SONGS 2 EMERGENCY DIESEL GENERATOR 2G003
CAMSHAFT ASSEMBLY FAILURE
RCE 91-022

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EXECUTIVE SUMMARY

DESCRIPTION OF 2G003 FAILURE

On September 16, 1991, during the SONGS 2 cycle 6 refueling outage, Emergency Diesel Generator (EDG) 2G003 was started to perform surveillance testing. One hour and 10 minutes later, the EDG was manually stopped due to erratic operation. An inspection revealed extensive damage to the left bank camshaft assembly and drive train of the 20 cylinder engine.

ROOT CAUSE

The failure scenario began when the bolts for the camshaft bearing block closest to the left camshaft gear lost preload and backed out. As a result, the bearing cap lifted and lube oil flow to the bearings was reduced. The downstream bearings began to seize and severe camshaft gear assembly vibration led to failure of the camshaft assembly, power packs, and gear train.

The root cause of this event has been attributed to a combination of 5th order torsional resonance, which was known to exist in the area of the failure, and the presence of short camshaft bearing block bolts coupled with worn bearing block bolt holes.

CORRECTIVE ACTIONS

Corrective actions included reworking and repairing all EDG damage. The 5th order torsional resonance problem was corrected by the installation of a previously planned driveline coupling hub modification, during the Unit 2 cycle 6 refueling outage, which shifted the resonance away from the operating speed of the engine. The short bolt problem was corrected by the installation of correct length bolts, and the worn bolt hole problem was corrected by the installation of helicoils.

EVALUATION OF OTHER EDGs

This failure scenario would not have occurred in the other emergency diesel generators because the camshaft bearing block bolts were considered to be the correct length and were verified to be tight, and the bearing block bolt holes were in acceptable condition.

During the cycle 6 refueling outages, a driveline coupling hub modification was also installed in the other three EDG's which corrected the 5th order torsional resonance problem by shifting the torsional resonance away from the operating speed of the engine.

DESCRIPTION OF EVENT

At 9:00 pm on September 16, 1991, during the SONGS 2 cycle 6 refueling outage, Emergency Diesel Generator S22420MG003 (EDG 2G003) was started to perform surveillance testing. The EDG was loaded at 9:13 pm and ran until 10:10 pm, when it was manually stopped due to erratic operation. Just prior to stopping the EDG, the Plant Equipment Operator (PEO) stationed at the EDG observed that the EDG sounded as if it was being unloaded and that ampere indication was fluctuating. In the same time frame, a Station Technical Engineer with cognizance over the EDGs was in the vicinity of the EDG building and observed white exhaust coming from the EDG. He immediately entered the EDG building and instructed the PEO to stop the EDG. The PEO hit the emergency stop button and the EDG rolled to a stop with a loud hammering noise. No abnormal alarms were annunciated before or after the event.

A preliminary inspection of the EDG revealed extensive damage to the left bank camshaft assembly and drive train on the 20 cylinder engine. The camshaft and camshaft bearing blocks showed signs of heat buildup and inadequate lubrication, the bearing cap on the camshaft bearing block closest to the camshaft gear was found loose on the top deck, the bolted flange connection between the rear camshaft and stubshaft was found separated, the camshaft gear stubshaft support bracket was found detached from the end sheet, and damage was evident to the camshaft gear drive train. Appendix B provides a detailed discussion of the as-found condition of the EDG.

EMERGENCY DIESEL GENERATOR INFORMATION

EDG 2G003 consist of a 20 cylinder and a 16 cylinder diesel engine in tandem which drive a single electrical generator. The engines are 2 cycle and manufactured by the Electro-Motive Division of General Motors. Figures 1 to 3 illustrate the diesel design.

Camshaft Assembly Configuration

On the 20 cylinder engine, the right bank contains cylinders 1 through 10 and the left bank contains cylinders 11 through 20. The crankshaft at the rear of the engine is coupled to the generator, and the rear of the engine contains the gear train that drives the overhead camshafts for the left bank and right bank cylinders. A crankshaft gear drives a number 1 idler gear, which drives a number 2 idler gear, which drives the left bank camshaft gear, which drives the right bank camshaft gear.

Each camshaft assembly consist of 2 camshaft segments coupled in the center by a spacer. The outside ends of the camshaft segments are connected to stubshafts. The rear stubshaft holds the camshaft gear and a counterweight, while the front stubshaft holds a counterweight. The camshafts segments are connected to the center spacer and stubshafts by flanges that contain 4 machine fit dowel bolts each. The 2 camshaft segments, which contain the lobes that actuate the valves, are supported by a total of 20 bearing blocks, such that, each cylinder has 2 bearing blocks that straddle the cylinder. Each bearing block consist of lower pillow block and an upper cap, and are connected to the engine top deck by 2 bolts, 1 inboard and 1 outboard. The stubshafts are held by stubshaft support brackets which are mounted to the end sheet of the engine by 2 vertical and 6 horizontal bolts. Each stubshaft has a single bearing surface which mates with the bearing surface of the support bracket.

To simplify the discussions in this report, the camshaft segment bearing blocks on the left bank of the 20 cylinder engine will be referenced as numbers 1 through 20, with number 1 being the bearing block closest to the left bank camshaft gear.

Engine Lubrication

The main lube oil pump takes oil from the strainer housing and pumps it into the main lube oil manifold where it supplies oil to the main crankshaft bearings and connecting rods. Lube oil exiting the main lube oil manifold enters the gear train at the rear of the engine where it is channelled up through the stubshaft support brackets and into the camshafts via the bracket bearing. The lube oil travels down the center of the camshafts supplying the camshaft segment bearings and the front stubshaft bearing. Every other camshaft segment bearing has a rocker arm lube oil line which supplies lube oil to the rocker arms and lash adjusters.

EVIDENCE COLLECTION

Camshaft Bearing Block No. 1

The inboard and outboard bolts from the Number 1 Camshaft Bearing Block were found loose on the top deck of the EDG indicating that the bolts came out of position during the event. A 5th order torsional resonance has been known to exist in the 20 cylinder engine, which caused a detrimental vibratory motion in the gear train and left rear camshaft assembly. This resonance coupled with normal vibration provided a motive force for the short bolts to lose preload and back out. Appendix D discusses in detail the 5th order torsional resonance.

The inboard and outboard bolts on bearing block 1 were found to be a nominal 4 1/2 inches in length, rather than the 4 5/8 inches specified by the vendor manual. The bearing block bolt holes were worn due to previous failures and work activities. This resulted in less than normal thread contact area which contributed to the bolts loosing preload and backing out. Appendix A briefly discusses the work history of 2G003, and Appendix C discusses in detail the short bolts and worn bearing block bolt holes. Appendix G discusses in detail the mechanical testing of bearing block bolts to determine the effect of short bolts.

On bearing block 1, the threads of the outboard bolt and bolt hole were found intact indicating that the outboard bolt must have lost preload and backed completely out under vibration. The first approximately 5 threads of the inboard bolt were deformed and the first approximately 5 threads of the bolt hole were stripped, indicating that the inboard bolt lost preload, vibrated partially out, and then was pulled out. Since approximately 6 1/2 threads is the engagement of a short bolt, the bolt had vibrated approximately 1 1/2 threads out, 1/16 inch, prior to being stripped out. The inboard and outboard bolts for bearing block number 1 had polished areas and wear marks corresponding to the bolts coming loose, backing out, and vibrating in place for sometime.

The configuration of the camshaft bearing block indicates that, with the outboard bolt backed all the way out, a 1/2 thread loosening of the inboard bolt would cause an gap of approximately 1/8 inch on the outboard side of the bearing. Thus, the 1 1/2 thread backing out of the inboard bolt, with the outboard bolt backed all the way out, provided the low resistance lube oil flow path which starved the downstream camshaft bearings for oil.

The bearing shells for camshaft bearing block number 1 were found to be free of damage while most of the downstream bearings were found to be damaged due to inadequate lubrication. This indicates that bearing block number 1 was the source of the loss of lubrication for the downstream bearings.

During the previous weekly run of the EDG, operations and engineering personnel logged a drop in the operating oil pressure of the EDG from approximately 77 psig to 71 psig, which appears to correspond to the establishment of the low resistance lube oil flow path when the number 1 camshaft bearing cap began to lift.

Note, the left rear stubshaft bracket bearing, which is upstream of bearing block number 1, was found with some damage due to severe camshaft gear vibration and loss of lubrication. However, the loss of lubrication damage has been attributed to a loss of lubrication flow after the bracket detached from the engine case, and the fact the camshaft gear continued to rotate on the idler gear until the engine was shutdown.

Other Camshaft Bearing Blocks

Many of the camshaft bearing blocks and rocker arm assemblies downstream of bearing block number 1 were found to have significant damage due to inadequate lubrication and wear. The most severe damage was found on the most downstream camshaft bearing block corresponding to bearing number 20 and cylinder number 11.

The outboard bolt of bearing block 2 was found lying on the top deck while the outboard bolt of bearing block 3 was found loose but in place. The outboard bolts on bearing blocks numbers 2 and 3 were short bolts. The outboard bolts of both bearing block 2 and 3 were found with approximately 5 deformed threads and the bolt holes had approximately 5 stripped threads indicating the bolts had lost preload and backed partially out, prior to being stripped out. The inboard bolts on bearing blocks 2 and 3 were correct length bolts. The inboard bolt on bearing block 2 was found loose, but not backed out, while the inboard bolt of bearing block 3 was found tight. The inboard bolt threads and hole threads for both bearing block 2 and 3 were basically intact but excessively worn. Thus, it is evident that the correct length inboard bolts in bearing block 2 and 3 held better in the event than the short bolts in the outboard locations of bearing blocks 2 and 3, and the short bolts in the inboard and outboard locations of bearing block 1.

Camshaft Flanges

The failure mode of the stubshaft to camshaft flange dowel bolts was ductile tearing due to a combination of torsional and tensile overload.

The camshaft flange was found with a crescent shaped polished wear mark in the vicinity of a dowel bolt hole indicating that one dowel bolt failed first and that the flange connection lost some rigidity during operation. The failure of the one dowel bolt resulted in increased vibration in the vicinity of the camshaft to stubshaft flange connection, the stubshaft bracket, and the camshaft bearing blocks. Appendix E discusses in detail the analysis of the stubshaft flange failure, and Appendix G discusses in detail the mechanical testing of the dowel bolts.

The dowel bolts were made from AISI 1144 alloy, which is the vendors first choice material. However, an analysis indicated that the dowel bolt alloy contained sulfur stringers/inclusions which resulted in a significant anisotropic material with very poor mechanical properties in the transverse direction.

The camshaft to stubshaft flange holes were elongated due to the excessive torsional loading.

Camshaft Bracket

The 6 horizontal and 2 vertical bolts which hold the camshaft bracket to the end sheet failed by reverse bending fatigue followed by overload. Laboratory analysis determined that the bolts failed by overload after approximately 41,000 fatigue cycles. Since the EDG rotates at 900 rpm and is subject to 5th torsional resonance, 41,000 cycles equates to approximately 9 minutes of operation. Appendix F discusses in detail the failure analysis of the stubshaft bracket failure.

The Supervising Cognizant Engineer of the EDG was in the room of the EDG approximately 10 minutes prior to the end of the event and the EDG appeared to be operating properly. He left the EDG room and approximately 10 minutes later he noticed the white exhaust exiting the EDG building, entered the EDG room and directed the Operator to stopped the engine. Thus, the approximate 9 minutes that it took for the stubshaft bracket to fail, after the initiation of fatigue cracks in the bracket bolts, is consistent with the Engineer being in the room 10 minutes before the end of the event with the EDG appearing to operate properly.

The camshaft stubshaft bracket detached from the end sheet shortly before the camshaft to stubshaft flange connection separated due to the evidence of material deformation on the top of the end sheet, and the absence of flange wear marks which would indicate that the flange connection failed first.

Other Information

The power packs were found damaged due to piston to valve contact.

An inspection of the gear train revealed extensive damage with evidence of gear misalignment and broken bolts meshing between the gears.

FAILURE SCENARIOS

1 - Failure of the Number 1 Camshaft Bearing Block Bolts (Most Likely)

1) On the number 1 camshaft bearing block on the left bank of the 20 cylinder engine, the inboard bolt lost preload and vibrated completely out of the threaded portion of its mating hole, and the inboard bolt lost preload and vibrated partially out of the threaded portion of its mating hole.

2) The bearing cap on camshaft bearing block number 1 lifted resulting in a low resistance flow path for camshaft lube oil and the starving of downstream bearing blocks of lube oil.

3) The camshaft bearing blocks downstream of bearing block number 1 began to heat up, burn and seize, resulting in excessive vibration and torsional loading of the rear camshaft to stubshaft flange connection.

4) One of 4 dowel bolts at the rear stubshaft flange connection failed, the flange connection lost some rigidity, vibration in the area of the camshaft to stubshaft flange connection increased, and the left rear camshaft gear and stubshaft bracket began to vibrate excessively.

5) Fatigue cracks were initiated and began to propagate in the stubshaft bracket bolts.

6) The stubshaft bracket, stubshaft flange connection and camshaft bearing blocks in the area, were subjected to increasing vibration which lead to increasing degradation.

7) Approximately 9 minutes after fatigue cracks initiated in the stubshaft bracket bolts, the cracks propagated to the extent that the bolts failed due to overload, the stubshaft bracket detached from the end sheet, and the stubshaft flange connection separated with the remaining 3 dowel bolts failing due to overload.

8) Timing was lost to the left and right bank cylinders resulting in a loss of coordination between the pistons and valves, and power pack damage. The gear train was damaged due to gear misalignment and broken bolts meshing between the gears. The Supervising Engineer with cognizance over the EDG notice white smoke exhausting from the EDG, enter the EDG room, observed abnormal operation, and directed the PEO to shutdown the EDG.

2 - A Failure Of The Left Rear Camshaft To Stubshaft Flange Connection (Less Likely)

In response to the 2G003 event, an inspection was performed on the 20 cylinder engine of 3G003 to ensure it was not experiencing a problem with camshaft bearing block bolts coming loose in the vicinity of the left rear camshaft gear. The 3G003 bearing block bolts were found tight, bearing block bolts were replaced in the vicinity of the left rear camshaft gear to ensure they were the correct length, and it was concluded that 3G003 was not experiencing a camshaft bearing block problem. However, during the inspection, the left rear camshaft to stubshaft flange connection was found to be degraded. One of 4 dowel bolts was found to be broken while cracks were found in the other 3 dowel bolts. The root cause of the 3G003 flange degradation has been attributed to a combination of poor quality 1144 alloy dowel bolting material coupled with 5th order torsional resonance and normal engine vibration. Appendix I discusses in detail the 3G003 stubshaft flange connection degradation event.

Since poor quality dowel bolting material was found in the degraded flange connection of 3G003 and the failed stubshaft flange connection of 2G003, and since 2G003 and 3G003 had similar 5th order torsional resonance problems, a failure of the camshaft to stubshaft flange connection was considered as a possible initiating event of the 2G003 failure. However, based on the following discussion, a failure of the flange connection is not considered the initiating event.

1) An analysis of the failed 2G003 dowel bolts indicates that 1 dowel bolt failed first under shear and the other 3 bolts failed due to a combination of torsional and tensile overload. Since it is apparent that the torsional overload must have been the result of the camshaft seizing, and that the tensile overload must have been the result of the flanges separating when the bracket detached from the end sheet, a failure of the flange connection could not have been the initiating event.

2) In the 1987 2G003 loose flange connection event and the recent 3G003 degraded flange connection event, there was no loss of lubrication damage.

3) In the 1987 2G003 loose flange event, an inspection of the flange faces revealed excessive fretting. To the contrary, in the 2G003 event, there was no excessive fretting, only a small wear pattern attributed to 1 bolt failing, prior to complete flange failure.

4) If the flange connection started to fail first, the loss of rigidity and increased vibration should have damaged the bearing surface of bearing block 1. To the contrary, there was no damage to the bearing surface of bearing block 1.

<u>3 - A Failure Of The Left Rear Camshaft Stubshaft Bracket (Less Likely)</u>

The failure of the stubshaft bracket was considered as a possible initiating event because of past failures of the left rear brackets on the 20 cylinders engines of 2G003 and 3G003. The following arguments were also considered as possible factors supporting a bracket failure, 1) the bracket was redesigned and made stronger transferring stresses to the bracket bolts which were not made stronger as a part of the redesign, and 2) a piece of broken bolt material which was meshed through the camshaft gear train displaced the bracket and fractured the bracket bolts. However, based on the following discussion, a failure of the stubshaft bracket was not the initiating event.

1) In October 1989, the left rear stubshaft bracket for 2G003 was replaced with a new design and stronger bracket approved by the vendor and SCE. Also in the 1988 and 1989 time frame, the new design and stronger brackets were installed in the 2G002, 3G002 and 3G003 EDGs. Since the installation of the new design and stronger brackets, there has not been a bracket failure at SONGS.

2) The 2G003 stubshaft bracket was inspected and found intact without the cracks or fractures typical of past failures.

3) In past stubshaft bracket failures at SONGS, there has not been a loss of lubrication problem. Also, the vendor does not recall lubrication problems with any past bracket failures at other facilities. However, in the 2G003 event, there was significant loss of lubrication damage.

4) It was postulated that perhaps the bracket bolts failed and the bracket separated from the end sheet, and since the camshaft lubrication oil is channelled through the bracket end sheet interface, the flow path was breached which resulted in the loss of lubrication. However, the as-found condition of the stubshaft bearing and the lack of damage to the number 1 camshaft bearing block are inconsistent with this postulated scenario.

5) The bracket bolts failed by fatigue followed by overload in approximately 9 minutes, which does not support a failure of the bracket due to displacement by bolting material meshing through the gear train. In addition, if this failure mode was true, the camshaft would have stopped rotating when the bracket detached from the end sheet and the stubshaft flange separated from the camshaft flange. Thus, there should not have been the loss of lubrication damage to camshaft bearings.

6) Stress testing of the new design and stronger brackets after installation in 1989 indicated acceptable stress levels with an adequate factor of safety.

7) In the 1981 and 1984 bracket failure events, there were a total of 3 bolt failures associated with bearing block number 1. In the 1981 event the inboard and outboard bolts failed and in the 1984 event the inboard bolt failed. In all 3 failures, the bolts fractured in the threaded area. In this recent event, the bolts for bearing block number 1 did not fracture.

As discussed in Appendix G of this report, the failure mode of both correct and short length bearing bolts subjected to high loading is to fracture, not to back out or strip out. Thus, it is reasonable to conclude that, if the bracket failed first, the increased loading of the number 1 bearing block should have resulted in a fracture of the bearing block bolts. Since the number 1 bearing block bolt was found to have backed out and stripped out, the bracket did not fail first.

4 - Poor Workmanship During Previous Work Activities (Less Likely)

In June 1991, approximately 3 months prior to the failure, the left bank camshaft gear was replaced on the 20 cylinder engine of 2G003 to satisfy a 250 hour limit on camshaft gear operation due to the 5th order torsional resonance problem. During work activities, cardboard was installed under a camshaft bearing cap to secure engine timing, a common and vendor approved practice. In the early stages of the investigation, it was hypothesized that the number 1 bearing block cap may have come loose because either the cardboard was left in place after the work activities or that the camshaft bearing block bolts were not properly torqued after work activities. In addition, a piece of cardboard debris of unknown origin was found in the engine which appeared to support this potential failure scenario. However, based on the following discussion, it is concluded that this was not a valid failure scenario.

1) In the camshaft gear replacement MO, there is documented evidence of the removal of the cardboard and the proper torquing of the camshaft bearing block bolts with a calibrated torque wrench.

2) A machinist present during the camshaft gear replacement activities recalled the removal of the cardboard and the torquing of the camshaft bearing block bolts.

3) On the left bank of the 20 cylinder engine the number 2 camshaft bearing block would be the bearing of choice to secure the timing with cardboard due to the attachment of a rocker arm lube line on the number 1 camshaft bearing cap. Thus, if there was a problem with leaving the cardboard in place or improper torquing of the bearing block bolts, it should have shown up on the number 2 bearing block. To the contrary, in the EDG failure, the number 1 bearing block cap came off.

4) Typically, the cardboard used to secure the camshaft is spare part box material. An analysis of the cardboard debris found on the top deck, as discussed in Appendix H, did not match microscopically or chemically to a sample of typical cardboard material or a sample of typical gasket material. The analysis was inconclusive about the origin of the cardboard debris.

ROOT CAUSE IDENTIFICATION

The root cause of the EDG failure is a combination of 5th order torsional resonance, which has been known to exist in the 20 cylinder engine, and the presence of short camshaft bearing block bolts in worn bearing block bolt holes.

The procurement and installation of short camshaft bearing block bolts during previous work activities contributed to this EDG event. Although a reasonable search did not reveal the procurement trail of the short bolts, the current MKW Power Systems dedication process will verify that future procurements of bolts are the correct length. Appendix C provides a detailed discussion of the procurement of bearing block bolts.

During this root cause investigation, it was discovered that the computer based Spare Parts Information System (SPIS) incorrectly specified the length of camshaft bearing block bolts as being a nominal 4 1/2 inches in length rather than the 4 5/8 inches specified by the vendor. Although this error did not contribute to the procurement of the short bolts, Procurement Engineering has corrected this error.

EVALUATION OF OTHER SUSCEPTIBLE DIESEL GENERATORS

The other emergency diesel generators (2G002, 3G002, and 3G003) are the same design as 2G003. Based on the following discussions, it is concluded that they will not experience the same failure as 2G003.

Evaluation Of 2G002 and 3G002

The failure scenario of 2G003 would not occur in 2G002 or 3G002 because the EDGs have not experienced the same magnitude of 5th order torsional resonance as 2G003. The camshaft bearing block bolts are considered to be original and of the correct length. The bolts holes were considered to be in good condition, because they have not experienced a stubshaft bracket or camshaft failure. In addition, a torque check verified the that the camshaft bearing block bolts in both the 16 and 20 cylinder engines were tight.

During the Units 2 and 3 cycle 6 refueling outages, a driveline coupling hub modification was installed which corrected the 5th order torsional resonance by shifting the resonance away from the operating speed of the engine.

Evaluation Of 3G003

After the 2G003 failure, a torque check verified that the 3G003 camshaft bearing block bolts in both the 16 and 20 cylinder engine were tight, and the camshaft bearing block bolts on the 4 bearing blocks closest to the camshaft gear on the left bank of the 20 cylinder engine were replaced to ensure they were the correct length. The bolt holes were considered to be in acceptable condition because 3G003 had experienced only 1 bracket failure in the past. Thus, although 3G003 has had a similar magnitude 5th order torsional resonance as 2G003, the correct length camshaft bearing block bolts in the vicinity of the camshaft gear coupled with good condition bolts holes were adequate to prevent a failure similar to 2G003.

During the Unit 3 cycle 6 refueling outage, a driveline coupling hub modification was installed which corrected the 5th order torsional resonance by shifting the resonance away from the operating speed of the engine. Also, the left rear camshaft segment bearing block bolts for bearings 5 through 10 were verified to be the correct length.

CORRECTIVE ACTIONS

Completed Corrective Actions

The 5th order torsional resonance problem was corrected by the installation of a previously planned driveline coupling modification, which shifted the resonance away from the operating speed of the engine, in accordance with NCR 90080184, MO 90062620, and FCN S5539M.

The short bolts were replaced with correct length bolts, and the worn and stripped bolt holes were repaired by the installation of helicoils, in accordance with NCR 91090168 and MO 91091835.

The EDG was repaired and reworked to correct all damage, as a part of previously scheduled overhaul activities, during the Unit 2 cycle 6 refueling outage. The NCRs and MOs which performed the work are available in the San Onofre Maintenance Management System (SOMMS) and Corporate Document Management.

Recommendations

During the previous 2G003 weekly surveillance run, the oil pressure of the 20 cylinder engine was noted to have decreased from approximately 77 psig to 71 psig, which may have corresponded to a the partial lifting of the number 1 camshaft bearing block cap. In discussions with Station Technical and MKW Power Systems representatives, it was decided that it would be prudent to incorporate guidance into the EDG operating procedures to contact Station Technical for an evaluation whenever oil pressures deviate from normal. Thus, Station Technical will be providing Operations with the normally expected operating oil pressures for each EDG, and Operations will be incorporating the normally expected operating oil pressures into EDG Operating Instructions. The Operating Instructions will require notification of the Station Technical for evaluation, whenever oil pressure deviates from normal.

The Maintenance Procedure for overhauling the EDGs does not include a section for working the EDG camshaft assemblies. Although the corrective actions taken should eliminate future camshaft assembly failures and associated repair activities, it would be prudent for the overhaul procedure to incorporate a section on the disassembly and reassemble of the camshaft assemblies, including a section on the locking of the camshaft to secure timing during work activities.

10CFR21 REPORT EVALUATION

The 5th order torsional resonance problem has been known to exist at SONGS and was the determined to be the root cause of previous stubshaft bracket failures. The NRC was made aware of the bracket failures by a 10CFR21 report by Morrison-Knudsen in May of 1988.

The short bolts which were found in the 2G003 EDG do not appear to be originally supplied bolts and a reasonable search did not reveal the circumstances of their procurement and installation. In any case, during the investigation, 3 short bolts located in bearing blocks 6 and 8 were found to be tight and still capable of performing their design function. The 3 short bolt holes were located in good condition bolt holes and in an area were 5th order torsional resonance has not been a problem. Based on this finding and the results of the mechanical testing of bearing block bolts, it is apparent that short bolts can perform their design function, provided they are located in acceptable bolt holes.

The worn bolt holes were a function of past failures and rework activities. Normally, slightly worn bolt holes would not be a problem, but worn bolt holes coupled with short bolts and a detrimental 5th order torsional resonance are considered to be the root cause the 2G003 event. The worn bolt holes were not a design defect but rather a function of EDG failures and insufficient rework activities.

Since the NRC is aware of the torsional resonance problem and this event was evaluated for reportability as an LER (an LER was not required), this failure is not considered to be reportable under 10CFR21.

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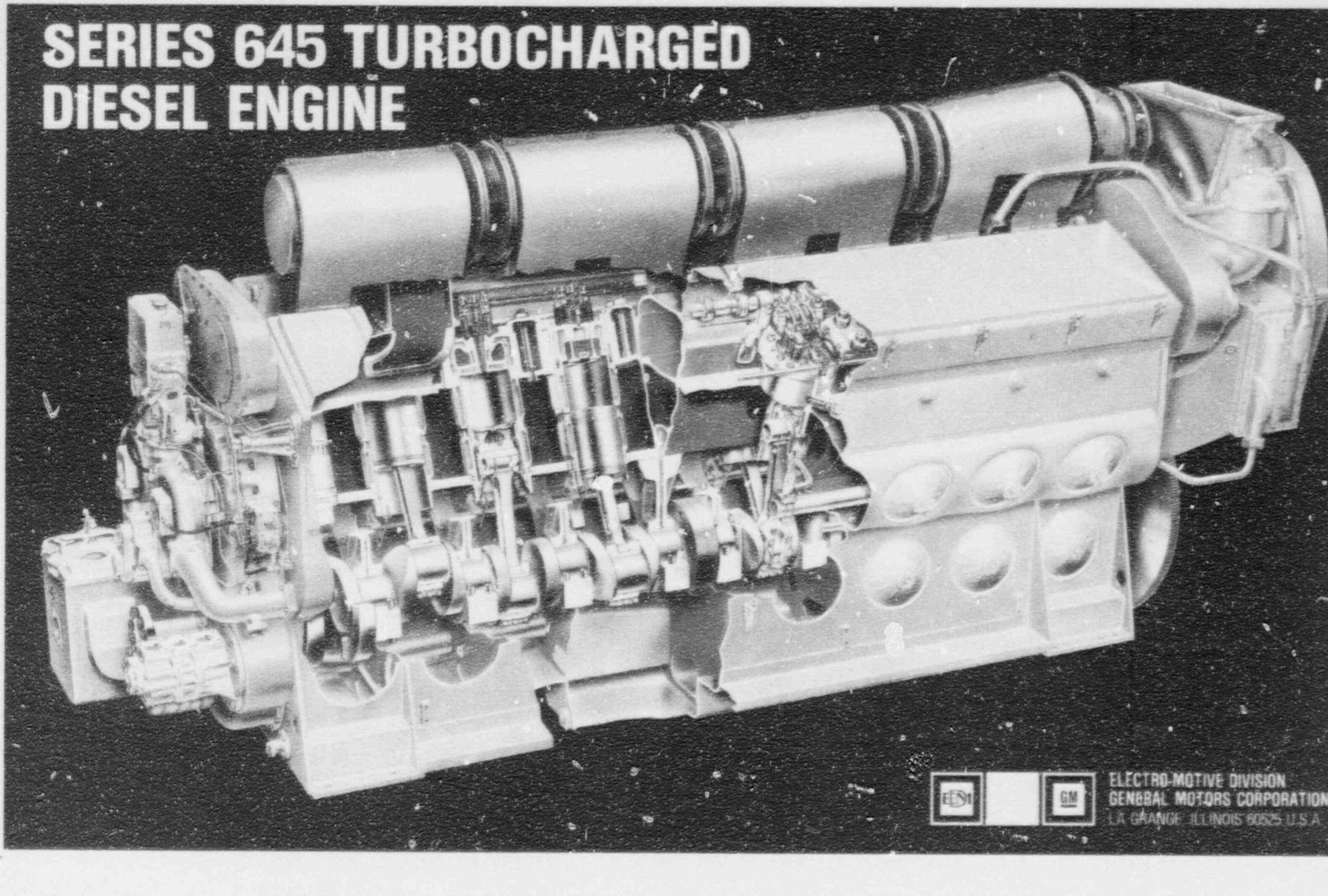
FIGURES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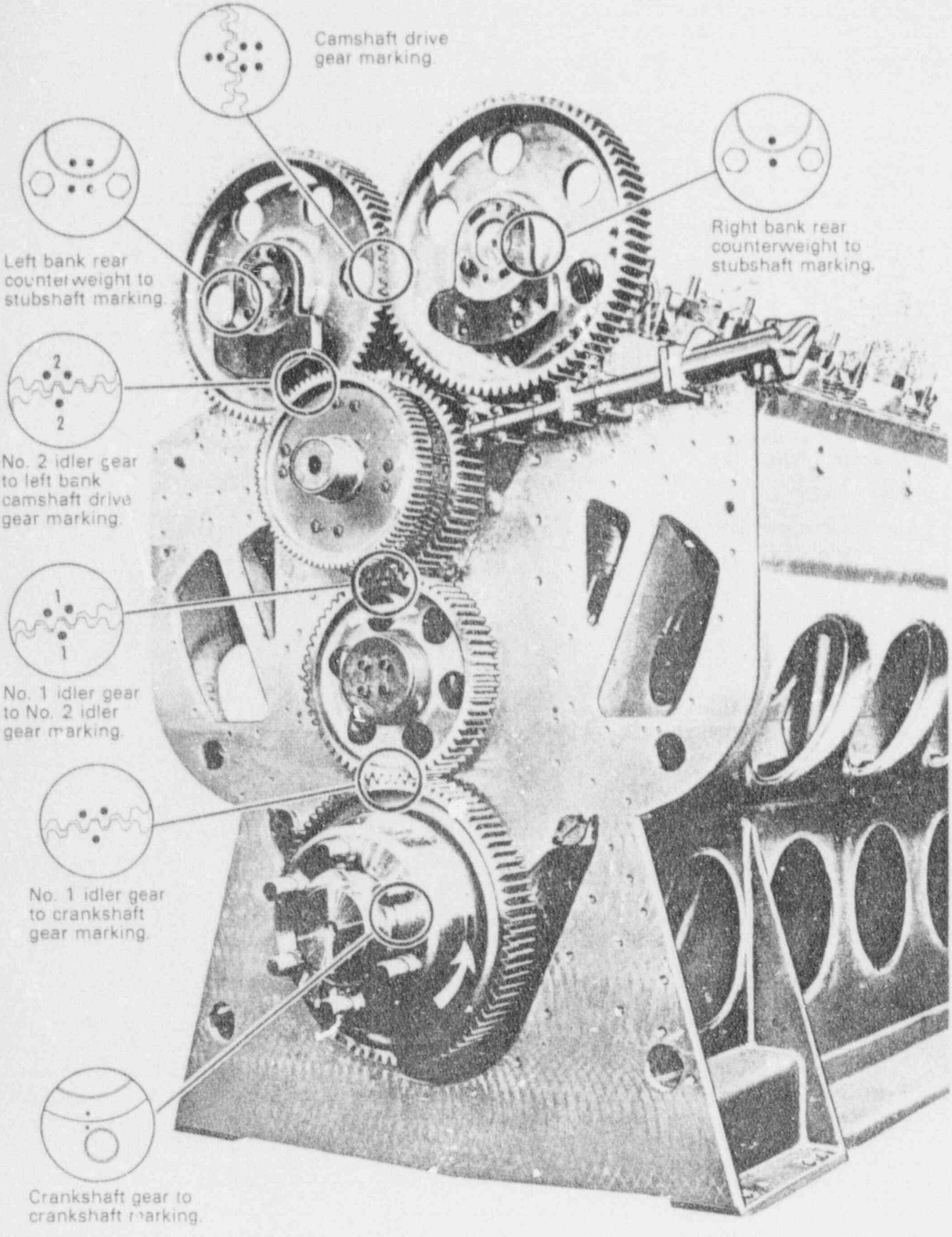
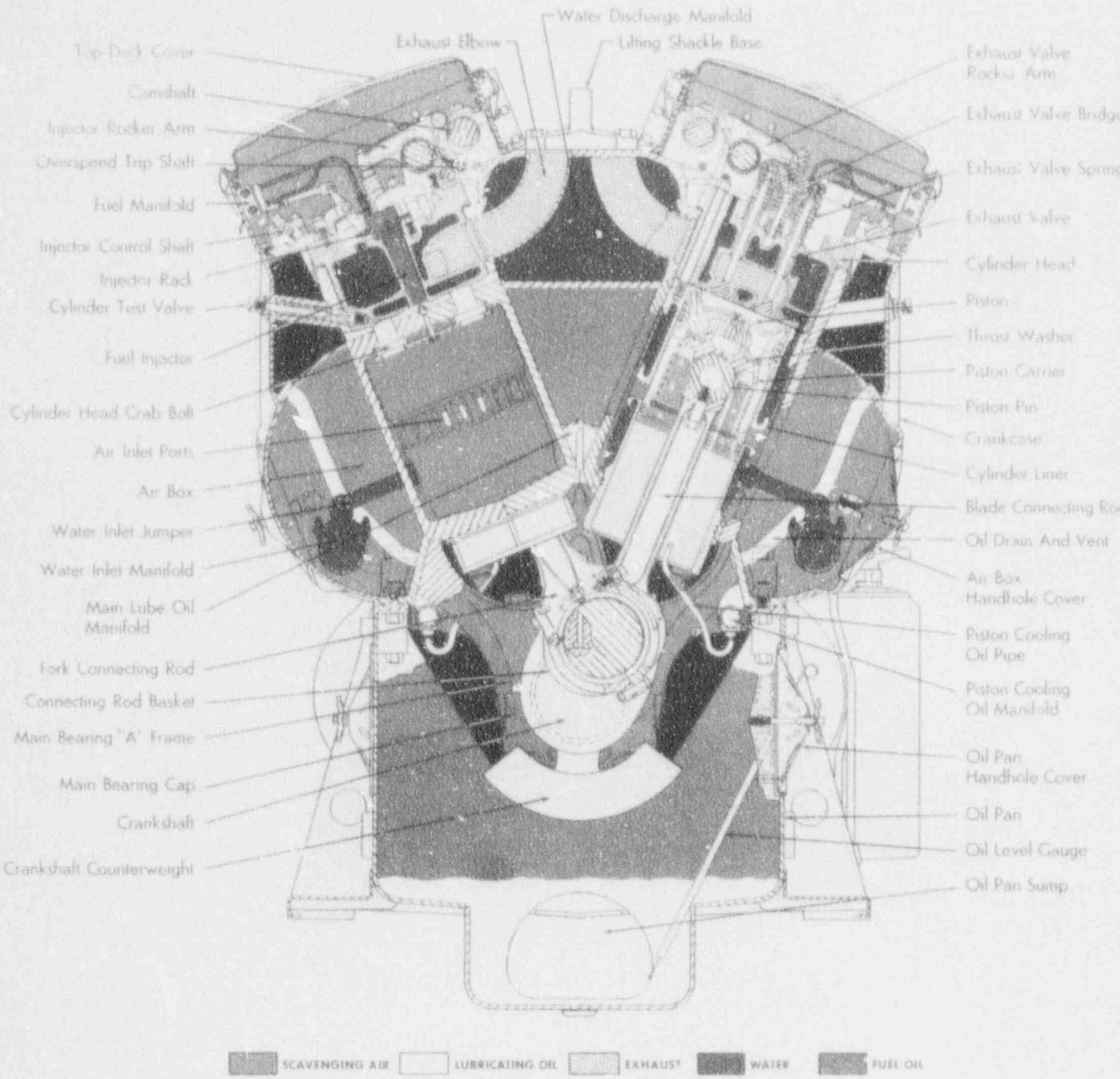


Fig. 7-21 - Camshaft Gear Train Marking



645 SERIES DIESEL ENGINE

ELECTRO-MOTIVE DIVISION
GENERAL MOTORS CORPORATION
LA GRANGE, ILLINOIS, U.S.A.

APPENDICES

APPENDIX A
Work History of 2G003

1981. EDG Failure During Pre-operational Testing

The following problems were found with the left bank rear camshaft assembly on the 20 cylinder engine. The vertical attachment leg of the stubshaft bracket was broken, 2 of 4 bearing cap bolts on the bracket were broken, the 2 bolts on the number 1 camshaft bearing block were broken in the threaded area, and the rocker arm oil line was broken.

At the time, this specific failure had been reported to only have occurred in 2 other EMD 20 cylinder engines, both in stationary commercial service. A final report concluded that this was a relatively isolated occurrence, that there was no generic issue, and that the EDG should be repaired and returned to service. A follow-up report by EMD attributed the failure to inadequate torquing of the bracket bolts which allowed movement of the bracket and eventual failure. Thus, it was considered a human error problem rather than a design or mechanical problem. The EDG was repaired and placed-in-service.

Reference: CDM Documents C810728G 7-28-81; C8109010 9-1-81; C810923G 9-23-81.

Nov 1984. EDG Problems Found During Planned Maintenance Activities

The following problems were found with the left bank rear camshaft assembly on the 20 cylinder engine. The stubshaft bracket was broken, 2 of 4 bolts were sheared on the stubshaft bracket, and 1 of 2 bolts was sheared on the number 1 camshaft bearing block.

The preliminary analysis attributed the failure to improper alignment of the stubshaft support bracket. The EDG was repaired and returned to service.

Reference: NCR 2-888; MO 84072372; MO 84111056; MO 84112456.

Sep 1987. EDG Problems Found During The Replacement Of The Stubshaft Bracket With A Higher Strength Bracket

The following problems were found with the left bank rear camshaft assembly on the 20 cylinder engine. The flange connection between the camshaft and the stubshaft had loose dowel bolts and the flange connection between the camshaft and the spacer had a broken dowel bolt. A crack was found in the removed stubshaft bracket during a subsequent inspection at EMD.

The loose dowel bolts at the camshaft to stubshaft connection were attributed to under torquing and the broken dowel bolt at the camshaft to spacer connection was attributed to over torquing. EMD stated that they would provide a complete discussion of stubshaft bracket failures with recommendations under a separate report.

The EDG was repaired and returned to service.

Reference: NCR 2-2082; NCR 2-2119; MO 87081407; MO 87090090; Memorandum for File, 12-26-1989, H. Shutter; EMD Report, 1-14-88, C. Cheng.

Oct 1989. Replaced Stubshaft Bracket With New Design

On the left bank rear camshaft assembly on the 20 cylinder engine, a new design bracket was fitted to the case. Also, the #1 idler gear, #2 idler gear and left camshaft gear were replaced due to excessive wear.

Reference: NCR 2-2972; NCR 2-3001; MO 89012553; MO 89101785; MO 89102990.

Jun 1991. Replaced The Cam Gear

The left camshaft gear was replaced on the 20 cylinder engine to satisfy the vendor imposed 250 hour run limit due to 5th order harmonic vibration.

Reference: NCR 2-3099; NCR 90080184; MO 90061854.

Sep 1991. EDG Was Manually Stopped Due To Erratic Operation During A Surveillance Run

The following problems were found with the left bank rear camshaft assembly on the 20 cylinder engine. There was extensive damage to the complete camshaft assembly and drive train, as well as other damage.

See this Root Cause Investigation for details.

The EDG was repaired and returned to service.

Reference: For actions taken on 2G003 see NCR 91090129; NCR 91090168; MO 91091294; MO 91091835; MO 91091837; MO 91091977; MO 91101694. For actions taken on 2G002 and 3G002 see MO 91100917, MO 91110219, MO 91091537, MO 91091650, MO 91100429. For actions taken on 3G003 see Appendix J, 3G003 Work History.

APPENDIX B
As-Found Condition of 2G003

This appendix documents the as-found condition of the 20 cylinder engine of 2G003 during early inspection and during disassembling of the camshaft and gear train assembly.

As-Found Damage Assessment

The following is a general damage assessment of the 20 cylinder engine of 2G003.

1) The camshaft, rocker arm assemblies, and camshaft bearing blocks were found with varying degrees of discoloration and damage due to a lack of lubrication and heat buildup. Bearing block number 1 showed no degradation and bearing block number 20 showed the worst degradation. The bearing blocks between 1 and 20 showed varying degrees of damage, but generally the blocks closest to bearing block 20 showed the worst damage.

2) The rear camshaft to stubshaft flange connection was found separated with the four dowel bolts broken, the camshaft was found bent at the end closest to the camshaft gear.

3) Camshaft bearing block number 1 was found with the upper cap and 2 bolts lying on the top deck, and the rocker arm lube oil line was found broken at both ends and lying on the top deck. The bearing block was found lifted at the outboard edge with some minor deformation of the key and key way. Approximately 5 threads of the inboard bolt hole were found stripped while the threads of the outboard bolt hole were found basically intact. The last approximately 5 threads of the inboard bolt were deformed while the outboard bolt threads had virtually no deformation. The inboard and outboard bolts were found to be slightly shorter than specified by the vendor.

4) Camshaft bearing block number 2 was found in place, but with the outboard bolt lying on the top deck and the inboard bolt loose but in place. The bearing block was found lifted at the outboard edge with some minor deformation of the key and key way. Approximately 5 threads of the outboard bolt hole were found stripped while the threads of the inboard bolt hole were found intact. The last approximately 5 threads of the outboard bolt were deformed while the inboard bolt threads had no deformation. The outboard bolt was found to be shorter than specified by the vendor while the inboard bolt was found to be the correct length.

5) Camshaft bearing block number 3 was found in place with the outboard bolt loose but in position and the inboard bolt tight. The bearing block was found lifted at the outboard edge. Approximately 5 threads of the outboard bolt hole were found stripped while the inboard threads were found basically intact. The last approximately 5 threads of the outboard bolt were found deformed while the inboard bolt threads had virtually no

deformation. The outboard bolt was found to be shorter than specified by the vendor while the inboard bolt was found to be the correct length.

6) The left rear stubshaft bracket was found detached from the engine end sheet but with the camshaft gear still engaged on the number 2 idler gear. The stubshaft flange was chamfered where it wore against a power pack crab bolt, after the bracket detached from the end sheet and the camshaft gear continued to rotate on idler gear . The center third of the bracket stubshaft bearing surface was found in generally good shape while the outside thirds of the bearing surface were found with some damage due to vibration and loss of lubrication. The 2 vertical and 6 horizontal bracket bolts were found broken. The end sheet where the stubshaft bracket bolts to the case was found with deformation due to the bracket pounding on the end sheet.

7) The left and right camshaft gears, the number 1 and 2 idler gears, and the crankshaft gear were found with significant tooth damage due to misalignment, vibration and the meshing of bolt pieces through the gears.

8) The power packs were found with bent valve stems and damage due to the pistons colliding with the valves.

9) The turbo charger housing and camshaft gear housing were found with wear damage due to the camshaft gear rubbing on the housings during the failure.

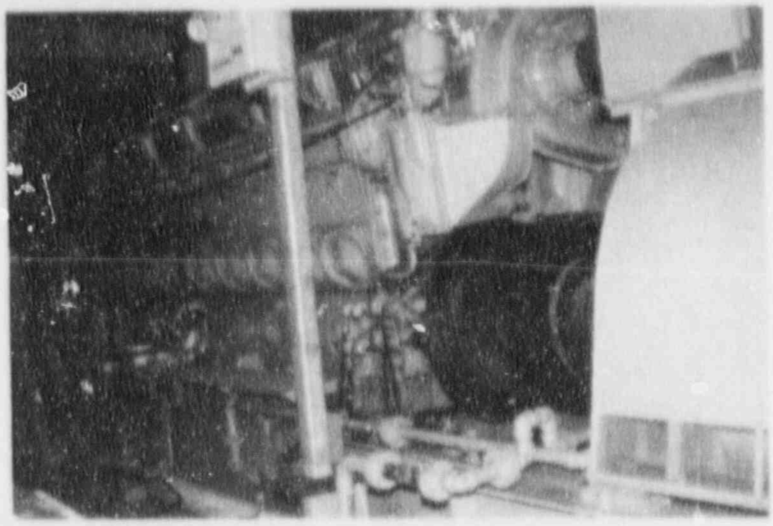


Figure B.1: Overall view of the left side and rear end of the 20 cylinder engine of 2G003.

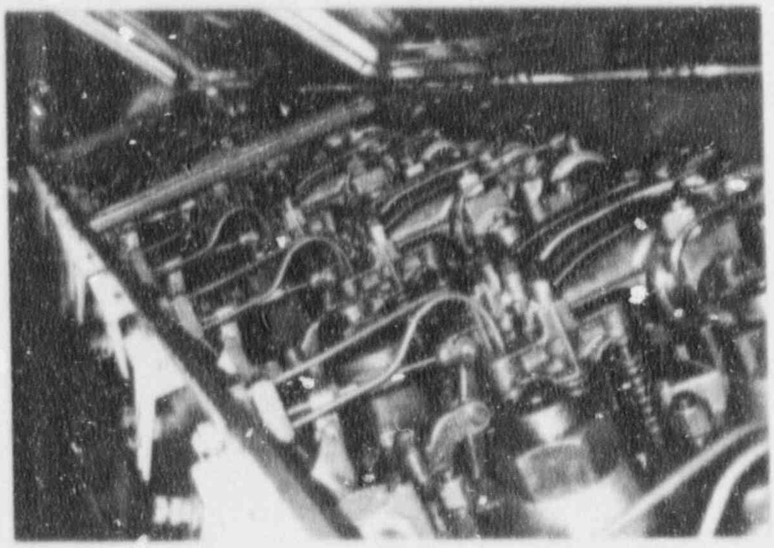


Figure B.2: Overall view of the left top deck area of the engine.

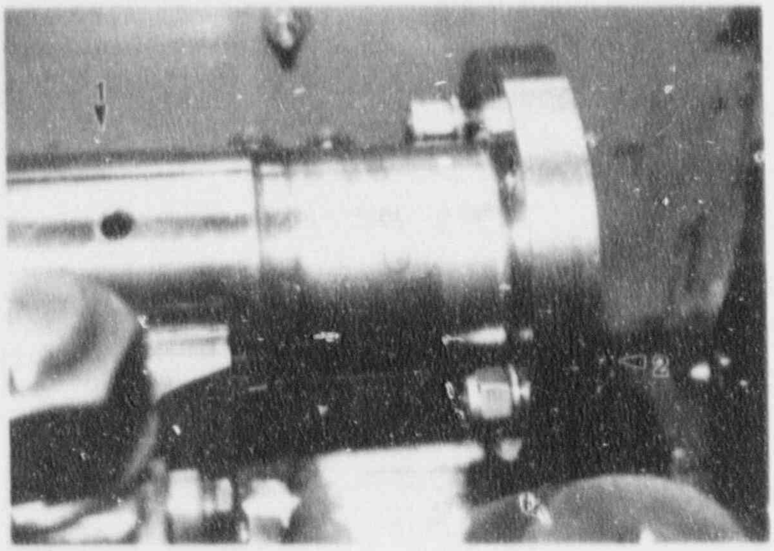


Figure B.3: View of the rear end of the left rear camshaft segment. Arrow 1 points to the camshaft bearing surface associated with camshaft bearing block number 1, and arrow 2 points to the broken dowel bolts at the separated camshaft to stubshaft flange connection. The good condition of the camshaft bearing surface for bearing block number 1 supports the accepted failure scenario, where the initiating event was the bearing cap coming loose.

Figure B.4: View of the left rear top deck area in the vicinity of cylinder number 20. The arrow points to bearing cap number 1, shown were it was found lying on the top deck.

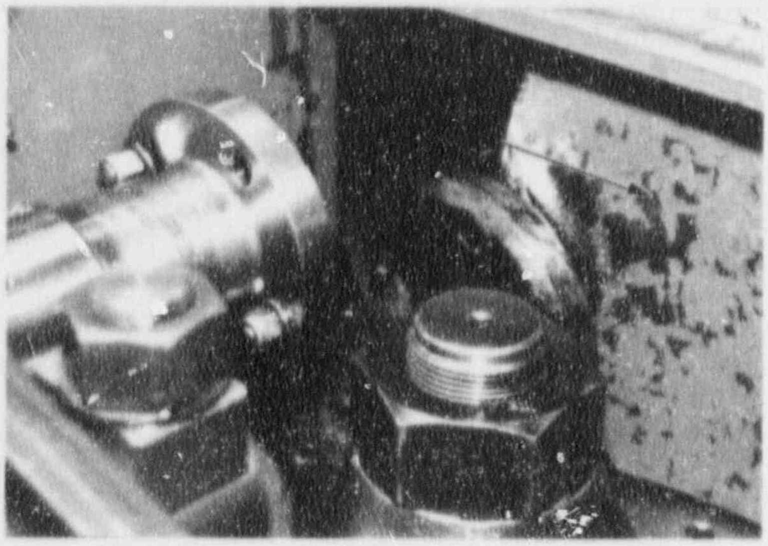


Figure B.5: View of the rear end of the left rear camshaft segment flange and the stubshaft flange. The arrow shows the direction in which the stubshaft moved after the bracket detached from the end sheet and th[illegible]ange connection was pulled a part. Note, the deformation and discoloration [illegible] end sheet. The chamfered wear surface on the stubshaft flange was the res[illegible] flange rubbing against a crab bolt, when the camshaft gear and stubshaft continued to rotate, after the bracket detached from the engine.

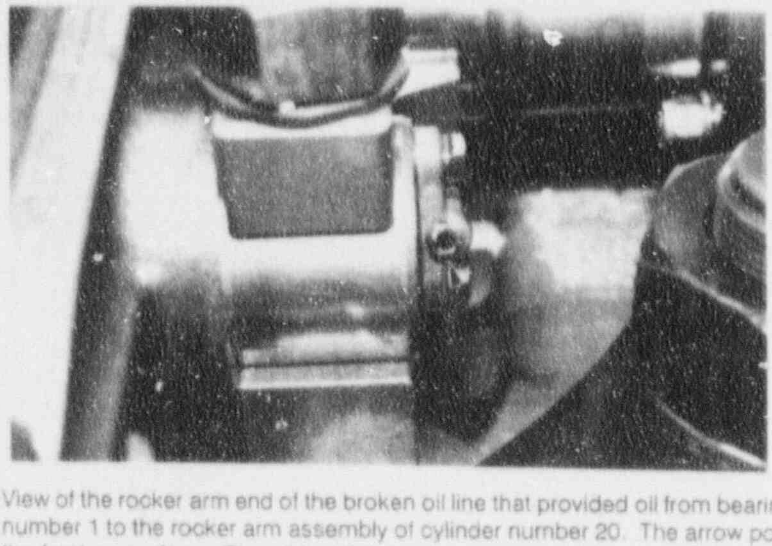


Figure B.6: View of the rocker arm end of the broken oil line that provided oil from bearing cap number 1 to the rocker arm assembly of cylinder number 20. The arrow points to the fracture surface. The oil line failure was considered a secondary event, as a result of the bearing cap coming loose.

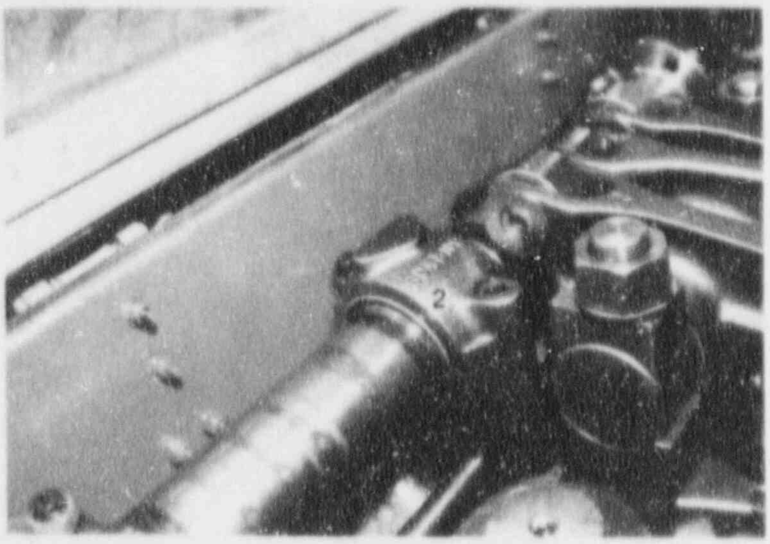


Figure B.7: View of the left rear top deck and bearing block number 2. The inboard bearing block bolt was in place but loose, and the outboard bolt was found lying on the top deck.

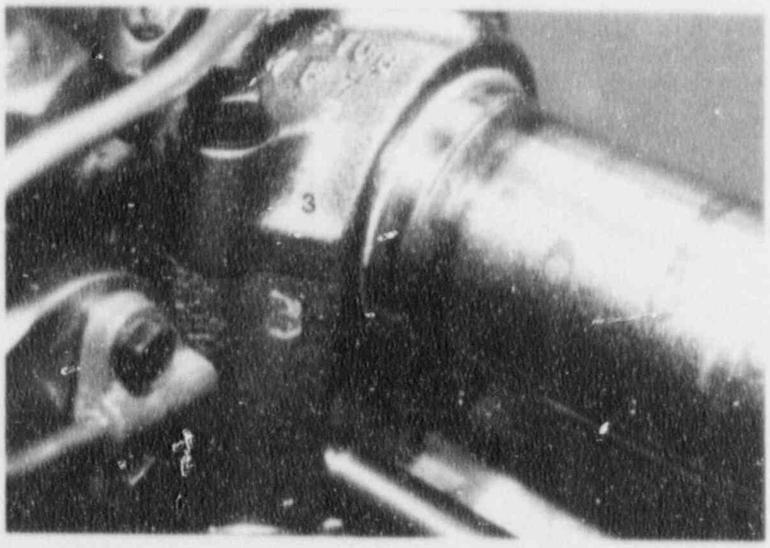


Figure B.8: View of the left rear top deck and bearing block number 3. The inboard bearing block bolt was found in place and tight, and the outboard bolt was found in place but backed out a few threads.

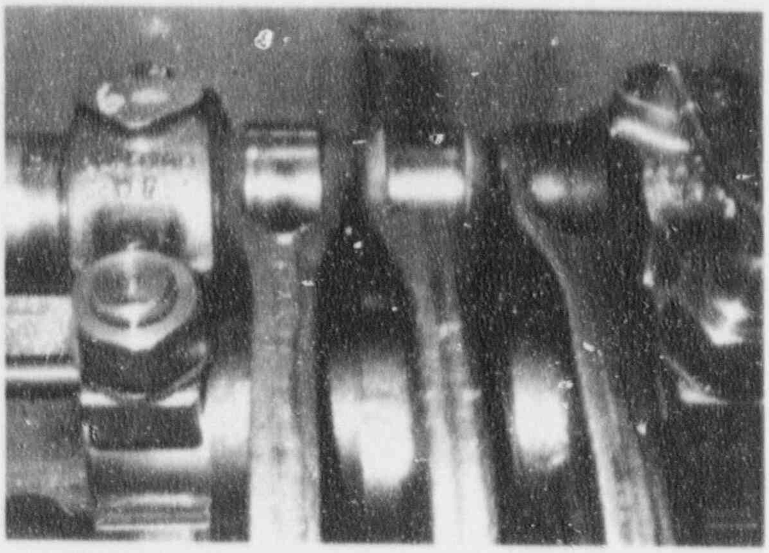


Figure B.9: View of the left rear top deck and bearing blocks number 5 and 6 which correspond to cylinder number 18. Note, the lack of lubrication damage and discoloration of the rocker arm rollers, and the charred material sprayed on the top deck.

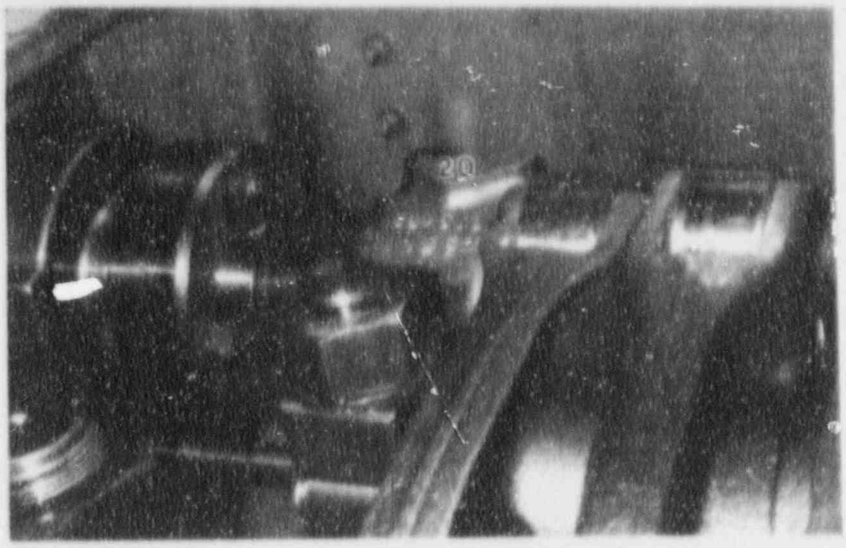


Figure B.10: View of the left front top deck area in the vicinity of the stubshaft to camshaft flange connection, bearing block number 20, and cylinder number 11. Note, the discoloration due to heat buildup, the loss of lubrication damage to the rocker arm rollers, and the charred material sprayed on the top deck. The lack of lubrication damage was greatest in this area.

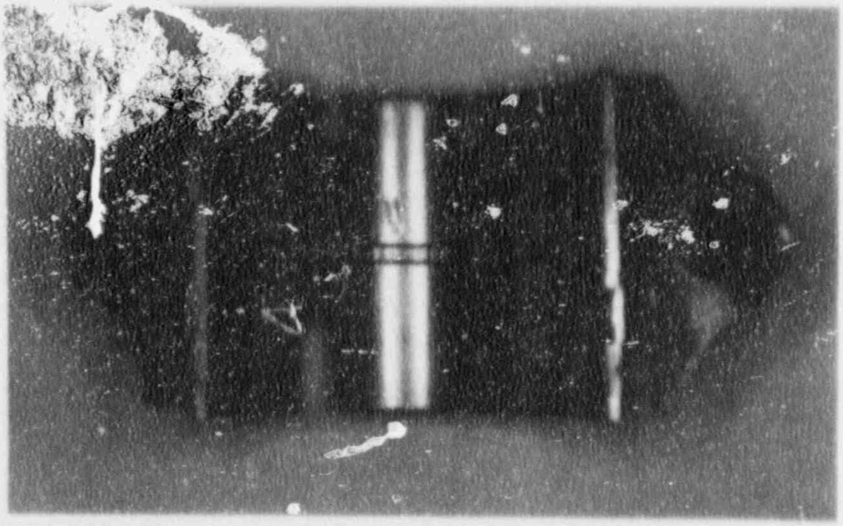


Figure B.11: View of the bearing surface of bearing block number 1. Note, there is no loss of lubrication damage, which supports the accepted failure scenario, where the initiating event was the bearing cap coming loose.

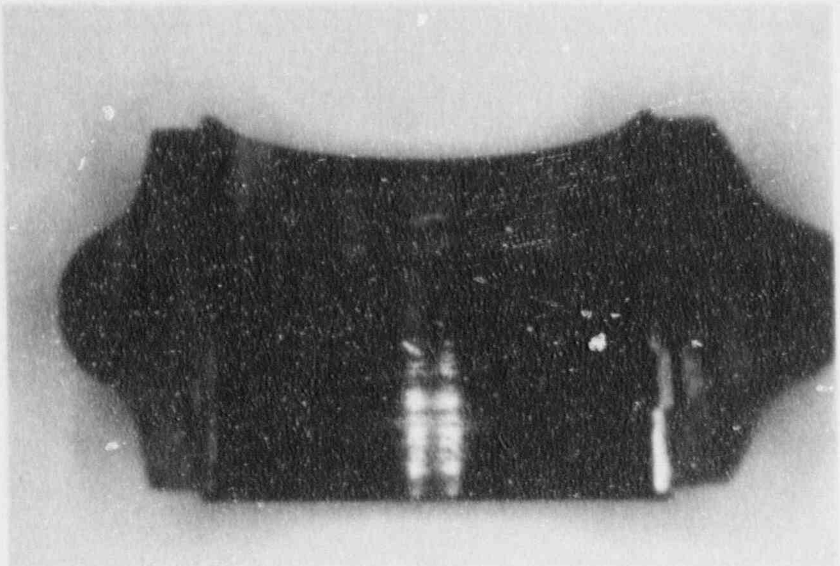


Figure B.12: View of the bearing surface of bearing block number 5. Note, the damage due to loss of lubrication.

Figure B.13: View of the bearing surface of bearing block number 20. Note, the damage due to loss of lubrication. The lack of lubrication damage was greatest in this area.

Figure B.14: View of engine block top left deck at the location of camshaft bearing block number 1. Note, approximately 5 threads of the inboard bolt hole are stripped while the threads of the outboard bolt hole are basically intact. The condition of these bolt holes supports the accepted failure scenario, where the initiating event is the bearing cap coming loose as a result of the bolts loosing preload. Both the inboard bolt and outboard bolt were found to be short.

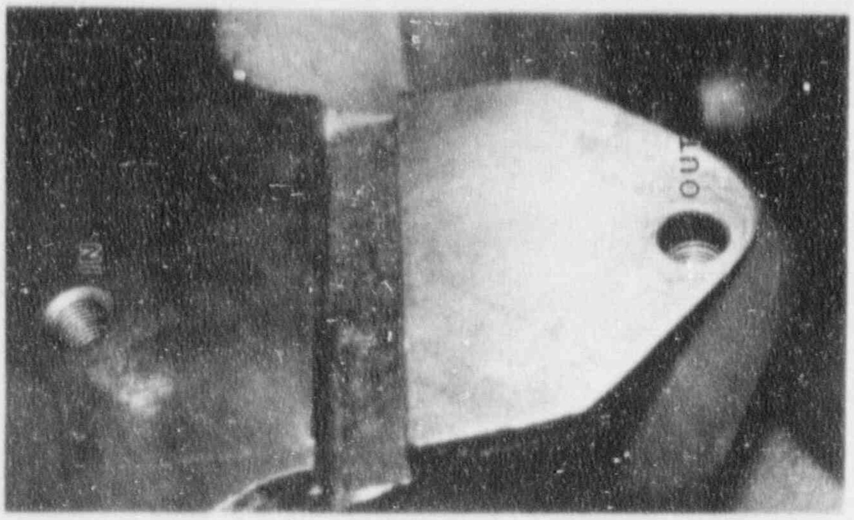


Figure B.15: View of engine block left top deck at the location of camshaft bearing block number 2. Note, the threads of the inboard bolt hole are basically intact while approximately 5 threads of the outboard bolt hole are stripped. The inboard bolt was found to be the correct length while the outboard bolt was found to be short.

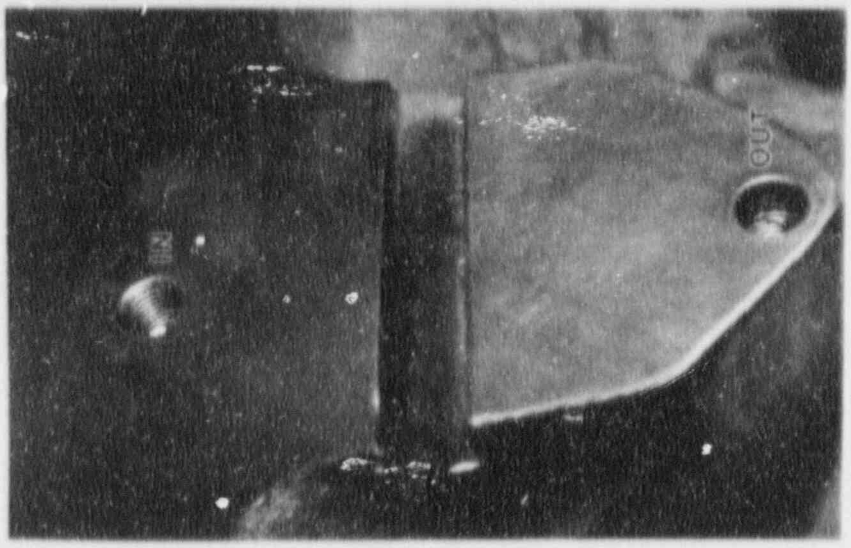


Figure B.16: View of engine block left top deck at the location of camshaft bearing block number 3. Note, the threads of the inboard bolt hole are basically intact while approximately 5 threads of the outboard bolt hole are stripped. The inboard bolt was found to be the correct length while the outboard bolt was found to be short.

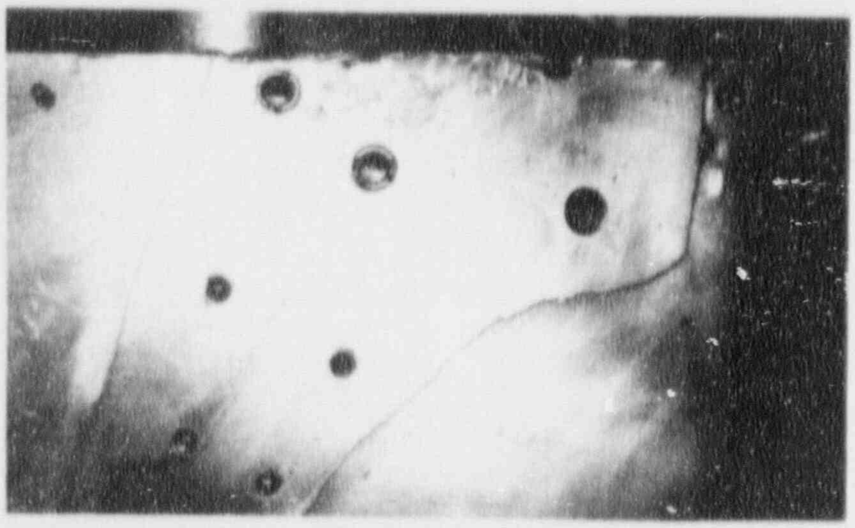


Figure B.17: Side view of the left rear end sheet at the location of the stubshaft support bracket. Note, the deformation of metal cause by a hammering of the bracket against the end sheet, for a short time, after the bracket detached from the end sheet.

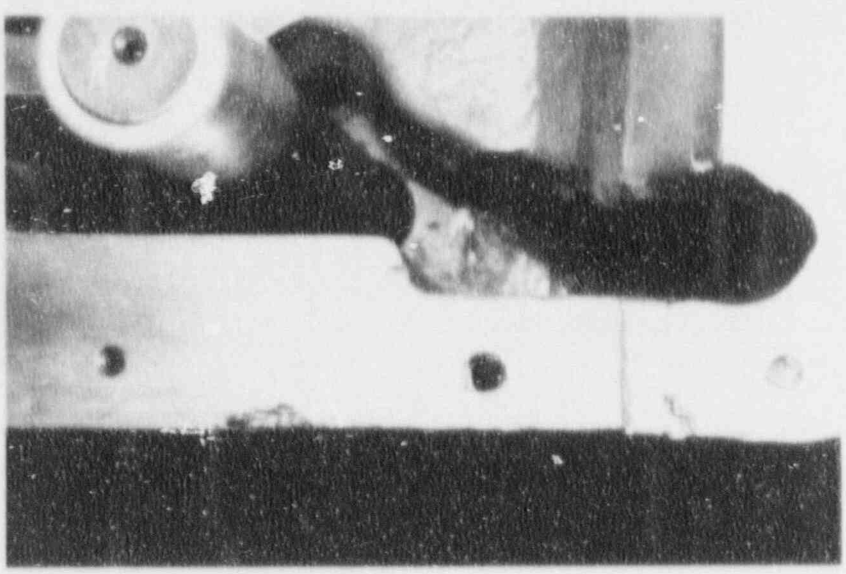


Figure B.18: Top view of the left rear end sheet at the location of the stubshaft support bracket. Note, the deformation of metal cause by a hammering of the bracket against the end sheet, for a short time, after the bracket detached from the end sheet.

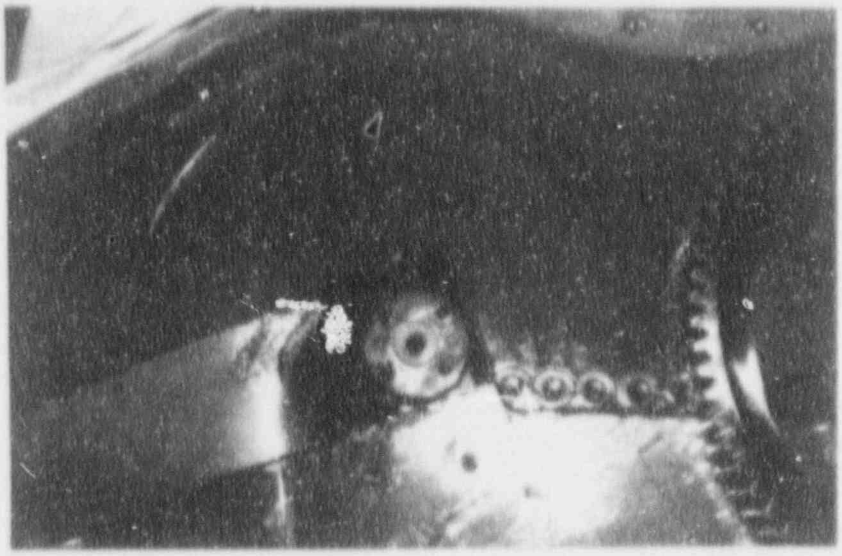


Figure B.19: Side view of the left rear end sheet. Note, the arrow shows were the camshaft gear contacted the camshaft gear housing just prior to the bracket detaching from the end sheet, and after the bracket detached from the end sheet.

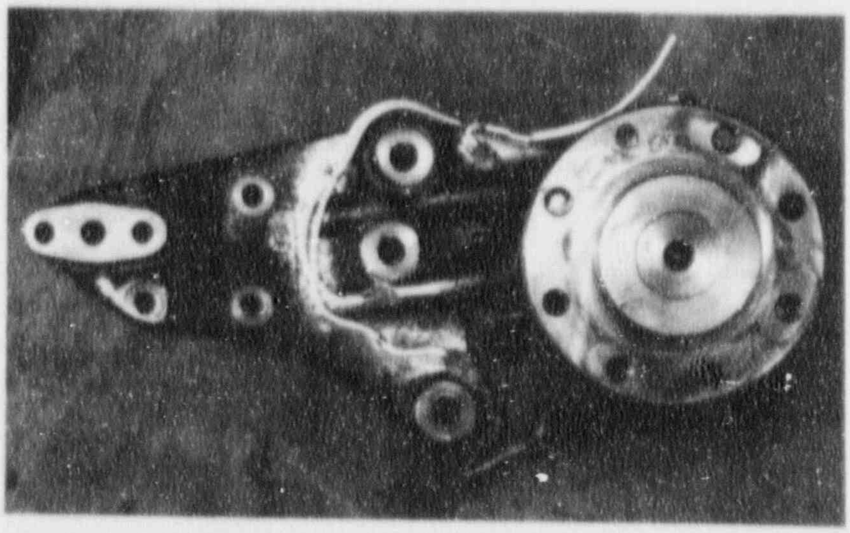


Figure B.20: View of the left rear stubshaft support bracket. Note, the bracket was not broken as in previous EDG failures. The wires are associated with strain gages which were used during previous testing of the bracket.

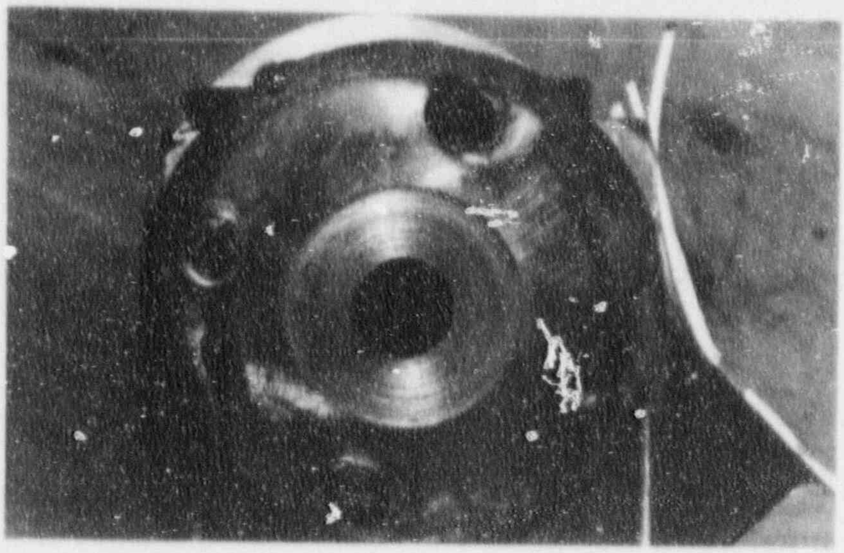


Figure B.21: View of the left rear stubshaft flange. Note, the elongation of the dowel bolt holes due to torsional loading of the flange as the camshaft was seizing, and rubbing against the crab bolt.

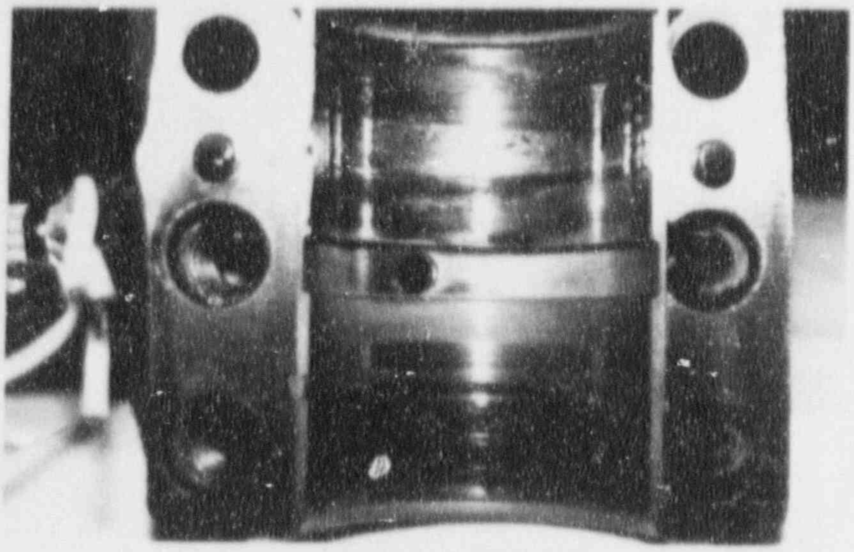


Figure B.22: View of the lower half of the stubshaft support bracket bearing. Note, the damage to the top half of the bearing surface was similar to the bottom half of the bearing. The damage has been attributed to severe camshaft gear vibration after the stubshaft flange began to fail, and a loss of lubrication damage after the bracket detached from the end sheet and the camshaft gear continue to rotate on the idler gear.

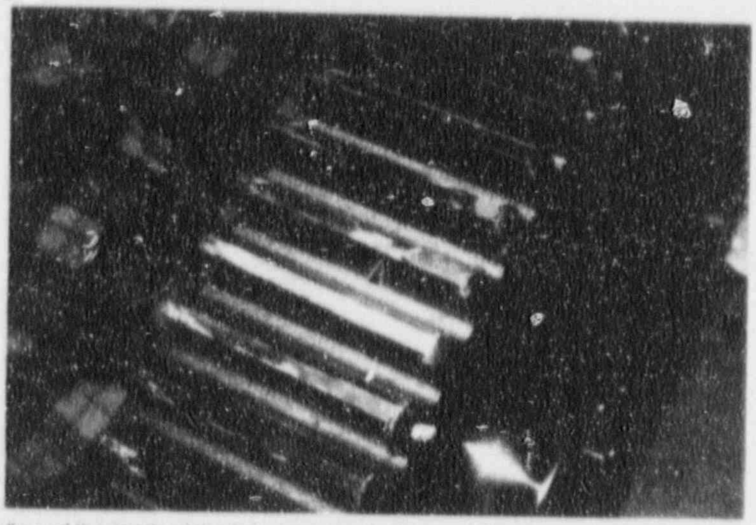


Figure B.23: View of the teeth of the left rear camshaft gear. The arrow points to damage due to the meshing of a metal fragment in the gear train. Note, there was extensive damage to the entire gear train due to gear misalignment and the meshing of metal fragments.

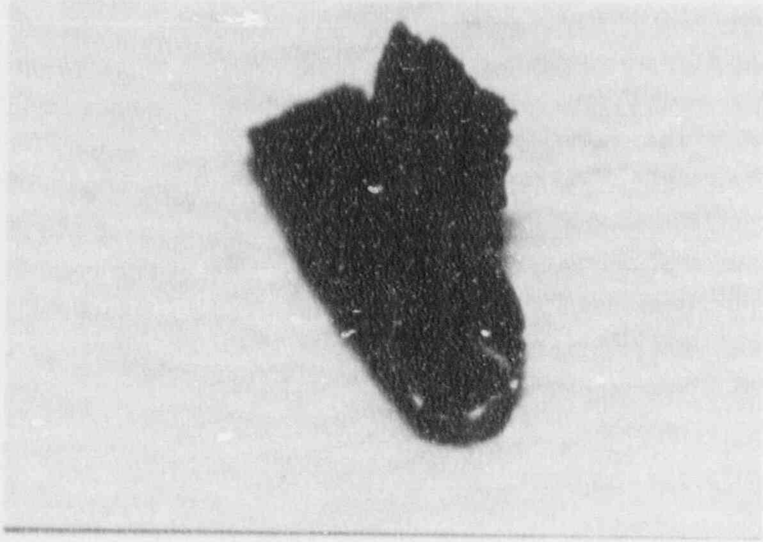


Figure B.24: View of a metal fragment that was meshed in the gear train. Note, the fragment has taken the shape of the gear teeth.

APPENDIX C
Bearing Block Bolt Discussions

Bolt Torque Discussion

The vendor specifies 32 ft-lbs as the required torque for camshaft bearing block bolts. A review of work history indicates that the left bank bearing block bolts were torqued to 32 ft-lbs with a calibrated torque wrench when the camshaft was last replaced in September 1987. Also, during camshaft gear replacement activities in June 1991, the number 2 bearing block, which was probably used to secure timing, was retorqued to 32 ft-lbs following work activities. Thus, improper torquing after past work activities is not an issue in this event.

During the EDG disassembly after the failure, breakaway torques were taken on the right and left bank camshaft bearing block bolts. Table C.1 lists the breakaway torques for all the left bank bearing block bolts. All of the bolts, with the exception of the bolts which were found loose, backed out, and stripped out, on the first 3 bearing blocks, were found to be tight. The average breakaway torque on the left bank bolts was found to be approximately 39 ft-lbs.

The 3 short bolts at bearing block numbers 6 and 8 had breakaway torques of 31 to 38 ft-lbs, which indicates that properly torqued short bolts in good bolt holes will remain tight during EDG operation. This conclusion is supported by laboratory testing, as discussed in Appendix G, which verified that short bolts torqued to 32 ft-lbs will remain tight during EDG operation even with high fatigue loads.

In reviewing this issue, post event actions included checking all camshaft bearing block bolts on all 4 EDGs for tightness, with the exception of the left rear camshaft bearing block bolts on the 20 cylinder engine of 2G003 which were a part of the failure and replaced during reassembly, and the camshaft bearing block bolts on the 16 cylinder engine of 2G003. All camshaft bearing block bolts that were checked were found to be tight. Thus, it is concluded that the loss of preload on the left rear camshaft bearing block bolts on the 20 cylinder engine of 2G003 was unique to the event. Also, there is no need at this time to check the torque of the camshaft bearing block bolts of the 16 cylinder engine of 2G003. Any significant bolt problems would have surfaced during the Unit 2 cycle 6 overhaul activities and there is nothing to indicate that there is a potential problem.

Short Bolt Discussion

During the investigation, it was identified that some camshaft bearing block bolts on the left bank of the 20 cylinder engine were shorter than others. Table C.1 lists the locations of the six short bolts. Based on inspections and bolt markings, it was concluded that all bearing block bolts on the right bank of the 20 cylinder engine were of the correct length.

The Vendor Manual SO23-403-12-302 specifies the use of 3/8 x 4 5/8 inch - 24 TPI bolts for use on the camshaft bearing blocks. The actual length of the nominal 4 5/8 inch bolts in the EDG, which will be referred to as long bolts in this discussion, were typically found to be 4 9/16 to 4 5/8 inches. The actual length of the short bolts in the EDG were found to be approximately 4 7/16 to 4 15/32 inches. Acceptable tolerances for bolts are given in SAE Standard 429J and ANSI Standard B18.2.1. In the case of a 4 5/8 inch bolt, the length tolerance is 4 5/8 inches, minus 0.100 inches, plus 0.060 inches. However, the EMD representative stated that the acceptable length of the bolts was 4 5/8 inch, minus 3/32 inches, plus 0.000 inches. Thus, the 4 7/16 to 4 15/32 inch length of the short bolts is outside the acceptable 4 17/32 to 4 5/8 inch vendor tolerance for camshaft bearing block bolts.

The thread engagement of the shortest acceptable long bolt is approximately 13/32 inch or 9.75 threads. Adequate thread engagement is typically considered to be at least 1 nominal bolt diameter or 3/8 inches or 9 bolt threads, thus the shortest acceptable long bolt with an engagement of 9.75 threads would be acceptable. This is reasonable considering the loading of a bearing block bolt. The loading forces on the bearing blocks are the weight of the camshaft, the downward force of the rocker arms, oil pressure, and vibration. Most of the loading force is downward and transmitted directly through the lower bearing blocks to the top deck.

In the case of short bolts, the worst case actual length was approximately 4 7/16 inches for a thread engagement of 5/16 inches or 7.5 threads. Also, if you consider the first and last thread of the bolt connection as being partially ineffective, the effective thread engagement was only 6.5 threads. Thus, short bolts have significantly less engagement that 1 nominal bolt diameter or 9 threads. However, as discussed in the general discussion on bolt torque, short bolts are capable of being torqued to the required 32 ft-lbs and performing their design function, if the bolt holes are not worn.

<u>Worn Bolt Hole Discussion</u>

Due to previous EDG failures and work activities in the area of the left rear camshaft on the 20 cylinder engine of 2G003, the number 1 camshaft bearing block bolt holes became worn reducing the bolt thread to hole thread interface. In reviewing the failure and work history related to the number 1 bearing block, there have been 2 previous inboard bolt failures and 1 previous outboard bolt failure. In all 3 failures, the bolts fractured in the threaded area, most likely resulting in some bolt hole thread damage. Also, the subsequent rework and maintenance activities would result in further wear to the bolt holes.

Worn bolt holes can result in poor bolt fit, less bolt to hole thread contact, plastic deformation of bolt threads, less thread shear area to resist bolt pullout under tensile load, and transverse sliding of threads. Normally, slightly worn bolt holes would not be expected to be a problem. However, in this case, the worn bolt holes coupled with the short bolts and 5th order torsional resonance are the root cause of the 2G003 failure.

Camshaft Bearing Block Bolt Markings

The markings on the head of the camshaft bearing block bolts on the 20 cylinder engine of 2G003 provided indication of the extent of the short bolt problem. All bolts had three tick marks indicating SAE grade 5 bolting material. The bolts for camshaft bearing blocks associated with the camshaft segments for cylinders 1 through 15 had a small "triangle" manufacturer's identification marking. Since a review of work history did not reveal any work to the camshaft segments for cylinders 1 through 15, bolts with the "triangle" marking were considered to be original installation and the correct length.

An inspection of the bolts associated with the camshaft segment for cylinders 16 through 20 revealed 13 bolts marked with either a "triangle", "CP", or "FM". These bolts were all found to have 3 ticks indicating grade 5 and to be of the correct nominal length of 4 5/8 inches. The remaining 7 bolts had 3 ticks indicating grade 5 but did not have any manufacturer's mark. These bolts are the 7 bolts which were found to be short and of a nominal length of 4 1/2 inches.

All of the right bank bolts were considered to be original bolts and of the correct length, and during repair activities, all the left bank bolts were replaced with the correct length bolts. Thus, short bolts are no longer a problem in the 20 cylinder engine of 2G003. During the inspection of the 20 cylinder engine of 3G003, in response to the 2G003 failure, bolts were found without a manufactures mark. However, a measurement check of these bolts indicated that they were the correct length, indicating that the lack of a manufacturer's mark is not positive indication of a short bolt.

2G003, Procurement of Short Bolts

A brief review of supplier history indicates that the EDGs were manufactured by the Electro-Motive Division of General Motors. However, since EMD would not supply directly to the nuclear industry, Stewart & Stevenson was the supplier until 1985 when Western Regional International and Cake Industries were qualified by SCE QA as suppliers. Subsequently, the Morrison Knudsen Company became the approved supplier, which is now known as MKW Power Systems.

In reviewing the short bolt issue, there was no evidence of a warehouse stock of 3/8 x 4 1/2 inch grade 5 steel bolts which could have been supplied in error by the warehouse for use in the EDG. Also, the EDGs do not use 3/8 x 4 1/2 inch grade 5 bolts which eliminates the possibility of a misapplication of EDG bolting during work activities.

New camshaft bearing block bolts have been procured and installed in the past as a result of previous failures and work activities. A search was conducted to find out under what circumstances the short bolts were installed in the plant. In 1984 and 1985, the Warehouse received new bolts from Western Regional International under POs 8E2N4036, 8E124085, and 8A095015, with receipt inspections of RSO-5960-84, RSO-8540-84, and RSO-6202-85, respectively. In 1985, the Warehouse received new bolts from Morrison Knudsen under PO 6H058020 with a receipt inspection of RSO-1163-88. A review of these RSOs was inconclusive with regard to whether the length of the bolts were checked during receipt inspection. No procurement trail could be found for the new bolts which were installed in 1981 after the bracket failure. However, correspondence at the time indicated that the new bolts were probably procured from EMD through Stewart & Stevenson. An inspection of bolts in current warehouse stock revealed that the current stock is the correct length. In conclusion, since there is an established record of SONGS correctly procuring camshaft bearing block bolts through approved suppliers, it is assumed that the short bolts where either supplied by one of the approved suppliers in the past, or that the short bolts are an isolated case where bolts were procured outside normal channels in the past.

The SPIS and MMSM computer based spare part systems indicate under Material Code 024-32326 that the bearing block bolts are 3/8 x 4 1/2 inch bolts which is inconsistent with the vendor manual specification of 3/8 x 4 5/8 inches. A search has determined that the error in specifying the correct length bolts should be attributed to personnel error by warehouse personnel during an evaluation in 1986 to physically obtain descriptions of parts in the warehouse. During the evaluation, the evaluator probably measured the bolts designated by M/C 024-32326 and determined that they were 4 1/2 inches long, which probably appeared reasonable to the evaluator, since the long bolts most likely measured between 4 9/16 and 4 5/8 inches.

In reviewing this issue, it is clear that the evaluation process did not adequately cross reference the vendor manual in determining the bolt length. However, the incorrect description of the bolts did not contribute to the procurement of short bolts. The bolts are ordered by part number and the last 4 documented procurements occurred prior to the SPIS and MMSM data error. A corrective action has been assigned to Procurement Engineering to correct MMSM and SPIS.

Table C.1
EDG 2G003, 20 Cylinder Engine
Camshaft Bearing Block Bolts Left Bank

	Bolt Length (inches)		Breakaway Torque (ft-lbs)		Bolt Engagement (threads)	
	Inboard	Outboard	Inboard	Outboard	Inboard	Outboard
1	4 7/16*	4 7/16*	XX	XX	6.5	6.5
2	4 5/8	4 7/16*	Loose	XX	9.5	6.5
3	4 5/8	4 7/16*	44	Loose	9.5	6.5
4	4 5/8	4 5/8	41	40	9.5	9.5
5	4 5/8	4 5/8	44	37	9.5	9.5
6	4 5/8	4 7/16*	35	38	9.5	6.5
7	4 5/8	4 5/8	33	33	9.5	9.5
8	4 7/16*	4 7/16*	31	33	6.5	6.5
9	4 5/8	4 5/8	35	33	9.5	9.5
10	4 5/8	4 5/8	35	33	9.5	9.5
11	4 5/8	4 5/8	41	37	9.5	9.5
12	4 5/8	4 5/8	35	41	9.5	9.5
13	4 5/8	4 5/8	44	41	9.5	9.5
14	4 5/8	4 5/8	33	33	9.5	9.5
15	4 5/8	4 5/8	48	41	9.5	9.5
16	4 5/8	4 5/8	41	38	9.5	9.5
17	4 5/8	4 5/8	41	48	9.5	9.5
18	4 5/8	4 5/8	44	44	9.5	9.5
19	4 5/8	4 5/8	44	44	9.5	9.5
20	4 5/8	4 5/8	37	44	9.5	9.5

* Denotes location of short bolts

Notes:

1) The list of bolt lengths reflects the locations where "short" and "long" length bolts were found. The 4 7/16 inch "short" bolts are of a nominal 4 1/2 inches in length, while the 4 5/8 inch "long" bolts are of a nominal 4 5/8 inches in length.

   The camshaft bearing block bolts are not machined to close tolerances. Typically, the documented 4 7/16 inch length bolts measured close to 4 7/16 inches, while the documented 4 5/8 inch bolts measured from 4 9/16 to 4 5/8 inches.

2) These are the as-found breakaway torques taken during disassembly of the engine. "XX" denotes bolts which came out of position during the event and were found lying on the top deck of the engine.

3) These are average effective thread engagements. A typical "short" bolt was considered to be 4 7/16 inches in length and had an effective thread engagement of 8.5 threads, while a typical "long" bolt was considered to be 4 9/16 inches in length and have an effective thread engagement of 9.5 threads.

APPENDIX D
5th Order Torsional Resonance

The 5th order torsional resonance problem has surfaced in a limited number of EMD EDGs in the nuclear and commercial industry. The following is a brief summary of SONGS EDG failures and root cause assessments which ultimately resulted in the identification and resolution of the problem at SONGS.

> In 1981, the stubshaft bracket of 2G003 failed during pre-operational testing. At that time, the specific failure had been reported only in 2 other EMD 20 cylinder engines, both in stationary commercial service. The root cause was attributed to inadequate torquing of the bracket bolts during assembly.
>
> In 1984, the stubshaft bracket of 2G003 was found broken during planned maintenance activities. At the time, the root cause was attributed to improper fit-up and alignment of the stubshaft bracket to the engine end sheet.
>
> In 1987, the stubshaft to camshaft coupling of 2G003 was found loose during the installation of a new design and stronger stubshaft bracket, and the stubshaft bracket was found cracked during subsequent investigation activities. The root cause of the loose coupling was attributed to inadequate torquing during previous work activities, and the root cause of the bracket failure was the subject of a continuing investigation by EMD.
>
> In 1988, the stubshaft bracket of 3G003 was found broken during the installation of a new design and stronger bracket. The failure was attributed to 5th order torsional resonance which was transmitted from the crankshaft through the gear train to the bracket, and EMD was continuing to evaluate the nature of the vibration problem.

The installation of the new design and stronger brackets on all 4 EDGs, corrected the bracket problem. However, excessive camshaft gear train wear began as a result of the 5th order torsional resonance. Thus, EMD imposed a 250 hour operating limit on the left bank camshaft gear.

The 5th order torsional resonance problem at SONGS involves only the 20 cylinder engines of the 4 tandem EDG sets. Although 5th order torsional resonance failures have only occurred in the 20 cylinder engines of 2G003 and 3G003, the 20 cylinder engines of 2G002 and 3G002 also have a smaller 5th order torsional resonance.

Briefly, the 5th order torsional resonance problem is a product of the physical and operating characteristics of the EDG sets. The 16 and 20 cylinder engine operate in tandem to drive a single electrical generator at 900 rpm. For only the 20 cylinder engine, at approximately 944 rpm, the 5th order engine harmonic excites the flywheel which has a natural frequency of approximately 79Hz. The presence of the flywheel resonance near the 900 rpm operating speed of the engine results in undesirable vibratory motion and additional stresses in the gear train and left rear camshaft assembly. To eliminate the vibratory problem, it was decided by the vendor and Station Technical to shift the resonance away from the operating speed of the engine.

In the commercial industry, the use of a high inertia "heavy" flywheel was shown to be an effective solution to the 5th order torsional resonance problem. However at SONGS, the use of a heavier flywheel would have been unacceptable because of seismic and 10 second start requirements. As a result, EMD designed a driveline coupling hub modification for SONGS which changed the stiffness of the driveline and shifted the 5th order torsional resonance away from the operating speed of the engine.

During the Unit 2 cycle 6 refueling outage, the EDG driveline coupling hub modification was installed on 2G003. Based on post installation testing, the coupling hub modification has shifted the flywheel natural frequency from approximately 79Hz to approximately 89Hz. Thus, the 5th order torsional resonance which use to occur at approximately 944 rpm is now expected to occur at around 10[illegible] rpm. The coupling hub modifications installed on 2G002, 3G002 and 3G003, during their respective cycle 6 outages, corrected their 5th order torsional resonance problems in a similar fashion.

APPENDIX E
Stubshaft Flange Analysis for 2G003

This appendix discusses the failure analysis of the broken dowel bolts that connect the left rear camshaft segment flange to the stubshaft flange on the 20 cylinder engine of 2G003.

Procedure:

The rear flange of the left rear camshaft segment was visually examined and photographed. The fracture surfaces of the portions of 3 dowel bolts found in the camshaft segment flange were examined under a binocular microscope. Only one bolt was selected for scanning electron microscope examination. The fracture surface was documented and x-rayed. A longitudinal microsection was prepared and the microstructure was documented in the as-polished, and the as-etched, conditions.

Results

Visual Examination:

Figure E.1 shows the as-found condition of the camshaft flange with 3 broken dowel bolts and 1 missing dowel bolt. For the purposes of this report, the 3 broken bolts were arbitrarily assigned numbers 1, 2 and 3, while the flange location of the missing dowel bolt was assigned number 4. Bolts 1, 2 and 3, exhibited deformation due to rubbing and a bluish discoloration due to overheating. Details of the deformation and discoloration are shown in Figures E.2 to E.4. The portions of the 3 broken bolts found in the flange, and fragments of bolt number 4 which were found lying of the top deck, are shown in Figure E.5. All of the bolts exhibited a fibrous fracture appearance.

The sequence of the flange failure appears to have started by a shear failure of bolt number 4. As a result, the flange connection lost some rigidity and the flange connection fluttered for a short period of time with the remaining 3 bolts experiencing increased levels of cyclical stresses. Shortly after bolt number 4 failed, the remaining three bolts failed in shear, when the stubshaft bracket detached from the end sheet and the flange was pulled apart. The 900 rpm operating speed of the camshaft flange resulted in a relatively brief but significant pounding of the fracture ends of the broken bolts that remained in the flange, when the flange connection was pulled apart. The sequence of the flange failure is supported by the slight crescent shaped wear mark on the flange face in the vicinity of bolt hole number 4, the deformation and bluish discoloration of the broken dowel bolts, and the elongation of the flange bolt holes, as shown in Figures E.1 to E.5.

Fractography

Visual macroscopic examination of the fracture faces of the broken bolts indicated a fibrous fracture. Typically, the cracks started in the threaded area of the bolts in the vicinity of the dowel shoulder. The cracks would initiate in the root of a thread, progressed for a short distance in the transverse direction, and then progressed in the longitudinal direction toward the center of the dowel bolt. The fractures showed a separation of shell type slivers occurring along the length of the broken dowels due to the presence of sulfide stringers and a banded microstructure. These slivers fractured in a fibrous fashion. The above failure mode was typical for bolts numbers 1, 2 and 4. For bolt number 3, the crack initiated in the threaded area and the bolt fractured across the threaded area. The fracture surface was obliterated due to rubbing.

Figure E.6 is a SEM photo of bolt number 4, showing that the crack initiated at the thread root, propagated a short distance in the traverse direction, and then propagated in the longitudinal direction. The fracture face had a woody fibrous appearance. Figures E.7 and E.8 show under magnification the fracture surface illustrating the presence of iron and manganese sulfide stringers.

EDX analysis indicated that the stringers/inclusions of dowel bolt number 4 were of high manganese sulfide content in comparison to the carbon steel base material. Trace E.1 shows the EDX analysis of an inclusion and Trace E.2 shows the EDX analysis of the base material. The height of the manganese and sulfur peaks on the traces correlates to the chemical concentration of the 2 elements.

The sulfide inclusions/stringers in the dowel bolt material (re-sulfurized grade 1144) were weak planes on which fractures tended to propagate. With the sulfide inclusions/stringers, the material became anisotropic with weak mechanical properties in the transverse direction. This type of material experiences a brittle fracture resulting from a significant reduction in the fracture toughness.

Metallography

A longitudinal microsection was prepared from dowel bolt number 3 at the location shown in Figure E.9. The cross-section was examined in the as-polished condition and there was not a significant sulfide inclusion anomaly. At a few locations there were long surface stringers, as shown in Figure E.10. The microstructure was found to consist of bands of ferrite (white phase) and pearlite (dark phase), as shown in Figures E.11 and E.12. The light grey paste represents sulfide inclusions. The banded structure facilitates a fibrous fracture.

Conclusion

The visual examination of the broken dowel bolts indicated that the cracks started in the threaded area of the bolts in the vicinity of the dowel shoulder. Scanning electron microscopy indicated fibrous fracture associated with longitudinal sulfide inclusions. This observation was further supported by microstructural examination which indicated the presence of a banded microstructure consisting of ferrite and pearlite with sulfide stringers. This type of microstructure creates a significant anisotropic material with very poor mechanical properties in the transverse direction. This type of microstructure promotes brittle fracture behavior.

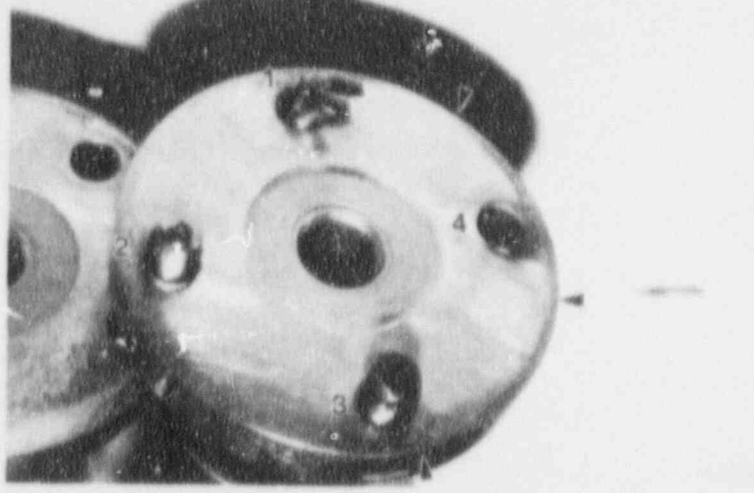


Figure E.1: View of the left rear camshaft flange with remnants of the 3 broken dowel bolts. The numbering of the bolts is arbitrary and for discussion purposes only. The arrows point to the crescent wear mark which indicated bolt number 4 fractured first. Note, the bluish discoloring and deformation of the broken bolts, and the elongation of the flange bolt holes.

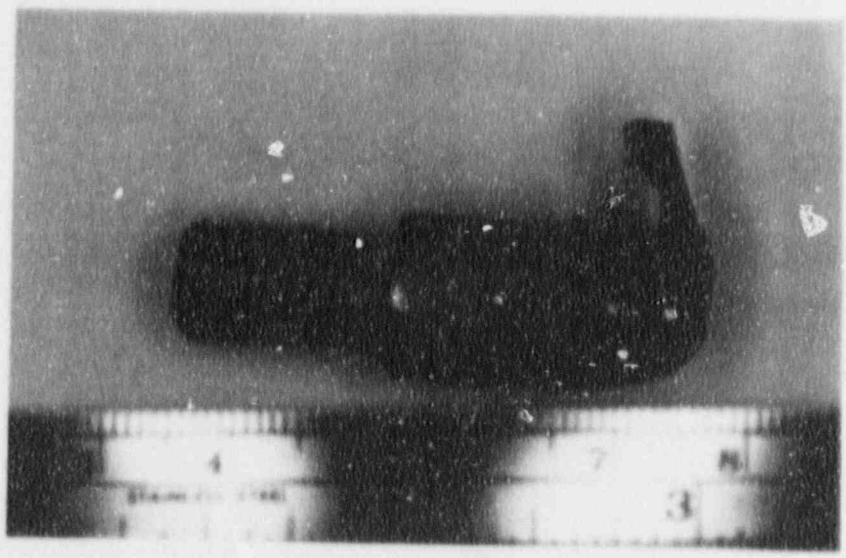


Figure E.2: View of dowel bolt number 1.

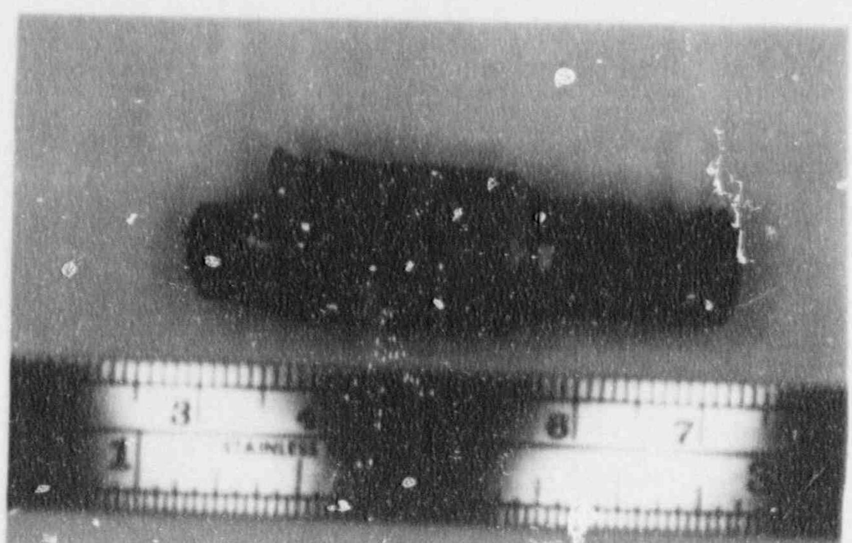


Figure E.3: View of dowel bolt number 2.

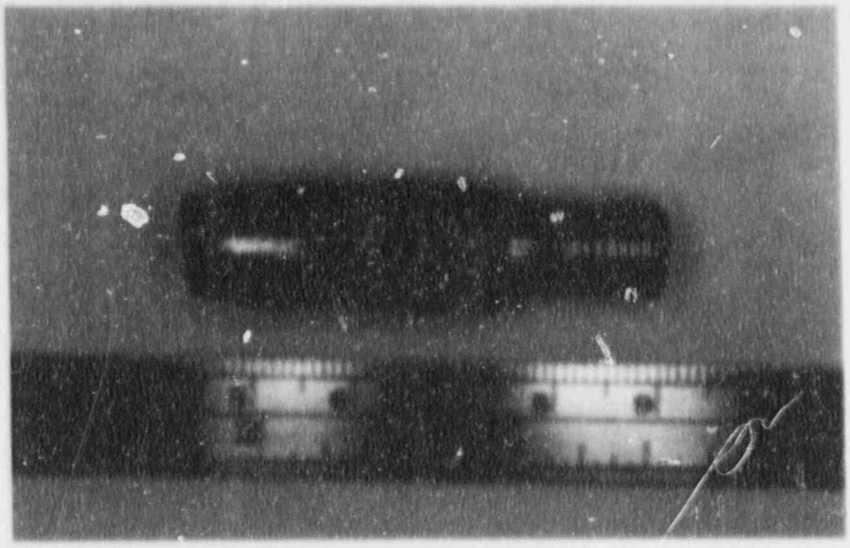


Figure E.4: View of dowel bolt number 3.

Figure E.5: View of fragments of the dowel bolts.

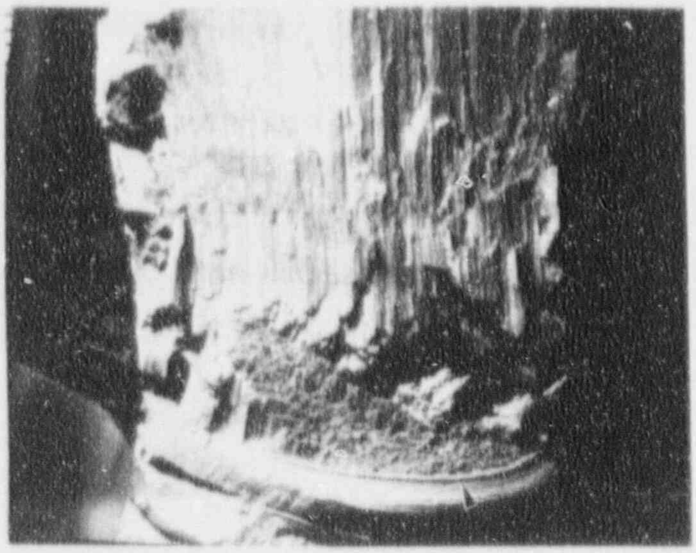


Figure E.6: SEM fractograph of fractured dowel bolt number 4, at 4 X magnification. The arrow points to fracture initiation.

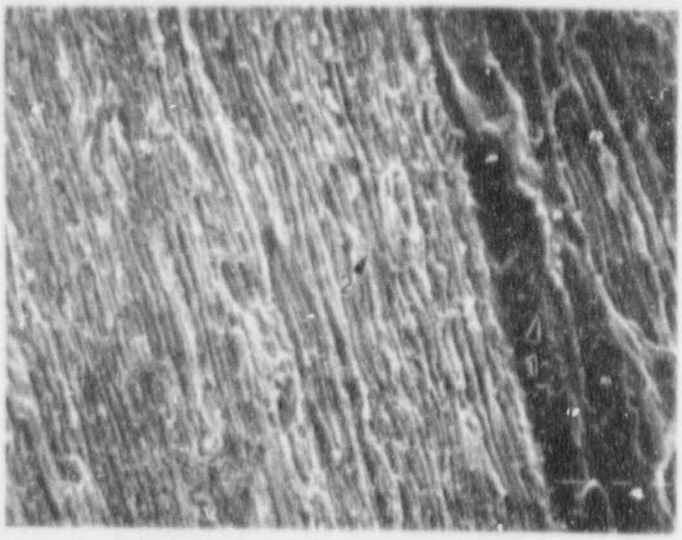


Figure E.7: SEM fractograph of fractured dowel bolt number 4, at 500 X magnification. Arrow 1 points to the location of a large sulfide stringer, and arrow 2 points to a sulfide inclusion.

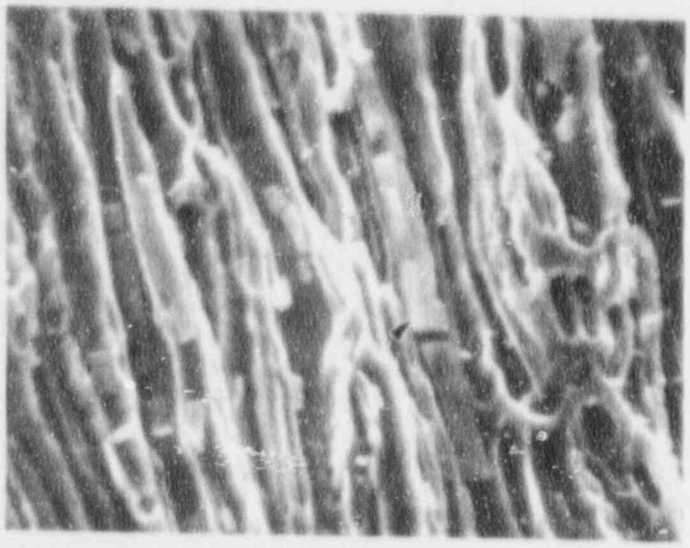


Figure E.8: SEM fractograph of fractured dowel bolt number 4, at 2000 X magnification. The arrow points to a sulfide inclusion.

Figure E.9: View of dowel bolt number 3 showing location of longitudinal microsection.

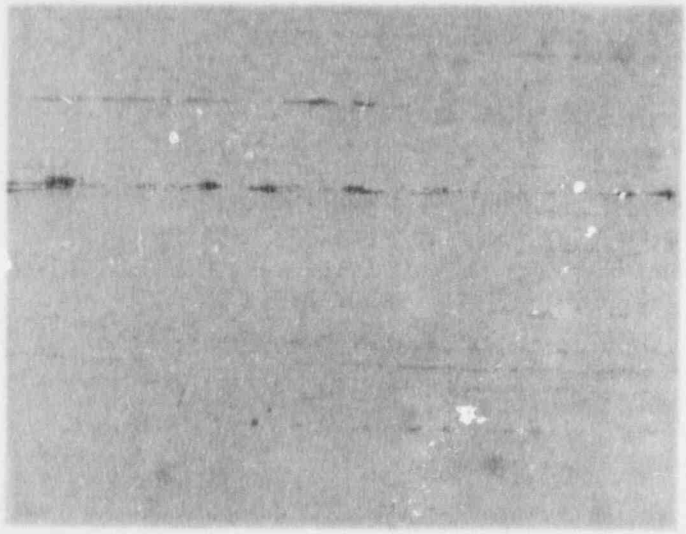


Figure E.10: Optical micrograph of dowel bolt number 3, with an as-polished surface, showing a sulfide stringer, at 100 X magnification.

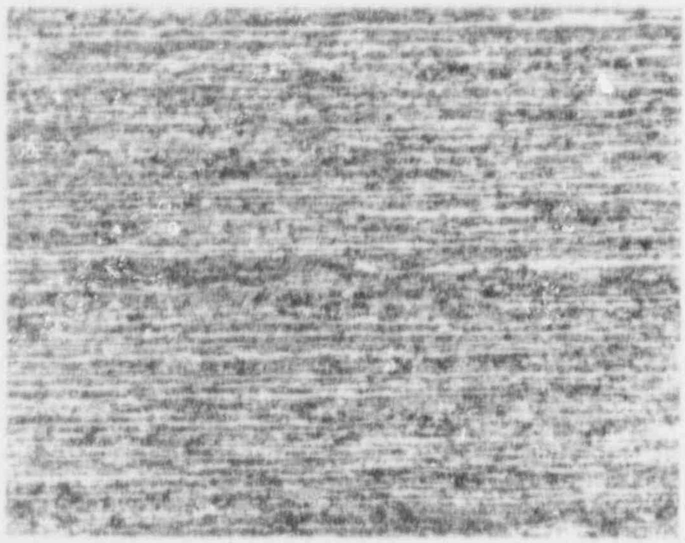


Figure E.11: Optical micrograph of dowel bolt number 3, showing banded microstructure (etched: vital), at 100 X magnification. The microstructure shows bands of ferrite (white paste) and pearlite (dark paste).

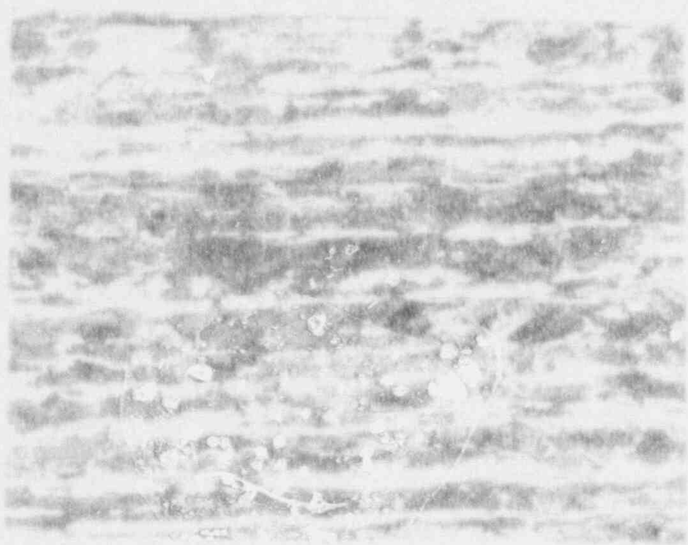


Figure E.12: Optical micrograph of dowel bolt number 3, showing the typical structure (etched vital), at 400 X magnification. The microstructure shows bands of ferrite (white paste) and pearlite (dark paste).

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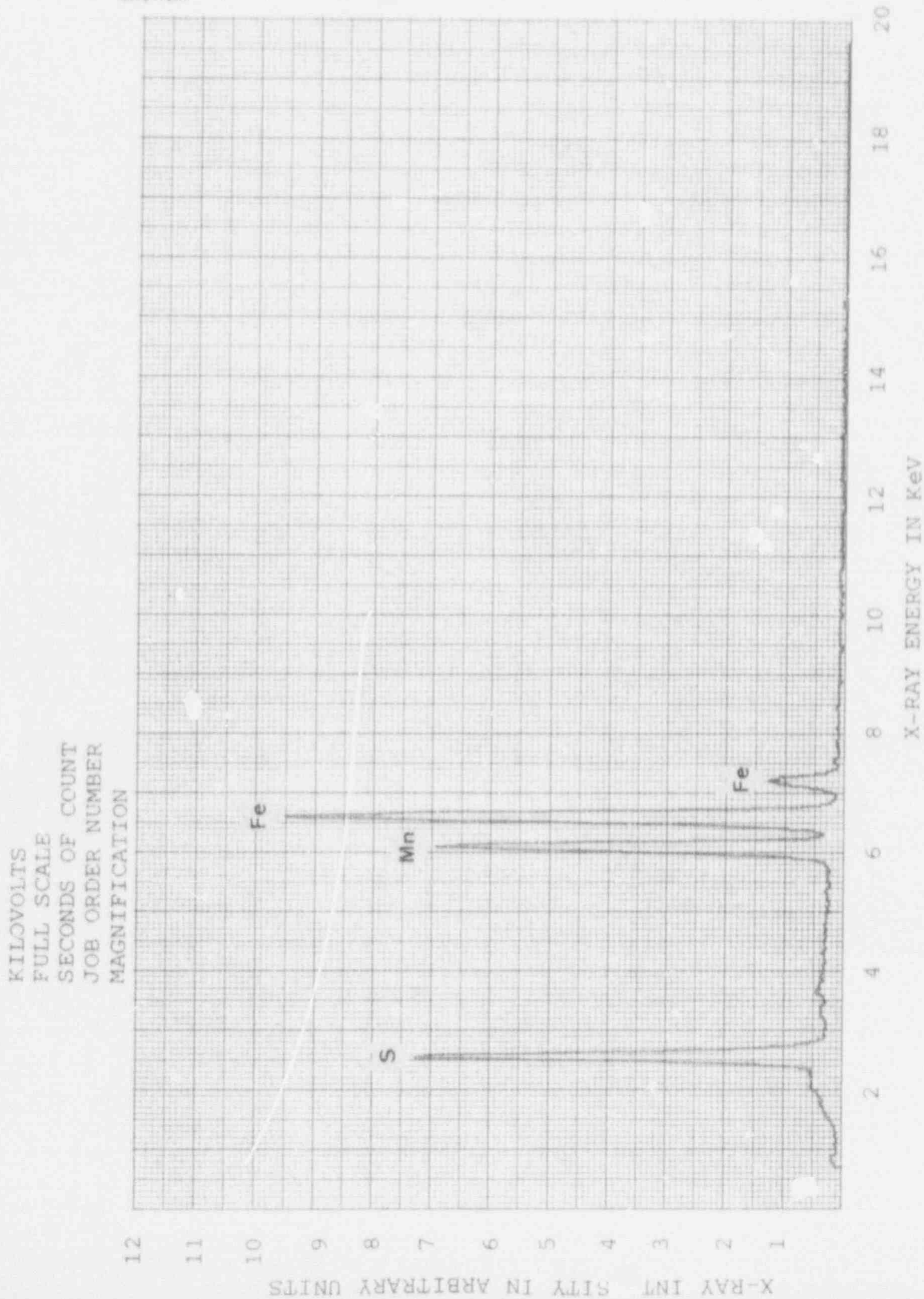
Trace E.1: EDX analysis of the inclusion in dowel bolt number 4, as shown in Figures E.7 and E.8. The height of the elements correlates to the chemical concentration in the material.



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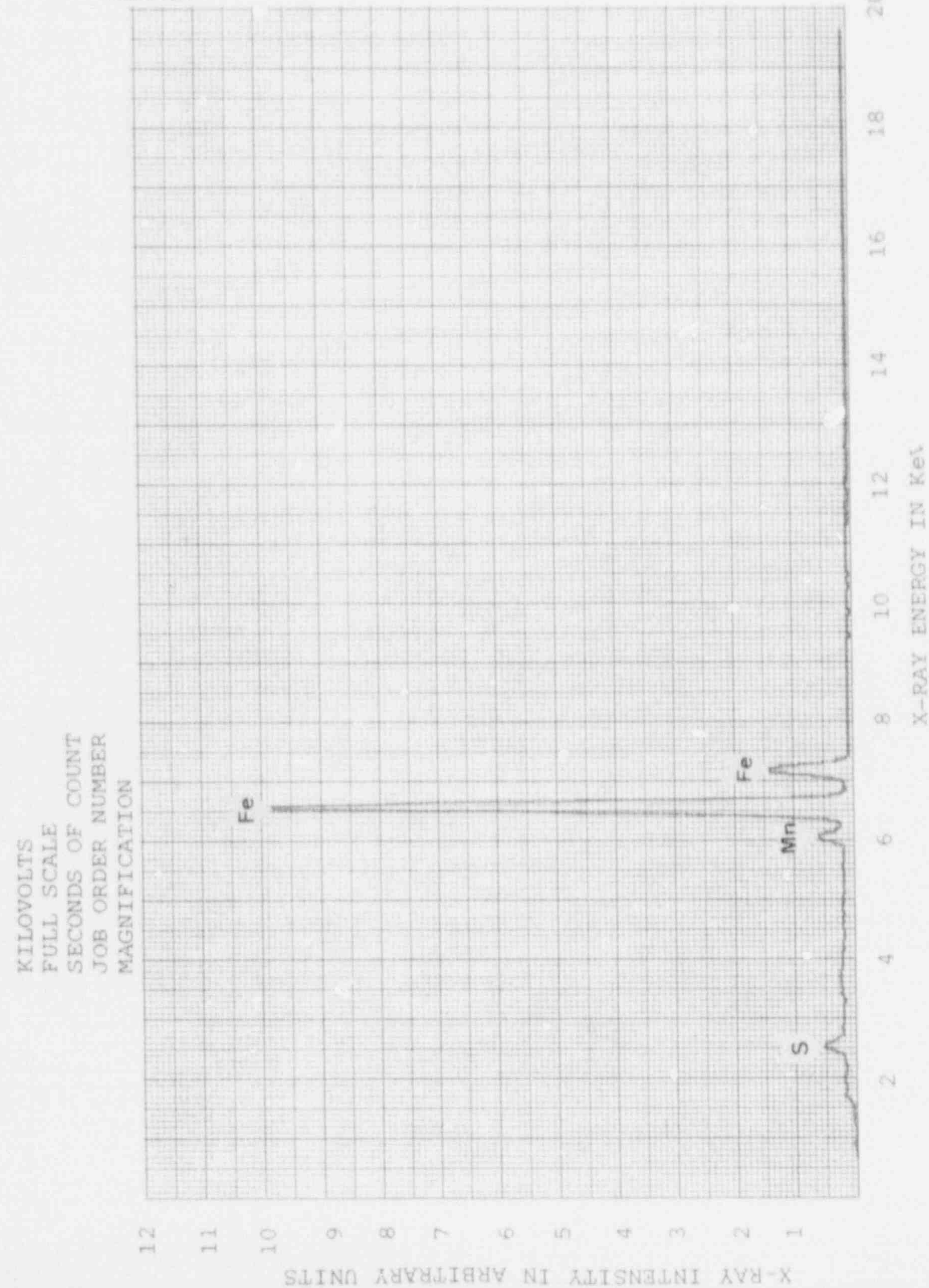
Trace E.2: EDX analysis of the base material of dowel bolt number 4, as shown in Figures E.7 and E.8. The height of the elements correlates to the chemical concentration of the material.



APPENDIX F
Stubshaft Bracket Bolt Analysis for 2G003

This appendix discusses the fracture analysis performed on the left rear stubshaft bracket bolts on the 20 cylinder engine of 2G003. The bracket is attached to the engine end sheet with 8 bolts, 2 vertical 1/2 x 4 3/4 inch - 20 TPI bolts and 6 horizontal bolts. The upper 3 horizontal bolts are 1/2 x 1 1/4 inch - 20 TPI and the lower 3 horizontal bolts are 3/8 x 1 inch - 24 TPI bolts. In addition, 2 other bolts, which attach the lubrication manifold to the bracket, travel through the bracket and thread into the end sheet.

Procedure

The bolts were visually inspected, photographed and macroscopic examined. Since the fracture surfaces of the bolts indicated similar reverse bending fatigue fracture conditions, only one bolt out of the 8 was selected for detailed SEM fractography.

Results

Figures F.1 and F.2 show the location and provide descriptive numbers for the bolts which attach the stubshaft bracket to the engine end sheet, and Figures F.3 to F.14 show the fracture surfaces of the bolts and the SEM fractograph examination of 1 bolt.

In reviewing the fracture surfaces of the bolts, all the bracket bolts failed under reverse bending fatigue conditions. The relative location of the overload zones coupled with the direction of crack propagation in each individual bolt was indicative of the overall loading and movement of the bracket. It appears the bracket was reverse loaded in a direction normal to the engine end sheet and parallel to the line shown in Figure F.1. The pivot axis of the bracket was a line that ran in the vicinity of the upper 3 horizontal bolts. The bolts that were located farthest from the pivot axis showed the most uneven bending stresses.

The estimated number of fatigue loading cycles was 41,000 cycles. Considering normal engine operation at 900 rpm and 5th order torsional resonance vibration loading, the bracket would experience 900 x 5, or 4500, loadings per minute. Thus, it is estimated that catastrophic failure of the bracket bolts occurred at 41000 divided by 4500, or approximately 9 minutes, after the bracket bolts started to fail.

Conclusion

The stubshaft bracket bolts failed due to reverse bending fatigue followed by overload under relatively low stress conditions, and it took approximately 9 minutes for complete bolt failure after the initiation of the fatigue cracks.

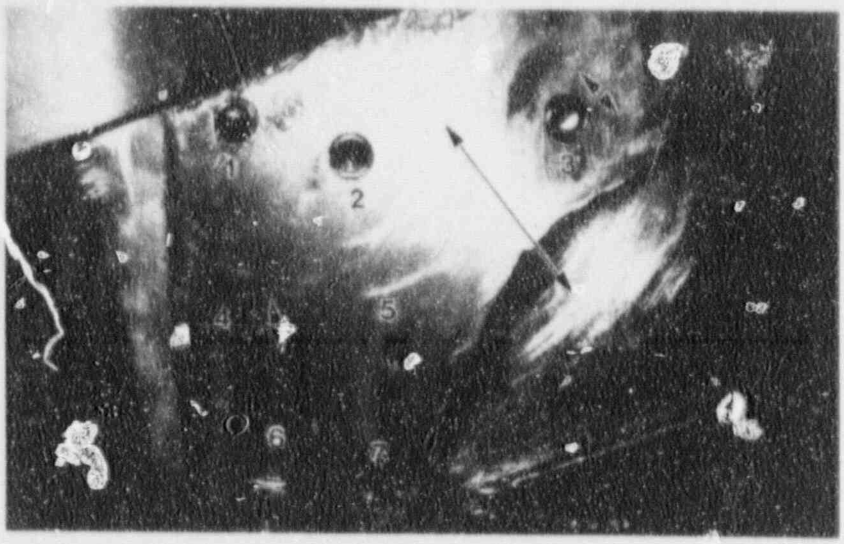


Figure F.1: Side view of the left rear end sheet at the location of the stubshaft support bracket. Note, bolt holes numbered 1-5 and 7 are the location of the primary bolts that attach the bracket, while bolt hole number 6, and a bolt hole directly below bolt hole number 6, attach the lubrication oil manifold to the bracket. The small arrows show the direction of reverse bending of the bolts while the long arrow shows the direction of reverse loading of the entire bracket.

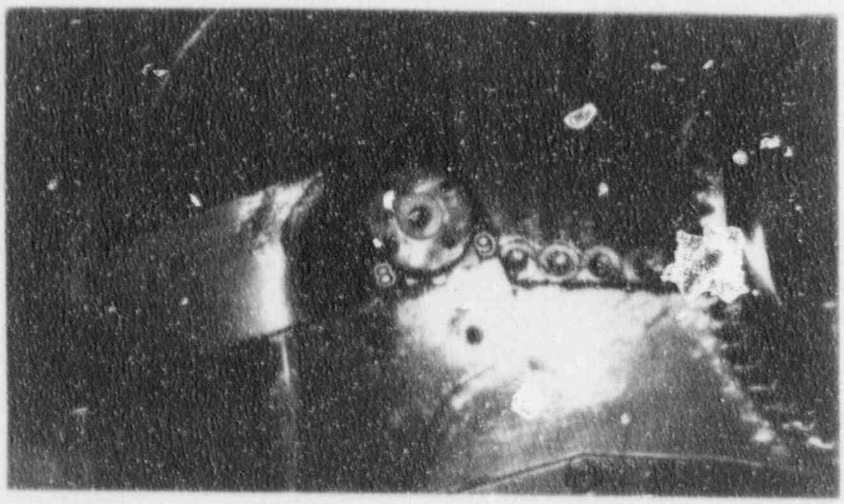


Figure F.2: View of the left rear end sheet of the 20 cylinder engine of 2G003, showing the location of the bolt holes for the 2 vertical bolts that attach the bracket to the engine end sheet.

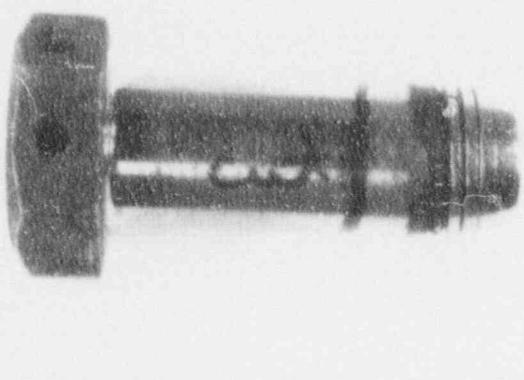


Figure F.3: View of the overall appearance of bolt number 3, illustrating the rubbing and polishing of remaining bolt threads.

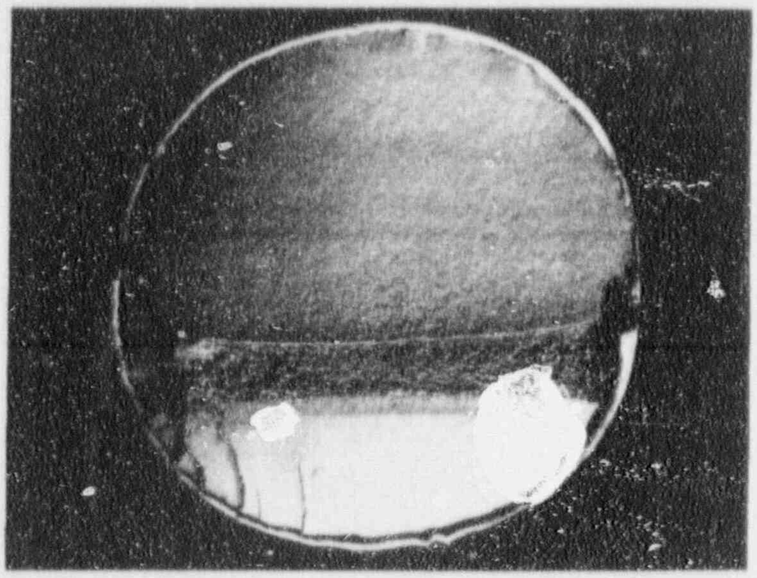


Figure F.4: SEM fractograph of bolt number 3, illustrating the reverse bending fatigue fracture. The width of the overload zone with respect to the overall cross-section was estimated to be 10 percent, indicating the fracture occurred under relatively low stress conditions.

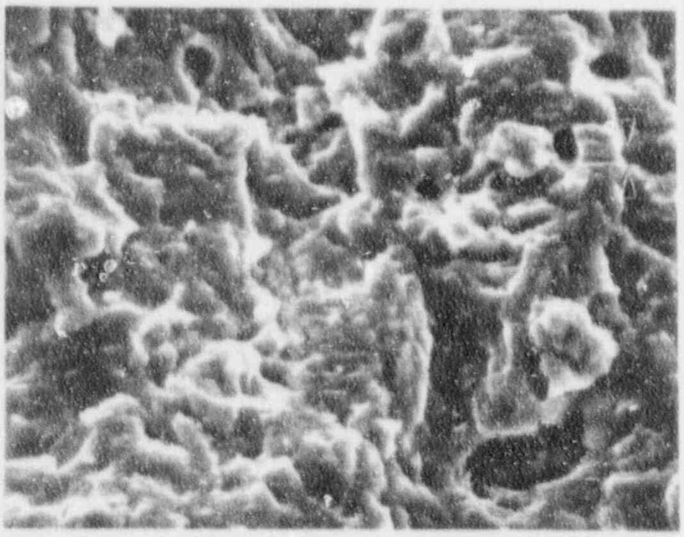


Figure F.5: SEM fractograph of bolt number 3, illustrating the fatigue zone. The arrows contain fatigue striations, and a rough estimate of the coarse fatigue striation was 3.7 x 10 E4 cycles. Taking into consideration the finer striations near the origin area, the total number of cycles would become 4.1 x 10 E4.

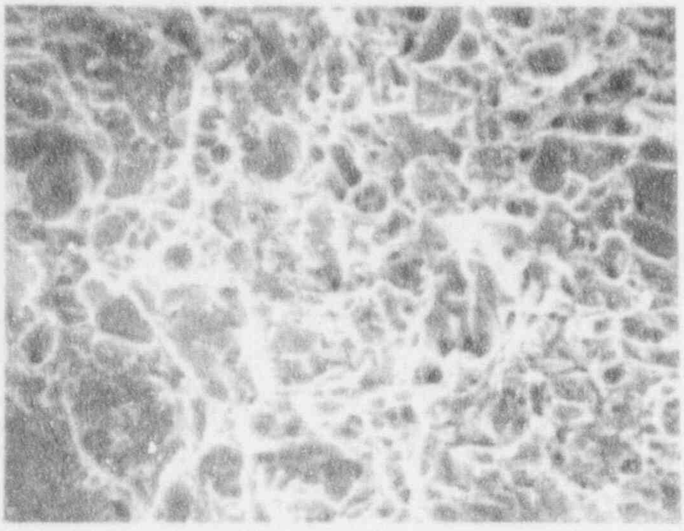


Figure F.6: SEM fractograph of bolt number 3, illustrating the overload zone ar dimple rupture which is indicative of the ductile behavior of the bolt, at 1000 X magnification.

F[illegible]: View of a macrofractograph of bolt number 1, illustrating reverse bending fatigue fracture. The overload zone is off center, indicating that the applied bending stresses were not equal in opposite loading directions. The arrows point to the fatigue initiation sites.

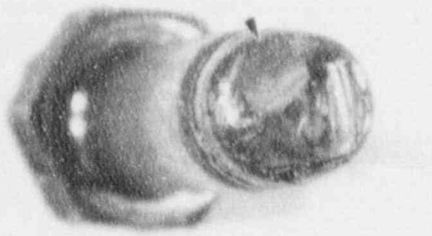


Figure F.8: View of the fracture surface of bolt number 2. The arrow points to the fatigue fracture origin. The fracture surface was rubbed and damaged which obliterated details of fracture.

Figure F.9: View of a fractograph of bolt number 5, illustrating reverse bending fatigue. The overload zone is bounded by the dotted lines and is only slightly off center, which is indicative of the reverse loading approaching uniaxial conditions.

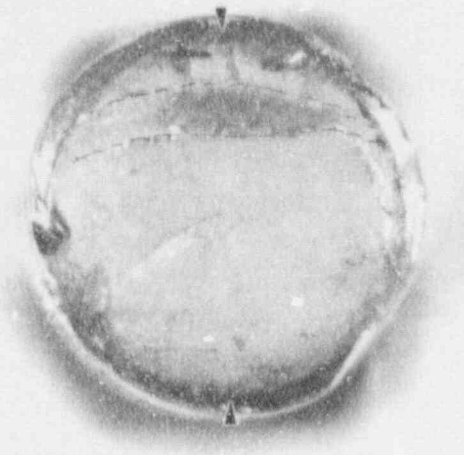


Figure F.10: View of a fractograph of bolt number 4, illustrating reverse bending fatigue. The overload zone is bounded by the dotted lines. The arrows in the figure point to fracture o..gins. The overload zone is off center which is indicative of unequal bending stresses.

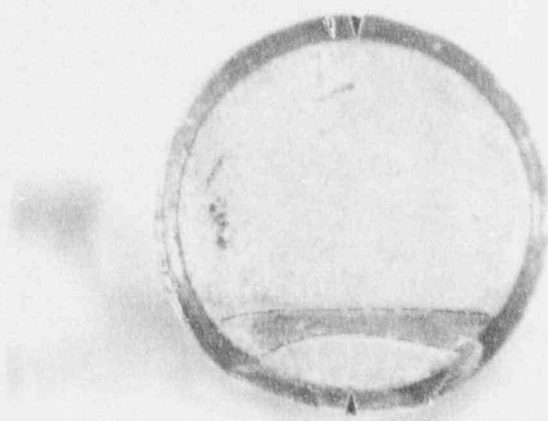


Figure F.11: View of a fractograph of bolt number 7, illustrating reverse bending fatigue. The overload zone is bounded by the dotted lines and the overload zone is off center which is indicative of unequal reverse bending loading.

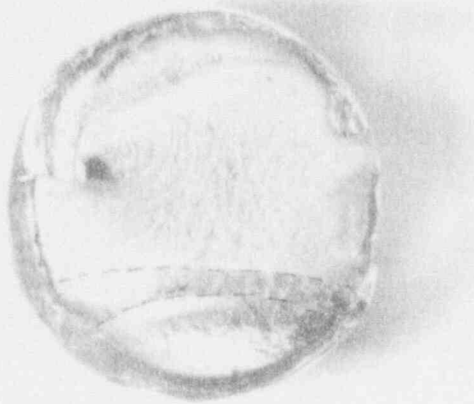


Figure F.12: View of a fractograph of bolt number 6, illustrating reverse bending fatigue. The overload zone is off center which is indicative of unequal bending stresses on both sides of the bolt.

Figure F.13: View of the fracture surface of vertical bolt number 9, as shown in Figure F.2, which was significantly rubbed, but as determined by the mating fracture surface, the fracture was indicative of a reverse bending fatigue condition.

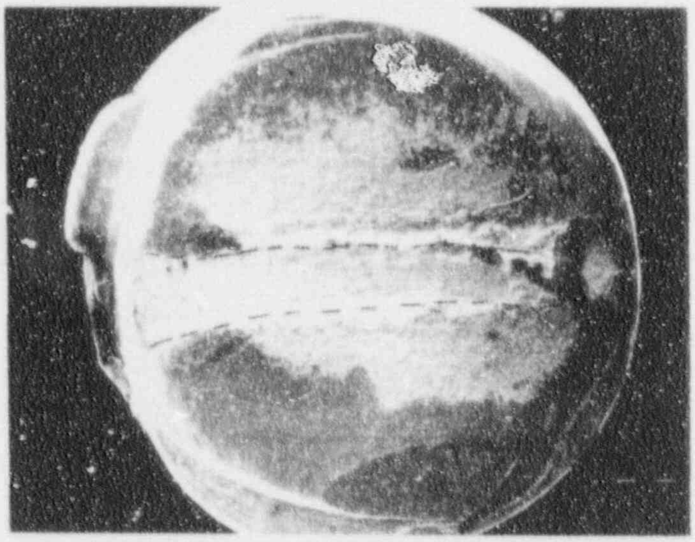


Figure F.14: View of the fracture surface of vertical bolt number 8, illustrating rubbing damage and reverse bending fatigue conditions. The location of the overload zone is in the center of the fracture face which is indicative of even reverse loading of bolt.

APPENDIX G
Mechanical Testing of Bearing Bolts and Dowel Bolts for 2G003

This section discusses the mechanical testing performed on exemplar short camshaft bearing block bolts and camshaft flange dowel bolts. The objective of the testing on the bearing bolts was to determine the mechanism that caused the short bolts on bearing blocks numbers 1, 2 and 3, to lose preload, backout and strip out of the engine block of 2G003. The objective of the testing of the dowel bolts was to compare the impact strength of the diesel manufacturers first choice 1144 carbon steel material verses the second choice 4140 carbon steel material.

Procedure

Camshaft Bearing Bolts

Testing was performed on exemplar bearing bolts to determine the failure mechanism of the short bolts. The first set of testing involved creating stripped threads of a carbon steel block, similar in hardness to the engine block, by cross-threading, tensile pull and overtorquing. The second set of testing involved fatigue testing of a bearing block assembly.

The tested bolts were the same grade and length as the short bolts found in the engine. The hardness of the of exemplar bolts, the 2G003 short bolts, the 2G003 engine block, and the exemplar block material, is listed in Table G.1. During the test, the thread engagement of the short bolts was maintained at 6 1/2 threads which is consistent with short bolt thread engagement found in 2G003.

The first set of testing involved a camshaft bearing block assembly, with washers and bolts, and a machined shaft of the same diameter as the camshaft. The cross-threading could only be achieved by screwing a bolt into a threaded block at an angle of 15 degrees from normal. The tensile pull was achieved using a universal testing machine. The overtorquing was achieved using a torque wrench. The obtained stripped threads were examined by SEM and compared to the stripped threads found in 2G003 on the outboard bearing bolt of bearing block number 3.

The second set of testing involved a series of fatigue testing at stress levels equivalent to full, one half and one quarter, of the specified 32 ftxlb bolt torque. The fatigue testing was run to achieve either 4.7 x 10E6 cycles, which is equivalent to 88 hours of operation at 900 rpm, or failure of the assembly. The mechanical testing was performed at EML Labs.

Flange Dowel Bolts

One of the 1144 dowel bolts removed from 2G003 was sent to AMS Labs for machining a sub-charpy V-notch (CVN) specimen to be impacted at room temperature. Also, a sub-CVN specimen of 4140 steel was made to the same exact dimensions as the dowel bolt sample and tested under the same conditions. The hardness of the 4140 material was in the same range as the 1144 dowel bolt.

Results

Camshaft Bearing Bolt Testing

Figure G.1 shows a typical camshaft bearing block with bolts. Figure G.2 is a SEM fractograph of stripped threads found entrapped on the threads of the outboard bolt of bearing block number 3. Figure G.3 shows a back scattered electron fractograph illustrating the presence of rubbed zone (A) in the direction of the arrow, and a relatively undamaged sheared zone (B). The details of sheared zone (B) is shown in Figure G.4 which illustrates elongated dimples typical of either a shear or tear fracture.

Figures G.5 and G.6 represent SEM fractographs of the stripped threads obtained in the lab by cross-threading. Note, the Figures illustrate the presence of a rubbed zone (A) in the direction shown, followed by a zone of cracking, tearing, and fragmentation (C). During the cross-threading procedure, the stripped threads were generated in a fragmented form instead of continuous helical coil form as found in 2G003, and there was no distinct shear zone evident on the stripped threads. Thus, the stripped threads obtained by cross-threading did not resemble the stripped threads found in the engine. Also, since stripped threads due to cross-threading could only be obtained at an angle of 15 degree from normal in the lab, it is virtually impossible to conceive that the stripped threads found in the engine were the result of cross-threading. The configuration of a bearing block basically ensures the bolts are inserted within a couple of degrees of normal.

Figures G.7 and G.8 represent SEM fractographs of the stripped threads obtained by tensile pull. The photos are oriented 90° away from that of Figure G.3. The fracture surface shows two distinct zones, rubbed zone (A) and shear zone (B). Figure G.8 illustrates shear elongated dimples in the shear zone. Also, the stripped threads generated by tensile pull were found contained between the bolt threads and were in a helical form. Thus, the stripped threads obtained by tensile pull closely resemble those of the stripped threads found in 2G003.

Figures G.9, G.10 and G.11, represent SEM fractographs of the stripped threads obtained by overtorquing. Figure G.9 shows the presence of three distinct zones, tearing zone (D), rubbed zone (A), and shearing zone (B). The appearance of the rubbed zone (A) and shear zone (B) resemble the stripped threads found in 2G003. The major difference between the fracture morphology of the stripped threads, as compared to the stripped threads found in 2G003, is the presence of the tearing zone. Thus, the stripped threads obtained by overtorquing do not closely resemble the stripped threads found in 2G003.

In summary, based on the above testing, the stripped threads found in 2G003 on the outboard bolt of bearing block 3 were most likely generated by a tensile pull mechanism.

Camshaft Bearing Bolt Fatigue Testing

The purpose of the series of tests was first to study the behavior of a camshaft bearing block at different fatigue stress levels, and determine whether the bolts would lose preload and become loose, or break prior to a loss of preload; and second, to determine at what stress level any of the above mentioned events would take place. Report G.2 of this appendix is the lab report.

The fatigue loads were selected as a fraction of the applied preload which would result from torquing the bolts to the vendor specified 32 ft-lbs. In the first test, the maximum fatigue load was equal to 1/4 the preload, in the second test the maximum fatigue load was equal to 1/2 the preload, and in the third test the fatigue load was basically equal to the preload. The minimum fatigue loading in the first and second test was 256 pounds, and in the third test the minimum fatigue load was 500 lbs. The testing speed was kept at constant 30 cycles/second.

The 6 exemplar bolts that were tested were ASME grade 5, 3/8" x 4 1/2 inch - 24 TPI, with a nominal hardness of 30 HRC. The mean thread area of each bolt was 0.0876 square inches. For an applied torque of 32 ft-lbs, the force experienced by a bolt was equal to 5120 pounds, based on equation T = 0.2FD. The fatigue tests used a complete bearing housing with two bolts, and as a results, the applied fatigue loads were twice the value required for a single bolt.

The first test, at a maximum fatigue load equal to 1/4 the preload, was stopped after achieving 4.864 X 10E6 cycles. The bolts did not lose preload or break, and there was no indication of a failure of the test assembly.

The second test, at a maximum fatigue load equal to 1/2 the preload, was stopped after achieving 4.89 X 10E6 cycles. The bolts did not lose preload or break, and there was no indication of a failure of the test assembly.

The third test, upon increasing the fatigue load to 10,000 pounds, one bolt failed in fatigue after 6.5 X 10E5 cycles followed by an overload failure of the other bolt.

In summary, the results of the 3 tests indicates that short bolts with a 6 1/2 thread engagement will not lose preload for fatigue loads as high as 1/2 the normally applied bolt preload, and upon increasing the fatigue loading, the bolts will break prior to loosing preload.

Discussion

Bearing Block Bolts

Considering that the stripped threads found in 2G003 have a similar appearance to the stripped threads of the tensile pull test, and that a 6 1/2 thread engagement is adequate to maintain joint integrity, it is obvious that factors other than vibration and loading contributed to the short bolts loosing preload in bearing block number 1, 2 and 3.

The seemingly undamaged threads in the engine block holes for bearing blocks 1, 2 and 3, did not pass a go and no-go test which indicated the threads were actually damaged and worn. Thus, if the first and second fatigue tests were preformed with worn bolt holes similar to those found in the engine, there may have been a loss preload and a backing out of the bolts. Thus, it is highly likely that worn bolt holes resulting from previous failures and rework activities contributed to the loss of preload in the bearing block bolts. Also, the short bolts in the engine had an average effective engagement of approximately 6 1/2 threads. Thus, a backing out of just a few threads would have reduced the engagement to below the critical engagement to prevent tensile pullout, as the as-found condition of the bearing block bolt holes illustrates.

Dowel Bolts

The camshaft to stubshaft flange dowel bolts are made of a re-sulfurized grade carbon steel that conforms to AISI 1144 specifications. The chemical analysis of one of 2G003 dowel bolts is listed in Report G.1. The main advantage of this grade over the other carbon steel grades is easy machining to close tolerances. According to the diesel manufacturers specifications, AISI 1144 carbon steel is recommended as first choice and AISI 4140 chromium molybdenum as an alternate.

The difference in mechanical properties of both alloys is significant. Alloy 4140 has a much higher impact strength which is almost four times greater than that of alloy 1144 at the same hardness level. Also, alloy 4140 has a much more homogeneous microstructure, when heat treated properly. In comparison, alloy 1144 has an inhomogeneous microstructure as a result of the resulfurization process. The microstructure is expected to have non-uniform sulfide inclusions, however, the size and distribution of the sulfide inclusions can be controlled during the manufacture of the material.

Since the dowel bolts function primarily to carry the shear loading of the flange connection, the dowel bolts may experience shock shear loadings during startups. Thus, the impact strength of the material is an important property, at the same time, easy machining in necessary to achieve the close dimensional tolerances of the machined fit.

Table G.2 lists the results of room temperature impact tests performed on a sub-size CVN sample machined from one of the failed 2G003 1144 dowel bolts and on a sub-size 4140 steel sample. The impact strength of the 1144 dowel bolt sample was 2.5 ft-lbs and the impact strength of the exemplar 4140 steel was 11.5 ft-lbs. The 1144 dowel had a hardness of 30 HRC which compares closely to the exemplar 4140 steel hardness of 32 HRC. As illustrated, the impact strength of 4140 alloy steel is 4.6 times greater than that of 1144 resulfurized carbon steel. Thus, considering impact strength, one would favor the 4140 alloy, but considering ease of machining to close tolerances, one would favor the 1144 alloy.

The vendor has successfully used 1144 alloy in engines for over 50 years. Based on conversations with the manufacturer of the engine, and in consideration of the above discussion and other information, it has been determine that at SONGS the 1144 alloy will remain the material of choice, provided the microstructure has no large sulfide stringers/inclusion.

Conclusions

1. Scanning electron microscope examination of the stripped threads removed from 2G003 were found to have features that resemble stripped threads generated in a laboratory by tensile pulling, and did not resemble stripped threads generated by cross-threading or overtorquing.

2. The failure mechanism of the short bolts in bearing block bolts number 1, 2 and 3, was a loss of preload, backing out, and stripping out. This is supported by the as-found condition of the bolt and bolt holes, and the testing discussed in this appendix.

3. At SONGS, 1144 alloy will remain the material of choice for dowel bolts, provided the microstructure has no large stringers of sulfide inclusion.

ACCURATE METALLURGICAL SERVICES, INC.
10005 FREEMAN AVENUE
SANTA FE SPRINGS, CA 90670
TELEPHONE: (213)946-1721

Customer: SOUTHERN CALIFORNIA EDISON   PO/SO: 02687L/MOSTAFA   Lab No: 159517   Date: 10/07/91

Material: Steel   P/N: Heat Number: NOT SUPPLIED

Specification: INFO ONLY   Other: Test Material

Bolt

CHEMISTRY ELEMENT		MINIMUM REQ.	MAXIMUM REQ.	ACTUAL	COMMENTS
C	Carbon	NO RE		0.47	
Mn	Manganese	NO RE		1.52	
P	Phosphorus	NO RE		0.025	
S	Sulfur	NO RE		0.30	
Si	Silicon	NO RE		0.19	
Cr	Chromium	NO RE		0.05	
Ni	Nickel	NO RE		0.02	
Cu	Copper	NO RE		0.01	
Fe	Iron	NO RE		BAL	

REPORT G.1
Chemical Analysis of 1144 Alloy

For information only.   Comment: Respectfully Submitted

Chemical analysis conforms to AISI limits for 1144

RS PAGE: 3 of 3

ACCURATE METALLURGICAL SERVICES, INC.

EML — ENGINEERING-MATERIALS-LABORATORY

Lab. No. 9110-3
P.O. No. Verbal/Mostafa
October 23, 1991

Southern California Edison
5000 Pacific Coast Highway
San Clemente, CA 92672

TESTING OF DIESEL ENGINE BOLTS

Introduction

Static and fatigue tests were done on 3/8"-24UNF Grade 5 bolts that hold a cam bearing tower in place on a diesel engine. The purpose of these tests was to provide known tensile, overtorque, cross-thread, and fatigue failures to compare with bolts that had failed on the engine. We were provided with the cam bearing housing, and we made a block that simulated the engine head so we could bolt on the cam bearing assembly. The ASME Grade 5 3/8"-24UNF x 4 ½" long hex head bolts were purchased new by us specifically for these tests.

The tensile, overtorque, and cross-thread tests were done under the direction and in the presence of Dr. M. S. Mostafa. The fatigue tests used the complete bearing housing with two bolts installed using 32 ft.-lbs. torque. A Baldwin/Sonntag 10,000 lb. capacity fatigue machine was used for the fatigue tests. Below is the data on the fatigue tests:

Fatigue Data

Test #1

Maximum Fatigue Load:	2,560 lbs.
Minimum Fatigue Load:	256 lbs.
Testing Speed:	30 CPS.
Number of Cycles Tested:	4,864,000

The test was stopped without failure of any component of the bearing assembly.

Test #2

Maximum Fatigue Load:	5,120 lbs.
Minimum Fatigue Load:	256 lbs.
Testing Speed:	30 CPS.
Number of Cycles Tested:	4,890,000

The test was stopped without failure of any component of the bearing assembly.

Test #3

Maximum Fatigue Load:	10,000 lbs.
Minimum Fatigue Load:	500 lbs.
Testing Speed:	30 CPS.
Number of Cycles Tested:	650,000

Fatigue failure of one bolt in the threads. Second bolt failed by overloading after the first bolt failed.

Respectfully Submitted,

B. L. Bland

B. L. Bland

8511 WELLSFORD PLACE — SUITE "G" — SANTA FE SPRINGS, CA 90670 — (213) 945-2138

APPENDIX H
Cardboard Debris Analysis for 2G003

This appendix discusses the Fourier Transform Infrared Analysis of the fibrous cardboard-like material found in the 20 cylinder engine of 2G003.

Three small fibrous fragments were found in the oil pan. The largest piece was a half circular shape approximately 1 1/2 inches in radius, 2 1/2 inches in length, 3/4 inches in width, and 0.02 inches in thickness. The other two small pieces were of similar thickness but much smaller in size, approximately 1/2 inches in length and 1/4 inches in width. All three pieces had a similar visual appearance.

The purpose of the analysis was to determine the origin of this material and compare it to a material that is used in the engine. One possible source of the fragments was considered to be camshaft gear replacement activities in June 1991, in which cardboard was placed under a bearing cap to temporary secure camshaft timing.

Procedure

Samples of the found fragment, exemplar gasket material, and exemplar cardboard were examined in an optical microscope for fiber appearance. Also, Fourier Transform Infra-Red (FTIR) analysis was performed to determine the nature of the fibers and the filler material that binds the fibers.

Results

Figures H.1 through H.6 document the fiber appearance under the optical microscope. Figures H.1 and H.2 represent the found fragments, Figures H.3 and H.4 represent the exemplar cardboard sample, and Figures H.5 and H.6 represent the exemplar gasket material. As shown in these Figures, the fragment sample has fine and coarse fibers that do not resemble the coarse fibers found in both the cardboard sample and the gasket sample.

The FTIR analysis indicated that all three materials have a cellulose basis but with different binding and filler material. The fragments had a brownish coating of a silicate nature, reference Trace H.1. The exemplar cardboard had a clear adhesive bonding material cellulosic in nature, reference Trace H.2. The exemplar gasket material had a yellowish filler of a silicate clay nature, reference Trace H.3.

Considering the above mentioned optical observations and FTIR results, it is concluded that the found fragments do not match the exemplar cardboard material or the exemplar gasket material. However, since cardboard boxes are made of many different types of fibers and different binding and filler materials, the found fragment may be of cardboard box material origin.

Conclusion

The fragments did not match microscopically or chemically either the exemplar cardboard material or the exemplar gasket material. However, this finding does not eliminate the possibility that the found fragment may have come from a cardboard material.

Figure H.1: View of found fragment at 14 X magnification.

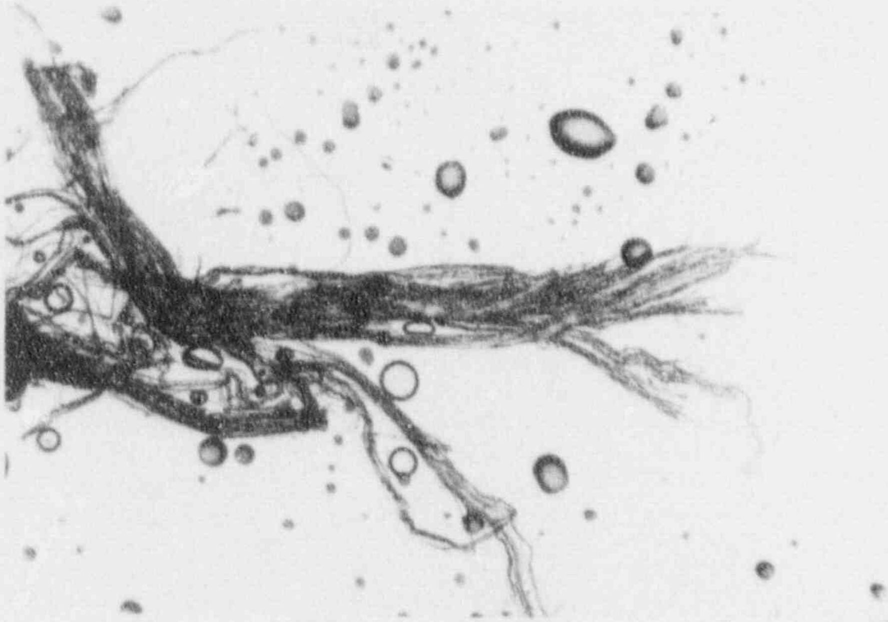


Figure H.2 View of found fragment fibers at 58 X magnification.

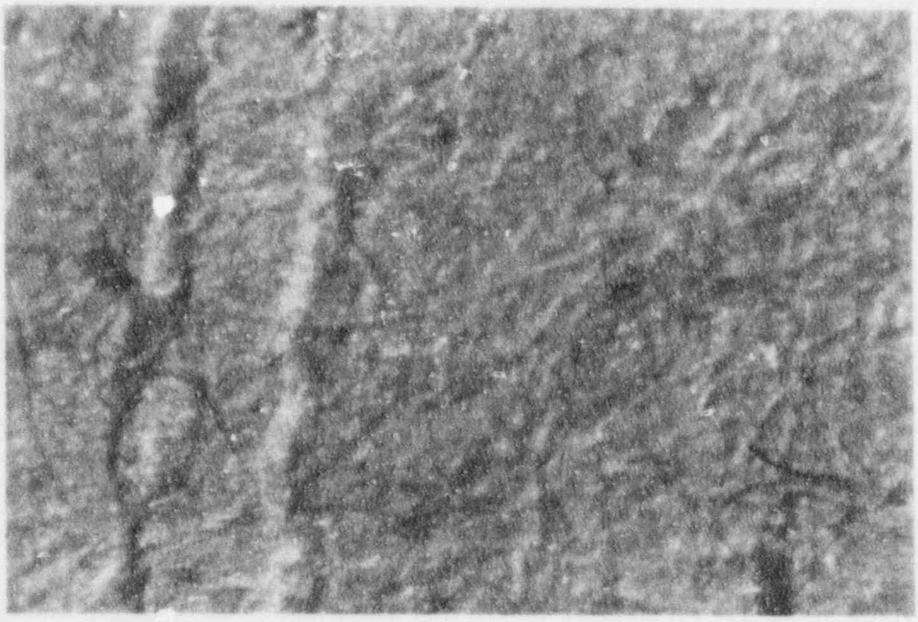


Figure H.3: View of exemplar cardboard at 14 X magnification.

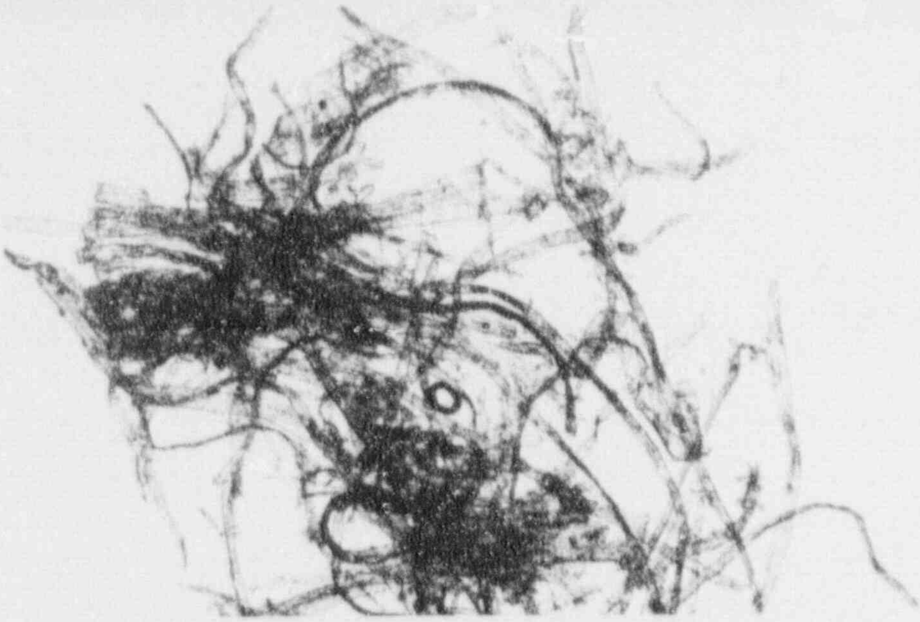


Figure H.4: View of exemplar cardboard fibers at 58 X magnification.

Figure H.5: View of exemplar gasket material at 14 X magnification.

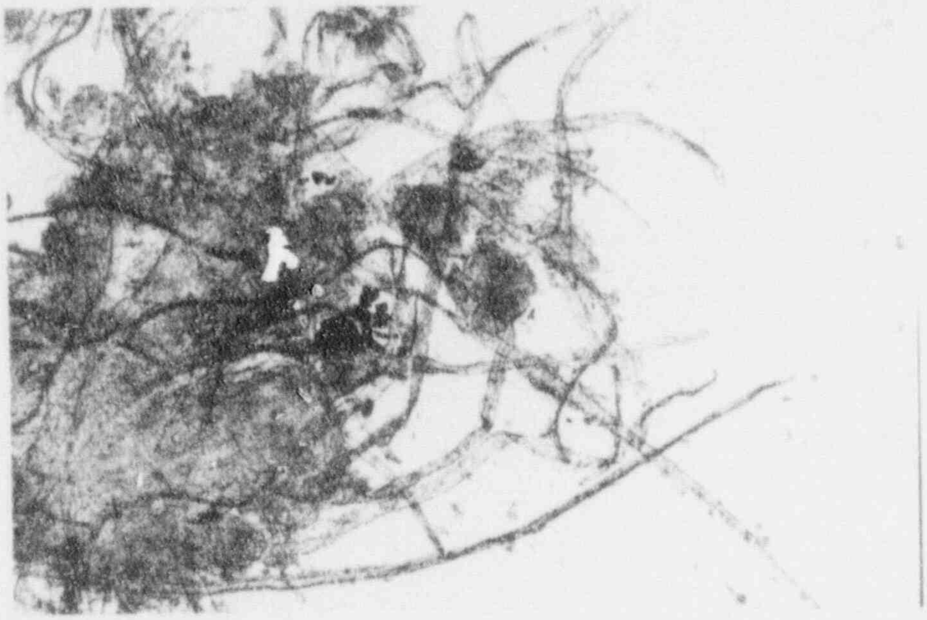
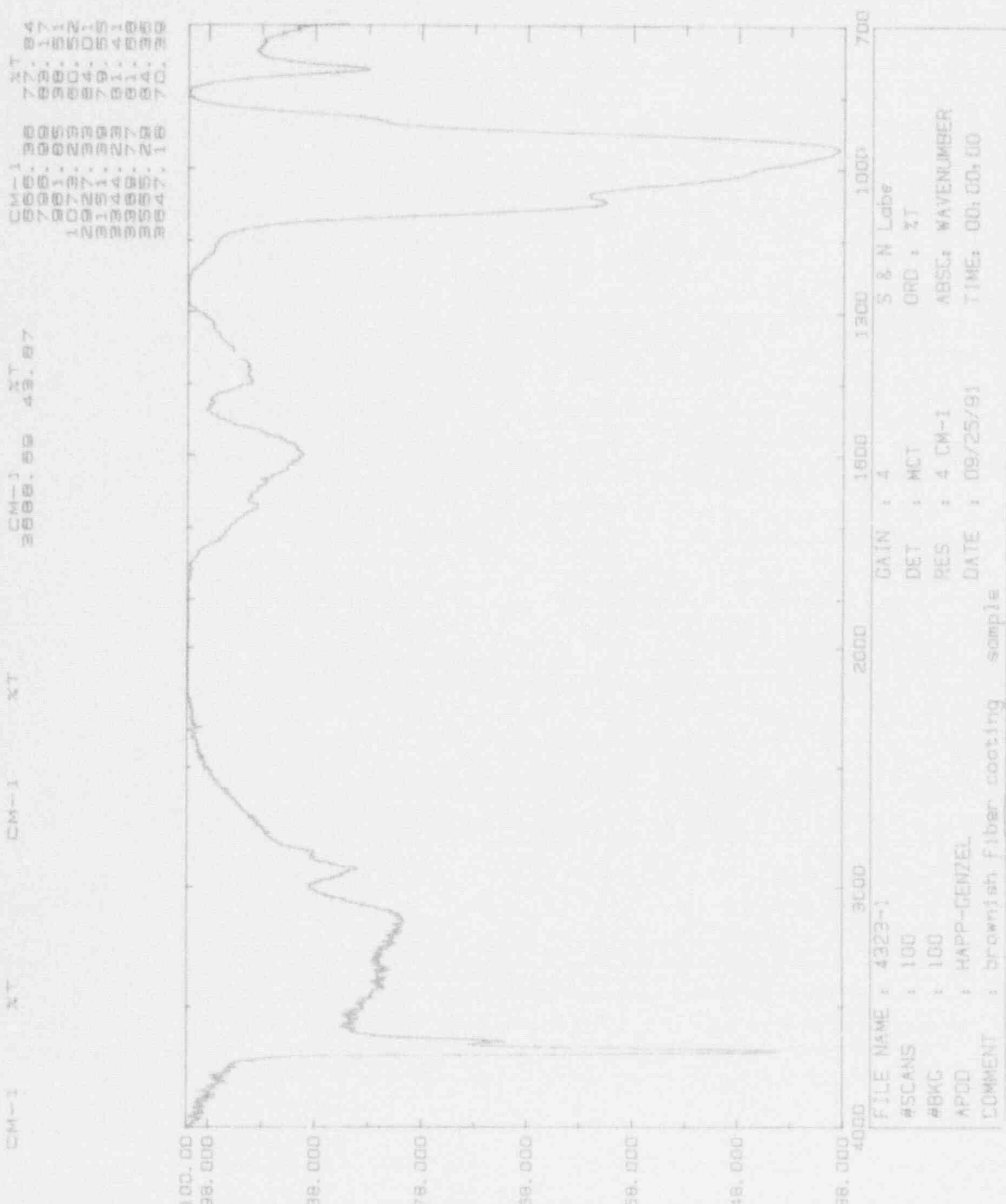
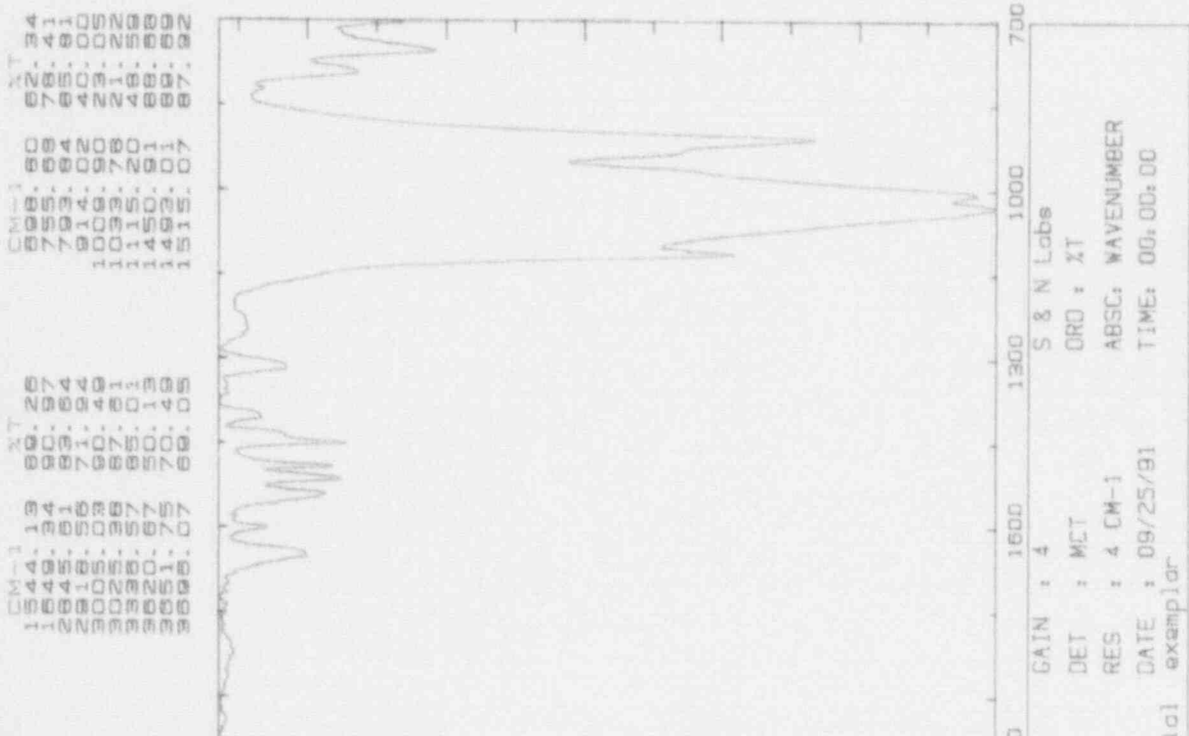


Figure H.6: View of exemplar gasket fibers at 58 X magnification.

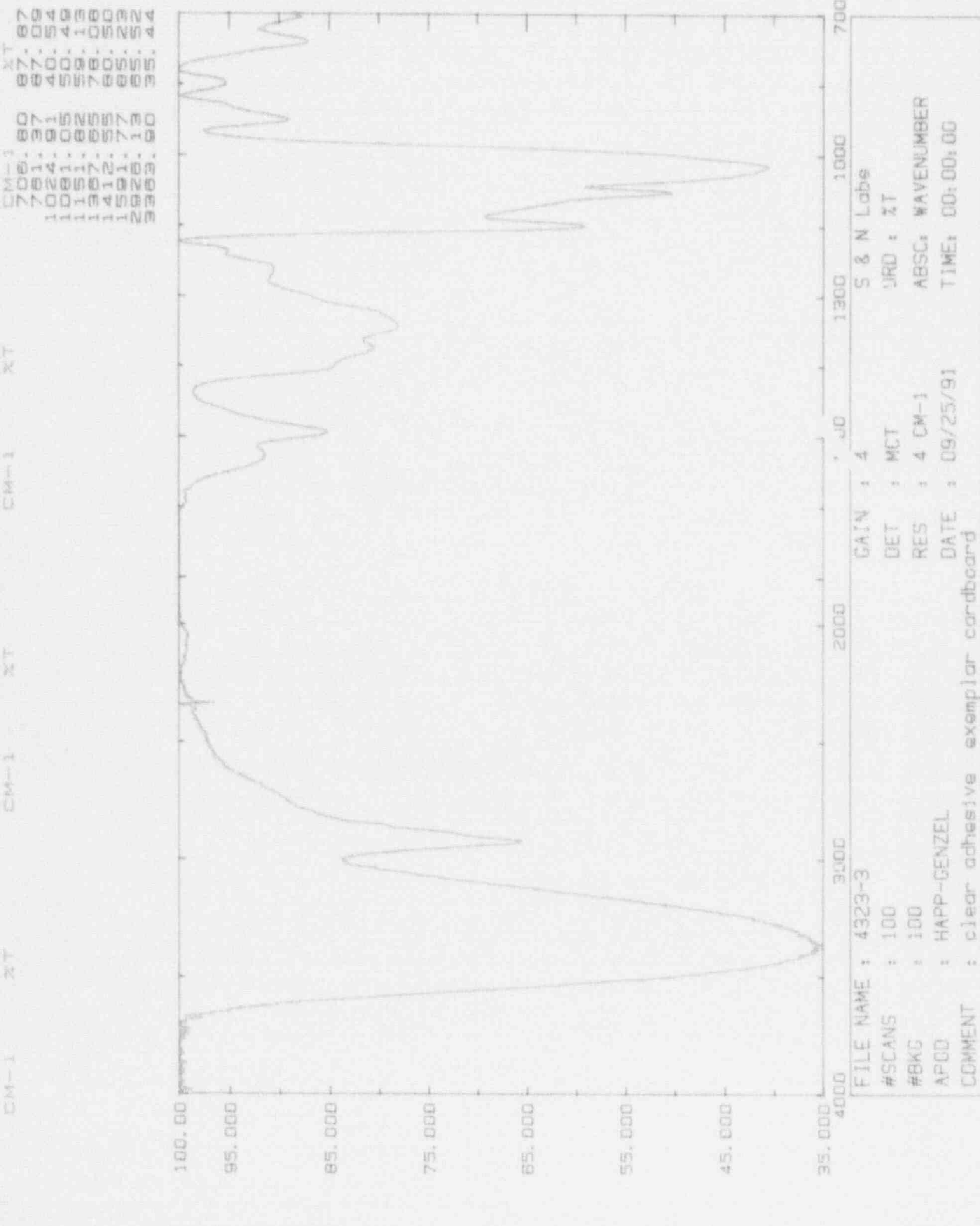
Trace H.1: FTIR analysis of found fragment.



Trace H.2: FTIR analysis of exemplar cardboard material.



Trace H.3: FTIR analysis of exemplar gasket material.



APPENDIX I

3G003, STUBSHAFT FLANGE CONNECTION DEGRADATION EVENT

DESCRIPTION OF EVENT

On October 1, 1991, in response to the 2G003 camshaft assembly failure of September 16, 1991, an inspection was performed on the left bank camshaft assembly of the 20 cylinder engine of 3G003 to ensure the camshaft bearing block bolts were not coming loose. Although it was determined that the camshaft bearing block bolts of 3G003 were tight and that 3G003 was not experiencing a bearing block problem, the camshaft to stubshaft flange connection was found in a degraded condition. One of 4 flange connection dowel bolts was found to be fractured while cracks were found in the other 3 dowel bolts. A subsequent inspection verified that the stubshaft support bracket was not cracked and that the bracket bolts were tight. Thus, it was determined that the problem was limited to degradation of the stubshaft flange connection.

A plan was developed and implemented to verify the tightness and condition of other camshaft flange connections and to replace the degraded dowel bolts with acceptable dowels. A justification of continued operation was written, as documented in NCR 91100002, the EDG was tested, and the EDG was returned to service.

STUBSHAFT FLANGE CONNECTION INFORMATION

Configuration information on the EDG and the camshaft assembly is provided in the Emergency Diesel Generator Information Section of this Report. The stubshaft flange connection consist of 2 flanges which are bolted together with 4 dowel bolts. The dowel bolts have a close tolerance machined fit, are threaded on each end for 3/8 inch nuts with washers, and are designed to carry the shear load of the flanges due to the torsional loading of the camshaft. One of the 4 dowel bolts is 7/16 inches in diameter while the other 3 are 1/2 inches in diameter. The dowel bolts size difference ensures the proper alignment of the camshaft lobes during assembly. The EMD dowels bolts are typically made of AISI 1144 material.

INFORMATION COLLECTION

Dowel Bolt Failure

On the left rear stubshaft flange connection of the 20 cylinder engine of 3G003, one of 4 flange connection dowel bolts was found to be fractured while cracks were found in the other 3 dowel bolts. The dowel portions of all 4 bolts were intact. The cracks in the 3 dowel bolts were in the thread to shoulder transition on the end of the dowel bolts that face the rear of the engine. The 3 dowel cracked bolts were found with varying degrees of preload present. The fracture in the 1 broken dowel bolt was in the thread to shoulder transition on the end of the dowel that faces the rear of the engine. The nut and threaded portion of the fractured dowel bolt were found as a unit on the top deck of the engine along with the corresponding washer. The remaining portion of the dowel bolt was found in the flange, but shifted approximately 1/4 inch toward the front of the engine. No other degradation was found in the vicinity of the left rear camshaft assembly, including the bearing blocks and stubshaft bracket assembly.

A 5th order torsional resonance has been known to exist in the 20 cylinder engine, which causes an undesirable vibratory motion in the gear train and left rear camshaft assembly. This resonance coupled with normal vibration contrib ' :d to the initiation and propagation of the fatigue crack. Appendix D provides a detailed di:.cussion on the 5th order torsional resonance. A run out measurement was taken on the stubshaft flange connection which verified the flange alignment was not a problem.

Camshaft Bracket

An inspection was performed which verified that the left bank camshaft bearing blocks were in acc('able condition and that the bearing block bolts were tight. Thus, eliminating a bearing block problem, similar to the 2G003 event, as being the root cause or a contributing factor to the degraded flange condition.

An inspection was performed which verified that the left bank stubshaft bracket was in acceptable condition and that the bracket bolts were tight. Thus, eliminating a bracket failure, similar to the past 3G003 failure and past 2G003 failures, as being the roo. cause or a contributing factor to the degraded flange condition.

Dowel Bolt Material

The vendors choice of dowel material is AISI 1144, which is a high temperature drawn manganese carbon steel. If 1144 is not available, the vendor considers AISI 4140 to be an acceptable material.

AISI 1144 dowel bolt material has been used by EMD for over 50 years with a very good record of performance. The 1144 alloy is preferred by EMD because it is a relatively high strength, hard and brittle alloy, which can be easily machined to the close tolerances necessary in camshaft flange connections. The 4140 alloy is a tougher material. However, since it is difficult to machine to the close tolerances necessary in camshaft flange connections, it is acceptable but not preferred by EMD.

A metallurgical analysis of the 1 broken and 3 cracked dowel bolts of the stubshaft flange connection revealed that the dowel bolts were made of the EMD preferred 1144 alloy. The failure mode of the broken dowel bolt was approximately 70% fatigue followed by 30% overload, and the fracture was across the threaded portion of the dowel bolt between the dowel shoulder and nut. The cracks in the other 3 dowel bolts originated in the same area as broken dowel bolt with some propagation into the shoulder area of the dowel bolt. Typically, the fatigue cracks would propagated in the traverse direction and then would run along sulfide inclusions/stringers in the longitudinal direction.

The dowel bolts of 3G003 were determined to be of poor quality because the 1144 alloy had an unacceptably large population of large sulfide inclusions/stringers. Also, the analysis determined that the broken dowel bolt had a greater extent of sulfur inclusions/stringers that the cracked dowel bolts.

The sulfide stringers were mainly the result of poor mixing of the molten steel during the fabrication of the 1144 alloy, which resulted in a anisotropic material condition, which produced a substantial decrease in transverse mechanical properties, such as, ductility, fatigue life, and fracture toughness.

FAILURE SCENARIOS

1) **Poor Quality Dowel Bolts Coupled with 5th Order Torsional Resonance (Most Likely)**

Under normal engine vibration and 5th order torsional resonance, a fatigue cracked initiated and began to propagate in a poor quality dowel bolt. The fatigue crack propagated to the point were the dowel bolt fractured due to overload. The stubshaft flange connection lost some rigidity resulting in increased vibration and cyclic stresses. Fatigue cracks initiated and propagated in the other 3 poor quality dowel bolts.

2) **Camshaft Bearing Block Failure (Less Likely)**

A failure scenario involving the number 1 camshaft bearing block, similar to the 2G003 event, could have resulted in the degraded flange connection. However, this scenario was proven invalid because an inspection of the left bank camshaft bearing blocks indicated that the bearing blocks were in good condition with tight bolts.

3) **Failure of Stub Shaft Bracket (Less Likely)**

A failure of the stubshaft bracket, similar to the past 3G003 failure and past 2G003 failures, could have resulted in the degraded flange connection. However, this scenario was proven invalid because an inspection of the left bank stubshaft bracket indicated that the bracket was in good condition with tight bolts. Also, previous bracket failures have not resulted in flange degradation.

4) **Improper Torquing (Less Likely)**

Improper torquing of the flange connection dowel bolts during previous work activities, similar to the 1987 2G003 loose flange connection event, could have resulted in the degraded flange connection. However, this scenario was proven invalid because a review of previous work history indicated that the flange dowel bolts were properly torqued to 32 ft-lbs. Also, breakaway torques were taken on the dowel bolts, which were not broken but fatigue cracked, that indicated that the proper torque was most likely applied during previous work activities. The 2 cracked dowel bolts with significant fatigue cracks had breakaway torques of 12 ft-lbs while the 1 dowel bolt with fatigue cracks to a lesser extent had a breakaway torque of 30 ft-lbs. The vendor specified torque for the dowel bolts is 32 ft-lbs.

ROOT CAUSE ANALYSIS

Based on the facts and evidence collected, the root cause of the EDG degraded flange connection was a combination of poor quality dowel bolts and normal engine vibration coupled with 5th order torsional resonance.

Corrective Actions

New AISI 1144 dowel bolts of acceptable quality, as verified by laboratory analysis, were installed in the stubshaft flange connection. Appendix L provides a detailed analysis of the new dowel bolts.

The 5th order torsional resonance problem has been corrected by the installation of driveline coupling modification, during the Unit 3 cycle 6 refueling outage, which shifted the resonance away from the operating speed of the engine.

Procurement Engineering has taken action to ensure the procurement of acceptable quality AISI 1144 dowel bolts in the future. Procurement Engineering Package K708 requires the supplier to verify the quality of a random sample of new procurements by laboratory analysis.

It is concluded that the replacement of the poor quality dowel bolt with the acceptable quality dowel bolts, as verified by laboratory analysis, will prevent a recurrence of the event. This conclusion is supported by the previous bracket failure in 3G003, and previous bracket failures in 2G003, where the stubshaft flange connection dowel bolts experienced significantly higher vibration and stress without fatigue or overload fractures. Also, AISI 1144 dowel bolt material has been used by EMD for over 50 years with a very good record of performance.

Also, it is concluded that the poor quality dowel bolts are an isolated occurrence. This conclusion is supported by inspections, which verified that the stubshaft to camshaft, and camshaft to spacer dowel bolts, were tight on the 16 and 20 cylinder engines of 2G002, 3G002 and 3G003. Also, dye penetrant examination of the left rear stubshaft flange dowel bolts on the 20 cylinder engines of 2G002 and 3G002, the left rear camshaft to spacer flange on the 20 cylinder engine of 3G003, and the right rear stubshaft flange dowel bolts on the 20 cylinder engine of 3G003, indicated that the dowel bolts were not experiencing a fatigue or overload problem.

10CFR21 REPORT EVALUATION

The poor quality dowel bolts are considered to be an isolated occurrence, because the AISI 1144 dowel bolt material has been used by EMD for over 50 years with a very good record of performance. This conclusion is supported by the previous bracket failure in 3G003, and previous bracket failures in 2G003, where 1144 stubshaft flange connection dowel bolts experienced significantly higher vibration and stress without fatigue or overload fractures. This conclusion is also consistent with the root cause which attributed the degraded flange connection to a combination of poor quality dowel bolts, normal engine vibration and 5th order torsional resonance.

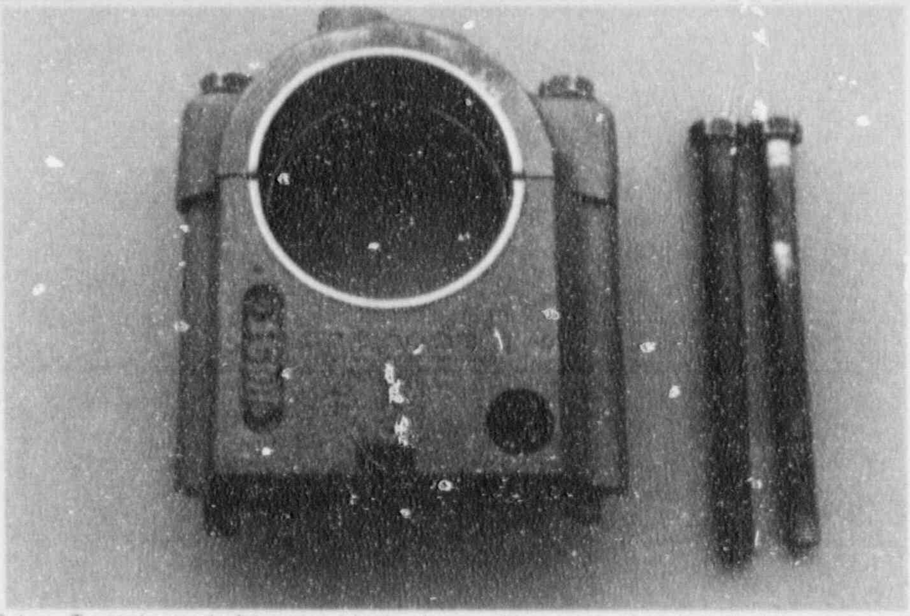


Figure G.1: Typical camshaft bearing block, shown with a correct length bolt at the outboard (left) location and a short length bolt at the inboard (right) location. Also, a correct length and short length bolt are shown for comparison.

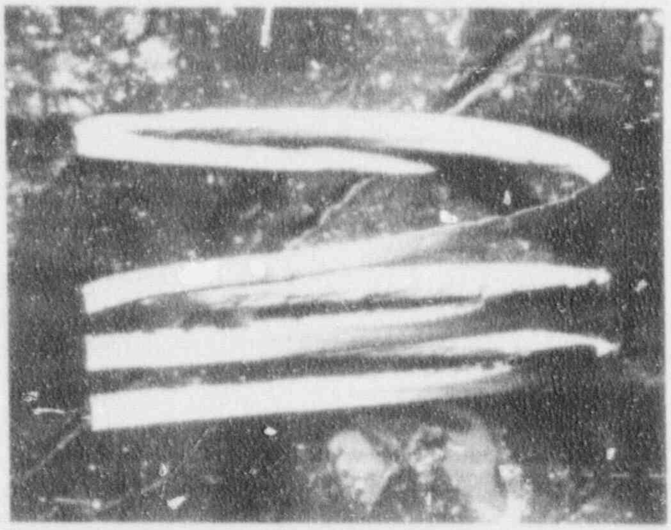


Figure G.2: SEM fractograph of stripped threads found entrapped on the threads of the outboard bolt of bearing block number 3, at 6 X magnification.

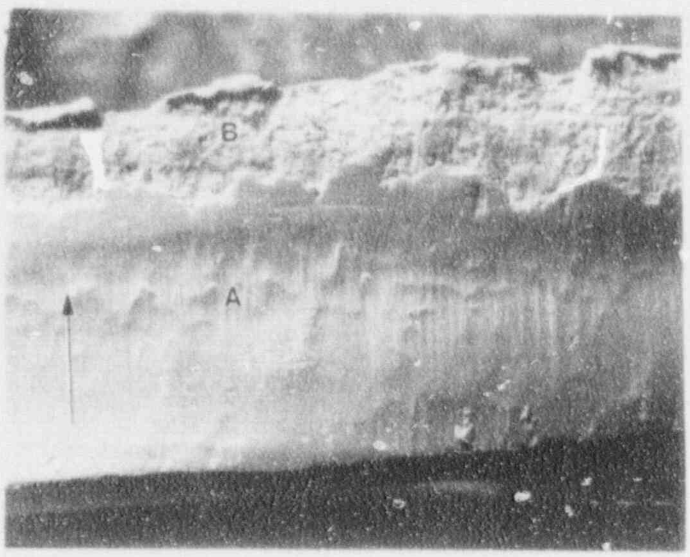


Figure G.3: Back scattered electron fractograph of the stripped threads found entrapped on the threads of the outboard bolt of bearing block number 3, illustrating the presence of rubbed zone (A) in a direction of the arrow and a relatively undamaged sheared zone (B), at 80 X magnification.

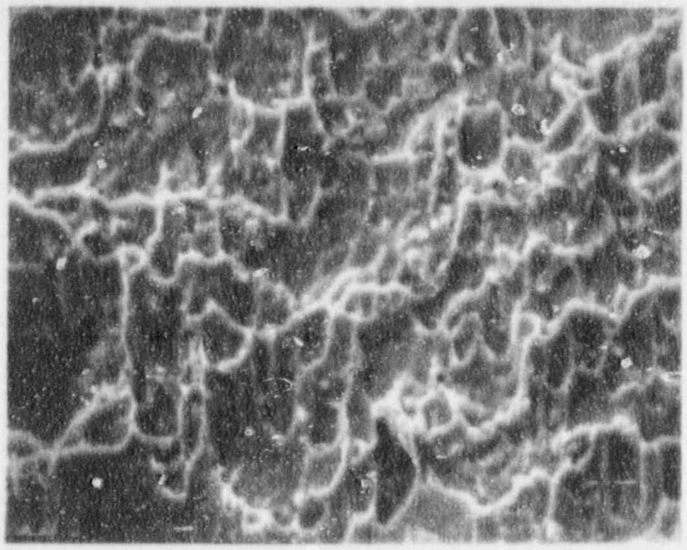


Figure G.4: Detail of sheared zone (B), as shown in Figure N.3, which illustrates elongated dimples typical of either a shear or tear fracture, at 1000 X magnification.

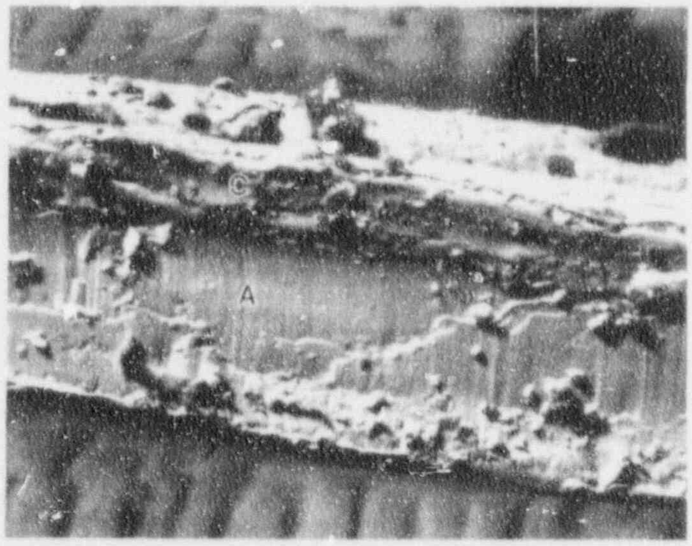


Figure G.5: SEM fractograph of the stripped threads obtained in the lab by cross-threading, illustrating the presence of a rubbed zone (A) in the direction shown, followed by a zone of cracking, tearing, and fragmentation (C), at 250 X magnification.

Figure G.6: SEM fractograph of the stripped threads obtained in the lab by cross-threading, at 500 X magnification.

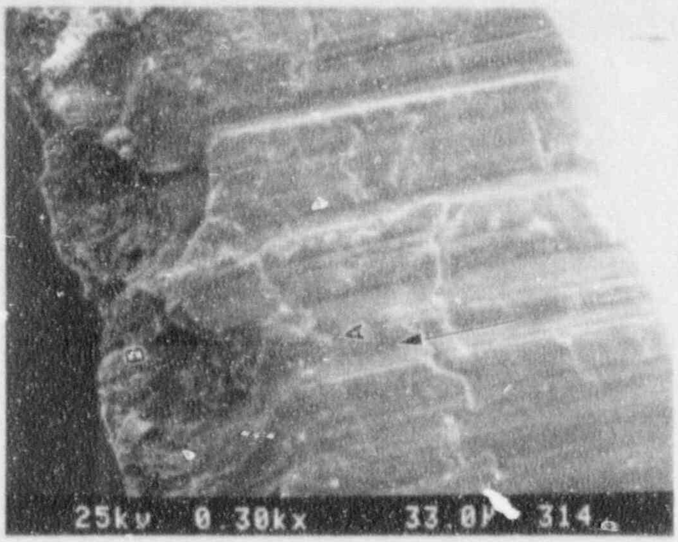


Figure G.7: SEM fractograph of the stripped threads obtained by tensile pull, at 300 X magnification. The photos are oriented 90° away from that of Figure G.3. The fracture surface shows two distinct zones, a rubbed zone (A) and a shear zone (B).

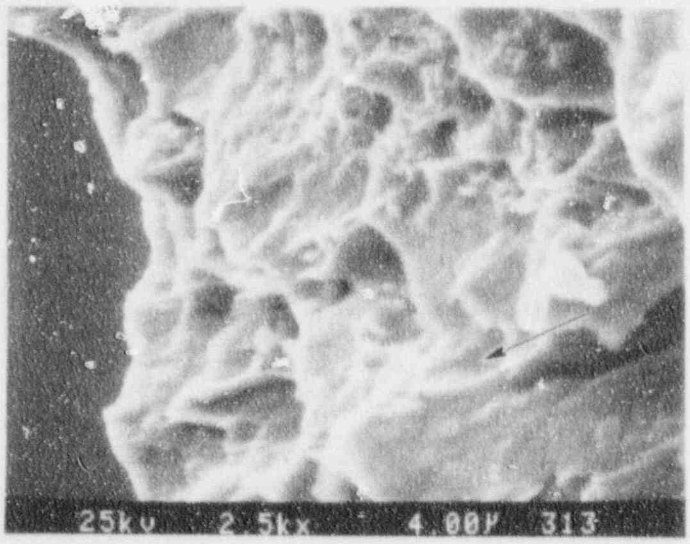


Figure G.8: SEM fractograph of the stripped threads obtained by tensile pull, at 2500 X magnification, illustrates shear elongated dimples in the shear zone.

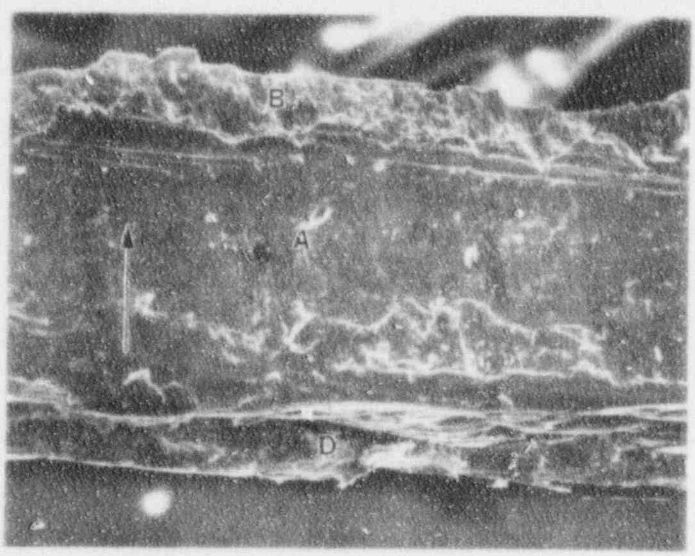


Figure G.9: SEM fractograph of the stripped threads obtained by overtorquing, illustrating the presence of three distinct zones, a tearing zone (D), a rubbed zone (A), and a shearing zone (B), at 150 X magnification.

Figure G.10: SEM fractograph of the stripped threads obtained by overtorquing, illustrating the tearing zone, at 750 X magnification.

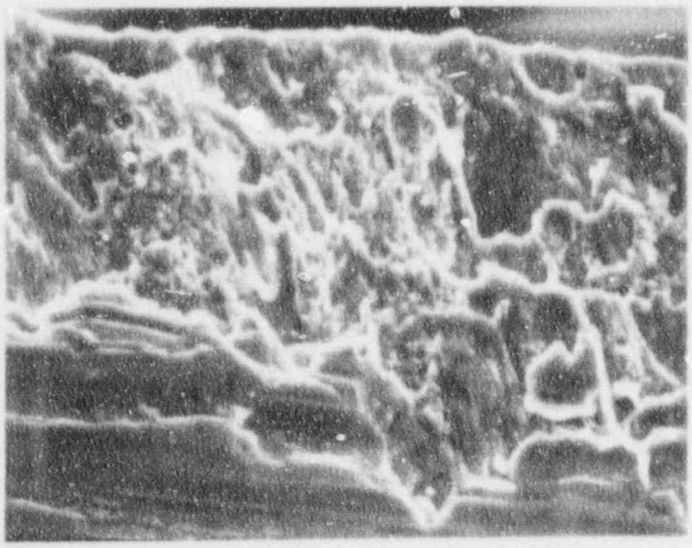


Figure G.11: SEM fractograph of the stripped threads obtained by overtorquing, illustrating the shearing zone, at 1000 X magnification.

TABLE G.1

HARDNESS TESTING

Material	Hardness	Average Measured
New short bolts 3/8 x 4 1/2 - 24	30 29 30	30 HRC
2G003 short bolts	29 HRC 29 28	29 HRC
Engine block in vicinity of bolt holes	78 HRB 80 82 82 84	81 HRB
Exemplar block material (1010 C.steel)	78 HRB 78 80 82 78	79 HRB

TABLE G.2

IMPACT TESTS OF SUBSIZE CVN SAMPLES

Sample	Ft-lbs	Hardness
Dowel Bolt from 2G003	[illegible].5	30 HRC
4140 Steel	11.5	32 HRC

A 10CFR21 report by Morrison-Knudsen in 1988 informed the NRC of the stubshaft bracket failure problems which have been attributed to 5th order torsional resonance. Thus, this problem is not considered to be reportable under 10CFR21.

EVALUATION OF ROOT CAUSE IMPACT ON EDGs 2G002, 2G003, AND 3G002

At SONGS, EDGs 2G002, 2G003 and 3G002, are the same design as 3G003. Based on the following discussions, it is concluded that the EDGs will not experience the same camshaft to stubshaft degradation condition as 3G003.

EDG 2G002

EDG 2G002 has not, and should not, experience this type of flange degradation. A torque check verified that all of the camshaft dowel bolts on 2G002 were tight. Also, a dye penetrant examination of the rear left stubshaft dowel bolts on the 20 cylinder engine indicated that no cracks were present.

During the torque check, one dowel bolt on the left rear camshaft to spacer flange of the 20 cylinder engine had an as-found torque of less than 20 ft-lbs. The dowel was examined with dye penetrant and found to be in acceptable condition. The dowel bolt was replaced and torqued to the proper 32 ft-lbs. Since this was a dowel bolt originally supplied with the EDG, the cause of the low torque was attributed to inadequate torque during original installation.

EDG 2G003

EDG 2G003 has not, and should not, experience this type of flange degradation. During repair activities associated with the 2G003 event, the left bank camshaft flange dowel bolts, and the right bank rear stubshaft flange dowel bolts, on the 20 cylinder engine, were replaced with acceptable quality dowel bolts. All the other camshaft dowel bolts on both the 16 and 20 cylinder engine are original installation and considered to be of acceptable quality.

In reviewing this issue, it appears that the camshaft flange dowel bolts on the 16 cylinder engine, and the right bank front and center camshaft flanges on the 20 cylinder engine, were not checked for proper torque. Thus, a maintenance order has been generated to verify the torque of the dowel bolts during the next appropriate work window. When this action is complete, it will be known that all flange dowel bolts on all 4 EDGs have adequate torque and that the flanges are not degrading.

EDG 3G002

EDG 3G002 has not, and should not, experience this type of flange degradation. A torque check was performed which verified that all of the camshaft dowel bolts on 3G002 were tight. Also, a dye penetrant examination of the left rear stubshaft dowel bolts on the 20 cylinder engine indicated that the dowel bolts were not experiencing a fatigue or overload problem. The stubshaft dowel bolts, which were dye penetrant examined, were considered to conservatively represent the condition of all camshaft dowel bolts in 3G002.

> NOTE: Coupling modifications were installed on all 4 EDGs, during the Unit 2 and 3, cycle 6, refueling outages, which corrected the 5th order torsion resonance problems by shifting the resonance away from the operating speed of the engine.

APPENDIX J
Work History of 3G003

Oct 1985. Routine EDG Overhaul

The EDG was overhauled and no problems were found with either the left rear stubshaft flange connection or stubshaft bracket on 3G003.

Reference: MO 85050805

May 1988. EDG Stubshaft Bracket Failure Found During Bracket Replacement

During disassembly of the EDG to install a new design and stronger stubshaft bracket, the left rear stubshaft bracket on the 20 cylinder engine was found broken.

The failure was attributed to actual bracket stresses exceeding allowable design stresses because of 5th order harmonic vibration. The new design bracket was installed, real time testing showed that the new bracket was acceptable, and the EDG was returned-to-service.

Reference: NCR 3-1934; MO 87122553; MO 88050483, MO 88050542

May 1990. Inspect Stubshaft Bracket and Replace Left Camshaft Gear

The stubshaft bracket and camshaft gear were inspected, and the camshaft gear was replaced due to pitting damage.

Reference: NCR 90050089; MO 89083636; MO 90051204

Feb 1991. Replaced Left Camshaft Gear

The left camshaft gear on the 20 cylinder engine was replaced to satisfy vendor imposed 250 hour run limit due to 5th order harmonic vibration.

Reference: NCR 90080183; MO 90070228

Oct 1991. Degraded Stubshaft Flange Connection Found During Inspection

The left rear stubshaft flange connection was found degraded during an inspection in response to the recent 2G003 failure. One of 4 dowel bolts was found broken and cracks were found in the 3 other dowel bolts.

The flange connection was repaired and the EDG was returned-to-service.

Reference: For actions taken on 3G003 see NCR 91100002; MO 91091538; MO 91091651; MO 91091895; MO 91100057; MO 91100118; MO 91100228; MO 91100240; MO 92012227. For actions taken on 2G002 and 3G002 see MO 91100917; MO 91110219; MO 91091537; MO 91091650; MO 91100429. For actions taken on 2G003 see Appendix A, 2G003 Work History.

APPENDIX K
Stubshaft Flange Analysis for 3G003

The purpose of this appendix is to discuss the failure analysis of dowel bolts found in the left rear camshaft to stubshaft flange connection of the 20 cylinder engine of 3G003.

In response to the 2G003 camshaft assembly failure, an inspection was performed on the left rear bank of the 20 cylinder engine of 3G003 to ensure the camshaft bearing block bolts were not coming loose. Although it was determined that the bearing block bolts were tight, the camshaft to stubshaft flange connection was found in a degraded condition. One of the 4 flange dowel bolts was found to be broken and backed out approximately 1/4 inch, while cracks were found in the other 3 dowel bolts. Since the camshaft bearings and stubshaft support bracket were found in good condition, it was determined that the degraded condition was limited to the flange connection dowel bolts.

Procedure

The 1 broken and 3 cracked dowel bolts were visually examined and photographed. The broken bolt was placed in a SEM and details of the fracture were documented. A longitudinal microsection was prepared and examined in the as-polished condition for inclusion distribution. The 3 cracked bolts were placed in a SEM in their as-found condition to illustrate the crack propagation pattern. Traverse cuts 180 degrees away from the cracks on each of the 3 dowels were made to expose the fracture surfaces. The fractures were placed in a SEM and details of the cracks were documented. Longitudinal microsections were prepared and examined in the as- polished condition for inclusion distribution.

The broken dowel bolt will be referred to as bolt number 1 and the cracked dowel bolts will be referred to as bolts numbers 2, 3, and 4. The number assignments are arbitrary.

Results

Figures K.1 and K.2 show the as-found condition of the degraded left rear camshaft to stubshaft flange connection on the 20 cylinder engine of 3G003. The arrows point to the dowel bolt that was found broken, and the closeup in Figure K.2 shows the approximately 1/4 inch displacement of the broken bolt. The displacement most likely occurred as a result of a cyclical working of the flange faces after the bolt failed and some of the rigidity of the connection was lost.

Broken Dowel Bolt Number 1

Figures K.3 to K.5, show the broken dowel bolt which has been identified as bolt number 1. The crack initiated in the root of the first thread, propagated in the transverse direction, and then propagated in the longitudinal direction. The change in direction has been attributed to the presence of longitudinal sulfide inclusions which were the path of least resistance for crack propagation. The fracture surface was fibrous in nature.

Figure K.3 is a macrophotogragh of the fracture surface of the broken bolt. Figure K.4 is an optical photograph of a longitudinal microsection, in the as-polished condition, illustrating the presence of large sulfide stringers and fine sulfide inclusions. The sulfide stringers were quite large, and larger than the largest sulfide inclusion size identified by ASTM Standard E-45. Figure K.5 shows the longitudinal microstructure, in the as-etched condition, illustrating platelets of ferrite and pearlite.

Cracked Dowel Bolt Number 2

Figures K.6 through K.10, show the cracked dowel bolt which has been identified as bolt number 2. The crack initiated in the root of the first thread, propagated in the transverse direction, and then propagated in the longitudinal direction. The change in direction has been attributed to the presence of longitudinal sulfide inclusions which were the path of least resistance for the crack propagation.

Figure K.6 is a SEM photograph of the crack, illustrating crack initiation at the root of the first thread and propagation in the transverse and then longitudinal direction. Figure K.7 is a SEM photograph of the crack, illustrating crack propagation to approximately 20 percent of the cross section of the bolt. Figure K.8 shows details of the fracture surface of the crack, with the arrows illustrating fatigue hackle marks. Figure K.9 shows an optical micrograph, in the as-polished condition, illustrating the sulfide inclusion size and distribution. The sulfide inclusion size is much smaller than that of the broken bolt number 1. Figure K.10 shows the longitudinal microstructure, in the as-etched condition, illustrating platelets of ferrite and pearlite similar to that of broken bolt number 1.

Cracked Dowel Bolt Number 3

Figures K.11 through K.17, show the cracked dowel bolt which has been identified as bolt number 3. The crack initiated in the root of the first thread, propagated in the transverse direction, and then propagated in the longitudinal direction. The change in direction has been attributed to the presence of longitudinal sulfide inclusions which were the path of least resistance for crack propagation.

Figure K.11 is a SEM photograph of the crack, illustrating crack initiation at the root of the first thread. Figure K.12 shows the crack branching and propagating in the longitudinal direction. Figure K.13 is a SEM photograph of the crack, illustrating crack propagation to approximately 40 percent of the cross section of the bolt. Figure K.14 is a SEM photograph of the fracture surface of the crack, illustrating the fatigue fracture. Figure K.15 is a SEM photograph of the fatigue zone of the fracture surface of the crack. Figure K.16 shows the longitudinal microstructure, in the as-polished condition, illustrating the distribution and size of stringers, which are larger in size than those in cracked bolt number 2, but smaller in size than those in broken bolt number 1. Figure K.17 shows the longitudinal microstructure, in the as-etched condition, illustrating platelets of ferrite and pearlite similar to that of broken bolt number 1.

Cracked Dowel Bolt Number 4

Figures K.18 through K.24, show the cracked dowel bolt which has been identified as bolt number 4. The crack initiated in the root of the first thread, and then branched and propagated in the longitudinal direction. The change in direction has been attributed to the presence of longitudinal sulfide inclusions which were the path of least resistance for crack propagation.

Figure K.18 is a SEM photograph of the crack, illustrating crack initiation the root of the first thread. Figure K.19 shows the crack branching and propagating in the longitudinal direction. Figure K.20 is a SEM photograph of the crack, illustrating crack propagation to approximately 67 percent of the cross section of the bolt. The fracture surface shown illustrates multiplane branch cracking which resulted in a fracture surface area which was actually larger than 67 percent. Figures K.21 and K.22 are detailed SEM photographs which illustrate the fatigue zone of the fracture surface. Figure K.23 shows the longitudinal microstructure, in the as-polished condition, illustrating the distribution of a larger population and size of sulfide inclusions than those observed in cracked bolts numbers 2 and 3, but less than those observed in broken bolt number 1. Figure K.24 shows the longitudinal microstructure, in the as-etched condition, illustrating platelets of ferrite and pearlite similar to that of the broken bolt number 1.

Conclusion

The 1 broken dowel bolt was found to have cracked in a fatigue fashion with crack initiation in the root of the first thread. The crack branched and propagated in the longitudinal direction following sulfide inclusions until complete fracture. The fracture was approximately 70 percent fatigue followed by 30 percent overload. The bolt was found to have backed approximately 1/4 inch in the flange connection.

Sulfide inclusions were found in all 4 dowel bolts. However, the broken dowel bolt was found to have a higher population and larger size of sulfide inclusions than the 3 cracked bolts.

The depth of crack propagation in the 3 cracked dowel bolts varied depending on size and distribution of sulfide inclusions. The greater the population and size of the inclusions the greater the crack propagation. The cracks were pure fatigue and involved approximately 20, 40 and 67, percent of the cross sectional areas of dowel bolts number 2, 3 and 4, respectively.

All the cracks in the 4 dowel bolts initiated at the root of the first thread and propagated in the longitudinal direction.

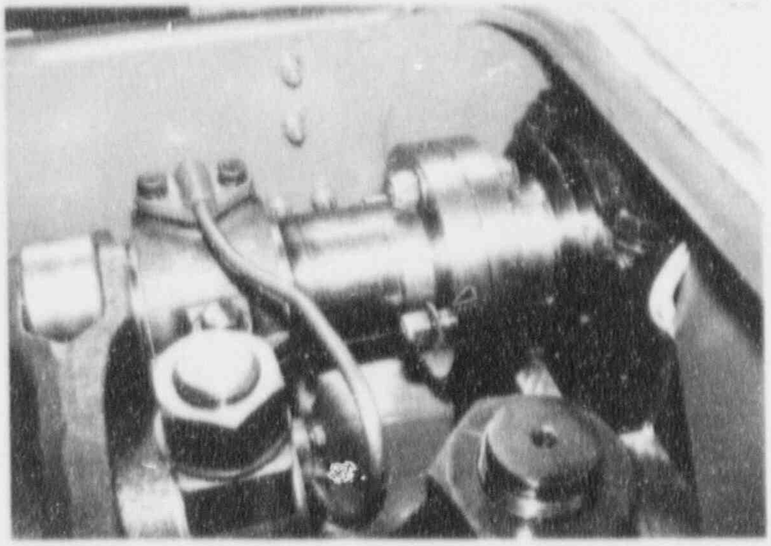


Figure K.1: View of the as-found condition of the degraded left rear camshaft to stubshaft flange connection on the 20 cylinder engine of 3G003. The arrow points to the dowel bolt that was found broken.

Figure K.2: View of the as-found condition of the flange connection illustrating the approximately 1/4 inch displacement of the broken bolt.

Figure K.3: A macrophotogragh of the fracture surface of broken bolt 1, at 7 X magnification.

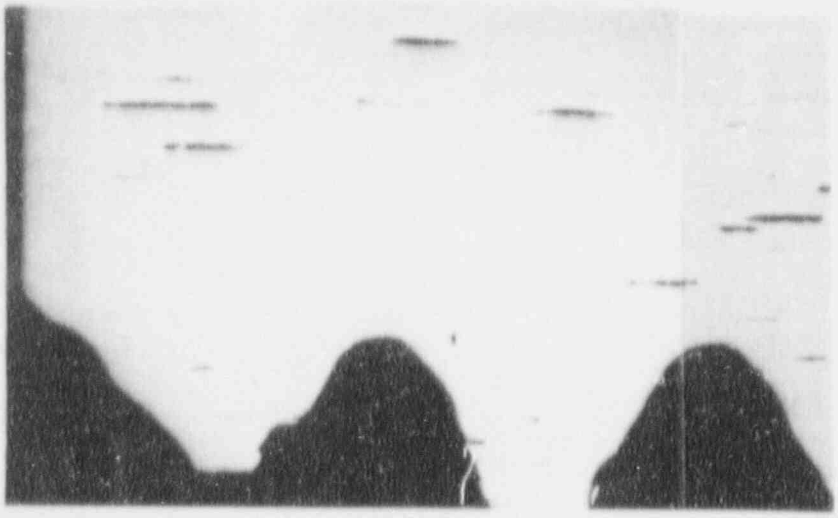


Figure K.4: An optical photograph of the longitudinal microsection of broken bolt 1, in the as-polished condition, illustrating the presence of large sulfide stringers and fine sulfide inclusions, at 50 X magnification.

Figure K.5: A photograph of the longitudinal microstructure of broken bolt 1, in the as-etched condition, illustrating platelets of ferrite and pearlite, at 400 X magnification.

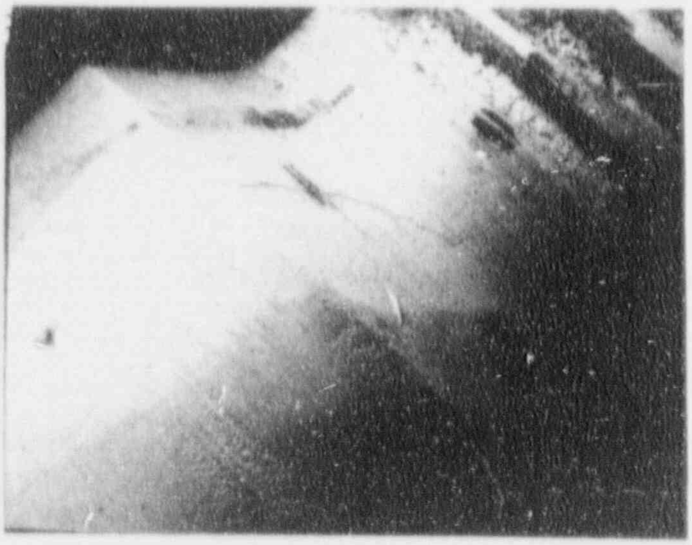


Figure K.6: A SEM photograph of cracked bolt number 2, illustrating crack initiation at the root of the first thread and propagation in the transverse and then longitudinal direction, at 10 X magnification.

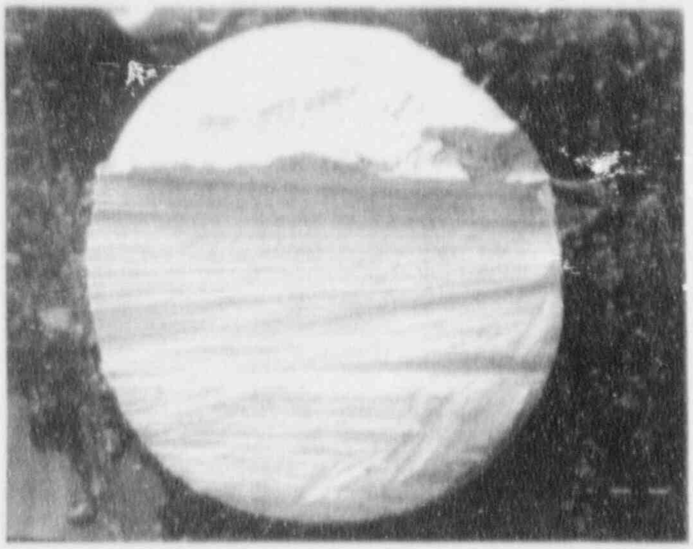


Figure K.7: A SEM fractograph of cracked bolt number 2, illustrating crack propagation to approximately 20 percent of the cross section of the bolt, at 6 X magnification.

Figure K.8: A SEM fractograph of cracked bolt number 2, illustrating details of the fracture surface of the crack, with the arrows illustrating hackle marks, at 60 X magnification.

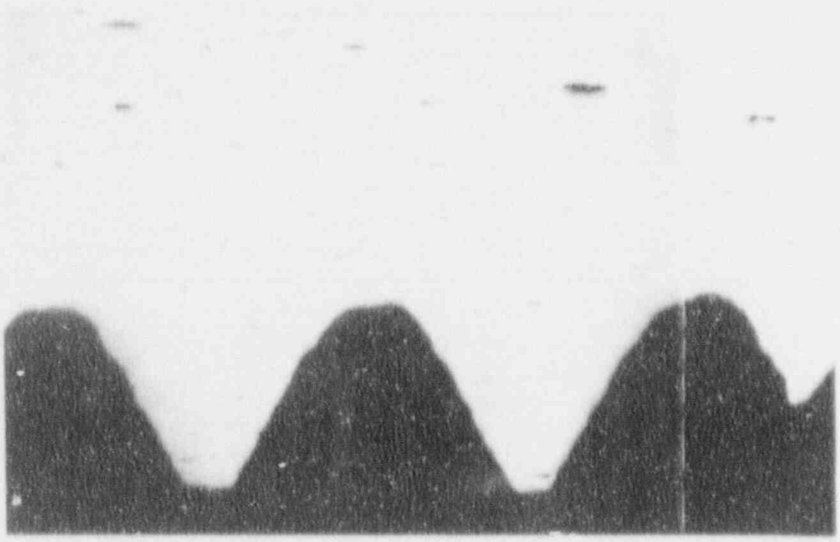


Figure K.9: An optical micrograph of cracked bolt 2, in the as-polished condition, illustrating the sulfide inclusion size and distribution, at 50 X magnification.

Figure K.10: A photograph of the longitudinal microstructure of cracked bolt 2, in the as-etched condition, illustrating platelets of ferrite and pearlite, at 400 X magnification.

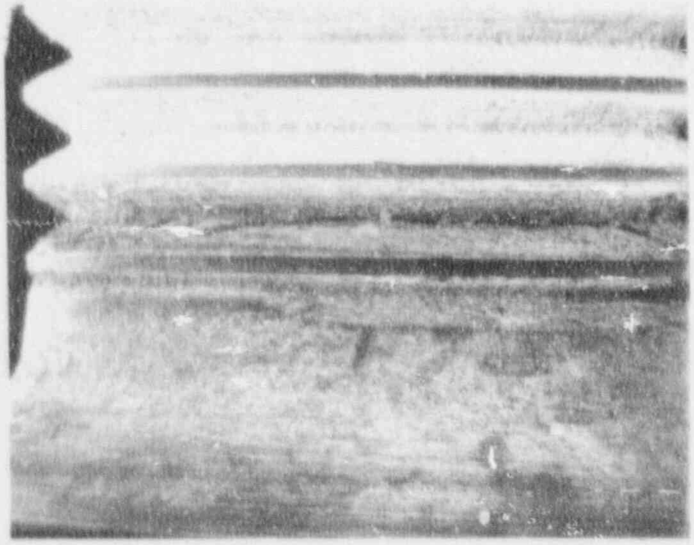


Figure K.11: A SEM photograph of cracked bolt 3, illustrating crack initiation the root of the first thread, at 10 X magnification.

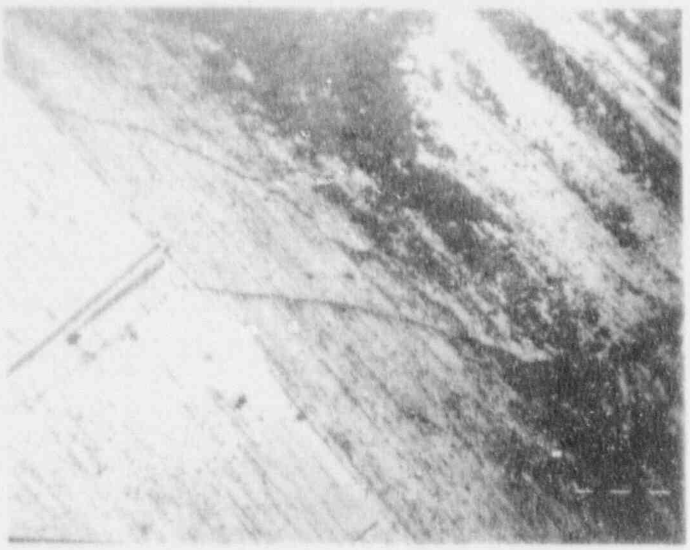


Figure K.12: A SEM photograph of cracked bolt 3, illustrating crack branching and propagation in the longitudinal direction, at 25 X magnification.

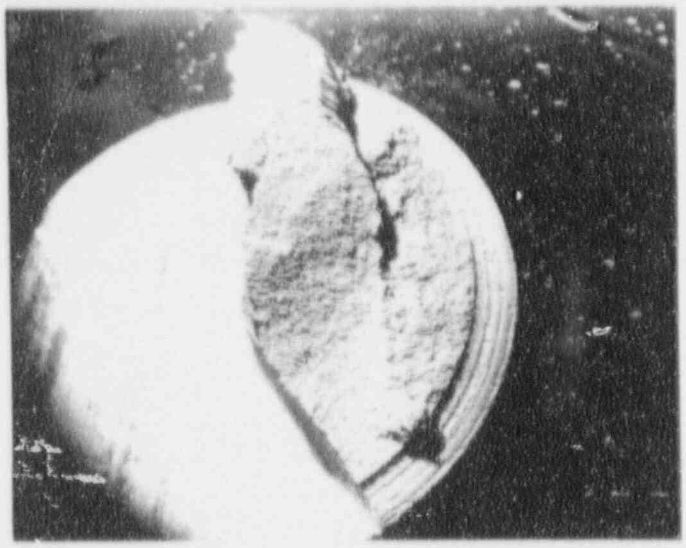


Figure K.13: A SEM photograph of cracked bolt 3, illustrating crack propagation to approximately 40 percent of the cross section of the bolt, at 9 X magnification.

Figure K.14: A SEM photograph of cracked bolt 3, illustrating the fatigue fracture, at 50 X magnification.

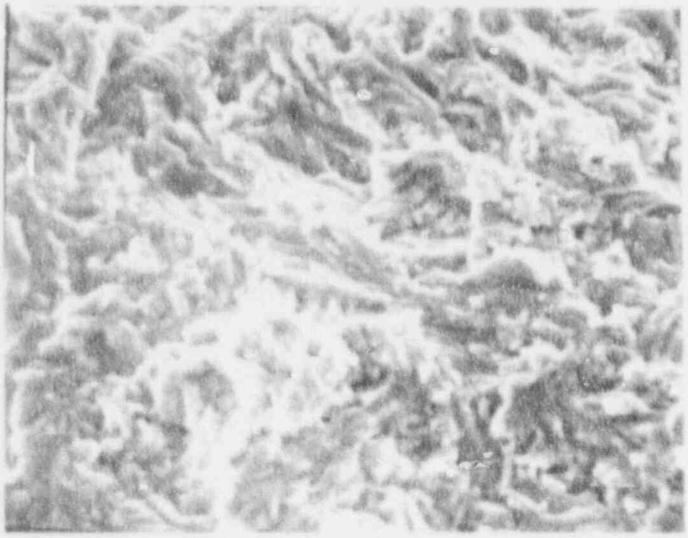


Figure K.15: A SEM photograph of cracked bolt 3, illustrating the fatigue zone of the fracture surface of the crack, at 1000 X magnification.

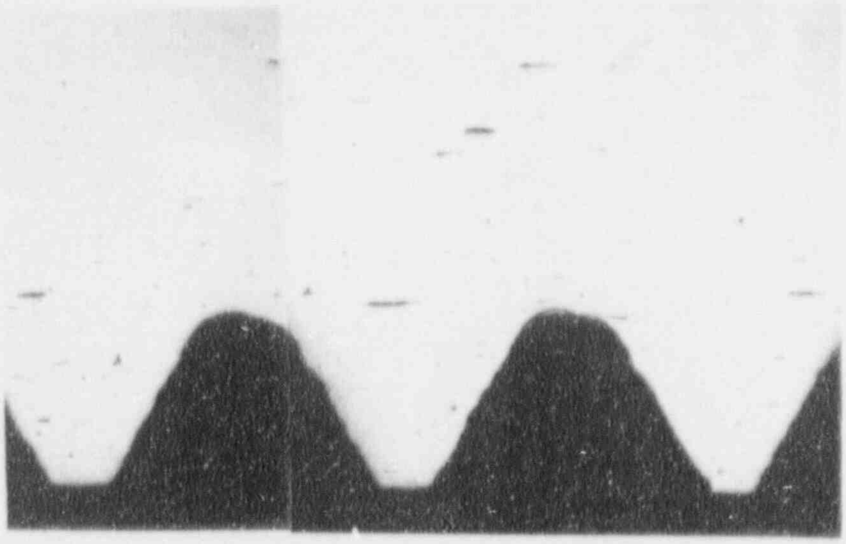


Figure K.16: A photograph of the longitudinal microstructure of cracked bolt 3, in the as-polished condition, illustrating the distribution and size of stringers, at 50 X magnification.

Figure K.17: A photograph of the longitudinal microstructure of cracked bolt 3, in the as-etched condition, illustrating platelets of ferrite and pearlite, at 400 X magnification.

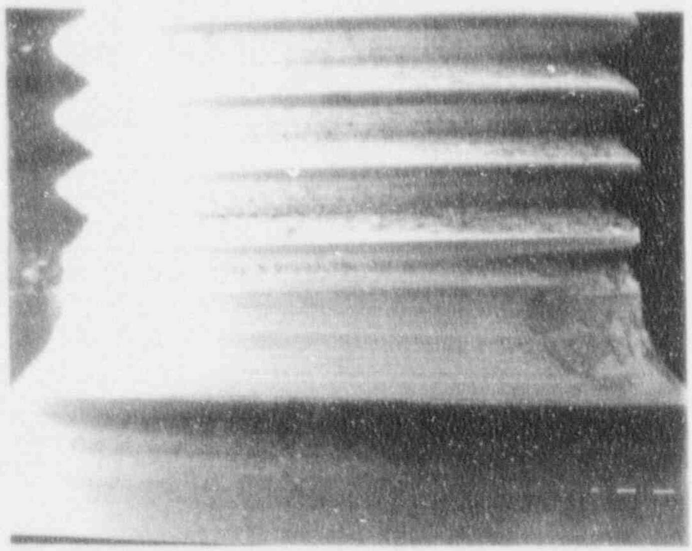


Figure K.18: A SEM photograph of cracked bolt 4, illustrating crack initiation the root of the first thread, at 7 X magnification.

Figure K.19: A SEM photograph of cracked bolt 4, illustrating crack branching and propagation in the longitudinal direction, at 15 X magnification.

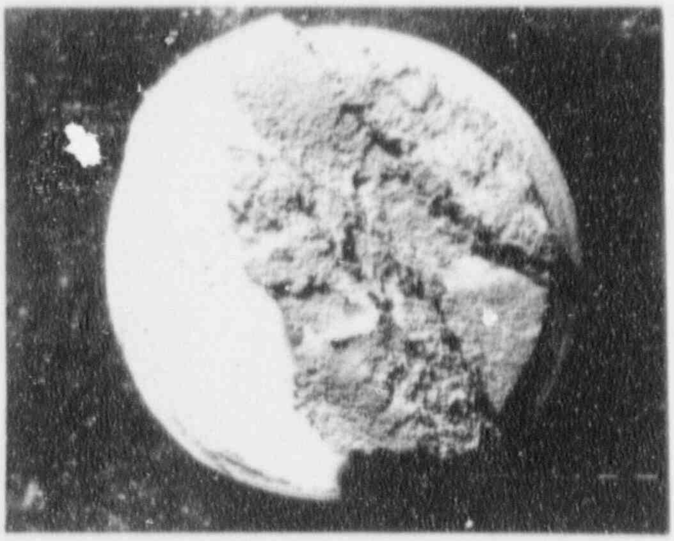


Figure K.20: A SEM photograph of cracked bolt 4, illustrating crack propagation to approximately 67 percent of the cross section of the bolt, at 6 X magnification.

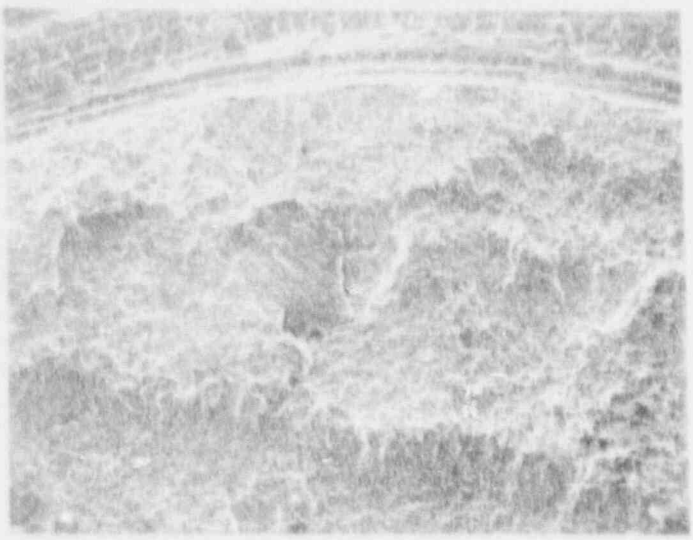


Figure K.21: A SEM photograph of cracked bolt 4, illustrating the fatigue zone of the fracture surface, at 50 X magnification.

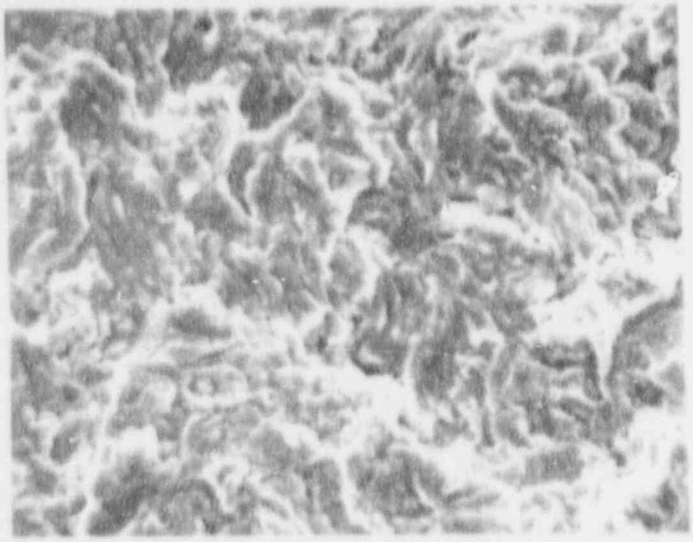


Figure K.22: A SEM photograph of cracked bolt 4, illustrating the fatigue zone of the fracture surface, at 1000 X magnification.

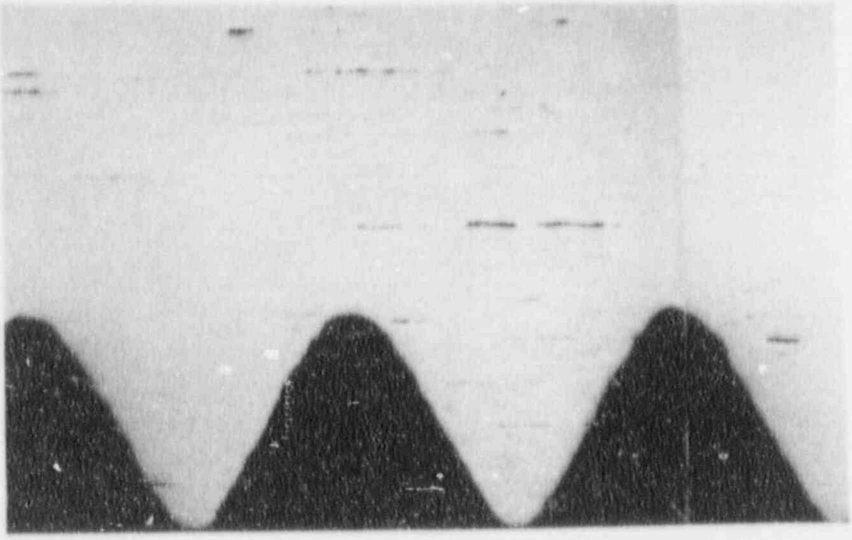


Figure K.23: A photograph of the longitudinal microstructure of cracked bolt 4, in the as-polished condition, illustrating the distribution and size of sulfide inclusions, at 50 X magnification.

Figure K.24: A photograph of the longitudinal microstructure of cracked bolt 4, in the as-etched condition, illustrating platelets of ferrite and pearlite, at 400 X magnification.

APPENDIX L
Analysis of New Dowel Bolts for 3G003

The purpose of this appendix is to discuss the analysis that was performed on new camshaft flange dowel bolts for 2G003 and 3G003. As discussed in Appendix K, poor quality 1144 alloy dowel bolts were found to be a part of the root cause of 3G003 degraded camshaft to stubshaft flange connection. Also, it was determined 1144 bolts were the first choice for use at SONGS provided they were analysis for acceptability, prior to use.

The poor quality 1144 alloy broken and cracked dowel bolts of 3G003 were found to contain a large quantity of large sulfide inclusions/stringers which substantially decreased the strength of the bolts. Thus, this appendix will document the acceptability of the new dowel bolts.

Procedure

There were 2 batches of dowel bolts received for analysis. Batch number 1 were 1/2 inch diameter dowels and batch number 2 were 7/16 inch diameter dowels. Remember, each flange connection is made-up of 3 of the 1/2 inch diameter dowels and 1 of the 7/16 inch diameter dowels. A sample of 2 dowels from each batch was analyzed to determine the acceptability of the entire batch. The sample dowel bolts were arbitrarily label Batch 1 Sample 1, Batch 1 Sample 2, Batch 2 Sample 1 and Batch 2 Sample 2.

The analysis consisted of making a longitudinal microsection of each of the sample dowel bolts and performing an as-polished and as-etched examination to determine the extent of sulfide inclusions/stringers.

Results

Figures L.1, L.3, L.5 and L.7, are photographs of the longitudinal microsections, in the as-polished condition, of the each of the sampled dowel bolts, illustrating a relatively small population of small sulfide inclusions. Figures L.2, L.4, L.6 and L.8, are photographs of the longitudinal microsections, in the as-etched condition, of each of the sampled dowel bolts, illustrating platelates of ferrite and pearlite.

Conclusion

The analysis of the sampled dowel bolts indicated an absence of large sulfide inclusions. The sulfide distribution was acceptable and the batches of new dowels bolts were approved for use in the EDGs.

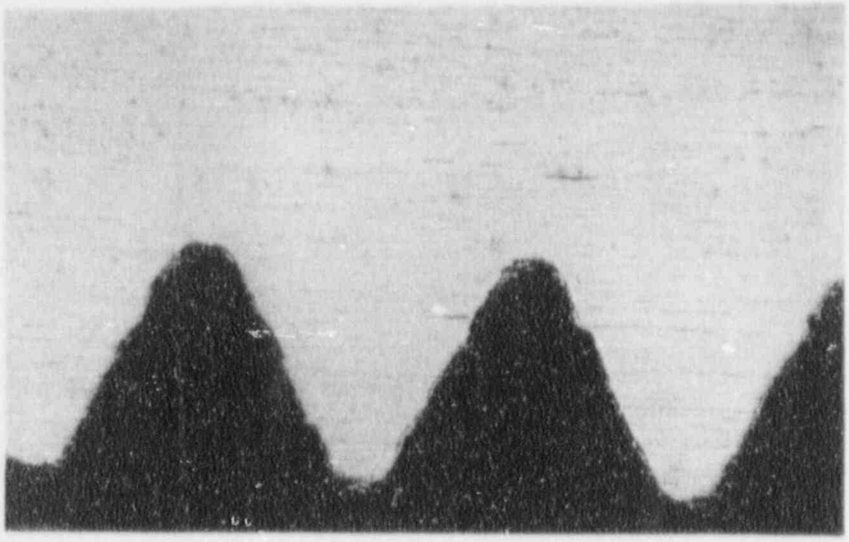


Figure L.1: Photograph of the longitudinal microsection, in the as-polished condition, of the Batch 1 Sample 1 dowel bolt, illustrating a relatively small population of small sulfide inclusions, at 50 X magnification.

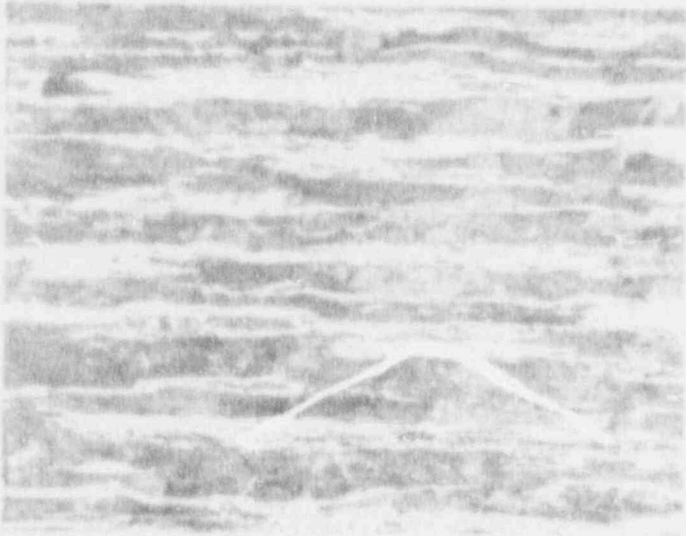


Figure L.2: Photograph of the longitudinal microsections, in the as-etched condition, of the Batch 1 Sample 1 dowel bolt, illustrating platelates of ferrite and pearlite, at 400 X magnification.

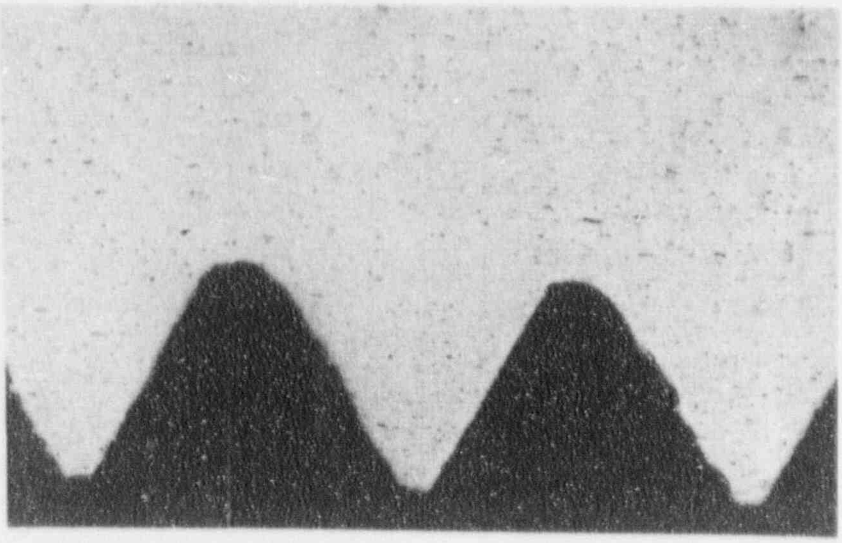


Figure L.3: Photograph of the longitudinal microsection, in the as-polished condition, of the Batch 1 Sample 2 dowel bolt, illustrating a relatively small population of small sulfide inclusions, at 50 X magnification.

Figure L.4: Photograph of the longitudinal microsections, in the as-etched condition, of the Batch 1 Sample 2 dowel bolt, illustrating platelates of ferrite and pearlite, at 400 X magnification.

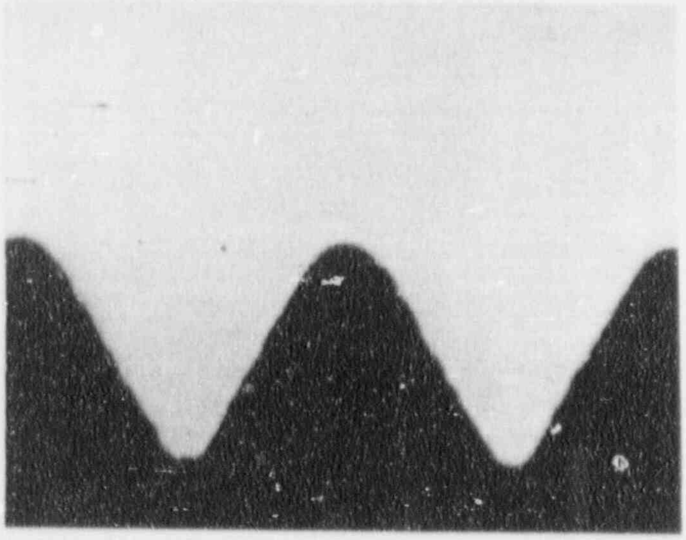


Figure L.5: Photograph of the longitudinal microsection, in the as-polished condition, of the Batch 2 Sample 1 dowel bolt, illustrating a relatively small population of small sulfide inclusions, at 50 X magnification.

Figure L.6: Photograph of the longitudinal microsections, in the as-etched condition, of the Batch 2 Sample 1 dowel bolt, illustrating platelates of ferrite and pearlite, at 400 X magnification.

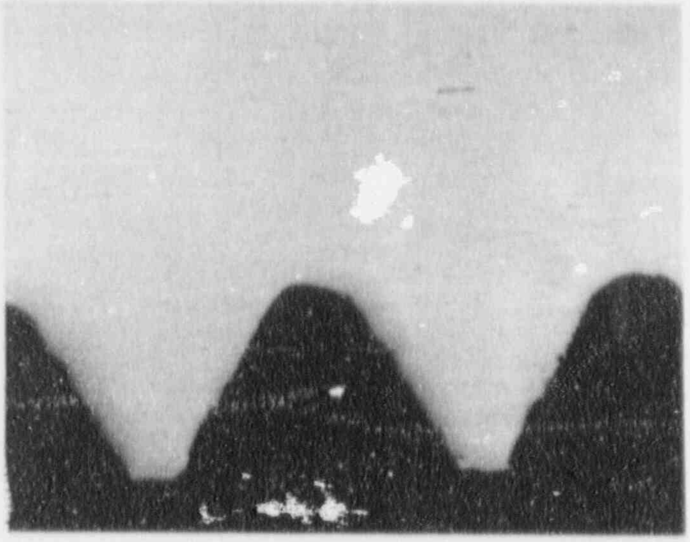


Figure L.7: Photograph of the longitudinal microsection, in the as-polished condition, of the Batch 2 Sample 2 dowel bolt, illustrating a relatively small population of small sulfide inclusions, at 50 X magnification.

Figure L.8: Photograph of the longitudinal microsections, in the as-etched condition, of the Batch 2 Sample 2 dowel bolt, illustrating platelates of ferrite and pearlite, at 400 X magnification.

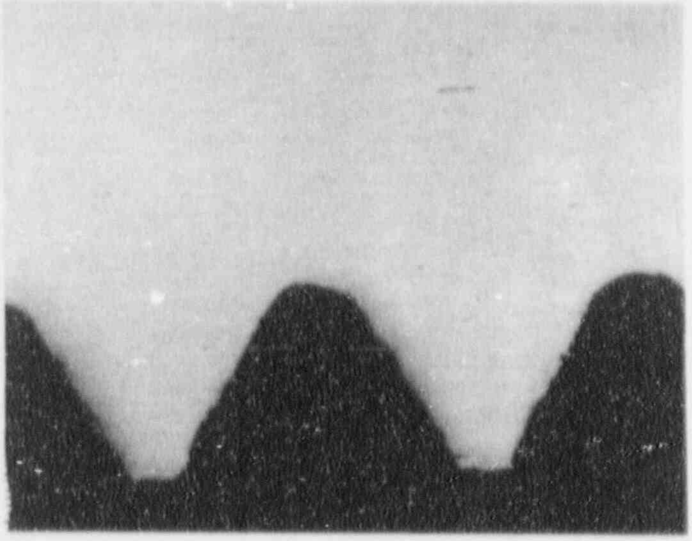


Figure L.7: Photograph of the longitudinal microsection, in the as-polished condition, of the Batch 2 Sample 2 dowel bolt, illustrating a relatively small population of small sulfide inclusions, at 50 X magnification.

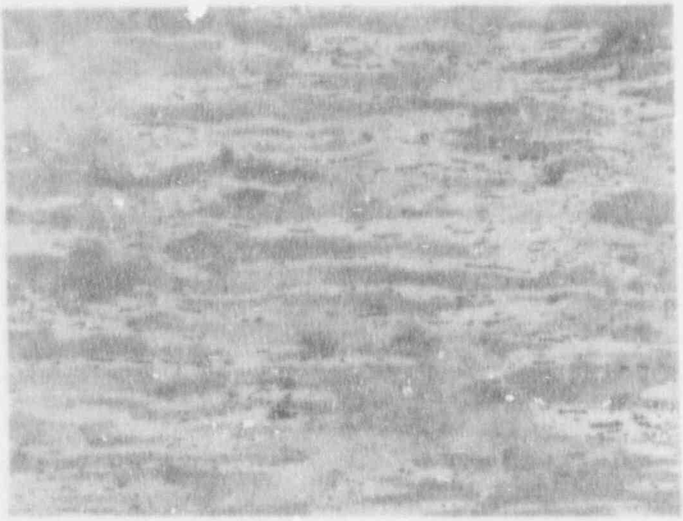


Figure L.8: Photograph of the longitudinal microsections, in the as-etched condition, of the Batch 2 Sample 2 dowel bolt, illustrating platelates of ferrite and pearlite, at 400 X magnification.