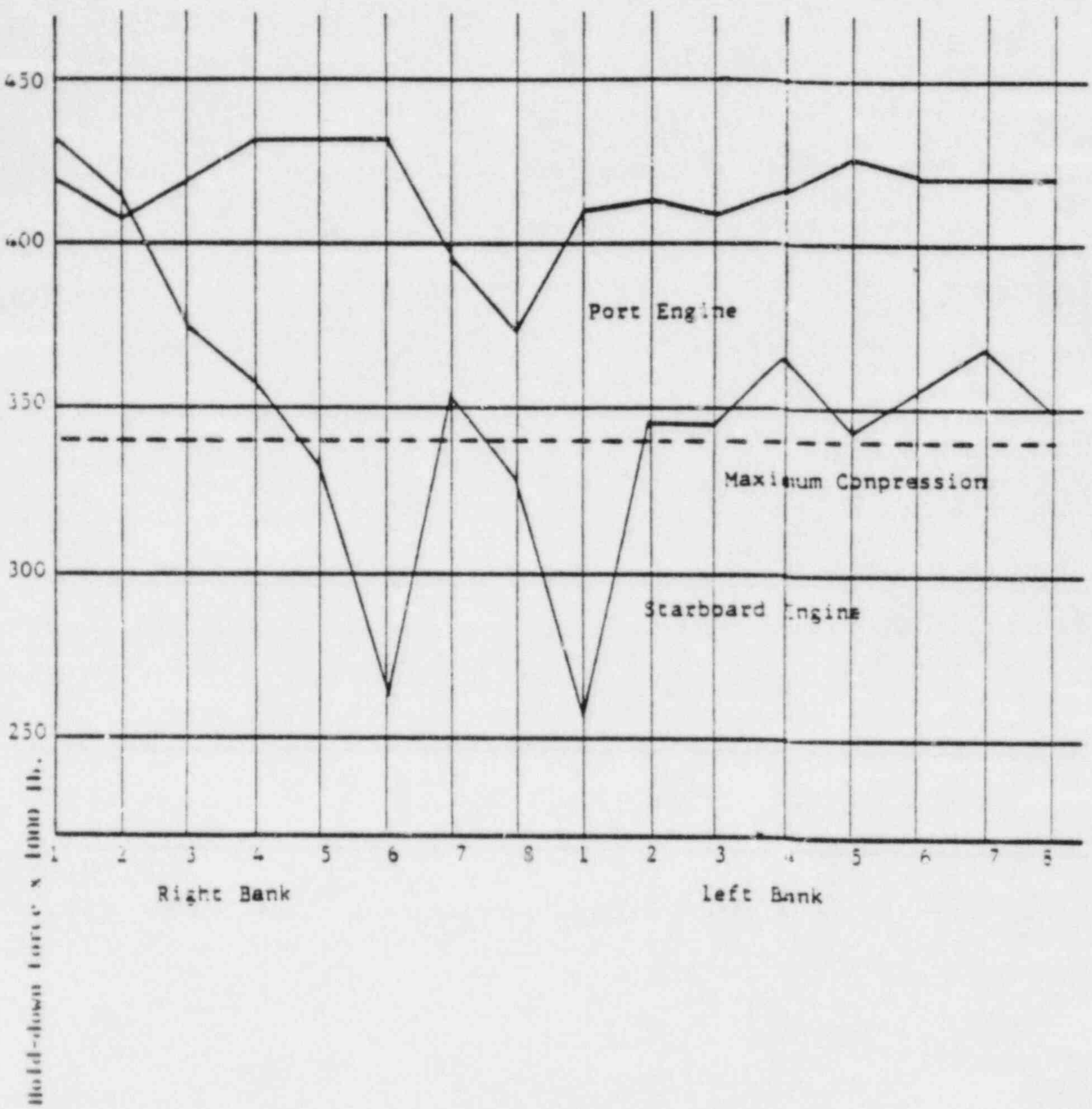


Figure 7. Engine Block to Base Hold-down Force

the engines, motion, and consequently fretting, occurred because of the reduced preload in the block bolts when the nuts were not fully torqued.

Fretting did not occur solely because of reduced preload in the block bolts. Although the pattern was similar in both engines, a greater amount of fretting was seen on the starboard engine where the lowest preloads were present. There was also fretting in the areas where maximum preloads were present. The author believes that a combination of lifting of the blocks due to firing pressure and moment from the piston side thrust contributed to lifting the blocks slightly more in the center of the engine than at the outside.

To reduce the possibility of fretting, maximum torque on the block bolts must be maintained at all times. But, because of piston side thrust, it probably cannot be eliminated, only minimized. The procedure by which the bolts are brought to full torque is critical and is explained under Engine Alignment, page V-12.

An observation of an interesting surface effect on the block face of the starboard engine requires mentioning. The left rear corner of the left block had a circular etching with deep outward radiating cracks up to 1/4 inch deep which appeared to be electrochemically caused. The circular etching corresponded to a recess in the block, possibly a filled core. No other similar features were observed on the block.

II

CYLINDER LINERS

The cylinder liners installed in the block can be removed and thus provide a renewable cylinder surface. Each liner is held in the block at the top by the bore and counterbore lip and at the bottom by the block bore. The major holding force comes from the clamping by the head holding the liner against the counterbore lip. The radial tolerance between the cylinder liner and the block, nominally .005 inch, is removed during operation when the liner is heated. During operation, the surface contact pressure is estimated at 27,000 psi at the bore diameter (19.000 inches). In addition to the metal-to-metal contact stresses at the bore and the counterbore lip, the liner is sealed at the top with a fire-ring inserted into a liner recess, a water seal in a head recess covering the edges of the block and liner, and at the bottom with multiple o-ring seals.

The cylinder liner problems studied were 1) changes in liner diameters, and 2) changes in clamping capability.

Changes in Diameters

Because of deformation of the blocks, the cylinder liners, which must mate with the block for proper function, required examination. These liners were measured at the same time as the blocks and their dimensions are shown in Tables 1, 2, 3 and 4 (pp. I-2 to I-5). Bore diameters for the starboard and port main engines are shown in Figures 8 and 11 (pp. II-2 and II-5). The diameter changes indicating ovalness of the cylinder liners are less dramatic than those for the block and may not be overly significant. But the liners may not have been in the block in the same cylinder for the lifetime of the engine. Because deformation of the liners had to follow that of the block, the effects of permanent deformation were less. The liner and the blocks are probably of different material specifications and the liner material may not be as subject to creep as is the block.

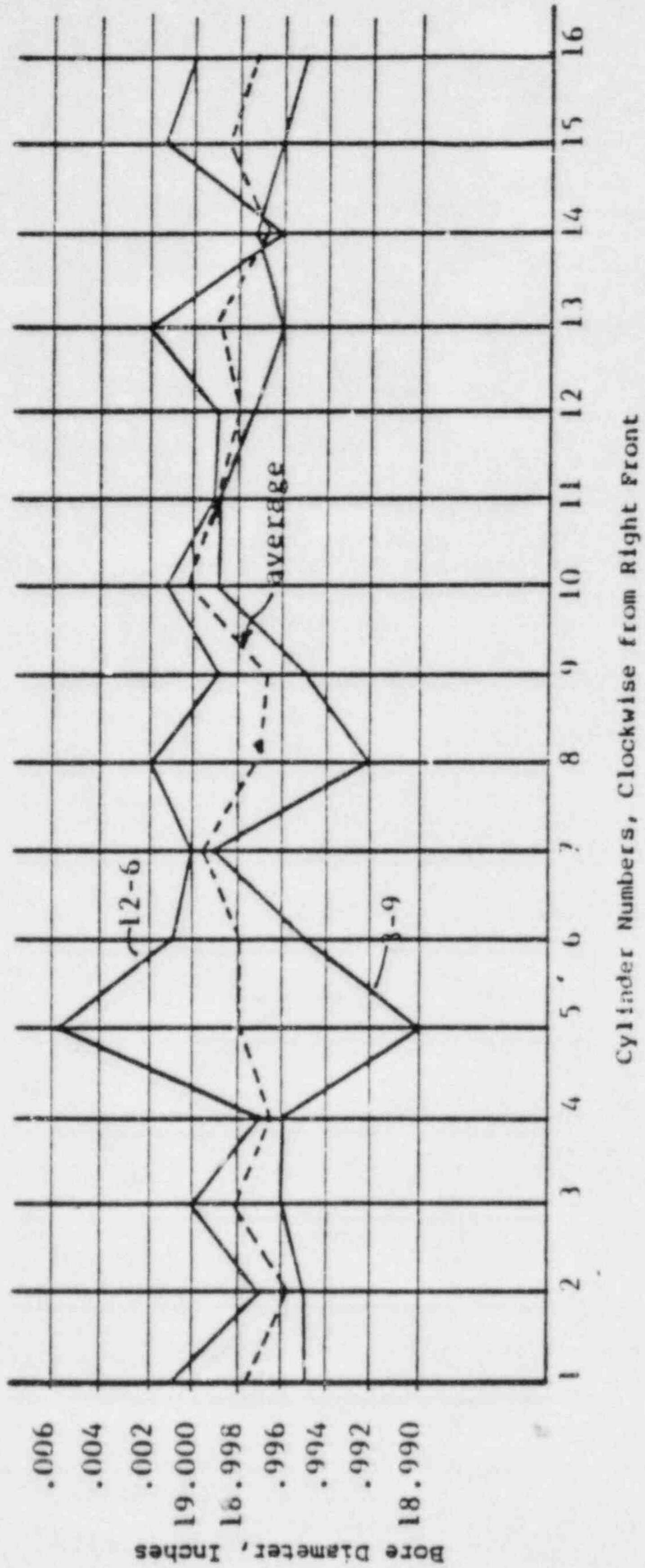


Figure 8. Permanent Liner Deformation, Bore Diameter
Starboard Main Engine

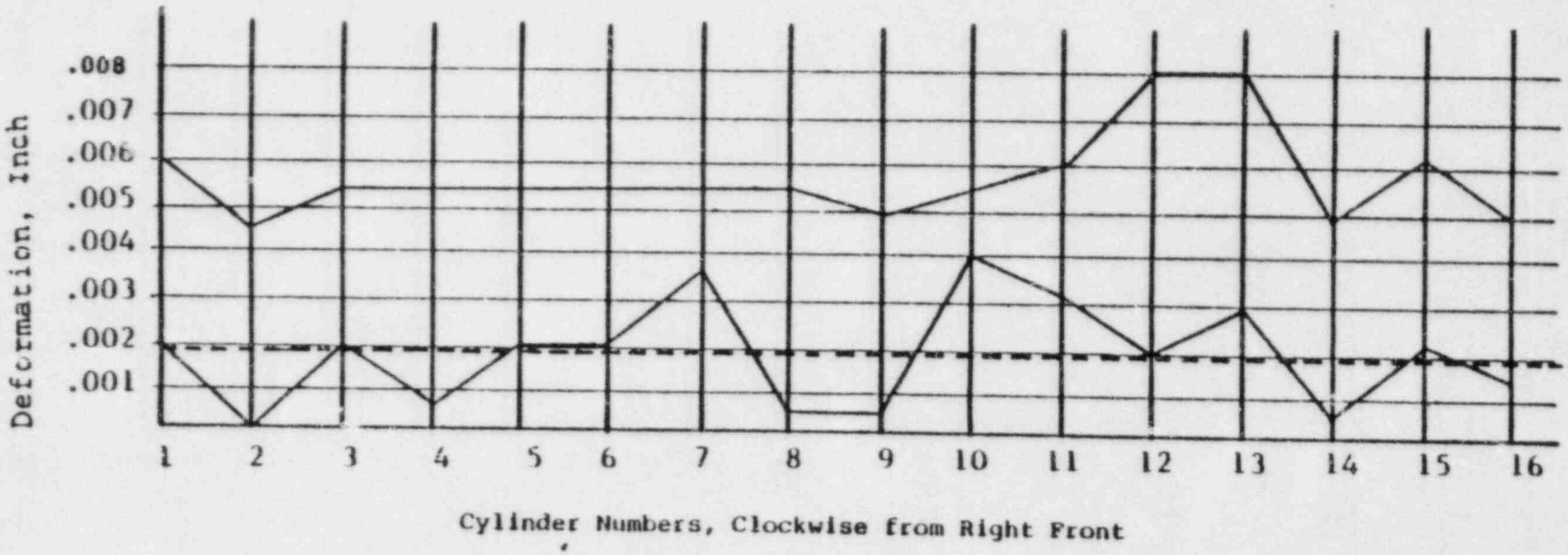


Figure 9. Permanent Deformation of the Cylinder Bore and the Liner Bore, Starboard Main Engine

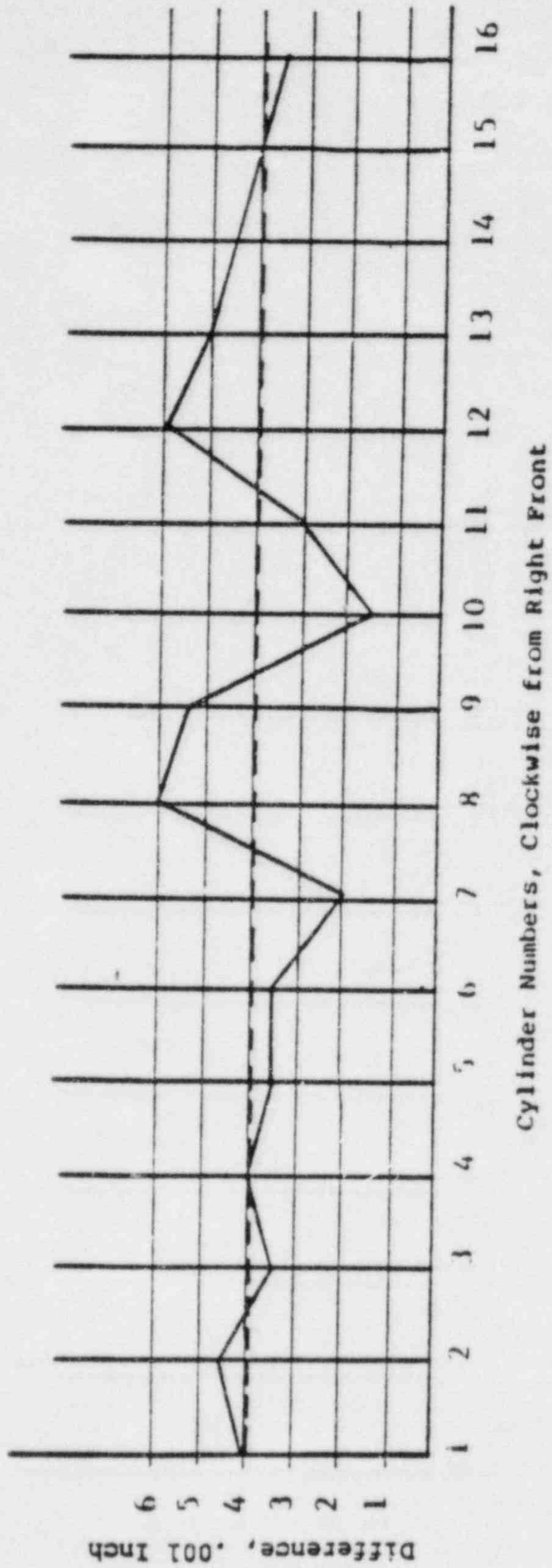


Figure 10. Average Difference Between the Block and the Liner Bore Diameter, Starboard Main Engine

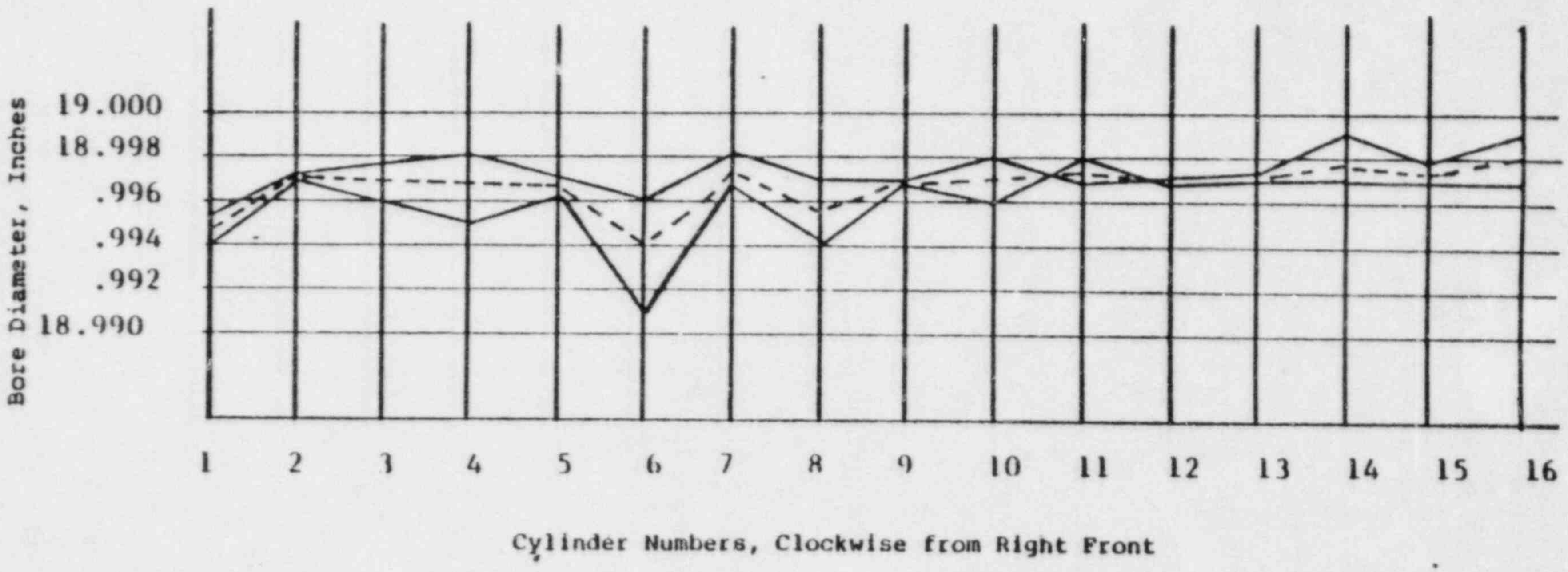


Figure 11. Liner Bore, Port Main Engine

A comparison of the difference in deformation of the blocks and that of the cylinder liners is shown for the starboard engine in Figures 9 and 10 (pp. II-3 and II-4). Figure 9 shows the average deformation of the block and the liners for each cylinder. Figure 10 shows that the design clearance of .005 inch had increased to a clearance of .009 inch. This difference explains why the liners were easier to remove than when they were new.

Changes in Clamping Capability

The major stabilizing force for the cylinder liners during installation is provided by the clamping of the head on the lip of the liner. The lip is 19.500 inches outside giving a .250 inch support surface, and is nominally 1.500 inches high. Because of a small difference in dimensions the liner protrudes .004 inch above the block surface. This difference in height is called the "crush." When the studs holding the head in place are torqued to full value (3600 ft-lbs), the entire force of all bolts is borne by the liner and the head is separated from the block surface.

When the engine was measured as recorded in Tables 1, 2, 3 and 4, it was found that the clamping capability--or crush--had undergone dimensional changes. Port main engine cylinder 3 had required machine work because of degradation. The counterbore depth had been increased .013 inch and a spacer ring had been installed to restore the original crush. (6)

Measurements showed some loss of crush, possibly contributing to the failure of fire-ring seals. Data relating to crush has been abstracted from Tables 1, 2, 3 and 4 and presented in Tables 5 and 6 (pp. II-7 and II-8). The liner lip is .001 to .002 inch deeper than specification. Discussions with ship personnel and measurements on new liners indicate they have been manufactured .002 inch larger than factory specifications providing a .006 inch design crush height. The liners are maintaining their manufactured dimensions during their useful lifetime.

(7) (8)

Table 5. Crush, Starboard Main Engine

	Counterbore	Avg.	Less 1st .5	Liner		Avg. Change -3.75
1 -	9/4	2.25	2.75	18/4	4.5	.75
2 -	11/4	2.75	3.25	16/4	4.0	.25
3 -	13/4	3.25	3.75	20/4	5.0	1.25
4 -	12/4	3.0	3.5	25/4	6.25	2.5
5 -	11/4	2.75	3.25	17/4	4.25	.5
6 -	5/4	1.25	1.75	23/4	5.75	2.0
7	9/4	2.25	2.75	24/4	6.0	2.25
8 -	10/4	2.50	3.0	24/4	6.0	2.25
9 -	11/4	2.75	3.25	20/4	6.25	2.5
10 -	12/4	3.0	3.5	23/4	5.75	2.0
11 -	13/4	3.25	3.75	24/4	6.0	2.25
12 -	16/4	4.0	4.5	23/4	5.5	1.75
13 -	10/4	2.5	3.0	22/4	5.5	1.75
14 -	11/4	2.75	3.25	27/4	6.75	3.0
15 -	8/4	2.0	2.5	23/4	5.75	2.0
16 -	12/4	3.0	3.5	17/4	4.25	.5
		Avg. Value 1.50251	Avg. Loss = 3.01			Avg. Growth 1.72

Table 6. Counterbore, Port Main Engine

	Average		Loss (i.e. +.5)	Liner		Growth	Avg. Crush
1 -	19.5/4	4.875	5.375	21/4	5.25	1.5	.375
2 -	17.5/4	4.375	4.875	21/4	5.25	1.5	.875
3 -	5.5/4	13.75	14.25	21/4	5.25	1.5	-8.5
4 -	14/4	3.5	4.0	20/4	5.0	1.25	1.5
5 -	15/4	3.75	4.25	16/4	4.0	.25	.25
6 -	18.5/4	4.625	5.125	22/4	5.5	1.75	.875
7 -	18/4	4.5	5.0	24/4	6.0	2.25	1.5
8 -	21.5/4	5.375	5.875	12/4	4.25	.5	-1.125
9 -	17/4	4.25	4.75	20/4	5.0	1.25	.75
10 -	10/4	2.5	3.0	18/4	4.5	.75	2.0
11 -	24/4	6	6.5	17/4	4.25	.5	-1.75
12 -	12/4	3	3.5	20/4	5.0	1.25	2.0
13	23.5/4	5.875	6.375	10/4	2.5	-1.25	-3.375
14 -	24/4	6	6.5	20/4	5.0	1.25	-1.0
15 -	19/4	4.75	5.25	20/4	5.0	1.25	.25
16 -	24/4	6	6.5	25/4	6.25	2.5	.25
		Avg. Loss (excluding #3)	5.125			Avg. Crush (excluding #3)	.225

Tables 5 and 6 show the counterbore depth of the starboard engine has increased by .003 inch and .005 inch for the port engine severely compromising the ability of the engine to fix the liners in place.

A design feature of the counterbore and lip may preclude avoiding the problem. The force from the eight studs when torqued to 3600 ft-lbs must be borne on the .250 inch lip face producing a compressive stress in excess of 76,000 psi. This value is above the normal design limits for cast iron and, with the sharp interior corner, will be a source of recurring failure.

Section IV, Nondestructive Testing, discusses the failures observed. These failures led to the decision to replace the original blocks with new units. Because the design stresses were so high, there was no foreseeable way to prevent failures from occurring without a significant redesign of the liner-block landing surfaces.

III
CYLINDER HEADS

The cylinder heads on the main engines have shown an excessively high failure rate. When the heads fail during operation, they are replaced with a new or reconditioned unit and the original is returned for renovation or scrap.

The problems identified by Alaska state personnel were warpage, cracking, loss of fire-ring seal, valve-stem blow-by, and the expected problems of valve wear.

Examination of the heads was confined to one unrefurbished head with 2,000 hours of use and two new heads. All units were visually inspected and the used head was sawed into quarter sectors for study. The valves were placed into the used head and the seat clearance checked with a .0015 inch guage. Intake and exhaust closures showed no warpage. Inspection of rebuild procedures at the Duamish Machine Works indicated that some of the valve guides had come loose, allowing blow-by into the valve chamber and possibly contributing to a misaligned seat closure. None of the heads currently being reworked had problems with warpage. The maximum out-of-flatness was .002 inch with most measurements being .001 inch or less.

Interior surfaces of the new head showed weld repair in transition corners excessive for a new casting. It was surmised that the condition had been present in the used heads when they were new. The used head, when cut, showed a weld repair on the firing face only partially filling a crack that extended through the entire thickness of the firing face. Because of this repair and the amount of weld repair present in the head x-rays were used to further analyze the head. X-rays showed a few gas pockets from casting and two or three welds with minor defects. Overall, the repair procedures seem to have corrected the casting defects in the head and it is in reasonably good condition. My opinion and that of Professor Paul Ford of the University of Washington is that the castings showed an excessive amount of casting flaws which, if not repaired, could produce head failures of undetectable and spurious occurrence. With the high cost of heads (dollars per pound) one would expect a higher quality product.

Inferences about the high frequency of head failure could be made with more specific historical information about the heads which were removed and refurbished or scraped.

IV
NONDESTRUCTIVE TESTING

The basic structural parts of the engine--the blocks and the bases--were examined by nondestructive testing. Testing began after presentation of a preliminary draft of the January 30, 1981 report.

Blocks

The top surface of the blocks for both engines was tested. Data from ultrasound examination of the blocks are presented in Figures 12 and 13 (pp. IV-2 and IV-3) with details in Figures 14 and 15 (pp. IV-4 and IV-5).

Fractures seen most frequently were radial cracks extending out from the cylinder counterbore. The radial cracks were either in areas of stress concentrations caused by holes for cooling water passage or stud drillings, or in the inter-web area between cylinders in the center of the block. The most destructive type of fracture was seen in cylinders 2 and 3 of the left bank of the starboard engine. Figure 14 shows the form of the delamination crack where the cylinder liner lip was separating from the block structure. This fracture prevented the liner from being properly installed and could have led to a catastrophic engine failure.

The fracture was caused by the following:

1. high compressive stresses on the counterbore lip,
2. localized stress condition from the combinations of sharp internal corner for lip (1/32 inch radius),
3. nearby drilling for waterjacket or stud,
4. termination of stud threading at the same level,
5. creep deformation, and
6. fatigue.

Because of the delamination cracks, one block was not serviceable, and so both blocks for the starboard engine were renewed.

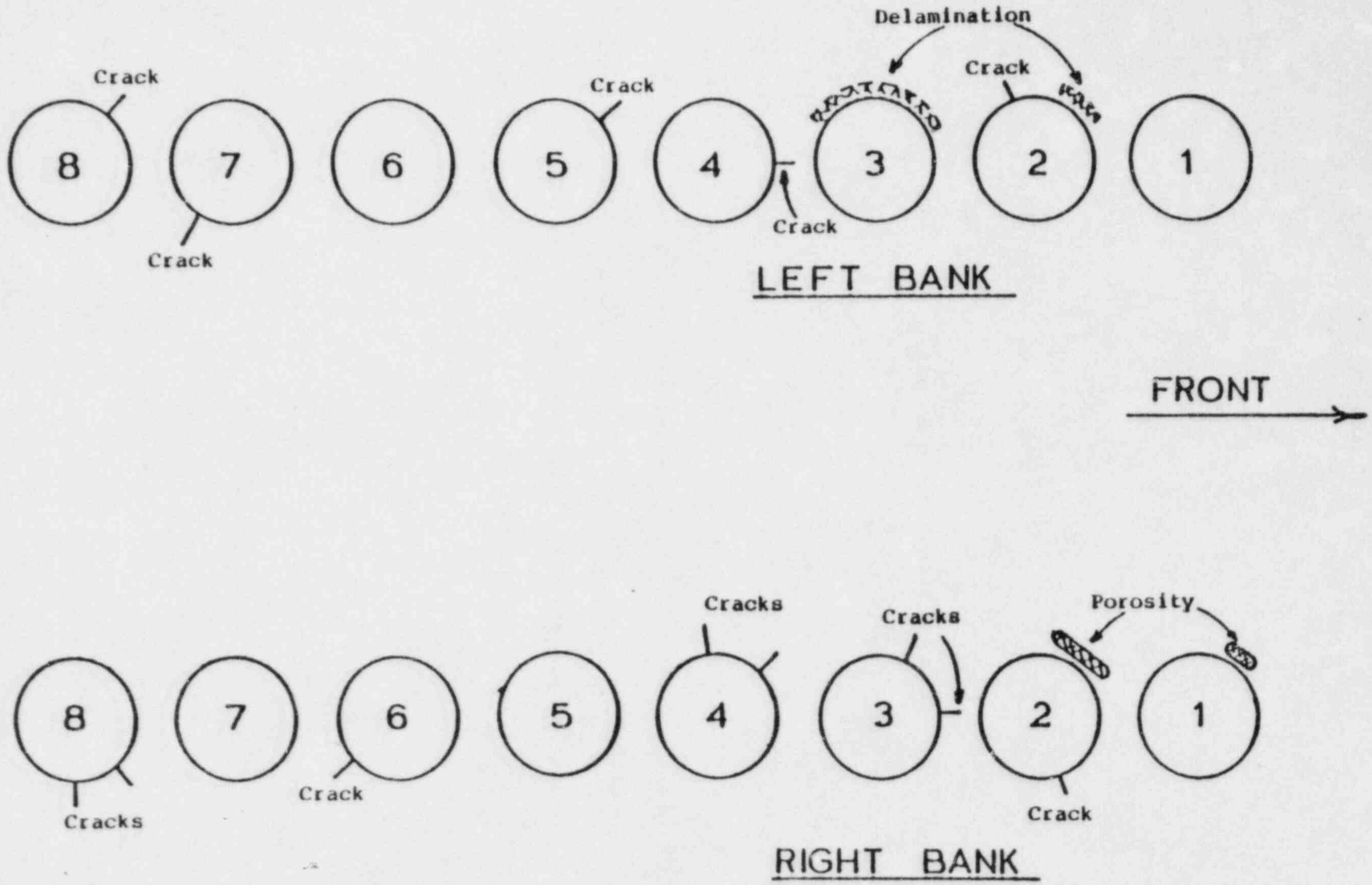


Figure 12. Nondestructive Testing, Starboard Main Engine

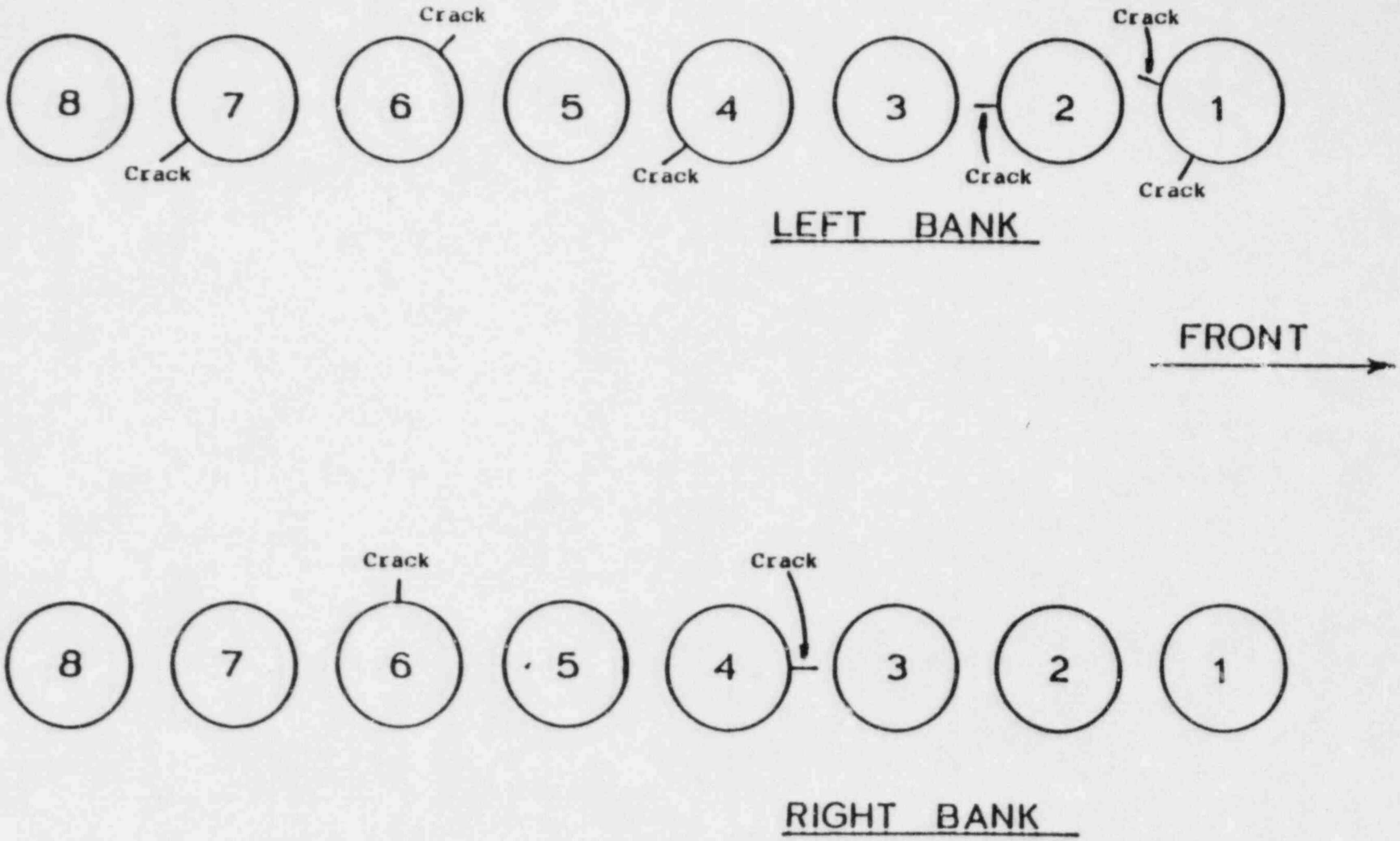


Figure 13. Nondestructive Testing, Port Main Engine

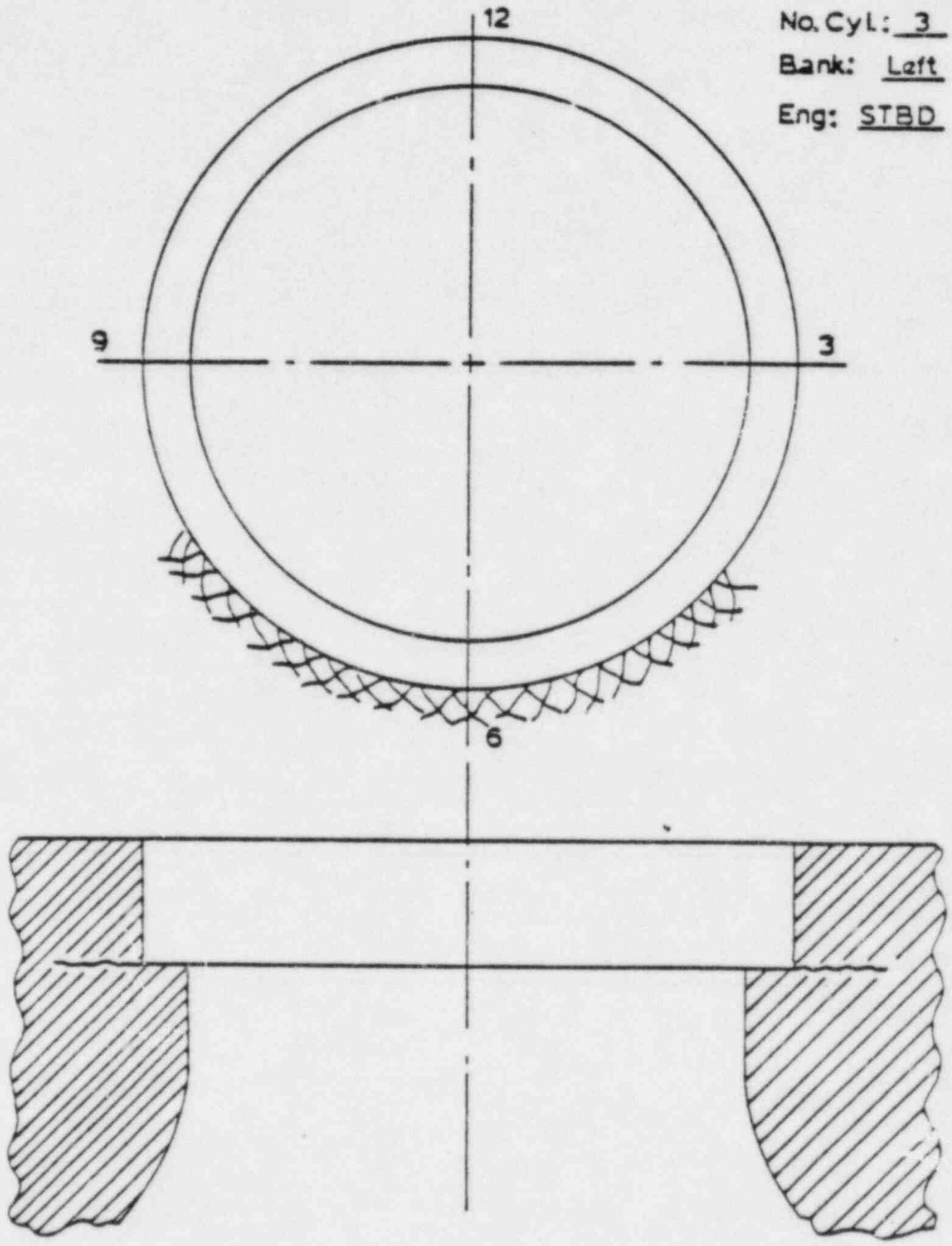


Figure 14. Nondestructive Testing, Cylinder Block, Delamination Cracks

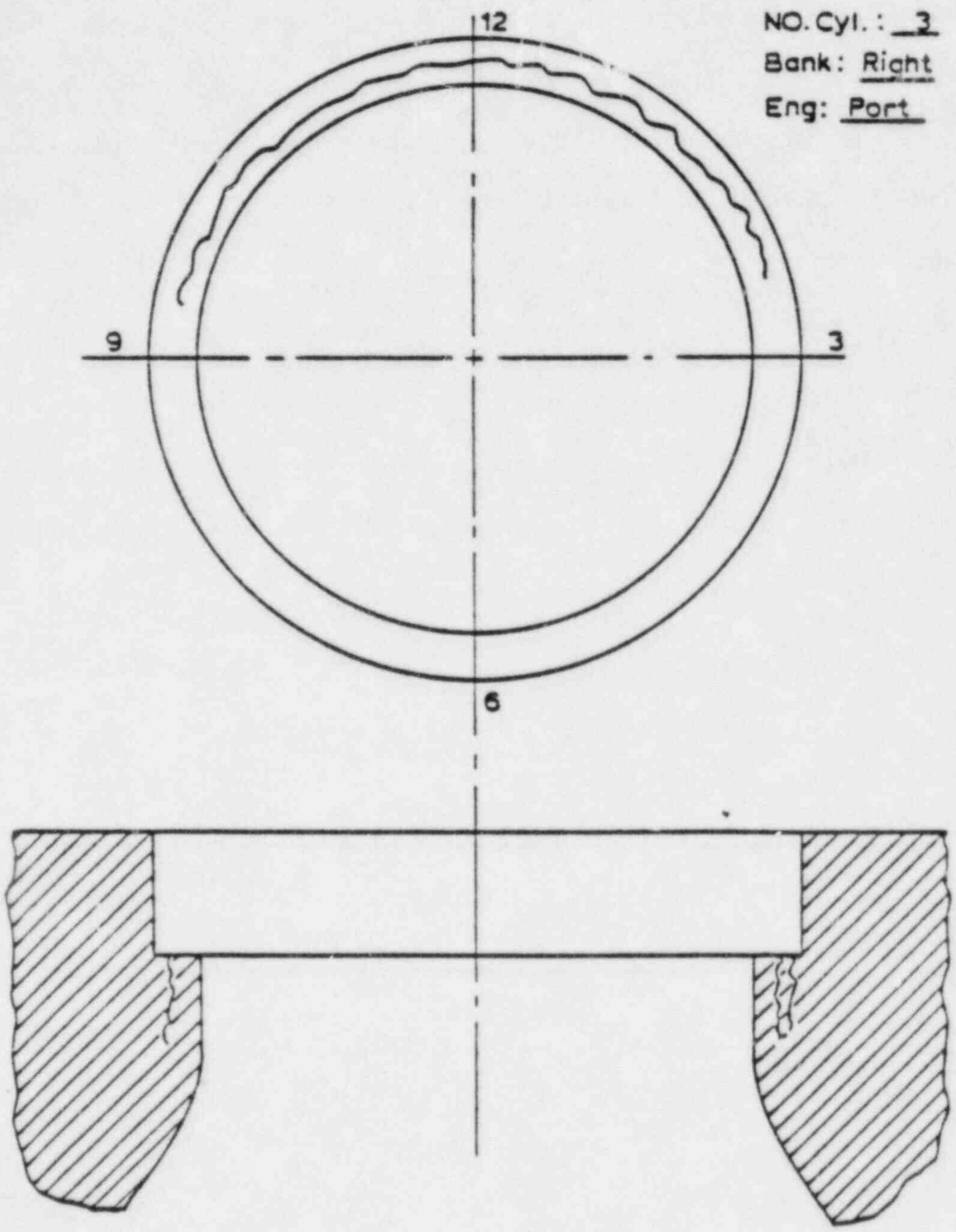


Figure 15. Nondestructive Testing, Cylinder Block, Shear Cracks, Counterbore Lip

The port engine, although showing radial cracks, did not have the delamination failure seen in the starboard engine. The port engine was renovated by boring the block to a larger diameter and resurfacing the counterbore lip to a consistent depth for all cylinders. When the first cuts were made on the counterbore lip, the exposed surface showed shear fractures extending downward in the counterbore lip. Specific ultrasound probes for curved surfaces confirmed the shear fractures in cylinder 3 of the port engine. Cylinder 14 also had a shear fracture at the counterbore lip.

Base

Using ultrasound nondestructive testing, the base of the engine was examined for fractures. Small radial fractures were detected, but not in areas that would severely compromise the integrity of the engine if refurbished with new blocks.

ENGINE ALIGNMENT

The alignment and trueness of engine surfaces were checked with optical sighting instruments. Flatness of the block surface, flatness of the exposed base, and trueness of the subbase along the ship structure were measured before and after retorquing the structural bolts. The results of the retorquing are discussed in quantitative terms in this section.

Structural Alignment

Figures 16 to 23 (pp. V-2 to V-9) show the fore to aft elevation differences for the block surfaces before removing the blocks from the engine. These measurements were taken on both engines in their pre-renovation condition with all tie bolts at their previous preload values. Before measuring, the base bolts were not checked nor were the block bolts changed from the values shown after retorquing when the broken block bolt was replaced (as described in Section I). The top and bottom of each block surface were recorded to verify the relative accuracy and to examine for surface twisting.

Port Engine, Right Bank

Figures 16 and 17 (pp. V-2 and V-3) show a sag in the middle of the engine from front to rear of .030 inch. Cylinder 2 shows a slight warping where the exhaust or top of the block is .020 inch below the bottom side. All other cylinders follow a uniform trend. Warping was a concern in setting up equipment to refinish the bore and counterbore surfaces.

Port Engine, Left Bank

The elevations are shown in Figures 18 and 19 (pp. V-4 and V-5). The surface elevation shows the block surface was bowed upward and twisted in the center. Cylinder 4 rose .108 inch and twisted .018 inch downward in the center. Cylinder 5 showed values nearly identical to those of cylinder 4. Cylinders on either side of the center taper to a uniform elevation at each end. All curves

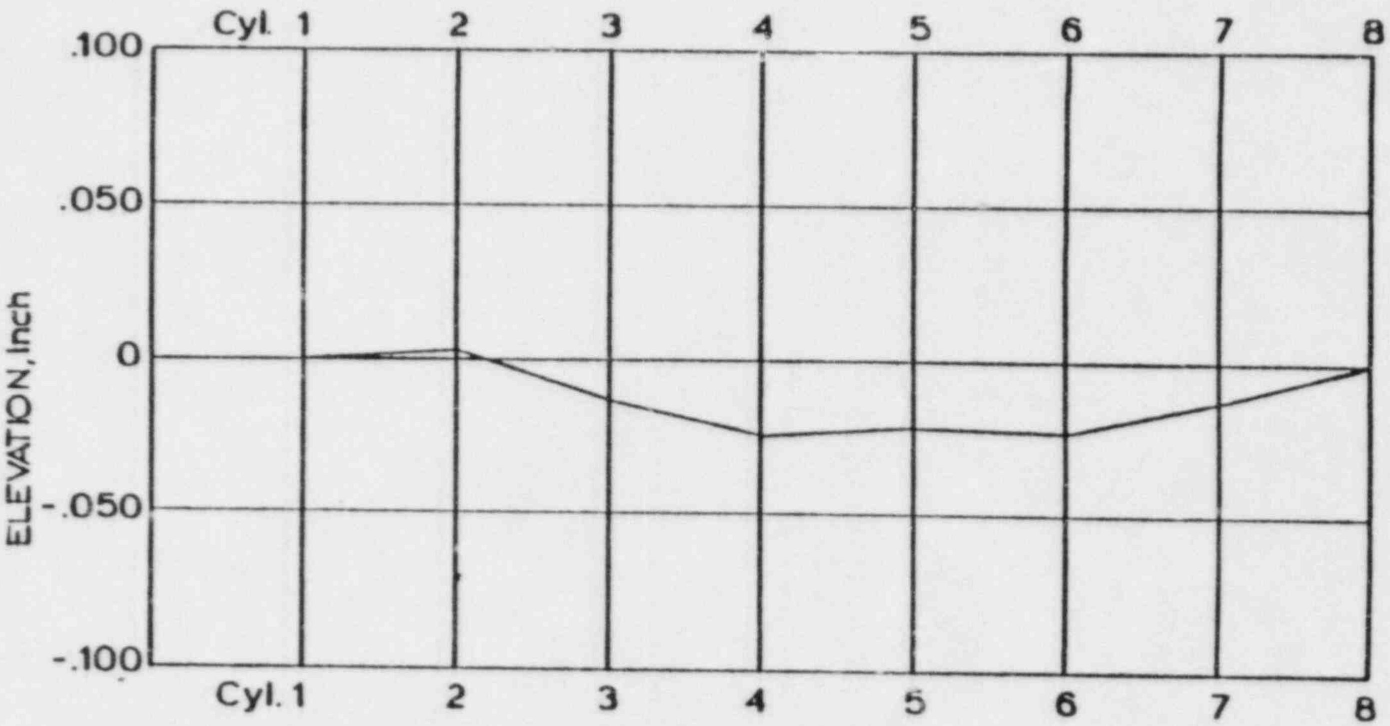


Figure 16. Elevation of the Air Side of the Cylinder Block for the Right Bank, Port Main Engine

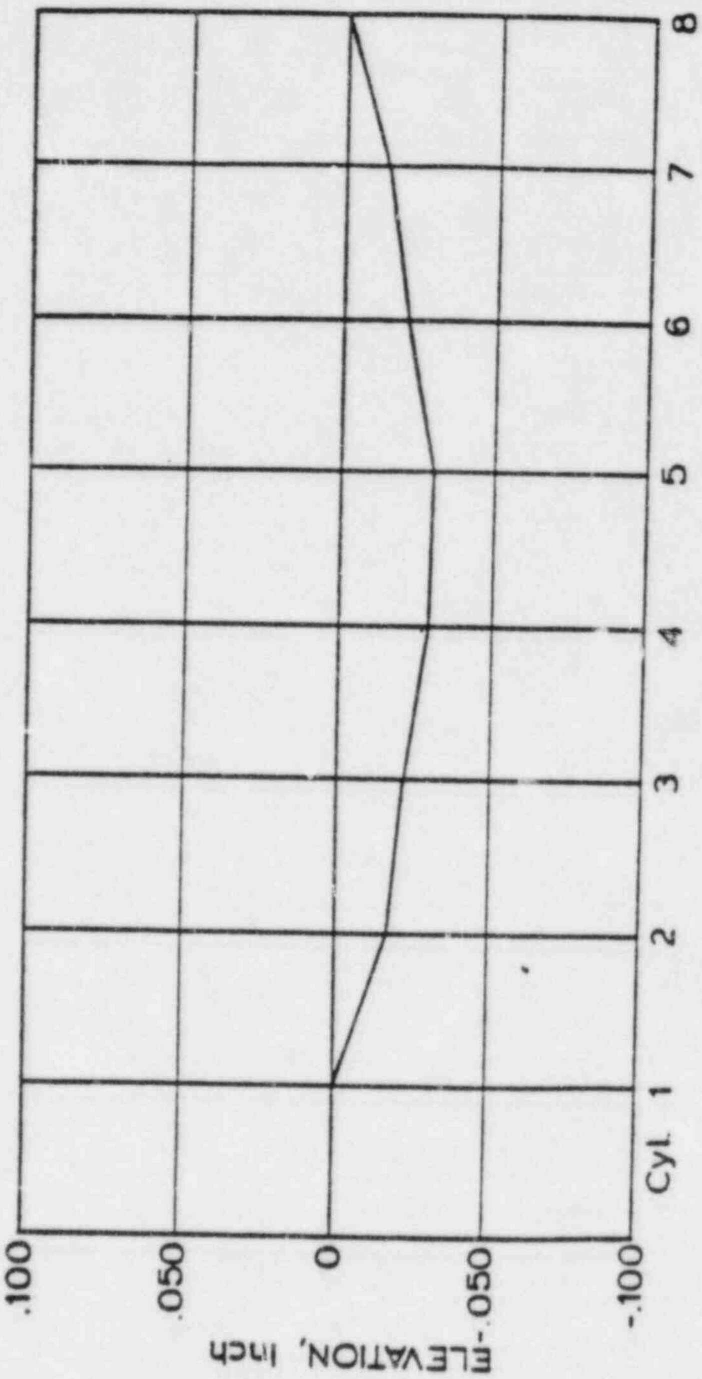


Figure 17. Elevation of the Exhaust Side of the Cylinder Block, for the Right Bank, Port Main Engine

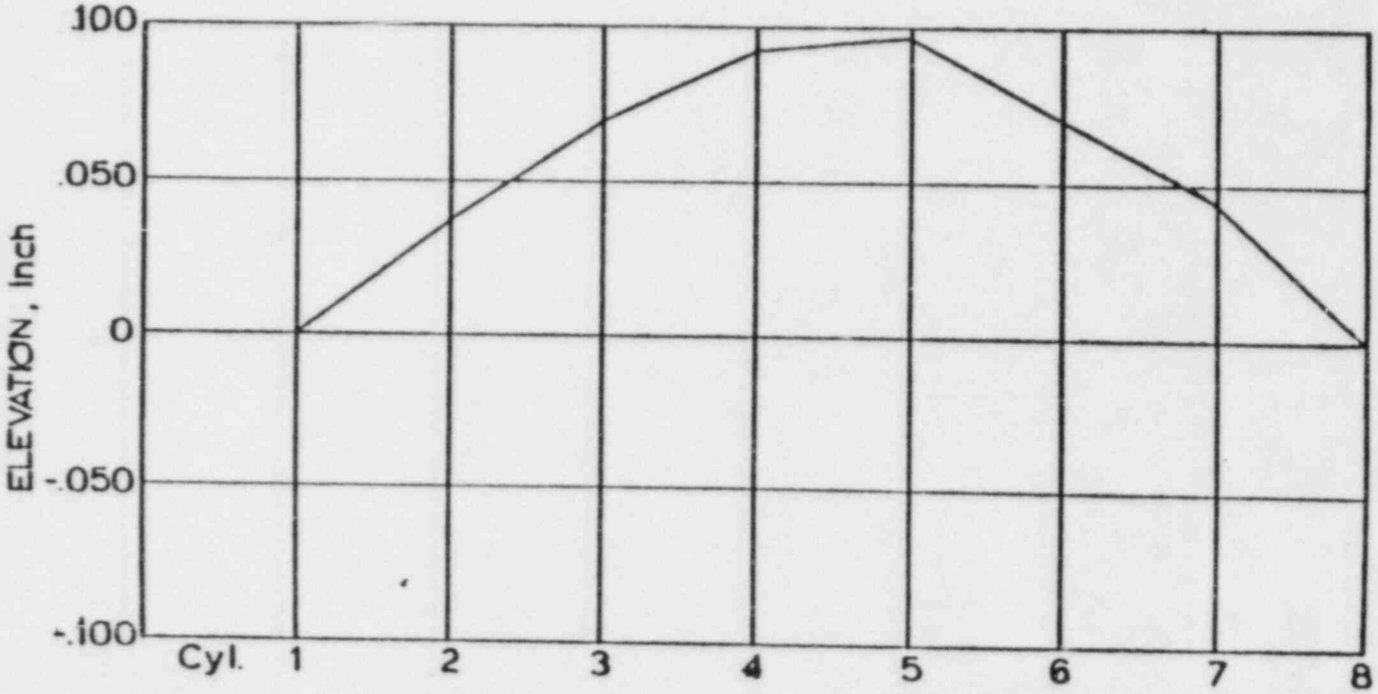


Figure 18. Elevation of the Exhaust Side of the Cylinder Block for the Left Bank, Port Main Engine

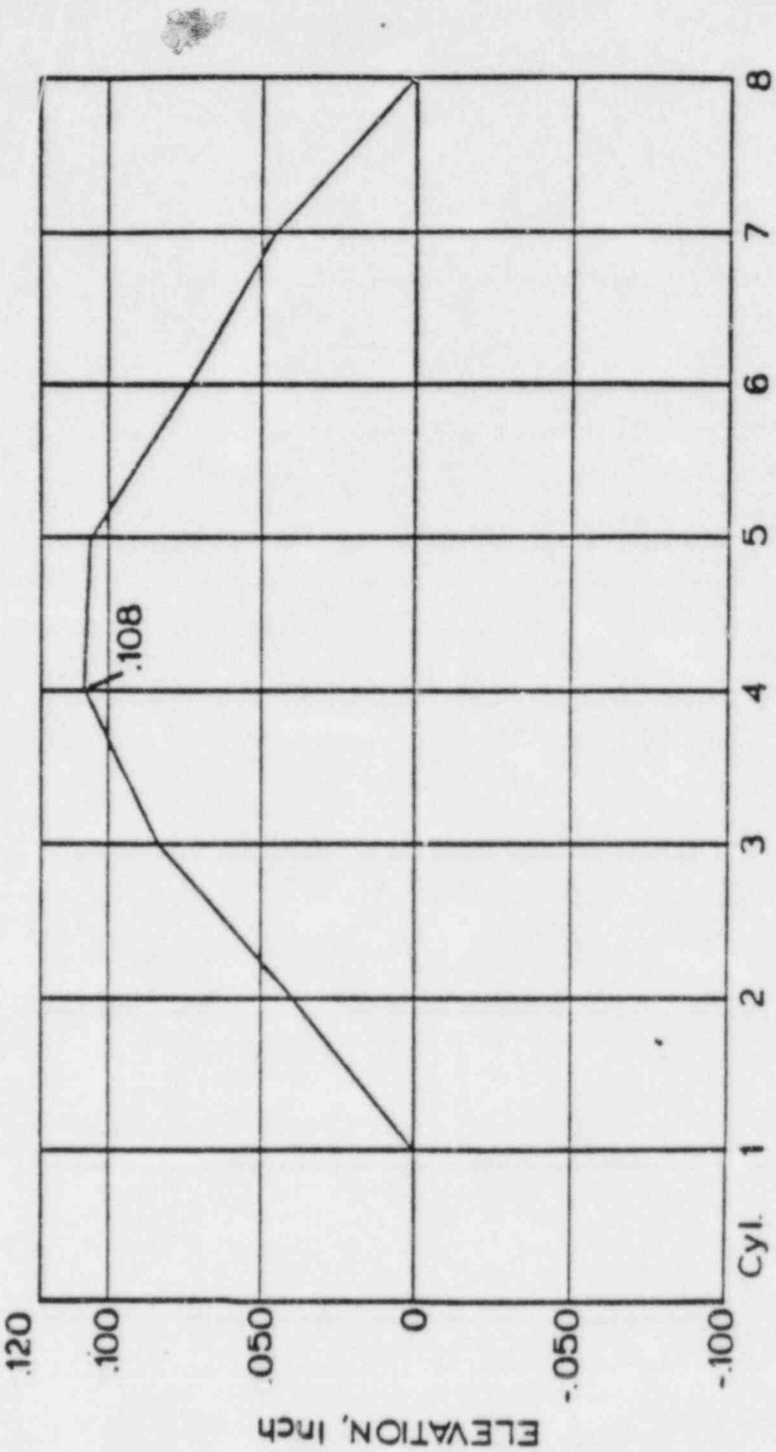


Figure 19. Elevation of the Air Side of the Cylinder Block for the Left Bank, Port Main Engine

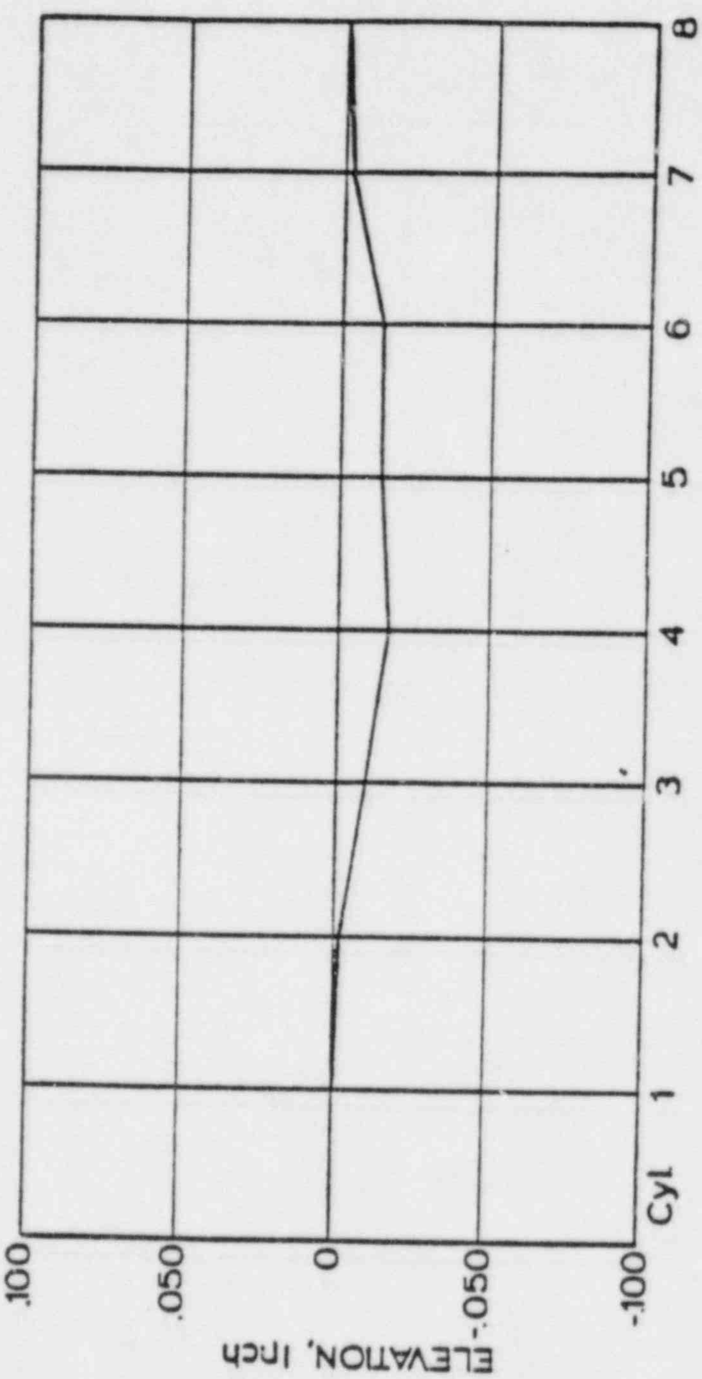


Figure 20. Elevation of the Air Side of the Cylinder Block for the Right Bank, Starboard Main Engine

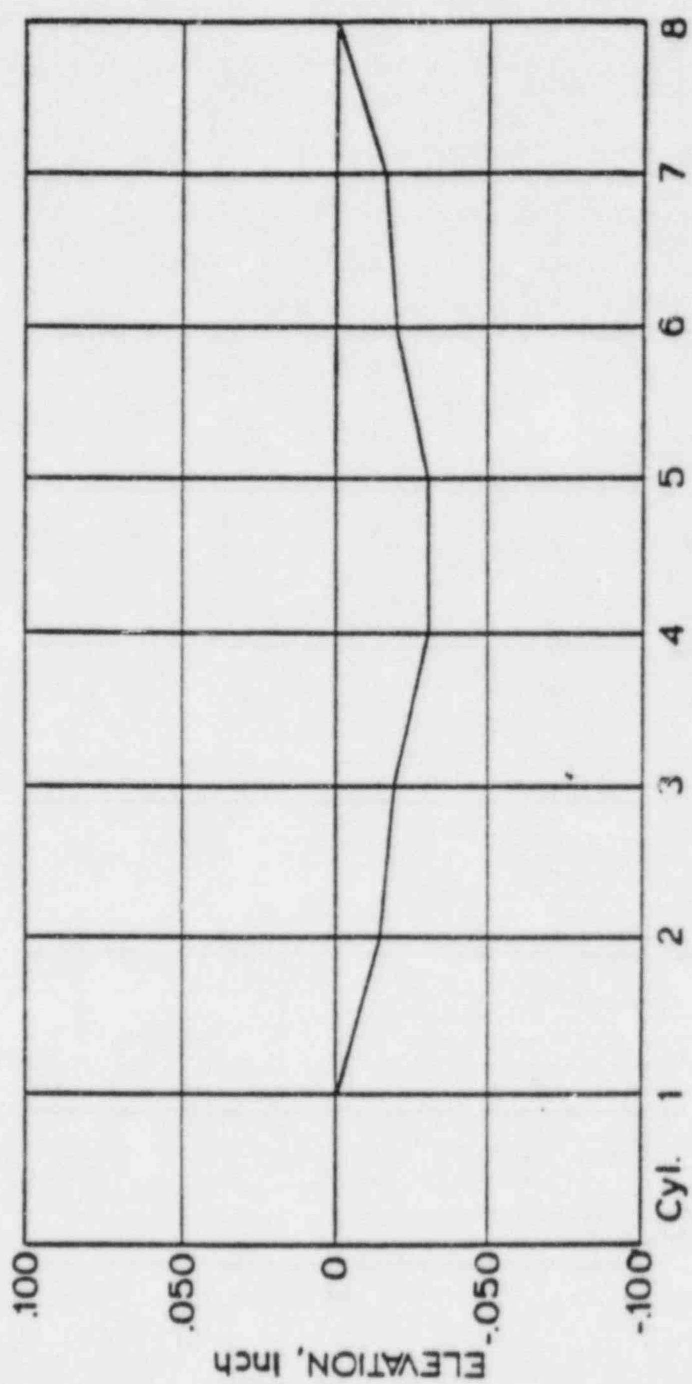


Figure 21. Elevation of the Exhaust Side of the Cylinder Block for the Right Bank, Starboard Main Engine

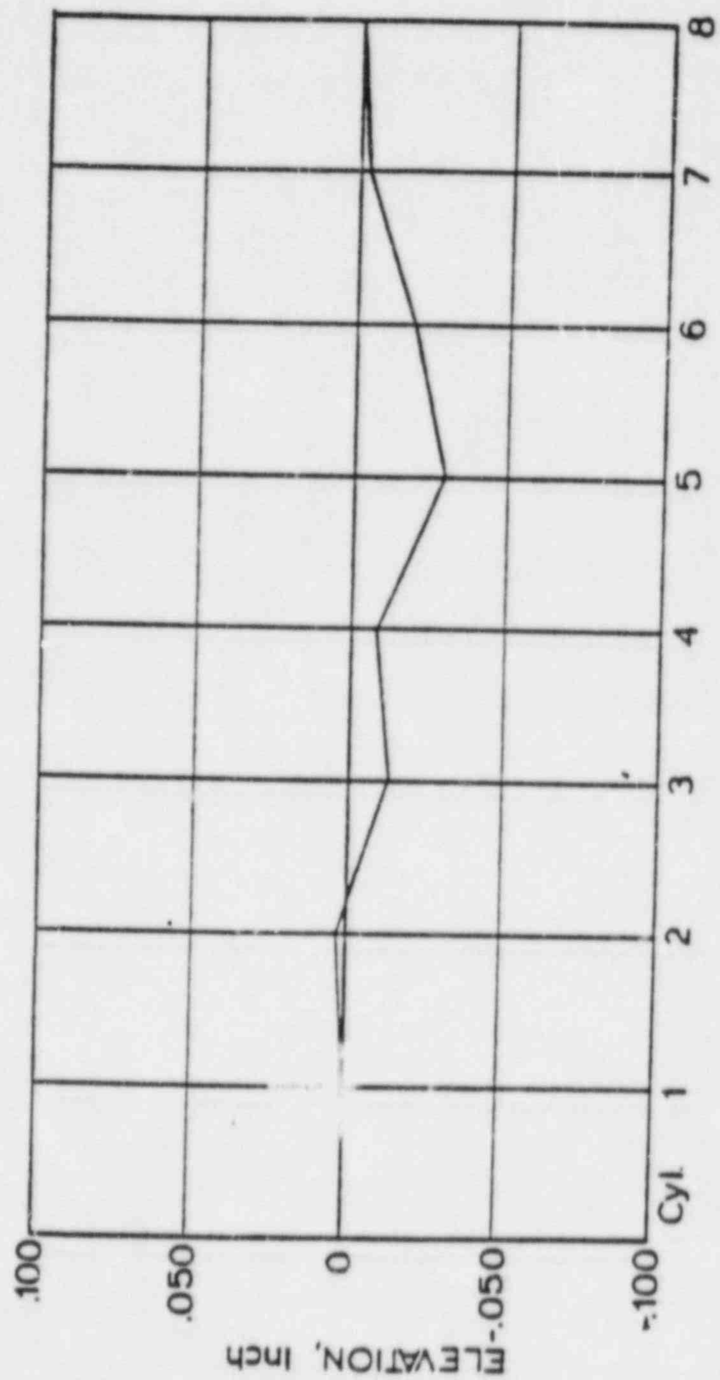


Figure 22. Elevation of the Exhaust Side of the Cylinder Block for the Left Bank, Starboard Main Engine

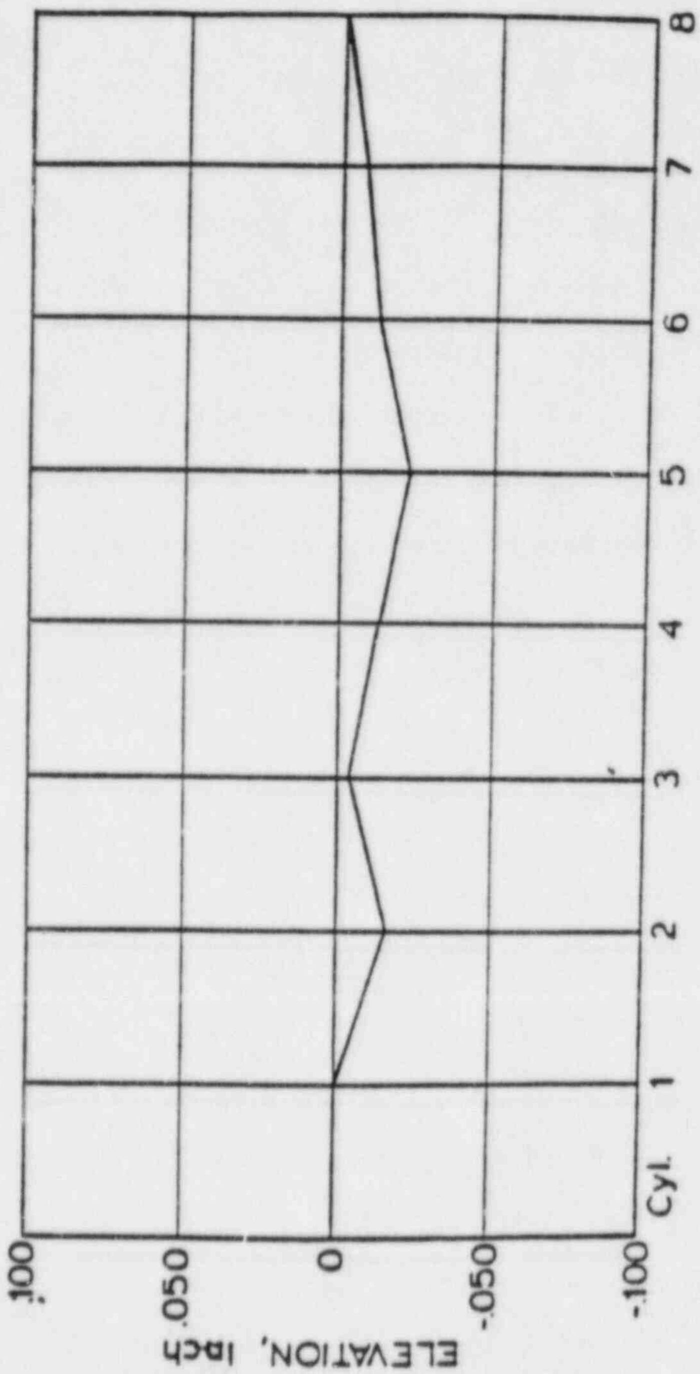


Figure 23. Elevation of the Air Side of the Cylinder Block for the Left Bank, Starboard Main Engine

return to zero at the ends because the measurements were taken using the ends as reference points. This bowing upward was a concern in the rebuilding. Upward bowing was removed in the preliminary alignment procedure and it must be remembered for future maintenance procedures.

Starboard Engine, Right Bank

Figures 20 and 21 (pp. V-6 and V-7) show a sag in the center of the engine and a slight twist with the block dropping on the exhaust side.

Starboard Engine, Left Bank

The left bank drops in the center and is similar to the right bank for the rear half of the engine. See Figures 22 and 23 (pp. V-8 and V-9). The front half of the engine is significantly different from the front half of the right bank. It warped severely where the surface had some s-twists. Severe delamination of the counterbore lip occurred in this region. The combination of metal failure, loosened tie rods, and warped surfaces may be interrelated.

Port Engine, Base

Optical sighting of the base of the port engine produced the data in Figure 24 (p. V-11). It shows the elevation of the engine from front to rear for the right and left sides of the engine. The front half of the engine was flat with some variation, but nothing over .010 inch. The rear of the engine showed a dramatic difference between the right and left sides. The left side returns to its zero point in a gradual fashion while the right side continues to drop to nearly .030 inch between cylinders 7 and 8. The dropping of the base explains variations in crankshaft deflection data.

Crankshaft Deflection

Measurements taken on crankshaft deflection show the degree to which the crankshaft is subject to bending during rotation as a result of misalignment

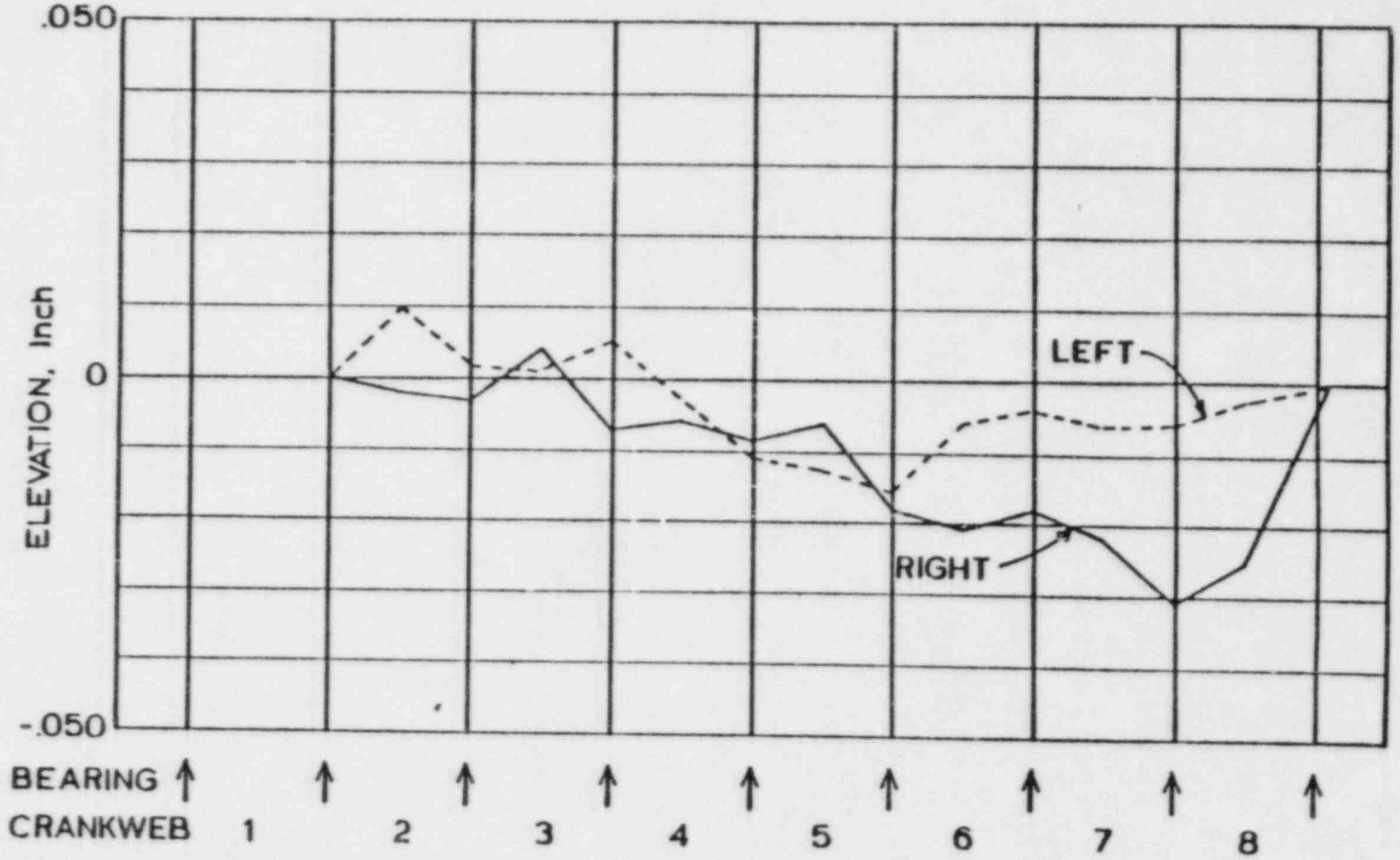


Figure 24. Elevation of the Subbase of the Port Main Engine

of the bering axes and direction. Figures 25, 26 and 27 (pp. V-13, V-14, and V-15) show an effect of misalignment of the engine and indicate where problems may arise.

Figure 25 shows historical data when the engine was hot and Figure 26 during rebuilding when the engine was cold. Deflection tolerance of .003 inch is allowed. The forward end of the engine, although changing sign (+ or -), is within acceptable limits. The aft end of the engine, however, is outside acceptable limits in both hot and cold conditions. Figure 27 shows the comparison between hot and cold. The front end of the engine is within acceptable limits. At the rear, both readings are similar and thermal changes do not alter the out-of-tolerance readings. Cold readings at the rear of the engine accurately represent hot reading for operating conditions.

Comparison between crankshaft deflection data (Figures 25, 26 and 27 and subbase elevation data (Figure 24) indicates the rear of the engine is out of alignment. The engines should be aligned before putting them back in service.

Retorquing

The preliminary report (Appendix) recommended properly retorquing the block bolts of the engines during rebuilding. While the engines were accessible, the base bolts were checked for proper torque and were found to be below acceptable limits. All structural bolts in the port engine were relaxed and retorqued according to the procedure recommended by the Enterprise Company. Retorquing was done in a proper criss-cross pattern from the center outward in three graduated steps of increasing torque. The surfaces of the blocks were checked again.

Figure 28 (p. V-16) shows the optical sighting of the port main engine blocks after relaxing and properly retorquing all the base and block bolts. Both block surfaces have a maximum of .010 inch of deflection and the previous bowing, sagging and warping had been removed.

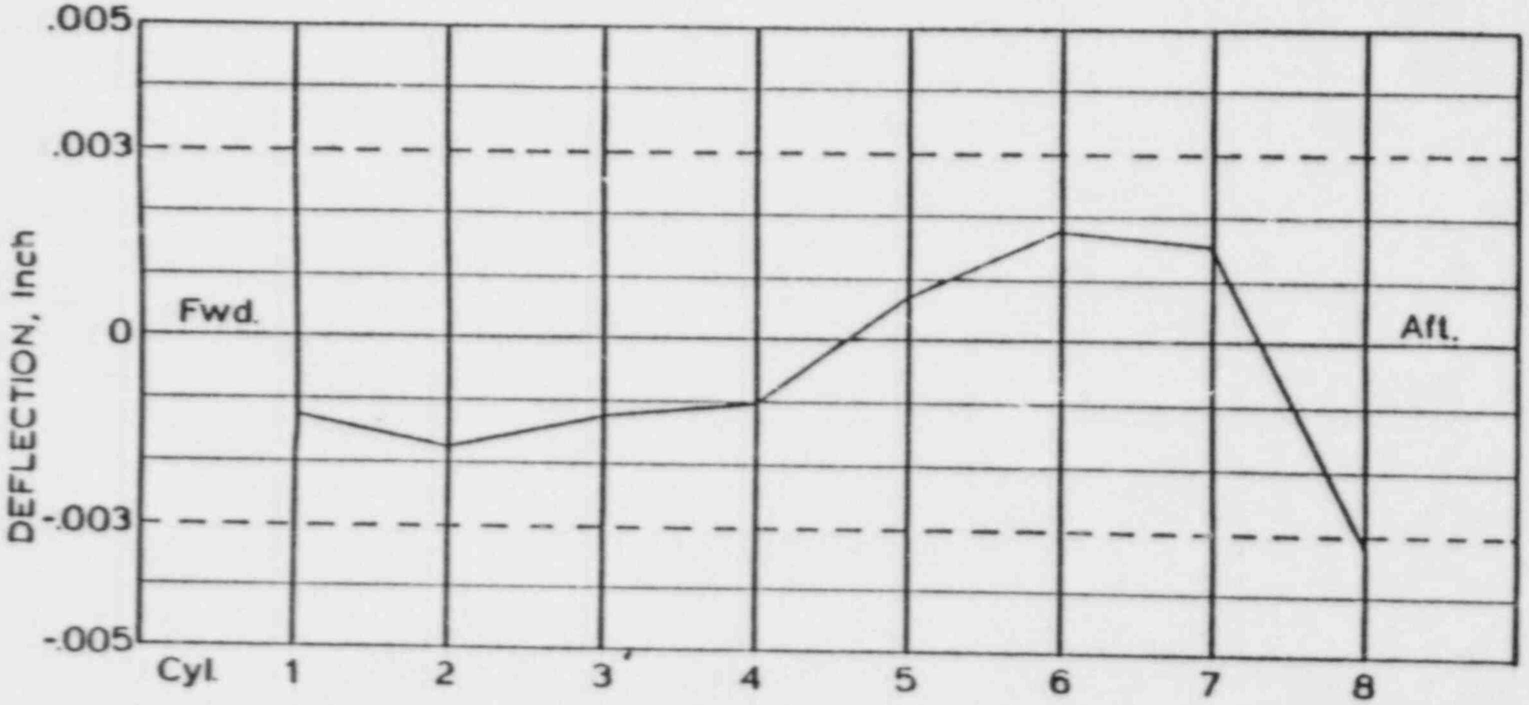


Figure 25. Crank Deflection of the Port Main Engine, Hot

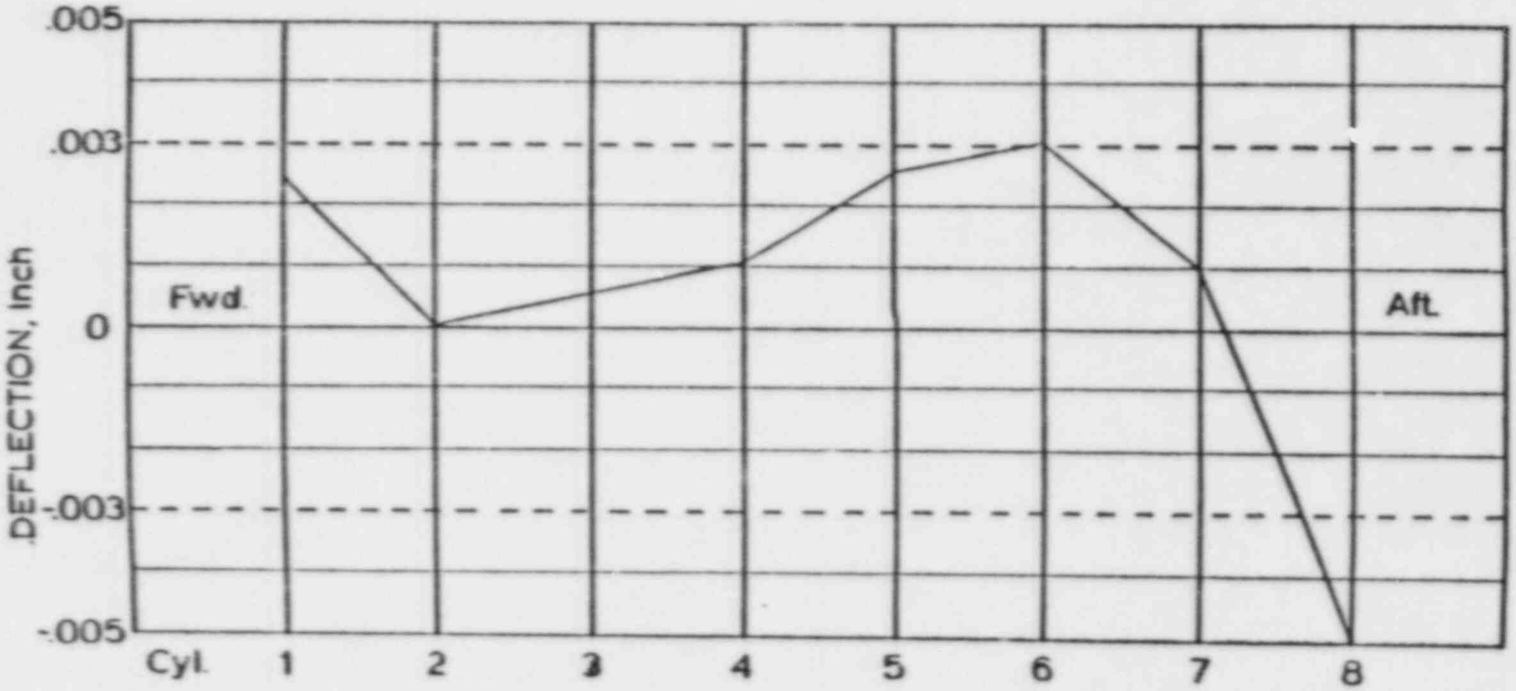


Figure 26. Crank Deflection of the Port Main Engine, Cold

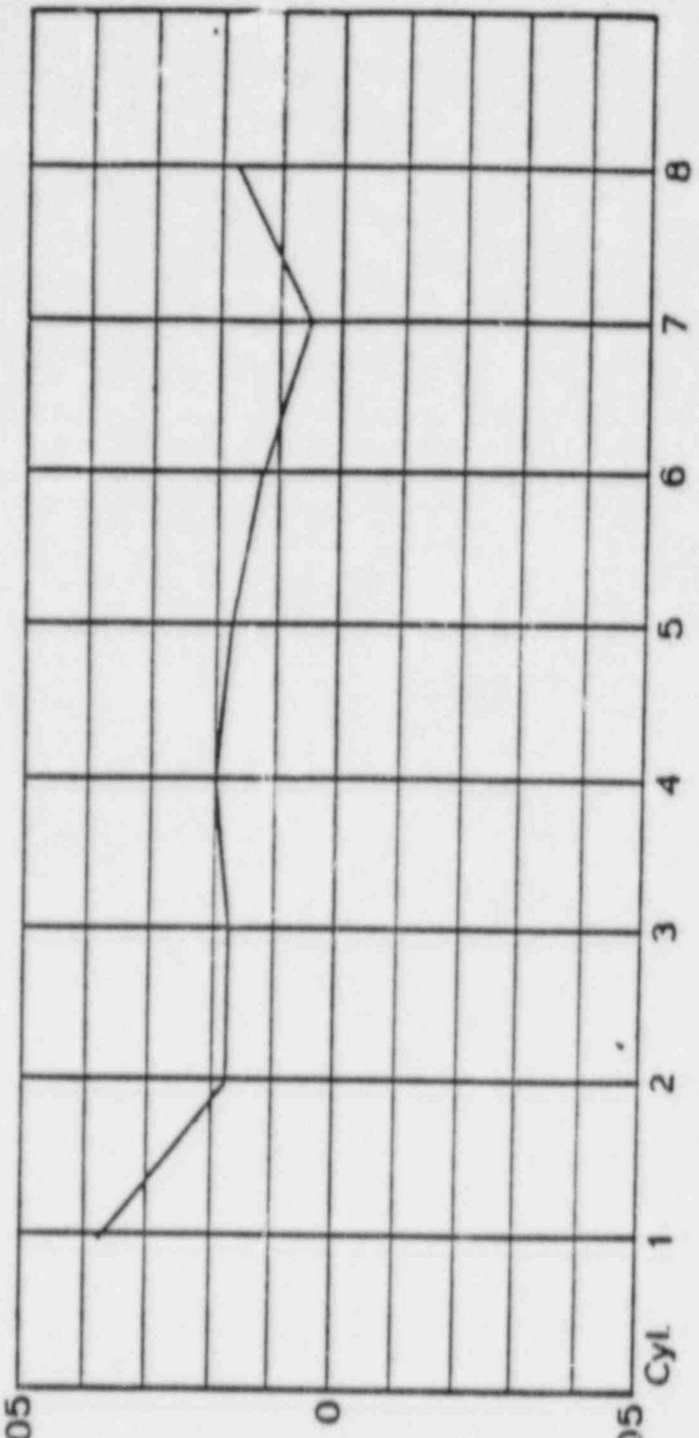


Figure 27. Change in Crank Deflection for the Port Main Engine, Hot vs Cold

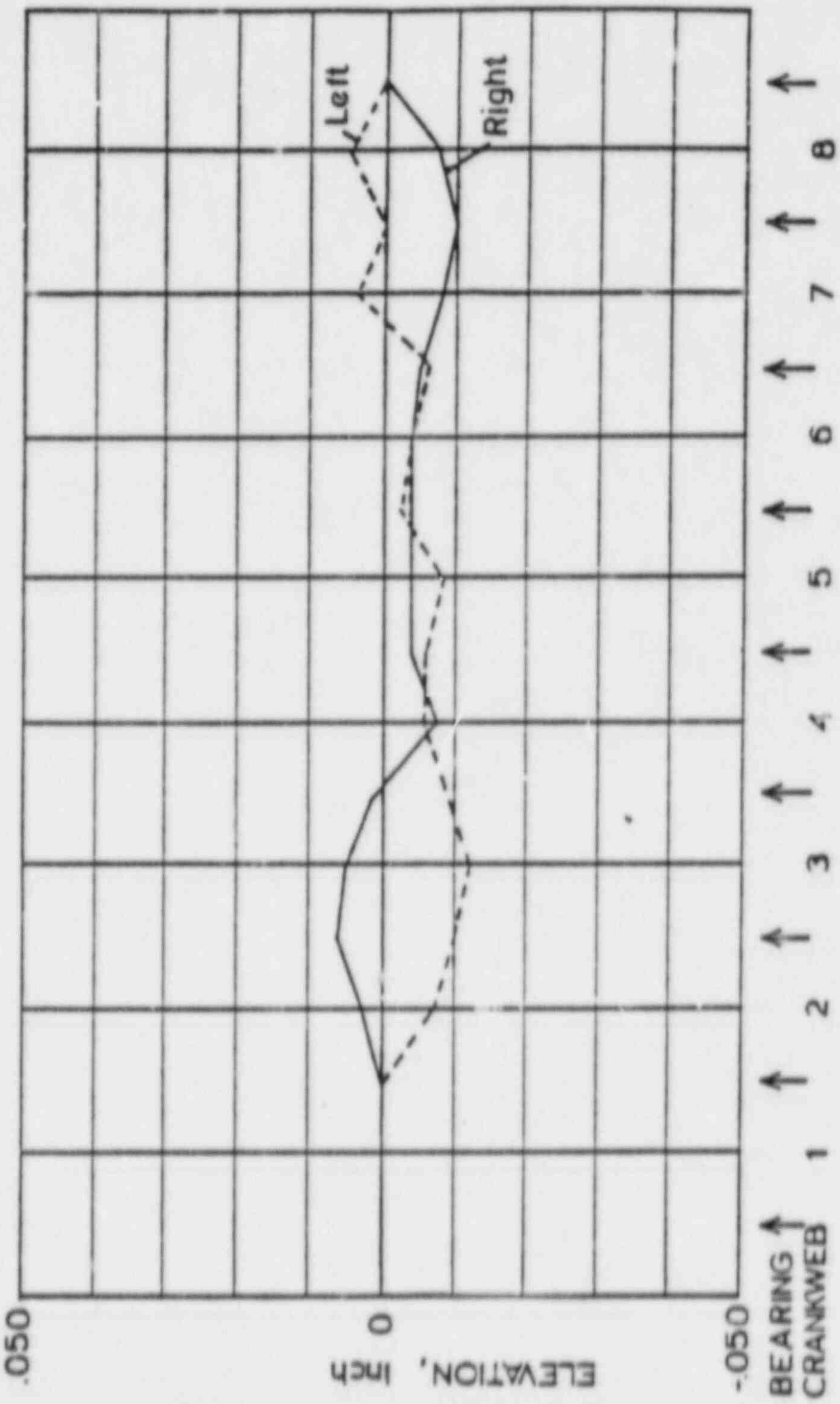


Figure 28. Elevation of Cylinder Blocks for Port Main Engine After Relaxing and Retorquing All Structural Bolts

A major portion of the misalignment was due to inaccurate prestress within the engines resulting from a relaxation of torque in the nuts and an improper retorquing procedure during repair operations. The critical effect of proper torque on all structural bolts mandates that proper torque be maintained in the future.

(16)

VI

CONCLUSIONS

Observations of the condition of the M/V Columbia engines during rebuilding through March, 1981 led to the following conclusions:

<u>Blocks</u>. Dimensional change in the blocks has occurred as a result of creep. Replacement of the blocks with new units will result in the same problem and they will have to be replaced in three to ten years. ← (11)

Failure of the blocks is due to several conditions: 1) creep and fatigue which cause fractures; 2) excessive overload of the counterbore lip; 3) close proximity of cooling water holes which produces stress; and 4) close proximity of head retaining studs and thread termination for the studs at counterbore depth which produces a high stress concentration area.

<u>Retorquing</u>. Moment from piston side thrust caused fretting between the block and base. Improperly torqued tie roads for the blocks produced a potentially catastrophic situation, and improperly torqued structural bolts throughout the engine produced severe dimensional changes. ← (12)

<u>Alignment</u>. The engines are misaligned in their current condition. ← (13)

<u>Heads</u>. The heads are manufactured with castings having excessive flaws. They appear to be adequately repaired during manufacture, but these flaws could be the cause of spurious failures.

(14)

VII

RECOMMENDATIONS

REBUILDING

(15)

Blocks: Replace the blocks for both engines.

Retorquing: Properly retorque all structural bolts.

Alignment: Realign both engines.

KEEPING OPERATIONS DATA

Counterbore Lip: Survey the counterbore lip during major overhaul and when head and/or seal failures occur.

Engines: Obtain detailed operating data in the reassembled engines.

Heads: Keep accurate historical data on head failures.

VIII

APPENDIX

PRELIMINARY ENGINE REBUILD REPORT