INTERIM TECHNICAL EVALUATION REPORT

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EVALUATION OF DIESEL GENERATOR FAILURE AT SHOREHAM UNIT 1

INTERIM REPORT ON PHASE 1, FAILURE CAUSE EVALUATION

NRC DOCKET NO. 50-322	FRC PROJECT C5506
NRC TAC NO. --	FRC ASSIGNMENT 20
NRC CONTRACT NO. NRC-03-81-130	FRC TASK 426

Prepared by

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Author: R. C. Herrick

FRC Group Leader: S. Ahmed

Prepared for

Nuclear Regulatory Commission
Washington, D.C. 20555

Lead NRC Engineer: R. J. Giardina

November 18, 1983

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FOREWORD

This Interim Technical Evaluation Report was prepared by Franklin Research Center under a contract with the U.S. Nuclear Regulatory Commission (Office of Nuclear Reactor Regulation, Division of Licensing) for technical assistance in support of NRC licensing actions. A final report will be issued after reviewing the final analysis on the Shoreham Unit 1 crankshaft failure, which the Long Island Lighting Company (LILCO) recently submitted to the Nuclear Regulatory Commission.

1. INTRODUCTION

In August 1983, a crankshaft of one of three emergency diesel generators at the Shoreham Nuclear Power Station, owned by the Long Island Lighting Company (LILCO), fractured during plant preoperational diesel generator tests. Inspection revealed severe cracking in the crankshafts of the other two diesel generators.

Subsequently, the Nuclear Regulatory Commission (NRC) requested the Franklin Research Center (FRC) to provide an independent technical review of the cause of failure determination performed by the Licensee and thereby to provide a technical basis for the NRC licensing actions regarding these failures.

Phase I of the two-phase review included the following:

a. attend an on-site inspection and review of the Shoreham diesel crankshaft failure and review operation and maintenance history provided by the Licensee.

b. analyze the data and information obtained in the on-site visit and prepare an interim report providing initial findings and conclusions regarding the courses of the crankshaft failures.

c. provide in the above report any conclusions regarding the other mechanical problems the Licensee has had with these diesel generators.

This report constitutes Phase I of the Shoreham Unit 1 failure cause evaluation and will be followed by a report concluding the Phase II effort.

On-site briefings and inspection of the diesel generators at the Shoreham plant on September 1 and 2, 1983, indicated that:

o the crankshaft of diesel generator 102 had fractured

o the extent of cracks in the crankshaft of diesel generator 103 precluded any additional operation of that engine

o diesel generator 101 could be used for a limited experimental testing program, as per the preliminary analysis performed by Failure Analysis Associates, Inc.

The briefings indicated that, with appropriate instrumentation installed, limited operational tests would yield information that would assist the identification of the cause, or causes, of the crankshaft failures, as well as provide information regarding previous problems.

Requests for review material were prepared by the NRC and the reviewer. Part of the material has been received and is under review. With respect to the test program, it was determined that the reviewer should be in attendance and observe all aspects of the test program. While the test observation consumed considerable time, it provided the reviewer with insight regarding the diesel's actual operational dynamics.

Although the tests have been completed, the reviewer has not yet been able to review the test data that were recorded on magnetic tape to facilitate data analysis, computation, and presentation. It is important for selected portions of the actual data to be reviewed so that an independent review and evaluation of the test results can be provided. As such, the effort of Phase I is not yet complete. For the same reason, conclusions from these tests cannot be drawn for this report. The report of the review of test results, analysis, and conclusions will be submitted later.

This review coordinated the efforts of Mr. H. W. Hanners, an independent diesel engine consultant who was coauthor of NUREG/CR-0660, "Enhancement of On-Site Emergency Diesel Generator Reliability." Mr. Hanners' preliminary commentary concerning selected problems experienced over the past 3 years by diesel engines manufactured by Transamerica Delaval, Inc., (TDI), is included as Appendix C of this report.

2. ON-SITE INSPECTION

2.1 PRELIMINARY BRIEFING

On September 1, 1983, a preliminary briefing was held in the NRC Resident Inspector's office with respect to the current state of events and plan of action [1] at the Shoreham plant; a brief overview of the performance history of the three diesel generators was included. The briefing was conducted by the NRC Senior Resident Inspector and supplemented by the Director of LILCO's Office of Nuclear Power.

2.2 INSPECTION TOUR OF DIESEL GENERATORS

A visual inspection was made of the three diesel generators. Although the observations are described in Appendix A, a brief summary follows:

- Diesel generator 101 was located in its operational room and was being prepared for a limited test program. This unit was reported by LILCO to have performed the initial qualification testing program for nuclear plant service and had been subjected to dynamic torsional testing as a part of that program. However, cracks were observed in the crank pin fillets of cranks 5 and 7.

- Diesel generator 102 was the unit with the fractured crankshaft. The diesel engine and generator had already been moved to the main turbine deck where space and crane facilities were available to disassemble the unit, make a thorough inspection, and rebuild it with the 13 x 12 crankshaft now recommended by Transamerica Delaval, Inc. Considerable attention was paid to the crankshaft fracture in this inspection because of the imminence and magnitude of the failure. The entire engine was also studied to gain a perspective necessary for an adequate review of the many types of failures experienced previously by the Shoreham diesels in order to determine if there may be a root cause not evidenced by the July 1983 study [2].

- Diesel generator 103, reported to have crankshaft cracks developed to an extent that precludes further engine operation, was observed in its operational room. It was under preparation for movement to the main turbine deck for disassembly, inspection, and reassembly with the 13 x 12 crankshaft.

2.3 PREPARATION OF REQUESTS FOR INFORMATION

A meeting with the NRC representatives was attended to discuss the immediate and past problems experienced by the diesels at the Shoreham plant and their implication for similar diesels at other plants. Questions were prepared concerning those aspects of the diesels and their performance records that would be required for an adequate independent evaluation. These questions were submitted to LILCO by the NRC during the public meeting held at the Shoreham plant on September 2, 1983.

2.4 PUBLIC MEETING

On-site activities included attendance at the public meeting held at the Shoreham plant on September 2, 1983 for discussion of the diesel engine problems. Representatives of the following organizations were in attendance:

Nuclear Regulatory Commission
Long Island Lighting Company
Hunton and Williams, LILCO legal counsel
Stone and Webster
Failure Analysis Associates
Counsel and Technical Consultant for Suffolk County
Newsday
Franklin Research Center.

During the meeting, the following points were established:

- There is no nuclear fuel at the Shoreham plant and, consequently, there is no demand on the safety systems.
- There is concern for similar diesels in other nuclear power plants.
- The problems with the Shoreham diesels are broader than the present crankshaft problem.
- The tests on the Shoreham diesels are significant for the whole nuclear power industry.
- The failure analysis team consists of Long Island Lighting Company, Failure Analysis Associates, Inc., and Stone and Webster Corporation.
- Transamerica Delaval, Inc., is cooperating with the failure analysis team to provide disassembly, inspection, alternate crankshafts and rework as necessary, and reassembly of the engines.

- Transamerica Delaval, Inc., management is committed to the failure analysis and engine rebuilding program and will submit its own assessment and recommended actions; for objectivity, however, the program is under the direction of an independent investigator, Failure Analysis Associates, Inc.
- Concern of the community is high as represented by counsel for Suffolk County and a technical consultant.
- A comprehensive failure analysis effort will be carried out to determine full understanding of the failures so that the corrective action will be most effective.

3. PRELIMINARY TECHNICAL REVIEW AND EVALUATION

3.1 REVIEW OF LILCO'S MASTER PLAN

A copy of LILCO's master plan [1] for the failure analysis and recovery of the diesel engines was received and reviewed. Comments [3] were submitted to the NRC, indicating where the reviewer's direct participation as an observer would be advisable. In general, this review concurred with the plan.

3.2 REVIEW OF TEST PROCEDURES

An early copy of LILCO's test procedure [4] for operational test of diesel generator 101 was also received. The procedure was reviewed and a copy was forwarded to Mr. Harvey Hanners, an independent diesel engine consultant. Commentary and recommendations of this review were combined with those of Mr. Hanners and reported to the NRC in early September before the start of operational tests. In the course of operational testing of diesel 101, the original procedure and three revisions [5, 6, 7] were reviewed.

Recommendations for modifications and additions to the last revision [7] to the procedure were made on September 24, 1983, by a memo [8] sent via the NRC Resident Inspector at the Shoreham plant for expediency. While the technical aspects of these considerations are discussed at greater length in Appendix B of this report, they provided means to assure that (1) all voltage phase references would be available and known, (2) transients associated with attachment of the generator to the electrical grid and to major electrical loads would be recorded, and (3) testing at a significant synchronous loading would be recorded for power factors ranging from 0.8 to 1.0. These considerations were included in the tests carried out on September 28.

3.3 PRELIMINARY REVIEW OF DIESEL DYNAMICS

Since the crankshaft failure and many of the earlier problems of the three diesels showed evidence of being associated with the dynamic response of the diesel engines, the torsional and lateral dynamics analysis summary prepared by TDI as a part of the original design effort was reviewed. These analyses, which were stated in the September 1 and 2 conferences at the Shoreham plant to be verified as sufficiently accurate by Failure Analysis Associates, defined the equivalent mass-elastic torsional dynamic model of the mechanical system, including the flywheel and generator rotor. They included the calculated natural frequencies and critical speeds. This information was needed to form a basis of understanding by which the reviewers could evaluate the test data and recognize the response of the various vibratory modes to the engine excitation orders in the course of the test runs.

3.3.1 Review of the TDI Mass-Elastic Model

The mass-elastic model [9] employed by TDI to represent the dynamic natural frequencies and mode shapes of the engine is made up of 11 inertias and 10 torsional springs. The inertias, identified in their order of position from the gear case end of the diesel to the generator, are:

- gear case and water pump inertia
- eight equivalent inertias representing the piston, connecting rod, and rotating portion of the crankshaft for each cylinder assembly
- flywheel
- generator rotor.

Torsional springs equivalent to that portion of the crankshaft or generator rotor shaft were calculated by TDI for application between the inertias in the model.

The analysis summary reviewed indicated that the inertia for each crank assembly is the equivalent average inertia. This is some average of the real inertia comprised of a rotating crank, linear motion piston, and a connecting rod that combines both motions, all of which combine to form an inertia that varies with crank angle. Various methods are available to average these crank angle-dependent inertias to equivalent average inertias for use in the mass-elastic model yielding the natural frequencies. The detailed methods by which TDI calculated the equivalent inertia and torsional spring constant for each crank assembly are not evident from the analysis summary [9]. Information that will identify the methods used was requested from TDI through NRC. When available, it will be reviewed to provide commentary and recommendations regarding TDI's methods. Methods developed by the industry over many years have been known to yield generally reliable results for most engine designs. This is not to imply that TDI did not use these methods correctly, only that they did not make their detailed methods evident in the analysis summary.

For this report, it is assumed that the calculated inertias and springs, resulting natural frequencies, and critical speeds are sufficiently accurate. This premise is based upon the facts that qualification testing was reported to verify these frequencies and that Failure Analysis Associates, Inc. reported in briefings during the Shoreham inspection visit that it had obtained virtually the same values using more comprehensive computer methods.

Using its model for the resonant frequencies, TDI calculated the participation of the various orders of known engine excitation and plotted the amplification factors of the more dominant excitation orders as shown in Figure 1, which is a reproduction of the TDI chart from Reference 2. Note that the I-4 (4th order) curve of amplification factor remains the single largest participant, providing more than double the amplitude of the 4 1/2th order during operation at 450 rpm. The excitation frequency of the 4th order is that of 4 times per revolution. This is the firing rate of the cylinders which generates a sharp and dominant excitation. In short, using its analysis, TDI expected to experience a large component of oscillatory torque at 30 Hz (engine firing rate) in the crankshaft. However, a large cyclic torque at 30 Hz is not necessarily bad, provided the associated stress levels in combination with stresses from other sources in the crankshaft are adequately within the endurance limit of the material.

3.3.2 Investigation of Additional Constraints in the Torsional Mass-Elastic Model

The influence of rotor-stator electrical coupling upon the purely mechanical torsional model employed by TDI was investigated in this review. Rotor-stator coupling of a synchronous generator may be approximated as an equivalent spring rate between the generator rotor and the inertia of the

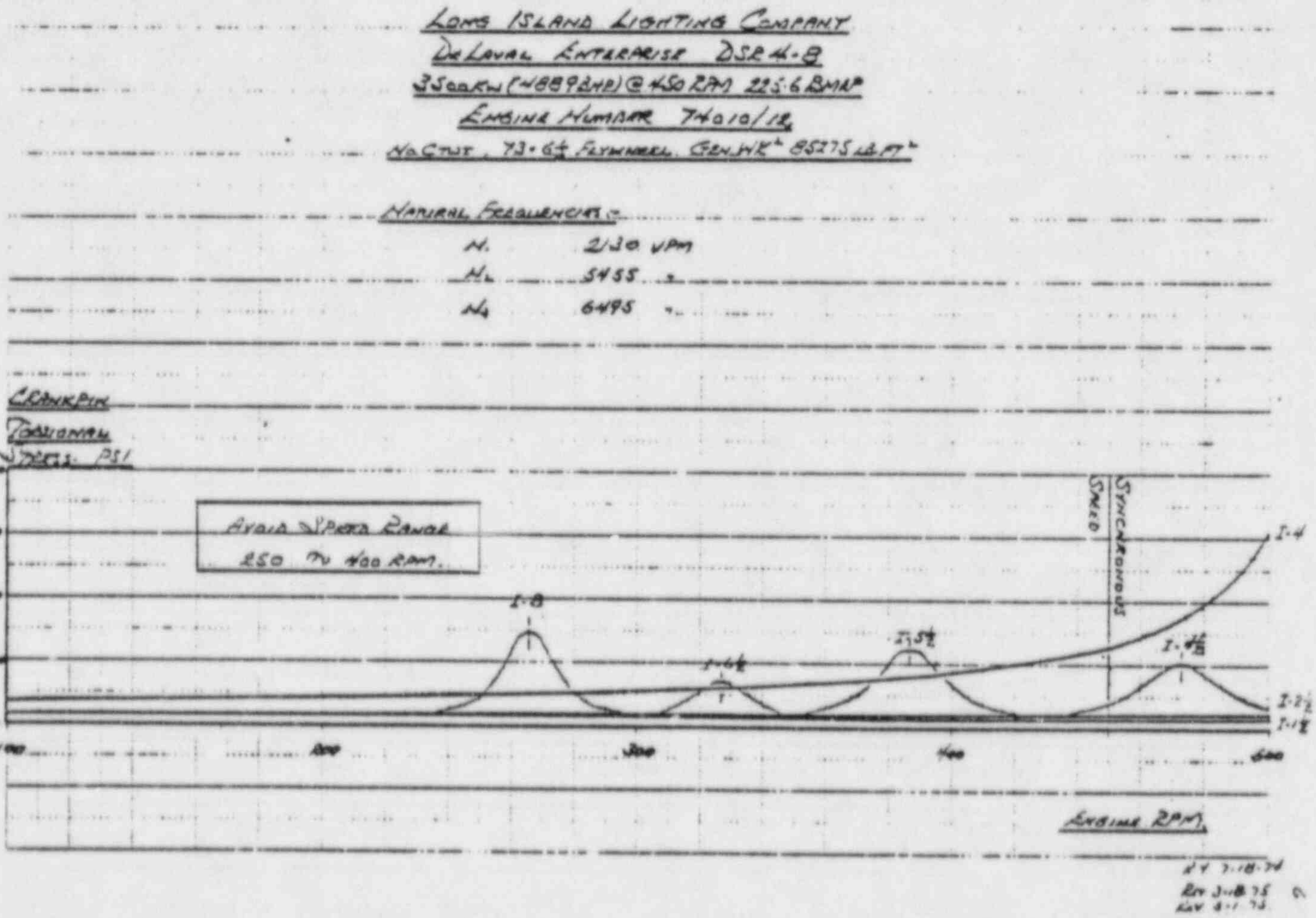

Figure 1. Torsional Stress and Critical Speeds

electrical load. When the generator is connected to the electrical power grid, this equivalent inertia can be very large. In such cases, it is valid to approximate the effect by calculating the equivalent spring rate of the rotor-stator system and inserting it into the torsional mass-elastic model between the generator rotor inertia and a new fixed rigid member (infinite inertia).

Review of TDI's mass-elastic system revealed that:

- the generator inertia was exceptionally large
- the flywheel inertia was only between one-third and one-half that of the generator rotor
- all other inertias representing crank assemblies, water pump, etc., were very small by comparison.

Thus, while the introduction of the rotor-stator equivalent spring had an exceedingly small effect upon the natural frequencies of the rotor and their dynamic response under the engine excitation, it did define a new mode of vibration not heretofore available from TDI's torsional model. This was essentially a rigid-rotor oscillation of the combined crankshaft, flywheel, and generator rotor system with the rotor-stator spring connecting the rigid-rotor system to the nearly infinite electrical load inertia mentioned previously. The natural frequency (resonance) of this vibratory mode was independently calculated to be approximately 3.0 Hz. This vibration mode contributed to the cyclic variation of power previously observed from the control room to be at 3.75 Hz, which is the frequency at which one complete set of eight cylinders fires, or the rate at which any one cylinder fires. Fortunately, the natural frequency of just under 3.0 Hz was sufficiently far from the 3.75 Hz excitation to prevent large amplitude vibration with resulting large swings in power. Also, the amortisseur windings of synchronous generators provide damping under oscillatory motions to limit amplitude buildup.

For diesel generators that may be coupled to the electrical power grid, TDI should have addressed this electrical-mechanical, rotor-stator coupling.

3.3.3 Investigation of Other Mechanical-Electrical Dynamic Coupling

When received, the torsional analysis report indicated that the 30-Hz firing rate of the engine (4th order) would be sufficiently close to the first mode natural frequency, 35.5 Hz, to build moderately high amplitudes of oscillation at 30 Hz, which is one-half the electrical generation frequency. Accordingly, recommendations were made [8] to ensure that any possible electrical-mechanical interaction would not be missed by the recording of data. These recommendations are included in Appendix B.

3.4 REVIEW OF TORSIONAL TESTING

3.4.1 Initial Tests

The torsional testing program, with operation of instrumented diesel 101, was conducted to establish correlation with a detailed computer dynamic model of the diesel formulated by Failure Analysis Associates, Inc., as well as to investigate the dynamic interaction of the diesel with various loadings and operational conditions. The torsional testing program was primarily concerned with the catastrophic failure of the crankshaft in diesel 102 and near failure crack propagations in diesels 101 and 103. The testing was observed as a part of this review.

Listings of measured parameters, sensors and transducers, and data recording equipment are provided in the test procedures [4, 5, 6, 7]. These include most engine operational temperature and pressure data, that is, lubrication temperature and pressure, combustion air pressure, each cylinder exhaust pressure, etc.

Instrumentation for the measurement and recording of vital dynamic data included the following:

- Cranks 5 and 7 were instrumented such that crankpin fillet and web dynamic strain were measured by three element strain rosettes bonded to the fillet and by a single gage on the crank web.
- Dynamic torque in the crankshaft adjacent to the flywheel were measured by a strain gage torque bridge.

- Cylinder firing pressure of cylinders 5 and 7 were measured with high-pressure piezoelectric transducers.
- Shaft dynamic displacement were measured by a torsional displacement transducer mounted on the gear case end of the diesel crankshaft.
- Linear acceleration of the engine base were measured by accelerometers mounted on the base at cylinders 5 and 7.
- Vertical, horizontal, and axial acceleration (vibration) were measured for the bearing housing next to the flywheel.
- Crankshaft position and revolution tachometer were referenced to top dead center of cylinder 7 provided by an optical sensor mounted on the generator shaft.
- Generator output voltages were recorded to measure (V_A - V_B) and (V_B - V_C).
- Generator output current was measured for individual recording of each phase.

Instrumentation on the rotating crankshaft was battery powered with signals transmitted by FM telemetry.

The initial tests were started on September 19, 1983, using the test procedure [6] dated September 15, 1983. Strain gage problems continued with gages dropping from service until five of the eight strain gages in the fillets and webs of the crankshaft were not operational. Testing was suspended at that point to repair the strain gage instrumentation. However, the test program had progressed through the initial checkouts, through the variable speed torsiograph tests, and included the 1750 kW synchronous load test with the generator connected to the electric power grid. The full load tests, 3/4 load tests, and the TDI torsiograph tests remained to be accomplished.

3.4.2 Completion of Torsional Tests

Following repair and improvement of the strain gage instrumentation in the crank fillets and on the crank web, testing resumed at 2:44 am on September 28, 1983. These tests included the test program in the test procedure [7] dated September 23, 1983. The test program, with instrumentation performing satisfactorily, continued to completion at approximately 7:30 am that same morning.

Testing began with Section 7.1 of the procedure [7], which involved measurements for verification of the analytic model at Failure Analysis Associates in Palo Alto, CA. This was a correlation procedure in which the initial dynamic measurements were telephoned to the Failure Analysis Associates offices and checked against the analytic (computer) model both to verify the model and to permit the model to predict the available run time on the engine before crack propagation would preclude further testing.

Testing continued through the balance of the test procedure, including measurements recommended bv this review, and concluded with tests requested by TDI using its own torsiograph and associated instrumentation.

Observations of data during the acquisition and recording of data on magnetic tape were somewhat limited, but these observations disclosed no instabilities with the electrical system or adverse transients in these tests upon connecting the diesel generator to various loads. As expected, the crankshaft torque signal and the crank fillet strain gages showed a significant 30-Hz component keyed to the pressure rise of each cylinder.

With the test data recorded on magnetic tape, the review plan at the completion of tests was to permit the Licensee and its contractors to review and verify calibration and zero settings of the various data channels in their home facilities before conducting an independent review of the test data. Further commentary regarding the test results must await a review of the test data.

3.5 REVIEW OF PRELIMINARY METALLURGICAL EXAMINATION, DIESEL 102 CRANKSHAFT

A copy of the preliminary metallurgical evaluation of the failed crankshaft from diesel generator 102 [10] was reviewed. This report of metallurgical examination and fracture analysis confirmed that the failure occurred by fatigue, with the fatigue crack originating at a machining mark on the fillet radius. While the report emphasizes that the findings to date are of a preliminary nature and that residual stress measurements are still in progress, the report does state that, from visual examination, "the fracture surface exhibited an obvious, unmistakable fatigue crack pattern."

Although no other review material concerning the crankshaft has been received, the reviewer did observe, during the test completion at the Shoreham plant, a color photograph of a fractured surface reported to be that of the diesel 102 crankshaft fracture. The clarity of the photo was sufficient to depict a classic fracture pattern. Full documentation is expected for review following completion of the analysis by Failure Analysis Associates, Inc.

The preliminary metallurgical report also stated that chemical analyses of samples of crankshaft material indicated that the crankshaft steel meets the ASTM A235-67 Class E specification said to be specified.

The preliminary metallurgical report also indicated that hardness, grain flow, and tensile properties were generally in order.

Again, items pertaining to the fracture analysis and metallurgical analysis will be reviewed as they are made available. A more comprehensive evaluation of these subjects will be reported later.

3.6 PRELIMINARY REVIEW OF DIESEL STATUS PRIOR TO CRANKSHAFT FAILURE

3.6.1 Review of Diesel Generator Test History

Documentation of the test program at TDI prior to delivery of the diesel generators to the Shoreham plant has not arrived for review; however, statements made by LILCO and TDI at the September 1-2 briefing indicate that a number of manufacturer's operational tests were performed on the engines in addition to the nuclear qualification program that was performed using diesel 101. It was stated in these briefings that the test data confirmed "to within 1%" the critical speeds calculated during design. No statements were made concerning whether these tests confirmed the amplification factors of each significant order of vibration.

Reference 11 is a summary of Shoreham's test program for the emergency diesel generators forwarded to this reviewer in advance of complete documentation. This summary indicated that the test program was responsive to Regulatory Guides 1.108 and 1.9 and IEEE Std 387, in accordance with LILCO's commitments in the Shoreham FSAR.

The test program was described as being of the "building block type" starting with checkout and initial operation tests for individual components, whereupon the components are combined into subsystems and tested again. The checkout and initial operation were stated [6] to consist of 138 test packages in addition to 12 flush procedures, followed by 15 functional test procedures.

After the above tests, the diesel generators were operated for the first time as follows [11]:

Diesel generator 102, October 1982
Diesel generator 103, March 1982
Diesel generator 101, April 1982.

Testing of each diesel continued according to procedure, and the final test was performed to demonstrate the capability of the diesel generators to complete successfully a total of 69 consecutive starts. According to Reference 11, "By June 24, 1983, the emergency diesel generator preoperational test program, including all mechanical, electrical and qualification tests, was completed for all three diesel generators."

In August 1983, all three diesels underwent a cylinder head stud replacement program, and one diesel generator completed the high load retest [11]. LILCO's summary continues, stating that "one remaining demonstration of diesel capability was scheduled prior to fuel load; the integrated emergency core cooling system and emergency diesel generator operational demonstration." It was not clear, in the review, whether each of the diesel generators was required to undergo this remaining test because the material reviewed clearly indicates that the engine failed during a retest.

LILCO reported [11] that, as of the August 12, 1983 crankshaft fracture, the diesel generators had accumulated 2182 hours of operation as follows:

Diesel generator 101 -- 646 hours
Diesel generator 102 -- 718 hours
Diesel generator 103 -- 818 hours.

In response to a request for information by the NRC regarding the total number of operating hours on each diesel generator (DG) and the total number of hours at 3900 kW or greater, LILCO responded [12] as follows:

DG Unit	Total Operating Hours on Each DG Unit			Total Operating Hours for Each DG Unit at 2-hour Overload Rating ($\geq$ 3850 kW) (These hours included in total operating hours)		
	At TDI	At Shoreham	Total	At TDI	At Shoreman	Total
101	128	518	646	3	16	19
102	30	688	718	3	19	22
103	40	778	818	3	20	23

3.6.2 Review of Conditions at the Time of Crankshaft Failure

In response to a request for information by the NRC about the test procedures in use at the time of the crankshaft failure, LILCO responded with the following description of the test [13]:

> "Cylinder heads on DG 102 were replaced under R/RR R43-1001 with new design stress relieved heads. With all eight cylinders equipped with the new heads, the 102 DG was run for 12 hours to allow hot torquing of the exhaust header bolts and air start valve nuts. Following this run, a retest of the engine was begun under 8.7-R43-042. The specific scope of the retest under this 8.7 Form was to:
>
> 1. Verify proper diesel generator start to synchronous speed and rated voltage in less than 10 seconds.
> 2. Verify proper DG operation for four hours at the continous load rating.
> 3. Verify proper DG operation for 2 hours at the two hour overload rating.
>
> Refer to the response to NRC Request for Information II.2, pages 10.5 through 10.17, for a copy of the retest procedure 8.7-R43-042, as completed up until the time of the failure of DG 102."

On page 10.1 of Reference 14, LILCO provided the following detailed description of the events just prior to the failure:

> "The diesel generator prior to the performance of 8.7-R43/42 was in its normal standby condition. An interim operating instruction was performed to ensure proper breaker positions, proper valve lineup and correct initial conditions. The diesel engine was started from its remote location, the main control room. Proper starting, acceleration to

synchronous speed and rated voltage within 10 seconds was verified by the test engineer and the OQA inspector. Plant Operator synchronized the diesel generator to BUS 102 by closing ACB 102-8 and then proceeded to increase the diesel generator load to 3500KW in less than 60 seconds. Once at the 3500 KW/300KVar load the operator was instructed to maintain this load for four hours. He was instructed that any deviations, caused by the LILCO grid, away from 3500KW/300KVars should be corrected. Another plant operator was stationed in the engine room with verbal communications established between operators via headsets. During the course of the four hour full load run, a LILCO technician was also stationed in the diesel engine room with the task of recording all pertinent test information every 30 minutes. No abnormal readings were observed by either operator nor was the data written down by the technician found to be out of its normal operating range as specified by the engine manufacturer for this size load.

Since this test was handled similar to a Station Surveillance Procedure no special test equipment was utilized for data recording. All data written down was taken off of normal plant gauges either in the main control room or in the diesel engine room. The two exceptions were the generators bearing temperature and the generator stator temperature, both of which were read off M&TE calibrated instruments. As stated in the 8.7 form high speed recorders were not used to record data on chart paper as a permanent record. Once, during the full load run the individual cylinder firing pressures were recorded and found balanced within manufacturer specified tolerances.

At the conclusion of the four hours the control room operator slowly increased the 102 generator load up to 3900KW/300 KVars. This load was to be maintained at this level for the remaining duration of the test and the operator was allowed to correct for any load deviations. During the increase in load, the lube oil low level alarm came in. The dipstick was checked and found to be below the shutdown level mark by 7-8". (This level is normal for high load operation of the DG units, and the alarm has been an occasional occurrence on all three engines). Lube oil pressure and turbocharger pressure were normal and the test was allowed to continue. Data readings were taken every 15 minutes. No abnormal noises were heard by the technician nor the local operator. Vibrations did not appear anything out of the ordinary; in fact the diesel engine seemed to be running fairly well.

The overload portion of the test was some one hour and 45 minutes into the two hour run when the diesel generator vibration was felt in the control room. The local operator reported no abnormal vibration. Generator load swings of 2.0 MW were observed in the control room meters, the operator reduced load to 1.0 MW and the oscillations, subceeded. It was at this point that the generator load shot up to 4.0 MW where the operator tripped the output breaker ACB 102-8 and manually depressed the 'stop' pushbutton. It was later observed that the engine overspeed trip had been activated and its alarm had been initiated. Other detailed descriptions of this failure are attached, as well as a copy of the data sheets. Again no traces are available for analysis. Inspection of diesel crankcase internals showed the crankshaft web in the area of No. 7 connection rod was cracked."

On page 10.3 of Reference 14, LILCO provided the following sequence of events when fracture is believed to have occurred:

"(Times are approximate and are intended to illustrate sequence rather than exact time of occurrence)

Background:	EDG at 3.9 MW for 1 hour and 45 minutes, 15 minutes from completion of scheduled 2 hour run. NASO - S. Livingston on headset at EDG 102 panel in Main Control Room, E. O. - M. O'Brien on headset in EDG 102 room.
5:15:00	Noticeable increase in vibration in Main Control Room - W. Uhl, W. Nazzaro, W. Gunther approached Main Control room panel. Slight, but normal, fluctuation in load around 3.9 MW - no other indication of problem. Communication to EDG room for observation of any problem - only response was technician was in area taking readings.
5:15:45	Vibration continued and suddenly load swing of 1.5 to 2.0 MW commenced between 2 MW and 4 MW. Communication from CR to field - 'are you doing anything'. Within 15 seconds, load was reduced by CR operator to 1 MW. Vibration ceased. This load was carried for about 15 seconds.
5:16:15	Load increased without cause to 4.0 MW. Vibration increased again. Again communication between CR and EDG room regarding what was going on. W. Nazzaro, instructed Livingston to decrease load. Load would not come down.
5:16:30	W. Nazzaro instructed Livingston to trip the machine who immediately opened the output breaker. Speed was noted to reach 600 RPM before coasting down to rest.

Elapsed Time - 1 1/2 minutes"

3.6.3 Review of Previous Vibration Survey

There was ample evidence of concern over the vibratory amplitudes of the diesels. Review of the partial listing [15] of selected previous problems with the diesel generators also provided evidence of high dynamic forces that had the potential of being associated, on preliminary evaluation, with large amplitude torsional vibration. Should subsequent thorough evaluation prove this to be true, then many of the various component failures would no longer be isolated independent events as previously reported but linked to a common cause.

Until more information is available, the following evidence of repeated failures in components directly connected to the crankshaft remains circumstantial:

Date	Failure Description
3/30/83	Holddown capscrews, rocker arm assembly (EDG-103)
9/17/82	Jacket water pump shaft (EDG-102 & 103)
10/05/81	Piston crown separated from skirt
	Failure of attachment stud bolts
	Grooving of crankshaft bearing and crank pin discolored
	Wrist pin grooved and pitted, wrist pin discolored

TDI's torsional analysis summary [9] does indicate a strong 30-Hz cyclic torque component expected in the crankshaft, as discussed earlier in this report. Subsequent analysis of these failures using TDI's torsional model would be meaningful, but, by that time, the full results of the cyclic amplitudes measured in the torsion testing program under various loadings using instrumented diesel generator 101 would be available. Test data will more accurately reflect the real life situation.

Concern over vibration was sufficient to initiate a vibration testing program in the late spring and early summer of 1983 [2]. The conclusion of this study states:

> "On the basis of comparisons of vibration data taken, the Shoreham diesels have only the expected and normal vibration and are not subjected to any excessive vibration and this normal, expected vibration does not prevent the diesels from reliably performing their functions."

It is noted that the study was based entirely on linear vibration measurements without any measurement of torsional vibration. It is true that rotating machinery can suffer from high torsional vibration with little evidence of linear vibration. However, the crank mechanisms of diesel engines provide coupling between the torsional and linear vibratory systems so that there is usually evidence of linear vibration associated with torsional vibration.

A more thorough review of possible vibration coupling giving rise to a common cause will be performed in Phase II.

4. CONCLUSIONS

Although there is conjucture at this time regarding common cause linking of past failures with the crankshaft failure, the major conclusion that can be drawn is the following: the mechanism of crankshaft failure was fatigue; however, the source and nature of the fatigue cannot be established at least until the torsional test data are analyzed and compared to mathematical models of stress and to verified material properties in the crankpin fillets.

It is concluded from the torsional analysis performed by Transamerica Delaval, Inc. that a significant cyclic torque was expected in the crankshaft. However, additional design information must be reviewed to conclude whether the resulting design stresses in the crankpin fillets were calculated using the full stress concentrations at critical points.

5. RECOMMENDATIONS

It is recommended that the NRC continue to encourage the completion of the comprehensive failure analysis being conducted as a result of the Shoreham diesel generator failures, and that the resulting data and analysis be employed to establish an increased state of reliability for diesel generator applications in nuclear power plants.

It is also recommended that a survey program be established throughout the nuclear power industry employing the findings of this endeavor to identify failure potentials in other installations and to identify possible cases of common cause.

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APPENDIX A

INSPECTION COMMENTS CONCERNING DIESEL GENERATORS

A.1 Diesel Generator 101

Diesel generator 101 was located in its operational room and was being prepared for a limited test program. Accordingly, the crankshaft was exposed for inspection, cracks in cranks 5 and 7 were being ground out to reduce the associated stress concentration, and preparations were being made to install instrumentation. Instrumentation specialists at diesel 101 indicated that the planned instrumentation included a strain gage torque bridge on the crankshaft adjacent to the flywheel, strain gage rosettes in the crankpin fillets of cranks 5 and 7, vibration transducers (accelerometers) on various bearing journals, pressure transducers in two combustion cylinders, an angular displacement transducer (torsiograph) on the free end of the crankshaft (opposite the flywheel and generator), and a sensor on the generator shaft to indicate shaft position relative to top dead center of crank 7. This instrumentation was in various stages of preparation and installation.

The cracks on the crankshaft appeared to have been nearly ground out in accordance with the torsional test procedure [7]. Cracks in the crankshaft of diesel 101 were reported at the time to be approximately 1 inch deep prior to grinding. Crack locations included cranks 5 and 7, with the cracks making an approximate angle of 45° relative to the crankshaft (or crankpin) longitudinal axis. The crack on crank 7 was located in a 5 o'clock position relative to top dead center of crankpin 7 and on the fillet toward crank 8. The crack on crank 5 was located in a similar manner but in a 7 o'clock position on the crank pin fillet toward crank 6.

A.2 Diesel Generator 102

Diesel generator 102 was the unit with the fractured crankshaft. Diesel 102 had already been moved to the main turbine deck where space and crane facilities were available to disassemble the unit, make a thorough inspection, and rebuild it with the 13 x 12 crankshaft. Disassembly and inspection of the whole engine was progressing part by part, and while it had not progressed to the point of removing the fractured crankshaft, the fracture was clearly visible and open to close inspection through the sides of the engine block where the cover plates had been removed. Inspection of crank 7 revealed a fracture through the crank web and partially through the crankpin, with the fracture passing through the crankpin fillet at approximately the 5 o'clock and 7 o'clock positions with respect to top dead center of that crank. The tip of the V-shaped crack propagating out into the crankpin reached approximately to the midpoint of the crankpin bearing surface.

Further inspection of the fractured crankshaft (still assembled in diesel 102) revealed that one edge of the web at the fracture evidenced a large discolored area characteristic of heating to a temperature range of 400°F to 600°F. This discoloration was attributed to the considerable energy dissipated in sliding contact at the point of fracture and against the connecting rod during the relatively short time (approximately 1 1/2 minutes) that the diesel was believed to be under power (see page 3 of Reference 14) following the fracture.

Inspection of the sump revealed considerable debris under crank 7 as compared to other crank positions. Although accumulated dirt in the engine sump was heaviest toward the flywheel and generator end of the sump, the excessive accumulated debris of crank 7 proved to be mainly bearing material scraped out of the connecting rod bearing by the displaced fractured segment of the crankpin that acted as a sharp cutting tool during those moments of operation following crankshaft fracture.

Inspection of the crankshaft failure beyond that reported here was not conducted because the crankshaft was to be removed over the holiday (Labor Day) weekend and transported to the facilities of Failure Analysis Associates, Inc., in Palo Alto, CA, for immediate extensive examination.

A.3 Diesel Generator 103

Diesel generator 103 was observed to be under disassembly in its operational room in preparation for moving it to the turbine deck.

The crankshaft of diesel 103 was reported in the initial briefing to contain cracks of sufficient depth and magnitude to preclude further operation. Testing will be performed using diesel 101 only. The action plan for diesel 103 reportedly calls for complete disassembly, inspection, rework as necessary, and reassembly with a 13 x 12 crankshaft (13-in journal bearing diameter and 12-in crankpin diameter) now recommended and supplied by Transamerica Delaval, Inc. Analytical studies of the engine with this crankshaft will be carried out concurrently, with updates to the analysis being made as test data on diesel 101 become available.

APPENDIX B

RECOMMENDATIONS FOR MECHANICAL AND ELECTRICAL COUPLING INVESTIGATION

The following three recommendations were made [8] to ensure the recording of possible electrical-mechanical dynamic interactions in the course of diesel generator testing.

First, the generator output voltages for the three phases were not all slated for recording -- only $(V_A - V_B)$ and $(V_B - V_C)$. Hence, if electrical interactions occurred during the tests, a positive voltage phase reference would not be assured, but would be dependent upon the 3-phase generator voltage output remaining balanced. That is, only two measurements were being made, and that fact required the third voltage to be calculated from the 3-phase electrical vector relationship. This is possible only with the assumption that the voltage remains balanced on all three phases. When it was reported that the third voltage for recording could only be obtained with considerable difficulty, it was recommended that the voltage on each of the three phases be read and recorded separately (from the control room) so that each voltage would be known, should it be required for vector calculations. Although it was believed that the electrical power grid would certainly remain balanced during the recording of data during the synchronous load tests, the reading of the voltages would remove all doubt. For loadings derived from plant equipment (core spray, etc., versus the electrical power grid), the measurement of voltage was more meaningful.

Second, even though the generator rotor inertia was large, it was believed prudent to provide for the investigation of generator instabilities, especially since there could be significant cyclic torque at 30 Hz. Accordingly, it was recommended [8] that all vibrational data be recorded at power factors between 0.8 and 1.0 in synchronous load tests under as high a load as feasible. A load of 2550 kW was chosen from the test procedure to minimize engine run time at or near full load.

The background of this recommendation is that synchronous generators tend to be more unstable with low excitation (1.0 power factor) than with higher excitation (0.8 power factor). Also, page 1 of Reference 14 indicated that a significant amount of the testing on diesel 102 was performed at a power factor of 1.0. Diesel 102 was operating at power factor of 1.0 at the time of failure [14]. Further, means were not available immediately prior to the test to determine if the 30-Hz cyclic torque could aggravate generator instability. Hence, this consideration appeared to be a prudent course of action for thorough coverage of possible instabilities or mechanical-electrical interactions.

The third recommendation was that assurance be provided for the recording of any transients, mechanical and/or electrical, associated with synchronization and attachment of the diesel generator to the electrical power grid, and to any of the isochronous loads.

APPENDIX C

COMMENTS BY H. W. HANNERS ON THE SUMMARY OF SELECTED FAILURES AND EVENT REPORTS OF TDI DIESEL GENERATORS

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COMMENTS BY H. W. HANNERS ON THE SUMMARY OF SELECTED FAILURES AND EVENT REPORTS OF TDI DIESEL GENERATORS

Comments on the items as dated:

08/12/83

The broken crankshaft is believed to have been the result of excessive stress due to torsional vibration.

03/30/83

These screws may have failed as the result of inertial forces from engine operation at or near a torsionally critical speed as well as possible low quality in material, design or manufacture.

03/08/83

The cracked cylinder heads could have been the result of design, but the new design apparently needs to be tested by actual use and acceptance tests.

03/03/83

The high pressure fuel line failures could surely be reduced by design improvements of the shroud (usually called sleeve). Again, sufficient proof remains to be seen through in-service experience and acceptance tests.

12/13/82

Better quality obviously needed.

09/17/82

The omission or removal of the keyway in the water pump shafts could be avoided by eliminating the "stress raiser" effect of the keyway in torsional vibration. An impeller design change to reduce the rotary moment of inertia could also help.

07/22/82

Probably fixed by the change of design.

06/23/82

Change to neoprene is certainly an improvement over isoprene.

05/13/83

This probably should have been 05/13/82 from the "backtracking" review scheme being used.

05/13/82

The shorter capscrews may be satisfactory, but were the original screws actually too long or the threaded tapped holes too shallow?

03/19/82

Neither the problem nor the solution (or fix) are clearly explained. The 53-minute bleed down time is too long as a practical fix. Even 53 seconds is rather a long time to consider acceptable. Successive starts should certainly be allowed more often than 53 minutes apart. Seismic qualification of the sensing line is recommended.

03/15/82

This implies that the rear crankcase cover is a stress bearing part. Neither the strongest bolts nor the reasons for the basic failure give faith in the TDI remedy or explanation of the failure. More proof and further explanation are needed.

12/09/81

The TDI remedy of a lower oil cooler mounting seems reasonable, but the complete system should be reviewed.

11/05/81

The use of Belleville washers in the two-piece piston design may or may not be satisfactory, depending on whether the heat from the hot piston crown anneals the Belleville washers. Heat barrier design may also be required for success.

The cylinder liner grooving and the bearing grooving may very well be caused by "built in" dirt and chips in the original factory assembly. All three engines should certainly have the crankcases or bedplates thoroughly cleaned and all bearings examined and replaced as needed. A tedious, careful, and expensive job is indicated. This means not only the bearings, but also the surface of the mating parts such as the crankshaft crankpin and main journals and other parts would be damaged.

07/14/83 (or 07/14/81)?

Another indication of possible excessive vibration and or lack of proper clamping to prevent cracking of oil lines. Danger of fire from oil line fracture should certainly be given more attention.

03/23/81

Motors should certainly be qualified and not merely be stated to be equivalent.

12/16/80

A redesign of the lube oil system is indicated as necessary so that the turbocharger bearings get oil immediately after a start. This may mean a change to an intermediate drain back sump in addition to the main oil sump of the turbocharger. Acceptance of occasional "fast starts" is not sufficient as this is tantamount to saying that dry bearings are tolerable.

All of the remarks and critique of the items regarding the TDI engines are intended to be constructive and helpful. However, practically all of the suggestions are subject to testing in actual service and qualification under NRC regulations.

During the nuclear power plant survey and inspections done in 1978 and 1979, performed at the University of Dayton (Dayton, Ohio), a grand total of 288 items were investigated. Most of these subject items were found in every power plant of this survey.