PNL-5485

Technical Evaluation Report

# Review and Evaluation of Transamerica Delaval, Inc., Diesel Engine Reliability and Operability—River Bend Station Unit 1

July 1985

Prepared for
the U.S. Nuclear Regulatory Commission
Division of Licensing
Office of Nuclear Reactor Regulation
under Contract DE-AC06-76RLO 1830
NRC FIN B2963

Pacific Northwest Laboratory
Operated for the U.S. Department of Energy
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Project Title: Assessment of Diesel Engine Reliability/Operability

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Date 7-3-85

## FOREWORD

This report is supplied as part of the Technical Assistance Project, Assessment of Diesel Engine Reliability/Operability, being conducted for the U.S. Nuclear Regulatory Commission, Office of Nuclear Reactor Regulation, Division of Licensing, by the Pacific Northwest Laboratory. The U.S. Nuclear Regulatory Commission funded this work under authorization B&R 20-19-40-42-1 FIN No. B2963.

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## ABBREVIATIONS

| | |
|---|---|
| BMEP | brake mean effective pressure |
| CDI | Cumulative Damage Index |
| CFR | Code of Federal Regulations |
| DBA | design basis accident |
| DEMA | Diesel Engine Manufacturers Association |
| DGs | diesel generator(s) |
| DR/QR | design review/quality revalidation |
| ECCS | emergency core cooling system |
| EDGs | emergency diesel generator(s) |
| EDGCTS | Emergency Diesel Generator Component Tracking System |
| ESF | engineered safety feature |
| ET | eddy-current testing |
| FaAA | Failure Analysis Associates |
| FDI | Fatigue Damage Index |
| FSAR | Final Safety Analysis Report |
| GSU | Gulf States Utilities Company |
| LILCO | Long Island Lighting Company |
| LOCA | loss-of-coolant accident |
| LOOP | loss of offsite power |
| LP | liquid penetrant |
| M/S | maintenance/surveillance |
| MT | magnetic-particle testing |
| NDE | nondestructive examination |
| NDT | nondestructive testing |
| NRC | U.S. Nuclear Regulatory Commission |
| OG | Owners' Group; the TDI Diesel Generator Owners' Group |
| OGPP | Owners' Group Program Plan |
| O/R | operability and reliability |
| PNL | Pacific Northwest Laboratory |
| RBS | River Bend Station |
| RT | radiographic test |
| SDs | standby diesel(s) |

| | |
|---|---|
| SER | Safety Evaluation Report |
| SIM | Service Information Memorandum |
| SNPS | Shoreham Nuclear Power Station |
| SWEC | Stone & Webster Engineering Corporation |
| TDI | Transamerica Delaval, Inc. |
| TER | technical evaluation report |
| UT | ultrasonic testing |

REVIEW AND EVALUATION
OF TRANSAMERICA DELAVAL, INC.,
DIESEL ENGINE RELIABILITY AND OPERABILITY -
RIVER BEND STATION UNIT 1

## 1.0 INTRODUCTION

Gulf States Utilities Company (GSU) is seeking a full power operating license for the River Bend Station (RBS) Unit 1. One matter of concern to the U.S. Nuclear Regulatory Commission (NRC) in considering this request is the operability and reliability (O/R) of the RBS standby emergency diesel engine-generators manufactured by Transamerica Delaval, Inc. (TDI). The O/R of these engines have been brought into question by a crankshaft failure at Shoreham Nuclear Power Station (SNPS) in August 1983 as well as by other problems reported by owners of TDI diesels in nuclear and non-nuclear service.

River Bend Station Unit 1 is served by two TDI model DSR-48 diesel engines, designated standby diesel (SD) generator 1A and 1B. These SDs are inline 8-cylinder four-cycle, turbocharged, aftercooled engines. Each is nameplate rated for 3500 kW, and operates at 450 rpm with a cylinder brake mean effective pressure (BMEP) of 225 psig. The latest information provided by GSU specifies the emergency load as a maximum of 3130 kW under design basis accident (DBA) conditions coincident with a loss-of-coolant accident (LOCA).

Gulf States Utilities Company has been actively involved in the TDI Diesel Generator Owners' Group, an organization formed by GSU and twelve other U.S. nuclear utilities to resolve the issues stemming from questionable emergency diesel generator O/R. As part of this involvement, GSU has comprehensively analyzed all major components of its TDI engines, replaced a number of components, and conducted tests to ensure engine O/R.

The Pacific Northwest Laboratory (PNL) is providing technical support to the NRC staff in reviewing and evaluating GSU's efforts to ensure reliable

engine performance. This technical evaluation report (TER) documents PNL's review and expresses the resulting conclusions and recommendations regarding the capability of the RBS TDI diesel engines to serve their intended function.

## 1.1 ORGANIZATION OF REPORT

This report is organized as follows:

- Section 2.0 presents PNL's overall conclusions and recommendations regarding the suitability of the two TDI diesel engines to perform their intended function as emergency standby power sources for the RBS.
- Section 3.0 provides relevant background information on efforts by both GSU and the TDI Diesel Generator Owners' Group to resolve the TDI engine concerns.
- Section 4.0 presents PNL's review and evaluation of the tests, inspections, and component upgrades undertaken by GSU to prepare the engines for nuclear service.
- Section 5.0 comprises a review and evaluation of GSU's resolution of known problems in 16 engine components identified by the Owners' Group through a review of TDI engine operating history. Pertinent aspects of the Owners' Group and GSU efforts on other RBS engine components of concern are also included in this section.
- Section 6.0 provides PNL's review of, and suggestions for, the maintenance and surveillance (M/S) program at RBS.

## 1.2 APPLICABILITY OF CONCLUSIONS

To derive the conclusions presented in this report, PNL reviewed the basic documents supplied by GSU, participated in various meetings with GSU and NRC, and observed components of the engines as disassembled for inspection. PNL also reviewed various relevant Owners' Group documents and participated in meetings of the Owners' Group with NRC, and drafted technical evaluation reports on some elements of the Owners' Group Program Plan (OGPP).

GSU has submitted to the NRC revisions for the River Bend Station Final Safety Analysis Report (FSAR). These revisions establish a qualified load for each of the diesel generators and clarify positions on Regulatory Guides 1.9 and 1.108. According to these revisions, the maximum "qualified" load considered necessary for SD 1A to support its designated share of the RBS emergency power needs is 3130 kW; the qualified load for SD 1B is 3034 kW. This TER addresses the adequacy of engine components relative to the 3130-kW load limit.

This TER precedes completion of the final review by PNL and the NRC staff of the Owners' Group Program. Accordingly, the conclusions expressed in this TER about the long-term suitability of the TDI engines at RBS for nuclear service are contingent upon GSU's commitment to implement all applicable recommendations and requirements identified in the NRC's final review of the Owners' Group Program. (Completion of that review is anticipated in mid-1985.)

In PNL's opinion, all RBS-related issues that require priority PNL/NRC attention have been reviewed sufficiently and are considered resolved, subject to the recommendations in this TER.

Unless stated otherwise, all recommendations and requirements identified in NRC's review of the Owners' Group Program should be implemented by the end of the first refueling outage.

## 1.3 REPORT PREPARATION

This report is based in part on PNL's review of documents cited in Section 3.0. Additional data were obtained from direct observations by PNL team members during a plant visit in September 1984. At that time, PNL reviewers observed SD 1A after reassembly and reviewed the SD 1B component inspections and preparation for reassembly. PNL also held technical discussions with GSU staff and management at that time, and again in February 1985, as well as in connection with various Owners' Group meetings in 1984 and 1985.

The PNL staff members and consultants who conducted this review and evaluation and authored this report include:

- R. E. Dodge, PNL project staff
- J. F. Nesbitt, PNL project staff
- B. J. Kirkwood, Covenant Engineering, diesel consultant to PNL
- P. J. Louzecky, Engineered Applications Corporation, diesel consultant to PNL.

Others whose contributions were valuable in formulating the conclusions presented herein include PNL Assessment of Diesel Engine Reliability/Operability Project team members J. M. Alzheimer, D. A. Dingee, W. W. Laity, and F. R. Zaloudek; and consultants S. H. Bush, A. J. Henriksen, N. Jaffrey, N. N. Rivera, A. Sarsten, T. W. Spaetgens, J. V. Webber, L. Wechsler, and A. Wendel. The report editor was A. J. Currie.

# 2.0 CONCLUSION AND RECOMMENDATIONS

This section presents PNL's overall conclusion and recommendations regarding the capability of the River Bend SDs to perform their intended function as emergency standby power sources.

## 2.1 CONCLUSION

PNL and its consultants conclude that, overall, SDs 1A and 1B at the River Bend Station are suitable for nuclear standby service at the "qualified" load of 3130 kW, subject to implementation of the recommendations herein.

PNL's overall conclusion is based on:

- review of the Owners' Group Program Plan
- review of Owners' Group and GSU actions taken to resolve generic and plant-specific problems and to upgrade the River Bend SDs
- documented results of engine testing
- documented results of engine inspections.

Other information on which PNL's overall conclusion is based includes the Owners' Group design review and quality revalidation (DR/QR) report for River Bend Station, the GSU Program Plan for the Transamerica Delaval, Inc., Standby Diesel Generators, the results of SD evaluations, GSU SD modification reports, and results of crankshaft torsional analyses and evaluations.

## 2.2 RECOMMENDATIONS

General recommendations offered by PNL as a result of this review are highlighted in the following paragraphs.

Recognizing that this report precedes the final NRC review of the implementation of the Owners' Group Program, *PNL recommends that NRC actions based on this review be contingent upon GSU implementing all relevant recommendations and requirements identified in the final NRC review.*

*All relevant actions should be implemented by GSU before or during the first refueling outage, insofar as this is practicable.*

GSU has committed to implement the maintenance and surveillance recommendations in the Owners' Group RBS DR/QR report. *PNL's recommendations for component M/S documented in Section 6.0 of this TER should also be implemented.*

PNL considers GSU's preoperational tests of the RBS engines sufficient to detect any abnormal engine behavior. These tests include those required by NRC Regulatory Guides. *PNL recommends that planned fast starts be limited to the number consistent with NRC requirements.*

# 3.0 BACKGROUND

This section presents background information on efforts undertaken by the TDI Diesel Generator Owners' Group and by Gulf States Utilities Company to resolve the problems identified in the River Bend Station TDI diesel engines.

## 3.1 OWNERS' GROUP PROGRAM PLAN

Thirteen nuclear utilities that own generators driven by TDI-manufactured diesel engines have established an Owners' Group to address questions raised by the major failure in one TDI diesel engine at the Shoreham Nuclear Power Station in August 1983 and other problems in TDI diesels reported in the nuclear and non-nuclear industry. On March 2, 1984, the Owners' Group submitted a plan to the U.S. Nuclear Regulatory Commission outlining a comprehensive program to qualify their diesel generator units as standby emergency power sources.

The Owners' Group Program Plan (OGPP) describes a two-phase approach for resolving the known and potential problems in TDI engines:

- Phase 1 addresses the evaluation and resolution of significant known problems in 16 components. These problems were identified by the Owners' Group through a review of the operating histories of TDI engines in nuclear and non-nuclear services.
- Phase 2 entails a comprehensive design review and quality revalidation (DR/QR) to identify critical components of TDI engines in addition to the 16 referred to above, and to ensure that these components are also adequate for their intended service.

The OGPP also describes a program for engine testing and component inspections, as appropriate, to verify the adequacy of the engines and components to perform their intended functions.

At NRC's request, PNL reviewed the OGPP. The results of that evaluation were reported to NRC in PNL-5161, Review and Evaluation of TDI Diesel Generator Owners' Group Program Plan (Pacific Northwest Laboratory June 1984).

Section 4.0 of PNL-5161 discusses considerations for interim licensing actions for nuclear stations prior to completion of the implementation of the OGPP. Recommendations in that report relevant to GSU's current request for licensing of River Bend Station Unit 1 are:

1. Preoperational testing should be performed as discussed in Section 2.3.2 of PNL-5161.
2. The engines should be inspected per Section 2.3.2.1 of PNL-5161 to ensure that the components are sound.
3. The engines should receive enhanced maintenance and surveillance.
4. A "lead engine" as described in Section 2.3.2.2 of PNL-5161 should be tested to $10^7$ cycles at "qualified" load to verify the design adequacy of key engine components subject to fatigue stresses, if components of the same design have not already been operated that many cycles under the same or greater load.

Implementation of these recommendations would 1) demonstrate fatigue-resistant designs for critical components, 2) provide reasonable assurance for site-specific installations, and 3) provide reasonable assurance about their continuing operability and reliability.

## 3.2 RIVER BEND STATION PLAN

The basic approach followed by GSU to qualify their TDI diesels was generally consistent with the Owners' Group Program Plan and the recommendations described in Section 3.1 above.

The utility has provided NRC with documents relevant to these activities. These documents and others reviewed by PNL in preparing this TER are:

- a letter dated November 30, 1983, from L. Duck (TDI) to J. C. Deddens (GSU), "Standby Diesel Generator - Model DSR-48, Units S/N 74039/40 Product Improvements", listing manufacturer-recommended product improvements

- a report entitled Delaval Diesel Generator Operation Experience (handout at TDI Owners' Group meeting, January 26, 1984), outlining the experience of various owners of TDI diesels with their engines to late 1983
- a letter dated May 7, 1984, from L. Duck (TDI) to J. R. Hamilton (GSU), "River Bend Station Unit 1 Diesel Generators S/N 74039/40, P.O. 244.700", formally advising of the liner dimensional improvements for job site changes
- a letter dated May 8, 1984, from L. Duck (TDI) to J. R. Hamilton (GSU), "River Bend Station Unit 1 Diesel Generators S/N 74039/40, P.O. 244.700", transmitting additional liner dimensional improvements
- a letter (RBG-17,838) dated May 16, 1984, from R. W. Helmick (GSU) to C. L. Ray (TDI OG), "File No. 244.700 Standby Diesel Generator Systems River Bend Station - Unit 1", providing instructions for work on cylinder liners
- a nine-volume Owners' Group report dated June 29, 1984, TDI Diesel Generator Design Review/Quality Revalidation Report - Shoreham Nuclear Power Station Unit 1, documenting the comprehensive DR/QR effort performed on the SNPS TDI engines and the results of that effort
- a GSU report (RBG-18,244) dated July 19, 1984, River Bend Station - Unit 1, Docket No. 50-458, addressing the program plans for evaluating and testing the standby diesel generators
- an NRC report dated August 13, 1984, Safety Evaluation Report - Transamerica Delaval, Inc. Diesel Generator Owners' Group Program Plan, presenting NRC staff recommendations for TDI diesel generator test and inspection programs
- a Stone & Webster Engineering Corporation (SWEC) report dated August 1984, entitled Survey of Start Experiences and Causes of Unscheduled Shutdowns of Transamerica Delaval Inc. Diesel Engines, summarizing data extracted from various diesel generators' logs

- a SWEC report dated September 1984, entitled Crankshaft Torsional Vibration Measurements DG 1A River Bend Nuclear Power Station, presenting the torsional vibration data developed for the TDI Owners' Group on the RBS crankshaft

- a GSU report (RBG-19,210) dated October 16, 1984, River Bend Station - Unit 1 Docket No. 50-458, presenting a revised plan for evaluating and testing the Division I and II SDs and data on the inspection and testing performed to date

- a letter dated October 18, 1984, from J. D. Leonard, Jr. (LILCO) to H. R. Denton (NRC), "Confirmatory Testing of TDI Diesel Generators at Shoreham Nuclear Power Station Unit 1, Docket No. 50-322", providing NRC with LILCO's testing protocol for the $10^7$ cycle confirmatory tests

- a letter dated October 18, 1984, to J. Kammeyer (Owners' Group) from P. Johnston/L. Shusto (Failure Analysis Associates), comparing RBS and Shoreham crankshaft loads and stresses

- a letter (RBG-19,576) dated November 29, 1984, from J. E. Booker (GSU) to H. R. Denton (NRC), "River Bend Station - Unit 1 Docket No. 50-458", presenting proposed revisions to the RBS FSAR

- a Failure Analysis Associates (FaAA) report dated December 1984, FaAA Support Package SP-84-6-10(g), containing data on the crankshaft (component 03-310A) at RBS

- a four-volume Owners' Group report dated December 1984, TDI Diesel Generator Design Review and Quality Revalidation Report - Gulf States Utilities River Bend Station, documenting the DR/QR effort performed on the RBS TDI engines, what was carried over from a "lead" engine review (Shoreham), and the results of these efforts

- a LILCO report dated December 3, 1984, TDI Emergency Diesel Generator $10^7$-Cycle Confirmatory Test/Inspection Report, Shoreham Nuclear Power Station Unit 1, describing LILCO's tests and inspection results for the $10^7$-cycle confirmatory test of EDG 103

- a PNL report dated December 3, 1984, Post-Test Examination of Transamerica Delaval, Inc., Emergency Diesel Generator 103 at Shoreham Nuclear Power Station, documenting PNL's review of the EDG 103 disassembly and inspection
- a letter dated December 4, 1984, from C. L. Ray (Owners' Group) to C. H. Berlinger (NRC), providing data on the crankshaft forging process and tensile specimens
- a PNL report dated December 14, 1984, Post-Test Examination of the TDI Emergency Diesel Generator 103 Pistons and Related Components at Shoreham Nuclear Power Station, documenting the component reviews made by PNL
- a GSU report (RBG-19,762) dated December 21, 1984, River Bend Station - Unit 1 Docket No. 50-458, presenting a revised plan for evaluating and testing the Division I and II SDs as well as data on the inspections and testing performed to date
- a letter (RBG-20,086) dated February 6, 1985, from J. E. Booker (GSU) to H. R. Denton (NRC), "River Bend Station - Unit 1, Docket No. 458", containing revisions to the RBS FSAR
- a letter dated February 12, 1985, from C. L. Ray (Owners' Group) to J. Hamilton (GSU), noting metallographic examination results for RBS engine blocks
- a letter dated February 18, 1985, from C. L. Ray (Owners' Group) to C. H. Berlinger (NRC), providing additional torsional dynamic data on the RBS crankshaft
- a letter dated February 21, 1985, from D. Stuart (TDI) to J. Hamilton (GSU), transmitting reports of ultrasonic testing and magnetic particle examinations on the RBS crankshafts
- a letter dated February 22, 1985, from J. E. Booker (GSU) to H. R. Denton (NRC), "River Bend Station - Unit 1, Docket No. 50-458" File No. G9.5, providing responses to information requests from PNL/NRC

- a letter dated February 22, 1985, from J. E. Booker (GSU) to H. R. Denton (NRC), "River Bend Station Unit 1, Docket No. 50-458" File No. G9.5, providing responses to 17 questions raised by NRC

- an Owners' Group report dated February 1985, TDI Diesel Generator Design Review and Quality Revalidation Report - Gulf States Utilities River Bend Station, Revision 1, providing changes, corrections, and additions to the original DR/QR report

- a letter (RBG-20,684) dated April 11, 1985, from J. E. Booker (GSU) to H. R. Denton (NRC), transmitting preoperational test plans and results

- a letter (RBG-20,891) dated May 3, 1985, from J. E. Booker (GSU) to H. R. Denton (NRC), transmitting Total Inspection Report and Owners' Group Modification Report, each dated April 22, 1985

- a letter (RBG-20,994) dated May 15, 1985, from J. E. Booker (GSU) to H. R. Denton (NRC), transmitting revised FSAR pages

- a letter (RBG-21,026) dated May 17, 1985, from J. E. Booker (GSU) to H. R. Denton (NRC), transmitting Revision 1 of GSU's Program Plan for the Transamerica Delaval, Inc. Standby Diesel Generators at RBS

- a report dated June 1, 1985, prepared by Forschungsgesellschaft fur Energietechnik und Verbrennungsmotoren MBH (FEV) of Aachen, West Germany, entitled Operational Safety of TDI DSR-48 Emergency Diesel Generator Crankshafts at River Bend Station, Gulf State Utilities

- a letter (RBG-21,276) dated June 12, 1985, from J. E. Booker (GSU) to H. R. Denton (NRC), transmitting responses to NRC requests for additional information on RBS crankshafts

- reports prepared by the TDI Diesel Generator Owners' Group on the 16 components with known problems addressed in Phase 1 of the Owners' Group Program

- GSU inspection reports supporting the Owners' Group DR/QR report.

In addition to reviewing these documents, PNL visited the RBS site to observe engine inspections and GSU procedures for component inspection. PNL project staff and consultants also gained perspective on TDI engines and their components through participation in inspections at other nuclear facilities.

## 4.0 TESTS, INSPECTIONS, AND COMPONENT UPGRADES

The RBS SDs have been subjected to testing/inspection programs comprising 1) shop qualification tests, 2) onsite preservice tests and inspections, including DR/QR activities, 3) confirmatory testing, 4) post-test inspections, and 5) preoperational tests. As one result of these tests and inspections, the engines have undergone component upgrades.

The RBS SD tests, inspections, and component upgrades are discussed in chronological order in Sections 4.1 through 4.5. The results and conclusions reported by GSU are documented in Section 4.6. PNL's evaluation of GSU's program is presented in Section 4.7.

### 4.1 SHOP QUALIFICATION TESTS

According to GSU, the test program for the River Bend SDs began with shop tests at the TDI manufacturing facilities in Oakland, California. These shop tests were performed to verify the operability of the SD units, including the interrelated functional capability of engine components. GSU reports that shop tests accomplished on the engines included those listed below.

- Start verification tests were performed on SD 1A. The engine successfully demonstrated its ability to perform 37 starts from the standby condition when given a LOCA start signal.
- Margin tests were performed on both engines. The units successfully demonstrated their ability to start one 1000-HP motor, one 700-HP motor, and pick up a resistive load of 1250 kW five seconds after picking up a resistive load of 1750 kW.
- Sequential load tests were performed on both SDs. The engines successfully demonstrated their ability to start and handle the required loads while remaining within all operating criteria.
- Load rejection tests were performed on both engines. The engines successfully demonstrated their ability to drop 3500 kW (100%) and 3850 kW (110%) load with only a momentary frequency increase, and then return

to normal frequency with all operating parameters remaining within the specified criteria.

- Functional tests were performed. Both units successfully demonstrated that their control, surveillance, and protection systems functioned properly.
- Load capability tests were performed. Both units successfully demonstrated the ability to pick up 100% load (3500 kW) and operate at this load for 22 hours. At the completion of 22 hours, the load was increased to 110% (3850 kW) and run for 2 hours.
- Air start capacity tests were performed. Engine 1A was started seven times with the compressor locked out. Engine 1B was started eight times with the compressor locked out.
- An acoustical test was performed on SD 1A.
- A torsiograph test was performed on SD 1A.

Operating hours at given loads that were accumulated during shop tests for each engine are:

| Power Level | Diesel 1A, hours | Diesel 1B, hours |
|---|---|---|
| 110% | 4 | 3 |
| 100% | 26 | 32 |
| 75% | 1 | 1 |
| 50% | 8 | - |
| 25% | 4 | 4 |
| 0% | - | 1 |

The number and type of starts for the engines were as follows:

- A start verification test was performed on SD 1A. This consisted of 37 emergency starts from standby temperature (150°F ±10°F). Each start included pickup of 1750 kW within 10 seconds of the start signal. There were no start failures.

- Based on a review of factory test logs, GSU determined that approximately 30 additional start tests for each engine were necessary to conduct the balance of the factory test program. These are assumed to have been normal starts from standby temperature.

## 4.2 PRESERVICE TESTS AND INSPECTIONS

The TDI engines were delivered to the RBS in mid-1981. After the installations were completed early in 1984, GSU initiated a preservice test/inspection effort to verify that the installations were complete and correct and that the manufactured quality of the engines complied with the design requirements.

GSU has reported that as-built installation verification inspections were performed. These included inspections by TDI and its major subvendors, including Electric Products (electric generator), RTE Delta (switchgear), Elliott (turbocharger), and Woodward (governor). In addition, GSU performed inspections on other engine components.

According to GSU, tests were conducted on the auxiliary systems, interlocks, controls, and alarms to verify their operation in accordance with design specifications. These tests included system flushing, hydrostatic testing, and relief valve testing for setpoint and seal leakage. Vibration testing of pumps and compressors, performance testing of air dryers, and individual checkout of all electrical components and instrument loops also were performed.

In 1984, GSU undertook a preservice disassembly inspection program to verify the manufactured quality of engine components in support of the Owners' Group DR/QR activities. This inspection encompassed 169 components of the diesel engines at RBS Unit 1. When they were disassembled for the DR/QR activities, these engines had not yet been operated onsite. Therefore, all operating hours, loads, and starts on the two engines were only those accumulated during the TDI shop tests. The results and conclusions of the RBS DR/QR effort were detailed in the Owners' Group report, TDI Generator Design Review and Quality Revalidation Report (December 1984) and Revision 1 of that report (February 1985).

GSU has reported that its basic approach to diesel qualification was to correct the known problems before the engines were operated at RBS. Several component improvements or upgrades were accomplished, and modifications were installed on or incorporated into the RBS engines, consistent with Owners' Group and/or TDI recommendations. These included:

- The cylinder block, cylinder liners, and cylinder studs were machined.
- The original piston skirts were replaced with type AE piston skirts.
- The original piston rings were replaced with an improved version.
- The original piston pin retaining rings were replaced with another type.
- The original cylinder heads were replaced with Group III heads.
- The original valve push rods were replaced with friction-welded push rods.
- A turbocharger prelube system was installed.
- The turbocharger mounting bracket was stiffened.
- The original fuel injector tips were replaced with 135-degree units.
- The fuel injection pump return line was replaced with heavier-walled tubing.
- The idler gear locking arrangement was modified.

Additional information on most of these changes is included in the component-specific subsections of Section 5.0 of this report.

## 4.3 CONFIRMATORY TESTS

Confirmatory tests were conducted to verify engine reliability following engine inspection and reassembly. The specific tests reported by GSU to have been conducted on each engine are described in Tables 4.1 and 4.2. According to GSU, the testing program complied with the requirements of Regulatory Guide 1.108.

TABLE 4.1. Confirmatory Tests Conducted on River Bend Station Standby Diesel 1A

| Test Objective | Acceptance Criteria | Results |
|---|---|---|
| 1. Manufacturer-recommended test in accordance with TDI SIM #99 | | |
| a. Initial start, slow idle, no load (15 minutes) | Operating parameters in normal range<br>Crankcase inspection | Satisfactory |
| b. 450 rpm, no load (30 minutes) | Adjust governor<br>Verify overspeed trip<br>Verify generator differential shutdown<br>Operating parameters in normal range<br>Crankcase inspection | Satisfactory |
| c. Generator phasing | Generator electrical checks<br>Set electrical portion of governor | Satisfactory |
| d. 1 hour at 25% rated load | Operating parameters in normal range | Satisfactory |
| e. 1 hour at 50% rated load | Operating parameters in normal range | Satisfactory |
| f. 2 hours at 75% rated load | Operating parameters in normal range | Satisfactory |
| g. Return to 25% rated load for 30 minutes | Operating parameters in normal range<br>Verify parameters consistent with Step d | Satisfactory |
| h. 4 hours at 100% load (3500 kW), followed by internal engine inspection and turbocharger vibration, bearing cooling, and lubrication test | Operating parameters in normal range<br>Crankcase inspection<br>Crankshaft web deflection<br>Piston skirt wear<br>Cylinder liner wear<br>Gear set wear<br>Valve and rocker arm wear and clearances<br>Cold compression pressure<br>Generator winding temperature | Satisfactory |

TABLE 4.1. (contd)

| Test Objective | Acceptance Criteria | Results |
|---|---|---|
| 2. Engine timing and adjustments - 24 hours at 100% load (power duration may vary) | Smooth operation<br>Cylinder firing pressures in balance<br>Operating parameters in normal range<br>Crankshaft web deflection | Satisfactory |
| 3. Crankshaft torsional vibration test | Crankshaft torsional vibration within allowable values | Satisfactory |
| 4. Engine performance test - Demonstrate that diesel operates within design parameters at 100% rated load, and demonstrate starting reliability | Operating parameters in normal range | All start attempts successful |
| a. 24 hours at 100% rated load | | Satisfactory |
| b. Ten modified starts[a] to the load required by a loss of offsite power (approximately 75% of rated load), and run for a minimum of 1 hour | | Satisfactory |
| c. Two fast starts[b] to 100% of rated load, and run for a minimum of 4 hours | | Satisfactory |

(a) A modified start is defined as a start including a prelube period as recommended by the manufacturer and a 3- to 5-minute loading to the specified load level. Modified starts may be conducted with the engine at operating temperature.

(b) Fast starts are those resulting from a simulation of an engineered safety feature (ESF) signal with the engine on ready-standby status.

TABLE 4.2. Confirmatory Tests Conducted on River Bend Station Standby Diesel 1B

| Test Objective | Acceptance Criteria | Results |
|---|---|---|
| 1. Manufacturer-recommended test in accordance with TDI SIM #99 | | |
| a. Initial start, slow idle, no load (15 minutes) | Operating parameters in normal range<br>Crankcase inspection | Satisfactory |
| b. 450 rpm, no load (30 minutes) | Adjust governor<br>Verify overspeed trip<br>Verify generator differential shutdown<br>Operating parameters in normal range<br>Crankcase inspection | Satisfactory |
| c. Generator phasing | Generator electrical checks<br>Set electrical portion of governor | Satisfactory |
| d. 1 hour at 25% rated load | Operating parameters in normal range | Satisfactory |
| e. 1 hour at 50% rated load | Operating parameters in normal range | Satisfactory |
| f. 2 hours at 75% rated load | Operating parameters in normal range | Satisfactory |
| g. Return to 25% rated load for 30 minutes | Operating parameters in normal range<br>Verify parameters consistent with Step d | Satisfactory |
| h. 4 hours at 100% load (3500 kW), followed by internal engine inspection and turbocharger vibration, bearing cooling, and lubrication test | Operating parameters in normal range<br>Crankcase inspection<br>Crankshaft web deflection<br>Piston skirt wear<br>Cylinder liner wear<br>Gear set wear<br>Valve and rocker arm wear and clearances<br>Cold compression pressure<br>Generator winding temperature | Satisfactory |

TABLE 4.2. (contd)

| Test Objective | Acceptance Criteria | Results |
|---|---|---|
| 2. Engine timing and adjustments - 24 hours at 100% load (power duration may vary) | Smooth operation<br>Cylinder firing pressures in balance<br>Operating parameters in normal range<br>Crankshaft web deflection | Satisfactory |
| 3. Engine performance test - Demonstrate that diesel operates within design parameters at 100% rated load, and demonstrate starting reliability | Operating parameters in normal range | All start attempts successful |
| a. 24 hours at 100% rated load | | Satisfactory |
| b. Ten modified starts[a] to the load required by a loss of offsite power (approximately 75% of rated load), and run for a minimum of 1 hour | | Satisfactory |
| c. Two fast starts[b] to 100% of rated load, and run for a minimum of 4 hours | | Satisfactory |

(a) A modified start is defined as a start including a prelube period as recommended by the manufacturer and a 3- to 5-minute loading to the specified load level. Modified starts may be conducted with the engine at operating temperature.

(b) Fast starts are those resulting from a simulation of an ESF signal with the engine on ready-standby status.

## 4.4 POST-TEST INSPECTIONS

Post-test engine inspections were undertaken to identify any potential latent problems not discovered in earlier inspections or tests, as well as to verify engine readiness for further operation. GSU believed that major disassembly was unnecessary because of the thoroughness of the preservice inspections and the Owners' Group DR/QR review. Component access covers were removed, and the critical engine components were subjected to visual inspection. The oil was analyzed.

The visual inspections sought to identify evidence of component distress conditions such as signs of greater than nominal wear, discoloration from overheating, water leakage, and wear products (metal particles). Oil samples were analyzed for the presence of foreign particles indicating abnormal wear of bushings or bearings.

Post-test inspection results reported by GSU are summarized in Table 4.3 for SD 1A. The results for SD 1B appear in Table 4.4.

TABLE 4.3. Post-Test Inspection Results for River Bend Station Standby Diesel 1A

| Component | Number | Results |
|---|---|---|
| Intake and exhaust tappet assembly | 03-345A | Satisfactory |
| Fuel tappet assembly | 03-345B | Satisfactory |
| Camshaft assembly | 03-350A | Satisfactory |
| Camshaft supports, bolting, and gear | 03-350C | Satisfactory |
| Idler gear assembly crank to pump gear | 03-355A | Satisfactory |
| Cylinder head bolting and gaskets | 03-360C | Satisfactory |
| Overspeed trip coupling | 03-410C | Satisfactory |
| Governor linkage | 03-413 | Satisfactory |
| Lube oil sump tank | 03-540B | Satisfactory |

TABLE 4.4. Post-Test Inspection Results for River Bend Station Standby Diesel 1B

| Component | Number | Results |
|---|---|---|
| Intake and exhaust tappet assembly | 03-345A | Satisfactory |
| Fuel tappet assembly | 03-345B | Satisfactory |
| Camshaft assembly | 03-350A | Satisfactory |
| Camshaft supports, bolting, and gear | 03-350C | Satisfactory |
| Idler gear assembly crank to pump gear | 03-355A | Satisfactory |
| Idler gear assembly | 03-355B | Satisfactory |
| Air start valve | 03-359 | Satisfactory |
| Cylinder head bolting and gaskets | 03-360C | Satisfactory |
| Governor drive coupling, pins, and keys | 03-402B | Satisfactory |
| Governor linkage | 03-413 | Satisfactory |
| Lube oil sump tank | 03-540B | Satisfactory |

## 4.5 PREOPERATIONAL TESTS

The preoperational tests conducted by GSU had four objectives: 1) to demonstrate the reliability of the standby diesel generator power sources; 2) to ensure SD capability to provide standby electrical power during normal and simulated accident conditions; 3) to demonstrate SD ability to pick up standby loads during simulated accident conditions; and 4) to demonstrate the operability of the SD auxiliary systems (e.g., fuel oil transfer, starting air supply).

As reported by GSU in the FSAR for River Bend Station, the types of preoperational tests performed and the overall results were as shown in Table 4.5.

## 4.6 REPORTED RESULTS AND CONCLUSIONS

According to GSU reports, few problems occurred during the operation of the RBS TDI diesel generators. However, it must be recognized that the number of operating hours on either SD has not reached that experienced at several other plants. Problems and areas of concern were found on a few engine

TABLE 4.5. Preoperational Tests Conducted on River Bend Station Standby Diesels

| Tests | Results 1A | Results 1B |
|---|---|---|
| a. Diesel starting and trip sequence | Satisfactory | Satisfactory |
| b. Auxiliary systems operate per specifications | ↓ | ↓ |
| c. Interlocks, controls and alarms operate per specifications | ↓ | ↓ |
| d. Proper manual and automatic start and operation | ↓ | ↓ |
| Voltage and frequency attained within time limits | ↓ | ↓ |
| e. Proper response and operation for DBA loading sequence | ↓ | ↓ |
| Voltage and frequency attained within time limits | ↓ | ↓ |
| f. Proper operation during load shedding, sequencing, and rejection | ↓ | ↓ |
| Loss of largest single load - maintain voltage and frequency | ↓ | ↓ |
| Complete loss of load without overspeed | ↓ | ↓ |
| g. Full load for 24 hours | ↓ | ↓ |
| Voltage and frequency maintained | ↓ | ↓ |
| Cooling system operation within limits | ↓ | ↓ |
| h. Reperform a fast start (d) at rated load immediately (within 5 minutes) after completion of 24-hour load test (g) | ↓ | ↓ |
| i. Ability to synchronize with offsite power while loaded | ↓ | ↓ |
| Transfer load from diesel to offsite | ↓ | ↓ |
| Isolate SD generator and put on standby status | ↓ | ↓ |
| j. Fuel consumption rate compatible with 7-day storage capacity | ↓ | ↓ |
| k. Reliability of SD per Regulatory Guide 1.108 | ↓ | ↓ |
| l. Capability to supply power within time limits during periodic surveillance testing | ↓ | ↓ |
| m. Reliability and independence of redundant SD through simultaneous starting during testing per FSAR Section 14.2.12.1.4.4 | Scheduled for performance during integrated ECCS test | |
| n. Ability to start with minimum air pressure | Satisfactory | Satisfactory |
| Number of starts from air pressure system without recharging | ↓ | ↓ |

components during the disassembly and inspection programs. GSU reports that all of these have been corrected or have no impact on engine O/R.

The Owners' Group has formally documented the results of their DR/QR effort in the four-volume TDI Diesel Generator Design Review and Quality Revalidation Report - Gulf States Utilities River Bend Station (December 1984) and in Revision 1 to that report (February 1985). Results of tests and inspections performed on the SDs at RBS have been reported in a series of GSU letter reports listed in Section 3.0 of this TER. Component-specific results and details of the findings are covered in Section 5.0 of this TER. Therefore, they are not repeated here.

Three conclusions were drawn by GSU based on the DR/QR effort and the onsite test and inspection activities:

- As a result of the Owners' Group efforts, the problems of the TDI DSR-48 diesel generators are now understood.
- Solutions to these problems have been implemented on the TDI diesels at River Bend.
- The TDI diesel generators at RBS are acceptable for their intended safety-related function, and they will provide reliable standby power for River Bend Station.

## 4.7 PNL EVALUATION

In evaluating GSU's engine tests, inspections, and component upgrades, PNL reviewed available documentation of the tests, inspection results, and operating history on the RBS TDI engines. PNL also considered the results of other TDI engine tests, including the DSR-48 lead engine test at SNPS. Based on these reviews, PNL concludes that the test and inspection program conducted by GSU and others was adequate to identify problems with engine components and that tests were adequate to verify component ability to meet the load and service requirements. PNL views the component upgrades at RBS as responsive to the inspection findings and to the Owners' Group recommendations.

## 5.0 COMPONENT PROBLEM IDENTIFICATION AND RESO'.UTION

This section documents PNL's review of GSU's actions to qualify the 16 engine components known to have had significant problems (termed Phase 1 components). These components were previously identified by the Owners' Group through a review of the operating histories of TDI engines in nuclear and non-nuclear service. Each component is described in terms of its function, operating history, and status as determined by the Owners' Group and GSU. Other GSU engine components found to be defective or that were replaced at RBS are also covered in this section.

Section 6.0 of this TER provides PNL recommendations for modifications to the GSU maintenance and surveillance program. These are generally not repeated in this section. The conclusions also reflect PNL's finding that GSU's procedures for dispositioning component inspection findings are adequate with respect to both documentation and engineering considerations.

### 5.1 ENGINE BASE AND BEARING CAPS

Part No. 03-305A, C, D

Owners' Group Reports FaAA-84-4-1 and FaAA-84-6-53

#### 5.1.1 Component Function

The engine base supports the crankshaft and upper structures, and carries the thrust of the cylinder combustion loads from the main bearings. The shaft is bedded in half-circle bearings set within "saddles" in the base. The bearing caps are structural members that hold the upper bearing shells in place over the shaft main journals while also absorbing the upward, reciprocating piston inertial loads. The studs and nuts hold the cap and therefore the shaft in place. A failure of base, cap, or bolting would allow shaft gyration or misalignment, potentially leading to shaft fracture and seizure, sudden engine stoppage, and possible ignition of crankcase vapors.

#### 5.1.2 Component Problem History

Four incidents of cracking have occurred in the engine base saddles of inline DSR-4 engines, causing this component to be evaluated as a generic

issue:

- SNPS EDG 102, reported following an inspection in September 1983
- SNPS EDG 103, reported following an inspection in September 1983
- U.S. Coast Guard cutter Westwind (a TDI DSR-46 engine)
- U.S. Coast Guard cutter Northwind (a TDI DSR-46 engine).

### 5.1.3 Owners' Group Status

Failure Analysis Associates (FaAA), a consultant to the Owners' Group, analyzed the base, bearing saddles, bearing caps, nut pockets, and bolting/nuts. FaAA conducted a finite element analysis to determine stresses acting on critical sections of the bearing saddle under lateral loading from the crankshaft. The loads were determined using a journal orbit analysis. The bearing cap, through-bolts, bearing studs, and nuts were similarly analyzed. The studs and bolts were tested for hardness.

FaAA concluded that the base assembly components have the strength necessary to operate at full rated load for indefinite periods, provided that all components meet manufacturer's specifications, that they have not been damaged, that mating surfaces are clean, and that proper bolt preloads are maintained.

The Owners' Group concluded that the cracks in the engine base saddle of SNPS EDG 102 were due to the crankshaft failure and the cracks in EDG 103 resulted from an inappropriate method of stud removal that introduced excessive side loads in the stud holes. Cracks in both U.S. Coast Guard cutters' engine base saddles were considered to be the result of undertorquing of the associated stud nuts.

### 5.1.4 GSU Status

A liquid penetrant (LP) inspection of the main bearing saddle area between cylinders No. 5 and No. 6 (two surfaces) was performed on SD 1A. The results were satisfactory; no cracks were found. In addition, no indications of excessive wear, erosion, or corrosion were found. A visual inspection of the mating areas on the bearing cap was performed; no indication of fretting was observed.

In the DR/QR report for RBS, the Owners' Group recommended that a visual inspection of the base be performed at each refueling outage. This inspection includes an examination of the area adjacent to the nut pockets of each bearing saddle for cracks.

5.1.5 PNL Evaluation and Conclusion

PNL believes that the origin of the cracks observed in the Shoreham EDGs was properly diagnosed and that the analysis conducted is appropriate to conclude that similar cracks should not start or propagate in the River Bend SDs.

On the basis of the inspections, diagnostics, and actions taken by GSU and the Owners' Group, PNL concludes that the engine base and bearing caps in SDs 1A and 1B are acceptable for their intended service.

PNL recommends that GSU incorporate the Owners' Group disassembly recommendations developed for Shoreham into the River Bend maintenance procedures (e.g., studs should not be torqued to twist or break nut locking pins). Also, due to the serious engine damage that could result from insufficient preload in the bearing cap bolts, PNL recommends that these bolts be checked for proper preload every 5 years.

## 5.2 CYLINDER BLOCK

Part No. 03-315A
Owners' Group Report FaAA-84-9-11.1
FaAA Support Package SP-84-6.12(g)

5.2.1 Component Function

The cylinder block, which is bolted to the engine base, provides structural support for the cylinder liners, cylinder heads, camshaft and valve assemblies, and other miscellaneous components. It also serves as the outer boundary for the engine coolant. The block is subjected to both mechanical and thermal stresses resulting from the combustion processes. Structural failure of the block could lead to inadequate support of components that confine combustion pressures, and thereby result in a sudden engine shutdown.

### 5.2.2 Component Problem History

Cracks have been reported in cylinder blocks of both DSR-4 (inline) and DSRV-4 ("V") engines in nuclear and non-nuclear applications. Several types of cracks have occurred in cylinder block tops. Cracks have also been found in the camshaft gallery of some inline engines, in the vertical wall just above the camshaft bearing supports. The following is a summary of the types of cracks and the engines in which they have been found.

1. Ligament cracks - A ligament crack is oriented vertically and extends between the counterbore for the cylinder liner landing and a cylinder head stud hole. Numerous cracks of this type have been identified in the top surfaces of the Shoreham EDG 101, EDG 102, and original EDG 103 engine blocks. Crack maps for the three blocks are presented in FaAA-84-9-11.1, Design Review of TDI R-4 and RV-4 Series Emergency Diesel Generator Cylinder Blocks (December 1984).

   Ligament cracks have also been reported by FaAA in the marine and stationary installations listed below. These engines have operated with such cracks for durations ranging from 6,000 to 28,000 hours.

   | TDI Engine Series | Installation |
   |---|---|
   | DSR-4 | Copper Valley Electric Corporation |
   | DSR-4 | MV Trader |
   | DSR-4 | MV Traveler |
   | DSRV-20-4 | Homestead, Florida |
   | DSRV-16-4 | MV Gott |
   | DSRV-16-4 | MV Columbia |

2. Stud hole-to-stud hole cracks - A stud hole-to-stud hole crack is also oriented vertically, and extends between two cylinder block stud holes of adjacent cylinders. A related type of crack can occur at the ends of blocks where the crack extends from a stud bolt hole to the vertical surface at the end of the block. This type of crack has been observed only in blocks having ligament cracks in the stud hole regions. In

nuclear applications, these cracks have been identified only in the original block for the Shoreham EDG 103 engine. Following replacement of the crankshaft in that engine and an engine test of 100 hours at or above the nameplate rating of 3500 kW, a crack was discovered that extended between two adjacent stud holes on the exhaust side of cylinders No. 4 and 5. Later, after EDG 103 had experienced an abnormal load excursion while being operated at full load, and had then been operated for a brief period (less than two hours) at 3900 kW, reexamination of the engine block revealed additional between-stud hole cracks. Furthermore, the original stud hole-to-stud hole crack between cylinders No. 4 and 5 had grown, as documented in the FaAA report referenced above. The EDG 103 block at SNPS that experienced the above cracking was found to have been cast of substandard material, and was replaced.

3. Circumferential cracks - Cracks of this type are found in the corner formed by the cylinder liner landing and the cylinder liner counterbore. They may extend circumferentially around the landing and downward into the block. Such cracks were discovered in the original Shoreham EDG 103 block through destructive metallurgical examinations, which revealed a maximum crack depth of approximately 3/8 inch. Because of the relatively sharp corner where these cracks occur, they are difficult to identify through nondestructive tests.

4. Cam gallery cracks - This type of crack appears as a horizontal indication in the upper radius of a camshaft bearing saddle support, and extends in essentially a horizontal plane toward the engine jacket cooling water system. Cracks of this type have been discovered in the cam galleries of Shoreham's EDG 101, EDG 102, original EDG 103, and replacement EDG 103 cylinder blocks. Weld repairs that are essentially cosmetic in nature were performed on the cam gallery cracks in the first three blocks. These repairs did not involve complete removal of the crack; furthermore, additional cracking occurred between the weld "nuggets" and the base material in the three original blocks. The cam

gallery cracks in the replacement EDG 103 block are much shallower than those in the other blocks.

Several indications were discovered in the DSRV-16-4 engines at Comanche Peak that differed from the types of cracks described above. These indications are oriented vertically and extend radially into the block from the cylinder liner landing and cylinder liner counterbore. Through metallurgical examinations, FaAA identified these cracks as interdendritic shrinkage or porosity resulting from the casting process. They have not been found in any other TDI engines in nuclear service.

### 5.2.3 Owners' Group Status

The structural adequacy of the TDI R-4 series diesel engine blocks was addressed in a study performed by Failure Analysis Associates for the Owners' Group. This study was directed principally at determining the significance of the various cracks in the SNPS engine blocks because these blocks represented the worst case of cracking experienced in TDI engines in nuclear service.

The FaAA analysis consisted of 1) materials evaluation of the SNPS blocks including chemical and microstructure analyses, tensile tests, and fatigue tests; 2) an analysis of the loads on the block that influence fatigue and fracture; 3) a stress analysis to estimate the level of stresses caused by these loads; and 4) a fracture and fatigue life analysis.

The measured tensile strength and fatigue resistance of the original SNPS EDG 103 block that failed in service was found to be much lower than the minimum expected properties of Class 40 grey cast iron. The metallurgical evaluation of the block material revealed that it contained extensive amounts of a degenerate graphite (Widmanstaetten) structure that was responsible for these severely degraded properties.

The load analysis considered the combined effects of 1) the preload on the cylinder head studs, 2) the load distribution between the cylinder heads and the block, 3) the load between the head and the liner, and 4) the thermal and pressure loads between the cylinder liners and the block. These loads were used as input to the stress analysis to provide estimates of the stress

levels in the block. The stress analysis consisted of 1) strain gauge tests performed on the original SNPS EDG 103 block and 2) both two- and three-dimensional finite element analysis to determine conservative scale factors to enable extrapolation of the strain gauge measurements to other locations in the block and to both cracked and uncracked ligaments.

The results of the stress analysis were compared with conservative material properties on a Goodman diagram to determine the likelihood of crack initiation. It was determined that 1) block top cracking may initiate at 100% of the nameplate load from high-cycle fatigue or after 100 starts to full power due to low-cycle fatigue, 2) the possibility of ligament cracks is much greater than the possibility of either stud hole-to-stud hole or stud hole-to-end cracks, and 3) once ligament cracks develop, the possibility of stud hole-to-stud hole and stud hole-to-end cracks increases, but their initiation is more difficult than the original ligament crack formation. The possibility of fatigue crack initiation below the block top was also examined; it was concluded that such cracks would not initiate at either the stud hole counter-bore or the stud hole threads.

FaAA applied a cumulative damage index technique to predict the propagation of stud hole-to-stud hole and stud hole-to-end cracks under anticipated service conditions assuming that ligament cracks already exist. This technique takes into account 1) the engine loads and durations for operations to date, 2) engine load and duration of operation required by a LOOP/LOCA event, 3) the results of inspections of the block top, and 4) the results of evaluations of the cast iron microstructure. This technique uses a Fatigue Damage Index (FDI) that allows comparison of the service history of any block with normal material properties versus the service history of the failed SNPS EDG 103 block with its degraded properties. FaAA outlined a procedure based on the cumulative damage index that defines inspections required, permissible operation to the next inspection, and the suitability of the block for further service. By this procedure, cylinder blocks that have been inspected and found free of ligament, stud hole-to-stud hole, or stud hole-to-end cracks can be operated without additional block top inspections for a combination of loads and durations that is predicted to produce less damage than that already

accumulated prior to the last inspection. FaAA recommended that engines that have not been inspected be conservatively assumed to have ligament cracks. For blocks with known or assumed ligament cracks and material typical of Class 40 grey cast iron, the basic approach to ensuring reliability is to inspect the region between cylinder heads with eddy-current methods following any engine operation at loads in excess of 50% of the rated load, i.e., 113 BMEP. If, upon more detailed inspection with adjacent heads removed, the cracks are found to be less than 1.5 inch, the block is suitable for further service.

FaAA also analyzed the circumferential cracks and determined that they would not be threatening to engine performance. However, FaAA noted that increasing the radial clearance and decreasing the proudness of the liner in the block will reduce the probability of radial and circumferential cracking, respectively.

Metallographic examination of the cam gallery cracks identified them as shrinkage cracks. Neither these shrinkage cracks nor other cracks associated with weld repairs of these cracks were found to have grown during engine operation. Further, it was determined that the stresses in the region of the cracks are compressive. Therefore, these cracks are not expected to propagate.

5.2.4 GSU Status

Based on recommendations from TDI, and under TDI field service supervision, the cylinder liner landings were machined with a special tool to align the surface. In addition, a uniform and larger than original radius was formed on the inside diameter of each of the liner landings for both of the River Bend SDs.

As part of the DR/QR effort for River Bend, the Owners' Group and GSU assembled and reviewed the cylinder block documentation including the Owners' Group component evaluation described in the preceding section. They also performed a series of dimensional checks and nondestructive examinations of the block.

The checks and examinations for SD 1A were as follows:

- Measurements were taken and recorded for all cylinder block liner landings.

- All cylinder block tops were visually inspected in the region adjacent to and between cylinders. No ligament cracks, stud hole-to-stud hole cracks, or stud hole-to-end cracks were found.
- A liquid penetrant test was performed along the top landing surface, fillet radius, and vertical face adjacent to the landing surface for all cylinder block liner landings. The reported results were satisfactory.
- A magnetic particle test was performed on the cylinder head mating surface on top of cylinder blocks No. 5, 7, and 8 in the areas between stud hole and liner and between adjacent cylinder stud holes. The results were satisfactory.
- No linear indications were found at the stud holes extending into the threads via a visual inspection.
- A metallurgical/microstructural analysis of the cylinder block material was made. This examination indicated that the 1A block microstructure was representative of typical grey cast iron, Class 40.

The checks and examinations conducted on SD 1B included the following:

- A dimensional check was made around the cylinder liner and all cylinder block liner landings. The results were satisfactory.
- A liquid penetrant test was performed along the top landing surface, fillet radius, and vertical face adjacent to the landing surface for cylinders No. 1 through No. 8. The results were satisfactory.
- A magnetic particle test was performed on the cylinder head mating surfaces on top of cylinder blocks No. 1 through No. 8 in the areas between stud holes and liner, and between adjacent cylinder stud holes. The results were satisfactory.
- After 40 hours of operation, all cylinder block tops were visually inspected in the region adjacent to and between cylinders. No ligament cracks, stud hole-to-stud hole cracks, or stud hole-to-end cracks were found.

- A metallurgical/microstructural analysis of the cylinder block material was made. This examination indicated that the 1B block microstructure was representative of typical grey cast iron, Class 40.

Based on these DR/QR findings, and with GSU's implementation of routine inspections, the Owners' Group concluded that cylinder blocks 1A and 1B at RBS are acceptable for their intended use.

GSU has also reported that visual inspections were made of the interior surface of the engine block adjacent to the camshaft and camshaft supports on both SD 1A and 1B. No evidence of cracks or undue stress was found.

5.2.5 <u>PNL Evaluation and Conclusions</u>

PNL's review of the cylinder blocks at River Bend included consideration of 1) the FaAA design review of the cylinder blocks, 2) test and inspection reports for the GSU engines, 3) the River Bend DR/QR report, and 4) meetings with TDI personnel, TDI engine owners, and the Owners' Group.

5.2.5.1 <u>Camshaft Gallery Cracks</u>

Evidence available from recent tests and metallurgical investigations strongly suggests that the known camshaft gallery cracks at Shoreham originated during the casting and subsequent cooldown of the cylinder blocks, and that the cracks have not grown since that time. Strain-gauge measurements taken by FaAA on Shoreham's EDG 103 demonstrate that the areas where the camshaft gallery cracks occur are subject to compressive stresses during engine startup, operation, and shutdown. The inspections performed by GSU on the areas adjacent to the camshaft supports have not revealed any cracks or weld repairs. Therefore, PNL does not see the need at RBS for a continuous monitoring program similar to that recommended for the SNPS EDGs.

5.2.5.2 <u>Circumferential Cracks in Liner Bore</u>

Circumferential cracks in the liner counterbore and counterbore landing were observed in the Shoreham engines and in other engines in non-nuclear applications. These cracks were not analyzed in the FaAA original design review; however, they were later dealt with by visual examination of cracks in the cutout section of the original EDG 103 block from SNPS. PNL believes that

the FaAA analysis of the origin of cracks (namely, stresses induced by cylinder liner proudness) is correct.

Further, FaAA's finite element analysis of the area reveals that the above-described region of high tensile stresses is immediately surrounded by a region of high compressive stresses resulting from the bolt-up of the cylinder head to the block. Therefore, it is PNL's judgment that any cracks formed in the cylinder liner counterbore and landing would be rapidly arrested as they move into the region of compressive stress, and will not represent any hazard to engine reliability. This judgment was supported by the results of sectioning of the circumferential crack that had propagated only 1/8 to 3/8 inch into the block even though this block had degraded mechanical properties. Further confirmation that such cracking is benign is furnished by operating experience; there are no records of any nuclear or non-nuclear engine failing because of cracks of this type.

Circumferential cracks have not been experienced in the TDI cylinder blocks at RBS. The TDI-recommended rework performed by GSU on the cylinder liners and liner landing as well as on the liner diameter also will reduce the stresses induced in the liner bore of the cylinder block. PNL concludes that circumferential cracks are not a concern regarding the O/R of the River Bend SDs.

5.2.5.3 Ligament Cracks

The inspections noted in Section 5.2.4 that were performed on the cylinder blocks by GSU have not revealed any indications of ligament cracks in either SD 1A or 1B. Further, the microstructure examinations show blocks 1A and 1B to be representative of typical grey cast iron.

PNL concludes that ligament cracks are not a concern regarding the operability/reliability of the two SDs at River Bend.

5.2.5.4 Stud Hole-to-Stud Hole Cracks

Stud hole-to-stud hole cracks are considered more serious than ligament cracks because they degrade the overall mechanical integrity of the block and

its ability to withstand firing pressures and piston side thrust. The analysis performed by FaAA indicated that, once ligament cracks occur, the stresses in the stud-to-stud region increase, providing a greater potential for cracking in this region. From cumulative damage analyses, FaAA determined that approximately the same amount of accumulated damage would be required to form stud hole-to-stud hole cracks following the formation of ligament cracks as would be needed to originally cause the ligament cracks themselves. Furthermore, the amount of damage that would be caused by operation during a LOOP/LOCA accident should be much less than that required to produce a stud hole-to-stud hole crack greater than 4 inches deep. Therefore, FaAA concluded that a block was able to meet its intended function if tests showed the absence of stud hole-to-stud hole cracks.

Based on the FaAA analysis of the SNPS blocks, the GSU inspection results showing the absence of cracks between stud holes of adjacent cylinders in the RBS blocks, and PNL's cursory examinations of one engine's block, PNL concludes that the blocks installed on both SD 1A and 1B are acceptable for the intended service, subject to the inspection recommendations of the Owners' Group and the surveillance recommendations of PNL (see Section 6.0).

## 5.3 CRANKSHAFT

Part No. 03-310A

Owners' Group Reports FaAA-84-3-16 and FaAA-85-5-10

### 5.3.1 Component Function

The crankshaft receives the reciprocating power strokes from the cylinders (via the pistons and connecting rods), converts them to rotary motion, and transfers the power to the generator. It also drives the gear train that operates the camshaft, which, in turn, operates the cylinder-head valves, fuel injection pumps, governor, etc. The crankshaft is supported by journal bearings mounted in the engine base. By means of holes drilled throughout the crankshaft, pressurized oil is picked up from the main journal bearing supply points and transmitted to connecting rod bearings, wrist pins, undersides of the pistons, and other parts.

The crankshaft is subject to a variety of complex stress fields. These include direct and torsional shear stresses and bending stresses due to the piston thrusts; inertial effects of reciprocating and rotating masses; torsional, axial and flexural vibration stresses; bending stresses due to overhung flywheel and generator; bending stresses due to wear-down in main journal bearings; and stresses due to variation in external support alignments. These nominal stress combinations are augmented in local stress fields due to the stress-raising influence of oil holes and crankweb/journal transition zones. Residual stresses introduced during crankshaft fabrication or operation also affect the final stress spectrum. The machined surfaces of the crankshaft journals and crankpins are subject to damage from oil impurities, bearing deterioration, and excessive heat. Therefore, a crankshaft fracture, if it occurred, would lead to immediate engine shutdown and probable significant conjunctive damage to other components.

### 5.3.2 Component Problem History

In August 1983, the SNPS EDG 102 crankshaft fractured during plant preoperational tests. This fracture occurred at the crankpin journal of cylinder No. 7, separating the crankshaft into two pieces. The fracture involved the web connecting the No. 7 crankpin journal to an adjacent main bearing journal. Inspection revealed severe cracking in the crankshafts of the other two SNPS engines. Independent studies performed by FaAA and the Franklin Research Center subsequently determined these failures to be due to torsional vibrations. No other torsional failures of DSR-48 crankshafts have been reported.

The original Shoreham crankshafts that had 11-inch diameter crankpins with 1/2-inch fillets were subsequently replaced with new crankshafts having 12-inch diameter crankpins with 3/4-inch fillets.

### 5.3.3 Owners' Group Status

The Owners' Group initiated an extensive investigation of the causes of the SNPS crankshaft failure. FaAA and Stone & Webster Engineering Corporation

(SWEC) were retained by LILCO to carry out intensive inspections and analytical and experimental investigations. The NRC requested the Franklin Research Center to perform an independent review. The conclusion of these investigations was that the original crankshafts failed from torsional vibratory stresses resulting from operation too near a critical speed.

The Owners' Group next evaluated the adequacy of the replacement Shoreham crankshafts. This evaluation was performed by FaAA and consisted of 1) reviewing the results of TDI's torsional calculations and SWEC's torsiograph tests for compliance with stress limits recommended by the Diesel Engine Manufacturers Association (DEMA) and 2) performing a fatigue analysis of the crankshafts to determine the factor of safety against fatigue.

The analysis of the factor of safety against fatigue failure consisted of 1) a torsional dynamic analysis to compute the nominal stresses at each crank throw, 2) a three-dimensional finite element analysis to determine local stresses in the crankpin fillet, 3) stress measurements at the points of maximum stress indicated by the finite element analysis, and 4) a determination of the factor of safety by comparing the measured stresses with the endurance limit for the failed Shoreham crankshaft.

FaAA reached the following conclusions, which are documented in report FaAA-84-3-16, pertaining to the SNPS R-48 engines:

- The TDI calculations of stresses using single orders are appropriate and show that the stresses in the replacment crankshafts are below DEMA-recommended limits for single orders of torsional vibration.
- The SWEC torsiograph tests show that the stresses in the replacement crankshafts are below DEMA-recommended limits for both single and combined orders of torsional vibration at 3500 kW (100% load) and at 3800 kW. A linear extrapolation to 3900 kW also shows compliance with DEMA limits.
- On the basis of an endurance limit established for the failed crankshafts and scaled to account for the higher ultimate tensile strength of the replacement crankshafts, together with stress levels computed from strain

gauge data, the factor of safety against fatigue failure of the replacement crankshafts is 1.48 for operation at 3500 kW. This factor of safety does not account for the effects of shotpeening, and could be greater if the shotpeening of the crankshaft fillets were considered.

- The replacement crankshafts are suitable for unlimited operation in the emergency diesel generators at SNPS.

5.3.4 GSU Status

The crankshafts in the TDI engines at RBS have the same dimensions as the Shoreham replacement crankshafts (i.e., 12-inch diameter crankpins with 3/4-inch fillets). The RBS crankshafts were made by Ellwood City Forge Corporation using a forged slab, hot-twist fabrication process.

Ellwood City Forge performed ultrasonic testing of the rough machined crankshafts (to detect subsurface flaws) and magnetic particle inspection (to detect surface and near-surface flaws) on the finished shafts. These inspections revealed no reportable indications.

5.3.4.1 Preservice Inspections by GSU

The following inspections and results were reported by GSU (December 21, 1984) for the crankshafts in SD 1A and 1B:

- visual inspection of eight crankpin journal surfaces - No signs of distress were evident.
- eddy-current inspection of seven of 16 crankpin journal fillets - No relevant indications were evident.
- liquid penetrant examination of journal fillets of eight crankpins - No relevant indications were evident.
- fluorescent liquid penetrant examination of crankpin and main bearing oil hole entrance regions - The examination of 14 entrance regions of seven oil holes showed no relevant indications.
- dental impressions of crankpin and main bearing oil holes (9 on SD 1A and 12 on SD 1B) to a depth of 3 inches - Some showed tool marks with a depth

of 6 mils. These were deemed acceptable, as they came within the Owners' Group acceptance criteria.

- visual inspection of entrance regions of crankpin and main bearing oil holes (9 on SD 1A and 12 on SD 1B) - All showed a polished surface finish.

5.3.4.2 Design Review/Quality Revalidation

Crankshaft inspections and results summarized by the Owners' Group in the River Bend DR/QR report include the following for the SD 1A and 1B engines:

- eddy-current and liquid penetrant tests of the oil holes of main journals No. 7, 8, and 9 - Results were satisfactory.
- eddy-current and liquid penetrant tests of the oil holes of crankpin journals No. 5, 6, 7 and 8 - Results were satisfactory.

Also included in the River Bend DR/QR report are the Owners' Group comments on stress analyses of the crankshafts. The Owners' Group noted the following:

- Using the pressure loading obtained from an engine test at the Shoreham Nuclear Power Station, a modal superposition analysis was performed to determine the nominal shear stresses in the crankpins and main journals of the River Bend crankshaft. The maximum torsional stress corresponding to a load of 3500 kW was found to be 7357 psi between cylinders No. 5 and 6. The predicted nominal stresses at this load do not satisfy DEMA Standard Practices, which recommend that stresses not exceed 5000 psi for a single order and 7000 psi for combined orders.
- The natural frequencies and free-end amplitudes from the torsiograph test performed on SD 1A were found to be in agreement with the modal superposition analysis. It was determined that the nominal stresses during steady-state conditions at 3130 kW (the maximum emergency load under DBA conditions) would satisfy DEMA recommendations.
- Nominal stresses in the crankshaft that was endurance tested at SNPS at 3300 kW are equivalent to crankshaft stresses in the SD 1A and 1B engines

at River Bend at 3130 kW (accounting for differences in the torsional systems of the engines at the two plants).

- Holzer calculations performed by TDI were found to be accurate and in agreement with the modal superposition analysis.
- The material certification reports for the SD 1A and 1B crankshafts are within the original design specifications. Based on a minimum ultimate tensile strength of 94 ksi for the SD 1A crankshaft, the factors of safety against fatigue failure in the main journal oil holes and the crankpin fillets are 1.36 and 1.29, respectively, at 3500 kW.

Based on the DR/QR review, the Owners' Group concluded that the crankshafts in the SD 1A and 1B engines are acceptable for their intended function at River Bend, provided that the engines are operated at loads no greater than 3130 kW.

5.3.4.3 FaAA Evaluation

Additional information on analyses and tests of the crankshafts for the engines at River Bend is presented by Failure Analysis Associates in report No. FaAA-85-5-10 (May 1985). Some of this information clarifies information presented earlier in the DR/QR report for River Bend. FaAA addresses the torsional calculations performed by TDI, the results of two torsiograph tests of the SD 1A engine, the fatigue analysis performed by FaAA to determine the safety margin of the crankshafts at 3130 kW, the endurance test of a SNPS engine and the applicability of the test to the RBS crankshafts, and the results of the crankshaft fillet and oil hole inspections performed by FaAA in July 1984. FaAA's comments and conclusions include those summarized under the four subheadings that follow.

5.3.4.3.1 Torsiograph Tests. SWEC performed two torsiograph tests on the SD 1A engine at RBS. The first, in September 1984, measured torsiograph responses during steady-state operation. The second, in May 1985, measured responses during transient operation and repeated the variable load portion of the first test to determine responses after the engine had been run in.

Between the first and second tests, the SD 1A engine accumulated 87 hours of operation at 3500 kW or greater loads. The torsiograph responses during the second test were lower than those during the first, which is typical for an engine after run-in. FaAA views the results of the second test as more indicative of the future response of the engine.

FaAA's conclusions from these tests include:

- The torsiograph test results show that the combined order stresses at 3500 kW and the rated speed of 450 rpm comply with DEMA Standard Practices.
- Based on RBS test data taken over a range of loads, there is a 7% change in torsional response for a 10% change in load. This linear relationship also holds for the SNPS torsiograph test data.
- Even though the 5th-order harmonic is in resonance at an engine speed of 455 rpm, the response is quite small and there are six other orders with greater magnitude. Accordingly, the 5th-order response is not large enough to be of concern.

5.3.4.3.2 Fatigue Analysis. FaAA computed a factor of safety against fatigue failure for the crankshafts in the RBS engines through a process that took into account fatigue data and strain-gauge data obtained in crankshaft tests at SNPS. The principal factors considered in the analysis are as follows:

- Through a dynamic torsional analysis of the crankshaft, FaAA determined the range of torque at each crank throw and the nominal torsional stresses at 3500 kW over the speed range of 450 rpm ±5%. The gas pressure loading used in this analysis was obtained from pressure versus crank angle data measured at SNPS by SWEC. The results of this analysis agree well with the torsiograph test results obtained by SWEC in May 1985. For example, the FaAA analysis predicts a front-end amplitude of 0.700 degrees at 3500 kW and 450 rpm, while the value measured by SWEC is 0.733 degrees. Over the speed range of 450 rpm ±5%, there is also good

agreement for both the RBS and SNPS installations between FaAA's stress predictions and stress predictions from COMHOL, a computer program developed by the late Prof. Sarsten of the Norwegian Institute of Technology. (As a consultant to the Pacific Northwest Laboratory, Prof. Sarsten participated in reviews of TDI diesel engine issues for NRC until his untimely death.)

- Torsional stresses at loads below 3500 kW were calculated from the values at 3500 kW, using the linear stress-load relationship determined from the torsiograph tests. FaAA found that the stresses in the RBS crankshafts at 3130 kW are comparable to the stresses in the SNPS crankshafts at 3300 kW, the nominal load at which a SNPS engine was tested to $10^7$ cycles.
- The maximum stresses in the RBS crankshaft fillets were determined from dynamic strain-gauge data taken at SNPS. The experimental values were adjusted for the differences in torsional crankshaft stresses corresponding to the differences in the mass-elastic systems of the two installations. To determine stresses in the oil holes, a stress concentration factor was applied to the computed values of the nominal torsional stresses.
- The fatigue endurance limit of the RBS crankshafts was determined from an analysis of the crankshafts that failed at SNPS. The predicted value was confirmed by other fatigue data published in the literature.

From the stress and fatigue data described above, FaAA determined that the factor of safety against fatigue cracking of the RBS crankshafts is 1.39 at 3130 kW and 450 rpm. FaAA concluded that this factor of safety provides sufficient margin for safe operation at loads up to 3130 kW.

5.3.4.3.3 Endurance Testing. Although the 8-cylinder engines at RBS are similar to the 8-cylinder engines that have undergone extensive testing at SNPS, the generators and flywheels differ between the two installations, resulting in differences in torsional crankshaft stresses. Furthermore, the fillets of the SNPS crankshafts are shotpeened while those of the RBS crankshafts are not. FaAA addressed the effects of these differences on the

applicability to the RBS crankshafts of the $10^7$-cycle endurance test performed on a SNPS engine at a nominal load of 3300 kW. Even with the differences, FaAA found that the endurance test at SNPS provides additional assurance of the adequacy of the crankshafts at RBS.

FaAA noted that the replacement crankshafts installed in the engines at SNPS are of the same design and were made to the same material specifications as the crankshafts in the engines at RBS. The crankshafts at both installations meet the minimum requirements of ABS Grade 4 steel and have UTS values within the expected range for this material. However, the lowest UTS measurement for the RBS crankshafts is about 7% less than the lowest measurement for the SNPS crankshafts.

FaAA commented as follows on the effects of the differences:

- Based on a 7% change in stress for a 10% change in load (the linear relationship FaAA determined from torsiograph data as discussed under the preceeding subheading), a load of 3071 kW at RBS produces the same crankshaft stress as a load of 3300 kW at SNPS.
- The crankshaft fatigue limit is approximately proportional to the UTS of the material. Thus, the factor of safety in the SNPS crankshafts at 3300 kW is approximately 7% higher than in the RBS crankshafts at 3071 kW. However, this effect is small in comparison to the factor of safety in the RBS crankshafts.
- FaAA's calculations show that the highest stress in a main journal oil hole is about 7% less than the highest stress in a crankpin fillet. Thus, if shotpeening has more than a 7% effect on the crankpin fillets, the oil holes will govern crankshaft life. This effect is also small when compared to the safety margin.
- The margin between RBS crankshaft stress at 3071 kW and the S-N curve for the RBS crankshaft corresponding to the lowest UTS measurement is adequate to ensure reliable operation of the RBS crankshafts for their intended service at 3130 kW.

5.3.4.3.4 Crankshaft Inspections. FaAA reached the following conclusions from nondestructive tests of the crankshafts in the two TDI engines at RBS in July 1984:

- The eddy-current inspection of the fillets revealed no reportable indications.
- No crack-like indications were observed in the liquid penetrant inspections of the main journal and crankpin journal oil hole radii.
- All readings from the eddy-current inspection of the main journal oil holes were within the acceptance criteria.

5.3.4.4 FEV Evaluation

The crankshafts in the TDI engines at RBS were also evaluated for Gulf States Utilities Company by Dr. Franz Pischinger, president of FEV (Research Society for Energy, Technology and Internal Combustion Engines) and a professor at the University of Aachen in West Germany. His evaluation is documented in the FEV report on this subject dated June 1, 1985.

FEV used the Kritzer-Stahl method to determine the equivalent stress amplitude at the highest stressed location of the crankshaft. FEV also determined an endurance limit that incorporates the experience with crankpin fillet fatigue damage identified in the three crankshafts originally installed in the TDI DSR-48 engines at SNPS. From the equivalent stress amplitude and the endurance limit, FEV calculated a safety factor of 1.205 for the RBS crankshafts operated at 3130 kW and 450 rpm. This safety factor, according to FEV, is within the range normally considered adequate by German engine manufacturers. The known fatigue data on which this safety factor is based also enabled FEV to conclude that the safety factor is sufficient to ensure the adequacy of the crankshaft for the operating conditions just mentioned.

The FEV report noted that the stress values computed by FaAA and FEV are in excellent agreement. Differences in the values of the endurance limit and the safety factor calculated by the two organizations were attributed by FEV to the use of different S-N curves. FEV uses an S-N curve that is based on bench tests of actual crankshafts and that contains known conservative features. FaAA, according to FEV, uses an S-N curve based on laboratory data for the given material.

5.3.4.5 Additional Information from Gulf States Utilities Company

In a letter dated June 12, 1985, to NRC (H. R. Denton), GSU (J. E. Booker) provided additional information concerning the RBS crankshafts. Items addressed in attachments to the letter include the following:

- Precautions to avoid operation of the engine at the resonant speed of the 5th-order harmonic

  FaAA has concluded that the response to the 5th-order harmonic (which is in resonance at 455 rpm) is quite small, and that there are six other orders with greater magnitude (as discussed in Section 5.3.4.3.1 of this report). Furthermore, the 5th order is excited only by variations in combustion pressure from cylinder to cylinder. GSU will adopt the following operating and maintenance practices to prevent sustained operations under conditions of cylinder unbalance and overspeed:

  - A caution statement will be added to the operation and surveillance procedures for the two engines to avoid continuous operation between 453 and 457 rpm.

  - During engine operation, exhaust gas temperatures will be monitored to verify that they remain within the range of $\pm 50^{\circ}F$ of the average for all cylinders. The temperature measurements will be recorded monthly, and cylinder firing pressures will be recorded quarterly. Trend analyses will be performed to detect changes that might indicate a need for maintenance of fuel injection equipment.

  - Station Operating Procedure SOP-0053 includes the requirement to monitor and maintain generator frequency within 60 Hz $\pm$0.2 Hz.

- Nondestructive tests of crankpins

  Nondestructive examinations of crankpins No. 5, 6, and 7 of SD 1A were conducted from June 4 to June 8, 1985. The crankpin fillets and oil hole entrance regions were inspected using liquid penetrant. The crankpin oil holes were eddy-current tested. These inspections confirm there is no evidence of fatigue crack initiation after 330 hours of operation.

5.3.5 PNL Evaluation

The following PNL consultants participated in various aspects of PNL's reviews of the crankshafts for the TDI DSR-48 engines at RBS and SNPS: H. Engja (Norway), H. Hardy, A. Henriksen, P. Louzecky, Ricardo Consulting Engineers (England), the late A. Sarsten (Norway), T. Spaetgens (British Columbia), and S. Bush. Through arrangements made by Prof. Sarsten, PNL also obtained advice on DSR-48 crankshaft stresses from Det Norske Veritas, a classification society in Oslo, Norway. In addition, S. Foreman, J. Spanner, and L. VanFleet of PNL's Nondestructive Testing Section reviewed NDT procedures used to examine the crankshafts at RBS and SNPS, and witnessed crankshaft inspections at the two installations.

5.3.5.1 Review of Crankshafts for SNPS Engines

The results of the analyses, tests, and inspections of the crankshafts for the SNPS engines constitute an important part of the basis for reaching conclusions regarding the adequacy of the crankshafts for the RBS engines. PNL's review of the crankshafts used at SNPS is discussed in report No. PNL-5342 (December 1984). This review encompassed the following activities:

- independent analyses performed by PNL's consultants to provide a basis for comparison with the torsional stresses computed by the consultants for the Owners' Group and for the Long Island Lighting Company - The results of these analyses and the conclusions drawn from them were the subject of testimony before the Atomic Safety and Licensing Board that addressed contentions on the SNPS engines.
- a review of the post-test inspection of SNPS EDG 103 following the $10^7$-cycle endurance test at a nominal load of 3300 kW - This review was performed by several of PNL's diesel engine consultants and by a PNL specialist in nondestructive testing. PNL's findings on the crankshaft are documented in a report dated December 3, 1984, for the Atomic Safety and Licensing Board.

PNL's conclusions and recommendations from this review included the following:

- A torsional stress analysis performed by Prof. Sarsten using his computer program COMHOL predicts that SNPS crankshaft stresses are within DEMA Standard Practices at 3300 kW over the speed range of 5% below rated speed through 5% above rated speed, except for that portion of the speed range above 466 rpm. His predicted stresses exceeded the DEMA limit of 7000 psi by a maximum of approximately 250 psi at 473 rpm.
- The $10^7$-cycle endurance test of EDG 103 at the nominal load of 3300 kW and the absence of any rejectable indications on critical crankshaft surfaces following that test provide definitive evidence of the fatigue resistance of the SNPS crankshafts under the conditions imposed during the test.
- Certain high-stress areas of the crankshafts should be examined with liquid penetrant and, as necessary, eddy-current techniques at each power plant refueling outage, to confirm that no cracks develop in service. The frequency of the inspections could be reconsidered if warranted by the inspection results over several refueling cycles.

5.3.5.2 Review of Crankshafts for RBS Engines

PNL's review focused on the differences between the crankshaft torsional systems of the RBS engines and the SNPS engines, and the effects of these differences on RBS crankshaft stresses. PNL also reviewed records of tests performed during manufacture of the RBS crankshafts, and witnessed the inspection in June 1985 of the crankshaft in the SD 1A engine. In addition, PNL staff and consultants attended meetings on April 26 and May 20, 1985, to discuss RBS crankshaft stresses with NRC staff and with GSU staff and consultants. Specific aspects of PNL's review included:

- Torsional Stresses - As in PNL's review of the crankshafts for the SNPS engines, torsional stresses in the RBS engines were analyzed using COMHOL, a computer program developed by the late Prof. Sarsten. The agreement with FaAA's results may be illustrated by comparing the predicted stresses for both the SNPS crankshafts and the RBS crankshafts operated at 3500 kW and 450 rpm. For each installation, the results of the two approaches agree within 2%. This agreement contributes to the

assurance that FaAA's torsional analysis of the RBS crankshaft is reasonable. Furthermore, PNL concurs with FaAA that the experimental data cited in FaAA-85-5-10 (May 1985) support the linear stress-load relationship used by FaAA to calculate torsional stresses at loads below 3500 kW.

- Crankshaft Endurance Limit - As discussed in Section 5.3.4.3.2 of this report, FaAA determined the fatigue endurance limit of the RBS crankshafts from an analysis of the crankshafts that failed at SNPS, and confirmed the prediction by other fatigue data published in the literature. PNL consultant S. Bush performed an independent review of fatigue data considered pertinent to the RBS crankshafts. In particular, he reviewed a paper by Nishihara and Fukui (1976)[a] regarding fatigue testing of large-diameter, slab-forged and hot-twisted crankshafts. He concluded that the data reported in this paper confirm the endurance limit determined by FaAA.

- Factor of Safety - Dr. Bush also reviewed the dynamic strain gauge data reported by FaAA for a SNPS crankshaft, and checked FaAA's equivalent stress calculations used in determining a factor of safety for the RBS crankshafts. He concluded that the factor of safety reported by FaAA is consistent with the data.

- Crankshaft Inspection - S. Foreman of the PNL Nondestructive Testing Section witnessed the crankshaft inspection performed at RBS on June 4 through June 8, 1985. The three most highly loaded crankpins of the crankshaft in the SD 1A engine were examined by fluorescent liquid penetrant and eddy current, as discussed in Section 5.3.4.5, above. No evidence of fatigue crack initiation was found.

#### 5.3.5.3 Conclusions and Recommendations

PNL concurs that the crankshafts for the SD 1A and SD 1B engines at RBS are acceptable for their intended service at loads up to 3130 kW, subject to

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[a] Nishihara, M., and Y. Fukui. January 1976. "Fatigue Properties of Full Scale Forged and Cast Steel Crankshafts." Transactions of the Institute of Marine Engineering. Series B on Component Design for Highly Pressure-Charged Diesel Engines, London.

implementation of the operating and maintenance procedures formulated by GSU as discussed in Section 5.3.4.5 of this report, and to the additional PNL recommendations discussed later in this section. The stress and fatigue analyses documented in the FaAA report of May 1985 and the FEV report of June 1985 substantiate the adequacy of the crankshafts for operation to 3130 kW. Furthermore, the results of these analyses are supported by the extensive testing of the SNPS engines and by the absence of any evidence of fatigue crack initiation in the RBS crankshafts.

PNL recommends that the continued absence of cracking in the RBS crankshafts be verified through the nondestructive examinations listed below. If these examinations reveal nothing of significance after several refueling outages, GSU may wish to propose a change in the frequency of the examinations to NRC.

- During the first refueling outage, the fillets and oil holes of the three crankpin journals (Nos. 5, 6, and 7) subject to the highest stresses in the crankshaft of the SD 1B engine should be examined with fluorescent liquid penetrant and, as appropriate, with eddy current. These examinations are not considered necessary for the SD 1A crankshaft at the first refueling outage because of the examinations just performed on that crankshaft in June 1985.
- In subsequent refueling outages, the crankshaft examinations recommended in Section 6.1.2.1 of this report should be performed.

## 5.4 IDLER GEAR

Part No. 03-355B

### 5.4.1 Component Function

The primary function of the idler gear is to transmit torque from the crankshaft to the camshaft.

### 5.4.2 Component Problem History

No industry or site experience of failures of this component is on record.

#### 5.4.3 Owners' Group Status

As a result of the Owners' Group DR/QR reviews, the importance of maintaining the prescribed torque on the idler gear-to-hub bolt has been emphasized.

#### 5.4.4 GSU Status

To guard against the potential for torque relaxation, GSU has installed new idler gear cap lock pins as recommended by the manufacturer.

#### 5.4.5 PNL Evaluation and Conclusion

Failure to maintain the prescribed torque on various fasteners has been cited as the cause of failure for a number of parts on all types of mechanical equipment. PNL concludes that GSU's change to improve the lock nut and pin arrangement will add to the RBS engines' reliability.

The Owners' Group recommendation in the DR/QR component design review checklist for River Bend to clean idler gear and hub mating surfaces should be incorporated into the River Bend M/S procedures, if not already done so. GSU should also resolve the discrepancy between the torque specifications (70 ± 20 ft-lb or 80 ± 20 ft-lb) as listed in the River Bend DR/QR report. GSU should perform a visual inspection of the idler gear on SD 1A prior to fuel loading.

### 5.5 CONNECTING RODS

Part No. 03-340A

Owners' Group Report FaAA-84-3-13

#### 5.5.1 Component Function

The primary function of the connecting rod is to transmit the engine cylinder firing force from the pistons and piston pin to the crankshaft such that the reciprocating motion of the pistons induces rotation and output torque of the crankshaft. The connecting rod must have sufficient column buckling strength and fatigue resistance to withstand the cylinder firing forces and inertial loads. The wrist pin bushing (or rod-eye bushing) and the crankpin bearings are contained by the connecting rod. The flexure of the rod must be such that the bearings are not unacceptably distorted. The passages within the rod must remain unblocked to provide flow of lubricant to the

bearings and pistons. Sufficient clamping force must be maintained by the bolts on the connecting rod cap to prevent relative motion of the components. The rod cap bolts must support the necessary preload without yielding, fracture, or unacceptable thread distortion. The wrist pin bushing must support the cylinder firing forces and inertial forces.

### 5.5.2 Component Problem History

Only one inservice failure of connecting rods in TDI DSR-48 series engines has been reported. This failure consisted of a longitudinal split through the oil hole in a DSR-46 engine at Glennallen, Alaska (Copper Valley Electric Corporation). Reportedly, this crack was initiated from fatigue. The failure report supplied by TDI did not identify the origin of the crack; however, no material abnormalities were reported. This engine had operated for over 8000 hours and, for part of that time, at much higher peak firing pressures (1975 psi) than those anticipated for TDI engines in nuclear service.

Linear indications were found by liquid penetrant testing on all SNPS rod-eye bushings. These indications were on both the inside and outside diameter of the bushings. The linear indications were determined to be casting defects and the result of interdendritic shrinkage or porosity. No service-induced fatigue extension of the casting defects was observed.

### 5.5.3 Owners' Group Status

The adequacy of the TDI inline connecting rods was addressed by FaAA for the Owners' Group. The objectives of their efforts were to assess the structural integrity of connecting rods in TDI model DSR-48 engines in standby emergency diesel generator sets at Shoreham, River Bend, and Rancho Seco nuclear power stations, and to determine the connecting rods' suitability to perform their required function.

The Owners' Group evaluation considered four major parts of the inline connecting rod assembly: the rod-eye bushing, the rod eye, the connecting rod bearing housing and cap, and the connecting rod itself. The rod-eye bushing, which is of the same design as that in the V engines, was analyzed because linear indications have been found in some bronze bushings during field

inspections. Journal orbit analyses, metallurgical evaluations, and stress and fracture mechanics analyses were performed. The rod-eye end of the connecting rods was evaluated by stress and fracture mechanics analyses, which included assumed surface flaws. The connecting rod bearing housing and cap were evaluated by stress and fatigue analyses. The connecting rod itself was analyzed for buckling stability.

The crankpin bearing cap is attached to the connecting rod with four bolts. Prestressing of these bolts creates compressive stresses in the connecting rod itself and tensile stresses in the bolts. The two extreme loading conditions, firing stroke and exhaust stroke, were considered. The stresses in the bolts and connecting rods were determined for the two load cases, and the fatigue crack propagation in the bolts was investigated because they were the most critically stressed component. A critical crack depth of 0.133 inch was determined at the thread root. While cracks in the root of the bolt threads are not permitted, the analysis showed that a crack as large as the critical crack could be tolerated and would not propagate. Fatigue was determined not to be a problem.

The buckling stability of the connecting rod was assessed under the maximum cylinder firing pressure. Factors of safety of 6.28 for yielding and of 5.72 against lateral buckling of the connecting rod were determined.

Wrist pin bearing performance was analyzed using a journal orbit analysis computer program. The oil pressure profiles imposed on the rod-eye bushing under piston firing and inertial loads were determined. A peak oil film pressure of 97,400 psi was predicted to occur at the bottom of the bushing due to power stroke. A peak oil film pressure of 5000 psi[a] was also predicted by FaAA to occur at the top of the bushing due to the inertial effects of the exhaust stroke. These two cases provided input to a rod-eye bushing stress analysis.

The calculated circumferential stresses and the oil film pressures were used as input to a fracture mechanics analysis. This fracture mechanics model

(a) The FaAA value reported in FaAA-84-3-13, page 2-4, was 500 psi. This was corrected by G. Derbalin (LILCO) in a telephone conversation with D. Dingee (PNL) on December 9, 1984.

indicated that bushing defects would not propagate if they originate on the outside diameter. This analysis also showed that cracks could grow only if the crack surfaces were subjected to peak oil film pressure, which occurs only within 15 degrees of the bottom dead center of the rod eye. Even if inside diameter defects are within ±15 degrees of the bottom center, they are predicted not to propagate unless the crack faces are exposed to the full range of oil film pressure. Because of the compressive hoop stress in the bushing, it was considered unlikely that the crack faces would separate and allow oil pressure to be exerted. However, the OG suggested that bushings containing linear indications in the lower 30-degree segment be replaced.

In conjunction with the rod-eye bushing stress analysis, the rod eye itself was analyzed with the same finite element and curved beam models and for the same load cases. The stress range calculated was below the fatigue initiation stress range for the rod material. Because of the possibility of pre-existing defects, as in the case of the Glennallen failure, the threshold crack size for fatigue was estimated by a fracture mechanics analysis using conservative values for the threshold range of stress intensity factor. A 0.043-inch deep flaw was determined to be the critical crack depth for the maximum tensile stress range (calculated) for load case 1. For load case 2, the maximum critical crack depth of 0.04 inch at the rod eye was determined.

The Owners' Group could find no conclusive explanation for the one reported rod eye fatigue failure. However, fracture mechanics analyses indicate that fatigue cracks could propagate from a 0.04-inch deep surface discontinuity at the intersection of the oil hole with the bore of the rod eye. Such discontinuities on the smoothly polished surfaces were judged to be readily apparent on visual examination.

Based on their evaluations, the Owners' Group concluded that the inline DSR-48 connnecting rod is adequate for its intended purpose, provided that there are no bushing defects in the region within ± 15 degrees of the bottom dead center of the bushing.

### 5.5.4 GSU Status

A number of tests, inspections, and NDEs were conducted on the connecting rods at RBS during the preservice inspection and the DR/QR program. Those

reported by GSU for both SD 1A and 1B include:

- an LP inspection of all wrist pin bushing inside diameter surfaces - No indications or surface flaws were found.
- a visual inspection of all upper connecting rod bushing oil passages (without removal of bushing) - No surface flaws were found.
- eddy-current inspection on all connecting rod oil holes - No relevant indications or cracks were found.

Those reported by GSU for SD 1A included:

- material comparator tests on rods No. 1, 2, and 3 - Results were satisfactory.
- superficial hardness tests on rods No. 2, 3, and 8 - The results were satisfactory.

The Owners' Group DR/QR program for the subject components did not include a design review because all Emergency Diesel Generator Component Tracking System (EDGCTS) experience had already been addressed, and the acceptability of the DSR-48 connecting rods was established by the Shoreham DR/QR. However, the Owners' Group did recommend that GSU verify that the torque preload on all connecting rod bolts is in accordance with TDI's latest recommended values. In the Shoreham DR/QR report, the Owners' Group concluded that the connecting rod assembly is acceptable for its intended purpose.

### 5.5.5 PNL Evaluation and Conclusion

The PNL reviewers evaluated the Owners' Group report and supplementary information on inline connecting rods. They found that the Owners' Group had examined the appropriate significant failure modes (namely, cracks in the rod-eye bushing; fatigue in the rod eye itself; fatigue and possible pretension loss in the connecting rod bolts; insufficient stiffness and buckling of the connecting rod; and undersized oil cooling holes and paths). The bounding load cases of exhaust stroke inertial loads and firing pressure loads were correctly used in the analyses. The analytical methods used were judged to be appropriate.

PNL also reviewed the inspections performed by GSU. Based on these reviews and the evaluations of component-specific information from the Owners' Group, PNL concludes that the connecting rods and bushings installed in the River Bend engines are acceptable for the intended service. However, GSU should verify that the preload torque on all connecting rod bolts is in accordance with TDI recommendations.

### 5.6 CONNECTING ROD BEARING SHELLS

Part No. 03-340B
Owners' Group Report FaAA-84-3-1

#### 5.6.1 Component Function

The connecting rod bearings interface the connecting rods with the crankshaft. They are of cast aluminum alloy with a thin babbitt overlay, and are furnished in two identical halves. They are lubricated under pressure, and a substantial flow of oil proceeds through machined channels in the shells from the drilled crankshaft oil holes to the passageways within the connecting rods and on to the pistons and intervening bearing surfaces. The upper bearing half is subject to the piston firing loads and is therefore more susceptible to failure.

Failure can occur through inadequate oil flow or pressure, excessive or unplanned loadings, structural anomalies (from design or manufacture), or fatigue and erosion of the babbitt layer in crucial areas. Bearings are also subject to particle, chemical, or water contamination of the oil, or improper oil selection, either of which can lead to degradation and failure. The failure mechanism usually is gradual, and its onset generally can be detected by prudent surveillance of oil and filter conditions. However, a substantial structural problem, excessive cylinder loads, or heavy contamination of the oil with water can lead to rapid failure. This can affect the crankshaft journals, sometimes with irreparable results.

In light of the severe conditions affecting bearings, the need for replacement is not uncommon. However, in customary service, bearing life

generally is measured in multiples of $10^4$ hours, given reasonable service conditions.

### 5.6.2 Component Problem History

Five incidents of cracking in the SNPS EDG connecting rod bearing shells have been reported. All but one occurred during operation with the original 11-inch crankshafts and were discovered during disassembly after the crankshaft failure on EDG 102. A number of bearings, other than the cracked ones, also have been replaced because of inservice conditions or nonconformance with the Owners' Group criterion for subsurface voids. No other connecting rod bearing shell incidents have been reported on any DSR-4 engines.

### 5.6.3 Owners' Group Status

Failure Analysis Associates analyzed the connecting rod bearing shells for the Owners' Group. The analyses, which encompassed both 11-inch and 12-inch diameter shells, included:

- journal orbit analysis to determine the pressure distribution in the hydrodynamic oil film
- finite element analysis to determine the stress distribution in the connecting rod bearing shell
- fracture mechanics analysis to determine the resistance to fatigue cracking
- computation of acceptance criteria using radiographic NDE
- evaluation of babbitt adhesion.

Based on their analyses, FaAA concluded that the cracking of the four 11-inch diameter bearing shells was due to bearing shell overhang causing undue bending stresses. They attributed the crack in the 12-inch bearing shell to excessive voids in the subsurface of the bearing shell in the area of the crack. The overall conclusion was that, provided they conform to the manufacturer's specifications and meet the criterion for subsurface voids developed by FaAA, the bearings are suitable for the intended service.

5.6.4 GSU Status

Following recommendations and instructions issued by FaAA and approved by the Owners' Group, GSU performed various examinations on all 16 bearing shells plus the spares for each engine, as follows:

- All 40 bearing shells were visually inspected. Only minor pitting and scratches were noted, and the shells were considered to be satisfactory in this respect.
- All 40 bearing shells were dimensionally checked. Dimensions were found to be in accordance with TDI specifications.
- All 40 bearing shells were subjected to LP inspection. No indications were evident.
- Radiographic tests were performed on all upper and lower connecting rod bearing shells. The disposition of bearing shells was as follows:
  - Six of the 16 shells from Engine 1A were rejected.
  - One of the 16 shells of Engine 1B was rejected.
  - All 8 spare shells were satisfactory.
- After the radiographic inspection, the 33 remaining shells were subjected to an eddy-current inspection. No relevant indications were evident.
- Of the 33 shells found acceptable, 6 bearing shells were dispositioned as suitable for use as lower shells and 27 halves were determined suitable for either lower or upper service.

Based on the review of the bearing shells, the Owners' Group recommended certain maintenance procedures based on the Shoreham DR/QR report as follows:

- Inspect and measure the connecting rod bearing shells to verify lube oil maintenance, which affects wear rate. The visual and dimensional inspection of the bearing shells should be conducted at the fuel outage that precedes 500 hours of operation by at least the sum of hours of operation in a LOOP/LOCA event plus the expected hours of operation between outages.
- Perform an x-ray examination on all replacement bearing shells using a procedure with sufficient resolution to implement recommendations for

acceptance criteria as documented in the Owners' Group connecting rod bearing shell report (FaAA-84-3-1).

The Owners' Group DR/QR effort for RBS did not include a design review of the bearing shells for two reasons. The DR/QR efforts on Shoreham and Comanche Peak were considered to have established the acceptability of bearing shells, and the River Bend engines and operating parameters are essentially the same as those at Shoreham. The Owners' Group concluded in the Shoreham DR/QR that the connecting rod bearing shells are acceptable for the intended design purpose.

### 5.6.5 PNL Evaluation and Conclusion

Based on review of the FaAA analyses and GSU and Owners' Group inspection reports, as well as a number of visual inspections conducted by PNL consultants on the subject bearings, PNL concludes that the connecting rod bearing shells at River Bend Station are acceptable for the intended service, subject to the M/S activities noted in Section 6.0. In addition to the x-ray examination of replacement bearing shells, PNL recommends that a liquid penetrant test be conducted on each replacement bearing prior to its installation.

## 5.7 PISTON SKIRTS

Part No. 03-341A

Owners' Group Reports FaAA-84-2-14 and FaAA-84-10-30

### 5.7.1 Component Function

The piston assembly (including the piston crown, piston skirt, rings, piston pin, and associated hardware) receives the thrust of inertia and combustion and transfers these loads to the connecting rod. The cast steel crown is subject to the direct combustion pressure and thermal conditions. The skirt, made of ductile iron, actually transfers the load to the piston pin/connecting rod and guides the reciprocating motion of the piston within the cylinder. Such a two-piece piston structure is relatively common to large, modern, high-output engines.

In general, failure is most apt to result from excessive pressure and thermal stresses of both high-cycle and low-cycle character. Durability is affected by material selection, fabrication quality, and design characteristics. A crown separation from the skirt will require immediate shutdown; it is likely to lead quickly to serious cylinder, head, and rod damage, and to piston seizure, with adverse impact on the crankshaft and possible crankcase explosion. Hence, adequate attachment of crown to skirt is necessary.

### 5.7.2 Component Problem History

TDI has utilized several skirt designs, including types AH, AN, AE, and modified type AF, in their R-4 series engine. Most early engines for nuclear service were furnished with type AF and AH skirts, although the engines in at least three facilities contained AN skirts. The RBS engines were originally furnished with type AN piston skirts.

The original two-piece piston skirt was designated type AB. Some changes were made to alter stud height; this version was labeled type AF. The spherical washers used in types AB and AF presented problems. Consequently, machining modifications were made so stacks of Belleville washers could be used (AB/AF modified). This resulted in cracks in ligaments at stud base areas. The next version, the type AH, used Belleville washers similar to previous designs. Machining modifications were made for oil control purposes, thereby leading to the type AN piston skirt. TDI incorporated fan cooling in the fabrication of the skirt coating to increase hardness values, changed the shape of the oil cavity, increased stud boss thickness, and reinstituted stress relief/temper at 1000°F which had been dropped previously in types AN-II and AN-III piston skirts. The type AE skirt was introduced to alleviate problems with the type AN skirt. It was strengthened with a tapered circumferential rib. It also retained increased stud boss thickness with a single stack of Belleville washers, fan cooling, and stress relief/temper.

Prior to their use at Shoreham, one of the primary sources of experience with the type AE piston skirt was the experimental TDI R-5 engine. In this engine, the type AE piston skirts were observed to contain no cracks, even after operating for 622 hours at a peak firing pressure of approximately 2000 psi.

5.7.3 Owners' Group Status

The Owners' Group experimentally and analytically evaluated both the type AF and type AE piston skirts. The Owners' Group first evaluated the cracked type AF skirts to assess the nature of the problem. This evaluation revealed that the observed cracking was the result of fatigue. Subsequently, both skirt types were experimentally tested for stress in a static hydraulic test, and these stresses were evaluated by finite element analysis of the skirt only. Then, the thermal stresses in the piston crown were evaluated by finite element analysis, and their effect on the stresses in the skirt determined. Finally, a fatigue and fracture analysis was performed.

It was concluded that the type AF skirts would crack in service at TDI nameplate rating (225 psig BMEP), but the cracks would not grow once they move out of the highly stressed region near the boss. For type AE skirts, the analysis indicated that cracks may initiate at high loads but will not grow. On these bases, the Owners' Group concluded that the modified type AF skirts are adequate for service, provided that they are 100% inspected for cracks in the stud boss area prior to use and that they are inspected periodically. Recommendations for operating load levels and inspection intervals were to be made on a plant-by-plant basis. The Owners' Group concluded further that the type AE piston skirts are adequate for unlimited life.

The Owners' Group also performed investigations on types AH and AN piston skirts. The integrity of AH and AN piston skirts was assessed by testing and analysis, studying the design and fabrication evolution of TDI piston skirts, and reviewing field experience. The results of the testing and analysis led to the conclusion that cracks may initiate in the AN and AH skirts under certain conditions, but such possible cracks will not grow in the absence of significant residual stresses. All AH skirts are subjected to a heat treatment that is not expected to induce significant residual stresses, whereas some AN skirts were heat treated by a process that could induce significant residual stresses. Performance history revealed no AH piston-related problems after tens of thousands of hours on several engines. However, many problems with AN piston skirts were in evidence.

The combination of experiments, analyses, and field experience provided the Owners' Group with adequate data to approve use of the type AH piston skirt for service in EDGs for nuclear plants. The Owners' Group also concluded that the type AN skirts are not suitable for the extreme reliability requirements associated with emergency standby power sources at nuclear plants.

5.7.4 GSU Status

GSU has replaced all of the originally supplied type AN piston skirts with type AE skirts. The AE skirt includes design changes such as thickening the stud boss region and more smoothly blending the thickened rib into the wrist pin bosses.

A review of piston skirts was included as a part of the Owners' Group DR/QR effort as well as in GSU preservice inspections and examinations. This review included the following inspections and examinations:

- Performed LP inspection of replacement AE piston skirts in the stud and pin boss areas. No indications were evident.
- Performed visual inspection of AE skirts outside diameter for scuffing and inside surfaces for pitting on SD 1B. No defects were observed.
- Performed visual inspection of SD 1A skirts and crowns outside diameter for scuffing and pitting. No defects were observed.

The Owners' Group DR/QR efforts at RBS did not include a design review of the piston skirts because they considered all applicable items had been covered in the either Shoreham/Comanche Peak DR/QR reports or the Phase 1 report on pistons. However, additional inspections on pistons were recommended for GSU's performance. In the Shoreham DR/QR, the Owners' Group concluded that type AE piston skirts were acceptable for the intended design function.

5.7.5 PNL Evaluation and Conclusions

PNL's evaluation of the GSU piston skirts is limited to the type AE pistons, because this is the piston skirt type currently installed in the engines.

The primary conclusion of the Owners' Group analysis of the type AE piston skirts was that cracks may initiate but will not grow. PNL reviewed this analysis and found the stress field in the region of the stud bosses so complex that it was difficult to conclude from such analyses with any degree of certainty whether cracks would initiate or not, and, if they did initiate, whether they would grow or not. However, available operating experience appears to support the conclusion that this piston skirt type is suitable for its intended function.

This operating experience was obtained from both the TDI R-5 test engine and from the SNPS EDG 103 confirmatory test. In the R-5 engine, two type AE piston skirts were installed and the engines tested for 622 hours at 514 rpm and a peak firing pressure of 2000 psi, at least 20% higher than that expected at Shoreham or River Bend. The type AE piston skirts used in this test were not quite identical to the type AE skirts used at Shoreham. However, they were sufficiently comparable to conservatively extrapolate the results to the Shoreham engines. Therefore, this R-5 test engine experience gives considerable confidence that the type AE skirt design is adequate. The other experience was obtained in SNPS EDG 103 during the 746-hour endurance test at 3300 kW. This test subjected the piston skirts to in excess of $10^7$ stress cycles; subsequent nondestructive testing revealed no apparent crack initiation. The successful completion of this test without occurrence of apparent fatigue of the piston skirts provides considerable confidence in the suitability of the skirt design for the intended function.

PNL also visually inspected all Shoreham piston skirts following the 746-hour test on EDG 103. Based on 1) the PNL examination of AE piston skirts, 2) the suitability of the AE design as demonstrated by the above-described experience, 3) the current serviceability of the piston skirts now installed in the Shoreham engines, and 4) the NDT inspection of the AE piston skirts at RBS, PNL concluded that the type AE piston skirts in the RBS SDs are acceptable for the intended service.

In the River Bend DR/QR report, the Owners' Group has recommended that liquid penetrant tests be performed on the rib area near the wrist pin, as well as on the rib at the intersection of the wrist pin boss for all of the piston skirts from at least one engine. They stipulated that this could be

done during the next major engine overhaul or the first time the pistons are removed. PNL agrees with the Owners' Group that the tests can be delayed until the first major engine overhaul or when the pistons become available prior thereto.

## 5.8 PISTON RINGS

Part No. 03-341B

### 5.8.1 Component Function

The piston rings seal the combustion chamber from the crankcase, allow heat flow between piston and cylinder liner, and control lube oil consumption and combustion gas blowby.

### 5.8.2 Component Status

GSU has replaced the piston rings originally installed on the RBS engines with those manufactured by Muskegon Piston Rings. The Muskegon design reduces the likelihood of cylinder liner scuffing during break-in. On October 16, 1984, GSU reported that the new Muskegon rings for SD 1A had been visually inspected with satisfactory results. GSU also verified that their installation was in compliance with the TDI manual. For SD 1B, the satisfactory results of the visual inspection and verification of proper installation were reported by GSU on December 12, 1984.

### 5.8.3 PNL Evaluation and Conclusion

After considering test and inspection results on Muskegon piston rings at Shoreham, PNL concludes that GSU's change to this type of ring will add to the serviceability of the SDs at RBS.

## 5.9 PISTON PIN ASSEMBLY

Part No. 03-341C

### 5.9.1 Component Function

The piston pin transmits the loads generated by cylinder firing pressures from the piston to the connecting rod, while permitting relative motion between these latter two components.

### 5.9.2 Component Status

Due to the presence of unsatisfactory surface defects, seven piston pins from SD 1A and 1B were replaced at RBS. To increase component reliability, the Owners' Group recommended replacing the piston pin spiral lock ring retainers with Waldes snap ring retainers. GSU has implemented this change of the retainer rings.

### 5.9.3 PNL Evaluation and Conclusion

PNL reviewers observed the defects in the piston pins during their site visit, and concur with GSU's action to replace them. In PNL's opinion, the change in retainer rings should enhance the performance of the piston pins.

## 5.10 CYLINDER LINERS

Part No. 03-315C

Owners' Group Report FaAA-84-5-4

### 5.10.1 Component Function

Engines of this size and character are designed with individual, removable cylinder liners, which fit inside the cylinder block. The liners contain the pistons and are capped at the upper end by the cylinder head. Thus, they act as containment for the firing forces, are subject to the stress and heat thereof, and guide the reciprocating travel of the pistons. The outer surfaces are cooled by jacket water circulating within the block. The lower end is sealed against an opening in the block with O-rings. The upper end has an external, circumferential ledge, which seats on the block's "liner landing." The head is gasketed and bolted in compression against the upper liner annulus, to seal in the high-pressure combustion gases. The liner is of nodular iron, selected for its strength, castability, and durability against the rubbing action of the pistons and rings.

Liners generally do not fail, but they can be adversely affected by inadequate or inappropriate lubrication, the forces and heat of the combustion processes, the character of the pistons and rings, and the quality of fuels and oils. Failure most often is in the form of scoring by broken rings or carbon deposits, or "scuffing" by the action of the piston on the cylinder

walls, due to one or more of the factors mentioned. If such conditions are severe enough, a piston will seize and cause significant damage to liner and connecting rod, and even to the crankshaft. A crankcase explosion can result.

5.10.2 Component Problem History

Only one incident of cylinder liner failure in nuclear service of TDI diesel engines is known. This failure occurred in 1982 at Grand Gulf when a piston crown separated from the skirt during testing of the Division II engine and marred the liner.

5.10.3 Owners' Group Status

The Owners' Group included considerations of liners in their study of cylinder blocks. Two concerns were uncovered:

- The TDI design calls for the liner to protrude slightly above the top deck of the block, to ensure a tight, compressive fit against the head and gasket. However, this produces bending moments in the head and substantial shear stresses on the cast iron liner landing of the block. Both aspects are suspect in some of the real or incipient failures in those components. TDI has approved remachining to reduce the protrusion, termed "proudness".
- The design also calls for a tight fit between the outer ring of the liner ledge and the matching counterbore of the block. There is some concern by the Owners' Group that this could increase hoop stresses in the block, which might lead to block cracks. TDI has approved reducing this fit in the cylinder liner.

5.10.4 GSU Status

As part of GSU's preservice activities and the Owners' Group DR/QR program, various efforts have been conducted on cylinder liners at RBS. These include the following:

- Measured bore, length, height, outside diameters, and shoulder height on each liner.

- Performed visual inspections of inside diameter, and top outside diameter in contact with cylinder block on all liners.
- One liner with a chipped surface was removed from service.
- Two liners found to be out-of-round were reworked back to within specifications and reinstalled in SD 1B.
- Machined "proudness" thickness or height of liners as required to reduce the protrusion above the cylinder block to 0.000 to 0.003 inch.
- Machined the outside diameter of liner top flanges as required to reduce liner-to-block counterbore interference fit and stresses.
- After machining, a dimensional check was made on bore, length, outside diameter and shoulder height on all liners.
- All liners were deglazed by crosshatched honing with a Sunnen hone.
- After honing, a visual inspection was made over the zone of piston travel for all liners.
- Performed a visual inspection on the outside flange diameter of all liners.
- Performed a material comparator test on a spare liner.

The RBS DR/QR effort did not include a design review of this component, as all applicable EDGCTS experience had been considered in lead engine DR/QR reports (Shoreham/Comanche Peak). In both of these reports, the Owners' Group concluded the cylinder liners were acceptable for their intended use.

5.10.5 PNL Evaluation and Conclusion

At Shoreham, PNL representatives viewed cylinder liners during at least three site visits. The liners that had been in service were glazed and showed some hard rubbing spots. This appearance was considered to be typical of the TDI liners.

PNL representatives also had the opportunity to visually inspect liners removed from the Catawba engines after extended operation. Most showed minor scuffing, which was considered to be the result of normal wear and acceptable for additional service.

PNL representatives viewed the liners from River Bend's 1B engine during a plant visit. Two of these had some evidence of minor scuffing (streaking).

PNL concludes that the liners in the River Bend SDs are acceptable for their intended service. This conclusion is based upon:

- a review of GSU's actions for both SDs with respect to inspection, remachining, and replacement (as needed)
- PNL's examination of the liners at Shoreham and Catawba after many hours of testing
- the very good general service record for these components.

## 5.11 CYLINDER HEADS

Part No. 03-360A
Owners' Group Report FaAA-84-15-12

### 5.11.1 Component Function

The cylinder heads cap the cylinders and, with the cylinder liners, provide the enclosure needed to direct the combustion forces against the pistons. In the TDI engine design, each cylinder uses a separate cylinder head assembly. The bottom surface of the cylinder head, facing the piston, is called the firedeck. There is also a top deck to enclose the internal water cooling passages, and an intermediate deck that provides structural rigidity to the assembly. The cylinder head assembly contains two inlet valves, two exhaust valves, a fuel injector, an air starting valve, and a test cock.

Each head is bolted to the cylinder block by means of eight studs extending through the head from the block. On top of the cylinder heads are two more components: the subcover or rocker box, which supports the valve actuating mechanism, and a top cover.

The TDI DSR-4 heads are cast from an alloy steel. The casting cores that produce the complex system of internal water, air and exhaust gas passages are large and are difficult to hold in place during the casting process. They can

shift during manufacture, causing uneven and/or incomplete sections, and can lead to a variety of flaws or indications, some of which can be repaired during subsequent manufacturing processes.

Cylinder head deficiencies that have been experienced have tended to be mostly superficial linear indications with inconsequential results. However, some deficiencies have led to warpage or cracks. The latter, if through to the jacket water passages, can result in the leakage of water into the affected cylinder when the engine is inoperative, and the introduction of combustion gases into the cooling jackets during operation. If an attempt is made to start an engine with water present in one or more cylinders, severe structural damage can result.

5.11.2 Component Problem History

Numerous failures of TDI cast steel cylinder heads have been reported in both nuclear and non-nuclear applications. For identification, the Owners' Group has categorized TDI cylinder heads into three groups. Group I heads include all those cast prior to October 1978. Group II heads were cast between October 1978 and September 1980. Group III heads were cast after September 1980. The distinction among groups involves both design changes to facilitate better casting control and improvements in quality control. Most instances of cracked heads have involved Group I heads. Only five instances of cracks resulting in water leaks have been reported in heads of Groups II and III, and these have all been in marine applications. Most of these cracks were observed to have originated at the stellite-faced valve seats.

The most recently reported head failure of a TDI nuclear EDG occurred at Mississippi Power & Light (MP&L) Company's Grand Gulf Nuclear Station. A 2-inch through-wall crack occurred in the right exhaust port casting surface between the valve seat area and the exhaust valve guide in their Division I diesel engine. This crack allowed water from the cooling jacket to enter a cylinder; the presence of this water was detected during the "barring-over" of the engine with the cylinder cocks open. The specific head group classification of this head was not reported. However, the affected head was supplied

with the engine and had undergone 1500 hours of operation, including 335 hours at 100% load (7000 kW, 225 BMEP) and 31 hours at 110% load.

5.11.3 Owners' Group Status

Failure Analysis Associates performed mechanical and thermal stress calculations for the Owners' Group to determine if these heads are suitable for the intended service. The results indicated that heads from all three groups would be suitable. However, FaAA recommended that Group I and II heads be inspected for cracks using liquid penetrant and magnetic particle testing. They also recommended that the firedeck thickness be determined by ultrasonic testing. For Group III heads, sample inspection as described for Groups I and II was recommended. For all three groups, FaAA recommended that the engine be rolled over before planned starts with the cylinder cocks open, to ensure that no water had leaked into the cylinders.

5.11.4 GSU Status

During GSU's preservice activities and the Owners' Group DR/QR program, the cylinder heads at RBS were subjected to a variety of checks and inspections:

- Prior to engine operation at RBS, all of the heads from both SDs were removed. Liquid penetrant inspections were performed on the exhaust and intake valve seating surfaces for all heads (64 surfaces). Four of the sixteen original heads were rejected due to observed cracks in the valve seating surfaces. Firedeck thickness was measured ultrasonically. All heads were found to be substandard and were replaced with new cylinder heads. All replacements are Group III heads, inspected in accordance with Owners' Group criteria. All have a firedeck thickness greater than 0.500 inch between valve seats.
- Magnetic particle inspections were performed outside the valve seat areas on the firing decks of the 32 replacement heads. No indications of weld repairs were noted.

Based on a review of the Phase 1 report and lead engine DR/QR reports, the Owners' Group concluded that a design review was not required for cylinder heads at RBS. Both lead engine DR/QR reports (Shoreham/Comanche Peak) included the Owners' Group conclusion that the cylinder heads are acceptable for their intended function.

5.11.5 PNL Evaluation and Conclusions

PNL reviewed the FaAA mechanical and stress analyses of the TDI cylinder heads, the service history of the Group III heads currently in nuclear service, and the results of the nondestructive tests performed as part of the component revalidation program and following the 746-hour confirmatory tests of Shoreham's EDG 103. PNL concluded that the cylinder heads currently installed on the two River Bend engines are acceptable for the intended service, provided that the engine is air-rolled at appropriate intervals with open cylinder cocks after and before planned operation to verify the absence of cracks that may allow water leakage into the cylinder. PNL recommends that this procedure be performed 4 to 8 hours, and again 24 hours, after any operation and prior to any planned start. If leakage is indicated by the ejection of water or vapor from any of the open cylinder cocks during air-rolling, the affected head should be removed, inspected, and replaced, if defective.

5.12 CYLINDER HEAD STUDS

Part No. 03-315E

Owners' Group Report Emergency Diesel Generator Cylinder Head Stud Stress Analysis (SWEC March 1984)

5.12.1 Component Function

Eight studs per cylinder are used to bolt the heads to the cylinder block. Together they transmit the firing load from the head to the block and provide a required preload on the cylinder head gasket.

Head bolts are not normally found to yield or break; however, these occurrences are possible, due to faulty design, materials, or fabrication, or

excessive firing pressure. Fatigue failure is a greater concern, given reasonable operating conditions. This will occur if preload is insufficient and the bolts go through many cycles of loading. Once a bolt yields or breaks, its neighbors must carry increased burden, and the head is unevenly stressed. This generally results in escaping combustion gases, with the attendant hazards of heat and fire, as well as physical and metallurgical damage to head and block.

5.12.2 Component Problem History

To date, no cylinder head stud failure has been reported in the nuclear industry. However, some isolated failures have been reported in the non-nuclear field. The cause has not been established.

TDI has employed two stud designs. One is of constant shank diameter, and there has been concern that its tight fit within the block stud opening, coupled with inadequate preload, could put side thrusts on the block and contribute to block fractures. The second design uses a necked-down shank. This design is relatively more flexible due to the higher spring rate inherent in the design.

5.12.3 Owners' Group Status

Stone & Webster Engineering Corporation has analyzed both stud designs and concluded that both are adequate for the service intended, provided that proper stud preload is applied.

5.12.4 GSU Status

The River Bend engines are equipped with cylinder head studs of the necked-down design. In accordance with the latest TDI and Owners' Group recommendations, the bottom two threads were machined off these studs. As a result, the stud threads are placed deeper into the cylinder block; this placement should help distribute the stud load.

A random sample of studs from each engine was visually inspected for signs of distress. Two of the 32 studs from SD 1A showed nicked threads; these were cleaned up. The other studs from both engines were considered satisfactory in their in-situ condition.

A hardness test and material comparator tests were performed on four studs from SD 1A. The results were satisfactory.

Upon installation, the studs in each engine's block were torqued, and the torque was verified.

5.12.5 PNL Evaluation and Conclusion

PNL concludes that the modified studs now installed on the River Bend SDs will be acceptable for the intended service. This conclusion is based on the following findings resulting from PNL's evaluation:

- The SWEC analysis has demonstrated that the stud design is adequate.
- No failures of cylinder head studs have occurred in TDI engines in nuclear service to date.
- GSU's action of inspecting and torquing the studs is deemed acceptable.

5.13 PUSH RODS

Part Nos. 03-390C & D

Owners' Group Report FaAA-84-3-17

5.13.1 Component Function

Push rods transmit the cam action from the camshaft on the engine side to the intake and exhaust valves in the head. One main rod extends from the camshaft to the subcover where it acts directly on the intake valve rocker lever. The second main rod transfers cam action to an intermediate rocker in the subcover and on through an intermediate (connector) push rod to the exhaust valve rocker arms. The push rods are subject to high-acceleration compressive forces and cylinder pressures on the valves as they respond to the cams. Fundamentally, these are steel tubes with rounded ends, to fit the various mating sockets.

A push rod failure would, at the least, reduce valve action and, thus, cylinder performance. Total inoperability of a cylinder could result, but would not necessarily lead to immediate engine shutdown. Because these

components are always in compression, failure modes are limited, assuming reasonably good design.

### 5.13.2 Component Problem History

TDI push rods originally had tubular steel bodies fitted with forged and hardened steel end pieces, attached by plug welds. An estimated 2% of these push rods reportedly developed cracks in or around the plug welds. A ball-end push rod design introduced later consisted of a tubular steel body with a high-carbon steel ball fillet-welded to each end. This design also proved to be prone to cracking at the weld. A third design, consisting of a tubular steel body friction-welded on each end to a forged plug having a machined, hemispherical shape, was then introduced. This third configuration is referred to as the friction-welded design.

### 5.13.3 Owners' Group Status

Because industry (both nuclear and non-nuclear) had expressed concern about the continued integrity of TDI push rods, the Owners' Group included the component in the known generic problem category for specific study and resolution. Failure Analysis Associates performed stress analyses as well as stress tests to $10^7$ cycles on samples of both the plug-welded and the friction-welded push rods, at conditions simulating full engine nameplate loading. No sign of abnormal wear or deterioration of the welded joints or ends was observed. Nuclear owners have run these versions in actual service beyond $10^7$ cycles with no adverse results.

FaAA concluded from their analyses and tests that both the plug-welded and friction-welded designs are adequate. They provided stipulations for inspection and action, including destructive examination of a random sample.

### 5.13.4 GSU Status

During a recent engine disassembly and inspection program, all of the intake and exhaust push rods and connector push rods were visually examined. All were verified to be of the friction-welded design.

Liquid penetrant tests were performed on the main and connector push rods for cylinders 5A, 3B, and 7B. No relevant indications were observed. The

connector push rods from cylinders 1A, 6A, and 7A also were penetrant-tested with satisfactory results. Visual inspections were made on all main and connector push rods with satisfactory results. No destructive examinations were conducted at River Bend.

5.13.5 PNL Evaluation and Conclusion

PNL reviewed the FaAA report and concurs with the conclusions. PNL has also noted information indicating favorable field experience of friction-welded push rods in other installations, and (to date) also at RBS. PNL has also reviewed documentation of GSU's inspection actions at RBS and the favorable resulting indications. Although GSU reportedly has not conducted a destructive examination of push rods at RBS, PNL concludes that the reportedly favorable results from those examinations done elsewhere, coupled with favorable inspections and operations at RBS and elsewhere, obviate the necessity of such an examination at RBS. PNL also recognizes the favorable physical restraints involved in push rod installations plus the probably insignificant consequences of a rod failure in service.

On these bases PNL concludes that push rods of the friction-welded design, as installed at RBS, are acceptable for their intended service. However, GSU should perform the inspections noted for the push rods in Section 6.0 of this TER. For future purchases of push rods, GSU should also specify destructive verification of weld quality by sectioning random samples from each manufacturing lot.

5.14 ROCKER ARM CAPSCREWS

Part No. 03-390G

Owners' Group Reports Emergency Diesel Generator Rocker Arm Capscrew Stress Analysis (SWEC March 1984) and supplement (April 1984)

5.14.1 Component Function

The rocker arm capscrews bolt the rocker arm shaft in place in the subcover assemblies. They transmit camshaft rolling loads, valve spring

loads, and residual cylinder pressure forces from the rocker arm shaft to the cylinder heads. A failure would weaken or cancel the restraints on a rocker shaft and cause malfunction of intake or exhaust valves. Reduced engine output would result.

### 5.14.2 Component Problem History

Rocker arm capscrew failures due to improper bolt preload have been reported at SNPS. There have been no reports of similar failures elsewhere.

### 5.14.3 Owners' Group Status

Stone & Webster Engineering Corporation performed stress analyses of both the original capscrew design with a straight shank (the type that failed at SNPS) and a newer design incorporating a necked-down shank. SWEC has concluded that both designs are adequate for the service intended. SWEC attributed the failure at SNPS to insufficient preload.

### 5.14.4 GSU Status

A magnetic particle inspection for linear indications in the thread root area was made on all the rocker arm capscrews for both engines. No indications were observed.

A material comparator test was performed on four rocker arm shaft capscrews from SD 1A. The results were satisfactory.

The proper rocker arm shaft bolt torque was verified in accordance with the TDI manual.

### 5.14.5 PNL Evaluation and Conclusion

PNL concludes that the rocker arm capscrews in the River Bend engines are acceptable for the intended service. This conclusion is based on 1) a review of the Owners' Group analysis, 2) the favorable checks of materials and design as-installed, 3) the confirmation of installation preloading, and 4) GSU's commitment to perform periodic preload checks.

## 5.15 TURBOCHARGERS

Part No. MP-020 (Model BCO-90G)

Owners' Group Reports FaAA-84-6-56 and FaAA-82-5-7.1

### 5.15.1 Component Function

The turbochargers on the GSU TDI DSR-48 engines are Model 90G units manufactured by the Elliott Company. One turbocharger per engine provides pressurized air to the cylinders for combustion of more fuel than would be possible with a "normally aspirated" engine. The turbochargers consist principally of a turbine, driven by engine exhaust gases, directly driving an air compressor wheel or impeller. The associated housing ducts the air and exhaust to and from the rotors; the exhaust inlet guide vanes direct the exhaust gases toward the turbine wheel blades. Turbine speed changes with engine load (i.e., gas volume, pressure, and temperature), with maximum speed depending on specific turbine selection and design parameters.

Because close tolerances and high rotating speeds are necessary for efficiency, and because temperature levels can approach 1200°F at the exhaust inlet, all components are sensitive to temperature, pressure, structural loads (vibrations), and contaminants or particles in the gas and air streams. The radial and thrust bearings require particular care and lubrication.

Vanes and blades are sometimes lost allegedly due to heat and vibration, or fractured by impact of objects such as bolt heads, fractured inlet guide vanes, or broken valve seat inserts. Missing inlet guide vanes have been noted in several installations, with no clearly evident cause. Undue stresses or vibration from connected exhaust piping or inappropriate supports can cause rotor wear at the stator interface. Inadequate bearing lubrication (and the cooling the oil provides) can lead to bearing failure. Depending on the severity of the situation, diesel engine shutdown can come quickly, but usually is not immediate.

### 5.15.2 Component Problem History

Various problems have occurred in the turbochargers on TDI engines in nuclear service. The principal problem has been the rapid deterioration of the turbine thrust/radial bearing, which has occurred at the Shoreham,

Comanche Peak, Catawba, and San Onofre nuclear plants. There also have been problems regarding missing turbine inlet vanes, missing or broken capscrews joining the inlet vane ring to the turbocharger, and broken capscrews and welds in the support mounts.

Because nuclear EDGs have, to date, had unusual quick-start requirements--and are tested extensively to ensure reliability for such duty--the owners and TDI investigated the failure parameters early in the history of such service. It was recognized that the original bearing and bearing lubrication systems were not adequate to provide lubrication of the bearing thrust pads and rotor thrust collars under fast startup conditions to high loads. TDI initiated two steps of modifications in an attempt to address this problem. The first instituted and later modified an oil drip system; the second provided for manual prelubrication prior to planned starts.

### 5.15.3 Owners' Group Status

On behalf of the Owners' Group, FaAA undertook an extensive study of causes of reported failures in nuclear service. The net result was an affirmation of inadequate startup lubrication. Briefly, the resulting recommendations were:

- Retain and use a "drip system" that directs a small flow of oil toward the bearings at all times in standby, but increases the flow of oil to 0.35 gph. (Higher flows are apt to flood past the bearing into the exhaust manifolds and create fire risk at startup.)
- Provide and use an auxiliary prelubrication pump to direct substantial flow to the bearings immediately prior to planned startups.
- Maintain oil filtration at 10 microns or better, and utilize spectrochemical and ferrographic oil analysis regularly.
- Enhance bearing inspection programs. The thrust/radial bearing should be inspected following every 100 starts of any nature. Inspection should also be done on a turbocharger following 40 starts without manual prelube.

In a separate study, FaAA also considered the various reported nozzle ring component failures in Elliott 90G turbochargers. They concluded that, on the basis of operating experience, these types of failures do not affect the operation of the turbocharger and, therefore, do not compromise the ability of the EDGs to perform their intended function. FaAA did, however, recommend that the engine operation be monitored to ensure that exhaust gas temperatures do not exceed maximums specified by Elliott.

### 5.15.4 GSU Status

Prior to any onsite testing or operation of the two River Bend engines, the turbocharger thrust bearings were inspected and found to be worn. It was concluded that the cause was insufficient prelubrication. The bearings were replaced, and a prelube system was installed on both engines. The drip flow system was retained as a safety measure for emergency starts and to provide post-operation lubrication.

The turbocharger thrust bearing on each engine was visually inspected for wear and cracking. The bearing thrust end clearance was also checked. The eight bolts holding the nozzle ring were inspected, and their torque was checked on both SDs.

The nozzle ring for the turbocharger on SD 1A was LP inspected; no cracks in the nozzle ring blades or housing were observed. No excessive dents were observed on the turbocharger nozzle ring blades.

### 5.15.5 PNL Evaluation and Conclusion

PNL has reviewed the FaAA reports, the results of the Owners' Group meeting with representatives of FaAA, the Owners' Group, NRC, and PNL, and the inspection data presented by GSU and the Owners' Group. PNL also has examined the prelube system at other plants. Based on these reviews, PNL concludes that the prelube system now installed on the diesels at River Bend should provide sufficient additional lubrication to augment the protection of the turbocharger bearings during planned fast starts. Further, in PNL's view, the

few unplanned fast starts that may occur without prelube during a given operating cycle will probably not lead to bearing failure prior to scheduled maintenance. According to FaAA, as confirmed in a telephone conversation between PNL (W. W. Laity) and FaAA (T. Thomas) on July 20, 1984, the shortest known time-to-failure of a turbocharger thrust bearing subjected to "dry" starts (for which no forced bearing prelubrication was provided) occurred at SNPS. That bearing experienced at least 62 "dry" starts before failure. The new operating procedure suggests that each engine is likely to experience very few, if any, "dry" starts in a given operating cycle.

PNL believes that GSU should implement all of the Owners' Group maintenance and inspection recommendations included in the RBS DR/QR report, to enhance turbocharger reliability and performance. In addition, because the failure rate of vanes, nozzle ring hubs, and fasteners on Elliott turbochargers on TDI engines has, in PNL's opinion, been surprisingly high, PNL recommends that GSU perform the inspections noted in Section 6.1 and monitor turbine inlet temperatures as outlined in Section 6.2 of this report.

In the DR/QR report for RBS, the Owners' Group recommended that a visual inspection be performed on the bearings and nozzle ring of SD 1B and that a liquid penetrant test be performed on the welds retaining the cone plug (hub nut) of both SD 1A and 1B. In addition, the Owners' Group recommended that GSU verify that TDI SIM 300 was implemented and that the hub nuts are staked on both engines. It is recommended that all of the above activities be implemented prior to licensing.

PNL notes that the engines at River Bend will be operated at a BMEP of about 200 psi. This engine rating is below the TDI full-load BMEP of 225 psi. The consequential reduction in pre-turbine exhaust temperature is beneficial to the turbocharger.

On the bases of the above considerations, PNL concludes that the turbochargers on River Bend SDs 1A and 1B are suitable for their intended service.

## 5.16 JACKET WATER PUMP

Part No. 03-425A

Emergency Diesel Generator Engine Driven Jacket Water Pump Design Review (SWEC April 1984)

### 5.16.1 Component Function

The engine-driven jacket water pump furnishes water to the engine jackets (i.e., the cylinder block surrounding the liners, the heads, the coolers, and the exhaust manifold). Water is circulated through the turbocharger water jackets. The pump is a typical centrifugal pump, driven from the front-end gear.

Without the water pump (or an emergency backup), the engine would quickly shut down due to excessive temperatures. Such pumps generally are trouble-free, but occasionally develop problems with shaft seals, bearings, and drive mechanisms.

### 5.16.2 Component Problem History

The jacket water pumps at Shoreham have encountered one significant problem: a pump shaft failure. This led to redesign of the method of attaching the impeller to the shaft. There is no history of other jacket water pump failures.

### 5.16.3 Owners' Group Status

Stone & Webster Engineering Corporation has investigated the jacket water pumps as installed on the TDI inline and V engines. They reviewed the River Bend jacket water pumps from the standpoints of mechanical design, material suitability, and hydraulic performance. SWEC recommended that the keyway on the impeller and shaft be eliminated, and that the impeller be made from ductile iron to the same specifications as the Shoreham impeller.

The Owners' Group recommended that the following be performed on SD 1A:

- Determine pump shaft hardness.
- Determine pump shaft material.
- Visually inspect the pump shaft for signs of excessive galling, wear or scoring. Document any questionable items with photographs.

- Visually inspect the pump-driven gears for signs of pitting or galling. Document any questionable items with photographs.
- Perform a liquid penetrant test on the gear teeth and transition area (gear to shaft).
- Visually inspect the wear ring for evidence of galling or excessive wear.

5.16.4 GSU Status

Jacket water pumps as recommended by the Owners' Group Phase 1 study were ordered and are at the plant site.

5.16.5 PNL Evaluation and Conclusion

The calculations performed by SWEC were reviewed. PNL agrees that replacing the original pumps with those having ductile iron impellers and no keyway is desirable. Based on the SWEC calculations, PNL concludes that the replacement pumps are acceptable for the intended service.

The torque values recommended by the Owners' Group for tightening the impeller and gear nuts seem reasonable. However, if the cotter pin holes do not line up at the specified torque, the nut washer or nut should be reduced in thickness until the pin holes do match.

PNL recommends that the Owners' Group-recommended inspections (Section 5.16.3) not performed to date be conducted, as applicable, when the new jacket water pumps are installed. The installation and the inspections should be done prior to the licensing of RBS.

## 5.17 FUEL INJECTION NOZZLE AND TIP
Part No. 03-365B

5.17.1 Component Function

The fuel injection nozzle assemblies in use at River Bend are Bendix Type H4L-400. Fuel oil under high pressure flows to these assemblies. At the proper pressure the nozzle opens, and fuel sprays into the cylinder through the spray tips, forming the desired spray pattern.

5.17.2 Component Status

To eliminate fuel spray on cylinder liner walls, thus reducing cylinder liner wear, GSU has replaced all of the originally supplied fuel injector tips having a 140° spray angle with TDI's current standard tips having a 135° spray angle.

5.17.3 PNL Evaluation and Conclusion

The replacement of 140° tips with 135° tips at RBS is identical to changes made by other TDI engine owners (e.g., LILCO). Based on component inspection results at Shoreham, PNL concludes that this change has not detracted from engine O/R; PNL supports its implementation at RBS.

5.18 HIGH-PRESSURE FUEL OIL TUBING

Part No. 03-365C

Owners' Group Report Emergency Diesel Generator Fuel Oil Injection Tubing (SWEC April 1984)

5.18.1 Component Function

The high-pressure fuel oil tubing carries the fuel oil from the cam-driven fuel injection pumps on the side of the engine to the injector nozzles (spray nozzles) in the heads. This oil is under pulsating and quite high pressure (∿500 psi to 15,000 psi once each cycle); hence, any flaws in the steel tubing or associated fittings, or any breaks caused by vibration or other factors, will release an oil spray in high-pressure bursts, with consequential personnel and fire risks, as well as engine load reduction.

5.18.2 Component Problem History

High-pressure fuel tubing leaks have developed during preoperational engine testing on SNPS and Grand Gulf engines. No other failures in nuclear applications have been reported.

5.18.3 Owners' Group Status

Stone & Webster Engineering Corporation analyzed the failed high-pressure fuel tubing and concluded that the failures originated in inner surface flaws

that were introduced during fabrication. If, through eddy-current inspection, the inner surface condition of new tubing is found to be within the manufacturer's specification, SWEC has concluded that the high-pressure tubing is suitable for the service intended. However, SWEC recommended that all future replacement lines be of a superior material and be "shrouded" to protect against open oil sprays in the event of future leakages.

The Owners' Group also has reviewed the compression fittings and concluded that they are adequate, provided that the injection lines are properly installed. The Owners' Group recommends that inspections for fuel leaks near the compression fittings be performed while the engine is running.

### 5.18.4 GSU Status

The fuel injection tubing (lines) from both engines were eddy-current inspected to Owners' Group criteria. Indications on four of the tube assemblies from SD 1A exceeded Owners' Group acceptance criteria. The tubing from SD 1B showed no relevant indications.

Fuel lines have been covered with shrouds. GSU has ordered tubing that has been given an auto-frettage treatment to improve fatigue resistance. This is to replace at least the four tube assemblies on SD 1A that did not meet Owners' Group acceptance criteria.

### 5.18.5 PNL Evaluation and Conclusion

PNL concurs with the Owners' Group analysis of the high-pressure fuel tubing. On the basis of 1) the eddy-current tests performed to date, 2) the shrouding of the lines, and 3) GSU's commitment to check fittings monthly for leakage, PNL concludes that the high-pressure tubing on or to be installed on the RBS engines is acceptable for the intended service.

PNL recommends that the four fuel injection tubing assemblies on SD 1A that exceeded Owners' Group acceptance criteria be replaced with acceptable tubing prior to the licensing of River Bend Station. To avoid personnel injury from possible high-pressure spray, PNL also recommends that detailed checks for fuel oil leaks not be done while the engine is running.

## 5.19 AIR START VALVE CAPSCREWS

Part No. 03-359

Owners' Group Report Emergency Diesel Generator Air Start Valve Capscrew Dimensional and Stress Analysis (SWEC March 1984) and supplement (April 1984)

### 5.19.1 Component Function

The air start valve capscrews hold the air start valves in place in the cylinder head. A failure, or an inappropriately long capscrew, will prevent the air start valve assembly from seating securely in the head. Insecure seating will result in loss of power in one cylinder due to escaping combustion gases.

### 5.19.2 Component Problem History

No actual failures of these capscrews have been reported. However, on May 13, 1982, TDI reported a potential defect due to the possibility of the 3/4-10 x 3-inch capscrews "bottoming out" in the holes in the cylinder heads, resulting in insufficient clamping of the air start valves.

### 5.19.3 Owners' Group Status

SWEC and TDI both have recommended that the 3-inch capscrews be either shortened by 1/4 inch or replaced with 2-3/4-inch long capscrews.

### 5.19.4 GSU Status

The valves and components were inspected and the results are as follows:

- The seating of the valves and valve rings was found to be adequate for both engines except for one air start valve on SD 1A. This valve had a defective valve seat, which was replaced.
- The gasket seals to cylinder head were verified to be copper and were satisfactory for both engines.
- The locking pin was installed in each lock nut for both engines and was satisfactory.

- Two valve holddown capscrews from both engines were checked dimensionally and found to comply with TDI requirements.
- The capscrew holddown torque was verified both cold and hot on all cylinders for both engines and was found satisfactory.

5.19.5 PNL Evaluation and Conclusion

The inspections and actions taken by GSU to eliminate potential problems with the air start valve capscrews are judged to be adequate to prevent failures. PNL recommends that, if it is necessary to remove the air start valve, a new copper gasket be used during reassembly, and the GSU installation procedure be supplemented with a recheck of the air start valve capscrew torque following the first period of engine operation, to ensure proper seating of this gasket. With this modified installation procedure, PNL concludes that the air start valve capscrews are adequate for the intended service at RBS.

5.20 ENGINE-MOUNTED ELECTRICAL CABLE

Part No. 03-688B

Owners' Group Report Emergency Diesel Generator Auxiliary Module Control Wiring and Termination Qualification Review (SWEC July 1984)

5.20.1 Component Function

The engine-mounted electrical cable and terminations are used for connecting auxiliary Class I skid-mounted devices such as the Woodward governor/actuator, the Air-Pax magnetic pick-up, and the starting air solenoid. Wire/cable materials unable to withstand the temperature or service environment could lead to short circuits, with adverse impact on the component functions and possible risk to personnel.

5.20.2 Component Problem History

Two defective cables were recorded by TDI in a 10 CFR 21 report. In addition, a TDI Service Information Memo warned of potentially defective engine-mounted cables.

### 5.20.3 Owners' Group Status

Analyses of the subject wiring, and of the recommended replacements, were conducted by SWEC, both generically and specifically for RBS. All functional attributes of the installed wiring and terminations were deemed serviceable for their intended functions.

### 5.20.4 GSU Status

The DR/QR report for River Bend indicates that the cable and terminations were visually inspected as part of the Owners' Group Phase 1 effort, and that no further action was indicated or taken.

### 5.20.5 PNL Evaluation and Conclusion

Based on the review of the actions taken by the Owners' Group, PNL concludes that the subject terminations and cables on SDs 1A and 1B are acceptable for their intended service at River Bend.

## 5.21 TDI PRODUCT IMPROVEMENTS

GSU has reported that all TDI product improvements recommended by the Service Information Memos (SIMs) listed below have been incorporated into the River Bend Station diesel generators.

| SIM No. | Subject |
|---|---|
| 321 | Actuator terminal pins Woodward Type EG and LSG actuators |
| 324 Rev 3 | Piston modification |
| 324-A | Piston crown studs |
| 360 | Air start capscrews bottoming in cylinder head |
| 361 | 1E nuclear qualified cable |
| 362 | Groove pin and sharp edge removal - piston skirts |
| 363 | Overspeed governor/fuel booster pump drive coupling |
| 364 | Connecting rod wrist pin bushings |

## 6.0 PROPOSED MAINTENANCE AND SURVEILLANCE PROGRAM

A maintenance and surveillance (M/S) program was previously identified by PNL as "...a key aspect of the overall effort for establishing TDI engine operability and reliability" (PNL-5161, June 1984). NRC also recognizes the importance of a comprehensive M/S program and has provided guidelines for development of such a program in the NRC staff Safety Evaluation Report on the Owners' Group Program Plan (NRC August 13, 1984).

This section documents PNL's review and evaluation of the proposed M/S program for the River Bend Station. GSU has agreed to implement the M/S program recommended by the Owners' Group as presented in Appendix II of the RBS DR/QR report. Hence, PNL based its evaluation on a review of the Owners' Group TDI Diesel Generator Design and Quality Revalidation Report Prepared for Gulf States Utilities River Bend Station, Revision 1 (February 1985).

Appendix II of the RBS DR/QR report presents a schedule of M/S procedures recommended for implementation at RBS. The schedule refers extensively to the TDI Instruction Manual and to other plant DR/QR reports issued previously by the Owners' Group.

The Owners' Group has recommended many more maintenance items than will be discussed in this section. The scope of PNL's review encompassed primarily those components and systems judged by PNL's consultants to be critical to engine operability/reliability and/or which have significant failure histories. The maintenance items recommended by the Owners' Group but not discussed herein were judged by PNL either to be sufficiently conservative to ensure component performance or to be outside the scope of PNL's review as stated above.

Reflecting the judgment and recommendations of PNL's consulting experts in diesel engine technology, comments on three aspects of River Bend's M/S program are presented:

- key maintenance items
- operational surveillance plan
- standby surveillance plan.

These comments are not intended to supplant the M/S plan for River Bend, but rather to augment it.

## 6.1 KEY MAINTENANCE ITEMS

Components classified as key maintenance items include certain engine structural components, moving parts, and parts with a failure history. The DR/QR proposed M/S plan for some of these components is summarized in Table 6.1.

Table 6.1 also summarizes PNL's comments regarding these M/S items. Comments are presented in more detail in the subsections that follow for items on which PNL's recommendations differ significantly from those presented in the River Bend DR/QR report. Recommendations that have been added to the M/S schedule are judged by PNL and its consultants to be important to diesel engine operability/reliability and to warrant special attention. Their inclusion in an M/S plan is considered consistent with good engine maintenance practice.

### 6.1.1 Cylinder Block

GSU proposes to inspect the cylinder blocks at intervals calculated using the cumulative damage index (CDI) model described by FaAA in Design Review of TDI R-4 and RV-4 Series Emergency Diesel Generator Cylinder Blocks (FaAA-84-9-11.1). The CDI model would permit operation of the RBS engines for 675 hours at 3130 kW prior to reinspecting the cylinder blocks.

PNL concurs with this proposal, assuming that the inspection would include LP examination of the top surface of the cylinder block. PNL also concurs with the recommendation in FaAA-84-9-11.1, that if a block is found to have ligament cracks, it be eddy-current inspected in the stud hole-to-stud hole and stud hole-to-end regions of the cylinder block top after any operation greater than 50% load. If these inspections reveal stud hole-to-stud hole or stud hole-to-end cracks, PNL recommends that the SD be declared inoperable pending analytic resolution of EDG reliability considerations to the satisfaction of NRC.

TABLE 6.1. Key Maintenance Items for River Bend Station

| Item | Gulf States Proposal | PNL Recommendations |
|---|---|---|
| Engine base and bearing caps (03-305A, 03-305C) | Perform a visual inspection of the base at each refueling outage. The inspection should include the areas adjacent to the nut pockets of each bearing saddle and be conducted after a thorough wipe down of the surfaces, using good lighting. | Concur with GSU. PNL recommends that the main bearing cap stud nuts be checked for proper preload every 5 years. In addition, the Owners' Group recommendations for SNPS should be followed. |
| Cylinder block (03-315A) | Perform an inspection of cylinder block per DR/QR report 02-315A at each refueling outage. | Concur with GSU (see Section 6.1.1). LP inspect liner landing area any time cylinder liners are removed. Visually inspect daily during continuous operation following automatic startup. |
| Crankshaft (03-310A) | Measure crankshaft web deflection at each refueling outage. | Concur with GSU. Hot and cold measurements should be taken. |
| | Measure diameter of crank journals during major engine overhauls. | Concur with GSU. |
| | | SD 1B: During the first refueling outage, inspect the fillets and oil holes of the three most heavily loaded crankpin journals (Nos. 5, 6, and 7) with fluorescent liquid penetrant and ET as appropriate. SD 1A and 1B: During the second and subsequent refueling outages, inspect the fillets and oil holes of two of |

TABLE 6.1. (contd)

| Item | Gulf States Proposal | PNL Recommendations |
| --- | --- | --- |
| Crankshaft (contd) | | the three most heavily loaded crankpin journals in the manner just mentioned.<br>SD 1A and 1B: During each major (5-year) engine overhaul, inspect the fillets and oil holes of the two main bearing journals between crankpin Nos. 5, 6, and 7, using fluorescent liquid penetrant and ET as appropriate. This inspection is in addition to the crankpin inspections. PNL also <u>suggests</u> that, as a conservative precaution, the fillets and oil holes of all journals exposed during a major overhaul be inspected in this manner. |
| Connecting rod bearing shells (03-340B) | Inspect and measure connecting rod bearing shells to verify lube oil maintenance which affects wear rate. The visual and dimensional inspection of the bearing shells should be conducted at the refueling outage which precedes 500 hours of operation by at least the sum of hours of operation in a LOOP/LOCA event plus the expected hours of operation between outages. | Concur with GSU. Also conduct an LP inspection. |
| | Perform x-ray examination on all replacement bearing shells. | Concur with GSU. Also conduct an LP inspection. |

TABLE 6.1. (contd)

| Item | Gulf States Proposal | PNL Recommendations |
|---|---|---|
| Cylinder heads (03-360A) | Visually inspect cylinder heads (all cylinders) every 5 years. | The visual inspection every 5 years should include MT inspection of the cylinder heads between the valve seats. |
| | Record cold compression pressures and maximum firing pressures at each refueling outage. | Concur with GSU. |
| | Air-roll the engine per TDI maintenance requirements, Vol. 1, or at appropriate intervals after engine shutdown, to ensure against harmful effects of water leaks. | The engine should be air-rolled before planned starts, and 4 to 8 hours, and then 24 hours, after each shutdown. |
| | Visually inspect the fuel injection port on each cylinder head "during" the normal monthly engine run for water leaks (monthly). | Concur with GSU. |
| | Visually inspect intake and exhaust valves, discs, stems, and seats for signs of drawing, pitting, distortion, concentricity, or any abnormal conditions every 5 years. | Concur with GSU. |
| | Measure intake and exhaust valve-to-guide clearance every 5 years. | Concur with GSU. |
| | | LP inspect the stellite valve seats every 5 years. |

TABLE 6.1. (contd)

| Item | Gulf States Proposal | PNL Recommendations |
|---|---|---|
| Cylinder head stud, rocker arm capscrew and air start valve capscrew (03-315E, 03-390G, and 03-359) | Verify rocker arm capscrew torque values at each refueling outage. | Concur with GSU. Note: Follow TDI reassembly procedures that recommend replacement of air start valve gaskets every time capscrews are removed. Retorque the air start valve capscrews following the first period of engine operation after gasket replacement. Also check all head studs for proper preload every 5 years. |
| Push rods (03-390C, 03-390D) | | Perform LP inspection of all push rods at major (5-year) engine overhaul until 800 operating hours are accumulated on the friction-welded assemblies. |
| Turbocharger (MP-020) | Measure vibration and check with baseline data at each refueling outage. | Concur with GSU. |
| | Clean impeller and diffuser at each refueling outage. | Concur with GSU. |
| | Measure rotor end play (axial clearance) to identify trends of increasing clearance, i.e., thrust bearing degradation, at each refueling outage. | Concur with GSU. |
| | Perform visual and blue check inspection of the thrust bearing every 5 years and after 40 non-prelubed starts. | Concur with GSU. |

TABLE 6.1. (contd)

| Item | Gulf States Proposal | PNL Recommendations |
|---|---|---|
| Turbocharger (contd) | Disassemble, inspect, and refurbish every 5 years. | Concur with GSU. |
| | Perform spectrochemical engine oil analysis with particular attention to copper levels and particulate size during the last monthly test run prior to oil change. | Concur with GSU. |
| | | Visually inspect the nozzle rings and vanes at first two refueling outages for damage or missing vanes. Subsequent inspection interval to be determined based on failure experience. |
| Idler gear (03-355B) | | Maintenance/surveillance procedures should include those recommended by the Owners' Group in the RBS DR/QR component checklist. |

PNL recommends daily visual inspection of the area between adjacent cylinder heads and the general block top during any period of continuous operation following automatic diesel generator startup. PNL also recommends a liquid penetrant, and as appropriate, ultrasonic inspection of the cylinder liner landing area any time a cylinder liner is removed. If any cracks are found, the crack characteristics should be recorded. If subsequent inspections indicate that the cracks are propagating, an analysis should be performed to justify the continued operable status of the SD.

### 6.1.2 Crankshaft

GSU proposes to measure crankshaft web deflections at each refueling outage and to measure the diameter of the crank journals during major engine overhauls.

#### 6.1.2.1 PNL Recommendations

PNL concurs (with some clarifications) and recommends an additional inspection of the main bearing journals.

Regarding the crankshaft web deflection, the timing of the measurements was not addressed. PNL recommends hot and cold web deflection measurements. The hot deflection measurements should be taken immediately after the 24-hour preoperational testing so as to reflect representative operational foundation temperatures. The hot checks should be initiated within 20 minutes after shutdown, and completed as rapidly as possible, preferably within 1/2 hour, starting with the last throw of the engine (generator end). Such a schedule, although strenuous, is deemed achievable. If the crankshaft deflection readings are outside the acceptable range, the foundation bolts should be checked for proper preload.

In addition, PNL recommends that the crankshaft examinations summarized in Table 6.1 be performed at refueling outages, to verify the continued absence of fatigue cracking. Any other inspections recommended by the engine manufacturer should also be performed.

### 6.1.3 Cylinder Heads

GSU proposes to perform regular visual inspections on the cylinder heads, monitor cylinder pressures, and air-roll the engines prior to scheduled engine startups.

#### 6.1.3.1 PNL Recommendations

PNL concurs with the GSU proposed M/S schedule with two clarifications, and recommends one additional surveillance item. First, the 5-year visual inspections should include an MT inspection of all cylinder head firing decks between the valve seats. Second, PNL recommends a schedule for air-rolling as follows:

- an initial air-roll at least 4 hours (but not over 8 hours) after engine shutdown
- a second air-roll approximately 24 hours after shutdown
- an air-roll immediately prior to any planned engine operation.

PNL recommends that the stellite valve seats be LP inspected every 5 years. Because stellite is a very brittle alloy and will be subjected to the impact loads from the cylinder valves, it may crack. Cracking of this material could result in fragments entering the combustion chamber and damaging the piston and liner, and/or passing through the turbocharger, with possible damage to the rotor. Excessive blowby past the valves may also occur, with damage to valves and/or seats.

### 6.1.4 Cylinder Head Studs, Rocker Arm Capscrews, Air Start Valve Capscrews

Loss of preload on cylinder head studs, rocker arm capscrews, and air start valve capscrews can adversely affect engine operability if it goes unnoticed. Because of their operational history, these items are included on the Owners' Group list of components with significant known problems. Thus, these components warrant regular maintenance and surveillance.

Head studs were not addressed in the proposed M/S plan. It has been proposed to verify rocker arm capscrew preload at each refueling outage and, by implication, to retorque the air start valve capscrews at each refueling outage.

6.1.4.1 PNL Recommendations

PNL concurs with the M/S plan for the rocker arm capscrews. PNL recommends that the air start valve installation procedure be modified to include the recheck of the capscrew torque after the first period of engine operation, to ensure that the copper gasket is fully seated and no further reduction of capscrew preload has occurred. PNL concurs with the intention to further recheck the air start valve capscrew torque at each refueling outage. PNL also recommends that the cylinder head stud preload be checked every 5 years.

6.1.5 Turbocharger

A recurring problem in the turbochargers on TDI engines has been thrust bearing wear. A modification to the lubrication system to provide minimal lube oil to the thrust bearing during engine standby proved to be inadequate. Subsequent modifications to the system have increased bearing prelubrication, which has substantially mitigated thrust bearing wear but may not have completely resolved the problem.

The turbochargers on some EDGs have also experienced failed nozzle ring capscrews and lost nozzle ring vanes.

GSU proposes to monitor turbocharger vibration, clean the impeller and diffuser at each refueling outage, and measure rotor end play at each refueling outage.

6.1.5.1 PNL Recommendations

PNL concurs with the proposed plans, but recommends in addition that GSU's M/S plan include stationary nozzle ring inspection (including vanes and capscrews) during at least the first two refueling outages.

6.2 OPERATIONAL SURVEILLANCE PLAN

Another aspect of M/S is operational surveillance, which refers to the parameters to be monitored and/or recorded during engine operation. These typically include temperatures and pressures at key locations in and about the engine, as well as cumulative parameters such as engine hours.

### 6.2.1 Rationale

Operational surveillance is necessary to ensure safe and efficient operation of the diesel engine. By monitoring and recording key engine parameters, trends in degradation can be detected, allowing timely preventive maintenance. Trend monitoring may also prevent major engine damage by providing early warning to allow engine shutdown prior to damage.

### 6.2.2 PNL Recommendations

PNL has not received a detailed operational surveillance plan from GSU. Recognizing the importance of operational surveillance, however, some recommended operational surveillance procedures are provided in Table 6.2. Justification for several of the recommendations is provided in the subsections that follow. As before, these items are not intended to supplant the recommendations of the manufacturer or the utility but rather to present specific operational surveillance practices that have been identified as important by PNL consultants.

#### 6.2.2.1 Pre-Turbine Exhaust Temperature

Pre-turbine exhaust temperature is valuable because:

- The individual cylinder exhaust pyrometer reports only a time average of a highly variable function.
- The turbine inlet temperature may be higher than any cylinder exhaust because it is subjected to a continuous stream of hot gases, and also because of possible continued exothermic reactions in the exhaust manifold.
- Blades and nozzle rings could be damaged by temperatures above the manufacturer's limit, which Elliott states is 1200°F.

#### 6.2.2.2 Air Manifold Temperature

The air manifold temperature indicates the effectiveness of the turbocharger aftercooler. Aftercooler efficiency is dependent on water flow rate and temperature and on fouling. Elevated air manifold temperatures

TABLE 6.2. Recommended Surveillance Plan for River Bend Station Standby Diesels

| Item | PNL Recommendation |
|---|---|
| Lube oil engine inlet pressure | Log hourly |
| Lube oil to turbocharger pressure | ↓ |
| Lube oil filter differential pressure | ↓ |
| Lube oil temperature (engine inlet and outlet) | ↓ |
| Fuel oil to engine pressure | ↓ |
| Fuel oil filter differential pressure | ↓ |
| Air manifold pressure | ↓ |
| Air manifold temperature | ↓ |
| Jacket water pressure (engine inlet) | ↓ |
| Jacket water temperature (engine inlet and outlet) | ↓ |
| Crankcase vacuum | ↓ |
| Exhaust temperature of all cylinders | ↓ |
| Exhaust temperature at turbine inlet (pre-turbine) | ↓ |
| Hour meter | ↓ |
| Generator load | ↓ |
| Fuel oil transfer pump strainer differential pressure | Log hourly unless strainer is auto/duplexed and alarmed |
| Starting air pressure | Check hourly |
| Fuel oil day-tank level | Check hourly or as required per tank size |
| Compressed air system | Drain condensate every 4 hours of engine operation |
| Leaks | Visually inspect engine and piping monthly and after 24 hours of operation |

reduce maximum load and result in less efficient combustion. Although the potential for such problems is less at the engine load of 3130 kW, it is considered prudent to monitor and trend the air manifold temperature.

6.2.2.3 Fuel Oil Transfer Pump Strainer Differential Pressure

This pressure should be monitored and recorded hourly unless the pump is equipped with an automatic duplex valve and an alarm to protect fuel feed.

6.2.2.4 Starting Air Pressure

This pressure must be monitored to ensure sufficient pressure is available for restart at all times.

6.2.2.5 Fuel Oil Day-Tank Level

This level must be monitored to ensure fuel availability, even if the tank is equipped with alarms.

## 6.3 STANDBY SURVEILLANCE PLAN

Included in Appendix II of the revised River Bend DR/QR report is a list of specific items to be conducted on a daily basis. This list reflects the TDI Instruction Manual inspection intervals, which are independent of engine operating hours.

### 6.3.1 Rationale

Standby surveillance is important to ensuring the operability of the diesel engines. The parameters monitored on an engine in standby status are intended to indicate the engine's preparedness to start rapidly and accept load. The two factors that contribute most to this are engine temperature and lubrication. By keeping the engine warm and all oil passages pressurized, the effects of a fast start are minimized. In addition, a ready supply of quality compressed air is required for starting the engines.

### 6.3.2 PNL Evaluation

GSU has not provided a detailed standby surveillance plan for RBS. PNL reviewed the TDI and Owners' Group surveillance plans and found that the proposals cover a number of items considered important to monitoring engine

condition while on standby status. However, several important items were not included in the available documentation.

Items recommended by PNL for inclusion in a standby M/S plan are presented in Table 6.3. The information in this table is not intended to replace any maintenance procedure(s) recommended by the manufacturer, the Owners' Group, or the utility, but rather to provide additional perspective in developing an integrated M/S plan. PNL also notes that several of the items listed in Table 6.3 are included in the RBS DR/QR, Appendix II.

Two points regarding the keepwarm lube oil filter are important:

- Entrained water or bacteria (in the absence of bactericide use) will tend to plug some filter media (or weaken others), and so would gradually increase pressure drops.
- The continuous keepwarm flow through the filters will (purposely) continuously filter the oil, with gradual buildup of contaminants in the filter media; the material scavenged out thereby itself helps filter even finer particles as time continues.

Thus, it is important to monitor oil filter pressure drop during standby periods. The changes are slow enough that a weekly check is deemed sufficient.

In conclusion, it appears that a standby surveillance plan needs to be formalized as a separate entity within the overall M/S program for RBS. PNL recommends that the plan include the items and time intervals listed in Table 6.3.

TABLE 6.3. Items Recommended for Inclusion in River Bend Station Standby Diesel Surveillance Plan

| Item | PNL Recommendation |
|---|---|
| Starting air pressure | Check visually every 8 hours<br>Log every 24 hours |
| Lube oil temperature in/out | ↓ |
| Jacket water temperature in/out | ↓ |
| Lube oil sump level | ↓ |
| Fuel oil day-tank level | ↓ |
| Annunciator test | Test every 8 hours |
| Alarm clear | Check daily |
| Compressed air trap operation | Check daily |
| Fuel rack and linkage operation | Check daily and lube monthly |
| Governor oil level | Check daily |
| Leaks on engine and auxiliary equipment | Inspect daily, with more detailed inspection monthly |
| Operational freedom of combustion air butterfly valve and cylinder | Check monthly |
| Keepwarm oil filter differential pressure | Check weekly |
| Jacket water pH, conductivity, and corrosion inhibitor | Test monthly |
| Air start distributor filter | Check monthly |
| Air start admission valve strainer | Check quarterly |
| Lube oil | Analyze monthly |

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