Cooper Industries
Cooper-Bessemer
Reciprocating Products Division
150 Lincoln Avenue
Grove City, PA 16127-1898
412 458-8000

P21 94247

COOPER
Cooper Energy Services

ENGINEERING REPORT NO. HE-02-1994

R4 SUBCOVER STRESS ANALYSIS

AUGUST 29, 1994

PREPARED BY: [signature] DATE: 9-1-94

REVIEWED BY: [signature] DATE: 9-1-94

APPROVED BY: [signature] DATE: 9-2-94

DISTRIBUTION:

GROVE CITY	ALAMEDA
D. T. Blizzard	L. A. Casterline
J. M. Horne	L. A. Duck
	B. C. Guntrum
	R. A. Johnston
	R. L. Nimmo

P21 94247
p.2

TABLE OF CONTENTS

OBJECTIVE

The objective of this report is to document the results of the strain gage testing performed on the Enterprise R4 subcover. All tests were conducted at Cooper Energy Services' R&D laboratory in Mt. Vernon, Ohio. For test details (i.e., part numbers, raw data, etc.) see the lab report in the appendix of the engineering file copy.

BACKGROUND

There is a long history surrounding the Enterprise R4 subcover in terms of indications being discovered during Design Review and Quality Re-validation (DR/QR) inspections in nuclear utilities and routine maintenance inspections in commercial installations. Current DR/QR requirements call for a liquid penetrant inspection of the rocker shaft mounting pedestals on a one-time 25% basis at five years and 100% at ten years.

Also, in accordance with the requirements of the Nuclear Regulatory Commission (NRC) Title 10, Chapter 1, Code of Federal Regulations, Part 21 Notification Letter #165 was sent to the Commission identifying the subcover as a potentially defective component. In it a recommendation was made that the inspection frequency be increased to five years on a 100% basis during scheduled refueling outages.

Early indications were located between the rocker shaft oil feed hole and either the inboard vertical machined surface or the rocker shaft hold-down bolt counterbore and, in many cases, both. See Figure 1. These cracks were believed to be created during the installation of a roll pin into the oil feed hole. The original intent of the pin was to guide and reduce oil flow to the rocker shaft. Service Information Memo (SIM) #372 was later written to eliminate the spring pin from the assembly.

Even after the elimination of the roll pin, indications were still being discovered. The majority were now located between the rocker shaft hold-down bolt counterbore and the vertical machined surface. See Figure 1. To date, all indications have been confined to the rocker shaft mounting pedestals on the transverse pushrod side of the subcover.

The subcover was redesigned to address the later type pedestal indications. The new design increased the amount of material between the rocker shaft holddown bolt counterbore and the machined vertical surface by 300% and also incorporated stiffeners to help handle the transverse pushrod reaction loads. See Figure 2.

To date, two catastrophic failures have occurred due to subcover failures; one at a nuclear utility and the other in a commercial installation. In one case a subcover was re-installed onto an engine after having identified the existence of pedestal indications. Within a few hours of operation, the subcover pedestal cracks propagated to the point where rocker shaft-to-subcover joint preload was lost and the fastener failed due to fatigue. This caused the valves to be incapacitated and the cylinder was unable to produce power. The other incident was similar with the exception that no indications had been identified prior to the failure.

Despite the previous catastrophic failures, the Part 21 letter, and the existence of a new design, many operators still feel the subcover cracking is not detrimental to the operation of their engines. Due to this controversy, a decision was made to test both the old and new subcover designs to determine the structural integrity of each.

DISCUSSION

STRAIN GAGE TEST

In order to evaluate the subcover redesign, a strain gage test was performed on both the old and new style subcovers. Details of the testing are as follows.

GAGE LOCATIONS

The original intent was to obtain data from gages mounted in more locations than just where the critical indications existed historically. Due to the extremely difficult wiring techniques required to instrument the assembly, this was not possible. Many gages dropped out due to wires being pinched, stretched and sheared, causing intermittent and permanent grounding as well as false readings. Therefore, the emphasis of the analysis was placed on eight (8) gages per subcover, where the four (4) on the transverse pushrod side were considered to be critical. The location of these strain gages are shown in Figure 3.

TEST SET-UP

The intent of the test was to simulate, as closely as possible, the loads seen by the subcover during actual engine operation. To accomplish this, the test arrangement consisted of mounting the subcover to an R4 cylinder head which was fastened to a specially fabricated test table. The table was meant to simulate the "infinitely stiff" cylinder block boundary conditions. In addition, installation and static loads of a sufficient magnitude were applied to mimic those experienced during assembly and operating conditions. See Figure 4.

TEST PROCEDURE

The basic test procedure was as follows (recording strain data at **each** step):

1. Bolt subcover down to cylinder head using correct fastener torque.
2. Install hollow dowels.

3. Install intake/intermediate and exhaust rocker shaft assemblies (with cylindrical bar stock in place of valve springs) and torque bolts to correct value.
4. Install main and intermediate exhaust pushrods and apply load to main pushrod in increments until maximum is reached. (Cycle load to ensure valid data is being collected.)
5. Repeat for both subcover designs.

TEST LOADS

During the early days of the DR/QR program, many reports were generated for critical R4 engine components. One of these reports entitled "Design Review of Push Rods for Transamerica Delaval Diesel Generators" (dated April, 1984) was authored by Failure Analysis Associates. Contained within this report is a detailed analysis of the loads experienced by the intake, intermediate, and exhaust pushrods during 100% load operation of a DSRV-16-4 engine.

Since the loads of interest are those which tend to separate the two subcover pedestals as a result of the operating transverse pushrod, only the exhaust pushrod loads need to be examined and applied during the testing procedure. The components of this load are a result of:

1. Opening the two exhaust valves against the pressure of the combustion gases acting on the faces of the valves.
2. Overcoming two exhaust spring opening forces.
3. Working against the inertia of the valve train components located downstream of the subcover pedestals in the direction of the valves.

Assumptions made during this load analysis are as follows:

1. No lash exists in the valve train during inertia calculations. (In order to account for possible lash in the system, twice the calculated inertia values were used.)
2. Maximum valve acceleration is used for inertia calculations.
3. The force to overcome the springs is at maximum spring deflection. (i.e., maximum valve opening.)
4. All these maximum force components occur at the same time in the valve cycle.

As a result, the load applied to the exhaust pushrod is conservative.

Figure 5 shows the percentage breakdown of the three load components.

STRAIN GAGE DATA

Figures 6 through 9 show the results of the first round of testing on the old style subcover for the eight strain gages located per Figure 3. The values plotted are each maximum at the given pushrod load. The first two plots give strains, the second two plots give stresses, and the latter of each set include assembly values.

Figures 10 through 13 represent the third round of testing and pertain to the new style subcover. The plot parameters are the same as in Round One test results. (Problems in the second round of testing caused the data to be regarded as unusable.)

INTERPRETATION OF DATA

In order to deal with more familiar values, data in the form of "stresses including assembly values" will be used in this discussion.

At first glance, Figures 9 and 13 (old and new designs, respectively) show similar trends. As expected, stress values rise with increasing pushrod loading. The maximum stresses for the old subcover design are approximately 40% higher than the new design and the maximum stress range is approximately 40% lower for the new design. This initial look at the data gives positive results for the redesigned subcover.

The data also shows that the stresses in the pedestals located on the non-transverse pushrod side are only a fraction of those on the pushrod side. This shows that the reaction forces caused by the transverse pushrod are significant.

Due to the failure of the extremely delicate strain gage instrumentation wire for varying gages during the entire testing procedure, a good back-to-back comparison for a single critical gage is not available. Therefore an alternative and valid approach, and the one taken here, is to compare the worst case (i.e., maximum stress magnitude and range) for each design. Fortunately, the gages that meet this criteria, although on different pedestals, **are** in the same relative critical location. These gages being 2D for the old design and 3D for the new design. Reference Figure 3.

RACHETING

Taking a closer look at the data reveals a very interesting phenomenon referred to during the testing as "racheting". Initially the strain data suggested the presence of plastic deformation as the strain values did not return to zero when the load was removed. This was suspicious because of the low levels of stresses being observed.

In order to further investigate this phenomenon, a series of maximum loading and complete unloading steps were performed on the redesigned subcover. Although accepted strain gage testing practice calls for consistently duplicating each load step for the purposes of determining repeatability, there is usually no reason to cycle multiple times unless a problem exists; as was the case with this test. The result of this load cycling for the new subcover is given in Figure 14. The load cycling continued until the percent change in maximum and no load stresses were approximately 1%. This indicates that the racheting motion had essentially stopped.

Unfortunately, due to the failure of the old style subcover, as described in the following section entitled "failure", a comparable loading sequence was not able to be performed.

Alternatively, a conservative analytical approach was taken using the existing limited repeated loading data. By making the assumption that the same rate of stress increase could apply to both subcovers, and tempering this by only applying 50% of this stress level rise to the recorded data, final dynamic loading maximum and minimum stress values were derived. Figure 15 shows the actual data taken for the old style subcover. Figure 16 includes the extrapolated data.

FAILURE

Between the time the first round of testing of the old style subcover occurred and what was to be the next series of old subcover testing, it became apparent from the strain readings that both the pedestals on the transverse pushrod side had cracked in the manner shown in Figure 1 under "later crack locations." A liquid penetrant inspection verified the existence of the failures.

ANALYSIS

The theorized mode of failure for the subcover and the resultant engine effects could be described as follows. Due to a marginal section thickness in the subcover pedestal between the rocker shaft hold-down bolt-hole counterbore and the inboard vertical machined surface, a crack would initiate. The most prominent loads being caused by the separating forces of the transverse pushrod as transmitted by the rocker shaft assemblies. When the crack propagated enough, the bolt preload would be lost and the fastener would then be subjected to a much larger portion of the cyclic loads caused by the operation of the valve train.

Fatigue failure of the fastener would follow to the point where the valves would no longer open. Fuel, however, would still be delivered to the combustion chamber, along with whatever oil-laden air could be drawn past the piston rings from the crankcase. Due to insufficient air, incomplete combustion would occur leading to cylinder glazing and blow-by. At the same time, the fuel traveling down the liner walls would tend to wash away and dilute the lube oil, also causing accelerated liner wear. All the while the remaining cylinders would be forced to share the failed cylinder's portion of the load.

As characterized by the stress plots in Figures 14 through 16, it is obvious that the subcover is subjected to repeated loading during engine operation and, as mentioned, a potential fatigue condition.

Figure 17 shows a typical fluctuating stress curve and some related terminology. Figure 18 gives the critical gages' maximum and minimum stresses as well as calculated values of mean stress and stress amplitude for the new and old subcover designs per the data in Figures 14 and 16, respectively.

In order to utilize the data in Figure 18 to evaluate the fatigue characteristics of each design, the use of a modified Goodman diagram is employed. Figure 19 shows this diagram with the critical gage data plotted for both designs. Since the subcover material is cast iron, the preferred fatigue criteria is given by the Smith line. The Cyclic Failure Factor (CFF) for the old design is 1.03 while the CFF for the new design is 2.03. This is an increase of 97%. This is due more to a reduction in stress amplitude than to the mean stress.

By increasing the thickness of the "web" material between the counterbore and machined surface by a factor of three, one might expect a larger increase in CFF. What has actually happened is by enlarging this cross-section, the web's stiffness has been increased considerably, along with its load-carrying capabilities. At the same time, the increase in section thickness is large enough to reduce the stress caused by this additional load.

Aside from what the data conveys, the fact that both of the pedestals on the old subcover broke in the critical locations suggests not only is the re-designed subcover superior, but the original design is marginal. Both subcovers were subjected to the same loading conditions.

CONCLUSION

1. The Cyclic Failure Factor (CFF) for the old design is 1.03 while the CFF for the new design is 2.03. This is an increase of 97% This is due more to a reduction in stress amplitude than to the mean stress.

2. Reinforcement of the results derived from the data was seen in the failure of both the rocker shaft mounting pedestals in the critical locations in the old style subcover during the test.

RECOMMENDATIONS

1.Based upon the test results presented herein, it is suggested that facilities currently using the old subcover design adhere to the recommended inspection frequency described in the Part 21 letter.

2.If it becomes necessary to investigate the consequences caused by the "racheting"

P21 94247
p. 9

effect detected during the testing, additional analytical and test efforts would be necessary.

3.Should there be a need to resolve any questions pertaining to the rate of pedestal crack propagation, a fracture mechanics analysis in conjunction with lab testing would be required.

Joseph S. Quadrone

Joseph S. Quadrone, Design Engineer
Enterprise Product Engineering