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August 16, 1984

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James L. Kelley, Chairman
Administrative Judge
Atomic Safety and Licensing Board
U.S. Nuclear Regulatory Commission
Washington, D.C. 20555

Dr. Paul W. Purdom
Administrative Judge
235 Columbia Drive
Decatur, Georgia 30030

Dr. Richard F. Foster
Administrative Judge
P.O. Box 4263
Sunriver, Oregon 97702

Re: Docket Nos. 50-413 and 50-414
Catawba Nuclear Station, Units 1 and 2

Dear Administrative Judges:

In the limited time available to us, Palmetto Alliance and Carolina Environmental Study Group have reviewed the recent reports prepared by Duke Power Company, Battelle-Pacific Northwest Laboratory (PNL) and the NRC Staff regarding the reliability of the Transamerica Delaval, Inc. (TDI) emergency diesel generators at the Catawba Nuclear Station. We strongly disagree with the conclusions expressed in those reports that the TDI diesel generators will provide a reliable source of back-up power as required by General Design Criterion 17 and that there is demonstrated reasonable assurance to support interim licensing of Catawba through the first refueling outage. We contend that a pattern of deficiencies exists in the Catawba diesels, precluding such a finding. These deficiencies, known and unknown,"stem from inadequacies in design, manufacture and quality assurance/quality control by TDI." SER on Catawba, Unit 1, TDI Diesel Generators, p. 1 (August 14, 1984).

The specific bases for our contentions regarding the Catawba diesels is amply reflected in the record and includes the long series of NRC Staff Board Notifications on the subject, beginning with B.N. No. 83-160 of October 21, 1983, and the items referenced in PNL's Catawba Technical Evaluations Report (TER) at pp. 6-8. To the extent these reports and documents are not already matters of record we ask the Board to consider them as such for purposes of further rulings on our contention.

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In a series of rulings beginning with the Partial Initial Decision of June 22, 1984 (pp. 272-74, fn. 50) this Board has conditioned the conduct of hearings on the Board's former sua sponte diesel contention on further showings by intervenors of their ability to "make a significant technical contribution" through certifying either that a sufficiently qualified diesel expert will appear at the hearings for us or that such an expert will provide substantial assistance to us by preparing a "detailed statement of technical position" regarding the Duke, PNL and Staff reports and prefiled testimony. This statement must also specify "the respects in which (intervenors) disagree with these reports, and (describe) how (intervenors) propose to substantiate their positions." Memorandum and Order (Concerning Hearing and Associated Dates and Expert Assistance for the Diesel Generator Contention) p. 4, July 20, 1984.

As we stated in our August 1, 1984 letter we were unable to certify that Dr. Anderson, our metallurgical expert, would be present at the Catawba hearings due to his prior commitments to consult with and prepare testimony for intervenor, Suffolk County, on the Shoreham diesel generator contentions. In its July 20, 1984 Order, p. 3, the Board observed that where Dr. Anderson's assistance to the Catawba intervenors was based upon his work at Shoreham such assistance would be inadequate because "the diesel engine models and the admitted contentions at Shoreham and Catawba are different. Indeed, the Catawba contention is restricted to problems that have actually arisen in testing the Catawba diesels."

To the contrary, we maintain that the work of Dr. Anderson and the other experts retained by Suffolk County in addressing the TDI Owners' Group Program, the investigation by Failure Analysis Associates, the inadequacies in design, manufacture and quality assurance/quality control by TDI, as well as the adequacy of critical components of the Shoreham diesels bears direct relevance for the resolution of the Catawba TDI diesel generator contention.

As is reflected in the Shoreham emergency diesel generator contention, attached hereto as Exhibit 1, the intervenor Suffolk County and its experts focus their claims and technical analysis on four critical components:

1. the heavier replacement crankshafts;
2. the cylinder blocks;
3. the cylinder heads;
4. the Model AE piston skirts.

Suffolk County contends that the TDI diesels at Shoreham "will not operate reliably and adequately perform their required functions because (they) are over-rated and undersized, improperly designed, and not satisfactorily manufactured." Id.

We maintain that the Shoreham experts' analysis of these four critical components, as well as of TDI design and manufacturing deficiencies, provides intervenors, here, with the ability to make a substantial contribution to a sound record for decision on the adequacy of these components and on other deficiencies in the Catawba TDI diesels.

The NRC Staff and its consultant, PNL, themselves rely on the results of Shoreham component analyses in reviewing the adequacy of the Catawba diesels as reflected in the August TER:

Component	PNL TER Page
Cylinder heads	16
Fuel Line Fittings	20
Fuel Oil Injection Pump Valve Holder	22
Turbocharger Bedrings	24
Turbocharger Lube Oil Drain Line	28
Turbocharger Prelube Oil Lines	29
Turbocharger Exhaust Gas Inlet Bolts	31
Lube Oil and Jacket Water Thermocouples	35
Rocker Arm (Subcover) Assemblies	37
Intermediate Rocker Arm Sockets	39
Exhaust Valve Tappet (Rocker Arm Adjusting Screw Swivel Pad)	41
Intake and Exhaust Valves	42
Spring Retaining Nut and Roll Pin or Air Start Valves	44
Cylinder Blocks	51
Rocker Arm Capscrews	57
High Pressure Fuel Tubing	64
Jacket Water Pumps	65

Clearly, no judgement can be reached about the significance of known problems at Catawba or the ultimate safety of the Catawba diesels without reference to the knowledge gained through the analysis performed on other similar TDI engines and components by the TDI Owners' Group <u>and</u> the expert consultants to other intervenors such as at Shoreham. The Staff's consultants acknowledge as much:

> PNL's conclusions and comments are based on the available Duke Power Company documents, on on-site inspections of the Catawba engine components and examination of identical or at least similar components of TDI diesels in other nuclear facilities, reviews of the specific known-problem issue reports prepared by (or under the auspices of) the TDI Owners' Group . . . .

PNL TER, p. 10.

Palmetto and CESG specifically dispute the Duke and NRC Staff conclusions regarding the adequacy of the four critical components as analyzed in the pre-filed testimony of the Shoreham experts, attached hereto as Exhibit 2.

Crankshafts

PNL acknowledges that three V-16 crankshaft failures have been reported in non-nuclear applications, two of which were attributed to torsional stress. Indications, characterized as minor, have been detected in the Catawba 1A crankshaft. Since the TDI Owners' Group analyses of the RV-16 crankshafts "are not yet finalized to acceptable conclusions, in PNL's view, PNL cannot conclude in an unqualified manner that the Catawba crankshafts are unreservedly reliable." PNL TER pp. 46-48. On the basis of the Shoreham intervenor experts' analysis we would seek to show that the Catawba crankshafts are inadequately designed and manufactured. Exhibit 2, pp. 106-142.

Cylinder Blocks

Numerous incidents of cylinder block cracking have been reported in TDI engines in both non-nuclear and nuclear applications. The Failure Analysis Associates study confirms that cracks will initiate in these blocks which they predict to be "benign." While Duke's 1A inspection has revealed no cracks, PNL acknowledges that

> (I)n light of the history of block cracks and the FaAA analysis, PNL and its diesel consultants remain concerned that even at Catawba there remains legitimate reason to maintain enhanced surveillance of the blocks at least through the first opportunity for heads-off reinspection and until a more definitive resolution of the problem is established by the Owners' Group and Duke.

PNL TER pp. 51-52, 84-85.

On the basis of the Shoreham intervenor experts' analysis we would show that the Catawba TDI cylinder blocks are not properly designed and manufactured to withstand the stresses of service, Exhibit 2, pp. 143-183; and that far from being "benign" such block cracks could lead to catastrophic failure of the emergency diesel. Id., at pp. 151-156.

Cylinder Heads

Numerous reports of TDI cylinder head failures have been identified in nuclear and non-nuclear applications, including a recent two-inch through-wall crack into the cylinder cavity in the DSRV-16 engine at Grand Gulf and small water jacket leaks in the Catawba 1A and 1B engines.

PNL review of the FaAA report and the Shoreham analysis leads it to support interim licensing of Catawba until first refueling "provided that the engine is barred-over ... (periodically), and thereafter prior to each planned start, to check for water leakage into the cylinders." PNL TER, pp. 16-19.

On the basis of the Shoreham intervenor experts' analysis Palmetto and CESG would show that neither the pre-1978 nor the post-1978 designed and manufactured heads are adequate for the intended service; that unacceptable variations in dimensions induce stresses; that changes in manufacturing techniques have not solved the flaw and crack problems; and that the "barring-over" procedure will not identify all leaks into the cylinder which could prevent starting, or cause catastrophic engine failure. Exhibit 2, pp. 59-105.

AE Piston Skirts

After identifying four cracked piston skirts in the 1A engine at Catawba, and upon the NRC Staff's insistence, Duke finally agreed to replace the Catawba "AN" Model piston skirts with TDI's improved design, Model "AE" skirts. FaAA analysis for the Owners' Group concludes that the "AE skirts may crack at 10% overload" but will not propogate. PNL and NRC Staff interim acceptance of the AE skirts is conditioned upon reduction in the generator loading from its 7000 KW nameplate rating to about 5750 KW such that stresses are maintained below 185 psig BMEP -- equivalent to the only significant operating experience with the AE skirts in the Kodiak station application. PNL TER, pp. 11-13.

> The need for this is based on PNL and Staff concerns regarding the acceptability of crankshaft stresses, and the lack of substantial AE piston operational data at higher BMEP loadings.

SER p. 6.

On the basis of the Shoreham intervenor experts' analysis of the inadequacies of the TDI "AE" piston skirts, Palmetto and CESG would demonstrate that the Failure Analysis Associates conclusions underestimate projected crack propogation due to dimensional variations, imperfections, and actual operating environment, temperatures and pressures. Excessive piston side thrust and tin plating also exacerbate stress failure potential. The diesels are over-rated for the "AE" piston design. Exhibit 2, pp. 25-59.

The reduction in diesel loading to 5750 KW to accomodate the crankshaft and piston skirt uncertainties reduces the diesel's capacity to only marginally above their 5714 KW loss-of-offsite power emergency service loads. SER p. 6. Such reduction in design conservation is inappropriate to sustain licensing.

Palmetto and CESG continue to assert that the Board has unfairly required intervenors to shoulder burdens not properly imposed upon us as the proponents of this diesel generator contention. We believe that Duke Power Company, as the Applicant, properly is charged with the burden of proving the safety of its nuclear plant, including the TDI emergency diesel generators. However, we submit that we have shouldered the burdens imposed upon us by the Board to demonstrate that our participation "may reasonably be expected to assist in developing a sound record," on this important contention. 10 CFR 2.714(a)(1)(iii).

As observed by Judge Edles, concurring, in Washington Public Power Supply System (WPPSS Nuclear Project No. 3), ALAB 747, 18 NRC 1167, 1182 (1983):

> Our cases clearly recognize that cross-examination can be an especially valuable tool in the development of a full record and that an intervenor may even establish its entire case through its use.

We submit the enclosed analyses of Dr. Robert N. Anderson, Professor Stanley G. Christensen, G. Dennis Eley, Aneesh Bakshi, Dale G. Bridenbaugh and Richard B. Hubbard, prefiled direct testimony on the Shoreham diesel generator contention, Exhibit 2, as an offer of proof pursuant to 10 CFR 2.743(e) and in support of our diesel generator contention as a statement of the substance of the evidence we seek to establish through cross-examination of Applicants' and NRC Staff's witnesses and the documentary evidence referenced herein.

We trust that this submission fully discharges the duties to be borne by intervenors and that the issues regarding the adequacy of the Catawba diesels will be resolved on the record of the scheduled public hearing.

Sincerely,

Robert Guild

cc: Service List
(w/ encl. to parties)

SHOREHAM EMERGENCY DIESEL GENERATOR CONTENTION

Contrary to the requirements of GDC 17, the emergency diesel generators at Shoreham ("EDGs") manufactured by Transamerica Delaval, Inc. ("TDI") will not operate reliably and adequately perform their required functions because the EDGs are over-rated and undersized, improperly designed, and not satisfactorily manufactured. There can be no reasonable assurance that the EDGs will perform satisfactorily in service and that such operation will not result in failures of other parts or components of the EDGs due to the over-rating or insufficient size of the EDGs or design or manufacturing deficiencies. The EDGs must therefore be replaced with engines of greater size and capacity, not designed or manufactured by TDI. [Suffolk County's Filing Concerning Litigation of Emergency Diesel Generator Contentions, June 11, 1984 ("June 11 Filing") at 2; Tr. 21,891]

BECAUSE:

1.(a) The replacement crankshafts at Shoreham are not adequately designed for operating at full load (3500 kW) or overload (3900 kW), as required by FSAR Section 8.3.1.1.5, because they do not meet the standards of the American Bureau of Shipping, Lloyd's Register of Shipping, or the International Association of Classification Societies. In addition, the replacement crankshafts are not adequately designed for operating at overload, and their design is marginal for operating at full load, under the German criteria used by F.E.V. [Tr. 21,878-79]

(b) The shot peening of the replacement crankshafts was not properly done as set forth by the Franklin Research Institute report, Evaluation of Diesel Generator Failure at Shoreham Unit 1, April 6, 1984, and the shot peening may have caused stress nucleation sites. The presence of nucleation sites may not be ascertainable due to the second shot peening of the crankshafts. [Tr. 21,880]

(c) The crankshaft oil passage plugs on the replacement crankshafts are inadequate, as evidenced by the failure of the same design plugs on a TDI DSR-48 engine owned by Rafha Electricity Corp., which damaged the pistons of that engine. [June 11 Filing at 4; Tr. 21,881-82]

2. Cracks have occurred in the cylinder blocks of all EDGs, and a large crack propagated through the front of EDG 103. The replacement cylinder block for EDG 103 is a new design which is unproven in DSR-48 diesels and has been inadequately tested. [Tr. 21882-3]

3. The replacement cylinder heads on the Shoreham EDGs are of inadequate design and manufacturing quality to withstand satisfactorily thermal and mechanical loads during EDG operation, in that:

(a) the techniques under which the replacement cylinder heads were produced have not solved the problems which caused the cracking of the original cylinder heads on the Shoreham EDGs;

(b) the "barring over" surveillance procedure to which LILCO has committed will not identify all cracks then existing in the replacement cylinder heads (due to symptomatic water leakage);

(c) the nature of the cracking problem and stresses exacerbating the cracks are such that there can be no assurance that no new cracks will be formed during cold shutdown of the EDGs;

(d) there can be no assurance that cracks in the replacement cylinder heads and concomitant water leakage occuring during cold shutdown of the EDGs (which would not be detected by the barring-over procedure) would not sufficiently impair rapid start-up and operation of the EDGs such that they would not perform their required function;

(e) there can be no assurance that cracks in the replacement cylinder heads occurring during operation of the EDGs would not prevent the EDGs from performing their required function;

(f) variations in the dimensions of the firedeck and water deck of the replacement cylinder heads create inadequate cooling, where too thick, and inadequate resistance to mechanical loads, where too thin, and create stress risers at their boundaries;

(g) the design of the replacement cylinder head is such that stresses are induced due to non-uniform bolt spacing and the different lengths of the bolts;

(h) the replacement cylinder head design does not provide for adequate cooling of the exhaust valves;

(i) at least one replacement cylinder head at Shoreham has an indication;

(j) the design of the replacement cylinder heads provides inadequate cooling water for the exhaust side of the head; and

(k) the replacement cylinder heads at Shoreham were inadequately inspected after operation, because:

(1) a liquid penetrant test was done on the exhaust and intake valve seats and firedeck area between the exhaust valves on only 9 of the 24 cylinder heads, and such tests were done after only 100 hours of full power operation;

(2) ultrasonic testing was done on the firedeck areas of only 12 cylinder heads;

(3) visual inspections were performed on the valve seat areas of only 32 of the 98 valves, and on only 7 firedecks of the 24 cylinder heads for indications of surface damage. [Suffolk County's Motion for Reconsideration of Portions of Board's July 5 EDG Order, at 1-3, as granted in part and modified (in sub-paragraph (j)) by order of the Board during a teleconference of the parties on July 11, 1984]

4. All AF piston skirts in the EDGs were replaced with TDI model AE piston skirts. The replacement AE pistons are of inade-

quate design and manufacturing quality to satisfactorily withstand operating conditions, because:

(a) the FaAA report conclusion that cracks may occur but will not propagate improperly depends on a fracture mechanics analysis of an ideal situation which is not valid for the actual conditions which may be experienced by the Shoreham diesels,

(b) excessive side thrust load, which could lead to catastrophic failure, has not been considered adequately, and

(c) the analysis does not adequately consider that the tin-plated design of the pistons could lead to scoring causing excessive gas blow-by, and thereby causing a failure of proper operation. [Tr. 21,886-88]

EXHIBIT 2

SUFFOLK COUNTY, 7/31/84

UNITED STATES OF AMERICA
NUCLEAR REGULATORY COMMISSION

Before the Atomic Safety and Licensing Board

In the Matter of	)	
LONG ISLAND LIGHTING COMPANY	)	Docket No. 50-322-OL
(Shoreham Nuclear Power Plant, Unit 1).	)	

JOINT DIRECT TESTIMONY OF DR. ROBERT N. ANDERSON, PROFESSOR STANLEY G. CHRISTENSEN, G. DENNIS ELEY, ANEESH BAKSHI, DALE G. BRIDENBAUGH AND RICHARD B. HUBBARD REGARDING SUFFOLK COUNTY'S EMERGENCY DIESEL GENERATOR CONTENTIONS

INTRODUCTION

Q. Dr. Anderson, please state your name, address and occupation.

A. My name is Robert N. Anderson, and my business address is Department of Materials Engineering, San Jose State University, San Jose, California. I am a Professor of Materials Engineering at San Jose State University.

Q. Please describe your qualifications and experience which are relevant to the matters you address in this testimony.

A. I have a doctoral degree in metallurgy, a masters of science degree in chemical engineering and a bachelor of science degree in chemistry. My duties as Professor of Materials Engineering include teaching courses in casting and nuclear materials. I am a licensed metallurgical engineer and nuclear engineer in the State of California, and I have qualified in court as an expert witness in metallurgy. I have actively consulted in the field of failure analyses for 10 years. During that time, I have served as consultant to a wide range of businesses, research facilities and local, State and Federal agencies and commissions, including the California Public Utilities Commission, Brookhaven National Laboratories, IBM, Memorex, Lawrence Livermore Laboratory, the California State Energy Resources and Development Commission, the Executive Office of the President of the United States, Council on Environmental Quality and Office of Science and Technology Policy, and the Office of Technology Assessment of the United States Congress. I have published over 50 articles and I have had numerous patents issued to me in the field of materials science, including fuel cycle patents and a nuclear reactor patent. I am actively involved in professional activities, holding membership in the American Nuclear Society, the American Institute of Chemical Engineers, the American Chemical Society, the

American Society of Metals and the National Society for Professional Engineers, among others. I am also a member and past Chairman of the Northern California Section of the American Institute of Metallurgical Engineers. A further statement of my professional qualifications is attached to this testimony as Attachment 1.

Q. What parts of this joint testimony have you especially sponsored?

A. I am particularly sponsoring all of the testimony pertaining to metallurgical science, including the properties of materials, crack initiation, propagation and arrest, details of the casting process followed by Transamerica Delaval, Inc.("TDI"), and analyses of the various methodologies applied by Failure Analysis Associates to matters of crack initiation and growth. I have not provided testimony regarding the functions or NRC regulatory requirements for emergency diesel generators.

Q. Professor Christensen, please state your name, address and occupation.

A. My name is Stanley G. Christensen. I am a Professor at the U.S. Merchant Marine Academy, Kings Point, New York.

Q. Please describe your qualifications and experience which are relevant to the matters you address in your portion of this testimony.

A. Since coming to Kings Point in 1978, I have had responsibility for teaching various courses on diesel engines, including Internal Combustion Engines I and II, Diesel Engine Maintenance, Marine Engineering I, II and III, Medium Speed Diesel Engines, Diesel Propulsion Systems for Marine Engineers, Fundamentals of Marine Diesel Systems, and Diesel Ship Operation and Control for Masters and Mates. From 1950 until 1978, I held various positions and was engaged in all aspects of diesel machinery for a variety of shipping companies and served as an engineer surveyor at Lloyd's Register of Shipping. Prior to 1950, I served as a senior lecturer at Poplar Technical College, London, England, and taught various subjects, including Strength of Materials, Thermodynamics, Theory of Machines, Mechanics Static and Dynamics, and Engineering Design. I also served at sea in merchant ships for 10 years, sailing finally as Chief Engineer. I have nearly 50 years experience with diesel engines. I am a long-standing member of the Institute of Marine Engineers, having served on the Membership, Financial and General Purposes, and Education Group Committees and on the Special Committee on Engineering Institutions Joint

Council. I have also served as a member of the Institute's London Council and as a member and past Chairman of the Eastern United States Council. I authored the latest edition of Lamb's Questions and Answers on the Marine Diesel Engine. I have read technical papers on subjects related to diesel engines and diesel engine repairs at many Technical Conferences in, among other places, Singapore, Lisbon, New York and London. A further statement of my professional qualifications is attached to this testimony as Attachment 2.

Q. Professor Christenson, what parts of the joint testimony have your particulary sponsored?

A. I have addressed all of the matters regarding the design, manufacture and rating of diesel engines and their componENTS. I have not provided testimony on NRC regulatory requirements or on matters purely of metallurgical science.

Q. Mr. Eley, please state your name, address and occupation.

A. My name is George Dennis Eley. I am a marine consultant employed by Ocean Fleets Consultancy Service, Midatlantic Corporate Center, 1501 Grandview Avenue, Thorofare, New Jersey 08086.

Q. Please describe your qualifications and experience which are relevant to the matters you address in your testimony.

A. I am a licensed marine engineer currently employed in providing services to the marine industry, especially with respect to large diesel engines. I also act as a marine consultant on machinery damage investigations and system design for fuel consumption efficiency, and lecture on fuel technology at the U.S. Merchant Marine Academy and other educational institutions. Between 1969 and 1981, I was employed as a marine engineer responsible for operating and maintaining diesel engine power plants on ocean-going vessels. Between 1966 and 1969, I was employed by an engineering firm providing consulting services on the machinery aspects of shipbuilding projects. Between 1959 and 1966, I was employed in the engine design department of a British marine diesel engine manufacturer. A more complete statement of my professional qualifications is attached to this testimony as Attachment 3.

Q. Mr. Eley, what parts of the joint testimony are you sponsoring?

A. I have addressed matters regarding diesel engine design, manufacture and operation, especially with respect to the replacement crankshafts. I have not provided testimony on NRC regulatory requirements or matters purely of metallurgical science.

Q. Mr. Bakshi, please state your name, address and occupation.

A. My name is Aneesh Bakshi. I am a marine surveyor and consultant employed by Ocean Fleets Consultancy Service, with my colleague, Mr. Eley.

Q. Please describe your qualifications and experience which are relevant to the matters you address in this testimony.

A. I am a licensed marine engineer. I hold a master of science degree in marine transportation management and a bachelor of science degree in marine engineering. As a marine surveyor and consultant, I coordinate machinery (including diesel engines) repairs and undertake hull and cargo surveys on ocean-going vessels. Between 1978 and 1981, I was employed as a chief engineer/port engineer coordinating machinery (including diesel engines) repairs and maintenance on ocean-going vessels for a British shipping company. Between 1969 and 1978, I was employed in various engineering capacities associated with marine machinery (including diesel engines) for two shipyards and a shipping company. A further statement of my professional qualifications is attached to this testimony as Attachment 4.

Q. Mr. Bakshi, what parts of the joint testimony have you particularly addressed?

A. I have addressed similar matters as Mr. Eley, except that I have especially focused on issues concerning the replacement crankshafts and cylinder blocks.

Q. Mr. Bridenbaugh, please state your name, address and occupation.

A. My name is Dale G. Bridenbaugh. I am president of MHB Technical Associates, a technical consulting firm on nuclear power plant safety and licensing matters located at 1723 Hamilton Avenue, Suite K, San Jose, California 95125.

Q. Please describe your qualifications and experience relevant to the matters you address in this testimony.

A. I hold a bachelor of science degree in mechanical engineering and am a licensed professional nuclear engineer. Since 1976, I have acted as a consultant to a large number of domestic and foreign government agencies and other groups on nuclear power plant safety and licensing matters. Between 1966 and 1976, I was employed by the Nuclear Energy Division of General Electric Company in various managerial capacities relating to the sale, service and product improvement of nuclear power reactors manufactured by that company. Between 1955 and 1966, I was employed in various engineering capacities working with gas and steam turbines for General Electric. I have written numerous technical papers and articles on the subject of nuclear power equipment and nuclear power plant safety that have been published in technical journals and have given extensive testimony on those subjects. A further statement of my professional qualifications is attached to this testimony as Attachment 5.

Q. Mr. Bridenbaugh, what parts of this joint testimony are you sponsoring?

A. I have addressed matters regarding NRC regulatory requirements for emergency diesel generators and, generally, engineering concerns with respect to the diesels.

Q. Mr. Hubbard, please state your name, address and occupation.

A. My name is Richard B. Hubbard. I am vice president of MHB Technical Associates, which was identified by my colleague, Mr. Bridenbaugh.

Q. Please describe your qualifications and experience relevant to the matters you address in this testimony.

A. I hold a bachelor of science degree in electrical engineering and a masters degree in business administration. I am a licensed quality engineer. Since 1976 I have acted as a consultant to a large number of domestic and foreign government agencies and other groups on nuclear power plant safety and licensing matters. Between 1971 and 1976, I was manager of quality assurance for two departments of General Electric Company engaged in the manufacture of nuclear energy equipment. Between 1964 and 1971 I was employed in various engineering capacities with the Nuclear Instrumentation Department of General Electric. Between 1960 and 1964 I worked in various engineering capacities for non-nuclear elements of General Electric. I have written numerous technical papers and articles on the subject of nuclear power plant safety and have given extensive testimony on that subject. A further statement of my professional qualifications is attached to this testimony as Attachment 6.

Q. Mr. Hubbard, what parts of this joint testimony are you sponsoring?

A. I have concentrated on the areas of emergency diesel generator functions and regulatory requirements, the manufacturing quality of the pistons, cylinder heads and blocks, and the inspections of those components.

Q. What is the purpose of your testimony?

A. The purpose of our testimony is to demonstrate the validity of the first paragraph of Suffolk County's Emergency Diesel Generator Contention by addressing the specific issues set forth in the numbered paragraphs of the Contention. The first paragraph states:

> Contrary to the requirements of GDC 17, the emergency diesel generators at Shoreham ("EDGs") manufactured by Transamerica Delaval, Inc. ("TDI") will not operate reliably and adequately perform their required functions because the EDGs are over-rated and undersized, improperly designed, and not satisfactorily manufactured. There can be no reasonable assurance that the EDGs will perform satisfactorily in service and that such operation will not result in failures of other parts or components of the EDGs due to the over-rating or insufficient size of the EDGs or design or manufacturing deficiencies. The EDGs must therefore be replaced with engines of greater size and capacity, not designed or manufactured by TDI.

Q. How is this testimony organized?

A. The testimony will first address the capacity and capability of the EDGs to perform their safety functions, and the regulatory standards for operating service and safety functions which the EDGs and their components are required to meet. Then, we will address the safety significance of deficiencies in four major EDG components: the AE model pistons, the cylinder heads, the crankshafts, and the cylinder blocks.

Q. What are the EDGs?

A. They are TDI model DSR-48 diesel engines with 8 cylinders in line, having a 17" stroke and a 21" bore. When combined with their generators, the EDGs are intended to provide reliable onsite emergency power to the Shoreham plant in conformity with 10 C.F.R. Part 50, Appendix A, General Design Criterion 17 ("GDC 17").

Q. Have the EDGs experienced problems?

A. Yes. A broad pattern of deficiencies in critical TDI diesel engine components has become evident at Shoreham and at other nuclear and non-nuclear facilities. These deficiencies stem from inadequacies in design, manufacture and quality control by TDI, and resulted in the NRC Staff losing confidence in the reliability of TDI diesels including the EDGs.1/

1/ See Board Notification 84-020, February 13, 1984, "Report of Meeting of Representatives of the Transamerica Delaval, Inc. (TDI) Emergency Diesel Generators Owners' Group."

Q. How did LILCO address these problems?

A. LILCO and the other nuclear utilities issued the TDI Diesel Generators Owners' Group Program Plan ("Owners' Group Program"),2/ which embodied three major efforts:

1. Resolution of 16 Known Generic Problem Areas;
2. Design Review of Important Engine Components and Quality Revalidation ("DRQR") of Important Attributes for Selected Engine Components and;
3. Expanded Engine Testing and Inspection.

Q. Has the Owners' Group Program adequately resolved all the deficiencies in the design, manufacture, and QA/QC of the EDGs?

A. No. We conclude, for the reasons set forth in this testimony, that this after-the-fact investigation of the EDGs conducted by the Owners' Group and its principal subcontractors, Failure Analysis Associates ("FaAA") and Stone and Webster Engineering Corp. fails to provide a sufficient level of assurance that the EDGs and their critical components, the

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2/ Board Notification 84-051, March 12, 1984, "TDI Diesel Generators Owners' Group Program Plan," dated March 2, 1984.

pistons, the cylinder heads, the crankshafts and the cylinder blocks, will operate reliably and with appropriate capacity and capability to adequately perform their required functions and that additional parts and components of the EDGs will not fail.

Functions and Requirements for EDGs

Q. What regulatory requirements must the EDGs meet?

A. The EDGs constitute the onsite electrical power system for the Shoreham plant. They must meet the requirements of GDC 17, which stipulates that, assuming the absence of the offsite electric power system, they shall

> provide sufficient capacity and capability to assure that (1) specified acceptable fuel design limits and design conditions of the reactor coolant pressure boundary are not exceeded as a result of anticipated operational occurrences and (2) the core is cooled and containment integrity and other vital functions are maintained in the event of postulated accidents.

(Emphasis added). LILCO has described in the Shoreham Final Safety Analysis Report ("FSAR") how the requirements of GDC 17 are addressed.

Q. What are the major required safety functions for the EDGs stated in the FSAR?

A. The FSAR provides that the EDGs must be fully capable of reliably performing two critical safety functions. First, it must be demonstrated that the EDGs will start and reach rated frequency and voltage within 10 seconds.3/ Second, it further must be demonstrated that the EDGs have sufficient load carrying capability to satisfy the continuous and overload performance rating.4/

Q. What is the rating for the EDGs?

A. Diesel engines for generators, such as the EDGs, are rated by their manufacturers as to engine speed and horsepower, and as being capable of meeting certain specific performance criteria within allowable temperature and pressure limits. TDI rated the EDGs at a speed of 450 RPM and at 4,890 horsepower (about 611 HP per cylinder), with a performance rating as required by LILCO's contract specification5/ and the FSAR for Shoreham. Section 8.3.1.1.5 of the FSAR requires each EDG to be rated to operate continuously (8,760 hours, or one year) at full load of 3,500 kW (with maintenance intervals required by

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3/ FSAR, p. 8.3-14.

4/ FSAR, p. 8.3-5.

5/ Stone and Webster Specification for Diesel Generator Sets, SH1-89, October 3, 1973 and addendum 1 to 5 thereto.

TDI) and for 2 hours per 24 hours at overload of 3,900 kW (without reducing the maintenance interval established for the continuous rating).

Q. Isn't this rating different from the actual loads the EDGs are likely to see in service?

A. Yes. The maximum continuous load imposed on the EDGs is less than the continuous rating, and the maximum intermittent load is less than the 2 hour rating.6/ However, the rating requirement is to provide necessary confidence that the maximum actual power demands will reliably be met and that accordingly the requirements of GDC 17 will be fulfilled. Therefore, the proper criterion for whether the EDGs and their components can satisfactorily withstand operating conditions is whether they can be expected to operate at the rated levels without experiencing failures or incipient failures.

Q. Hasn't LILCO applied to the NRC to reduce the performance rating for the EDG and revise the FSAR accordingly?

A. It appears so. In a recent letter to the NRC,7/

6/ FSAR, Section 8.3.1.1.5, p. 8.3-8; see also FSAR Tables 8.3.1-1 and 8.3.1-2.

7/ Letter from J. D. Leonard, Jr. (LILCO) to Harold R. Denton (NRC), dated July 3, 1984, SNRC-1065.

LILCO proposed to remove one service water pump from auto-start on an accident signal, thereby reducing the maximum load on EDG 103 (prior to 10 minutes) from 3880.7 kW to 3442.7 kW. Section 8.3.1.1.5 of the FSAR would be revised to read:

> The rating of each diesel generator is 3500 kW. The required load on each diesel generator is enveloped as follows:
>
> | | |
> |---|---|
> | Continuous | 3475 kW |
> | 2 hr per 34 hr period | 3500 kW |

Q. What is your reaction to this proposal?

A. Insofar as it would reduce the performance rating for the EDGs, in contrast to reducing the actual loading on the EDGs, we believe the proposal would be detrimental for providing confidence that the EDGs can operate reliably. The existing performance ratings already lack conservatism. For example, the maximum loads (after 10 minutes) on EDGs 101 and 102 are approximately 3400 kW each; the continuous rating is only 100 kW more, a margin of only 2.9%.8/ The EDG 103 load condition may be even less conservative. While the proposed change reduces the "prior to ten minutes" load to less than 3500 kW, LILCO's proposed change also includes the possibility

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8/ FSAR Table 8.3.1-1, 4 of 4.

of manual start of the second service water pump after ten minutes. Depending on what other equipment is available, it may not be possible to stop the second RHR pump coincident with this post-ten minutes load, and the EDG 103 load would then be back up to approximately 3900 kW. The usual practice for diesel engines in non-nuclear electric generating plants and in marine applications is to operate them at only about 75-85% of their ratings, in order to provide a conservative margin of safety.9/ To provide a similar safety margin for the EDGs, LILCO should have procured diesels with a continuous rating of at least 3910 kW. Clearly there should be no further reduction in the margin of confidence intended to be supplied by the current EDG rating.

Q. How do manufacturers of large diesel engines like the EDGs establish the rating of their engines?

A. In our experience, manufacturers generally establish the rating of a new model engine by running the engine on a test stand for thousands of hours at the load levels at which they seek to rate the engine. The engine is inspected

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9/ Mr. Museler of LILCO agrees. Deposition of William J. Museler (May 22, 1984) ("Museler Deposition") at 9. (Exhibit 1).

periodically. If adverse effects appear, such as cracking or unusually high wear rates, changes may be made to attempt to remedy the problems and the engine testing will begin again. In short, the rating process is empirical and involves many test hours.

Q. How did TDI establish the rating of the EDGs?

A. TDI establishes the rating for its engines by testing.10/ TDI uses the DEMA standard for rating, which calls for continuous operation at full load with a 10% overload for two hours in each 24 hour period.11/ However, TDI tested the first DSR-48 engine (the model of the EDGs) rated at about 610 HP per cylinder for only 24 hours or less.12/ In our opinion, such a test is grossly inadequate to determine the proper rating of the EDGs. Even the diesel expert for LILCO and the TDI Owners' Group, Dr. Chen, testified that to establish the proper rating for the first DSR-48 model engine it should have been tested in each 24 hour period for 22 hours at 3,500 kW and for 2 hours at 3,900 kW for at least 1,000 hours, be fitted with

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10/ Deposition of Clinton Mathews (May 8, 1984) ("Mathews Deposition") at 27, 29. (Exhibit 2).

11/ *Id*. at 25-26, 30.

12/ *Id*. at 35.

strain gauges to estimate stresses, and then disassembled to look for wear rates and indications.13/

Q. Does TDI believe the EDGs were properly rated by the 24 hour test of the first DSR-48?

A. Yes, because according to Mr. Mathews, vice president and general manager of the Engine Compressor Division of TDI, before the 24 hour test, most components of the DSR-48 had been tested extensively in other model TDI engines at equivalent loads.14/ Those components common to the other TDI engines and tested in them included the cylinder heads and pistons, but not the crankshafts or cylinder blocks.15/

Q. Do you agree with this position?

A. No. We strongly disagree with TDI that testing of certain common components in other model TDI diesels adds sufficiently to a 24 hour test to result in properly rating the DSR-48 engine. In testing an engine to establish its proper rating, it is imperative to adequately test the engine as a

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13/ Deposition of Simon K. Chen (May 15, 1984) ("Chen Deposition") at 55-58. (Exhibit 3).

14/ Mathews Deposition at 32-33. (Exhibit 2).

15/ *Id.* at 36-40.

whole to determine the operation and interaction of its many components. Further, we do not believe any engine can be properly rated when its crankshaft and cylinder block have not been sufficiently tested.

Q. Do you believe the EDGs were properly rated by TDI?

A. No. We believe the EDGs are over-rated and undersized.

Q. What do you mean by the term "over-rated"?

A. By the term "over-rated," we mean that the performance rating of the EDGs is higher than the EDGs are capable of meeting without suffering adverse consequences, such as cracking of components which may lead to catastrophic failure of the engines. In other words, the EDGs do not and will not operate reliably at their rating of 3,500 kW continuously and 3,900 kW two hour overload; therefore, the rating given the EDGs by TDI was improperly high.

Q. What do you mean by the term "undersized"?

A. Simply that the EDGs are too small to reliably operate at the levels required by the contract specification and Section 8.3.1.1.5 of the Shoreham FSAR, and thus the EDGs do not meet the requirements of GDC 17.

Q. Does the operating history of the EDGs confirm your position that they are over-rated and undersized?

A. Yes. Operation of the EDGs has been confined to their testing by LILCO. The EDGs are supposed to be capable of meeting their performance ratings. Moreover, they are expected to last for the entire 40-year life of the Shoreham plant. Yet after only about 800 to 900 hours of testing all three EDGs had experienced extensive cracking of components.16/ These included:

1. Cracks in 23 of the 24 piston skirts;17/

2. Cracks in three cylinder heads resulting in water leaking into the cylinders;18/

3. The severing of the crankshaft on EDG 102 and cracks on the crankshafts of the other EDGs;19/ and

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16/ See generally Board Notification 83-160 dated, October 21, 1983. (Exhibit 4).

17/ 10 C.F.R. 50.55(e) report dated November 16, 1983. (Exhibit 5).

18/ 10 C.F.R. 50.55(e) report dated April 15, 1983. (Exhibit 6).

19/ NRC Information Notice No. 83-58, August 30, 1983.

4. Cracks on the block tops and camshaft gallery areas of all three cylinder blocks.20/

These failures of these four major components evidence that the EDGs are over-rated and undersized.

Q. Didn't LILCO replace all of these four major components?

A. LILCO replaced the crankshafts on the three EDGs with crankshafts having a larger (nominal 12" diameter) crankpin. All piston skirts were replaced with TDI model AE skirts. LILCO replaced the block on EDG 103 with a different design TDI block. Two of the cylinder blocks (on EDG 101 and 102) have extensive cracks on the block top, running from the stud holes radially and vertically to the cylinder bores, and cracks in the camshaft gallery areas. LILCO has not replaced these blocks and intends to use them at Shoreham during full power operation of the plant. All of the cylinder heads were replaced with TDI heads of the same design, but allegedly of better manufacture and quality.

20/ Design Review of TDI R-4 and RV-4 Series Emergency Diesel Generator Cylinder Blocks and Liners, June 1984 ("FaAA Block Report"). (Exhibit 7).

Q. Did the replacement of these major components potentially impact other safety functions of the EDGs?

A. Yes. In 1976 over 300 tests were conducted at the TDI factory to establish the capability of the prototype EDGs to start and accept load. All these starts were performed on one EDG (EDG 101). No more than two failures in the 300 tests were allowed.21/ Since these tests, there has been a wholesale replacement of critical engine components including the four major components discussed in this testimony.

Q. Has LILCO adequately requalified the startup reliability of the modified engines?

A. No. We believe the 1976 prototype qualification tests are no longer valid and applicable, and additional qualification tests are required to demonstrate startup reliability. LILCO has proposed to perform only 100 starts on a single EDG, allowing no failures in 23 consecutive starts, and only one failure in the other 77 starts.22/ We believe that the original criteria for startup prototype qualification should be

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21/ FSAR, p. 8.3-14 and 8.3-15.

22/ Shoreham Diesel Generator Recovery Program Summary, attached to LILCO letter SNRC-1003, January 6, 1984.

implemented, which would require 300 starts on a single engine, or a minimum of 100 starts on each of the three engines.

Q. Has the replacement of the pistons, cylinder heads, crankshafts and EDG 103 cylinder block solved the problems experienced by the EDGs in the past?

A. No. The EDGs are still over-rated and undersized, improperly designed and not satisfactorily manufactured. The reasons for this conclusion will be presented in detail in our testimony concerning each of the current four major components of the EDGs.

MODEL AE PISTONS

Q. How does Suffolk County's Contention relate to the TDI pistons in use at Shoreham?

A. The EDG Contention provides that its first paragraph is supported because:

> All AF piston skirts in the EDGs were replaced with TDI model AE piston skirts. The replacement AE pistons are of inadequate design and manufacturing quality to satisfactorily withstand operating conditions because:
>
> (a) The FaAA report conclusion that cracks may occur but will not propagate improperly depends on a fracture mechanics analysis of an

ideal situation which is not valid for the actual conditions which may be experienced by the Shoreham diesels,

(b) excessive side thrust load, which could lead to catastrophic failure, has not been considered adequately, and

(c) the analysis does not adequately consider that the tin-plated design of the pistons could lead to scoring causing excessive gas blow-by, and thereby causing a failure of proper operation.

Q. Why were the AE model piston skirts installed in the EDGs?

A. The AE piston skirts were installed after 23 TDI model AF piston skirts in the EDGs were discovered to have linear indications, that is, cracks, in the crown-to-skirt stud attachment bosses. Failure Analysis Associates ("FaAA"), an organization retained by LILCO (through its attorneys) and the TDI Owners' Group, has published a report entitled "Investigation of Types AF and AE Piston Skirts" dated May 23, 1984 (the "FaAA Piston Report"),23/ which concluded that the cracks in the AF piston skirts were fatigue cracks.

Q. What are the bases for your conclusions that the AE pistons at Shoreham are inadequately designed and

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23/ FaAA Report 84-2-14. (Exhibit 8).

unsatisfactorily manufactured, as set forth in the EDG Contention?

A. The bases for our conclusions are described in detail below.

Cracking of AE Piston Skirts

Q. Did FaAA conclude that the AE piston skirts might crack?

A. FaAA conducted a finite element stress analysis of the AE piston skirt, which showed that cracks may initiate in the skirt.24/ FaAA also carried out experimental measurements of strain under static load in the AE piston skirt,25/ which predict that cracks will not initiate in the skirt under the cyclic stress levels obtained in the experiments.26/ The disagreement between the finite element analysis and the experimental results is 28%, which FaAA maintains is "quite good" agreement.27/

24/ FaAA Piston Report at 6-1.

25/ *Id.*, Section 3.

26/ *Id.* at 6-1.

27/ *Id.* at 5-1. The disagreement between an earlier finite element analysis and the experimental results was 33%. Initial FaAA Piston Report, February 27, 1984, at 5-7.

Q. Do you agree that the 28% disparity is "quite good"?

A. No. That disparity is the difference between two opposite conclusions -- cracking or structural integrity -- which are critical to the results of FaAA's study.

Q. Which is more reliable -- the finite element analysis result or the experimental results?

A. The usual methodology is to confirm the finite element analysis by the stress experiments. The finite element analysis, when properly done, may be an excellent tool for evaluating a structure. It tends to be non-conservative (that is, it would be expected to show <u>less</u> likelihood of cracking than experiments) because it averages the properties of the piston skirt material and ignores possible imperfections in the material. Because the experimental results differed significantly from the finite element analysis results, it would appear to us that the experiments were inadequate. The experiments should have been carried out until crack initiation was shown, and then analyzed. Where, as in this case, the experiments do not confirm the analysis, additional work is required. Instead of doing that additional analysis, FaAA concludes that the 28% disagreement of the results is acceptable and <u>could</u> be accounted for by incorrect assumptions in the finite element model, omissions or approximations in the finite element technique, or inaccuracies in the experiments, or all of the above.28/ This is not a helpful conclusion, because the two results -- that cracks will initiate or will not occur -- are opposing. We believe that this conflict has not been adequately investigated. We note, for example, that an unstated number of strain gauges in the stud boss area did not work.29/ Since no attempt has been reported to qualify the relative accuracies of the analytical and experimental techniques, and given the importance of the conclusion in terms of the safety requirements for Shoreham, we believe the greater weight must be given to the results of the finite element analysis -- that cracks are predicted to initiate.

Q. Do you believe the FaAA Piston Report underestimates the probability that cracks will initiate in the AE skirt?

A. Yes. FaAA determined for purposes of its finite element analysis and experiments that "The maximum stresses in the piston skirt under peak firing pressure are of primary interest. This pressure is approximately 1670 psig as independently measured by FaAA and reported by TDI."30/ To justify a peak

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28/ Id.

29/ FaAA Piston Report at 3-6.

30/ Id.; see also Id. at 4-1.

firing pressure of 1670 psig, FaAA cites only TDI reported values for a DSRV-16-4 engine at Grand Gulf Nuclear Station,31/ and FaAA pressure measurements of 2 cylinders at Shoreham which FaAA has acknowledged to be unreliable and too low.32/ In fact, the peak firing pressure in cylinders of the EDGs at full load (3500 kW) is known to be as high as 1750 psig, and at overload (3900 kW) the peak firing pressure is at least 1800 psig. The stresses on the AE piston skirt used by FaAA in its analysis and experiments are thus understated.

Q. What evidence do you have that the peak firing pressures in the EDGs are as high as 1750 to 1800 psig?

A. Test documents for the EDGs and for other DSR-48 diesel engines establish these maximum peak firing pressures. These documents are attached as Exhibit 46.33/ The test data show numerous peak firing pressure readings of greater than 1670 psig for the Shoreham engines at 100% load (the 1/24/76 run on EDG 102 shows 1750 psig, for example) and pressures as

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31/ Id. at 3-14 (Ref. 3-1) and at 4-7 (Ref. 4-2).

32/ Id. at 4-7 (Ref. 4-1); Emergency Diesel Generator Crankshaft Failure Investigation, Shoreham Nuclear Power Station, FaAA, October 31, 1983 (FaAA 83-10-2) at 4-9.

33/ See Exhibit 46 at documents 5-9.

high as 1800 psi are reported for the overload condition (3/19/76 run on EDG 103. This evidence contrasts with the readings on an EDG taken by FaAA. One must also remember that firing pressures differ from cylinder to cylinder and engine to engine. TDI gives no specific authoritative peak firing pressure for the DSR-48. Rather, its manual for operation of the EDGs permits a variance in peak firing pressures of the cylinders in one engine of ± 100 psi.34/ This means that any single peak firing pressure read in one cylinder may be exceeded in another cylinder by 200 psi, so that firing pressures may be even greater than 1800 psi in the EDGs.

Q. What is the impact of the higher actual peak firing pressure on the FaAA Piston Report?

A. The higher actual peak firing pressures mean that cracks are more likely to initiate in the AE piston skirts in the EDGs than FaAA predicts. FaAA underestimates the crack initiation in 3 respects concerning firing pressures. First, FaAA uses a too-low peak pressure of 1670 psig for its finite element analysis and the reported strain gauge tests. FaAA tested the pistons to 2000 psig, but only reported the data at

34/ TDI Instruction Manual at 8-3 (Exhibit 9) the 1600 psig point. Second, certain strain gauge measurements are limited to a maximum of 1600 psig.35/ Third, FaAA made no analysis or strain gauge experiments at overload (3900 kW), even though the EDGs have a 2 hour per each 24 hour overload rating and an actual maximum peak load of 3881 kW. TDI has testified that the peak firing pressure of the EDGs at 3900 kW is about 1800 psi.36/ These factors would, if taken into consideration by FaAA, result in a much greater likelihood of AE piston skirt crack initiation than predicted in the FaAA Piston Report.

Q. Aside from the peak firing pressure, are any other issues of particular concern to FaAA's conclusions concerning crack initiation?

A. The initial size of the gap between the outer ring of the AE skirt and the crown is, according to FaAA, important in predicting whether or not cracks will initiate in the skirt.37/ The FaAA Piston Report states:

35/ FaAA Piston Report at 3-6 to 3-7, 3-16 and 3-17, 3-19.

36/ Deposition of Gerald Edgar Trussell (May 7, 1984) ("Trussell Deposition"), at 128-29. (Exhibit 10).

37/ FaAA Piston Report at 8-1; see, also Figure 3-2 for an illustration of this gap.

> The experimental results of Section 3 showed that the stresses due to pressure are dependent on the initial gap size, g_o, because this parameter influences the gap closure pressure and load transfer between inner and outer load rings. As shown in Figure 3-2, the initial gap can vary from 0.007 to 0.011 inch and still be within TDI specified tolerance.38/

Neither FaAA nor the TDI Owners Group personnel has measured the initial gaps present in the AE pistons in the EDGs.39/ Based upon foundry practices and the lack of effective quality assurance at TDI, discussed below, it is quite likely that the TDI tolerances may be exceeded. Actual measurements of the gaps in the AE pistons at Shoreham would be useful in testing FaAA's assumption that all AE pistons have gaps within TDI's tolerances.

Another factor bearing upon the likelihood of crack initiation is the tensile properties of the skirts.40/ We do not know the actual tensile properties of the AE skirts at Shoreham, but we note that the range of values reported for

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38/ Id. at 6-4.

39/ "Design Review and Quality Revalidation Report, TDI Diesel Generators For Shoreham," TDI Diesel Generator Owners Group, June 29, 1984 (the "DRQR Report"), Vol. 5, Pistons, at B1 to B6. (Exhibit 11).

40/ FaAA Piston Report at 6-5.

typical material used at TDI shows ultimate tensile strengths as low as 85 Ksi.41/ If such a piston were subjected to the higher firing pressures possible (1750 psig or higher), the conclusions regarding crack initiation would certainly be invalid.

Q. Do you agree with FaAA's conclusions that even if cracks do initiate in the AE piston skirt, they will not propagate?

A. No, because that conclusion is based upon a highly theoretical fracture mechanics analysis which does not take all potential effects into account for predicting crack growth under the actual conditions that will be experienced at Shoreham. The FaAA analysis assumes:

(1) complete adherence to TDI drawing dimensions of the AE skirt (and crown);

(2) the AE piston material is isotropic, meaning it is free of any small inperfections such as sand inclusions or grinding marks, and with no subsurface defects such as hot tears or slag

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41/ Id. at 2-7

inclusions, with the ultimate tensile strength uniform in all directions;

(3) a non-corrosive operating environment free of gases, water or vapor;

(4) stresses resulting from a maximum peak firing pressure of 1670 psi; and

(5) a uniform skirt temperature, both circumferentially and axially.42/

Each of these idealized assumptions is incorrect in terms of the "real world."

Q. Explain why each assumption is incorrect, and the impact of the error on FaAA's crack propagation analysis.

A. (1) The dimensions of each AE piston at Shoreham are not perfect. Only a very limited dimensional check on a sampling basis was made on piston groove and ring height and piston pin bore diameter and depths on the AE pistons at Shoreham. No dimensional check was made of other parts of the piston

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42/ FaAA did not independently measure the thermal gradience in the AE piston skirt. Harris Deposition at 41. (Exhibit 12).

skirt, including the thickness of the boss areas or the gap between the piston skirt and crown.43/ Even relatively small dimensional differences in the skirt and in the assembly of the skirt and crown would change the mathematics of FaAA's analysis, and could influence the results.

(2) The AE piston skirts in the EDGs are not free of defects. They are known to have some small defects, and it is highly likely that many more imperfections are present. At Shoreham, only 10 of the 24 AE piston skirts were subjected to liquid penetrant tests at the bosses for bolt attachment to the crown.44/ These tests did disclose some defects, but in any case were totally inadequate to determine whether there are small imperfections on the surface or subsurface of the AE skirts. Such small imperfections are likely to be present in the skirts in the EDGs. TDI does not use vacuum processes to ensure a dirt-free casting. Indeed, the foundry is poorly lighted and has a dirt floor, which increases the likelihood of sand or slag inclusions. Control of scrap material for castings is rather informal. Effective quality control is absent,

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43/ DRQR Report, Vol. 5, Pistons, at B1-B6.

44/ Id. Eddy-current inspections were conducted by FaAA on 12 skirts on the EDGs. See FaAA Piston Report at 7-1 and discussion below.

so that small imperfections are unlikely to be discovered. Mr. William Foster of the NRC's Vender Inspection Program staff, who had participated in a number of NRC inspections at TDI, stated recently that the nature and number of violations and non-conformances at TDI indicated to him that the TDI QA system was "ineffective."45/ The presence of even a small imperfection would permit a crack to initiate and propagate at stress levels below those predicted by FaAA as necessary for initiation and propogation. If a crack initiates in an area of the skirt where imperfections are present, its growth may be entirely different than as calculated by FaAA, which assumed no flaws in the material. With the presence of some imperfections, FaAA's fracture mechanics analysis is invalid.

(3) The environment of the piston during EDG operation is not a vacuum. Combustion gases are present, and there may be small amounts of water or vapor. If a crack initiates in the skirt, these gases will tend to corrode the crack edges and hasten crack propagation. Corrosion products formed on the crack opening of a skirt during EDG operation will act as wedge when the crack closes (after EDG operation ceases),

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45/ Deposition of William Foster (May 22, 1984) ("Foster Deposition"), at 16. (Exhibit 13).

producing additional crack growth. The FaAA fracture mechanics analysis does not consider these factors at all.

(4) FaAA's analysis postulates stresses resulting from a peak firing pressure of 1670 psi. The proper maximum peak pressure of 1800 psi, as discussed above, would result in greater stresses and a higher likelihood of crack propagation.

(5) The temperature around the skirt is not uniform. Actually, the side of the piston skirt taking the piston thrust on the firing downstroke becomes much hotter during EDG operation than the side taking the piston thrust on the compression upstroke. The temperature of these TDI pistons will be even higher than is normally expected in other makes of engines where the initial side thrust is designed to be much lower, as discussed below. FaAA assumes that the piston skirt is "nearly isothermal",46/ when in fact, one side of the skirt runs at a much higher temperature than the opposite side. Estimates for the piston skirt temperatures were provided by TDI based on "templug" measurements taken on a non-Shoreham engine operating at only 213 BMEP.47/ The EDGs operate at 225 BMEP,

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46/ "The Influence of Thermal Distortion in the Fatigue Performance of the AF and AE Piston Skirts", June 1984 (FaAA-84-5-18) (the "FaAA Piston Thermal Distortion Report"), at 2-7.

47/ Id. at 2-6, 2-7.

and would therefore have higher piston skirt temperatures.

Q. Given all of these variations from FaAA's idealized assumptions, is it possible to predict accurately how cracks in the AE skirt will propagate?

A. No. It is not possible to make accurate predictions of crack propagation in the AE skirts, given all of the possible variables. However, the FaAA analysis would have been far more useful if actual properties of the AE piston skirts in the EDGs had been recorded, to the extent possible, and sensitivity analyses performed to account for a range of potential variables. Thus, the principal dimensions of each AE skirt at Shoreham could have been measured, especially in the boss area. The gap between the outer ring of each skirt and the attached crown could have been measured. Each AE piston skirt in the EDGs could have been inspected for imperfections, especially in the boss area, by liquid penetrant tests, magnetic particle tests, eddy current examination and radiographic inspection. The tensile properties of each skirt could have been sampled. The analysis could then have been performed using a range of more realistic peak firing pressures (up to 1800 psi) and including the combined effects of maximum side thrust and its corresponding gas pressure, temperatures, and environmental conditions. The analysis could have included sensitivity tests to take into consideration the potential for undiscovered dimensional variations, defects in the skirt and differences in tensile strength, and the possibility of multiple cracks. Such analyses would give a far better prediction of crack propagation than the idealized study performed by FaAA.

Q. What else, besides the inspections and crack propagation analyses you suggest, would be necessary to give adequate confidence that the AE piston skirts are adequate for operation at Shoreham?

A. First, an adequate crack initiation analysis should be performed, using actual data as to dimensions, tensile properties, imperfections, and gap sizes of the AE skirts at Shoreham, and the appropriate peak firing pressures of up to 1800 psi. Experimental stress tests should confirm the results of finite element analyses, or a more refined finite element analyses or better experiments should be performed. The AE pistons could be instrumented and tested during EDG operation for additional experimental data. These analyses could predict multiple cracks initiating with larger initial sizes, thereby affecting the crack propagation analyses. The design deficiencies involving excessive piston side thrust load and tin plating of the skirt would have to be considered, as discussed below. Finally, the AE piston skirts would have to be tested and inspected adequately in the EDGs.

Q. Does FaAA believe the AE piston skirts have been adequately tested and inspected?

A. Yes. FaAA has concluded that on the basis of the results of its stress analyses (which were contradictory as to crack initiation) and "the results of inspections of engine-operated AE skirts," the AE piston skirts "are adequate for unlimited life."48/ We strongly disagree that the AE skirts have been adequately tested or inspected to justify any conclusions about their expected life.

Q. What inspections was FaAA referring to?

A. FaAA was referring to inspections of 15 AE skirts, as follows:

(1) 12 AE skirts of the 24 skirts were subjected to eddy-current inspections after over 300 hours of total operation each (including 100 hours at full load), and no "relevant indications" were found;

(2) One skirt in an RV-16-4 engine was inspected after over 6,000 hours of

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48/ FaAA Piston Report at 8-1.

operation at a peak firing pressure of about 1200 psi, with no "relevant indications" found; and

(3) Two skirts from a TDI R-5 development engine were inspected after operating at a peak pressure of 2000 psi or more after over 600 hours, with no finding of "relevant indications."49/

Q. Why don't you believe this experience and these inspections are adequate to support FaAA's conclusions?

A. For several reasons. First, fifteen skirts is simply too small a number from which to reach any general conclusions, particularly without a valid statistical analysis.

Second, the inspection of only 50%, rather than 100%, of the AE skirts on the EDGs is inadequate. Mr. William Foster, the NRC Staff official with responsibility for vendor inspections of TDI, has testified that TDI has an ineffective quality control program, and consequently inspection on a sampling plan basis of TDI components "would not tell you anything."50/ In fact, Mr. Foster testified that even a 100% inspection of TDI components would not identify all defects.51/ We agree.

49/ Id. at 7-1.

50/ Foster Deposition at 14-16, 54-55, 82. (Exhibit 13).

51/ Id. at 55.

Third, the number of hours and the amount of full loads and overloads run on each AE skirt at Shoreham are insufficient to reach conclusions about their expected life. To meet the rating specifications of the EDGs, the AE skirts must be capable of running many thousands of hours, including significant hours at overload at 3900 kW. The AE piston is supposed to last the lifetime of the Shoreham plant -- 40 years.52/ Testing them for only 300 hours without significant, if any, overload does not begin to be adequate. It is also important to note that TDI did not test the AE piston before supplying it to customers in the field.53/

Fourth, the AE skirt in the RV-16-4 engine was operated at a peak firing pressure of only 1200 psi, while the EDGs have a peak firing pressure of about 1700 to 1800 psi at full load and overload. Thus, the operation of that single skirt was at such low stress as to be useless for purposes of reaching any conclusions relevant to the AE skirts in the EDGs.

Fifth, the two piston skirts operated in the TDI R-5 engine are of limited relevance. The R-5 engine is significantly

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52/ Trussell Deposition at 111-13. (Exhibit 10).

53/ *Id.* at 107.

different from the EDGs, including its operating speed (514 RPM). This would change the inertia effects which in turn lowers the piston lateral loading. Therefore, before determining the impact of the R-5 skirts on the Shoreham AE skirt report, a study would have to be made analyzing the effects of the different parameters.

Sixth, the referenced inspections were incomplete and the standards for acceptance were unsatisfactory.

Q. Please be more specific about your last point.

A. FaAA stated that only eddy current examination was performed on the Shoreham piston skirts.[54] Further, only certain portions of the skirt were subjected to the eddy current examination, namely, "machined areas on the boss where color contrast penetrant show (sic) linear indications greater than 1/32 inch."[55] This means that linear indications smaller than 1/32 inch, non-linear indications such as sand or slag inclusions, and areas of the boss which were not machined were omitted from consideration. As we noted earlier, even small

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54/ FaAA Piston Report, at 7-1.

55/ FaAA NDE Procedure 11.5, November 2, 1983, para. 6.1. (Exhibit 14).

imperfections could significantly increase the possibility of crack initiation and propagation. Finally, the only indications which were to be recorded were cracks "greater than 10% of the crack signal in the reference standard PAO-C-1."56/ Unfortunately, FaAA does not indicate, nor does the NDE procedure specify, the size of the flaw contained in the reference standard, so there is no way to judge the sensitivity of this screening processing. In our opinion a crack eliminated from further consideration by these criteria could be relevant to issues of crack initiation and propagation. Accordingly, we have no way of knowing how many cracks or other imperfections there may actually be on the 12 AE skirts at Shoreham.

Q. What about the inspections of the skirts in the RV-16-4 and R-5 engines?

A. On the RV-16-4 piston skirt, a liquid penetrant test showed an indication 3/4 inch long. This indication was subjected to eddy-current examination and FaAA determined that there were "no crack-like indications."57/ The two AE skirts from the TDI R-5 engine were not of the same design as the skirts at Shoreham.58/ Three indications were found on one of

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56/ Id. at para. 7.1.

57/ Memorandum from D. Johnson (FaAA) to M. Milligan and B. Judge (LILCO), Feb. 17, 1984. (Exhibit 15).

58/ Memorandum from D. Johnson (FaAA) to M. Milligan and N. Irvine (LILCO), Feb. 3, 1984. (Exhibit 16).

the skirts, but FaAA decided these were "of no consequence to structural integrity of the skirt."59/ For the reasons given above, we believe the eddy current inspections do not support FaAA's conclusions that the AE skirts can be expected to have unlimited life. FaAA's standards for a "relevant indication" permit the presence of imperfections which could increase the likelihood of crack initiation and propagation; thus such defects should have been considered by FaAA in its analyses.

Q. What might happen if cracks in the boss area of the AE piston skirts do propagate?

A. Given the many variables and unknown factors, we cannot give any meaningful estimates of how cracks will propagate, or how rapidly they will do so. We do know that the tip of a crack is unstable. It is at higher energy than the surrounding material and will tend to corrode or link with impurities, inhomogeneities or imperfections in the metal to lower its energy. Corrosion will increase crack propagation. At some point a crack, unless arrested by a sufficiently thick area or by physical movement of material allowed by the crack reducing the stress, will reach a critical point beyond which crack

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59/ Memorandum from Wells and Johnson (FaAA) to Milligan and Irvine (LILCO), Feb. 9, 1984. (Exhibit 17).

growth will be very rapid. Circumferential crack propagation could lead to crown separation from the skirt with disastrous results. Axial crack propagation, depending on location, could reduce piston clearance, adversely affect lubrication, and result in piston seizure or crankcase explosion or both.

Q. Please summarize your conclusions about the probability of AE piston skirt cracking.

A. FaAA's conclusion that the AE skirts are adequate for unlimited life is inadequately substantiated and invalid. Cracks are even more likely to initiate in the AE skirts than FaAA's finite element analysis predicts, because the peak firing pressures in the EDGs are significantly higher than those used by FaAA. FaAA's experiments do not confirm the finite element analysis and should be reanalyzed to explain the significant 28% discrepancy. FaAA's conclusion that cracks initiate but will not propagate in the AE skirts is based on theoretical idealized assumptions which are unrealistic. Under actual operation cracks which initiate are likely to propagate due to such factors as variations in dimensions of the skirts, the presence of imperfections in the skirt material, the operating environment in the cylinder, and actual firing pressures and temperatures. Finally, the tests and inspections of AE skirts cited by FaAA are insufficient to support conclusions that the skirts are adequate for nuclear service.

Excessive Piston Side Thrust

Q. What is piston side thrust?

A. Piston side thrust occurs at all positions of the piston during operation except top dead center and bottom dead center. In all of those other positions, the connecting rod is at an angle to the vertical line of the piston stroke. The side thrust on the piston is the result of the force acting to the line of piston stroke.

Q. Have you calculated the piston side thrust of the AE piston in the EDGs?

A. Yes. The calculations for piston side thrust of the AE piston are shown attached as Exhibit 18. These calculations show that at the first two midordinate positions the mean unital thrust on the AE piston at Shoreham is over 123 psi and 111 psi respectively.

Q. Is that unital side thrust excessive?

A. Yes it is. An upper unital limit of 85 psi has been prescribed in a standard design text.60/ Another source states

60/ Diesel Engine Design, T.D. Walshaw, Newnes, London, 1949, at 140.

that side thrust should not exceed 30 to 40 psi for slow speed diesel engines and 70 psi for high speed engines.61/ Medium speed engines like the EDGs should fall within these two limits. In most engines with which we are familiar built by other manufacturers, the unital side thrust does not exceed 85 psi and we have reviewed the design of an engine comparable to the EDGs which has a unital side thrust of 35 psi. Thus, the calculated mean unital side thrust of the AE piston of 123 psi exceeds the upper value by 44 percent. We believe that the actual maximum unital side loading of the AE piston will be more than the calculated figure, because the piston pin in the AE piston is located above the vertical center of the effective piston skirt height. The additional increase will depend upon the stiffness of the skirt.

Q. What affect does this excessive side thrust load have on the EDGs?

A. The excessive side thrust increases the temperature differences around the circumference of the piston skirt, by causing the side of the piston bearing the higher side thrust to run hotter than if side thrust were normal. This

61/ Internal Combustion Engines, V.L. Maleev, McGraw-Hill, 1945, at 501-02.

temperature non-uniformity will be exacerbated by minor inbalances, minor gas leakage past the piston rings, or lesser lubrication availability after fitting new oil control rings. As the temperature differences in the circumference of the skirt increase, piston distortion begins. Distortion further reduces the arc of contact between the piston skirt and the cylinder liner. As this contact is decreased, the effective area of the skirt sustaining the side load is drastically reduced, causing the unital thrust to increase. The increase of thrust increases the friction between the side of the skirt and the liner, further increasing the temperature differences. Once the temperature differences increase above a certain critical point, partial and complete piston seizure occurs very rapidly -- in just minutes or seconds -- and usually without warning. Piston seizure, if complete, will almost always cause catastrophic EDG failure.

Q. Why can piston seizure occur so quickly?

A. The breakdown can occur very rapidly because of the combined effect of distortion of the piston in both the vertical and horizontal plane caused by the differences in temperature in the circumference of the piston skirt. The vertical distortion causes the piston to bend to the shape of a banana, with the hot side rubbing on the liner at the outer part of the curve in the banana shape. As clearance between the skirt and the liner further decreases, the top and bottom parts of the inner side of the curve on the cool side of the skirt rub the liner, the effective clearance approaches zero, and the piston seizes.

Q. Are your calculations for piston side thrust in the EDGs at full load or overload?

A. Our calculations were based upon 4890 HP of the EDGs, the full load. At the rated overload of approximately 110%, the horsepower is 5379 and the maximum and mean gas pressure increases considerably. Under such conditions, the danger of piston seizure is even greater.

Q. Is the piston side thrust load affected by the fast start requirements of the EDGs?

A. Yes. During the required acceleration of the EDGs to rated speed in 10 seconds the piston inertia forces go from zero to running "normal" while the firing pressures are high almost immediately. Since the inertial forces are subtractive from the side thrust imposed by the piston pressure, the lateral load on the piston is substantially increased during the fast start portion of the cycle. This load condition occurs while the engine is still "cold" and before lubrication is fully established.

Q. Are you aware of any evidence of excessive AE piston side thrust in the EDGs or elsewhere?

A. According to the DRQR Report for Shoreham, the TDI Owners' Group inspections were supposed to verify "lack of scuffing at the piston skirt" in all three EDGs.62/ Scuffing was reported in the DRQR Report on a number of AE piston skirts,63/ but we have not yet had an adequate opportunity to examine LILCO's deficiency and disposition reports cited in the DRQR Report to see how these conditions were evaluated. These reports were only received a few days ago, so our review of them has necessarily been preliminary and cursory. If our more complete review discloses significant information, we will file supplementary testimony. The DRQR Report concludes that "inspections performed on AE skirts have not revealed excessive side load wear."64/ Based upon our preliminary review of the

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62/ DRQR Report, Vol. 5, Pistons, at B2. (Exhibit 11).

63/ Id. at B4-5, referencing TER Q-326; LDR 2275; TERs Q-41, Q-82, Q-83: LDR 2147; TER Q-159; LDR 2198.

64/ Id. at 3.

inspection data and personal inspections of some AE skirts at Shoreham, we disagree.

Q. What inspections did you make?

A. During June of 1984, we inspected one AE skirt at Shoreham which showed a heavy wear pattern. The worn area of the skirt was completely devoid of any tin plating or sandwich layer plating. The appearance of the damaged area showed the light mottled patterning and surface roughness consistent with micro seizure. We believe this abrasion of the skirt most likely resulted from heavy side loading resulting in localized distortion. The profile of the skirt indicated local distortion. During this same inspection, we examined seven other AE piston skirts. While these skirts did not show the same heavy wear pattern described above, they did show signs of distress in the tin-plated area (abraded surfaces and evidence of debris that had previously been embedded in the plating, but since removed).

Q. Are you certain the AE skirt you have described was damaged by excessive piston side thrust?

A. We cannot be absolutely certain, but that is the probable cause. Evidence of excessive side thrust is usually also evident on the cylinder liner against which the skirt has rubbed. All of the liners we inspected at Shoreham showed evidence of heavy deglazing, which obliterates any markings associated with high side thrust loading from the skirt. We might surmise that side thrust markings made the heavy deglazing necessary. Deglazing is a maintenance operation in which the cylinder liner surface is honed in a criss-cross pattern leaving relatively deep "scratches" for the purpose of maintaining better lubrication of the piston rings, skirt, and liner.

Q. Did the FaAA Piston Report address the issue of piston side thrust loading?

A. FaAA has never addressed this issue, notwithstanding that it is both a "functional attribute" and "evaluation" factor in the TDI Owners' Group Program Plan Component Design Review for Pistons, Part No. 03-341 (DR-03-341-1). Under "Evaluations," item 9 states: "Evaluate the effect of piston side loading on wear." We were surprised that FaAA chose to ignore this matter, not only because of its importance to reliable EDG operation and the physical evidence of excessive side load described above, but also because of the impact of this issue on FaAA's crack initiation and propagation analyses.

Q. What is the effect of excessive AE piston side thrust on FaAA's analyses?

A. As explained above, excessive piston side thrust causes localized and later more widespread uneven overheating of the skirt. The resulting higher thermal stress will generally contribute to crack initiation and propagation, especially where the higher surface temperature of the skirt is on the other side of the section where the crack is located. The hot side increases the tensile loads on the cold side, contributing to propagation of any crack there. FaAA supplemented the FaAA Piston Report with a second report documenting an investigation of the thermal effect on the AE skirt. This report concluded that the influence of thermal distortion does not change the conclusions of the FaAA Piston Report as to the AE piston skirts.65/ The FaAA Piston Thermal Distortion Report, however, does not address the issue of piston side thrust at all and deals principally with effects of thermal distortion of the piston crown. Proper consideration by FaAA of the effects of excessive piston side thrust in the AE piston would likely change the analytical conclusions and probably would have shown crack initiation and propagation in the AE skirt to be more likely.

65/ FaAA Piston Thermal Distortion Report at 5-1.

Q. Was evidence of excessive side thrust in AE skirts found in the TDI R-5 engine or the DSRV-16-4 engine referred to in the FaAA Piston Report?

A. We don't know. If the DSRV-16-4 ran at a peak pressure of only 1200 psi, excessive side load would be highly unusual.

Q. What do you conclude with regard to the piston skirt side thrust condition on the EDGs?

A. We conclude that the piston side thrust is excessive and that the AE piston is inadequately designed to accommodate this load. The FaAA reports have totally failed to address this concern. There is, therefore, no assurance that the EDGs will not experience serious failures induced by this condition. Accordingly, the EDGs have not been shown to be adequately designed to satisfactorily perform the service intended.

Tin Plating of AE Piston Skirt

Q. Did FaAA consider the potential effect of the tin plating of the AE skirt in the context of its design?

A. No. FaAA did not address this issue despite the fact that a functional attribute for the Task Description for pistons was

5. The piston skirt must provide a suitable sliding surface against the cylinder liner.

Q. What are your concerns about the tin plated design of the AE piston skirt?

A. During trips to Shoreham in 1983 and 1984, we observed relatively heavy vertical scoring in a sufficient number of cylinders to rule out a "case of one" phenomenon. The scores were vertical grooves located in line with the location where maximum side thrust takes place. Examination of pistons during a visit in 1983 showed accumulations of detritus embedded in the tin plated surface of the skirt. The scoring was visible despite heavy deglazing of the liner. We believe this scoring results from detritus which tends to collect in the soft tin plated surface of the skirt. The scoring in the liner caused by detritus embedded in the tin plating of the skirt can result in gas blow-by. If the cylinder liner is scored, small grooves or deep scratches are made in the liner surface. The piston rings "bridge" the groove or deep scratch and high pressure gases blow down the groove on the outside of the piston ring.

This action in turn leads to piston ring distortion which will allow more gas "blow-by". When this occurs, the piston skirts tend to overheat. This situation is potentially dangerous in the EDGs, where the piston design causes a high side thrust on the skirt. The high side thrust causes the AE piston to run hotter leaving little reserve for a further temperature rise from gas blow by. Small amounts of gas blow by may therefore lead to an early piston seizure.

Q. Why are the AE piston skirts tinned?

A. The piston skirts may be tinned to offset the bad effects of very high unital side thrust. This is yet another indication of over-rating of the EDGs.

Q. Aside from the liner scoring potential described above, does the tin plating present any other detrimental effects to reliable operation?

A. Yes. Tin and copper/tin plating of the AE skirts could initiate two types of failure mechanisms. If the tin (or copper/tin) is electroplated on the piston skirt, catastrophic failure could occur through the mechanism of hydrogen embrittlement. The plating process liberates hydrogen at the cathode which enters the metal structure. This classical embrittlement mechanism has been responsible for many dramatic failures of ferrous metals. It is difficult to detect and a hazard in all plated metal components. It is difficult, therefore, to predict if or when such a failure may occur. If the tinning is applied by a "dipping" process, the resulting structure at the plating interface can contain an intermetallic compound that forms when the tin matter comes into contact with the iron. This compound is covalent so it acts as a ceramic. This material, if present in significant quantities, can behave in an abrasive manner and thus contribute to scoring of the cylinder liner and piston skirt. Such liner scoring could lead to the failures resulting from gas blow-by and piston seizure described in the side thrust discussion above.

Q. What do you then conclude regarding the "tinned" AE piston skirts?

A. We conclude that the EDG rating is well in excess of the design limitation of the AE piston. Accordingly, there is no reasonable assurance that they will perform satisfactorily in service.

REPLACEMENT CYLINDER HEADS

Q. What is the purpose of this part of your testimony?

A. This part of our testimony addresses the County's concerns regarding cylinder heads; the relevant portion of the EDG Contention states:

The replacement cylinder heads on the Shoreham EDGs are of inadequate design and manufacturing quality to withstand satisfactorily thermal and mechanical loads during EDG operation, in that:

(a) the techniques under which the replacement cylinder heads were produced have not solved the problems which caused the cracking of the original cylinder heads on the Shoreham EDGs;

(b) the "barring over" surveillance precedure to which LILCO has committed will not identify all cracks then existing in the replacement cylinder heads (due to symptomatic water leakage);

(c) the nature of the cracking problem and stresses exacerbating the cracks are such that there can be no assurance that no new cracks will be formed during cold shutdown of the EDGs;

(d) there can be no assurance that cracks in the replacement cylinder heads and concomitant water leakage occuring during cold shutdown of the EDGs (which would not be detected by the barring-over procedure) would not sufficiently impair rapid start-up and operation of the EDGs such that they would not perform their required function;

(e) there can be no assurance that cracks in the replacement cylinder heads occurring during operation of the EDGs would not prevent the EDGs from performing their required function;

(f) variations in the dimensions of the firedeck [and water deck] of the replacement cylinder heads create inadequate cooling, where too thick, and inadequate resistance to mechanical loads, where too thin, and create stress risers at their boundaries;

(g) the design of the replacement cylinder head is such that stresses are induced due to non-uniform bolt spacing [and the different lengths of the bolts];

[(h) the replacement cylinder head design does not provide for adequate cooling of the exhaust valves];

(i) at least one replacement cylinder head at Shoreham has an indication;

[(j) the design of the replacement cylinder heads provides inadequate cooling water for the exhaust side of the head]; and

(k) the replacement cylinder heads at Shoreham were inadequately inspected after operation, because:

(1) a liquid penetrant test was done on the exhaust and intake valve seats and firedeck area between the exhaust valves on only 9 of 24 cylinder heads, and such tests were done after only 100 hours of full power operation;

(2) ultrasonic testing was done on the firedeck areas of only 12 cylinder heads;

(3) visual inspections were performed on the valve seat areas of only 32 of the 98 valves, and on only 7 firedecks of the 24 cylinder heads for indications of surface damage.

The bracketed portions of the foregoing contentions are deleted and not addressed in this testimony.

Q. What are your conclusions regarding the adequacy of the design and manufacture of the replacement cylinder heads?

A. Contrary to the conclusions reached by FaAA in its report evaluating TDI cylinder heads66/ and by the DRQR Report on cylinder heads, we conclude that:

(a) The replacement cylinder heads are inadequate for their intended service due to the potential for cracks to initiate and to propagate in the heads, leading to leaks into the cylinders.

(b) The potential for flaws in replacement heads of the EDGs still exists, since the manufacturing techniques for casting, inspecting, and testing the replacement heads have not been demonstrated to resolve the deficiencies which resulted in the cracking of the original heads.

(c) Cracks in the replacement heads could leak water into the cylinders of the EDGs during cold shutdown. The "barring over" surveillance procedure, dated August 5, 1983, proposed by LILCO will not preclude the presence of water in the cylinders.

66/ "Evaluation of Cylinder Heads of Transamerica Delaval, Inc. Series R-4 Diesel Engines," FaAA 84-5-12, May, 1984 (the "FaAA Head Report"). (Exhibit 19).

Water in the cylinders could impair or prevent rapid startup and operation of the EDGs.

(d) The casting process at TDI is not reproducible. Thus, there is no assurance that each casting will exhibit identical or even similar characteristics.

(e) The inspections of the replacement heads after operation were inadequate in that the operating time was insufficient (only 100 hours). Further, the sampling inspections utilized were not appropriate since it was not demonstrated that the population of heads was homogeneous.

(f) The stress analysis performed by FaAA failed to demonstrate that the predicted deformation of the replacement heads due to thermal and mechanical loads will not progress to the point of impacting acceptability of the heads.

In addition, as a result of our evaluation, we concur with the Owners Group conclusion in the DRQR Report for Shoreham that:

> The absence of detectable flaws in the Shoreham cylinder heads does not preclude the eventual propagation of a crack from a subsurface defect or a defect in an inaccessible location.67/

67/ DRQR Report, Vol. 8, Cylinder Heads, at 3. (Exhibit 20).

Indeed, Dr. Wells of FaAA acknowledged at the June 22 meeting between the Owners' Group and PNL that:

> not knowing the distribution of flaws below the surface of these heads, that we would in fact acknowledge the possibility that cracks would grow and leaks would develop, and confidence in the -- or lack thereof, in the behavior of these heads really has to be established by inspection and by examining the causes of leaks . . . ."68/

Based on the preceding conclusions, we do not believe that the replacement cylinder heads are adequate for nuclear service, and thus, there can be no assurance that the EDGs will perform satisfactorily in service.

Q. What prompted Suffolk County's concern with the cylinder heads in the EDGs?

A. Three of the original cylinder heads in the EDGs developed cracks in their firedecks which allowed cooling water to leak into the cylinders. Subsequently, the County filed a contention in these proceedings, which was admitted by the Board, and discovery concerning the cylinder heads commenced. LILCO then committed to replace all of the original cylinder heads in the EDGs prior to fuel load of Shoreham with heads of allegedly superior manufacturing quality.69/

68/ Meeting Transcript (June 22, 1984) at 124.

69/ Affidavit of Edward J. Youngling, July 22, 1983, para. 3. (Exhibit 21).

Q. Did LILCO replace all of the cylinder heads in the EDGs?

A. It is unclear that they did. FaAA states in one part of its cylinder head report of May 1984 that "all but two (E71 and F64)" of the original heads had been replaced with heads cast by TDI after September, 1980 (hereinafter called the "Group III heads"); elsewhere in the report FaAA says that all of the original heads in the EDGs have been replaced with Group III heads.70/ The DRQR Report asserts that all heads have been replaced with Group III heads.71/

Q. Are the failures of three of the original cylinder heads at Shoreham and of other pre-Group III heads relevant to your conclusions?

A. Yes. FaAA acknowledges that pre-Group III TDI heads were subject to numerous defects, but asserts that these defects were caused only by inadequate manufacturing processes and/or poor quality control at TDI.72/ Based upon information given by TDI as to changes in manufacturing techniques,73/ FaAA

70/ FaAA Head Report, at 1-3 and ii.

71/ DRQR Report, Vol. 8, Cylinder Heads, at 3. (Exhibit 20).

72/ FaAA Head Report at ii 1-2 to 1-4.

73/ *Id.* at 1-5 to 1-6.

has concluded that Group III heads (including the replacement heads at Shoreham) are "adequate for their intended service."74/ However, FaAA has not independently examined this data and in fact stresses its data "has not been verified as normally required under FaAA's quality assurance procedures."75/ FaAA also concluded that "there is a potential for cracks to propagate from pre-existing flaws in the head leading to leaks into cylinders," but that "the potential for the pre-existing flaws in Group III heads is significantly less than for" heads cast earlier.76/

Q. Do you agree with FaAA's conclusions stated above?

A. No. The replacement heads are not adequate. The FaAA conclusions are based in large part upon TDI's reviews of pre-Group III heads and *ad hoc* changes in TDI's manufacturing processes. While we agree with FaAA that cracks may well propagate from pre-existing flaws in the heads, causing water leaks into the cylinder, we do not agree that the likelihood of such flaws existing in the Group III heads has been demonstrably

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74/ *Id*. at 4-1.

75/ *Id*. at 1-5.

76/ *Id*. at 4-1.

educed by changes in TDI's manufacturing processes. Our estimony will also address the fact that cracks may occur in the replacement heads for reasons other than the presence of casting flaws, including deficiencies in the design of the replacement heads.

Q. Are the Group III cylinder heads in the EDGs of the same design as the original Shoreham heads and others cast prior to September, 1980?

A. Basically yes. All of these TDI cylinder heads are of the same design, except for a change to weld thicker covering plates over the core holes in the head, according to the TDI drawing of the head. This change is not significant to any of our conclusions as to the head designs.

Q. How is this portion of the testimony organized?

A. First, we will show that various deficiencies exist in the design of the replacement heads at Shoreham which may lead to failures. These deficiencies are unacceptable variations in dimensions of the firedeck and non-uniform bolt spacing which induce stresses. Second, we will demonstrate that changes introduced by TDI in manufacturing techniques have not solved or significantly diminished problems which result in flaws or cracks in the replacement heads. Third, we will document that the replacement heads in the EDGs have not been adequately inspected and include at least one flawed head. Fourth, we will examine the nature and effects of crack initiation and propagation in the replacement heads, and explain why the "barring over" procedure adopted by LILCO will not identify all leaks and make the use of the replacement heads sufficiently safe for nuclear service.

Inadequate Design

Q. What are the major design issues with cylinder heads in large medium speed diesel engines like the EDGs?

A. The cylinder head is one of the most intricate and difficult-to-design components in the engine. It must be strong enough to withstand the mechanical stress to which it is subjected during engine operation, but must also provide sufficient cooling through numerous water passages in the head to permit thermal stresses to be handled. Thus, the two major general design concerns are to provide sufficient strength and adequate cooling.

We were therefore surprised to discover that TDI did not change the design of the cylinder head when it increased the horsepower of the R-4 series diesel, because a significant increase in horsepower also increases thermal and mechanical loads.

Q. What changes were made in the TDI R-4 engines to increase horsepower?

A. In 1966-1967 the R-4 series diesel was developed. Compared to its predecessor, the TDI R-3 series engine, the R-4 increased engine speed from 375 to 400 RPM, and increased fuel and air supply to raise its brake mean effective pressure (BMEP) from 165 to 185 psi.77/ At the same time, changes were made in the design of the pistons, connecting rods, cylinder block, bed plate, cylinder liners and cylinder heads.78/

In 1970-71 the horsepower of the R-4 series engine was boosted to that of the EDGs (about 610 HP per cylinder) by increasing engine speed from 400 to 450 RPM.79/ The BMEP increased from 185 to 225. To deal with the consequent higher thermal loading, the piston design was changed from a one-piece iron cast to a two-piece steel casting and flanges were removed

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77/ Trussell Deposition at 81-82. (Exhibit 10).

78/ *Id.* at 74-81.

79/ *Id.* at 82.

rom connecting rod bearings, but no design changes were made n the cylinder head.80/ The replacement heads at Shoreham are thus of the same design as the heads designed for an engine with a speed of only 400 RPM and horsepower per cylinder of only 445 HP, as compared to over 610 HP per cylinder in the EDGs.

Q. What deficiencies have you noted in the design of the firedeck of replacement heads?

A. TDI permits wide variations in the thickness of the firedeck. The acceptance standard for the thickness across the firedeck was 0.500 inch ± .005 inch instrument accuracy and ± .010 inch per applicable drawing.81/ On July 28-29, 1983, NRC inspectors measured the firedeck thickness in thirteen replacement heads at Shoreham and found variations from 0.460 to 0.881 inch.82/ TDI takes the position that the minimum acceptable firedeck thickness is 0.400.83/ Apparently TDI designers

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80/ *Id*. at 85-87.

81/ NRC Inspection Report No. 50-322/83-25, August 11, 1983 ("I&E Report 83-25") at 3. (Exhibit 22).

82/ *Id*. with attachments thereto.

83/ Transmittal letter dated August 15, 1983, for I&E Report 83-25. (Exhibit 23).

do not apply any acceptance standards for maximum firedeck thickness.

Q. What are the consequences of the wide variations in firedeck thickness?

A. Where the firedeck is too thin, it is susceptible to cracking from the high mechanical stresses imposed on the firedeck during EDG operation, particularly at higher horsepower and loading. Firing pressure could cause stress which exceeds the material strength. Where the firedeck is too thick there may be insufficient cooling; the diminished heat transfer increases stress. Where there are wide variations in the thickness of the firedeck, as in the replacement heads, a stress gradient is created at the boundary of a thick and thin portion, which makes cracking more likely to occur.

Q. Has TDI conducted any studies or analyses to determine when the firedeck wall is too thick or too thin?

A. No. Mr. Lowery, TDI's manager of design engineering and research and development, has testified that "no calculations have been done to determine what the firedeck [thickness] should be."84/ The only documentation supporting the reduction

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84/ Deposition of Maurice H. Lowrey (May 11, 1984) ("Lowrey Deposition") at 85. (Exhibit 24).

the acceptance criterion for minimum firedeck thickness to ly 0.400 (from 0.500) is an inspection report dated ebruary 21, 1981, covering the firedeck inspection of four eads and bearing the notation "Functionally Acceptable (.400 in. Tolerance),"85/ and an internal TDI memorandum, prepared after the NRC inspectors had measured the firedeck thickness of 13 heads at Shoreham in July, stating "The smallest nominal firedeck thickness is specified as 1/2 inch. This dimension is allowed to vary to a minimum of 0.400 inches" (sic.)86/ Neither of these documents is an adequate engineering evaluation of minimum firedeck thickness.

TDI ignores the maximum firedeck thickness standard, which should be 0.515 inch with tolerance allowances, except between the intake valve ports, where .765 inch with allowed tolerances is required.87/ Both of these maximum thickness requirements are exceeded on at least 20 measured areas of the firedecks of 18 replacement cylinder heads at Shoreham.88/

85/ TDI Inspection Report No. Q-0783. (Exhibit 25).

86/ Memorandum dated August 1, 1983, from G. King (then TDI, now FaAA) to R. Boyer and E. Wilson (TDI). (Exhibit 26).

87/ I&E Report 83-25 did not refer to the special thickness specification between the intake valve ports.

88/ I&E Report 83-25 (Exhibit 22); FaAA Head Report at 1-8.

Q. Please describe the bases for your belief that the non-uniform head stud spacing induces stresses in the replacement heads.

A. When the cylinder head studs are pretensioned the head is stressed due to the bending moments arising from the tension in the studs. The bending moments in the head are balanced by the bending moments in the block and the liner. The bending moments in the block are induced from the tensile stress in the studs. When the head stud spacing is non-uniform, the bending moments set up around the circumference of the head are also non-uniform. The stud location is such that the bending moment on the head from stud pretensioning is greater in the transverse direction (90 degrees to crankshaft polar axis) than in the direction of the crankshaft axis. This non-uniformity of bending moment means that head deflection from pretensioning is greater in the transverse direction. The head is further deflected by thermal distortion resulting from the thicker dimension of the firedeck between the intake valves. The deflection of the head may lead to exhaust valve leakage and problems attendant with valve leakage.

Q. Did FaAA adequately review the design of the replacement cylinder heads?

A. No. FaAA did not address all of the functional attributes of the cylinder head as set forth in the Task Description for the cylinder head design review.89/ Rather FaAA limited its design review to an evaluation of thermal and pressure stresses on the firedeck, using an extremely simplified idealized version of the firedeck and making assumptions which invalidate the conclusions of the review. We believe the FaAA analyses is unreliable, and the TDI Owners Group apparently agrees. Mr. Coleman of the Owners Group agreed that no reliance could be placed in the design analysis of the FaAA Head Report in his statement to PNL at the June 22, 1984 meeting that: "The idea that we're trying to give you today is that we didn't depend on the [cylinder head] report either from the standpoint of the analysis, other than to give us some idea of what's going on there, but our conclusions of our recommendations are based on the fact that we did not have enough information in our analysis. We were unable to do the complicated analysis necessary to get that."

Q. Why do you believe the results of the FaAA analytical evaluation of thermal and pressure stresses are invalid?

89/ FaAA Head Report, Appendix B.

A. Dr. Wells of FaAA stated that "these are approximate calculations only intended to show the general levels of thermal and pressure stress."90/ We agree for the following reasons. First, FaAA used an idealized one-dimensional model of a flat plate for the firedeck, and therefore assumed a uniform thickness of the plate.91/ Solutions in the thermal analysis were obtained for 3 different uniform plate thicknesses.92/ The actual firedeck is non-uniform and has many thickness variations in a single firedeck. The temperature distribution in the firedeck is significantly affected by these thickness variations, as explained above. Second, FaAA assumed a peak firing pressure of 1600 psi.93/ The actual peak pressure is about 1800 psi. This large difference between the assumed and the actual firing pressure would substantially alter the results of both the thermal and pressure stress evaluations by FaAA. Third, FaAA's pressure stress analysis idealizes the firedeck as if it were a plate uniformly clamped at its outer boundary.94/ In reality, the bolts holding down the head are

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90/ Transcript of June 22, 1984 meeting between PNL and the TDI Owners Group, at 136.

91/ FaAA Head Report at 3-1.

92/ *Id*. at 3-3.

93/ Deposition of Clifford H. Wells (May 14, 1984) ("Wells Deposition") at 130-31. (Exhibit 27).

94/ FaAA Head Report at 3-5.

not uniformly spaced. FaAA admits that "the local stresses in the critical areas ... defy analysis because of the complexity of the geometry."95/ Fourth, the underlying data in support of the calculations is not provided and thus the report's conclusions are inscrutable. For instance, the conclusion that "provided the range of stress does not exceed twice the yield stress, the fire deck should be dimensionally stable even if yielding occurs . . . ." is not supported by calculations. Finally, the FaAA evaluations assume a perfect cylinder head material free of any defects or imperfections. The strength of the actual casting and the presence of imperfections will affect the ability of the firedeck to withstand mechanical and thermal stresses.

Changes in Manufacturing Techniques

Q. Do you believe that the cracks in the three original Shoreham heads and in other heads cast prior to September 1980 are the result of casting flaws, as suggested in the FaAA Head Report?96/

95/ Id. at 3-6.

96/ Id. at 1-2 to 1-4.

A. Yes. From the two TDI failure analyses of the three Shoreham head failures,97/ we believe there is evidence of casting defects in those heads. But there is no basis for eliminating other contributory causes of failures of these and other TDI heads referred to in the FaAA Head Report, including the design defects described above.

The causes of cracks in any 4-cycle engine cylinder head are generally related to a combination of stresses from cylinder pressures, thermal stresses from cooling strains (set up during the solidification and the cooling of the castings), and stresses arising from bolting the heads onto the engine frame. Failures such as the ones that have occurred at Shoreham can come about from fatigue and from the fact that stresses affect the endurance limit of the castings. Failures can also occur if there is thinning in the casting process, even if the thinning is insufficient to cause porosity or hot tears in the casting, since gas pressure loads can then overstress the thin areas. Failures can also occur if there is a thickening of critical areas of the cylinder heads due to core shift. The reduction in working stresses from the thickened material does

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97/ TDI Failure Analysis Reports No. 0150 and 0151, March 28, 1983, signed by R. A. Pratt. (Exhibit 28).

ot generally compensate for the increase in thermal stress, nd failure usually occurs, starting with cracks develop ıg within the cooling water space and moving outward.

Q. Will cracks develop if there is porosity or hot tears in the casting process?

A. Porosity, hot tears, shrinkage and sand or slag inclusions are all examples of casting defects which can result in cracking of the cylinder heads. For this reason, it is appropriate to discuss not only the cracks that were found in the three original Shoreham cylinder heads, but also the kinds of casting defects which can cause cracking.

Q. Hasn't the cause of the cracks in the three Shoreham cylinder heads been established?

A. Based upon the failure analyses performed by TDI, LILCO asserts that the cracks in the three original cylinder heads were caused by operating stresses acting upon latent casting defects -- hot tears and shrinkage in the case of cylinder head S/N E94 and sand inclusions in the case of cylinder heads S/N E27 and E31. This assertion, however, is unjustified because the failure analyses are inadequate and of insufficient completeness. The analyses do not rule out possible tributory causes of the failures. Complete failure analyses ld have included metallography, bulk chemical analysis, anning electron microscopy, and perhaps localized chemical alysis of the fractured surfaces. Metallography would have sclosed whether the heads had been suitably heat treated. tallography would also have revealed information about the ain structures of the casting at the failure site. It would ave detected the presence of coring material, which can be eleterious to the integrity of the casting, and could have indicated the presence of residual stresses. Scanning electron microscopy would have identified the site of crack initiation and therefore would have helped reveal the mode of failure. Localized chemical analysis would have confirmed the type of casting defect present. Without these tests and analyses, TDI could not have accurately ascertained the cause or causes of the cracks. For example, while a hot tear can generally be recognized on a clean and fresh casting surface, the cracks experienced at Shoreham, when sent back to TDI for analysis, were corroded. Thus, the cracks should have been cleaned and examined by appropriate means such as scanning electron microscopy. Among other things, examination of the corrosion products would have given an indication of how long the crack had existed. However, none of this was done. With respect to the sand inclusions, chemical analysis of the filings would have differentiated sand from slag inclusions. While TDI performed a microscopic assessment of filings, they failed to chemically analyze the material to establish its true origin. Moreover, metallography would have shown if "sand inclusions" were concealing other defects, such as gas porosity. Again, however, these tests were not performed.

Q. Why is a complete failure analysis necessary?

A. Because until the actual cause (or causes) of the cracks is determined, judgments regarding the adequacy of solutions to the problems which permitted the cracking to occur cannot be made with any degree of assurance.

Q. Is it possible to determine with any confidence whether the changes in manufacturing techniques adopted by TDI have solved the casting problems with cylinder heads?

A. No. Since 1976 there have been over 74 changes which TDI has reported it made in its casting techniques and foundry procedures.98/ Not all of the changes were in response to specific problems. Indeed, many of the changes were made in response to production costs.99/ However, the multiplicity of

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98/ "4 Valve Steel Head -- 03-360-03-OF" (undated) (Exhibit 29).

99/ See Deposition of Edward S. Dobrec (August 3, 1983), at 52-62. (Exhibit 30).

changes and the interrelationship between changes, makes an assessment of the total effects of the process changes impossible. Thus, the changes claimed by TDI do not reflect a clear evolution in techniques and procedures, but rather an ad hoc "hit or miss" approach. In addition, TDI had no detailed foundry practice procedures at the time the original cylinder heads at Shoreham were produced, so the original and the replacement head casting processes cannot be accurately compared.

Q. The FaAA Head Report refers to particular manufacturing procedures to support its conclusion that, although the replacement heads might crack due to pre-existing flaws, they are less likely to do so than the pre-September 1980 heads. Do you agree?

A. No. FaAA states that TDI's casting problems of inadequate mold quality, core shifting, and poor gaging procedures in machining the firedeck "were apparently addressed" by:

(1) "Improvements" in mold and core design, and

(2) "Changes" in materials used for mold and core fabrication, especially use of a sodium silicate ester sand for the mold and use of core shells.100/

100/ FaAA Head Report at 1-5 to 1-6.

Second, FaAA says that unsatisfactory flow and supply of liquid metal to the mold and the inadequate solidification pattern in the mold "were apparently addressed" by:

(3) "Modification" of gates and risers, and

(4) Use of chills.101/

FaAA does <u>not</u> conclude that these changes have <u>solved</u> TDI's casting problems, because FaAA could not support such a conclusion. FaAA has undertaken no analysis of the changes in the techniques which it mentions. It does not describe, and admits it has not verified, what techniques were used by TDI prior to the current ones. Without a careful analysis of <u>both</u> the current <u>and</u> the previous casting procedures, one simply cannot conclude that the changes are "improvements."

Q. Please explain your views as to each particular matter referred to by FaAA in the previous answer.

A. (1) The "improvements" in mold and core design are not described. This is a purely conclusory statement with no supporting analysis; we don't know what changes FaAA believes were made in mold and core design, so we can't evaluate whether

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101/ *Id*. at 1-6.

r not they were improvements. Our own investigation disclosed that TDI never used design drawings of molds, so accurate comparisons of current and older mold and core designs could not be made. As TDI experimented with different mold and core designs, improvements may have resulted, but poorer results could also have occurred with equal probability.

(2) The change to sodium silicate ester sand for molding sand can increase the chances for gas porosity in the casting since sodium silicate ester sand is more resistant to gas flow and the gas can be trapped in the casting.

(3) The manner in which gates and risers were modified is not described by FaAA, and there is no information to serve as a basis to determine whether the changes effectively addressed the casting problems. For example, placing a gate in a mold may reduce the rate of metal flow so that the flow is too slow, thereby permitting metal already in the mold to cool before the casting is complete. A riser which is too small can contribute to shrinkage defects.

(4) The use of chills may reduce the likelihood of hot tears in some instances. Chills also increase the likelihood of gas porosity in the casting.

The claim that these changes in casting methods and techniques have successfully addressed TDI's casting problems is belied by the extremely high rate of defects in cylinder heads produced since all of these changes were made. TDI documents102/ for foundry rework on cylinder heads show that nearly all of the heads cast in 1982-83 had defects and required reworking.

Q. What other changes in cylinder head manufacturing processes were referred to by FaAA?

A. FaAA refers to a 1978 TDI procedure to post weld heat treat the heads after deposition of the Stellite valve seat overlay and to a 1980 TDI Service Information Memo changing valve seat weld repair procedures.103/ The changes are not analyzed as to their adequacy, implementation, or effects. We have no basis to believe that these changes have solved the cracking of the Stellite weld deposits seen in TDI heads at Grand Gulf.

102/ TDI Documents, "Casting and Machining Problems with RV-4 Cylinder Heads." (Exhibit 31).

103/ FaAA Head Report at 1-5.

FaAA also states that TDI claims that all heads cast after tober 1978 received a second stress relief treatment. Stress lieving, or normalizing, can reduce stresses in the casting, t does not eliminate or affect geometrically-induced stress, s porosity, inclusions, shrinkage or hot tears, each of which an cause cracking of the heads and increase crack propagation.

FaAA raises the problem of poor gaging procedures during iredeck machining, but does not state how TDI addressed that roblem. Given the large variations in firedeck thickness in the replacement heads at Shoreham, we believe TDI has not addressed this problem. Moreover, in our opinion it is not a gaging problem; firedeck thickness is rather a design, manufacturing, and quality control problem.

Q. Does the operating history of the Group III heads (including the replacement heads at Shoreham) support FaAA's conclusion that the replacement heads are adequate for nuclear service and are significantly less likely to have pre-existing flaws than earlier heads?

A. No. The only operating history of Group III heads verified by TDI is that pertaining to 16 replacement cylinder heads at Shoreham, out of 311 Group III heads TDI says it has produced.104/ FaAA states that Messrs. Trussell and Pratt of

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104/ FaAA Head Report at 1-2; Wells Deposition at 103. (Exhibit 27).

TDI said in December, 1983, that "there have been only five instances of water leaks in Group II and Group III cylinder heads that have resulted in water in the cylinders...."105/ However, Mr. Mathews, vice president and general manager of TDI, testified in May 1984 that TDI had never in the past two years conducted any review of its files to ascertain failure rates of cylinder heads.106/ There is simply insufficient evidence from TDI's operating history to conclude that Group III cylinder heads will not crack or will have any less likelihood of cracking than pre-group III heads.

Inspections of Replacement Heads

Q. Have the inspections of the replacement cylinder heads at Shoreham ensured that they are adequate for nuclear service?

A. No. The inspections performed on the Shoreham replacement heads have been inadequate in a number of respects. First, there can be no confidence in inspections carried out by TDI before the heads were delivered. Second, the inspections

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105/ FaAA Head Report at 1-4.

106/ Deposition of Clinton S. Mathews (May 8, 1984) ("Mathews Deposition") at 79-82. (Exhibit 32).

of the replacement heads performed at Shoreham after 100 hours of operation were insufficient because inspections were done on a sampling basis, not all of the inspection techniques necessary to detect flaws were used, and the inspection standards were inadequate.

Q. What inspections is TDI supposed to have performed on the replacement cylinder heads?

A. TDI has written procedures for carrying out visual inspections, magnetic particle inspections, liquid dye penetrant testing and hydrostatic testing.107/ However, these procedures are seriously deficient. The magnetic particle inspection procedure does not specify which areas of the cylinder heads are to be inspected. Indeed, the procedure is only a general procedure "for the testing of ferromagnetic parts and assemblies," and is not specifically written for cylinder head inspection. In fact, TDI did not inspect the replacement heads by magnetic particle techniques, because it only started to use this procedure on cylinder heads in April 1984.108/ The hydrostatic test procedure, which is written for use in "welded

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107/ Respectively, TDI QC Procedures 600-10, 600-30, 600-20 and 600-70.

108/ FaAA Head Report at ii.

assemblies and cast products," is not expressly applicable to cylinder heads. TDI interprets its inspection procedures to permit acceptance of a cylinder head which fails a visual inspection (by having a visible indication), so long as it does not leak during the hydrostatic test.109/ A further example of TDI's inadequate test and inspection procedures is the in-process inspection procedure (I.P.-300), which directs the QA inspector to use the same gauge blocks as the machinist and sets forth no measures for ensuring that the gauges are properly controlled, calibrated and adjusted so as to maintain accuracy. Mr. Mathews of TDI testified that TDI may well deliver cylinder heads to nuclear plants that have cracks or sand inclusions.110/

Q. Are TDI's inspections and testing techniques, if they are properly performed, capable of detecting all casting defects and cracks in the replacement cylinder heads?

A. No. It is unlikely that any of the techniques used by TDI will detect cracks or other casting defects more than 1/4 inch beneath the surface of the casting. Visual

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109/ I&E Report 83-25 at 4. (Exhibit 22).

110/ Mathews Deposition at 86-87. (Exhibit 32).

inspections and dye penetrant testing, if done correctly by trained personnel, will only reveal surface cracks. Hydrostatic testing only discloses through-wall cracks in or around the cylinder head passageways that are tested, and will not detect subsurface cracks. Magnetic particle inspections can reveal subsurface cracks or other casting defects, but only to an approximate depth of 1/4 inch.

Q. What inspections were subsequently carried out on the replacement heads at Shoreham?

A. A liquid penetrant test was done on the exhaust and intake valve seats and firedeck area between the exhaust valves on 9 of the 24 cylinder heads, after 100 hours of full power operation. Ultrasonic measurements were taken of the firedeck areas of 12 cylinder heads. Finally, visual inspections were performed on the valve seat areas of 32 of the 98 valves, and on 7 firedecks of the 24 cylinder heads for indications of surface damage.111/

Q. Were these inspections adequate to conclude that the replacement cylinder heads at Shoreham are qualified for "unlimited operation"112/ in nuclear service, as FaAA

111/ DRQR Report, Vol. 8, Cylinder Heads, at B3-B4. (Exhibit 20).

112/ FaAA Head Report at iii.

concludes?

A. Absolutely not. In fact, the DRQR Report for Shoreham states

> The absence of detectable flaws in the Shoreham cylinder heads does not preclude the eventual propagation of a crack from a subsurface defect or a defect in an inaccessible location.113/

We agree with this statement, but we also believe that the inspections were not sufficient to detect even all relevant flaws and defects in accessible areas of the replacement heads. Accordingly, the probability of cracking of the replacement heads may be much higher than indicated in the DRQR Report.

Q. What are your reasons for concluding that these inspections did not sufficiently disclose even surface defects in the replacement heads?

A. First, only a limited number of samples of the replacement heads were inspected. As described above in our discussion of the AE piston skirt inspections, a sampling inspection is particularly inappropriate because of TDI's ineffective QA/QC program. Region IV of the NRC informed TDI that results of NRC Vendor inspections of TDI show

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113/ DRQR Report, Vol. 8, Cylinder Heads, at 3. (Exhibit 20).

> [s]erious deficiencies have existed in the implementation of your committed quality assurance program for manufacture of emergency diesel generators. What concerns us greatly is that certain of these findings are of a nature which brings into question both the adequacy of existing manufacturing process controls and the level of compliance by manufacturing and quality control personnel.114/

We agree with Mr. Foster of NRC Region IV that TDI's ineffective QA/QC program makes a samplying inspection next to useless and means that even a 100% inspection is unlikely to reveal all defects.115/ However, given the importance of the heads, a 100% inspection should have been performed.

Second, of the sample heads, only selected portions were examined. For example, the liquid penetrant test was performed on the firedeck only in the area between the exhaust valves. Other areas of the firedeck are as likely to have indications or inclusions.

Third, inspections were restricted to visual and liquid penetrant. The ultrasonic measurement was done only to measure firedeck thickness. It is likely that more defects would have

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114/ Letter dated January 17, 1984, from V. Potapovs (NRC) to C. Mathews (TDI). (Exhibit 33).

115/ Foster Deposition at 54-55. (Exhibit 13).

been detected if magnetic particle examination, eddy current examination, and radiograph testing had been employed. The visual examination is unfortunately of limited value.

Q. Why is the visual examination of limited use?

A. Apart from the obvious fact that it is limited to what the naked eye can see, the results of the visual inspection have apparently been ignored. The NRC Staff discovered an indication about 3/8 inch long on the machined bottom part area of replacement head S/N H-34 at Shoreham.116/ TDI advised the staff that this crack was within TDI's acceptance criterion because the head had not leaked under hydrostatic test. LILCO and FaAA have not replaced the cylinder head with this indication, apparently accepting TDI's criterion.

Q. Do you believe that the LILCO response was appropriate?

A. No. A 3/8 inch indication such as on head H-34 may grow under operating stresses and with the effects of corrosion. Yet LILCO, TDI and FaAA would permit one or more small cracks or inclusions in the replacement cylinder heads. This

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116/ I&E Report 83-25 at 4. (Exhibit 22).

is also shown by the acceptance criteria used by LILCO and FaAA.

Q. What is the basis for the FaAA/TDI Owners' Group inspection criteria for cylinder head inspections?

A. No bases are provided for the liquid penetrant inspection or the ultrasonic measurement criteria cited in Appendix A of the FaAA Head Report. For the magnetic particle inspection, no basis is provided to demonstrate that the ASTM criteria are appropriate for the intended service. For the firedeck UT measurement, the thickness is only required to be recorded. No maximum thickness is specified and the technical basis for the minimum thickness is not cited. The bases for all the acceptance criteria should have been provided by TDI and assessed by FaAA. The acceptance criteria bases must be demonstrated because without knowing the distribution of flaws below the surface, any crack or void can be assumed to grow.

Cracks in Replacement Heads

Q. If cracks similar to those in the three original heads occurred in the replacement cylinder heads at Shoreham, is it true that only a very small amount of water could leak into the cylinders after shutdown of the EDGs?

A. No. This proposition was asserted by LILCO based upon TDI's inadequate and incomplete failure analyses of the original failed heads, which determined that the cracks were caused only by operating stresses acting upon pre-existing casting defects in the cylinder heads.117/ TDI contends that since these operating stresses are caused by the cylinder firing pressure, once the EDG is shut down and operating stresses are substantially reduced, any cracks would close.118/ In addition, TDI asserts that the stresses are further reduced when the cylinder heads cool to a steady-state temperature. Thus, it was concluded that the cracks were self-relieving and would not have propagated.

While the evidence suggests that a cause of the failed cylinder heads was casting defects, there is no support for TDI's assertion that only the operating stresses were acting upon the casting defects and that the cracks were therefore self-relieving and would not have propagated. In fact, cracks

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117/ Affidavit of Edward J. Youngling, dated July 8, 1983 (Exhibit 21).

118/ Contrary to the preceding assertion, PNL consultant Mr. Louzecky stated at the June 22 meeting (Tr. at 129) between PNL and the Owners' Group that ". . . in the cooling-off period, that's usually when your (cylinder head) crack opens up . . . ."

such as those found in the three failed cylinder heads at Shoreham will always propagate and grow, unless arrested by heavy material or a void.

Q. What factors other than operating stresses would cause cracks to propagate and grow?

A. Cracks propagate (i.e., deepen and/or travel) and grow (i.e., lengthen and/or widen) due to operating stresses, residual stresses (i.e., manufactured-in stresses, such as from the casting and welding processes), geometrical stresses (e.g., stresses arising from design, such as stresses which exist at sharply-angled edges) and corrosion. What must be kept in mind is that cracks are stress raisers, and that stresses other than operating stresses will propagate a crack. Residual and geometrical stresses commonly accelerate crack propagation and growth, and corrosion occurs preferentially at cracks. All of these mechanisms (residual stress, geometrical stress and corrosion) will act to propagate a crack even when a diesel is not in operation. Further, the environment may increase the growth of the crack at a higher rate than one would calculate by merely summing the cyclic loads.119/ Indeed, cracks in the

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119/ "Introduction to Fracture Mechanics," Kare Hellan, McGraw-Hill, 1984, at 135.

cylinder head by their very nature propagate and grow until they hit a massive part or a void, such as an exhaust valve. When a crack enlarges, the flow of water through the crack will increase. Furthermore, cracks are seldom self-relieving, except perhaps when they split open, and cracks never decrease in dimension, especially when the crack surfaces are covered with corrosion products. Therefore, water can continue to leak into the combustion chamber after shutdown and at any time thereafter.

Q. Could cracks in the replacement cylinder heads first begin to leak during cold shutdown of the EDGs?

A. Yes. For example, a crack which initially occurred from operating stresses may not leak during operation. That same crack may not leak for some time after the EDG is shut down. However, stresses other than operating stresses, such as stresses from corrosion products acting to force the crack apart, may cause the crack to propagate or grow after shutdown.120/ Cracks may grow very slowly for some time, but once a crack reaches its critical size it will grow very rapidly and

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120/ "Analysis of Oxide Wedging During Environment Assisted Crack Growth," S.J. Hudak and R.A. Page, NACE, Vol. 39, No. 7, July, 1983, at 285 to 290.

rupture. Thereafter, the flow of water through the crack could be significant. The amount of such water leakage would depend upon the number and the size of the cracks and their location. The existence and interaction of these factors cannot be predicted. However, depending upon the circumstances, significant leakage could occur in a matter of days or even hours.

Q. Would undetected leakage from a cracked head into the cylinder affect the rapid restart capability of the diesel generators?

A. Yes. If liquid is contained in the cylinders, there will likely be damage to the engines. Quantities of liquid can cause dangerous pressure rise within the cylinders. If liquid is contained in the cylinders, the compression pressure increases and will continue to increase until it equals the firing pressure; the volume of liquid contained in the cylinders then becomes known as the "critical volume." If the liquid in the cylinders is greater than the critical volume but less than the clearance volume, the liquid may not show up during the barring procedure proposed by LILCO, and dangerous pressures may build up during the start period. This very high and dangerous pressure buildup can cause studs holding the head in place to stretch, thereby "blowing" the head gasket. When this occurs, the EDG cannot be operated because of flames blowing out between the head and liner faces.

Water leakage into the cylinder head could also lead to a catastrophic failure should the cylinder head go "solid with water." The Shoreham piston crowns have a dished configuration, and should there be leakage the dish area could fill up and the water overflow down past the piston rings into the lube oil sump. This could cause water contamination of the lube oil. Leakage, even in very small amounts, could also impair lubrication of the cylinder. Scoring of the cylinder liner bores can occur, followed by rapid seizure of the piston and consequential damage.

Catastrophic consequences can also result from cracks in the cylinder head firedeck, even when there is no water leakage. Higher pressure combustion gases can leak into the cooling water space. In the short term, the combustion gases enter the cooling water and may "air lock" the heads. Alternatively, the heat exchangers may not be able to handle the heat input to the cooling water and a rise in temperature could cause a shutdown. A further problem could arise when the cooling water pumps "gas up," causing the cooling water temperature to rise and the engine to shut down.

Q. Could the corrosion inhibitors in the cooling water of the EDGs affect rapid restart if leakage occurred?

A. Yes. These corrosion inhibitors can alter the cylinder liner diameter by building up salts and other corrosion products, if cooling water leaks into the combustion chamber and cylinder space. This, in turn, prevents adequate lubrication and causes a number of dry strokes during the starting of the engine. The dry strokes would result in localized heating, with probable additional failure of lubricant and seizure of the pistons.

Q. But won't the corrosion inhibitors prevent corrosion in the cylinder, should leakage occur?

A. No, the corrosion inhibitors act to passivate a surface by providing a stable film to act as an oxygen barrier. Corrosion would preferentially occur in the space between the cylinder walls and the piston. Thus, it is possible that corrosion products could form that would act as a barrier and prevent the passage of water betweeen the piston and the walls and into the lube oil sump. In other cases, muck, carbonaceous material and detritus from the piston ring grooves can act as a sealant and prevent leakage down the side of the piston. Then, water would collect in the cylinder, causing the cylinder head to go "solid with water."

Q. How fast could this corrosion occur?

A. The passivation occurs immediately on contact with the metal. However, the speed at which subsequent corrosion processes occur is dependent upon a variety of factors and their interaction, including temperature, surface area and driving force. Hence, the speed of corrosion development for this case is inherently unpredictable. What must be kept in mind is that the concern lies not only with corrosion in the cylinder, but also with the effect of corrosion on cracks in the cylinder head. As previously mentioned, corrosion products put a stress on cracks. Thus, a crack may grow slowly until it reaches a critical size. Thereafter, however, it grows much more rapidly. Indeed, cracks can change significantly in a matter of days or even hours.

Q. Will water flow through a crack during cold shutdown even though there is essentially no water pressure to drive the water through the crack?

A. Yes, because the water has substantial driving force through the crack without the water pressure of the cooling system. The cooling water flows into the crack in an effort to dilute the corrosion products and creates an osmotic pressure. In addition, the driving force from the capillary action causes flow through the crack. As the crack grows, the flow of water increases proportionally.

Q. But isn't a steel cylinder head strong enough to resist cracking caused by corrosion?

A. No, it is not. The stresses generated by corrosion products are extremely high. Moreover, the tip of a crack acts as a stress riser and can synergetically exceed the tensile strength of the metal without any additional stresses. In addition, TDI has changed the steel in its cylinder heads to a lower strength alloy (TDI's No. 7 steel) with less carbon content. This reduction in carbon can cause cracks to initiate, to propagate, and to grow.

Q. Could leakage from cracked replacement heads also have an adverse impact on EDG's performance during operation?

A. Yes. Operating stresses could cause the cylinder head to crack or could exacerbate existing cracks' growth. LILCO and TDI contend that there would be no adverse impact on the EDG's performance, since any water leaking into the cylinder during operation would be expelled along with combustion by-products. However, depending upon the location and size of the leak, water in the cylinder could be sufficient to impair lubrication in the cylinder and cause seizure of the piston and fracture of the piston skirt, leading to engine shutdown. In other cases, only partial seizure may occur; however, this can lead to heavy bearing wear and misalignment.

Q. But isn't water sometimes injected into the combustion chambers of diesel engines to improve performance?

A. Yes. Sometimes distilled water in very small amounts is homogenized with fuel and injected into the combustion chambers. This is done to reduce the emissions of nitrous oxides with the exhaust gases. However, this process requires strict control of the quantity of water that is homogenized with the fuel prior to injection. In addition, the cooling water in the EDGs contains corrosion inhibitors. If the cooling water leaks into the combustion chamber and cylinder, the salt residues from these corrosion inhibitors can cause abrasive wear on the cylinder liner bore, thereby reducing piston ring life.

Q. Could cracks in the cylinder heads also cause problems in the long term?

A. Yes. While it is true that water leakage into the cylinders generally flashes to steam and passes out with the exhaust gases, if any water remains it is sprayed out with the exhaust gases and erosion of the turbocharger blading will occur in a manner similar to steam turbine blading erosion. In that event, the turbo blower speed falls and the engine overheats due to a reduction in air flow. Moreover, cracks in the cylinder head firedeck may cause a reduction in cooling water pH value, leading to the formation of acids which attack various parts of the engine cooling system and cause corrosion of the engine. Water leakage may also damage or score the cylinder liner, damage the piston rings, reduce power and allow gases into the cooling water system. The scored liners allow hot combustion gases to blow down between the cylinder and the piston skirt. This causes distortion of the piston, further scoring of the cylinder liner and serious overheating, which may eventually lead to a crankcase explosion.

Q. Has LILCO committed to perform a "barring over" procedure at certain intervals after EDG shut-down to detect water which might have leaked into EDG cylinders due to cracks in the replacement heads?

A. Yes. LILCO intends to use the procedure referenced in SP27.307.02.121/

121/ DRQR Report, Vol. 8, Cylinder Heads, at 3. See LILCO Procedure SP 27.307.02, Emergency Diesel Generator Cylinder Head Leak Detection Test. (Exhibit 34).

Q. Do you believe that the proposed barring over procedure, if implemented, will ensure that leakage, if it occurs during testing or operation, will be detected?

A. No. LILCO's proposed procedure will not ensure the detection of leakage of water into the cylinders. In fact, given the nature of cracks in cylinder heads, no barring over procedure can ensure that leakage will be detected prior to an emergency rapid startup of the diesels. Cracks which occur during operation may not leak during operation or even within the first 12 hours after shutdown, the time under LILCO's proposed procedure when the EDGs would last be barred over. For example, cracks formed during operation could be focal points for corrosion, which would make it difficult for the cracks to close. Water could therefore leak into the combustion chamber of the EDG after shutdown, including more than 12 hours thereafter, in amounts sufficient to impair an emergency start. Such a leak would not be detected by LILCO's proposed barring over procedure. Even swinging over the engines with starting air might not detect small amounts of water symptomatic of a leak.

Q. Would your concerns with LILCO's barring over procedure be alleviated if the barring over were performed more frequently than proposed by LILCO?

A. Even if barring over were done more frequently, there would be no assurance that leaks which could impair emergency startup of the EDGs would be detected. It is not possible to predict when emergency startup would be needed, and it is therefore impossible to bar the engine over immediately before startup is required. Unless the barring over is done immediately prior to emergency startup, there can be no assurance that water from one or more cracks would not leak into the cylinder of one or more EDGs and impair startup.

REPLACEMENT CRANKSHAFTS

Q. How does Suffolk County's Contention relate to the crankshafts in use at Shoreham?

A. The EDG Contention provides that its first paragraph is supported because:

> (a) The replacement crankshafts at Shoreham are not adequately designed for operating at full load (3500 kW) or overload (3900 kW), as required by FSAR Section 8.3.1.1.5, because they do not meet the stardards of the American Bureau of Shipping, Lloyd's Register of Shipping, or the International Association of Classification Societies. In addition, the replacement crankshafts are not adequately designed for operating at overload, and their design is marginal for operating at full load, under the German criteria used by F.E.V.
>
> (b) The shotpeening of the replacement crankshafts was not properly done as set forth by the Franklin Research Institute report, Evaluation of Diesel Generator at Shoreham Unit 1, April 6, 1984, and the shotpeening may have caused stress nucleation sites. The presence of nucleation sites may not be ascertainable due to the second shotpeening of the crankshafts.

Q. What is the type of crankshaft now in the EDGs?

A. The EDGs now have replacement crankshafts with 13-inch diameter main bearing journals, 12-inch (nominal) diameter crank pins (or connecting rod journals), and 3/4-inch crank pin fillet radii. The original crankshafts had 11-inch (nominal) diameter crank pins and 1/2-inch crank pin fillet radii. The replacement crankshafts were installed after the original crankshaft on EDG 102 fractured into two pieces during an engine test run following the replacement of cylinder heads. The fracture occurred mostly through the web connecting the number 7 crank pin adjacent to the number 9 main bearing journal. Subsequently, inspections identified cracks in the number 5 and 7 crank pins of EDG 101 at the generator end and cracks in the number 6 crank pin of EDG 103 at the governor end. FaAA has published a report entitled "Emergency Diesel Generator Crankshaft Failure Investigation, Shoreham Nuclear Power Station" dated October 31, 1983, that concluded that the original crankshafts were inadequately designed and had failed due to high cycle torsional fatigue.

Q. Have you examined any materials concerning the original and replacement crankshafts?

A. Yes. We have examined the drawings for the original and replacement crankshafts and associated parts, and have reviewed numerous documents concerning the crankshafts, including the various reports by FaAA. LILCO also allowed us to make a brief visual inspection of the replacement crankshaft as installed in EDG 103.

Q. Have you reached any conclusions concerning the adequacy of the replacement crankshafts in the EDGs?

A. Yes. We have concluded that the replacement crankshafts in the EDGs are inadequately designed for operating at the FSAR-specified full load (3500 kW) or overload (3900 kW). The replacement crankshafts do not meet the published standards of the American Bureau of Shipping, Lloyd's Register of Shipping, the International Association of Classification Societies and other major international classification societies for operation at the full load or overload operating conditions of the EDGs. The replacement crankshafts also are not adequately designed for operating at overload, and their design is marginal for operating at full load, under the standards of the German design criteria used by the TDI Owners Group's diesel engine consultant, FEV.

In addition, we have concluded that the shotpeening of two of the replacement crankshafts was improperly performed initially and may have caused nucleation sites which may not be ascertainable due to the second shotpeening of those crankshafts.

Standards for Crankshaft Design

Q. Are there any standards governing the design of crankshafts in diesel engines?

A. There is no single set of engineering standards governing the design of crankshafts in diesel engines. However, the various ship classification societies have adopted standards for evaluating the adequacy of the design of crankshafts in diesel engines in marine applications. We believe that these standards provide minimum guidance for applications where reliability is a significant evaluation factor. The ship classification societies include Lloyd's Register of Shipping ("Lloyd's"), the American Bureau of Shipping ("ABS"), Nippon Kaiji Kyokai ("NKK"), Det Norske Veritas, and Germanischer Lloyd.

Q. What are ship classification societies?

A. To assure the safety of their vessels, shipowners require shipyards to build and equip their vessels in compliance with the rules of classification societies. Those rules include limitations on propulsion equipment such as diesel engines. Engine builders use these rules as design criteria when designing new engines and major engine components, when increasing the rating of an engine, and when changing the design of major engine components. Prudent engine builders ensure that their engines comply with these rules.

As reported by the NRC's Consultant, Franklin Research Center ("FRC"):

> "Ship classification associations such as the American Bureau of Shipping and Lloyd's Register of Shipping, represent possibly the oldest machinery review and evaluation associations functioning today. Lloyd's Register began operations in 1760 and published its first set of rules in 1834. As ships and ship propulsion systems became more sophisticated, the classification associations served as design review agents to evaluate functional adequacy and safety. Considerable experience in the review and evaluation of diesel engines was realized from the long-term use of diesel engines for propulsion and electric power generation in ships. The ship classification rules probably represent the most extensive experience in large diesel engines available."122/

Q. Why do you believe that the standards set by ship classification societies should be applied to determine the adequacy and reliability of the replacement crankshafts at Shoreham?

122/ Evaluation of Diesel Generator Failure at Shoreham Unit 1, Final Report, Failure Cause Evaluation, April 6, 1984, by Franklin Research Center ("FRC Report") at 33-34. (Exhibit 35).

A. Because these standards embody the only comprehensive collections of meaningful guidelines controlling crankshaft design in diesel engines to be used in applications where reliability is a controlling factor. There are no other adequate standards.

Q. The purchase specifications for the EDGs required that the crankshafts conform to the guidelines of the Diesel Engine Maufacturers Association ("DEMA"). Aren't those guidelines a reasonable alternative set of design standards by which adequacy of the design of the replacement crankshafts can be measured?

A. No. Those guidelines are not a design code. As the foreward to the DEMA guidelines explicitly states, "[I]t is not the purpose of this book to attempt to set forth basic design criteria for engines because such approach would be impossible within this volume and yet do justice to the many types of engines on the market, notwithstanding the fact that many technical texts are available to the student who may be undertaking the design criteria aspects of engines in general."123/

123/ Standard Practices for Low and Medium Speed Diesel and Gas Engines, 6th ed., 1972 at iii.

Q. Generally speaking, what factors do the classification societies take into consideration in evaluating the adequacy of crankshafts on diesel engines?

A. The various classification societies evaluate the adequacy of the design of diesel engines in different ways and in varying degrees of detail. For instance, Lloyd's rules evaluate the adequacy of the design by calculating the maximum power rating for engines. This calculation takes into consideration 26 inputs, including the manufacturing or forging process of the crankshaft, the strength of the crankshaft material and the existence of fillet radii. Lloyd's rules also calculate the maximum allowable torsional vibration stresses. In addition, unlike most other rules, Lloyd's rules require that auxiliary oil engines that are coupled to electrical generators must be capable under service conditions of developing the power to drive the generators for 15 minutes at an overload power of not less than 10 percent. Lloyd's rules also consider misfiring in the cylinders.

The ABS rules evaluate the adequacy of crankshaft design by calculating the minimum allowable dimensions of the crankshaft pins and journals, and crankshaft webs. These calculations take fewer inputs into consideration than Lloyd's rules.

For example, the ABS rules do consider the strength of the crankshaft material, but do not consider the forging process nor do they directly consider the existence of fillet radii. The ABS rules also calculate the maximum allowable torsional vibration stresses. The ABS rules, however, make no provision for operating an engine at an overload condition.

The draft rules of the International Association of Classification Societies ("IACS"), which are used by some of the classification societies, are somewhat unique in that they consider the adequacy of the crankshafts on the assumption that the most highly stressed areas are the fillet transitions between the crankpin and crankshaft web as well as between the journal and the web. Rather than calculating the adequacy of crankshaft dimensions or torsional vibrations, the IACs rules calculate a factor of safety based upon torsional and bending stresses and stress concentration factors.

Q. Do you believe that the rules of any particular classification society should be adopted to evaluate the adequacy of the replacement crankshafts?

A. No. We do not believe that any particular classification society has the "ideal" standard. However, it is pertinent that Lloyd's generally is considered to be the most conservative of the major classification societies, hence providing the greatest margin of safety. In view of the potentially catastrophic consequences resulting from the failure of the EDGs at Shoreham, we believe that, at a minimum, the crankshafts should be compatible with the rules of all of the major classification societies.

Q. Professor Christensen, have you performed any calculations under Lloyd's rules to determine the adequacy of the design of the replacement crankshafts at Shoreham?

A. Yes. I have performed calculations under Lloyd's rules for maximum allowable horsepower for the replacement crankshafts at Shoreham. Those calculations show that for 1680 psi, the highest peak firing pressure assumed by FaAA in its studies at full load (3500 kW), the allowable horsepower permitted under Lloyd's rules is just under 4621 HP. Using the actual measured peak firing pressure of 1750 psi, the allowable maximum horsepower under Lloyd's rules is 4422 HP. In addition, my calculations also show that for 1800 psi, the peak firing pressures at overload (3900 kW), the allowable horsepower under Lloyd's rules is just under 4252 HP. Shoreham's horsepower rating of 4890 HP at full load and 5379 HP at overload exceeds the allowables for horsepower under Lloyd's rules. A copy of my calculations is attached as Exhibit 36.

Q. Messrs. Eley and Bakshi, have you also performed calculations under Lloyd's rules to determine the adequacy of the design of the replacement crankshafts at Shoreham?

A. Yes. Our calculations confirm that the replacement crankshafts fail to comply with Lloyd's rules for maximum allowable horsepower. Our calculated figures are only slightly different from those of Professor Christensen. Our calculations show that, for 1680 psi firing pressure, the allowable horsepower under Lloyd's rules is just under 4636 HP; for 1800 psi firing pressure, the allowable horsepower rating under Lloyd's rules is just under 4269 HP. (Exhibit 37). Shoreham's horsepower rating of 4890 HP exceeds the allowable horsepower under Lloyd's rules.

Q. What accounts for the differences in your calculations?

A. The minor differences result from conversions and rounding of decimals -- such differences are normally encountered when different individuals make computations of this nature.

Q. What is the significance of your findings?

A. Lloyd's rule on allowable horsepower calculates the maximum power that can be developed safely and reliably in an engine when taking into consideration its various parameters. The Shoreham EDGs are required to operate at a higher horsepower rating -- 4,890 -- than would be considered acceptable for them under the Lloyd's Rules. The failure of the Shoreham EDGs to comply with the allowable horsepower limitations under Lloyd's rules signifies that the EDGs cannot be operated reliably at their rated power.

Q. What is the IACS?

A. The IACS is an organization consisting of three minor and nine major ship classification societies, including the ABS and Lloyd's.

Q. Are you familiar with the draft rules of the IACS entitled "Rules for the Calculation of Crankshafts for Diesel Engines"?

A. Yes. Those rules are based upon a proposal by an international group of engineers, CIMAC, entitled "Rules on Calculation of Crankshafts for Diesel Engines (4. Draft)" which is still under discussion among IACS members and between CIMAC and IACS. Portions of these rules are being used by the various classification societies. The rules state that they "are to be applied for checking the sufficient dimensioning of crankshafts for diesel engines for main propulsion and auxiliary purposes."124/

Q. What does a calculation under the IACS rules involve?

A. In order to determine the adequacy of the design of a particular crankshaft under the IACS rules, you must first determine the nominal alternating bending and torsional stresses. Those stresses, when multiplied by the appropriate stress concentration factors using the deformation hypothesis (von Mises' Criterion), give a comparative alternating stress. The IACs rules state that adequate dimensioning of the crankshaft is ensured where the ratio of the fatigue strength to the comparative alternating stress is greater than or equal to a factor of safety of 1.15.

Q. Have you performed any calculations to determine the sufficiency of the dimensions of the replacement crankshafts under the IACS rules?

124/ Exhibit 38, at 1.

A. No, not directly. However, we have reviewed TDI's calculations under the IACS rules, a copy of which is attached as Exhibit 39 and we agree that they are correctly computed. Those calculations show that the replacement crankshafts at Shoreham do not comply with the IACS rules. Significantly, those calculations were performed by TDI using 1650 psi as the maximum firing pressure. As previously indicated, the actual maximum firing pressure in the Shoreham engines is higher (by as much as 100 psi at full load). When the correct maximum firing pressure of 1750 psi is taken into consideration, the replacement crankshafts fail to conform to the IACS rules by an even greater margin.

Q. Professor Christensen, have you performed any calculations to determine the adequacy of the design of the replacement crankshafts under the ABS rules?

A. Yes. I have performed calculations under the ABS rules to determine the adequacy of the design of the webs on the Shoreham replacement crankshafts. Those calculations demonstrate that the replacement crankshafts do not meet the ABS rules. (Exhibit 40).

Q. What are the ABS requirements concerning crankshaft webs?

A. In order to provide for adequate bending stiffness in the crankshaft webs, the ABS rules dictate that the crankshaft webs should be in a specific proportion. Section 34.17.4 of the ABS rules for crankshafts with solid webs provides that

> The proportions of the crankshaft webs are to be such that the effective resisting moment of the web in bending is not less than 60% of the resisting moment of the minimum required diameter of pins and journals in bending.

Normally, this rule is expressed in the formula $wt^2 \geq .35d^3$, where w equals the effective width of the web, t equals the thickness of the web, and d equals the minimum required diameter of the pins and journals.

Q. Was it possible for you to use this formula?

A. No, because the Shoreham replacement crankshafts have a reentrant or crankpin fillet radius of 3/4 inches. The existence of this fillet in the replacement crankshaft precludes the use of the formula because the effective resisting moment cannot be obtained from the rectangle created by w, the effective width of the web, and t, the thickness of the web. This is so because the replacement crankshafts have a re-entrant fillet cut into the crankwebs. Thus, the fillet section, instead of being positive in value, is negative in value. If these negative values are not considered in the calculation of the moment of inertia, the value of the resisting moment will be too high.

Q. What are the specific results of your calculations?

A. My calculations show that the web strength in bending is equivalent to a crankpin or journal diameter of 10.9337 inches. Using this value, I then calculated the maximum allowable firing pressure for the replacement crankshafts. My calculations show that the maximum allowable firing pressure under the ABS rules is 1746 psi at full load and 1651 psi at overload. Thus, when the actual firing pressures of the EDGs are considered, the replacement crankshafts do not comply with the ABS rules at overload and are marginal at full load.

Q. Do you know of any other design standards that bear on the adequacy of the webs on the replacement crankshafts?

A. Yes. The rules of Nippon Kaiji Kyokai ("NKK") and the standards of the German register reflecting the experience of German engine manufacturers.

Q. Have you performed any calculations under the standards of the German register?

A. No, but we have reviewed the deposition of Dr. Pischinger, FaAA's diesel engine consultant, who has performed calculations using the German register standards. According to Dr. Pischinger, this register is used for designing and assessing the adequacy of the design of diesel engines and is accepted by most of the European diesel engine companies.125/ According to Dr. Pischinger's calculations, which he described as "preliminary", the dimensions of the crankshaft webs are inadequate under the German register.126/ Dr. Pischinger expressly stated that he would have designed the webs thicker.127/ Dr. Pischinger also regards the cyclic stresses in the crankshaft as excessive under the register.128/ Dr. Pischinger's preliminary conclusion was that the replacement crankshafts did not meet the standards of the German register at overload and were marginal at full load.129/

125/ Deposition of Franz Pischinger (June 21, 1984) ("Pischinger Deposition") at 94, 97. (Exhibit 41).

126/ Id. at 108.

127/ Id. at 98.

128/ Id. at 185-187.

129/ Id. at 100-101.

Q. Have you made any calculations concerning the adequacy of the crankshaft webs under the NKK Rules?

A. Yes. Our calculations show that the webs on the replacement crankshafts do not comply with the NKK rules for full load or overload conditions. The NKK rules provide for two different ways to determine whether the webs are adequate. One method is based upon the relationship of the ratio of the breadth of the web and the actual diameter of the pin to the ratio of the thickness of the web and the actual diameter of the pin. The other method requires a calculation for the diameter of the pins and journals which takes into account various factors such as the maximum firing pressure. We made our calculation using 1680 psi and 1800 psi as the maximum firing pressures. A copy of these calculations is attached as Exhibit 42.

Q. Have you undertaken any other calculations under the ABS rules regarding the adequacy of the design of the replacement crankshafts?

A. Yes. We have evaluated the design from the standpoint of torsional vibration stress and found that the replacement crankshafts exceed the limits for torsional vibration stress set forth in Section 34.47 of the ABS rules. The total torsional vibration stress imposed on the replacement crankshaft was calculated by FaAA to be 5,640 psi at the member between Pistons 6 and 7. 130/ By contrast, the maximum stress allowable for all harmonics is under the ABS rules for a crankshaft of the same design is 5,069 psi according to our calculations. The calculations of torsional vibration stress by the ABS yielded a slightly lower limit of 5,035 psi. 131/ Thus, the total torsional vibration stress imposed upon the replacement crankshaft exceeds the maximum permissible under ABS rules for the design and materials in question by a factor of more than 10 percent.

Q. Did TDI obtain ABS approval of the replacement crankshafts?

A. Yes. In effect, ABS has approved the crankshafts in a letter dated May 3, 1984 from the ABS to TDI. ABS stated that it has "no objection to the submitted torsional critical speed arrangement for use on diesel generator sets on an ocean

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130/ Analysis of the Replacement Crankshaft , dated October 31, 1983, at 1-2. Dr. Pischinger, FaAA's diesel expert, believes that the Tn values used by FaAA in this calculation are very reasonable. Pischinger Deposition at 110.

131/ Exhibit III to the Depositions of Richard Woytowich, Howard Blanding and Robert Giuffra ("ABS Deposition") (July 18, 1984). (Exhibit 43).

going vessel, insofar as our classification requirements for marine service are concerned." A copy of this letter is attached as Exhibit 44. However, the ABS letter was issued on the basis of special consideration of supplemental information submitted by TDI which we believe is inaccurate and incomplete.

Q. What information did TDI submit to the ABS in seeking approval of the crankshafts?

A. TDI's submittal consisted of a "Report on Crankshaft Torsional Stresses, Transamerica Delaval Model DSR-48, Serial No. 74010/12 for Long Island Lighting Company," dated April 4, 1984. A copy of TDI's submittal is attached as Exhibit 45.

Q. Did the ABS issue its May 3 letter in reliance on all of the information submitted by TDI?

A. No. Because the predictions of torsional vibratory stress submitted by TDI exceeded the allowable limits under the published ABS formula, the ABS relied on supplemental information submitted by TDI -- the alleged effect of shotpeening the crankshafts, strain gage test measurements, and certain operating experience of the EDGs.132/ The ABS also performed

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132/ Id. at 163, 165.

its calculations using the value given to it by TDI for the maximum firing pressure in the EDGs, 1700 psi.133/

Q. Did the ABS independently verify the accuracy of any of the supplemental information submitted by TDI?

A. No.134/

Q. What is the basis for your belief that the supplemental information submitted by TDI and relied on by the ABS was incomplete and inaccurate?

A. We have reviewed testimony and documents obtained from TDI and LILCO showing that (i) contrary to the representations in its submission to the ABS, TDI did not believe that shotpeening would substantially improve the fatigue endurance of the crankshafts, nor did TDI disclose to the ABS that the original shotpeening of two of the replacement crankshafts was performed improperly; (ii) the actual maximum firing pressure in the EDGs is higher than the value that TDI submitted to the ABS; (iii) the strain gage measurements are based on tests subject to significant inaccuracies that affect the accuracy of

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133/ Id. at Exhibit III; Id. at 112.

134/ Id. at 167.

the measurements, but TDI did not inform the ABS of those inaccuracies; (iv) the EDG operating experience data submitted by TDI to the ABS did not include any of the many significant problems experienced by the EDGs.

Q. Has Suffolk County notified the ABS of your beliefs that the information submitted by TDI was incomplete and inaccurate?

A. Yes. By letter dated July 25, 1984, the County's counsel notified the ABS of our beliefs and identified specific data which we believe is more accurate and complete than the information submitted by TDI. A copy of that letter is attached as Exhibit 46. There has been no response.

Q. Did the ABS perform any calculations on the replacement crankshafts?

A. The ABS performed six calculations of combined safety factors for the replacement crankshafts under two methods and compared those calculated values against its desired minimum value for safety factor.

Four of those calculations showed that the replacement crankshafts did not meet ABS's desired minimum safety factor value. None of those calculations considered the effects of shotpeening. Only when the ABS took into consideration the full 20 percent increase in the fatigue limit from shotpeening as submitted by TDI, did the ABS calculations show that the replacement crankshafts exceeded its desired minimum safety factor. A copy of these calculations is attached as Exhibit 47.

Q. In making these calculations, did the ABS ascertain whether the shotpeening of the crankshafts had been performed properly or whether the shotpeening would in fact increase the fatigue limit of the crankshafts by 20 percent?

A. No. The ABS performed its calculations and reached its conclusions on the assumption that the crankshafts were shotpeened properly and that the shotpeening would in fact increase the fatigue limit of the crankshafts by 20 percent. The ABS made no inquiry as to whether the shotpeening was performed properly, even though it believes that improperly performed shotpeening could increase the stresses in a crankshaft.135/

Q. Is 20 percent a conservative minimal value of the increase in the fatigue limits from shotpeening the fillet regions of the replacement crankshafts as asserted by TDI in its submission to the ABS?

135/ ABS Deposition at 93, 98, 99. (Exhibit 43).

A. No. In fact, TDI had recommended against shotpeening the crankshafts based upon its experience and upon the opinion of its metallurgical consultant, Professor Wallace, that shotpeening would not provide more than a 5 percent increase in the fatigue strength of the crankshafts.136/ In addition, TDI was informed by Kobe Steel, Ltd., a Japanese manufacturer of crankshafts for TDI, that shotpeening crankshafts of this size is "a waste of time" because the hardened depth by shotpeening was estimated to be quite shallow compared with the depth of the highly stressed area at the fillets.137/ TDI never informed the ABS of any of this information.

Significantly, in its April crankshaft report, FaAA stated that "the effect of shotpeening may produce widely differing increases in fatigue endurance limit; however, a conservative range of values of this increase is 5% to 20%."138/ However, FaAA has withdrawn from that position in its May version of this report, which suggests no range of increases in fatigue endurance limit to be expected from shotpeening. The May

136/ Trussell Deposition at 45-48. (Exhibit 10).

137/ Letter dated February 17, 1984, from Shinpei Denoh to Gregory M. Beshouri. (Exhibit 48).

138/ FaAA Crankshaft Report, April 19, 1984, at 3-11.

report merely states generally that shotpeening "will produce increase in fatigue endurance limit [sic]."139/ According to FaAA, the references to a numerical value were deleted when the final version of the report was reviewed by FaAA's quality assurance program.140/ We are unaware of whether TDI has informed the ABS that FaAA no longer attributes any numerical value to the increase in the fatigue endurance limit from shotpeening.

Q. If the full 5 percent value were used for the increase in the fatigue limit from the effects of shotpeening, would the replacement crankshafts meet the ABS's desired minimum safety factor?

A. Assuming that the shotpeening was performed properly, and if the full 5 percent value were taken into consideration using the fatigue limit values derived from the information submitted by TDI to ABS, the replacement crankshafts would not meet the ABS's desired minimum safety factor (1.34) under one of the ABS's methods (1.2852) and would only marginally meet the ABS's desired minimum value under the other method (1.3713).

139/ FaAA Crankshaft Report, May 22, 1984, at 3-11.

140/ Transcript of TDI Owners Group Meeting, May 24, 1984 at 114.

Q. Were the crankshafts in fact shotpeened properly?

A. No. As described in greater detail below, two of the crankshafts were not shotpeened properly. As a result, the fatigue limits of the two crankshafts may actually be less than if they had not been shotpeened at all.

Q. Did the ABS safety factor calculations consider the actual maximum firing pressure of the Shoreham EDGs?

A. No, and it is pertinent that the maximum firing pressure is a significant factor in those calculations. The ABS calculated the safety factors based on a maximum firing pressure of 1700 psi, the value supplied to it by TDI.141/ However, as we have explained above, the firing pressure in the Shoreham EDGs has been measured as high as 1750 psi at full load and is conceded by TDI to be as high as 1800 psi at overload of 3900 kW.

Q. Were the strain gage measurements submitted by TDI and relied on by the ABS accurate?

141/ ABS Deposition at 112. Id. at Exhibit III.

A. No. TDI submitted the results of strain gage measurements from tests on EDG 103 with a replacement crankshaft and EDG 101 with the original failed crankshaft. TDI, however, did not submit the actual test reports. Those reports explicitly state that the strain gage measurements could be as much as 5 percent higher.142/

Q. Was the service experience of the DSR-48 engines submitted by TDI and relied on by the ABS complete?

A. No. TDI submitted data on the service experience of the Shoreham EDGs, but that information consisted only of the total numbers of hours that the EDGs had operated, and the hours they had operated at 3500 kW and above (EDG 101 -- 114 hours; EDG 102 -- 116 hours; EDG 103 -- 110 hours).143/

TDI did not specify how many of these hours were at full load or how many hours were above full load. The ABS incorrectly assumed from this information that the Shoreham EDGs had operated the entire 114, 116 and 110 hours above full load, and relied on this operating experience in issuing its May 3 letter.144/ It therefore appears that ABS was relying on a

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142/ Exhibit 49 at 7-3, Exhibit 50 at 7-2.

143/ Exhibit 45 at 28.

144/ ABS Deposition at 81.

misunderstanding of TDI's operating experience data.

Q. Did the ABS in fact know whether the EDGs had operated at loads higher than 3500 kW?

A. No.145/ In fact, as of April 30, 1984, none of the Shoreham engines had accumulated as many as 100 hours of operation above full rated load since the replacement of the crankshafts.146/

Q. Did TDI inform the ABS about the other abnormalities that have arisen during actual operating experience of the EDGs, such as the cracking in the blocks?

A. No. TDI only submitted information to the ABS concerning the number of hours that the EDGs had operated.

Q. Based upon your review of the information submitted by TDI to the ABS, your knowledge as to what factors the ABS relied upon in issuing its May 3 letter, and your belief that significant information submitted by TDI and relied on by the ABS is inaccurate and incomplete, do you believe that the ABS will reconsider the conclusions stated in its May 3 letter?

145/ *Id*. at 80.

146/ Design Review of TDI R-4 and RV-4 Series Emergency Diesel Generator Cylinder Blocks and Liners, June 1984 ("FaAA Block Report") at 1-8, 1-9, 1-10. (Exhibit 7).

A. Yes. In fact, Mr. Blanding of the ABS testified that the ABS would have to reconsider its conclusions if any of the information submitted to it by TDI were incomplete and inaccurate.147/

Crankshaft Shotpeening

Q. What is shotpeening?

A. Shotpeening is a cold working process that produces a shallow layer of residual compressive stress on the surface of the metal being treated. The process consists of the bombardment of the metal surface with small beads of metal propelled by air pressure at high velocity.

Q. What is the purpose of shotpeening the crank pin fillet areas of crankshafts?

A. Shotpeening is intended to increase the fatigue resistance of the crank pin fillets, an area which is subjected to cyclic loading and which is the most critical area for fatigue initiation in a crankshaft. Shotpeening, however, cannot increase the ultimate tensile strength or the yield stress of the fillet material.

147/ ABS Deposition at 167-168.

Q. Would properly performed shotpeening of the crank pin fillets of the Shoreham replacement crankshafts significantly improve their fatigue resistance?

A. No. Indeed, as previously stated, a major manufacturer of crankshafts informed TDI that shotpeening crankshafts of this size is "a waste of time" because the hardened depth of the shotpeening is quite shallow compared with the depth of the highly stressed area at the crank pin fillets.148/ In addition, the effectiveness of any shotpeening will be further reduced if the material is subject to appreciable heat as the crankshafts are.

Q. Did TDI recommend that the replacement crankshafts be shotpeened?

A. No. In fact, TDI recommended against shotpeening the replacement crankshafts based upon its experience and the opinion of its metallurgical consultant that shotpeening would not increase the fatigue strength of the crankshafts more than 5 percent. As Mr. Trussell of TDI explained, "Shot peening a

148/ Letter dated February 17, 1984 from Shinpei Denoh of Kobe Steel, Ltd., to Gregory M. Beshouri of TDI. (Exhibit 48).

thin piece of steel of the same specifications of the crank shaft would substantially improve its fatigue strength, while applying the same surface improvement to a thick section, like a crankshaft, would not provide a substantial improvement in the fatigue strength of the piece."149/

Q. Generally speaking, are there any adverse side effects to shotpeening?

A. Yes. If not performed properly, shotpeening "could serve as a source of added stress concentrations which would make the crankshafts more susceptible to fatigue."150/

Q. Can even properly performed shotpeening cause any adverse side effects?

A. Yes. Even if shotpeening is performed properly, shotpeening raises the stresses below the compressed surface. When shotpeening introduces compressive residual stress on the surface layer, the adjacent underlying layers are put under tensile stress. This shotpeen-induced tensile stress is

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149/ Trussel Deposition at 48. (Exhibit 10). See also Stone & Webster Engineering and Design Coordination Report ("E&DCR") No. F-46109-G, at 4 of 4. (Exhibit 51).

150/ FRC Report at 65 (Exhibit 35); Pischinger Deposition at 168. (Exhibit 41).

additive to the already present calculated stresses. A fatigue failure does not necessarily have to begin on the surface of the fillet; it may begin in a sub-surface area.151/ The critical area in this regard is the transition stage between the surface layer (which is under the residual compressive stress from shotpeening) and the layer of material further below in which tensile stresses is first experienced.

Q. Were the crankpin fillet regions of all of the replacement crankshafts at Shoreham shotpeened?

A. Yes, the crankshaft for EDG 101 was shotpeened once, by Metal Improvements Company at the Shoreham plant, while the crankshafts for EDGs 102 and 103 were shotpeened twice, once by TDI in Oakland and once again at Shoreham by Metal Improvements Company.152/

Q. Was the shotpeening of EDGs 102 and 103 performed properly?

151/ Dr. Johnston of FaAA agrees. Deposition of Paul Johnston (May 9, 1984) ("Johnston Deposition") at 39-40. (Exhibit 52).

152/ FRC Report at 64-65. (Exhibit 35).

A. No. Although TDI's shotpeening procedure required "full and complete intensity and coverage,"153/ some of the fillet areas of the crankshafts lacked shotpeen coverage. This was the first time TDI had ever shotpeened a crankshaft for a DSR-48 engine.154/ As reported by Stone & Webster, "holidays," or lack of shotpeening coverage, existed in the crankpin fillet areas. TDI reported that holidays occurred in two areas of the EDG 103 crankshaft: on the top of the number one crankpin directly adjacent to the crankpin and at the outer edge of the crank radius.155/ Although TDI dispositioned the holidays as functionally acceptable, Stone & Webster recommended that the crankshafts should be shotpeened again.156/ According to Stone & Webster, both EDG 102 and 103 were inadequately shotpeened in the lower third of the re-entrant fillet of the crankshaft pin junction.157/

153/ E&DCR No. F-46109-G at 3 of 4. (Exhibit 51).

154/ Lowrey Deposition at 62. (Exhibit 24).

155/ E&DCR No. F-46109-G at 2 of 4. (Exhibit 51).

156/ *Id*. at 1 of 4.

157/ Interoffice memorandum dated September 20, 1983, from Gary V. Luther to D. E. Ellis. (Exhibit 53).

Q. Is the location of the inadequate shotpeening in the lower third of the re-entrant crankpin fillet area important?

A. Yes, the lower third of the re-entrant fillet of the crankshaft pin generally is the most critical area with respect to crankshaft failure. Furthermore, FaAA specified three reasons why this area was most critical on the replacement crankshafts. First, FaAA concluded that this area is highly stressed at loading. Second, FaAA discovered through x-ray diffraction that a residual stress existed at the fillets. Third, FaAA found roughness in the surface finish at the fillets. Scanning electron microscope photographs in this area showed that cracks in the initial stages of propagation were initiating at one of the radially machined "valleys" of the fillet.158/

Q. Have you inspected the original shotpeening on EDGs 102 and 103?

A. No. However, LILCO made available to us some, but not all, of the photographs taken of the original shotpeening. From the photographs, it appeared that the depth of the

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158/ Interoffice memorandum dated September 20, 1983, from Gary V. Luther to D.E. Ellis. (Exhibit 53).

undercut areas for machined tool runout was excessively deep in some areas, although it was difficult to tell how deep because of the effect of light and shadows from the photographs. Reshotpeening would exacerbate the problem of stress raisers arising from the deep runout and may mask the critical point in way of the tool runout so that the residual compresive stress in these areas would be insignificant. In addition, it appears that damage to some of the journal fillets may have occurred from deep single shot impacts which may act as stress raisers because the areas around the deep impacts go into tension -- the very thing to be avoided. Other photographs showed what appeared to be cracks in the shotpeened surfaces. In some cases it was possible to determine whether these deficiencies occurred in critical areas of the crankshaft, other photographs were insufficiently identified by their captions to be sure whether they showed pins or journals.

In addition, according to FRC's inspections of photographs of the original shotpeening, the surface texture of the shotpeened areas looked "more like grit blasting than shotpeening, i.e., the surface appeared to have been gauged [sic] by sharp particles instead of by round, smooth particles."159/ FRC believes that such improper shotpeening could

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159/ FRC Report at 64. (Exhibit 35).

serve as a source of added stress concentrations to make the crankshafts more susceptible to fatigue.160/ We agree.

Q. Have you come to any conclusions based on your review of these photographs and the documents identifying deficiencies in the original shotpeening?

A. Yes. We have concluded that the original shotpeening of EDGs 102 and 103 was improperly performed and may have created nucleation sites on the fillet radii, the most critical area with respect to crankshaft failure. Shotpeening of pre-existing cracks in this area could cause the cracks to propagate further.

Q. Does the repeening of EDGs 102 and 103 by Metal Improvements Co. alleviate your concerns about the original shotpeening?

A. No. Instead of adequately correcting the improperly performed shotpeening, the repeening of EDGs 102 and 103 serves to mask deficiencies already present on the fillet radii caused by the first shotpeening. The presence of nucleation sites due to the improperly performed shotpeening may not be

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160/ Id. at 65.

ascertainable due to the second shotpeening of EDGs 102 and 103.

Q. Professor Anderson, do you have any concerns about shotpeening in general and about the procedures used for shotpeening the crankshafts?

A. Although it is generally true that shotpeening produces compressive forces in the surface of the metal which enhance its physical properties, shotpeening adversely affects the chemical properties of the crankshafts.

The shotpeening procedure used for the Shoreham crankshafts will produce some real reliability problems. Prior to shotpeening, the areas adjacent to the fillet radii are masked off. This results in stressed (shotpeened) areas located directly next to unstressed (un-shotpeened) areas. This difference in surface energy is the driving force for corrosion and environmental attack of the fillet and stress cracking. Furthermore, since the un-shotpeened area is larger, the rate of corrosion is increased because of the cathode-anode area law.161/

161/ Fontana and Greene, Corrosion Engineering, McGraw Hill 2d ed. 1978.

Q. Please summarize your conclusions about the replacement crankshafts.

A. The replacement crankshafts should be required to comply with the Lloyd's rule on allowable maximum horsepower, the IACS rule for allowable safety factor, the ABS rules on crankshaft webs and allowable maximum cylinder pressure, the NKK rules on crankshaft webs, the ABS rule on allowable torsional vibration stresses and the standards of the German register for crankshaft webs and cyclic stresses in order to ensure their reliability for nuclear service. The failure of the replacement crankshafts to comply with these standards shows that the crankshafts are not adequately designed for operation at full load and overload and does not give adequate assurance that they can operate reliably.

Q. What are your conclusions regarding the shotpeening of the crankshafts?

A. Any credit for increasing the fatigue strengths as a result of the shotpeening performed on the replacement crankshafts is negligible. Indeed, the shotpeening may introduce detrimental effects. Furthermore, the shotpeening on EDGs 102 and 103 was not properly performed and may have caused nucleation sites which may not be ascertainable due to the second shotpeening of these crankshafts.

CYLINDER BLOCKS

Q. What is the purpose of this testimony?

A. The purpose of this testimony is to set forth the results of our evaluation of that portion of the County's contention which addresses the cylinder block problems of the EDGs. That portion states:

> "Cracks have occurred in the cylinder blocks of all EDGs, and a large crack propagated through the front of EDG 103. Cracks have also been observed in the camshaft gallery area of the blocks. The replacement cylinder block for EDG 103 is a new design which is unproven in DSR-48 diesels and has been inadequately tested."

Q. What are your conclusions regarding the adequacy of the design and manufacture of the cylinder blocks?

A. We believe the block cracks are evidence that the EDGs are over-rated and undersized. The EDG cylinder blocks are not properly designed and manufactured to withstand the stresses to which they are subjected. We are concerned that LILCO proposes to use the cracked blocks of EDGs 101 and 102 for EDGs in nuclear service during the operation of the Shoreham plant. Those blocks are unreliable and are likely to experience crack propagation which can lead to catastrophic failure of the EDGs. The newly designed block for EDG 103 is unproven and inadequately tested.

Contrary to the conclusions reached by FaAA in the cylinder block report[162/] and by the Owners' Group DRQR Report on cylinder blocks, we conclude that:

1. The cracks in the ligament between stud holes and liner counterbores of the blocks of the EDGs are not benign and may be lead to catastrophic failure of the engine. Further, the cracks may not be fully contained between the liner and the region of the block top outside the stud hole circle.

2. Field experience in non-nuclear service has not been systematically documented or reviewed in order to demonstrate the extent of ligament cracking or the immediate consequences of such cracking.

3. The deepest crack (5-1/2 inch depth) between stud holes was measured after the immediate shutdown of EDG 103 following crack propagation during overload

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162/ "Design Review of TDI R-4 and RV-4 Series Emergency Diesel Generator Cylinder Blocks and Liners," FaAA-84-5-4, Failure Analysis Associates, June, 1984 (the "FaAA Block Report"). (Exhibit 7).

testing of EDG 103, and contributed to the decision to replace the block. The replacement block has not been adequately tested.

4. Blocks with ligament cracks (those of EDGs 101 and 102) have not been demonstrated to be capable of withstanding a LOOP/LOCA event. While we agree with FaAA's conclusion that cracks between stud holes are likely to occur and propagate in blocks with ligament cracks, we disagree that FaAA can predict with any accuracy when such cracks will initiate or the rate at which they will propagate.

5. The preliminary material evaluation by FaAA of the microstructure of a small region of each block top of the EDGs is not representative of the properties of the entire block and does not demonstrate that the block EDG 103 is significantly weaker than the other two blocks. To reach conclusions regarding the sufficiency of the material strength of the blocks of EDGs 101 and 102 in comparison to that of EDG 103, the material of all three blocks must be adequately evaluated.

6. The cracks in the cam gallery support region of the EDG blocks may be detrimental to the operation of the engine. Further, the assessment of these cracks has failed to demonstrate that the cracks will grow very slowly at full load and not at all at 75 percent load, or that the cracks can be attributed solely to the casting process.

Based on the foregoing, we conclude that it has not been demonstrated that the cylinder blocks of the EDGs will reliably perform their required functions, and thus, there can be no assurance that the EDGs will perform satisfactorily in service.

Q. Please describe the cracks which have occurred in the cylinder blocks of the EDGs.

A. There is no disagreement that numerous cracks exist on the block tops of EDGs 101 and 102, running in the radial/vertical plane between stud holes and the cylinder bores. These cracks are shown in drawings, and some of them are described, in the FaAA Block Report.[163/] Similar cracks were found in the top of the block of EDG 103, which also had cracks between stud holes for adjacent cylinders 4 and 5.[164/] On

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163/ FaAA Block Report at 1-2 to 1-3 and Figures 1-2 and 1-3.

164/ *Id*. at 1-2 and Figure 1-4.

April 14, 1984, during qualification testing at 3900 kW, a crack was noticed starting under the no. 1 cylinder head and extending across the front of the EDG 103 block and about 5 inches down the front of the engine.165/ Subsequent inspection of the EDG 103 block showed that many existing cracks had propagated, and that additional between-stud hole cracks had developed at four other locations.166/ In addition, there are cracks in the camshaft gallery areas of all three EDG blocks.167/ These cracks have been observed to grow in the EDG 103 block.168/

Q. Does the FaAA Block Report provide a satisfactory design review of the cylinder blocks?

A. No. Rather than a design review of the blocks, it is a summary of FaAA's "investigation of the structural adequacy" of the blocks.169/ FaAA fails to address most of the

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165/ Letter dated April 17, 1984, to Administrative Judges from E.J. Reis (NRC Staff). (Exhibit 54).

166/ FaAA Block Report at 1-2 to 1-3 and Figures 1-5 to 1-8.

167/ *Id.* at 4-6.

168/ Morning Report, NRC Region I, March 20, 1984. (Exhibit 55).

169/ FaAA Block Report at i and ii.

functional attributes of the cylinder blocks set forth in the Task Description for the Component Design Review.170/ We believe it is significant that FaAA does not conclude that the cylinder blocks are adequate for nuclear service and capable of unlimited operation. However, based solely upon the FaAA Block Report and its supporting packages, the TDI Owners Group concluded that the cracked blocks of EDGs 101 and 102 and the replacement block for EDG 103 (pending final material study results for the original and replacement EDG 103 blocks)

> are acceptable for intended function with implementation of routine inspections in accordance with E&DCR F-46505.171/

Q. What does the TDI Owners Group mean by the phrase "acceptable for intended function"?

A. The DRQR Report does not expressly define this phrase, but indications are that it refers to the ability of the cylinder block "to withstand with sufficient margin a LOOP/LOCA event."172/ There is no suggestion of what a "sufficient margin" might be. Mr. William Museler, a vice president

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170/ Id., Appendix.

171/ DRQR Report, Vol. 4, Cylinder Block, at 3. (Exhibit 56).

172/ Id. at 2; see also Id. at C1 and C2.

of LILCO and former technical manager of the TDI Owners Group program, testified that the ad hoc acceptance criterion applied by the Owners' Group program for adequacy of the EDGs was <u>not</u> the performance rating of the EDG established by the FSAR and the contract specification.173/ Rather, the TDI Owners Group criterion was reliable operation during the testing required to be performed plus one LOOP/LOCA event for seven days.174/

Q. Is the TDI Owners Group acceptance criterion intended to be applied to qualify the EDGs only for operation during the approximately 18 month period until the first refueling outage at Shoreham, when the newly purchased Colt EDGs are scheduled to be installed?

A. Not according to Mr. Museler. He testified that although LILCO intends to replace the EDGs with Colt diesels by the first refueling outage, the Owners Group criterion was intended to qualify the EDGs for a period "far beyond the interim period."175/

173/ Deposition of William J. Museler (May 22, 1984) ("Museler Deposition") at 7-8. (Exhibit 57).

174/ Id. at 14-17.

175/ Id. at 43-46.

Q. Is the criterion used by the TDI Owners' Group appropriate to ensure that the EDGs, and specifically their cylinder blocks, are adequate and reliable enough to meet the requirements of GDC 17?

A. No. The Owners Group criterion is extremely limited, subjective and does not meet the technical requirements of GDC 17. As discussed above, the proper technical standard for GDC 17 is the performance rating for the EDGs set forth in the FSAR. That rating -- 3500 KW continuously for one year and 3900 kW for 2 hours per 24 hour period -- was established by LILCO and approved by the NRC Staff on the basis of the required service for the EDGs. There is no rational or regulatory basis to eliminate that performance standard.

Q. Did the FaAA Block Report use the same improper acceptance criterion as the TDI Owner's Group for determining the adequacy of cylinder blocks?

A. FaAA issued an interim report on the cylinder block and liner, which concluded preliminarily that the DSR-48 cylinder blocks may be adequate "for interim use" depending on further analysis.176/ Mr. Robert Taylor of FaAA, who prepared the

176/ Exhibit 1 to Taylor Deposition. (Exhibit 58).

interim report, testified that in determining "interim use," he used an "intended load profile" for two years of about 260 hours of EDG operation, including 80 hours at full load and less than one hour at 3900 kW.177/ In the final FaAA Block Report no statement is made as to whether or not the cylinder blocks are adequate for interim or any other use, so no acceptance criterion is expressly applied. However, FaAA appears to have further reduced the inadequate and improper criterion of the two year "intended load profile," because the FaAA Block Report only specifically addresses whether an engine block with cracks between the stud holes and cylinder bore (so called "ligament cracks"), but with no stud hole to stud hole cracks, can be predicted to survive a LOOP/LOCA event.178/ This criterion is totally inadequate to satisfy the standards required by GDC 17.

Q. The FaAA Block Report sets forth a number of conclusions and recommendations which are applicable to the EDGs. Do you agree with the FaAA conclusion that the cracks in the ligament between the stud holes and liner counterbore are "benign."179/

177/ Taylor Deposition at 69-70. (Exhibit 59).

178/ FaAA Block Report at 4-3 to 4-5.

179/ Id. at 5-1.

A. We strongly disagree with FaAA's conclusion that these ligament cracks are "benign." First, FaAA states, and we agree, that one consequence of the ligament cracks might be leakage of coolant (although not into the cylinder).180/ Such leakage is far from "benign," and could lead to catastrophic failure of the EDG.

Q. How could the leaking of coolant lead to a catastrophic failure?

A. The leaking of the coolant could result in temperature increases of the upper part of the cylinder liner and head. The consequent thermal stresses on the cylinder block, cylinder heads, pistons, and other engine components increase the likelihood of cracking. For example, the overheating of the cylinder liner could crack the liner and/or cause a partial piston seizure. A partial piston seizure makes combustion gas blow-by highly probable, which may lead to a crankcase explosion and complete piston seizure. Lack of sufficient coolant could also lead to distortion of the cylinder head, which could cause the exhaust valves to fail to seat completely. Distortion of the cylinder head and the leakage of gases from the

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180/ *Id.* at ii to iii.

exhaust valves could lead to overspeeding of the turbocharger and damage to the blades and rotor, which would stop the turbocharger. This would result in an insufficient quantity of air supply to the engine, further increased temperatures of the operating parts, and ultimately to a complete piston seizure. Complete piston seizure would cause bent or broken connecting rods, serious overloading and possible cracking of the main bearing shells, cracking in the engine base and stretching of the main bearing hold down studs. A complete piston seizure will almost always stop the EDG.

Q. Can you predict how quickly the coolant would leak from the ligament cracks?

A. Coolant water could leak rapidly from ligament cracks. The coolant water is under pressure of 40 psi. The rate of leakage would depend on the number of cracks and their widths. The leakage becomes critical when the expansion tank (coolant reservoir) either cannot replace the loss of coolant water fast enough or is depleted. A dangerous overheating condition occurs when the temperature is high and the water low so that the circulating coolant mixture consists of liquid and vapor.

Q. Do you agree with FaAA's conclusion that the ligament cracks are benign

> because the cracked section is fully contained between the liner and the region of the block top outside the stud hole circle.181/

A. It is not clear what FaAA means by this description. FaAA describes the ligament cracks accurately as running between the stud holes and the liner counterbore, so the cracks do run to the stud hole itself. We believe that FaAA is referring to the "apparent arrest" of the ligament cracks at the liner landing ledge.182/ This conclusion as to the "apparent arrest" of ligament cracks is based upon observation of ligament crack depth on the EDG blocks, and unconfirmed183/ and incomplete information regarding selected blocks of TDI engines in non-nuclear service.

Q. Were ligament cracks "fully contained" during the testing of the EDGs?

181/ Id. at 5-1.

182/ Id. at 1-2 and 1-3.

183/ Id. at 1-1.

A. No. The history of the ligament cracks on the EDG blocks does not support the conclusion that they are "fully contained" and therefore "benign." On the contrary, the large 5" crack which occurred on the EDG 103 block during overload testing ran from a stud hole at cylinder No. 1 which already had a ligament crack. Compare Figures 1-4 and 1-8, FaAA Block Report. That comparison also discloses that after the overload test was aborted, nine new stud hole to stud hole cracks had initiated. Thus, even if the ligament cracks on the EDGs had not propagated downward past the liner landing, they cannot be described as benign. If the ligament crack is in fact arrested at the liner landing ledge, it would appear that continuing sufficient operating stress causes cracks to initiate and propagate radially and vertically from the stud hole with the ligament to adjacent stud holes or to the outer wall of the block.184/ Finally, Figure 1-8 contradicts FaAA's assertion that ligament cracks will not grow beyond the 1-1/2" depth of the liner landing ledge, because it shows six ligament cracks with a depth of 2 to 2-1/2."

184/ Note that Figure 1-8 of the FaAA Block Report shows that most of the ligament cracks had reached a depth of at least 1.5", the reported depth to the liner landing.

Q. Doesn't FaAA's data on cracked blocks in non-nuclear service demonstrate that the ligament cracks are "benign" and cannot have adverse "immediate consequences"?185/

A. No. The unconfirmed information given in the FaAA Block Report186/ does not support FaAA's conclusion at all. FaAA concludes that the mechanism of crack initiation in the cylinder block tops are low cycle fatigue during startup to high load levels, high frequency fatigue from firing pressure stresses, and overload rupture occurring at loads above rated power levels.187/ These factors, which also affect crack propagation, are all related to the loads at which an engine is run, that is, the higher the load, the greater the stress and the more likely is crack initiation and rapid propagation. FaAA states the hours which the non-nuclear have run, but does not disclose the loads at which they ran during those hours. We believe it inappropriate that FaAA has relied at all on the marine non-nuclear cases they cite. When asked why FaAA had decided not to examine cracks in blocks other than at Shoreham, Mr. Taylor of FaAA responded:

185/ FaAA Block Report at 5-1.

186/ Id. at 1-3 to 1-4.

187/ Id. at ii.

Well, the engines in the Marine service see a different service than shore-based engines. Their load profiles are different. They're operated differently, and just looking at the block for the COLUMBIA without knowing the size of the liners, how much the liners protruded, exact load history, even if I were to go look at that block, I would -- there's a wealth of other data that would be pertinent that I don't have yet and probably would not be able to reconstruct.188/

Mr. Taylor also testified that data such as load factors would make examination of other cracked blocks useful. FaAA concedes that non-nuclear engines generally operate at lower loads and with fewer starts than nuclear diesels.189/

Q. Do you have additional comments on the specific cases of non-nuclear engine block cracks relied upon by FaAA?

A. Yes. The information on the M.V. Gott does not disclose load levels for this DMRV-16-4 engine, the methods by which crack depth was measured, or the fact that as the result of the cracks the engine blocks were repaired and modified.190/ During the telephone conversation on which FaAA relies for its

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188/ Taylor Deposition at 40- 41. (Exhibit 59).

189/ FaAA Block Report at 4-3.

190/ Letter dated November 30, 1983 from Lowrey (TDI) to Blanding (American Bureau of Shipping). (Exhibit 60).

information on the M.V. Gott, the owners also told FaAA that (i) the blocks on the Gott were being machined to reduce stresses, (ii) the engines on the Gott had been so extensively modified they could no longer be considered "stock" TDI diesels, (iii) a maintenance/inspection program for the engines much more comprehensive than the recommended TDI program was being used, and (iv) the design of the TDI blocks, with a cylinder liner placed in a counterbore, "is an old design which nobody uses anymore because of the resulting thermal problems."<u>191</u>/ The FaAA Block Report fails to disclose this information.

The statement on the M.V. Columbia fails to disclose load levels or that the State of Alaska replaced the cracked block and derated the TDI DMRV-16-4 engines by approximately 43%.<u>192</u>/ Further, these engines were originally rated at over 35 HP <u>less</u> per cylinder than the EDGs. Information on the St. Cloud, Copper Valley, Homestead and Bhiel engine blocks do not disclose

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<u>191</u>/ FaAA Block Report Ref. 1-3, Memo of June 7, 1984 telephone conversation between Spiegel (FaAA) and Liberty (U.S. Steel). (Exhibit 61).

<u>192</u>/ Evaluation of the Operational and Maintenance History of, and Recent Modifications to, the Main Engines in the M.V. Columbia, SES Report No. 123-01, by Seaworthy Engine Systems, Inc., April 1983, at 2-1. (Exhibit 62).

load levels or other pertinent operating information, such as peak firing pressures. The engine at Homestead is rated at 8800 kW, but is operated at only about 6000 kW. Three of the TDI engines owned by Copper Valley have been derated by 20%. Maintenance history documents obtained by LILCO or FaAA from Copper Valley disclose many problems, including replacement of a block on engine S/N 75011, but do not specifically refer to ligament cracks in the blocks.193/ Finally, FaAA has supplied no information on the block material properties or chemical composition of the cylinder blocks in non-nuclear service. Yet FaAA believes these factors are very important to crack initiation and propagation.194/ In summary, FaAA's information on non-nuclear service does not demonstrate its conclusion that the ligament cracks on the EDGs are "benign."

Q. Do you agree with FaAA's conclusions that ligament cracks and stud hole to stud hole cracks are predicted to occur after operation at high loads and/or engine starts to high load?195/

193/ Maintenance History on TDI S/N 75011 and 75012, Copper Valley Electric Ass'n. (Exhibit 63).

194/ FaAA Block Report at 4-5 to 4-6, iv.

195/ *Id*. at 5-1.

A. Yes. But FaAA understates the stresses to which the blocks of the EDG are subjected, and thus underestimates the likelihood and rapidity of the initiation of ligament cracks and stud hole to stud hole cracks, and the speed of propagation of those cracks. Thus, FaAA has failed to demonstrate that blocks with ligament cracks are capable of reliably withstanding a LOOP/LOCA event.

Q. Please explain why you believe these stresses are underestimated by FaAA.

A: First, FaAA understates pressure loads on the block by assuming a peak firing pressure of only 1600 psi196/ rather than the actual value of 1700 psi or greater at 100% load.

Second, FaAA has not properly determined the preloading stress or how much of the preload is borne by the liner collar onto the liner landing ledge and how much is borne by the block.197/ FaAA states that "much" of the preload is transmitted to the liner collar, depending upon several variables. But it does not address these variables in terms of their importance or give any calculations. The liner collar

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196/ Id. at 2-3.

197/ Id. at 2-1.

protrusion, or "proudness," above the block top on the EDGs is greater than current TDI specifications, and would result in greater preload on the liner landing ledge.198/ FaAA measured the liner proudness for the cylinders of EDG 103; the measurements varied from 1 to 9 mils.199/

Third, FaAA has not calculated the amount of thermal load on the block due to thermal expansion of the liner.200/ FaAA correctly points out that thermal expansion stress of the liner will not all be transferred to the block, depending upon the clearance between the liner and block.201/ But there are no calculations of the optimum clearance or the amounts of stress not transferred under those optimum conditions. Further, there are no calculations of the actual clearances in the blocks of the EDGs, so there is no basis for FaAA's statement that "interference stresses in the block are as small as possible."202/

198/ Id. at 1-5.

199/ Calculation "Liner Proudness of DG 103, Project No. 03315A", by John H. Lau, dated 6/10/84. (Exhibit 64).

200/ FaAA Block Report at 2-2.

201/ Id. at 2-3.

202/ Id.

Q. Does FaAA's finite element analysis accurately show the effects of stresses on the top of the block?

A. No. The FaAA analysis does not accurately reflect actual probable stress effect. First, it incorrectly assumes a peak firing pressure of only 1600 psi, thereby significantly understating the stresses due to pressures. Second, it assumes the optimum clearance between the liner and block necessary to close the clearance by thermal expansion.203/ If the actual clearance for each cylinder is less than the assumed optimum, the stress effect will be greater. Third, FaAA assumes thermal stresses are symmetric between cylinders. This would only occur if the firing pressure and load in all cylinders were the same. Actually, firing pressures differ significantly from cylinder to cylinder of the same EDG, and TDI's operating manual permits a variance of ± 100 psi. Fourth, FaAA assumes all thermal stresses act radially in the plane of the top of the block. Actually, there are also longitudinal stresses in the upper surfaces of the block, so the thermal stress pattern is an oval shape.

203/ *Id*. at 3-3.

Q. Please explain how FaAA's incorrect and/or non-conservative assumptions affect its conclusions that ligament cracks and stud hole to stud hole cracks are predicted to initiate and propagate in the cylinder blocks?

A. FaAA predicts that these cracks could occur in fewer than 100 starts from 0 to 90% power or above and/or steady operation for over 100 hours at 90% or higher power, with a block having minimum material properties.204/ The incorrect and/or non-conservative assumptions of FaAA and its understated peak total stress figure of 33 ksi (as compared to the minimum ultimate tensile strength of 32 ksi for a 2-1/2 section) mean that the cracks might well initiate under FaAA's predicted conditions in blocks having higher than minimum material properties for ASTM A48-64 Class 40 gray cast iron, or at below 90% of power or at steady operation for fewer than 100 hours, or any combination of these factors. It is not possible to state by what percentage the FaAA conclusion is in error because the many variables, such as actual firing pressures, cylinder block and liner clearance, and "proudness" of the liner are impossible to predict without further experimental data for a specific engine.

204/ Id. at 3-6.

Q. FaAA predicts crack initiation to occur at steady running for more than 100 hours at 90% power or above.205/ Wouldn't one expect that at loads above 90% cracks can initiate at fewer than 100 hours of operation, even taking all of FaAA's incorrect assumptions as correct?

A. Yes. The higher the operating load, the fewer hours would be required before cracks initiate. FaAA does not address this issue.206/ This is a significant omission. A 90% load on the EDGs is only 3150 kW, well below the required actual maximum load of 3881 kW an EDG is required to carry during a LOOP/LOCA event. After 10 minutes into a LOOP/LOCA event, two EDGs must each produce a maximum coincident demand of about 3400 kW, or 97% of rated load.207/ When this factor is combined with accumulated damage from past start-ups and operation, it is apparent that cracks can initiate in a block during a LOOP/LOCA is much less than 100 hours.

205/ Id.

206/ The FaAA Block Report does state that 110% load "is clearly more damaging relative to 100% load than 100% load is relative to 90% load" (at 4-1).

207/ FSAR Table 8-3.1-1 at 4.

Q. FaAA suggests that stud hole to stud hole cracks might not be dangerous, because "the deepest measured crack in this region (5 1/2-inch depth) did not degrade engine operation or result in stud loosening."208/ Do you agree?

A. No. FaAA fails to state, indeed if it knows, when this crack grew to a 5 1/2 inch depth or how long EDG 103 operated with this crack. Even if we assume that this crack grew during the "abnormal load excursion" affecting EDG 103 on April 14, the engine could only have run less than 2 hours before it was shut down and the crack was discovered.209/ The very deep stud hole to stud hole crack contributed to the decision to replace the block. Such cracks could cause the loosening and breaking of the cylinder head studs, with consequent loss of power and overloading of the remaining cylinders. This condition would probably lead to engine failure.

Q. FaAA concludes that the cracked blocks on EDGs 101 and 102 can survive a LOOP/LOCA event if they have no cracks between stud holes and if the block material of the original

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208/ FaAA Block Report at 5-1.

209/ Id. at 1-2. EDG ran for 10 minutes after the "abnormal load excursion," then was run for 100 minutes before being shut down when the 5" crack running from cylinder no. 1 was noticed.

EDG 103 block "is shown to be sufficiently less resistant to fatigue than typical gray cast iron, class 40."210/ Do you agree?

A. No. The FaAA's conclusion is based upon a purported ability to accurately predict crack initiation and growth in EDGs 101 and 102 by "cumulative damage analysis of the known experience during operation of DG 103 between 3/11/84 and 4/14/84."211/ FaAA's analysis is based upon faulty premises and insufficient data. FaAA cannot accurately predict whether and when the cracks in the blocks of EDGs 101 and 102 may cause a failure during a LOOP/LOCA event.

Q. What are FaAA's faulty premises?

A. FaAA bases its analysis on a "linear cumulative damage approach (presented in Section 4.1) to obtain the total fatigue damage" of a block.212/ The use of the linear fatigue damage index is not limited by FaAA, that is, it is assumed applicable for all ranges of stress, load and duration. Extremely high loads for a short duration are known to result in failures or excessive cracking;213/ this fact is not reflected

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210/ Id. at 5-1.

211/ Id. at 4-3.

212/ Id.

213/ Indeed, FaAA emphasizes that the large crack running from the no. 1 cylinder down the front of the EDG 103 block

(Footnote cont'd next page)

by FaAA's linear damage index. Further, FaAA assumes that the damage index recorded for EDG 103 between 3/11/84 and 4/14/84 is an appropriate benchmark to predict the behavior of other blocks. On this basis, FaAA concluded that:

> A block with no existing stud-to-stud cracks and material properties sufficiently better than those of DG 103 should be able to complete the LOOP/LOCA requirements without any cracks as deep as the 5-1/2 inch crack in DG 103, while continuing to run normally.214/

However, the assumption for this conclusion is erroneous.

Q. What are the errors in the assumption?

A. First, it completely ignores the large crack which appeared in the EDG block during overload testing and ran from cylinder no. 1 about 5 inches down the block front, resulting in aborting the test, shutting down the engine, and ultimately contributing to the decision to replace the block. The damage caused by that crack and its impact on the ability of an EDG "continuing to run normally" is not assessed by FaAA. Second,

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(Footnote cont'd from previous page)

occurred after a 23 second unusually high load. FaAA Block Report at 1-2.

214/ FaAA Block Report at 4-5.

applying FaAA's damage index to EDGs 101 and 102 in comparison to the EDG 103 index for the stated period does not take into account the effects of differing load spectra on the three engines. Crack dynamics are affected by sequence of loads as well as their duration. FaAA provides insufficient evidence that the EDG 103 block damage in the stated period is a worst possible case.

Q. Do you have other concerns with the validity of FaAA's analysis?

A. Yes. Although we have not had an opportunity to review some of FaAA's underlying calculations which were only obtained a few days ago, we are concerned with FaAA's conclusion that an amount of additional damage required to initiate cracks between studs after ligament cracks initiate must at least equal the cumulative damage required to initiate the ligament cracks.215/ This conclusion does not appear to take into account the results of FaAA's finite element analysis, which shows that after ligament cracks have formed, the transverse stress between stud holes doubles.216/ This increase in stress

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215/ Id. at 4-1.

216/ Id. at 3-4.

ld appear to cause the damage level to accumulate more pidly than FaAA considers, and the additional damage required r cracks between studs to initiate would be less than assumed y FaAA.

Second, the quality of the cast iron determines the ease of initiation for a given damage index. This is presented as "n" (Paris law exponent) which is normally an unvarying constant for a given material condition. However, FaAA has considerable trouble in finding the best value of "n" and gives a value of 5.37 to 9.62. The proper value would be determined by testing the metal of the blocks. The conservatively assumed estimates of "n" in the FaAA report have no relation to the actual values for EDG 101, 102, and 103 blocks. The values are expected to be different for each block, because of the significant variance in the TDI casting procedures and its poor quality control. As discussed below, all three blocks should be properly evaluated to determine their material properties, rather than relying upon assumptions which may or may not be correct.

Third, while the FaAA analysis purports to be empirically based on EDG block behavior, it lacks information of significant importance. When did the ligament cracks first initiate in each of the three EDG blocks, and what was the cumulative damage index of each at that point? When did the original crack between the stud holes in the EDG 103 block first initiate, and what was the additional damage index accumulated between the initiation of the ligament cracks in the same block and that point? When and under what conditions did the original crack between the stud holes in the EDG 103 block grow to 5-1/2 inches in depth, and what was its rate of growth? When did the large crack running from cylinder no. 1 down the front of EDG 103 first inititate and at what rate did it propagate? The answers to these questions would provide some meaningful empirical data.

Q. Did FaAA use fracture mechanics techniques to predict the rate of crack growth of the cracked block tops of EDGs 101 and 102?

A. No. The FaAA Block Report does not use a fracture mechanics analysis to predict the growth of ligament cracks or the initiation or growth of stud hole to stud hole cracks. But FaAA does use fracture mechanics to predict the propagation of cracks in the camshaft gallery areas of the blocks and of cracks which may initiate in the AE piston skirts. We believe this is a significant inconsistency in the approach FaAA has used to predict crack growth.

Q. Can the excessive cracking in the original block of EDG 103 be attributed to significantly weaker material than those of EDGs 101 and 102?

A. No. There is insufficient evidence of any actual block material properties. FaAA examined only a small area of each block top.217/ But within the same block the cast iron properties may vary widely due to the presence of trace elements in certain areas. A meaningful analysis of the material properties of a cylinder block would require metallurgical examination of numerous sample areas of the block.

The performance of the EDG cylinder block is dependent on the properties of its materials of construction. FaAA's examination of a "small region of the block tops" of the EDGs was inadequate to characterize the materials of each of the blocks. FaAA has assumed that the block is homogeneous, but in actuality the casting is not uniform because of the segregation which naturally occurs during the casting process. Therefore, more than a single small area must be evaluated to determine whether or not there are differences in the entire blocks of EDGs 101, 102 and 103. FaAA states, "Specific materials testing is

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217/ Id. at 4-4.

equired to quantify any degradation in fatigue or fracture properties of the thick section block casting."218/ We agree. However, FaAA proposes that only the material of the original block for EDG 103 be completely evaluated. If that block material is "shown to be sufficiently less resistant to fatigue than typical gray cast iron, Class 40,"219/ the blocks of EDGs 101 and 102 would be predicted by FaAA as capable of surviving a LOOP/LOCA event. This assumes that the materials of those blocks are at least as strong as "typical" material. There is no adequate basis for this assumption. To reach conclusions about the material strength of the blocks of EDGs 101 and 102 compared to that of EDG 103, the material of all three blocks must be properly evaluated.

Q. Can the excessive cracking of the EDG 103 block be attributed to the "abnormal load excursion" at Shoreham on April 14?

A. FaAA did not do so. FaAA notes that the power outage affected EDG 103 with an excess load for 23 seconds, and that the large crack from the no. 1 cylinder down the front of EDG

218/ Id. at 4-5.

219/ Id. at 5-1.

103 occurred after the excess load event. But FaAA refrains from making any causal connection between the two matters. Neither FaAA nor LILCO documents describing the effects of the power outage220/ disclose the amount of the load during the 23 seconds. We do know that EDG 103 ran at test overload for 100 minutes thereafter before the large crack down the block front was noticed. With the available facts we are unable to determine what, if any, effect the 23 seconds had on the block. Two observations are in order. First, the "abnormal load excursion" demonstrates again that accidents happen, even if they are thought to be unlikely. The EDG's and their blocks should be strong enough to survive such an accident, which might have occurred during the inception of a LOOP/LOCA. Second, EDG 103 ran for ten minutes after the 23 second episode in an unloaded condition and without cooling water.221/ That fact, coupled with the subsequent block damage resulting from the overload test, suggests that other components of EDG 103 may have been damaged. LILCO has committed to repeat the entire start-up test program with EDG 103 after installation of its replacement block, and then disassemble and inspect the engine.222/ This

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220/ Letter dated April 24, 1984, from J.A. Notaro to W.E. Steiger. (Exhibit 65).

221/ *Id*. at 2.

222/ LILCO's Response to Suffolk County's Filing Concerning Litigation of Emergency Diesel Generator Contentions, June 21, 1984, at 55.

ommitment is very important. The inspection should be subject o the scrutiny of all parties in this proceeding.

Q. Do you agree with FaAA's conclusion that the cracks in the camshaft gallery areas of the blocks will not grow to any significant degree?

A. No. FaAA gave one example applying its formula for fatigue crack growth, which predicted the assumed crack to grow, but at a slow rate.223/ In its analysis, FaAA uses the simple Paris empirical relation, which does not take into account important parameters such as mean stress effects on fatigue crack propagation. In addition, FaAA evaluated the parameters in the Paris evaluation based on gray cast iron without the defects apparently present in the EDG 103 block. The conclusions presented on crack growth are meaningless without presenting the sensitivity of initial crack size to fatigue life and the physical properties of the actual block material. We should also point out that our general comments on the limitations of a fracture mechanics analysis discussed above with regard to the AE piston skirts also apply to the FaAA predictions for the growth of the camshaft gallery area cracks.

223/ FaAA Block Report at 4-6 to 4-7.

Q. Did you also discover other inconsistencies in the aAA evaluation of the camshaft gallery cracks?

A. Yes. First, FaAA assigns different values to n (Paris Law exponent) in their cumulative damage index (n = 9.6) and in the camshaft gallery crack analysis (n = 5.37). Since the same material is used in both cases, this change in exponent value confuses the results. Second, the value of "n" should be evaluated for the specific material used in the EDG 103 block and Table 4-1 should be recalculated. FaAA failed to obtain the "n" value from testing of specific block material. Further, FaAA failed to provide the basis for its selection of generic "n" values. Third, crack growth rate is very sensitive to the value of "n." For example, if n = 9.6 is used in the gallery crack growth rate example given on page 4-7 of the FaAA Block Report, the rate is increased by 10,000.

Q. Have the cracks in the camshaft gallery area of the EDG blocks been mapped and measured for propagation?

A. Apparently LILCO did map these cracks and some appeared to have grown.224/ The FaAA Block Report does not

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224/ Museler Deposition at 97-99 (Exhibit 57); Morning Report, NRC Region 1, March 20, 1984. (Exhibit 55).

eport any empirical data concerning propagation of these cracks.

Q. How could cracks in the camshaft gallery area of the cylinder block affect the operation of the EDGs?

A. If the known cracks propagate (and there is no reported metallurgical evidence that they will not) the first effect will be increased flexing of the camshaft. The flexing will then increase the load on adjacent bearings, which could further increase the propagation rates of cracks at these locations. As flexing of the camshaft takes place, the load on the cylinder where camshaft flexing is occurring will be reduced. Consequently, the loads on the other cylinders will be increased, and cylinder balance will be lost. As there appears to be almost no reserve of power in the EDGs, the ability to take full load will be seriously affected by the unbalance. In the worst case, the cracks could result in a broken camshaft leading to irreparable damage of the cylinder block and loss of engine.

Q. How is the load imbalance evaluated by FaAA?

A. The interaction resulting from changing loads due to crack propagation in one location and increased loading in ther locations is not part of the crack growth forecasts made by FaAA.

Q. The DRQR authors conclude that cam gallery support cracks "are predicted to grow very slowly at full load and not at all at 75 percent load."225/ What is the basis for this conclusion?

A. No basis for the conclusion is provided in either the DRQR Report or the FaAA Block Report. Further, the information provided by FaAA does not support, and in fact contradicts, a conclusion that cracks will not grow "at all."

Q. Will FaAA's recommendation that the cracked blocks on EDGs 101 and 102 be examined for cracks between stud holes by eddy current after each operation ensure the safe and reliable operation of the EDGs?226/

A. No. As discussed previously, cracks between stud holes can initiate rapidly during a LOOP/LOCA event and lead to catastrophic failure. Inspection of the block after periodic testing does not therefore ensure reliable operation in an

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225/ DRQR Report Vol. 4, Cylinder Block, at 3. (Exhibit 56).

226/ FaAA Block Report at 5-2.

emergency. Moreover, as discussed above, ligament cracks can cause leakage of coolant which itself can result in catastrophic failure. The propagation of the large crack down the front of EDG 103 running from a stud hold in cylinder no. 1 (which had a ligament crack) demonstrates that unanticipated and dangerous crack propagation, other than of cracks between stud holes, may occur rapidly during a LOOP/LOCA event. Ligament cracks similar to that on the stud hole for cylinder no. 1 currently exist at two stud holes for cylinder no. 8 of EDG 101 and at one stud hole for cylinder no. 8 and another for cylinder no. 1 of EDG 102.[227]

Q: Aside from the radial/vertical ligament cracks, the cracks between stud holes, and the cracks in the camshaft gallery area, have other types of cracks been found to occur in the R-4 and RV-4 series TDI cylinder blocks?

A: Yes. The FaAA Block Report refers to cracks in the blocks of TDI DSRV-16-4 engines at Comanche Peak Steam Electric Station. These cracks appear to extend down the counterbore and through the counterbore landing.[228] FaAA also refers to

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227/ *Id*. at Figures 1-2 and 1-3.

228/ *Id*. at 1-3.

"circumferential cracks in the liner counterbore at the liner landing ledge."229/

Q: Has FaAA determined the causes of these cracks and addressed whether they could occur in the EDG blocks at Shoreham?

A: No. FaAA states that the cracks at Comanche Peak have been "metallurgically examined and were identified as interdendritic shrinkage or porosity resulting from the casting process."230/ However, FaAA does not state who performed this examination, give any results in detail, or address whether similar cracks might occur at Shoreham. If the conclusion stated by FaAA is correct -- that these cracks are due to casting defects -- it supports our view that castings by TDI, including the blocks, piston skirts, and cylinder heads, are not reliable. FaAA does not discuss the circumferential block cracks at all. When questioned about the circumferential block cracks, Mr. Robert Taylor of FaAA, who headed the block study, testified that the FaAA report would not address the circumferential cracks:

229/ Id. at 1-1.

230/ Id. at 1-3.

> [B]ecause I am receiving pressure from management and LILCO to put a report out so that they can start a dialogue with the NRC. It's my understanding there have been promises made to NLCA (sic -- NRC) a block report will go out in the very new (sic -- near) future. And I just can't -- it just won't be a complete analycis, but it will start things moving.231/

Q: Are you concerned about circumferential cracks developing in the EDG blocks?

A: Yes. Such cracks could be very dangerous and lead to EDG failure. There is no reason to believe they will not develop in the EDGs. The causes of the circumferential cracks have not been determined.

Q: Did FaAA determine the causes of the ligament cracks and stud hole to stud hole cracks in the block tops of the EDGs?

A: Not precisely. FaAA only concluded that these cracks were service-induced and identified "three possible mechanisms of crack initiation (acting separately or in combination) in the block top, . . . low cycle fatigue . . . , high frequency fatigue . . . , [and] overload rupture."232/ These same

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231/ Taylor Deposition at 67. (Exhibit 59).

232/ FaAA Block Report at ii.

mechanisms could cause the intitiation of the circumferential cracks.

Q: Do you agree that the cracks in the block tops of the EDGs were service-induced?

A: All of the evidence available to us certainly supports that theory. We believe these cracks are indications that the EDGs are over-rated and undersized. They cannot operate at rated and required loads without the cracking of the blocks and other components. Dr. Chen, the diesel consultant to LILCO and the TDI Owners Group, testified that the high firing pressure of the EDGs contributes to the block cracking, and recommended that peak firing pressure be reduced to 1,500 to 1,550 psi.233/ Of course, such a reduction in firing pressure would reduce the horsepower of the EDGs to below the required amount for service at Shoreham.

Q. What is the basis for your assertion that the replacement block for EDG 103 is of an unproven design and has not been adequately tested?

233/ Deposition of Simon K. Chen (May 15, 1984) ("Chen Deposition") at 129. (Exhibit 66).

A. Mr. Lowrey of TDI testified that the design of the replacement block was only developed in the last two months of 1983, in an attempt to solve the block cracking problems of the R-4 series engines.234/ The newly designed replacement block was never tested by TDI, according to Mr. Mathews, the general manager.235/ Rather, TDI relied on the fact that the top portion and boss section of the replacement block design was the same design as similar portions of the block of the TDI RV-5 engine, and the RV-5 block had been tested.236/ A block is a single casting. We do not believe that a new design of an engine block is adequately tested simply because a portion of the casting is the same as a portion of an entirely differently designed block.

Q. Do you believe that the replacement block for EDG 103 is likely to crack?

A. Even if the design were adequate, and we believe such has not been demonstrated, the material properties used in all

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234/ Lowrey Deposition at 15-16. (Exhibit 24).

235/ Mathews Deposition at 106-107. (Exhibit 32).

236/ *Id*. In 1981 TDI decided to use the RV-5 blocks in current production for RV-4 engines, to address the block cracking problems. *See* Memo dated 4/1/81 from Lowrey to Pratt (TDI). (Exhibit 67).

of FaAA analyses are dependent on the casting process. The casting process can introduce defects such as porosity, tears, inclusions, and degenerate phases which critically effect the results of analysis. From the results of our inspection of the TDI casting processes and review of pertinent documents relating to changes made in those processes, we are not satisfied that TDI can produce a defect-free block. Therefore, any new replacement block must be completely inspected and tested.

Q. Have you recently received documents cited in the "Component Review" section of the DRQR Report on cylinder blocks?

A. Yes. A number of the underlying documents were recently received by the County. We have only had time to preliminarily review these documents. Many are illegible or have missing pages.

Q. What do you conclude based on your initial review of some of these documents?

A. Contrary to the conclusion in the DRQR Report that the "Owners Group has completed its review of the TDI diesel generators installed at SNPS" (p. 4-1) and that the Report provides the <u>results</u> which provide the basis for the conclusion that the EDGs "presently installed are fully capable of reliably performing their intended safety function" (Executive Summary, p. iii), we have discovered that final resolution of a number of unsatisfactory conditions documented on LDRs had not occurred when the Report was issued. Further, our review has disclosed that objective standards were not applied to resolve identified deficiencies. Thus, rather than documenting the completion of the DRQR assessments, the Report in fact provides only a status of the ongoing investigation. Should further review reveal additional information relevant to our testimony, the testimony will be supplemented.