Engineering Change

Company Name : CONSTELLATION ENERGY GENERATION, LLC

Print Date: 1/22/24

EC Number : 0000640630 000

Constellation

Status/Date : MODIFIED 1/22/24
Facility : BRW BRAIDWOOD GENERATING STATION
Type/Sub-type: EVAL MECH

EC Title: DOCUMENTATION OF TEST RESULTS WITH DILUTED LUBE OIL FROM FUEL IN-LEAKAGE - 2B AF DIESEL ENGINE PAST OPERABILITY

Mod Nbr : KW1: KW2: KW3: KW4: KW5:

Master EC :	N	Work Group :		Temporary :	N
Outage :	N	Alert Group:	A8952MECH	Aprd Reqd Date:	
WO Required :		Image Addr :		Exp Insvc Date:	
Adv Wk Appvd:		Alt Ref. :		Expires On :	10/17/26
Auto-Advance:	Y	Priority :		Auto-Asbuild :	N
Caveat Outst:		Department :		Discipline :	
Resp Engr :	MIKOFF		MARK		
Location :					

Units

Fac	Unit	Description
BRW	02	UNIT TWO

Systems

Fac	System	Description
BRW	AF	AUXILIARY FEEDWATER

Engineering Change

EC Number : 0000640630 000

Constellation

Status/Date : MODIFIED 1/22/24
Facility : BRW
Type/Sub-type: EVAL MECH

EC Title: DOCUMENTATION OF TEST RESULTS WITH DILUTED LUBE OIL FROM FUEL IN-LEAKAGE - 2B AF DIESEL ENGINE PAST OPERABILITY

KW1: KW2: KW3: KW4: KW5:

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Master EC :	N	Work Group :		Temporary :	N
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Adv Wk Appvd:		Alt Ref. :		Expires On :	10/17/26
Auto-Advance:	Y	Priority :		Auto-Asbuild :	N
Caveat Outst:		Department :		Discipline :	

Resp Engr : MIKOFF MARK
Location :

Milestone	Date	Req By	
110-PREPARE EC	1/19/24	APPROVED	
User Id: E061949		Name: MIKOFF	MARK
120-REVIEW EC	1/22/24	APPROVED	
User Id: BRZYP		Name: PANICI	GIOVANNI

I reviewed the EC and concur with its conclusion. The MPR test report gives reasonable assurance that
the 2B AF Diesel was operable with the lube oil diluted from fuel oil inleakage.

240-ITPR-OTHER	1/19/24	APPROVED	
User Id: BREWAX		Name: BREWER	ANDREW

See Topic Notes "EC Scope" for comments and resolution from MPR.
Note: Review comments panel is corrupt w/new AS9 rollout, ticket in to IT.
****
Overall, Risk Score 3 - ITPR req'd (Ref. Att. 5, Table. 4.1).
Consequence risk factors (3) - M.1, M.2, M.4
Human performance risk factors (5) - H.4, H.5, H.8, H.11, H.19
Process risk factors (3) - P.3, P.5, P.12

200-DISC RVW-M	1/22/24	APPROVED	
User Id: E078842		Name: FISHER	MATTHEW
300-APPROVE EC	1/22/24	APPROVED	
User Id: BRZBY		Name: BERGMANN	BRIAN
800-ATTR CLOSED		CLOSED	
User Id:		Name:	

Units

Fac	Unit	Description
BRW	02	UNIT TWO

Systems

Fac	System	Description
BRW	AF	AUXILIARY FEEDWATER

Affected Equipment List

Fac	Unit	Op Sys	Division	Area	System	Class

Engineering Change

Print Date: 1/22/24

EC Number : 0000640630 000

Constellation

Status/Date : MODIFIED 1/22/24
Facility : BRW
Type/Sub-type: EVAL MECH

BRW 02 AF

Equipment : PMPA 01PB Minor Rev:
Component : P30 K Major Rev:
Equip. Tag: 2AF01PB-K
State: Reviewed? Y Inst/Rm: Rev Trackable: Y Inc: N
Name : U2 AUX FEED PUMP DIESEL

Engineering Change Print Date: 1/22/24

EC Number : 0000640630 000

Status/Date : MODIFIED 1/22/24
Facility : BRW
Type/Sub-type: EVAL MECH

Page: 1

EC Title: DOCUMENTATION OF TEST RESULTS WITH DILUTED LUBE OIL FROM FUEL IN-LEAKAGE - 2B AF DIESEL ENGINE PAST OPERABILITY

KW1: KW2: KW3: KW4: KW5:

Modification Number :

Master EC :	N	Work Group :		Temporary :	N
Outage :	N	Alert Group:	A8952MECH	Aprd Reqd Date:	
WO Required :		Image Addr :		Exp Insvc Date:	
Adv Wk Appvd:		Alt Ref. :		Expires On :	10/17/26
Auto-Advance:	Y	Priority :		Auto-Asbuild :	N
Caveat Outst:		Department :		Discipline :	
Resp Engr :	MIKOFF		MARK		
Location :					

Cross References

Ref. Type	Number	Sub-Number	Description
EC	0000640287		PAST OPERABILITY TEST PLAN ACCEPTANCE RELATED
AR	04703982		Degraded Oil in 2AF01PB Crank Case
AR	04724536		Follow-up testing results for 2B AF Engine fue

4.1.4.1 IDENTIFY Basic SSC Functions.

The Auxiliary Feedwater (AF) System supplies emergency feedwater to the Steam Generators to remove decay heat from the Reactor Coolant System upon the loss of the normal feedwater supply (Ref. UFSAR Sec. 10.4.9). The AF pumps normally take suction from the condensate storage tank and pump to the steam generator secondary side via separate and independent connections to the feedwater piping outside containment.

The AF System consists of a motor driven AF pump and a diesel driven pump configured into two separate trains. Each pump provides 100% of the required AF capacity to the steam generators, as assumed in the accident analysis.

4.1.4.2 IDENTIFY Configuration Change safety classification.

The AF System is a safety related system. However, the testing will not be performed on plant equipment. Therefore, the contract for the Test Plan is non-safety related.

4.1.4.3 IDENTIFY Seismic Classification of the SSC.

The AF pump is Seismic Cat. I. However, the testing will not be performed on plant equipment. Therefore, the Test Plan does not require seismic consideration.

4.1.5 PROVIDE the performance requirements and design conditions (including margin) of the SSC needed to evaluate the change from the existing to the modified systems, structures, or components.

Response contained in Eval Details section of this EC.

4.1.16 REVIEW the Operating Experience databases through the INPO Internet Site or equivalent in accordance with PI-AA-115.

OPEX search in CAP noted that in 2019, IR 04238259 was written to document a degrading trend in regard to viscosity most likely due to fuel on the Braidwood 1B AF pump. Review of oil sample results for the 1B AF Pump crankcase obtained under WO 4866253 revealed a degrading trend with regards to viscosity and fuel oil content. The current fuel content was 4.9 percent by volume with an alert limit of 2 to 5 percent and a fault limit greater than 5 percent per MA-AA-716-230-1001, Oil Analysis Interpretation Guideline. Mission time was evaluated per EC 628306.

Other industry events related to dilution of lubricating oil from fuel oil in-leakage were also reported at Byron Station (Ref. IR 1084641).

It is also worth noting that similar past-operability demonstration by testing was utilized in the 2012 timeframe at Braidwood to resolve issues related with gas voids in the suction supply piping to the AF pumps from the Essential Service Water System. Based on discussions with technical staff from the timeframe, one of the takeaways from the testing by demonstration was documenting the Test Plan and formally documenting the alignment within the organization (including Subject Matter Experts – SMEs). Therefore, this EC applies the lessons learned.

In addition, a lesson learned from the test was to clearly state that the purpose of the test for the 2B AF Diesel Engine is to assess past operability under the condition with lube oil diluted by fuel oil leakage. The results of the test will not be used to establish a new design/licensing basis.

4.1.33 IDENTIFY Mechanical System Characteristics where design limits are placed on the mechanical properties of a system or components.

See Eval Details section of this EC.

Background / Reason for Evaluation:

In September 2023, elevated fuel content was identified in lube oil samples from the 2B Auxiliary Feedwater (AF) diesel engine (2AF01PB-K). A confirmatory sample determined the fuel content was above fault limits (Ref. IR 4703982 and Root Cause Report contained in ATI 04703982-21). Based on the reported dilution levels, Braidwood Station has elected to perform testing on a similar Diesel Engine to support past operability. Braidwood contracted MPR Engineering to coordinate the performance test.

This evaluation documents Braidwood Design Engineering's acceptance of the Test Report (attached below) which assesses the impact on the past operability of the 2B AF Diesel Engine. The Test Report is based on the Test Plan that was accepted via EC 640287.

Evaluation:

In order to evaluate the past operability of the 2B AF Diesel Engine, testing was performed at a Vendor facility (SWRI) on a Detroit Diesel Series 149 diesel engine. The objective of the test was to determine if the Braidwood 2B AF Pump Diesel Drive could have performed its safety function of driving the 2B AF pump and other connected equipment for a period of at least 24 hours.

The prime mover for the 2B AF pump is a Detroit Diesel 16V-149TI diesel engine, which is used to provide a driver diverse from the electrical buses in the case of a loss of all AC power. The 2B AF diesel engine also drives a cubicle cooler fan and a service water (SX) booster pump. The Technical Specification mission time for the 2B AF diesel-driven pump is 7 hours, and the probabilistic risk assessment (PRA) mission time is 24 hours.

On September 21, 2023, Braidwood personnel received analysis results that indicated the 2B AF engine Lube Oil (LO) was contaminated with 18.2 weight percent (wt.%) Fuel Oil (FO - Reference 1), which is well above the engine manufacturer's limit of 2.5 volume percent (vol.%) (Reference 2). The FO contamination was determined to be the result of defective fittings in the FO supply and return lines to several individual cylinder fuel injectors, which have since been replaced. The FO contamination resulted in a significant decrease in the LO/FO mixture viscosities (by approximately 40-60%, depending on temperature) relative to the pure LO viscosities. The 2B AF engine operated for 6.39 hours based on review of engine data between the maintenance period when the defective fittings were installed and discovery of the LO dilution. At the time of the LO dilution event, the 2B AF engine had a lifetime total of 606.9 operating hours.

<u>Effects of Fuel Oil Dilution of Lube Oil:</u>

The primary concern with FO contamination of LO is a reduction in the LO viscosity, which reduces the load carrying capability of the lubricant between lubricated engine parts (e.g., hydrodynamically lubricated bearings and bushings). The reduced viscosity of the mixture can result in metal-to-metal contact between moving engine parts leading to accelerated wear, seizure and/or catastrophic failure. A second concern with an active FO leak into the engine sump is that the added FO volume may raise the mixture level to the point that rotating and reciprocating components of the engine (i.e., the crankshaft, counterweights, and connecting rod bearing caps) contact the mixture. This will increase drag, add impact loads to the engine components, and heat and aerate the mixture further degrading its load carrying capability.

The prime mover for the 2B AF pump is a Detroit Diesel series 149, 16 cylinders diesel engine. The dilution test was performed on a Detroit Diesel series 149 engine with 12 cylinders.

The test engine performance is representative of the expected Braidwood 2B AF engine performance based on the following factors:

- ***Engine Type*** – The tested engine is the same make and model (Detroit Diesel Series 149) as the 2B AF engine.
- ***Equipment Similarity*** **–** The principal difference between the test engine and the 2B AF engine was the number of cylinders (12 vs. 16, respectively). An explicit similarity evaluation was performed to compare the test engine to the 2B AF engine (see Appendix **Error! Reference source not found.**). The similarity evaluation concludes that the key components critical to assessing the lubrication system performance, such as bearings and bushings, are identical or sufficiently similar for the 2B AF engine and test engine, and that results from the testing are directly applicable to the 2B AF engine.
- ***FO Similarity*** – The LO and FO used during the diluted LO testing are identical to the LO and FO used in the 2B AF engine.
- ***Conservative Loading*** – Loads on the test engine critical components (e.g., bearings and bushings) during the diluted LO test exceeded the design basis loading on the 2B AF engine.

<u>Conclusion:</u>

Constellation has reviewed the attached Test Report and finds it technically accurate. Constellation concurs with the conclusion of the report as it relates to the past operability of the 2B Auxiliary Feedwater Diesel Engine. There is reasonable assurance the Braidwood 2B AF Pump Diesel Drive would have performed its safety function of driving the 2B AF pump and other connected equipment for a period of at least 24 hours (would be expected to run considerably longer than 24 hours) following the as found LO dilution event identified on September 21, 2023.

<u>Note:</u> the results of the test will not be used to establish a new design/licensing basis.

References:

1. Bureau Veritas Oil Condition Monitoring Lube Oil Analysis Management System Report for Braidwood 2AF01PB-K-PMPA-01PB-E15-K (Braidwood 2B AFW Diesel Drive Lube Oil), October 4, 2023
2. Detroit Diesel Corporation Document No. 6SE313, "Detroit Diesel Corporation Series 149 Service Manual, Detroit Diesel Series 149 Engine," August 1997 (Braidwood Vendor Manual #D446-0029)

Attachments:

Att. 1 MPR Test Report

4101-0031-RPT-001
Rev 0 - AF Diesel Dri

MPR

4101-0031-RPT-001
Revision 0

Test Report and Past Operability Evaluation

Braidwood AF Diesel Drive Test with Lube Oil Diluted by Fuel Oil

Prepared for: Braidwood 1 & 2

Preparer:	Mark O'Connell	E-signed by: Mark O'Connell on 2024-01-19 21:41:36
Preparer:	Gary Thompson	E-signed by: Gary Thompson on 2024-01-19 21:44:57
Checker:	Edward McCarty	E-signed by: Edward McCarty on 2024-01-19 21:45:36
Checker:	Daniel McCray	E-signed by: Daniel McCray on 2024-01-19 21:45:49
Reviewer:	Craig B. Swanner	E-signed by: Craig B. Swanner on 2024-01-19 21:47:04
Approver:	Craig B. Swanner	E-signed by: Craig B. Swanner on 2024-01-19 21:47:23

QA Statement of Compliance

This document has been prepared, reviewed, and approved in accordance with the Quality Assurance requirements of the MPR Standard Quality Program.

Created: 2024-01-19 21:41:35
Project-Task No. 41012303-0031

MPR Associates, Inc.
320 King St. • Alexandria, VA 22314
(703) 519-0200 • www.mpr.com

RECORD OF REVISIONS		
Revision Number	**Pages /Sections Revised**	**Revision Description**
0	All	Initial Issue

Table of Contents

Tables

Figures

1.0 Introduction

1.1. Purpose

This report documents and evaluates the results of testing performed to determine the ability of a Detroit Diesel Series 149 engine to operate with lube oil (LO) diluted by a high and increasing concentration of fuel oil (FO). The test simulated operation of Constellation Energy's Braidwood Generating Station (Braidwood) 2B auxiliary feedwater (AF) pump diesel drive with LO diluted by FO due to an active FO leak. MPR subcontracted Southwest Research Institute (SwRI) to perform the full-scale test using a similar Detroit Diesel Series 149 engine.

1.2. Event Description

At Braidwood, the 2B AF pump is one of two supplies for emergency feedwater to the Unit 2 steam generators. The 2B AF pump prime mover is a Detroit Diesel 16V-149TI diesel engine, which is used to provide a driver diverse from the electrical buses in the case of a loss of all AC power. The 2B AF diesel engine is also referred to as the plant engine. The Technical Specification mission time for the 2B AF diesel-driven pump is 7 hours, and the probabilistic risk assessment (PRA) mission time is 24 hours (Reference 1).

On September 21, 2023, Braidwood personnel received analysis results that indicated the 2B AF engine LO was contaminated with 18.2 weight percent (wt.%) FO (Reference 2), which is well above the engine manufacturer's limit of 2.5 volume percent (vol.%) (Reference 3). The FO contamination was determined to be the result of defective fittings in the FO supply and return lines to several individual cylinder fuel injectors, which have since been replaced. The FO contamination resulted in a significant decrease in the LO/FO mixture viscosities (by approximately 40-60%, depending on temperature) relative to the pure LO viscosities. The 2B AF engine operated for 6.39 hours (Reference 4) between the maintenance period when the defective fittings were installed and discovery of the LO dilution. At the time of the LO dilution event, the 2B AF engine had 606.9 total operating hours (Reference 5).

1.3. Effects of FO Dilution of LO

The primary concern with FO contamination of LO is a reduction in the LO viscosity, which reduces the load carrying capability of the LO between lubricated engine parts (e.g., hydrodynamically lubricated bearings). The reduced viscosity of the LO/FO mixture can result in metal-to-metal contact between engine parts leading to accelerated wear, seizure and/or catastrophic failure. A second concern with an active FO leak into the engine sump is that the added FO volume may raise the LO/FO mixture level to the point that rotating and reciprocating components of the engine (i.e., the crankshaft, counterweights, and connecting rod bearing caps) contact the mixture. This will increase drag, add impact loads to the engine components, and heat and aerate the LO/FO mixture further degrading its load carrying capability.

2.0 Conclusions

Testing was performed on a Detroit Diesel Series 149 diesel engine to determine if the 2B AF diesel engine could have performed its safety function of driving the 2B AF pump and other connected equipment for a period of at least 24 hours. The test engine performance is representative of the expected 2B AF engine performance based on the following factors:

- ***Engine Type*** – The tested engine is the same make and model (Detroit Diesel Series 149) as the 2B AF engine.
- ***Equipment Similarity*** – The principal difference between the test engine and the 2B AF engine was the number of cylinders (12 vs. 16, respectively). An explicit similarity evaluation was performed to compare the test engine to the 2B AF engine (see Appendix A). The similarity evaluation concludes that the key components critical to assessing the lubrication system performance, such as bearings and bushings, are identical or sufficiently similar for the 2B AF engine and test engine, and that results from the testing are directly applicable to the 2B AF engine.
- ***LO and FO Similarity*** – The LO and FO used during the diluted LO testing are identical to the LO and FO used in the 2B AF engine.
- ***Conservative Loading*** – Loads on the test engine critical components (e.g., bearings and bushings) during the diluted LO test exceeded the expected design basis loading on the 2B AF engine during its PRA mission.

The test engine started with FO-diluted LO representative of the 2B AF engine conditions and operated in this condition for over 24 hours with additional FO being added to the LO during the test to represent the September 2023 as-found condition. The high FO concentrations in the LO of the test engine had no significant impact on engine performance. Most test engine parameters monitored during diluted LO operation remained consistent with the same parameters monitored during baseline testing. The high FO concentration caused two test engine parameters, LO pressure and temperature, to be initially lower than during baseline testing and to decrease slowly during diluted LO operation. Although affected, these test parameters remained well within normal ranges through the conclusion of diluted LO testing when the engine was secured. The results/trends support that the test engine would have operated with further increasing FO concentrations for substantially longer than the test duration (at least an additional 24 hours beyond the end of the diluted LO test). See Section 7.0 for the bases for these conclusions.

The testing adequately addressed all likely engine failure modes related to operation with FO-diluted LO. Specifically:

- ***Lubrication*** – The primary factor that characterizes the ability of LO to support loads is viscosity. LO dilution (and the resulting reduction in viscosity) adversely impacts the ability of the LO to adequately support bearing loads. The range of FO concentrations tested produce overall LO viscosities that are similar to the expected range for the 2B AF engine in the as-found condition. The test engine satisfied all performance requirements with FO-diluted LO with no apparent degradation of lubricated components (confirmed through the analyses of LO samples collected during the diluted LO test and the visual inspection of several lower main bearing shells before baseline testing and after the diluted LO test).

- ***High Level Oil Volume*** – Increasing LO/FO volume due to an active FO leak can cause the sump level to rise and contact rotating and reciprocating engine components, creating drag on the components, adding impact loads to the engine components, and heating and aerating the LO/FO mixture. Testing results showed that, as the sump level increased and LO/FO viscosity decreased, excess fluid leaked out of the rear crankshaft seal without any other adverse consequence. Similar leakage is expected to occur from the rear main seal of the 2B AF engine.[1] As such, the engine design adequately mitigates this potential failure mode.

Based on the excellent performance of the test engine with FO-diluted LO and MPR's evaluation determining that the test addressed all of the likely engine failure modes, MPR concludes that there is reasonable assurance the Braidwood 2B AF Pump Diesel Drive would have performed its safety function of driving the 2B AF pump and other connected equipment for a period of at least 24 hours (would be expected to run considerably longer than 24 hours) following the as-found LO dilution event identified on September 21, 2023.

3.0 Background

3.1. 2B AF Engine Design

The 2B AF engine is a Detroit Diesel 16V-149TI model number 9163-7301[2] diesel engine, which is a 16-cylinder, Vee-configuration, two-stroke, turbocharged and intercooled diesel engine. The engine was manufactured in 1978, and its serial number is 16E0004838. The engine has a continuous rating of 1,500 hp (Reference 6). Figure 3-1 shows the 2B AF engine. Note that the engine is shown painted gray in the background behind the jacket water cooler shown dark blue in the foreground.

The 2B AF diesel engine (also referred to as the plant engine) drives the 2B AFW pump as well as two smaller loads – a cubicle cooler fan and a service water (SX) booster pump. The maximum required power to drive the 2B AF diesel loads under design basis conditions is 1,222 hp (Reference 6).

[1] Detroit Diesel states in Reference 3 that leakage from the rear main seal is expected under some operating conditions, e.g., if the LO level is too high.

[2] Detroit Diesel Series 149 engine numbers consist of two four digit numbers. The 9 in the first digit position of the first number refers to the Series 149 engine. The second and third digits in the first number are the number of cylinders. The fourth digit in the first number refers to the engine application with 3 meaning an industrial engine. The 7 in the first digit position of the second number indicates right-hand rotation when viewed from the front of the engine (counter-clockwise rotation when viewed from the drive end). The 3 in the second digit position of the second number indicates the engine is turbocharged with optional intercoolers. The third and fourth digit positions in the second number are the specific model number. The plant engine model number of 9163-7301 identifies a 16-cylinder, counter-clockwise rotation, turbocharged Series 149 industrial engine.

3.2. *Engine Lubricating Oil*

Section 5.2.1 of the Detroit Diesel Series 149 Manual (Reference 3) recommends the use of SAE viscosity grade 50 LOs, which have viscosities of 16.3 to 21.9 cSt at 100°C (Reference 7), in Series 149 industrial engines. Reference 3 also notes that at ambient temperatures below 50°F, the starters may not provide sufficient cranking speed to start the engine, and SAE viscosity grade 40 LOs, which have viscosities of 12.5 to 16.3 cSt at 100°C (Reference 7), may be used. The LO used in the 2B AF engine is Mobil Delvac 1640, which is an SAE 40 viscosity grade diesel engine oil. The specification for the LO is included as Appendix B. Mobil Delvac 1640 has nominal viscosities of 14.5 cSt at 100°C and 132 cSt at 40°C. The FO used in the 2B AF engine is No. 2-D FO. A FO analysis result showing parameters for the FO is included as Appendix C. No. 2-D FO has a viscosity at 40°C of 1.9 to 4.1 cSt (Reference 8).

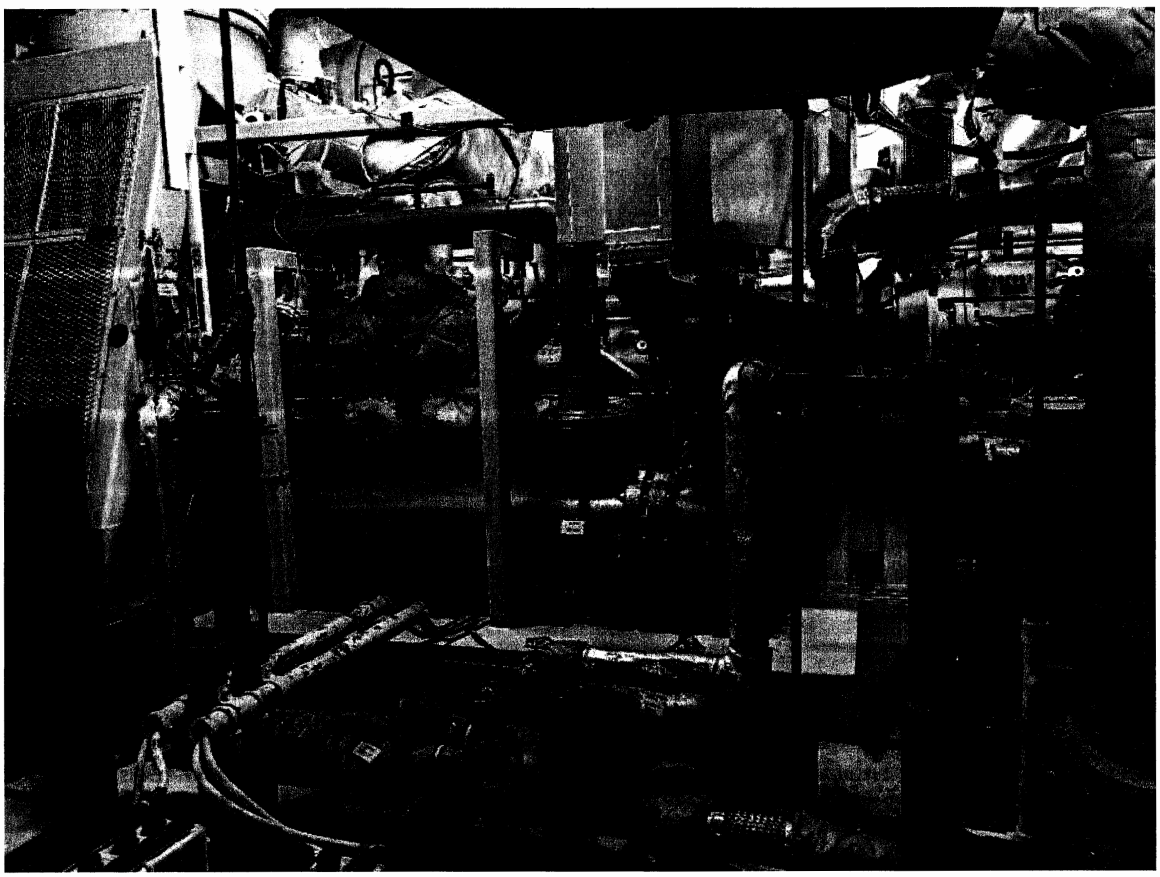

Figure 3-1. Braidwood 2B AF Pump Diesel Drive

4.0 Test Approach and Design

4.1. *Test Objective*

The test objective was to determine if the 2B AF engine could power its driven equipment (the 2B AF pump, cubicle cooling fan and SX booster pump) with its LO diluted by FO from a simulated active FO leak (with the specific LO conditions consistent with the as-found conditions from the LO dilution event identified in September 2023 and the subsequent degrading conditions during operation in response to a postulated plant accident). Specifically, the testing was intended to:

- Evaluate the ability of a similar Detroit Diesel Series 149 engine to operate according to a prescribed load profile (consistent with the expected 2B AF engine loads in response to a plant accident) with reduced LO viscosity with the as-found FO concentration in the LO and expected increase in the FO concentration during continued 2B AF engine operation.
- Monitor the test engine's performance, LO condition, and overall health throughout the test.

The test objective was accomplished through full-scale testing of a Detroit Diesel Series 149 engine-generator set (genset) with LO diluted by FO.

4.2. Test Plan

MPR prepared a test plan (Reference 9, which is included as Appendix D) to govern the test. The test plan:

- Defined the work scope performed by SwRI to prepare the test genset for the test, perform the testing, and document the test results,
- Described the test system and its design and monitoring requirements,
- Described the commissioning of the test system,
- Defined and described the requirements for baseline and diluted LO tests, and
- Described the test documentation to be provided by SwRI.

SwRI prepared a safety plan, test procedure, and test report (Reference 10, which is included as Appendix E) in accordance with the requirements of Reference 9. Testing was performed in accordance with the MPR test plan and the SwRI safety plan and test procedure.

4.3. Test Engine

For the test results to be applicable to the 2B AF engine, the configuration of the test engine should be as close to the same design as the 2B AF engine as possible. Ideally, it would be the actual 2B AF engine or another Detroit Diesel 16V-149TI model engine with the same continuous rating, number of operating hours, and model number as the plant engine. The capability to match the 2B AF engine configuration was limited by several factors. These included:

- Manufacture of the Series 149 engine ceased in approximately 1999, so only used engines manufactured more than 20 years ago were available for the test,
- The most straightforward method of loading the engine for a test was for the engine to drive a generator that was connected to a load bank, so only engine-generator sets could be considered for the test, and

- It was desired to complete testing before the end of calendar year 2023, so only engine-generator sets that were immediately available and in good-running condition could be considered for the test.

A single, used genset with a Detroit Diesel 12V-149T engine as a prime mover was identified that satisfied these criteria. This genset (also referred to as the test genset or test engine) was purchased from Power Zone Equipment, Inc. Figure 4-1 shows the test genset at Power Zone. A copy of the Power Zone quotation (Reference 11), including pictures of the test genset at Power Zone, is included as Appendix F.

The test genset is a Detroit Diesel 12V-149T model number 9123-7305[3] diesel engine, which is a 12-cylinder, Vee-configuration, two-stroke, turbocharged diesel engine, connected to a 750 kWe Marathon generator. The engine was manufactured in 1980 (Reference 12), and its serial number is 12E0006264. The test engine does not have an intercooler. The test genset has a continuous rating of 750 kWe, which is limited by the generator's continuous rating. The engine has a continuous rating of 1,130 hp (Reference 12). At the time it was purchased, the test genset's run hour meter showed approximately 1450 hours of operation (Reference 11).

[3] The test engine model number of 7123-7305 means a 12-cylinder, counter-clockwise rotation, turbocharged Series 149 industrial engine.

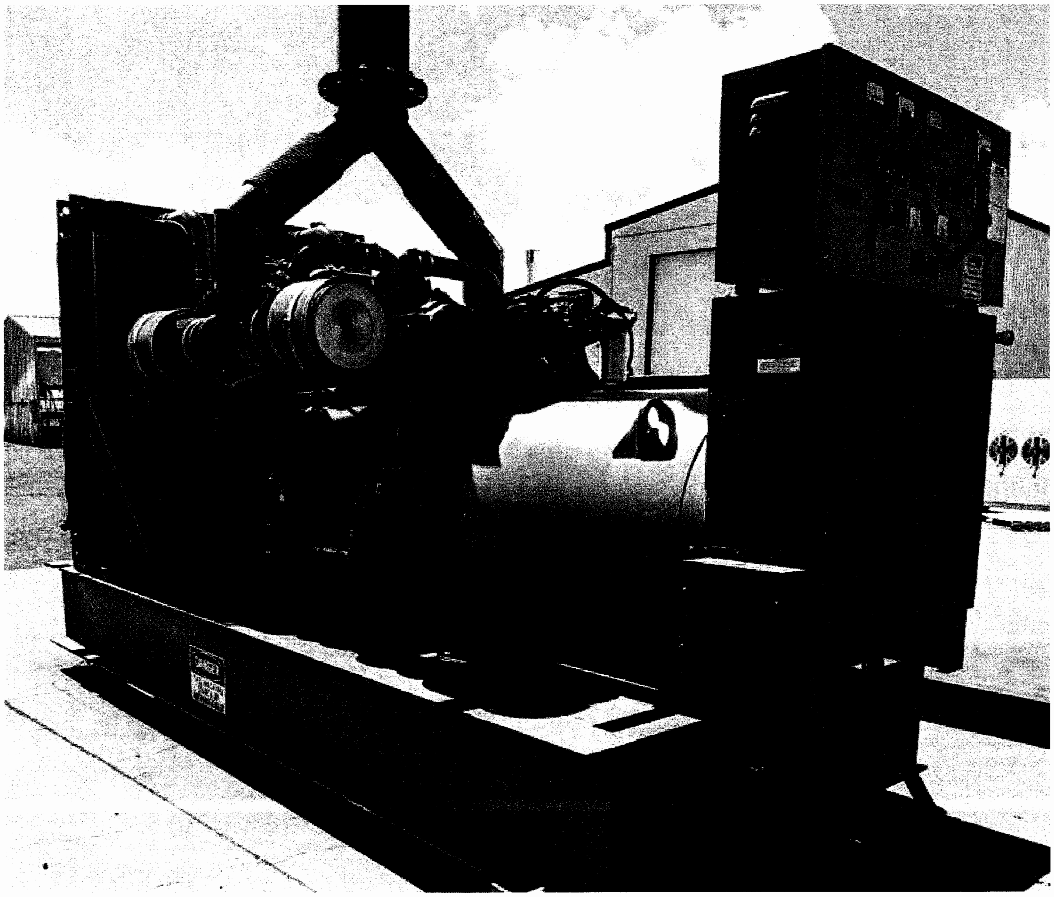

Figure 4-1. Test Genset at Power Zone Equipment, Inc.

4.4. Similarity Evaluation

MPR performed a detailed similarity evaluation between the 2B AF engine and the test engine. The similarity evaluation is included as Appendix A to this report. The similarity evaluation concludes that the test engine is sufficiently similar to the 2B AF engine that conclusions regarding operation of the plant 2B AF engine with LO diluted by FO can be drawn based on the results of testing the test engine with LO diluted by FO. The bases for this conclusion include:

- Both engines are Detroit Diesel Series 149 engines. The overall design of the major engine components (cylinder, cylinder bore, piston, cylinder head, etc.) are the same. Engine power during the test will be similar to the plant engine on a per cylinder basis.
- The test engine is representative of the 2B AF engine such that the results of diluted LO testing performed at SwRI can be used to simulate the operation of the 2B AF engine with LO diluted by FO.
- The test engine operating conditions at SwRI are representative of those of the 2B AF engine, which supports the use of the diluted LO testing performed at SwRI to evaluate the ability of the 2B AF engine to perform its safety function with LO diluted by FO.
- All of the important engine bearings and bushings that could be affected by decreased LO viscosity are identical in the 2B AF engine and the test engine. These include the main

bearings, crankshaft thrust bearings, connecting rod bearings, piston pin bushings, rocker arm bushings and camshaft bearings. Operation of these components in the test engine with LO diluted by FO is directly applicable to the 2B AF engine. In addition, the piston skirts, piston rings and cylinder liners in the 2B AF and test engines are the same.

- Use of a test engine of the same make and model as the 2B AF engine results in other engine bearings and bushings in the test engine, such as those in the engine-driven pumps, being sufficiently similar to simulate operation of the 2B AF engine with the test engine.
- The lubrication systems of the 2B AF and test engines provide nearly identical per-cylinder LO flow rates and have identical pressure LO pressure regulator settings, so LO system flow and pressure in the test engine are nearly the same as in the 2B AF engine.
- The turbochargers on the 2B AF engine and test engine are manufactured by the same supplier, are of similar design and are sized based on the number of cylinders and rating of each engine. They are sufficiently similar that operation of the test engine turbochargers with LO diluted by FO is directly applicable to the 2B AF engine.

4.5. Determination of Test Engine Load

The test engine is part of a genset. To ensure that the loading of lubricated engine/turbocharger components during the test is sufficiently similar to the loading on lubricated components of the 2B AF engine during performance of its mission, the electrical load applied to the test engine by the genset's generator is scaled from the 2B AF engine load such that the load per cylinder was at least equal to the load per cylinder applied to the 2B AF engine. The 2B AF engine load is based on the loading assumed in Braidwood's design-basis calculation for the 2B AF pump diesel drive FO consumption (Reference 5). The test engine loading is determined in Reference 13, which is included as Appendix G. Table 4-1 summarizes the required test genset loads to bound the PRA mission loads for the 2B AF engine.

Table 4-1. Test Genset Load to Simulate 2B AF Engine PRA Mission

Period	Duration (hr)	2B AF Engine Load (hp)	% of 2B AF Engine Rating	Test Engine Output (hp)	Test Genset Output (kWe)
1	2	1,222	81.5	921	666
2	4	1,087	72.5	819	593
3	1	1,046	69.7	788	570
4	3	1,046	69.7	788	570
5	14	939	62.6	707	511

4.6. Matching LO Conditions Between 2B AF Engine and Test Engine

As discussed previously, the two most likely failure mechanisms are bearing/bushing failure due to decreased LO viscosity and contact of rotating and reciprocating components with the LO/FO mixture in the engine sump due to excessive sump volume and a high mixture level. To accurately simulate 2B AF engine lubrication during the LO dilution event, the key test parameter to match is the expected LO viscosity throughout the duration of the test. Since LO viscosity is a function of FO concentration in the LO, the test attempts to match the LO conditions in the 2B AF engine at the time of the LO dilution event. Since the 2B AF engine had an active FO leak that would further reduce LO viscosity with additional operating time, the test also attempts to simulate the increasing FO concentration in the LO over time. Matching the sump level relative to the level of rotating and reciprocating components over the test duration is also important. To accomplish these objectives, the test attempts to match as best as possible the following test engine parameters to the 2B AF engine conditions:

- The initial FO concentration in the LO,
- The increasing FO concentration in the LO with additional operation,
- The initial sump level, and
- The increasing sump level with additional operation.

Because the engine sump volumes are different sizes and shapes, it is difficult to match both the sump level and FO concentration throughout the duration of the test. Furthermore, additional uncertainties (e.g., the exact amount of LO in each engine is not known because some amount of residual LO remains in the engine after LO is drained from the oil pan) make it difficult to add the correct amount of FO to obtain a given target FO concentration. As such, differences in the actual tested FO concentration and the target FO concentrations are expected. Test results are analyzed in subsequent report sections to evaluate test engine performance in comparison to the 2B AF engine. The following subsections describe how the target test FO concentrations are derived and how the test attempted to achieve the targets.

4.6.1. Initial FO Concentration

As stated in Section 1.2, analysis of a LO sample drawn from the 2B AF engine on September 21, 2023, indicated that the FO concentration in the LO was 18.2 wt.%. As shown in Reference 14 (included as Appendix H), this is equivalent to 18.82 vol.%. The initial target FO concentration in the test engine LO is 18.2 wt.% (18.82 vol.%). The target FO concentration in the test engine LO was achieved by premixing known volumes of LO and FO outside the engine and accounting for an estimate of the LO that could not be drained from the engine.

According to Section 3.9 of the engine manual (Reference 3), oil level is to be checked after the engine has been stopped for at least 20 minutes to permit oil to drain back to the oil pan; however, there is some LO in the engine that will not drain back to the pan. In order to get the best possible estimate of the initial FO concentration in the LO and the correct FO addition rate, it is necessary to determine the total volume of oil in the test engine.

Based on measurements of the test engine upper and lower oil pans and the high and low marks on the test engine dipstick, MPR calculated the oil pan volume as a function of test engine LO level. Midway between the high- and low-level dipstick marks corresponded to 28 gallons of LO in the pan. MPR targeted a total LO volume of 30 gallons (Reference 15) for the start of the diluted LO test. This would give an initial FO volume of approximately 7 gallons to achieve the target of 18.82 vol.% FO dilution of the initial LO in the test engine.

4.6.2. FO Concentration During Additional Run Time

In Reference 16, station personnel stated that the LO volume in the 2B AF engine is 42 gallons. After operating for 6.39 hours with the FO leak (Reference 4), analysis of a LO sample from the 2B AF engine showed the FO concentration to be 18.2 wt.%/18.82 vol.% (Reference 1). As shown in Reference 14, this results in a calculated FO leakage rate into the 2B AF engine LO of 1.524 gph.

To achieve an equivalent test engine FO concentration, the calculated 2B AF engine FO leakage rate is multiplied by the ratio of the test engine to 2B AF engine oil volumes. This results in a leakage rate of 1.089 gph in the test engine (Reference 14). The calculated FO leakage rate assumes that no LO is consumed by or leaks from the engine, which is conservative, because loss of LO through consumption or leakage would increase the FO concentration.

Figure 4-2 shows the projected FO volume concentrations in the test engine and 2B AF engine LO as functions of operating time based on an initial FO concentration of 18.82 vol.%. The predicted FO concentration in both engines after operating through the PRA mission time of 24 hours is 52.45 vol.%.

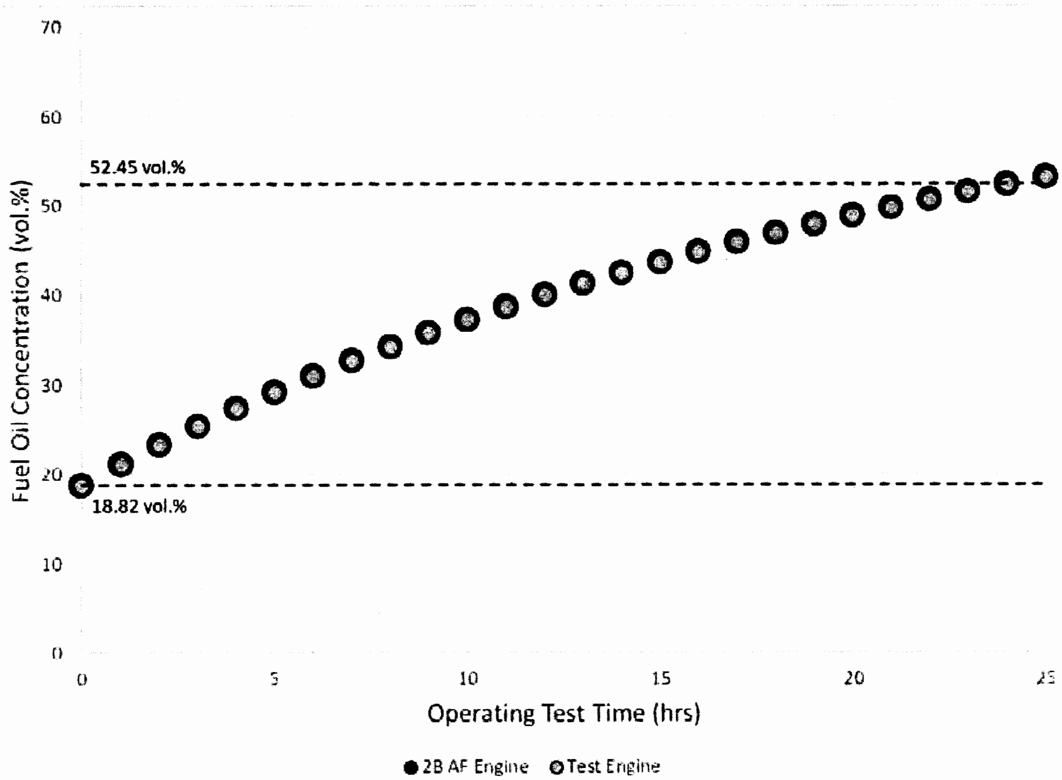

Figure 4-2. Predicted FO Concentrations for Test Engine and 2B AF Engine LO vs. Operating Time

4.6.3. Initial Sump Level and Increase with Additional Run Time

The initial LO level of the 2B AF engine with 42 gallons of LO in the lubrication system is between the high- and low-level marks on the dipstick (Reference 16). Similarly, the LO level of the test engine with 30 gallons of LO in the lubrication system is between the high- and low-level marks on the dipstick (Reference 15). Adding 18.82 vol.% FO to the LO in both engines (9.74 gallons of FO for the 2B AF engine and 6.95 gallons of FO for the test engine) would raise the oil pan levels above the full marks. In neither engine would the initial FO addition cause rotating and reciprocating engine components to contact the LO/FO mixture in the oil pan (i.e., the fuel leak on the 2B AF had not yet caused contact by the time the leak was identified). For the 2B AF engine, MPR calculated that an additional 15.05 gallons of FO would be required for contact to occur. At a FO leakage rate into the LO of 1.524 gph, it would take approximately 9.87 hours for contact to occur, assuming that none of the LO/FO mixture is consumed or leaks from the 2B AF engine. For the test engine, MPR calculated that an additional 8.90 gallons of FO would be required to make contact. At a FO leakage rate into the LO of 1.089 gph, it would take approximately 8.17 hours for contact to occur, assuming that none of the LO/FO mixture is consumed or leaks from the test engine. As a result, it was expected that contact between the rotating/reciprocating engine components would occur for both engines prior to the PRA mission time of 24 hours being reached. Further, the test engine condition is conservative compared to the 2B AF engine condition because the test engine would reach a more severe condition sooner.

4.7. Potential for Mixed FO and LO to Separate or Stratify

Insoluble liquids of different specific gravities will stratify when mixed and left undisturbed for some period of time. The denser liquid will sink, and the light liquid will rise to the top. The LO has a specific gravity of 0.89 (Appendix B) and a density of 7.42 pounds per gallon. The FO used for the diluted LO testing has a specific gravity of 0.854 (Appendix C) and a density of 7.12 pounds per gallon. Both are mixtures of hydrocarbon molecules and additives.

If FO and LO mixed in the 2B AF engine were to separate or stratify, the lighter FO would rise to the top. Since the LO pump draws suction from low in the oil pan, the initial LO supplied to the engine would have little or no FO, improving lubrication conditions during the start, when typical lubrication conditions in an engine are at their worst (because oil has drained from lubricated surfaces during standby conditions and because a minimum speed is required to establish hydrodynamic lubrication of journal bearings). If the mixed LO and FO do not separate or stratify, the initial LO supplied to the engine would be a mixture of FO and LO with corresponding reduced viscosity, making for worse lubrication conditions during the start. Either condition could have been established for the start of the diluted LO test by either mixing the FO and LO prior to adding them to the engine or by adding the FO on top of the LO.

To determine what would occur in the 2B AF engine and therefore, the initial conditions for the diluted LO test, a mixture of approximately 20 vol.% Constellation-provided FO and 80 vol.% Mobil Delvac 1640 LO was mixed thoroughly in a plastic bottle. After more than a week, there was no visible separation or stratification of the FO and LO. It was concluded that, once mixed, the FO and LO would not stratify or separate. As such, the FO and LO were mixed together prior to addition to the test engine for the diluted LO test.

5.0 Test Setup

5.1. Test Genset

The test genset was transported to SwRI's Locomotive Technology Center (LTC) in San Antonio, TX, and installed in a building called the "Back Shop." The building is a former locomotive maintenance shop. The building had facilities to support the test, including:

- An overhead crane to move the test genset,
- A secondary containment pit under the genset to collect and contain any fluids that leaked from the test engine,
- A steel wall barrier to protect test personnel in the event of a catastrophic failure of the test engine,
- Space outside the back shop for the load bank and FO used in the test,
- A secondary building inside the back shop for test control and monitoring (the test control room), and
- Access to an exterior wall for the exhaust pipe outlet.

The receipt inspection of the test engine radiator revealed that the tubes were internally plugged. The radiator and its fan were removed and replaced by a SwRI-provided external radiator system that used a motor-driven fan. The fan motor was powered by the load bank and included in the genset power. During testing this motor-driven radiator fan drew approximately 27 kWe from the load bank and was powered by the test genset. This load on the genset was included in the test genset load levels listed in Table 4-1.

Figure 5-1 shows the test genset installed in the SwRI LTC Back Shop during the diluted LO test. The radiator is behind the engine in the picture. The engine exhaust pipe goes over the radiator to the external wall. The metal plates under the genset cover the secondary containment pit. The steel wall barrier is at the left edge of the figure.

Figure 5-1. Test Genset Installed in SwRI LTC Back Shop

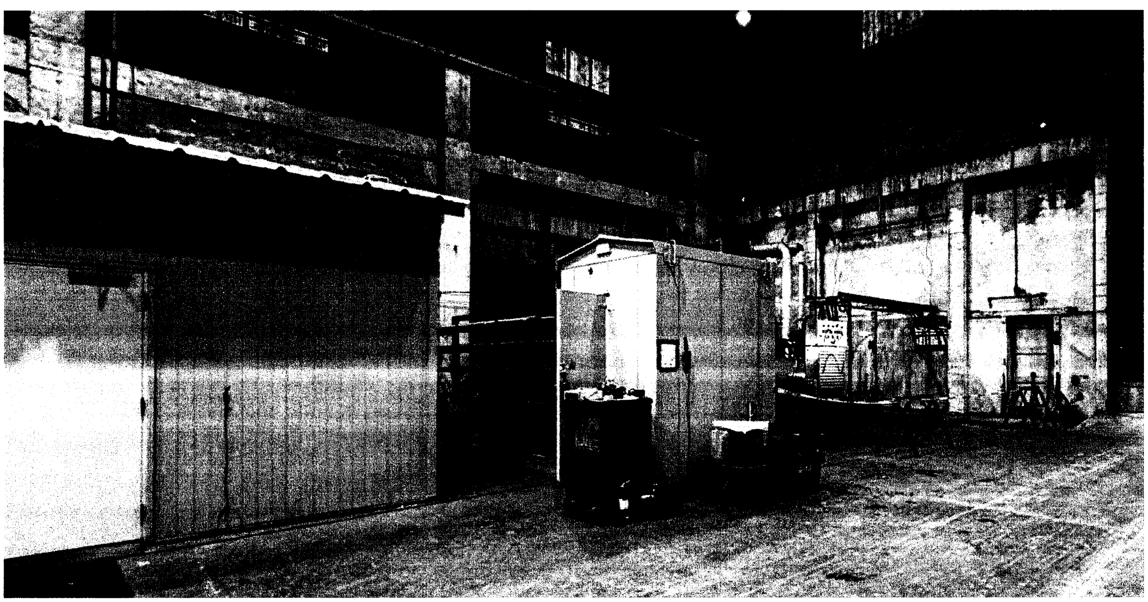

Figure 5-2. SwRI LTC Back Shop Showing Locations of Test Genset (Right) and Test Control Room (Left)

An exhaust pipe with a back pressure throttle valve was added to the genset with the pipe terminating outside of the Back Shop. Consistent with Reference 9, the throttle valve was adjusted to provide 13 inches of water exhaust back pressure when the test genset was operating at approximately 675 kWe.

Figure 5-3. Exhaust Pipe with Throttle Valve

During troubleshooting and break-in, several test engine components were replaced including the thermostats, the analog FO pressure gauge near the FO filter housing, and the cylinder 4L fuel injector. The speed of the test engine continued to vary during the last 20 minutes of the second 12-hour baseline test, so the electronic speed control governor was replaced.

Other modifications and changes that were made to the genset at SwRI to facilitate the testing are described in the following subsections.

5.2. Instrumentation and Data Acquisition System

The test genset was instrumented to record a number of parameters important to the test. These included:

- Ambient temperature at the back of the datalogger,
- Engine intake air temperature at the left rear engine intake filter,
- LO sump temperature in the side of the lower oil pan,

- Engine outlet coolant temperature at the engine jacket water manifold,
- LO pressure at the front left corner of the engine block,
- FO pressure at the top of the FO filter housing,
- Crankcase pressure at the gear cover at the front of the engine,
- Generator output voltage at the panel at the back of the generator,
- Generator output current at the panel at the back of the generator, and
- Engine speed at the crankshaft harmonic balancer.

Figures showing the locations of these instruments are included in the SwRI Test Report in Appendix E. The test parameters were captured and recorded by a Campbell Scientific Model CR3000 Measurement and Control Datalogger. The signals were displayed on a laptop computer located in the test control room.

Figure 5-4. Test Control Room

Two automotive knock sensors were mounted on the left side of the engine block to detect vibration resulted from engine degradation. Knock sensor outputs were monitored on a four-channel oscilloscope located in the test control room. Data were also manually collected from the test genset instrumentation. These included LO pressure, FO pressure, coolant temperature, generator voltage and generator frequency.

5.3. LO Sampling System

Since the possibility of a catastrophic engine failure was increased by the FO-diluted LO, no personnel were allowed to be in the plane of rotation of the test engine during the diluted LO test for safety reasons, and direct access to the oil pan drain was not possible. To permit sampling of the LO during testing, a continuous LO circulation loop was installed. The system was used during baseline testing to demonstrate its functionality and was used during the diluted oil test to draw hourly samples.

The sampling loop drew LO suction from the bottom of the engine oil pan and returned the LO to the upper pan through the same access cover used for FO addition. The sampling loop used a 35-gallon-per-hour pump (Appendix E) with ½-inch hoses connected to and from a sample point, which was located in a metal enclosure (the "hut") located between the test control room and the genset but outside the plane of rotation of the test genset (see Figure 5-5). The pump ran continuously during the diluted oil test, and the distance between the oil pan and the pump suction port was minimized. The transit time from the oil pan to the sample point was less than one minute. Figure 5-6 shows the LO sampling station in the hut.

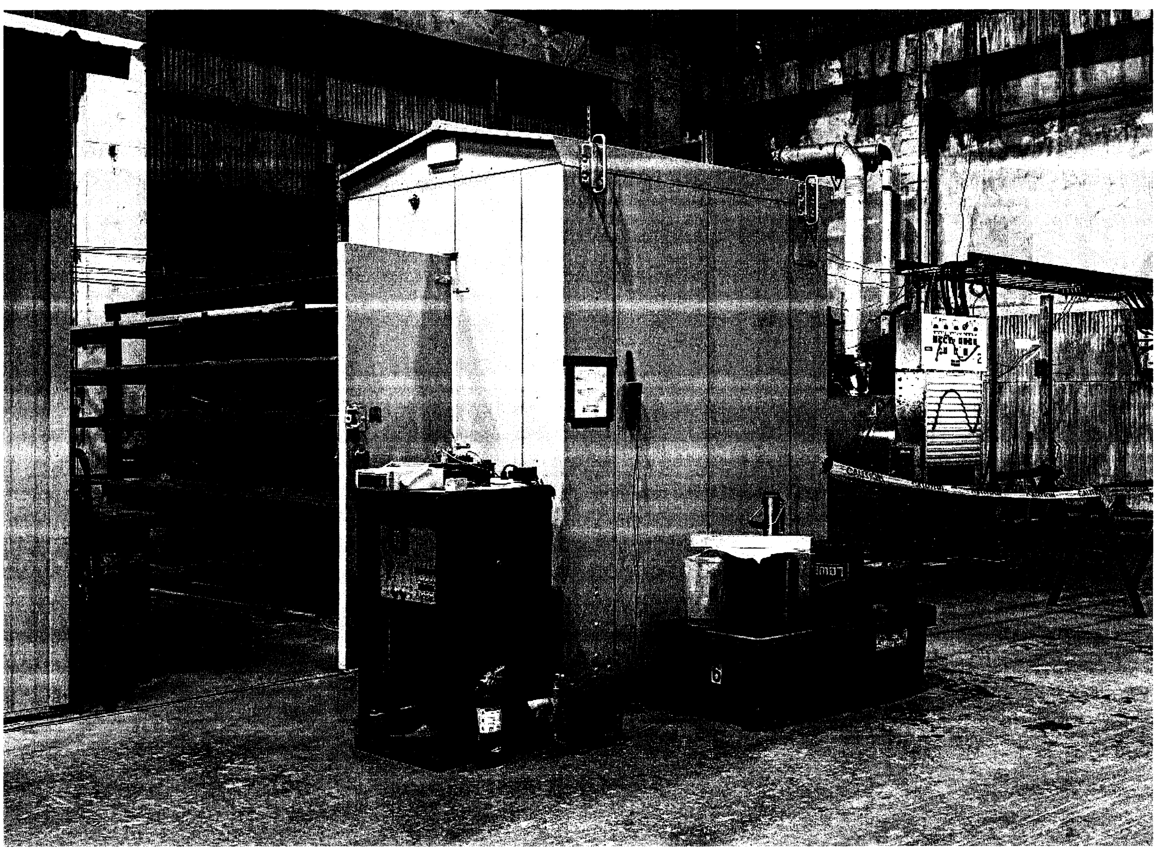

Figure 5-5. Hut for FO Addition and LO Sampling

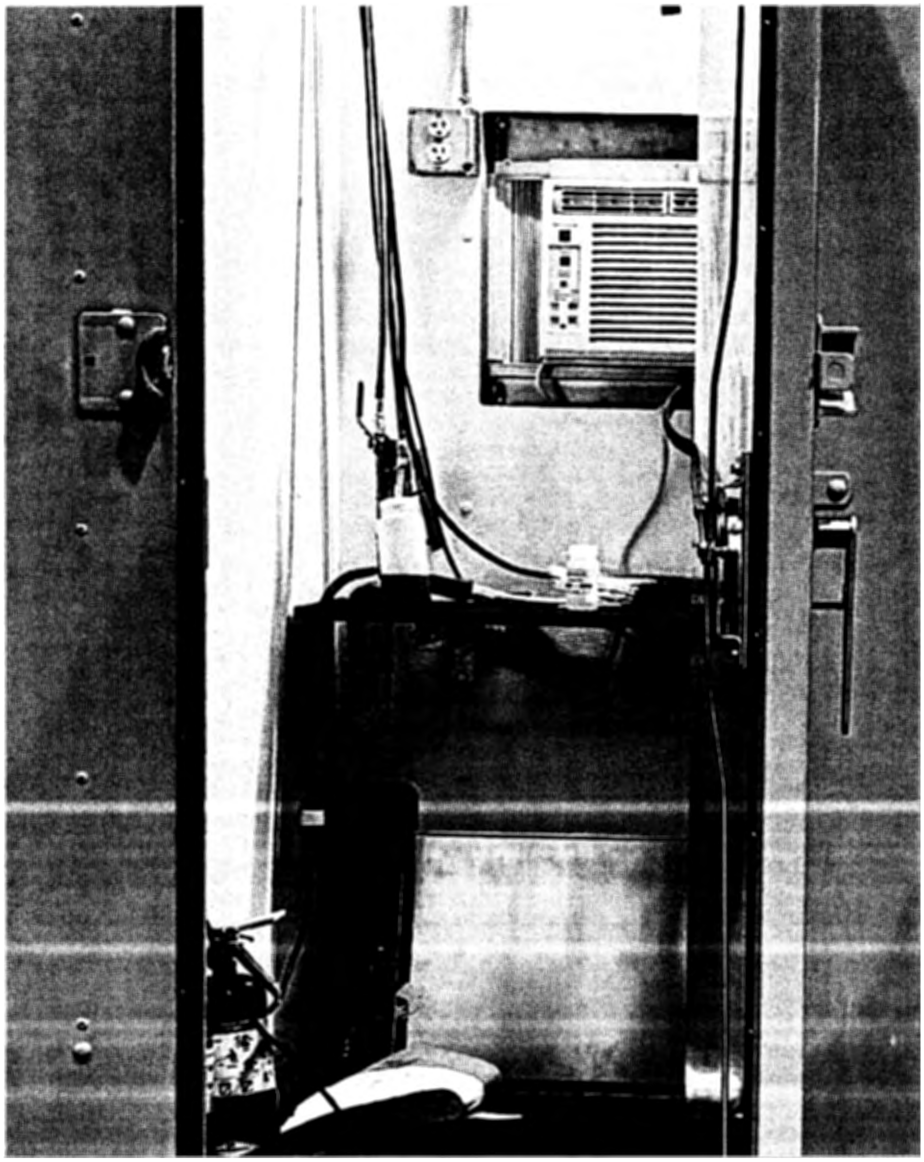

Figure 5-6. LO Sampling Station in Hut

5.4. FO Addition System

The FO addition system was installed to mimic the active FO leak on the 2B AF engine. The system used a Walchem Model EWN-B21VCUR metering pump rated for 1.6 gph and 60 psi (Appendix E). The pump was calibrated through a series of tests, culminating in a ten-hour test run on December 7, 2023, that demonstrated the desired FO addition rate of 1.09 gph (see Section 4.6.2) at a stroke-length setting of 53 percent (Figure 5-7).

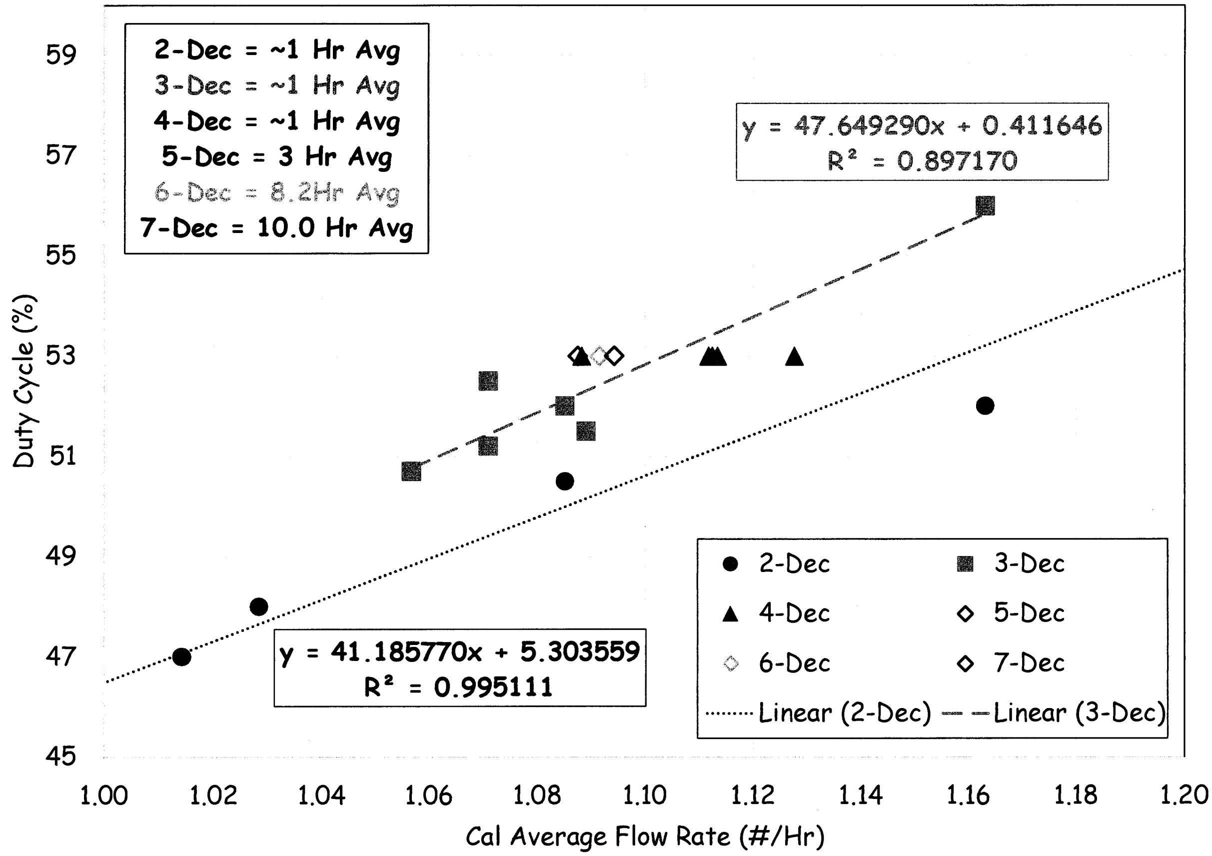

Figure 5-7. FO Metering Pump Calibration (from Reference 10)

During the diluted LO test, the FO added to the test engine was pumped from a bucket located on a scale in the hut. The FO addition rate was tracked by recording the weight of FO pumped every 10 minutes during the diluted oil test. The pump ran continuously during the diluted oil test with the exception of two periods during the first 4 hours of the test when it was stopped for a total of approximately 12 minutes. The pump was stopped because the rate of FO addition calculated from the change in weight of the bucket in the hut indicated that the flow rate was initially above 1.09 gph. The pump flow rate was later increased by increasing its duty cycle during the test when the FO addition rate tracking indicated that the flow rate was below 1.09 gph. Figure 5-8 shows the FO addition system metering pump, bucket, and scale in the hut.

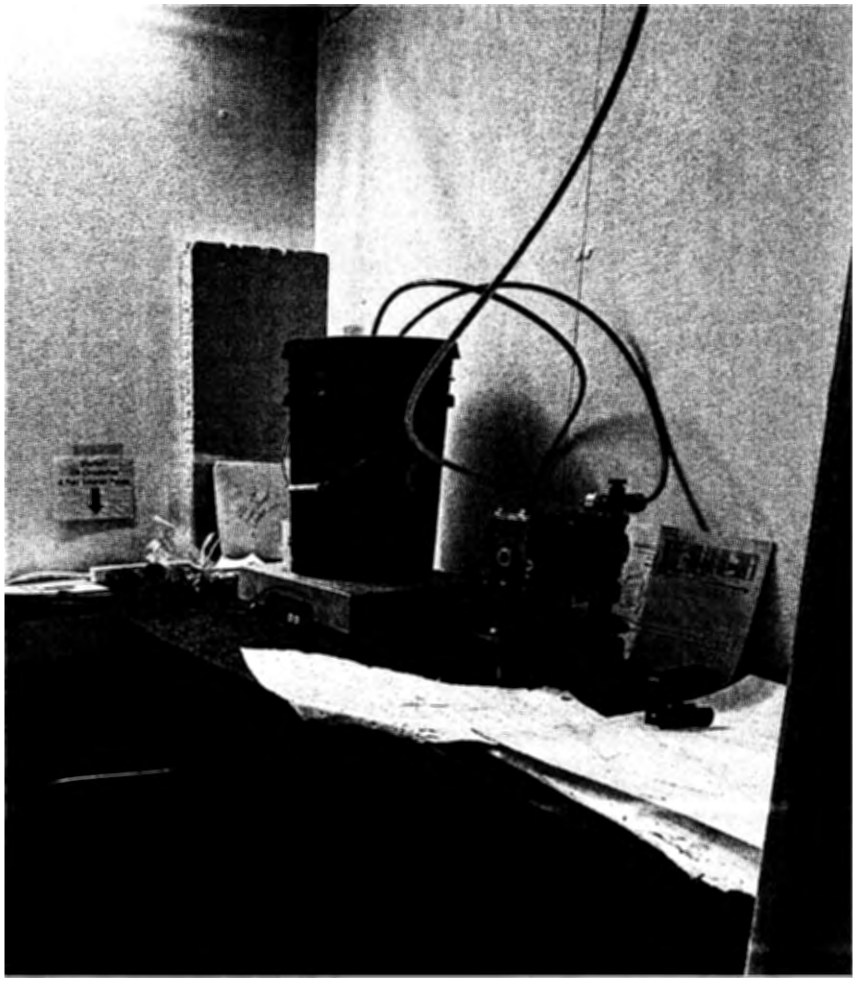

Figure 5-8. FO Addition System in Hut

5.5. Filters

The test genset was equipped with four air intake filters mounted on the turbochargers, four LO filters mounted on the right side of the engine block, and one FO filter mounted inboard of the right rear turbocharger. The test genset troubleshooting and break-in were performed using the filters supplied with the genset. Three of the four air intake filters (only three filters could be located for purchase within the timeframe needed to support the testing), all four LO filters, and the FO filter were replaced with new filters prior to baseline testing.

5.6. Load Bank

The test genset was connected to a 2 MWe resistive load bank located outside of the Back Shop. The load bank had three 500 kW resistor banks, one 200 kW resistor bank, two 100 kW resistor bank, and two 50 kW resistor banks. These discrete steps necessitated operating the test genset above the prescribed test loads identified in Section 4.5. Figure 5-9 shows the load bank. Figure 5-10 shows the load bank control panel. Figure 5-11 shows the arrangement of load bank switches used for each load step and the resulting expected test genset load for each step. Since the motor-driven radiator fan was powered by the load bank, its load is included in the genset and load bank loads.

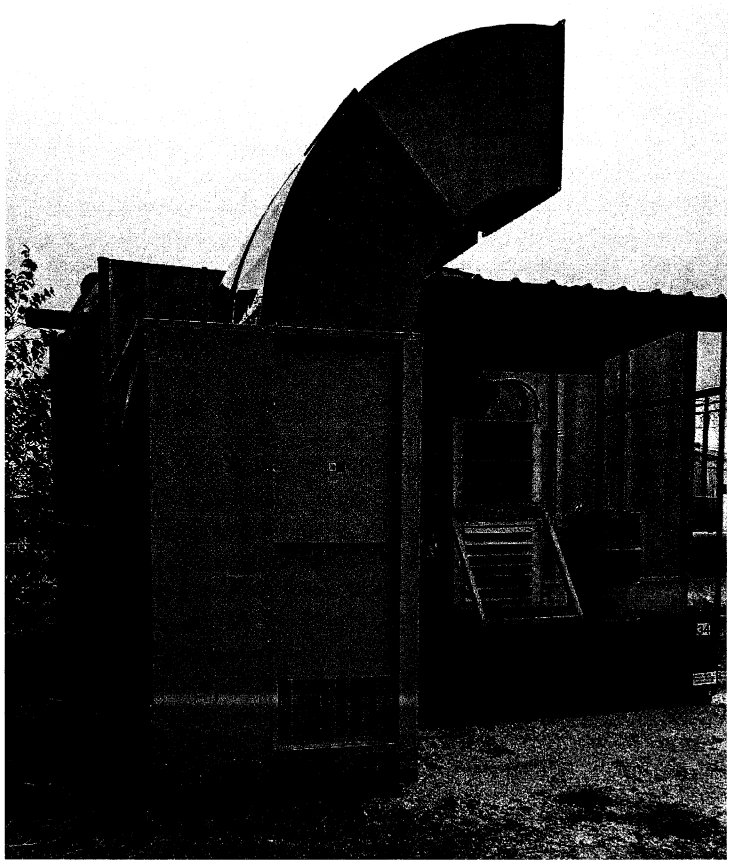

Figure 5-9. Load Bank

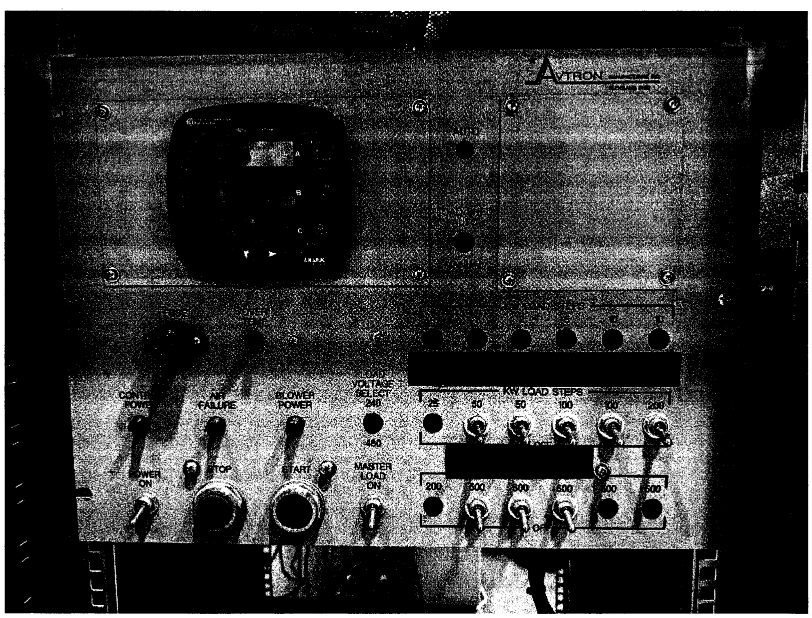

Figure 5-10. Load Bank Control Panel

Baseline Test

Clock Time (complete based on test start)	Test Time (hrs)	Target Load (kWe)	Load Bank Switches "ON"	Expected Load (kWe)	Load Delta (kWe)	Expected Genset Speed (rpm)
0858	0 – 12	666	A + C + F	674.6	+ 8.6	1775
0851 ~~0852~~	12 – 14	666	A + C + F	674.6	+ 8.6	1775
1051	14 – 18	593	C + F	626.7	+ 33.7	1779
1451	18 – 22	570	A + F	579.2	+ 9.2	1783
1851	22 – 24	511	F	531.5	+ 20.5	1791

Diluted Lube Oil Test

Clock Time (complete based on test start)	Test Time (hrs)	Target Load (kWe)	Load Bank Switches "ON"	Expected Load (kWe)	Load Delta (kWe)	Expected Genset Speed (rpm)
~~0711~~ 0712	0 – 2	666	A + C + F	674.6	+ 8.6	1775
0912	2 – 6	593	C + F	626.7	+ 33.7	1779
1312	6 – 10	570	A + F	579 2	+ 9.2	1783
1712	10 – End	511	F	531.5	+ 20.5	1791

Figure 5-11. Load Bank Switches and Test Genset Load Steps

5.7. FO Supply

The FO supply system for the test genset (i.e., FO burned by the engine) consisted of a 550-gallon metal tote located outside of the Back Shop. Hoses were run from the tote to the test engine for FO supply and from the engine to the tote for FO return (i.e., FO delivered to the engine by the engine-driven FO pump but not consumed by the engine).

A pneumatically-controlled isolation valve was installed at the outlet of the tote as an emergency FO shut-off. The valve required air to open, and shop air was supplied through plastic tubing run from the test control room under the test genset to the FO tote outside of the Back Shop. An air shut-off valve was located inside the test control room and would have been used to remotely isolate the FO supply to the test engine in the event of an engine failure.

Constellation provided approximately 2,500 gallons of FO for the test. The FO was received at SwRI and stored in clean 550-gallon metal totes (separate from the tote used to supply FO to the test engine). The Constellation-provided FO was used for the first baseline test and the diluted LO test but concerns about the volume of FO being consumed during break-in and troubleshooting led to locally-sourced FO being used for the second baseline test. The FO system was purged of the locally-sourced FO prior to the start of the diluted LO test.

5.8. Cameras

Two camera systems were used to monitor the test. SwRI installed four Reolink security cameras that could be monitored in real-time, including over the internet, but only recorded when motion was sensed. MPR provided a network video recorder and four cameras that recorded continuously during the diluted LO test. Both sets of cameras were monitored from the test control room throughout the test. The cameras provided general overviews of the test genset as well as views of the test engine and test generator gauges.

6.0 Test Results

The results of the testing performed by MPR and SwRI are summarized in the following sections. Where appropriate, specific test results are compared to the requirements of MPR Test Plan 4104-0031-OTHR-001, Revision 0 (Reference 9).

6.1. Pre-Test Engine Inspection

As required by the test plan, a pre-test inspection of select engine components was performed as part of the commissioning activities for the test setup. The purpose of the inspection was two-fold. First, the inspection would provide a representative assessment of the overall condition of the engine. Second, the inspection would provide a baseline condition for specific components for direct comparison after the diluted LO test to determine what damage, if any, occurred during the test. Table 5-7 of Reference 3 recommends that lower main bearings #2 and #7 are inspected for damage if a high FO concentration (> 2.5 vol.%) in the engine's LO is identified. If damage to these main bearings is observed, then the replacement of all main bearings is required. Based on this recommendation, the lower main bearings #2 and #7 were removed from the test engine for inspection. Two adjacent lower main bearings, #3 and #6, were also inspected to increase the value of the inspection.

Figure 6-1 shows photographs of lower main bearings #2, #3, #6, and #7 after removal. All four bearings are in good condition and only show minor wear and a few shallow particulate scores, both of which are normal and consistent for the bearings' service time (assumed to be approximately 1,450 hours based on the genset control panel hour meter). Based on these inspection results, it was assumed that the remainder of the main bearings, as well as the other engine/turbocharger bearings and bushings not inspected, were in similar good condition.

The inspected main bearings were reinstalled and used for the baseline and diluted LO tests discussed in Section 6.2 and Section 6.3, respectively.

6.2. Baseline Test

As required by the test plan, a baseline test was performed to demonstrate that the test engine could operate reliably at the required genset loads for a cumulative period of 24 hours under normal engine LO conditions (i.e., no significant FO dilution of the LO). Data recorded during the test were used to generate a baseline for each test parameter; these baselines are plotted and discussed in Section 6.2.2 through 6.2.9. In Section 6.3, the results of the diluted LO test are directly compared with the baselines to determine how and to what extent(s) the FO contamination of the engine LO affected engine performance.

As permitted by the test plan, the baseline test was performed over two sessions. The first test session, which covered the first 12 hours of the test, started at 08:55:48 and ended at 21:02:00 on December 9, 2023 (the total test session duration was 12.10 hr). The second test session, which covered the second 12 hours of the test, started at 08:48:48 and ended at 20:53:06 on December 12, 2023 (the total test session duration was 12.07 hr).

Detailed results for the baseline test are documented in the following sections.

6.2.1. Initial Test Conditions

Table 6-1 compares the initial test conditions for the baseline test (both sessions) with the requirements of the test plan. In summary, all initial test conditions satisfied the requirements of the test plan (see Table 6-1, Note 4 regarding engine sump LO level).

Table 6-1. Baseline Test Initial Conditions

Test Parameter	Initial Condition, Baseline Test Hours 0-12	Initial Condition, Baseline Test Hours 13-24	Test Plan Requirement
Engine LO FO Concentration (wt.%)	< 0.3	< 0.3	No FO (above trace levels) [1]
Engine LO Temperature (°F) [2]	143.5	63.9	≥ 40
Engine Coolant Temperature (°F) [2]	113.2	65.5	≥ 40
Engine Intake Air Temperature (°F) [2,3]	71.6	53.4	≥ 40
Engine Sump LO Level	~ 0.25 in above high-level mark	~ 0.33 in below high-level mark	At high-level mark on engine dipstick [4]

1. Trace level is considered to be below the repeatability limit for the ASTM D3524 test (i.e., < 0.3 wt.% FO).
2. The first baseline test session was immediately preceded by a short run to confirm proper operation of the test genset prior to the start of the test. This prior run explains the higher initial engine LO, engine coolant, and engine intake air temperatures for the first baseline test session.
3. The test plan required that the temperature in the immediate vicinity of the test genset shall be ≥ 40°F. The temperature of the intake air, measured at one of the engine's four air filters, was used as a surrogate.
4. The high-level mark on the dipstick is located approximately 2 in above the low-level mark. Given the spacing between the marks and the volume of oil that it represents (approximately 9 gal), MPR considers that a LO level within 0.33 in of the high-level mark meets the intent of the test plan requirement.

(Note that the test plan required the use of qualified FO provided by Constellation for combustion during both the baseline and diluted LO tests. Qualified FO was used for the first baseline test session and also for the diluted LO test; however, FO provided by SwRI was used for the second baseline test session. As discussed in Section 6.2.2, troubleshooting operation of the test genset was required between the first and second baseline test sessions as part of resolving an engine electronic governor issue. The troubleshooting and second baseline test session were performed using the SwRI FO to conserve the qualified FO and ensure there was a sufficient volume remaining for the full duration of the diluted LO test. MPR considers that the use of the SwRI FO for the second baseline test session did not impact or compromise the results of the baseline test. The SwRI FO was purged from the engine prior to the diluted LO test.)

6.2.2. Genset Speed

Figure 6-2 shows genset speed plotted as a function of elapsed time for the baseline test.[4] The test plan required that genset speed be maintained within the band of 1,800 ± 36 rpm (± 2%). As shown, genset speed met the test plan requirement for the full test duration.

Genset speed was on average lower and varied more during the first 12-hour session than the second 12-hour session. The variability in speed during the first session was indicative of a problem with the engine's electronic governor (specifically the governor's droop setting). This behavior worsened after the completion of the first session and prompted the replacement and tuning of the electronic governor prior to the second baseline test session. Genset speed was on average higher and more consistent during the second baseline test session using the replacement electronic governor. A small amount of speed droop occurred at the start of the second baseline test session (i.e., when the generator load was highest); this was eliminated by a minor adjustment of the governor's droop setting after the second baseline test session was completed. MPR considers that the variations in speed are minor, and they have no impact on the validity or significance of the baseline test.

6.2.3. Generator Load

Figure 6-3 shows generator load plotted as a function of elapsed time for the baseline test. The test plan required that the load during the first 12-hour session meet or exceed the peak test load (666 kWe) for the full session duration. The test plan further required that the loads during the second 12-hour session meet or exceed the loads of the accident profile for the 2B AF engine (i.e., the load stepped downward as time progressed). As shown, generator load exceeded the minimum required test plan loads at all times during the baseline test.

Figure 6-4 shows generator load plotted as a function of elapsed time at the start of both baseline test sessions. The test plan required that the peak test load be reached within 55 sec after the start of the test (this is consistent with the loading requirement for the Braidwood 2B AF pump engine per Reference 17). Load was first applied approximately 30 sec after the start of both baseline test sessions. The peak test load was reached approximately 132 sec after the start of the first 12-hour session, and approximately 120 sec after the start of the second 12-hour session. The delay in applying load and reaching the peak test load was an unanticipated limitation of the

[4] During both the baseline and diluted LO tests, test parameters were recorded by the data acquisition system every 6 seconds per the test plan. Approximately 15,000 data points were recorded for each parameter over the full duration of the two tests. For clarity, Figure 6-2 and similar figures containing plots for a full test duration include data points at 5-minute intervals (i.e., only every 50th data point is plotted).

test setup. Specifically, increasing the generator load required multiple steps to be completed in the proper sequence, including: (1) energizing the engine radiator fan (which was powered by the test genset), (2) energizing the generator load bank controls, and (3) energizing the individual load bank resistor circuits in a prescribed order. The intent of the test plan requirement was to ensure that transient loading of lubricated engine/turbocharger components occurred during the test. The pump load on the 2B AF engine increases progressively as pump speed and flow rate increase, with the full load being reached within 55 sec. The individual resistor circuits of the load bank used for the baseline test sessions are either energized or de-energized. The energizing of the load bank circuits to increase load resulted in step increases in load instead of a progressive increase. Although the peak test load was not reached within the required time, the step loading that occurred during testing ensured that transient loading of components occurred. Based on this, MPR considers that the intent of the test plan requirement for load addition was satisfied during the baseline test.

6.2.4. Engine LO Pressure

The test plan required that the LO pressure be ≥ 65 psig for the full test duration. The test plan requirement was taken from Section 11.3.1 of Reference 3, which states the following: "Pressure should not fall below 450 kPa (65 lb/in.^{2}) at 1800 r/min. Normal operation pressure should be higher." Subsequently, further evaluation identified that Table 11-3 through Table 11-18 of from Reference 3 provide specific operating conditions for different engine configurations. Table 11-4 contains the operating conditions for 12-cylinder turbocharged engines with no intercooler (i.e., the specific configuration of the test engine). The table states that the normal range of engine LO pressure is 45-70 psig. The test plan should have identified this range as the requirement for the baseline test.

Figure 6-5 and Figure 6-6 show engine LO pressure plotted as a function of elapsed time for the baseline test. As shown in the figures, LO pressure was steady and consistent during both baseline test sessions (in Figure 6-6, the slight decreasing and increasing trends were due to the change in ambient temperature during the test). The average LO pressure was 56.1 psig during the first baseline test session and 57.4 psig during the second session. The pressure only exceeded 65 psig for a short time immediately after engine start when the LO was cold. Overall, the LO pressures did <u>not</u> meet the test plan requirement of > 65 psig during either baseline test session. However, the LO pressures were always within the manufacturer's normal range, and they significantly exceeded the 2B AF engine low LO pressure trip setpoint of 10 psig.

6.2.5. Engine LO Temperature

Figure 6-7 and Figure 6-8 show engine LO temperature plotted as a function of elapsed time for the baseline test. The test plan required that the LO temperature be ≤ 230°F for the full test duration. As shown in the figures, LO temperature was steady and consistent during both baseline test sessions (in Figure 6-8, the slight increasing and decreasing trends were due to the change in ambient temperature during the test). The average LO temperature was 213°F during the first baseline test session and 208°F during the second session. LO temperature did not exceed 230°F at any point during either test session. Overall, the LO temperatures satisfied the test plan requirement during both baseline test sessions.

6.2.6. Engine Coolant Temperature

Figure 6-9 and Figure 6-10 show engine coolant temperature plotted as a function of elapsed time for the baseline test. The test plan required that the coolant temperature be between 160°F and 185°F for the full test duration. As shown in the figures, coolant temperature was steady and consistent during both baseline test sessions (in Figure 6-10, the slight increasing and decreasing trends were due to the change in ambient temperature during the test). The average coolant temperature was 170°F during the first baseline test session and 168°F during the second session. Coolant temperature did not fall outside of the specified range at any point during either test session (after warm-up), and temperatures were always significantly below the 2B AF engine trip setpoint of 205°F. Overall, the coolant temperatures satisfied the test plan requirement during both baseline test sessions.

6.2.7. Engine Intake Air Temperature

Figure 6-11 shows engine intake air temperature plotted as a function of elapsed time for the baseline test. The test plan required that the intake air temperature be ≥ 40°F for the full test duration (see Note 3 of Table 6-1). As expected, there were slight increasing and decreasing trends in the intake air temperature due to the change in ambient temperature during the test. The average intake air temperature was 90°F during the first baseline test session and 86°F during the second session. Intake air temperature did not fall below 40°F at any point during either test session. Overall, the intake air temperatures satisfied the test plan requirement during both baseline test sessions.

6.2.8. Engine Crankcase Pressure

Figure 6-12 shows engine crankcase pressure plotted as a function of elapsed time for the baseline test. The test plan required that the engine crankcase be properly ventilated to mitigate excessive positive pressure; however, a specific limit or range for crankcase pressure was not specified. As shown in the figure, the crankcase pressure fluctuated slightly, but overall it was consistently positive at a low level during both baseline test sessions. The average crankcase pressure was 0.023 psig during the first baseline test session and 0.024 psig during the second session. The crankcase pressures were well below the Detroit Diesel crankcase pressure limit of 1.5 inH_2O (0.054 psig).

6.2.9. Engine FO Pressure

Figure 6-13 and Figure 6-14 show engine FO pressure plotted as a function of elapsed time for the baseline test. The test plan did not include a specific requirement for FO pressure; however, Table 11-4 of Reference 3 states that normal FO pressure is between 60 psig and 80 psig. As shown in the figures, FO pressure was steady and consistent during both baseline test sessions (in Figure 6-14, the slight decreasing and increasing trends were due to the change in ambient temperature during the test). The average FO pressure was 67 psig during both baseline test sessions. FO pressure did not fall outside of the normal range at any point during either test session.

6.2.10. Test Anomalies

No test anomalies occurred during the baseline test (other than the minor variations in genset speed, which did not impact the validity or significance of the test – see Section 6.2.2). Specifically, there were no adverse trends in any of the test parameters recorded. Further, no significant leaks of engine LO, FO, intake air, or exhaust gases occurred during the test.

6.2.11. Post-Test Engine Sump LO Level

The engine sump LO level was documented after the completion of the first baseline test session and compared with the pre-test level to determine the change in level during the test and the representative change in LO volume. The LO level was approximately 1 in below the high-level mark on the engine dipstick (i.e., approximately halfway between the high- and low-level marks) after the test session. Per Table 6-1, the LO level was approximately 0.25 in above the high-level mark prior to the test session. The LO level dropped by approximately 1.25 in, which represents an approximate 5.5 gal decrease in LO volume over the 12-hour test session (i.e., slightly less than 0.5 gal/hr).

LO consumption (by combustion) is normal and expected during engine operation, in particular for a two-stroke engine of the test engine's configuration, size, and power rating. Significant LO leakage from the engine did not occur during the baseline test. Since there was no leak, the full volume of LO lost during the test can be attributed to consumption. LO consumption typically increases with engine load. The first baseline test session was performed at a constant load at the highest level of the test (673-680 kWe; see Figure 6-3). The engine's FO consumption rate exceeded 50 gal/hr at this load. Based on this, the LO consumption rate was slightly less than 1% of the FO consumption rate, which is typical and normal. LO consumption was not excessive during the first baseline test session.

6.2.12. Engine LO Sampling and Analyses

Per the test plan, engine LO samples were collected at four-hour intervals during both baseline test sessions and analyzed by SwRI. A total of eight samples, four from each baseline test session, were analyzed. Table 6-2 contains the results of the LO analyses. In summary:

- The viscosity of the LO remained within the range for an SAE 40 viscosity grade oil (12.5 to 16.3 cSt at 100°C, Reference 7) and did not change significantly during either baseline test session.
- None of the samples contained FO above a trace level (see Table 6-1, Note 1).
- Wear metals were consistent at either trace levels (aluminum, chromium, copper, lead, and tin) or a normal level (iron).

The analysis results support that LO quality was good and remained consistent for the full duration of the baseline test. The results also support that no significant wear or other damage to any lubricated surfaces in the engine and turbochargers occurred during the baseline test.

6.2.13. Baseline Test Results Summary

The baseline test confirmed that the test engine could operate reliably at the required loads for a cumulative period of 24 hours under normal engine LO conditions. The test engine operated and performed normally without any unexpected behavior or adverse trends. The test genset, including all existing and added instrumentation, operated as expected and according to the requirements of the test plan for the full test duration. No known damage to any engine components occurred during the test.

MPR considers that the baseline test was successful, and specifically that the test results represent an appropriate baseline for comparison with the results of the diluted LO test.

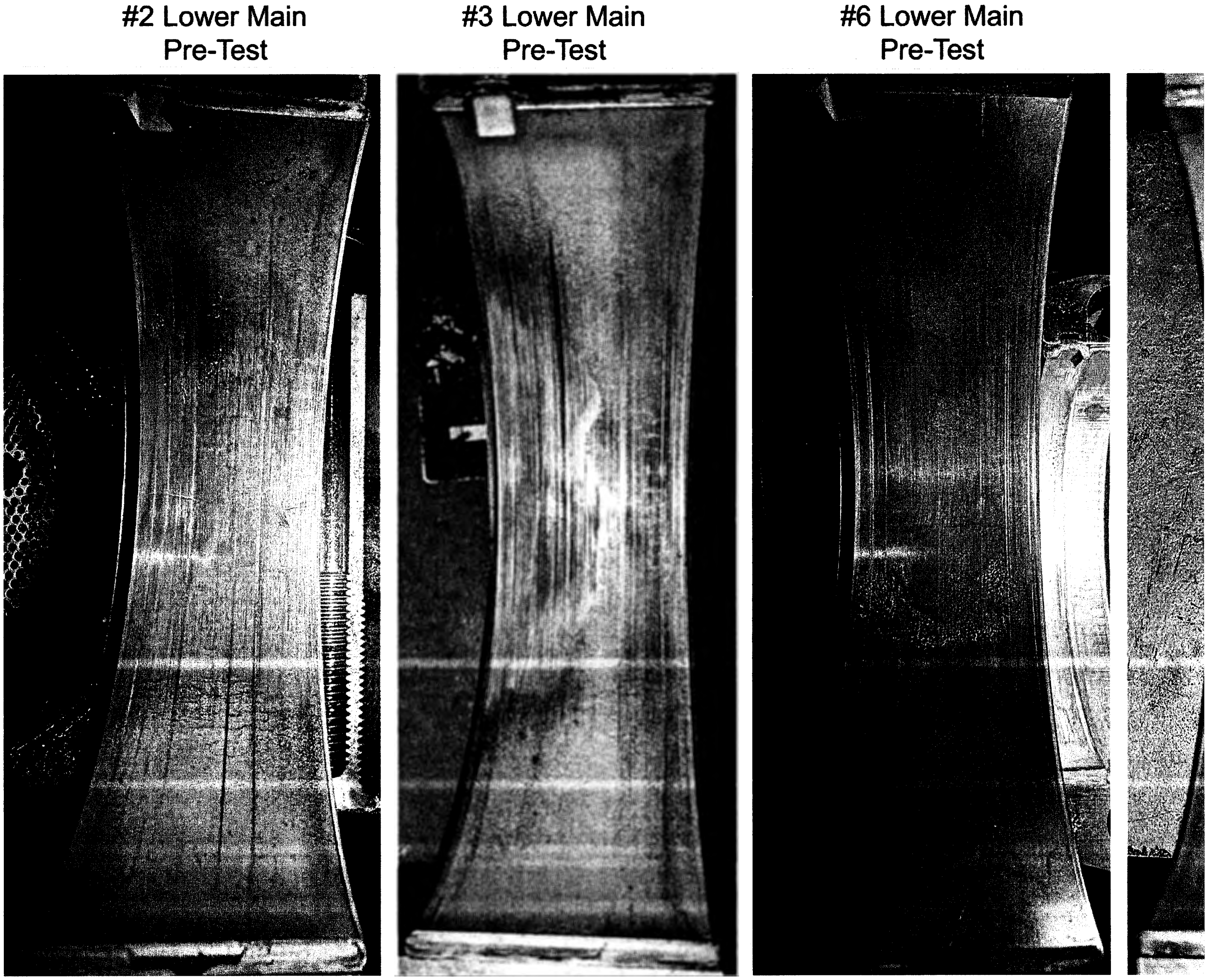

Figure 6-1. Pre-Test Inspection Results for Engine Lower Main Bearings #2, #3, #6, ar

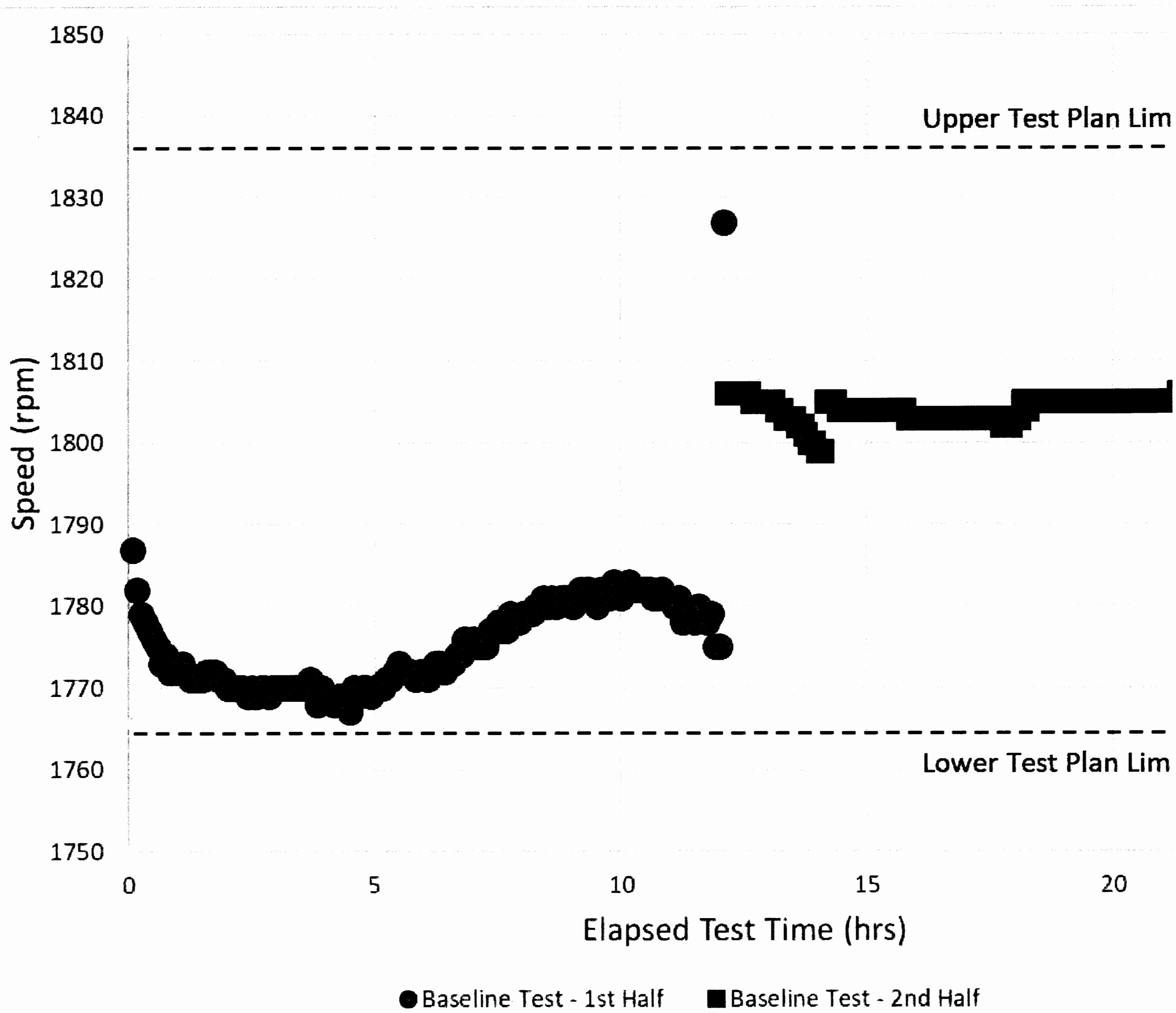

Figure 6-2. Baseline Test – Genset Speed vs. Elapsed Test Time

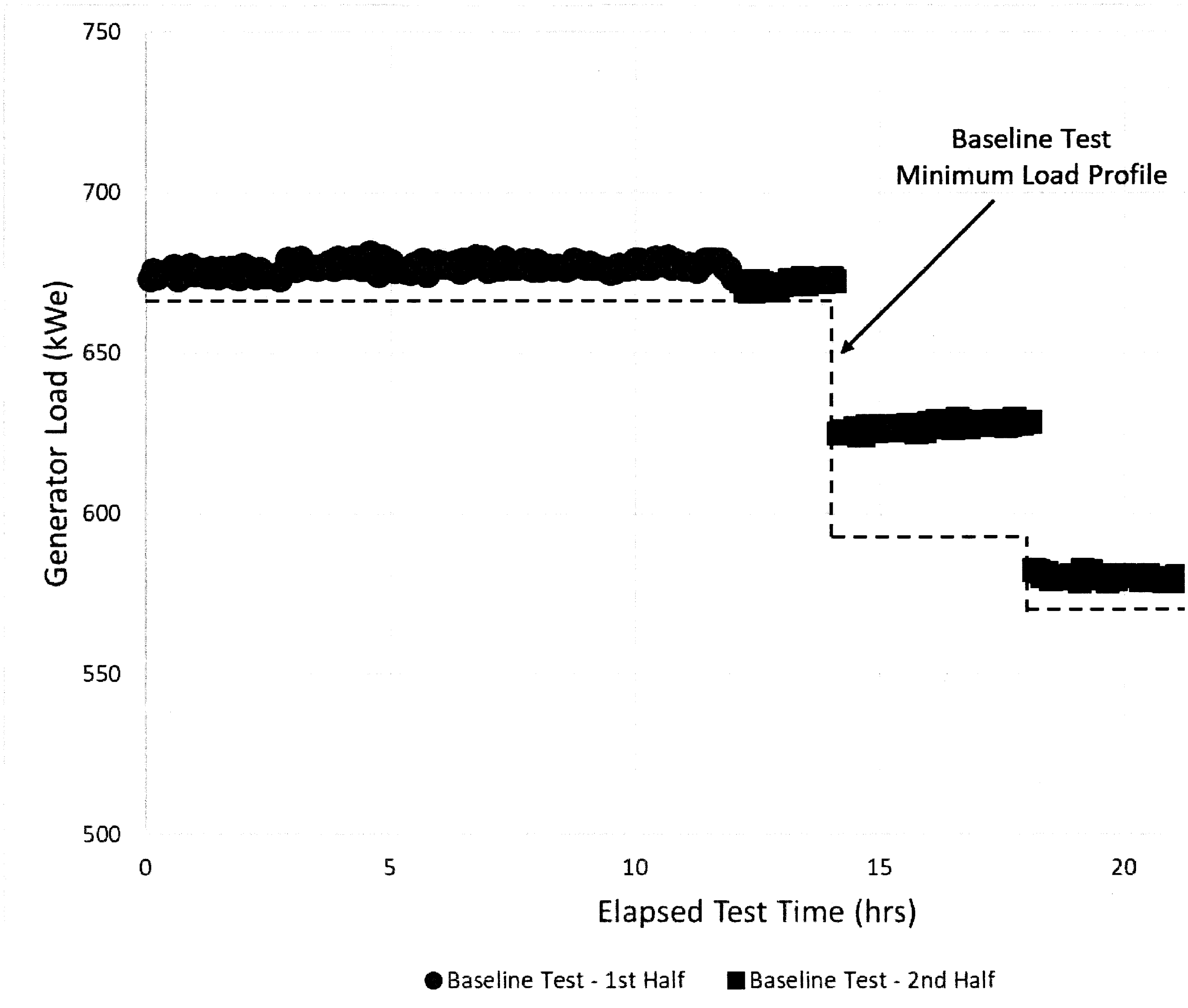

Figure 6-3. Baseline Test – Generator Load vs. Elapsed Test Time

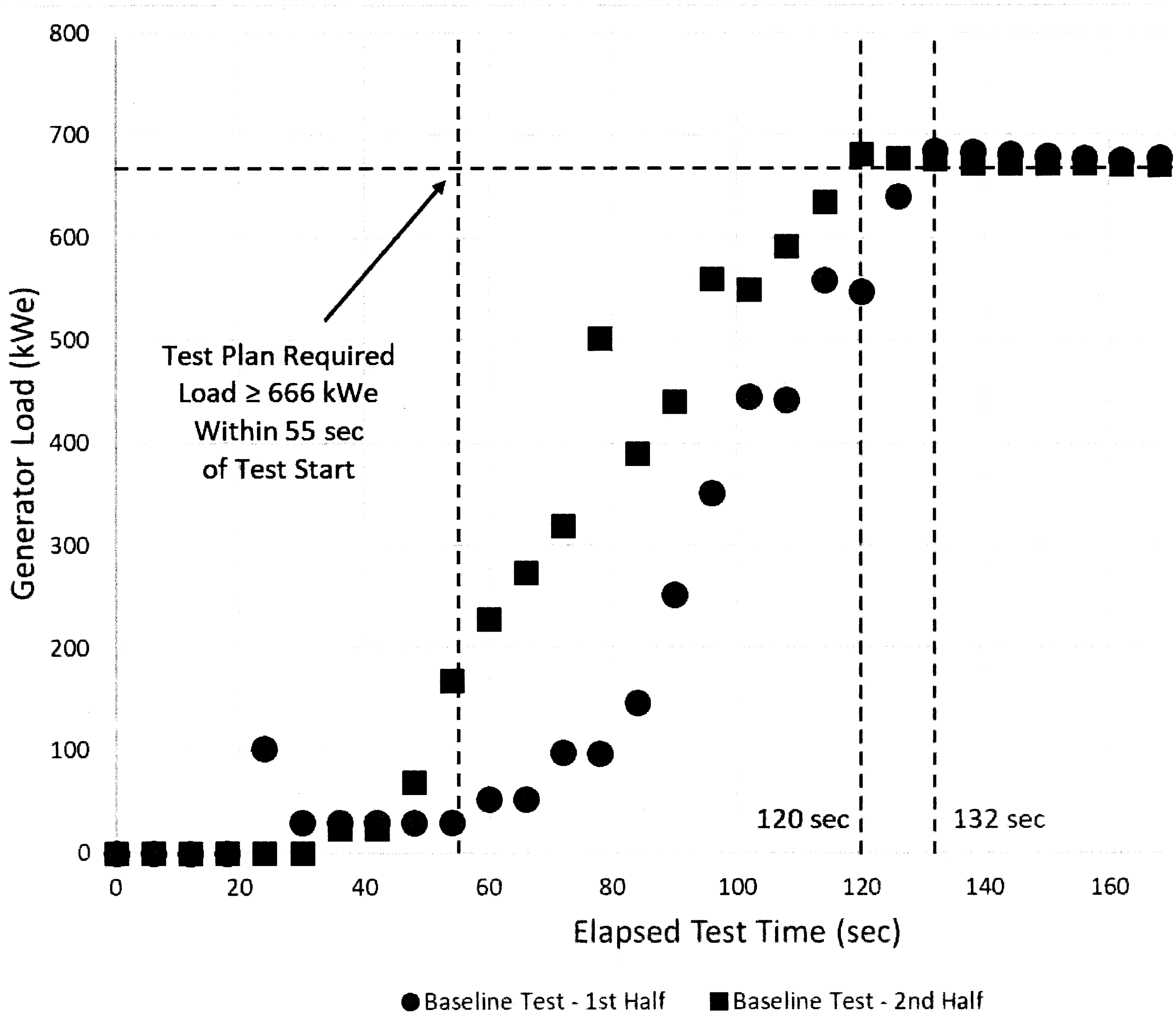

Figure 6-4. Baseline Test – Generator Load vs. Elapsed Test Time at Test Start

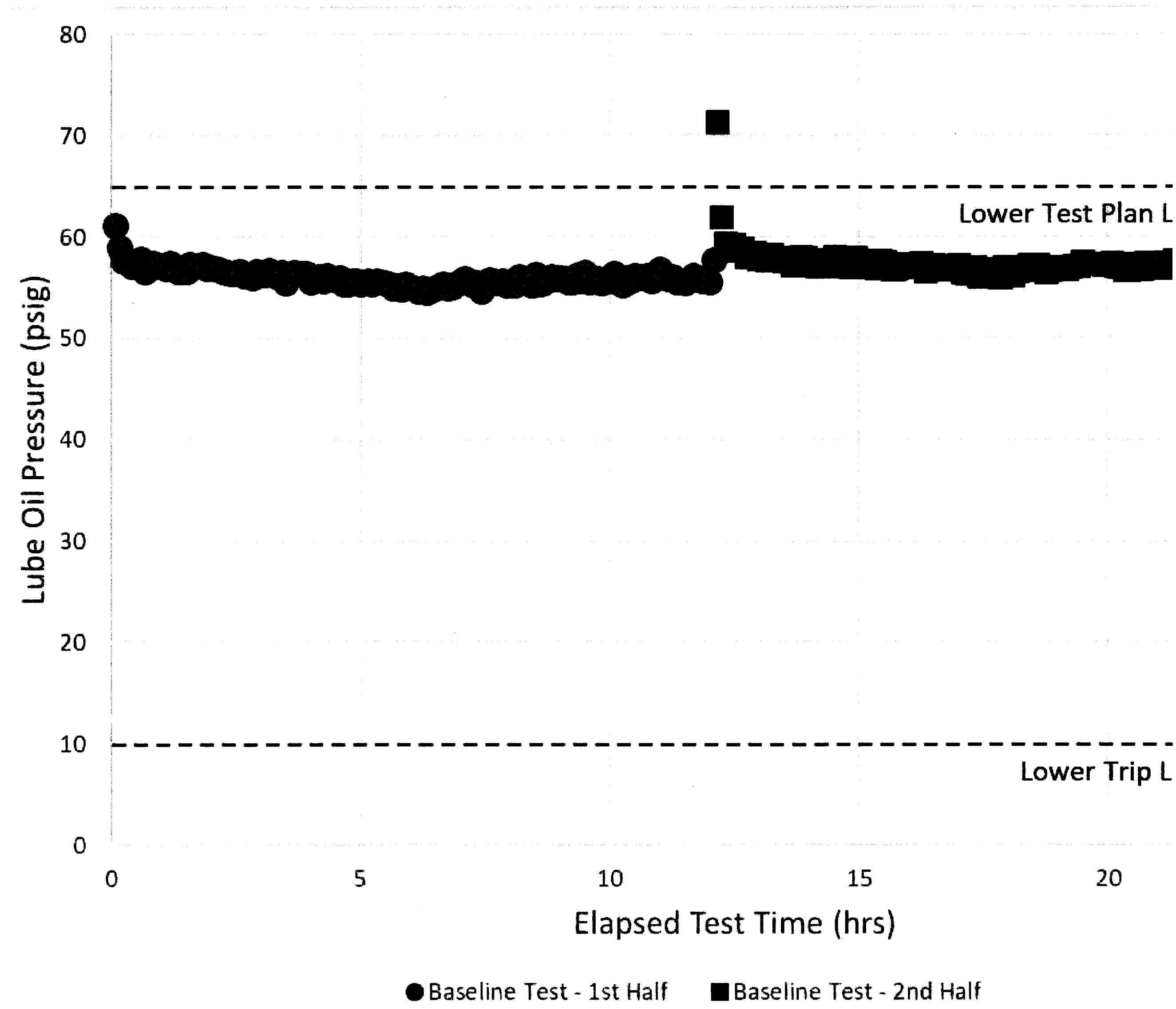

Figure 6-5. Baseline Test – Engine LO Pressure vs. Elapsed Test Time

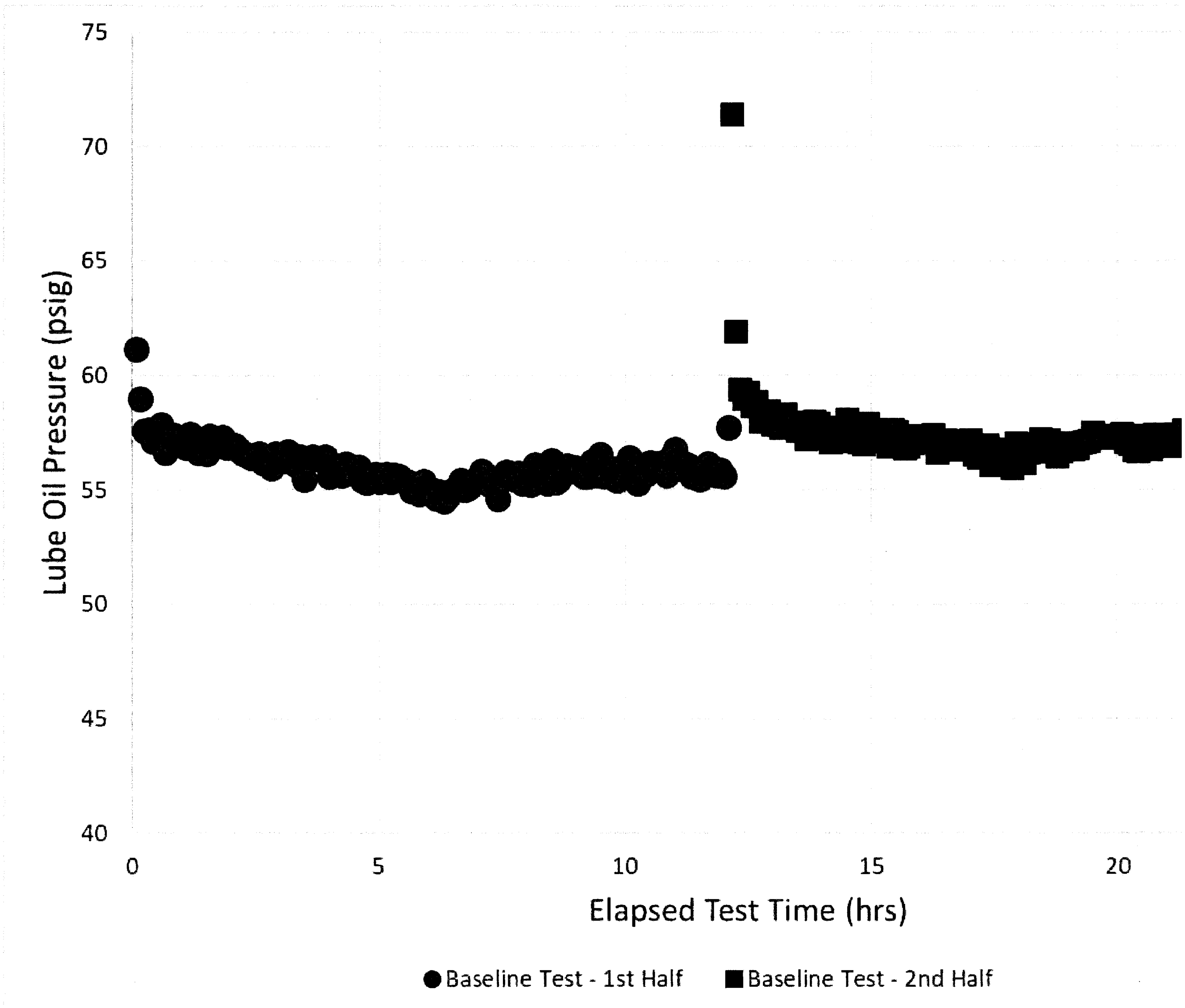

Figure 6-6. Baseline Test – Engine LO Pressure vs. Elapsed Test Time

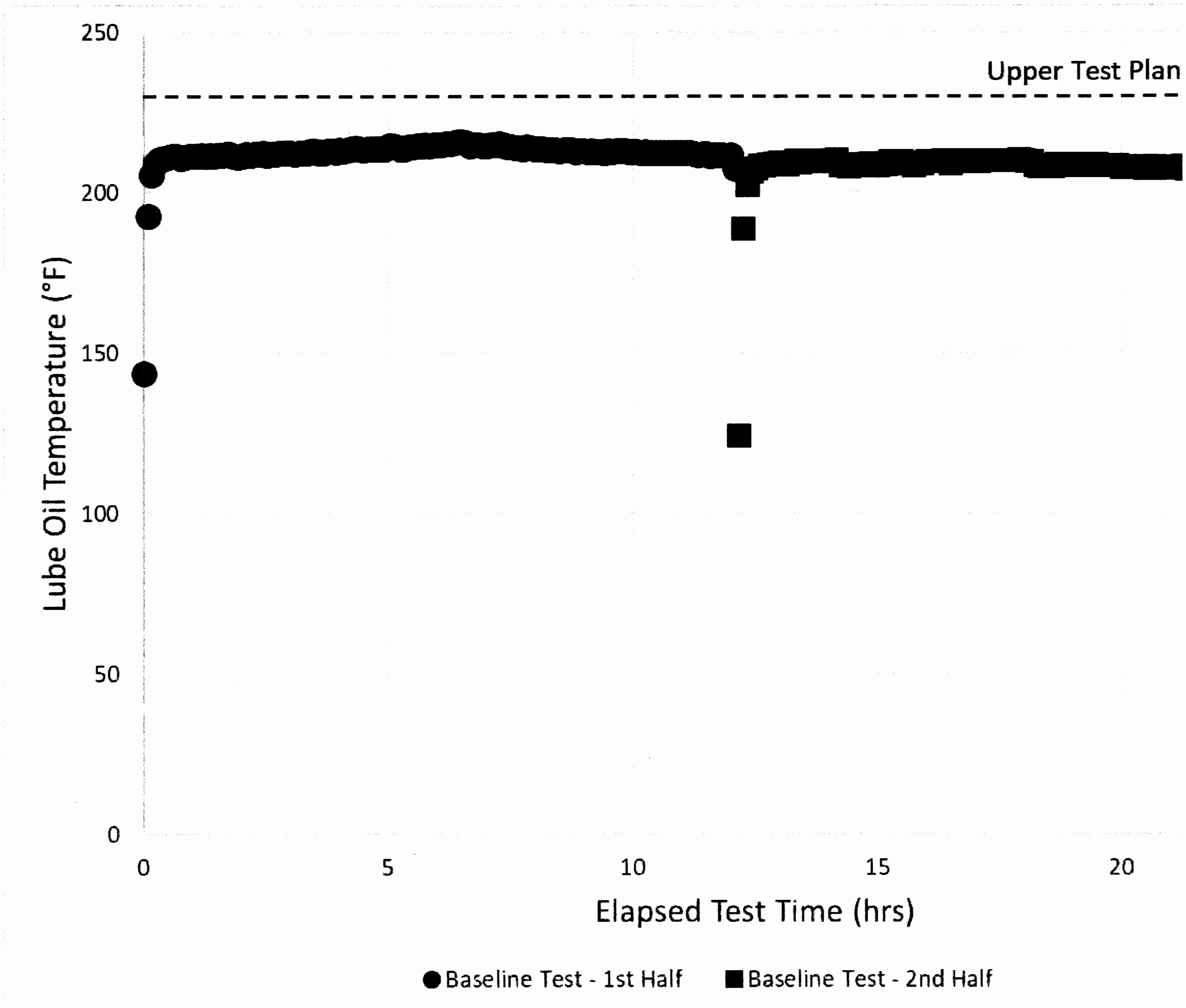

Figure 6-7. Baseline Test – Engine LO Temperature vs. Elapsed Test Time

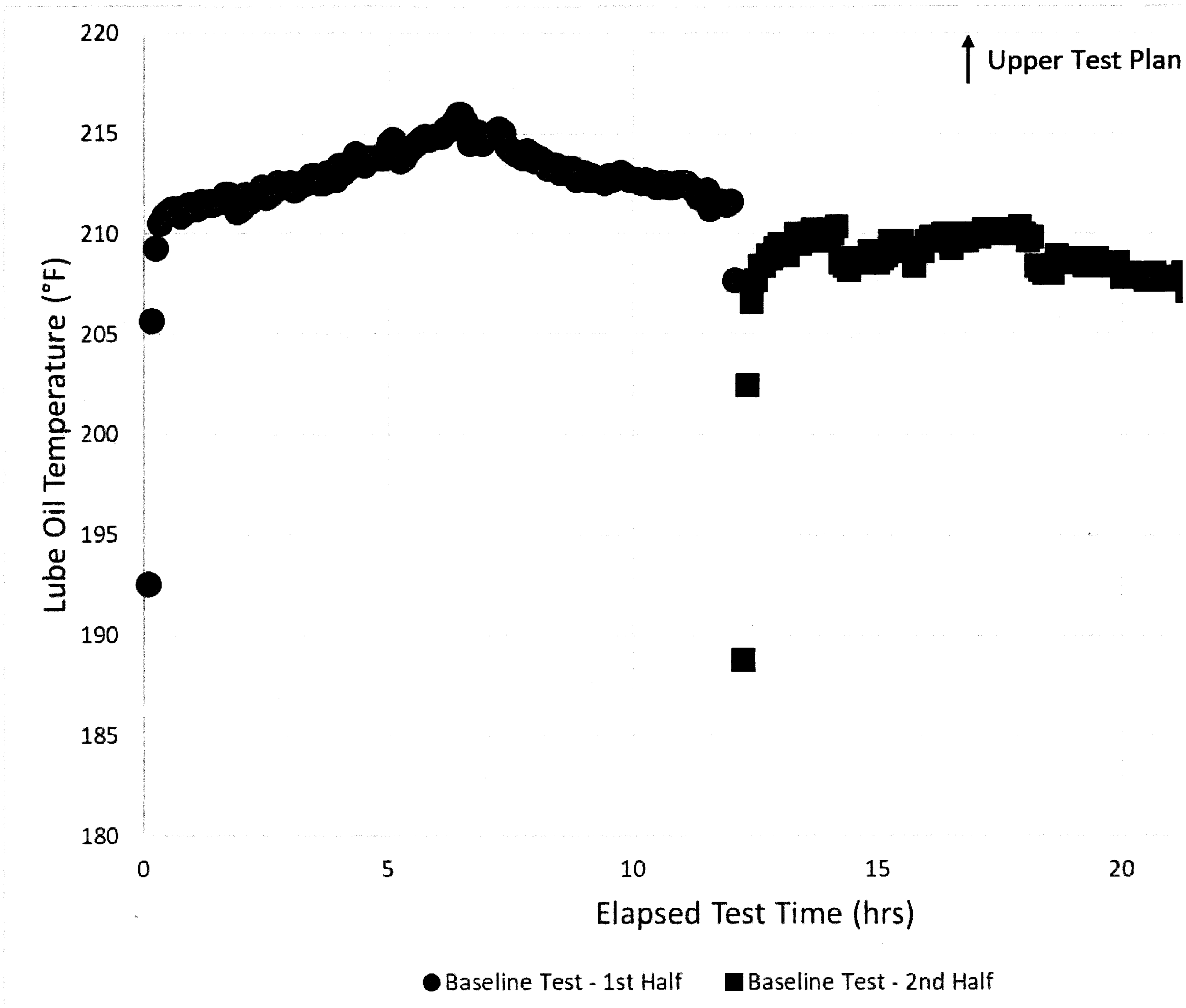

Figure 6-8. Baseline Test – Engine LO Temperature vs. Elapsed Test Time

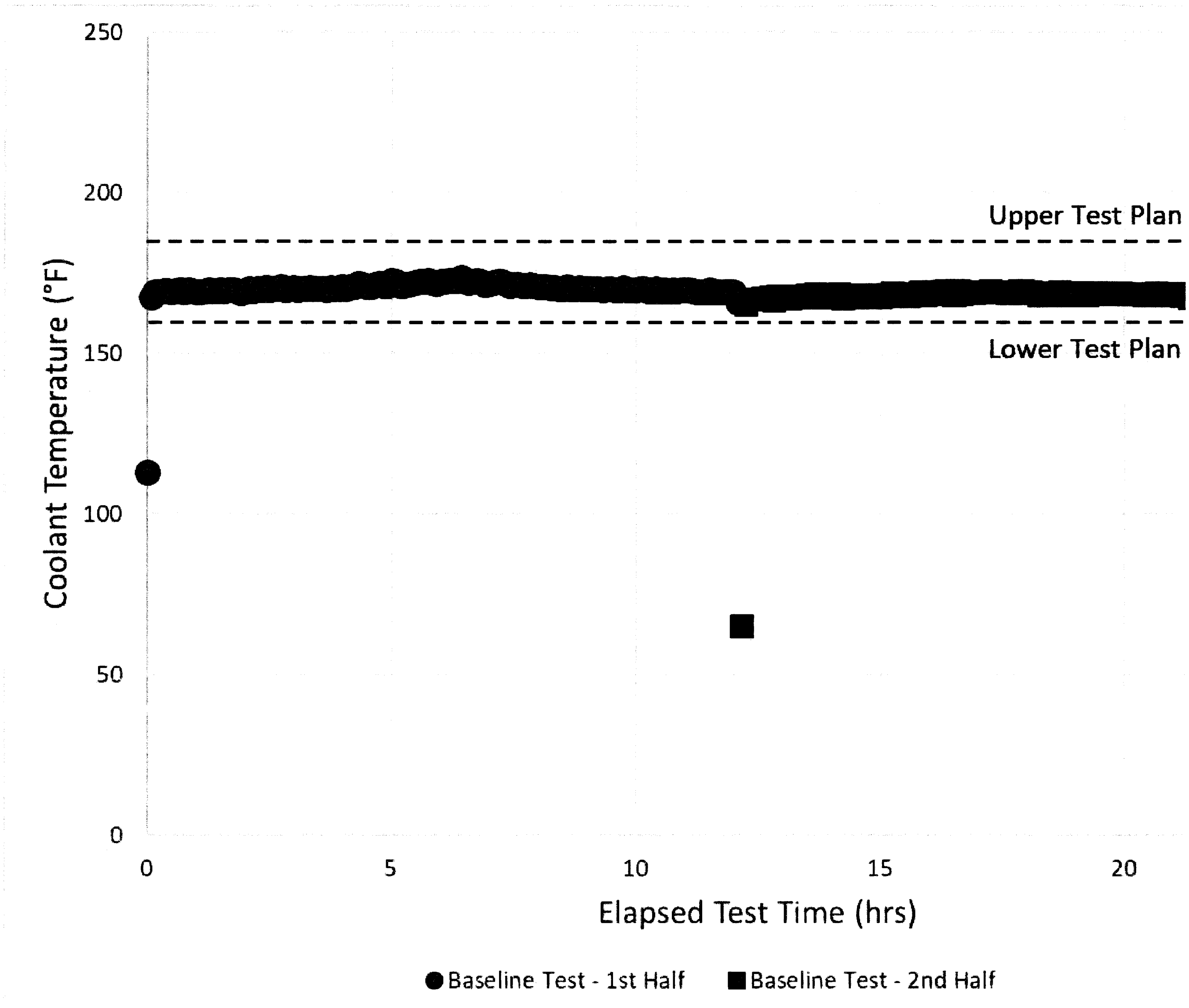

Figure 6-9. Baseline Test – Engine Coolant Temperature vs. Elapsed Test Time

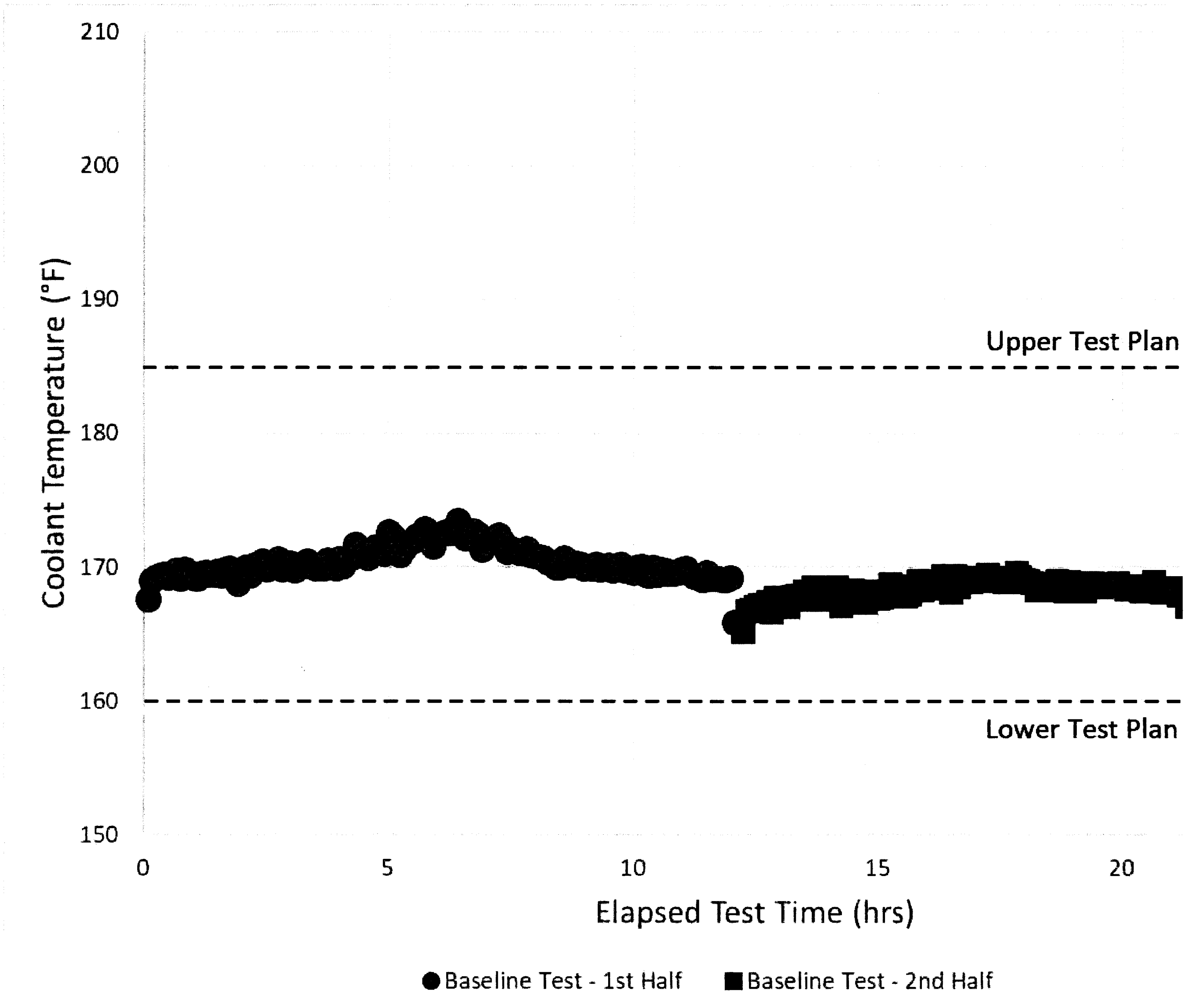

Figure 6-10. Baseline Test – Engine Coolant Temperature vs. Elapsed Test Time

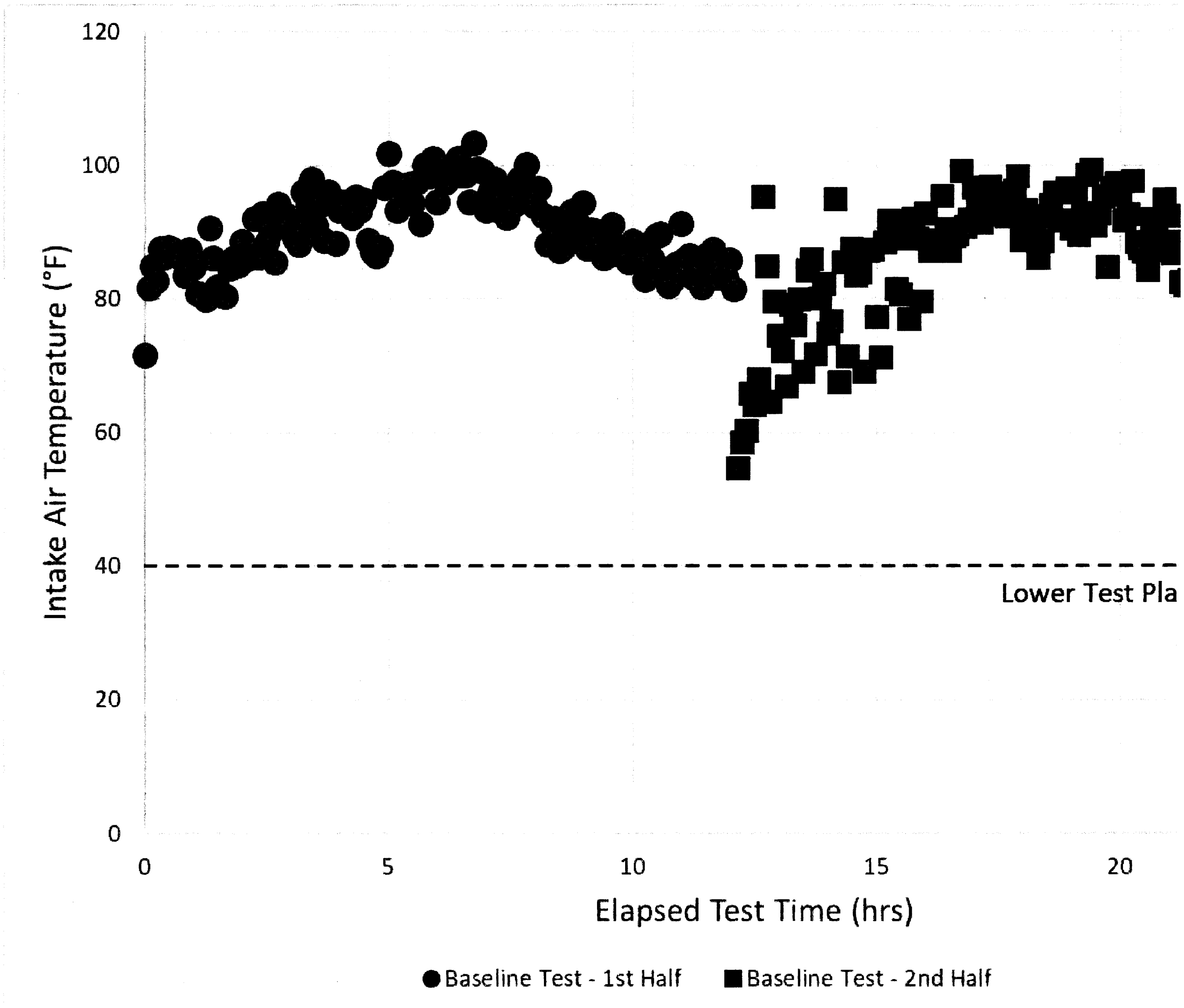

Figure 6-11. Baseline Test – Engine Intake Air Temperature vs. Elapsed Test Time

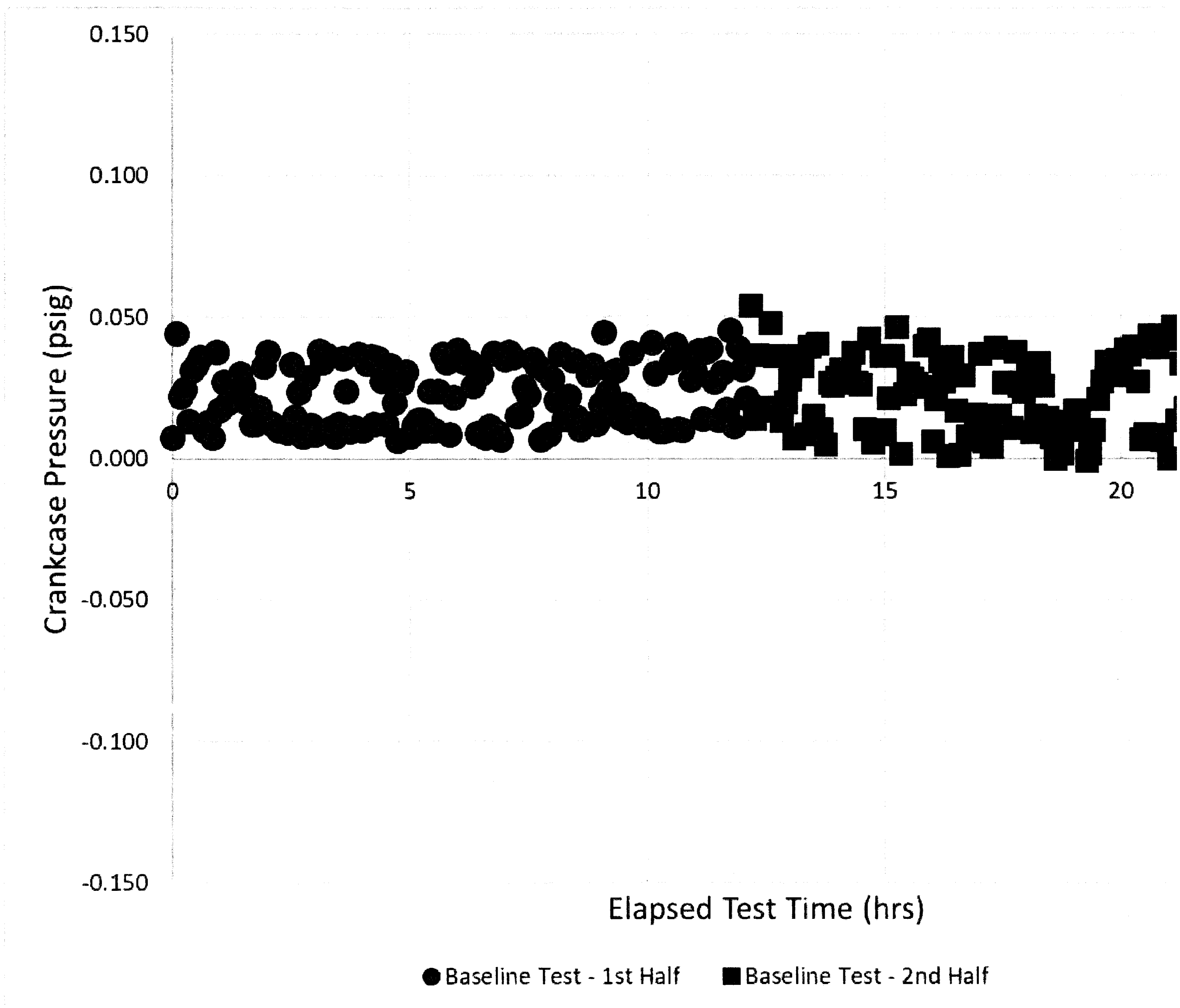

Figure 6-12. Baseline Test – Engine Crankcase Pressure vs. Elapsed Test Time

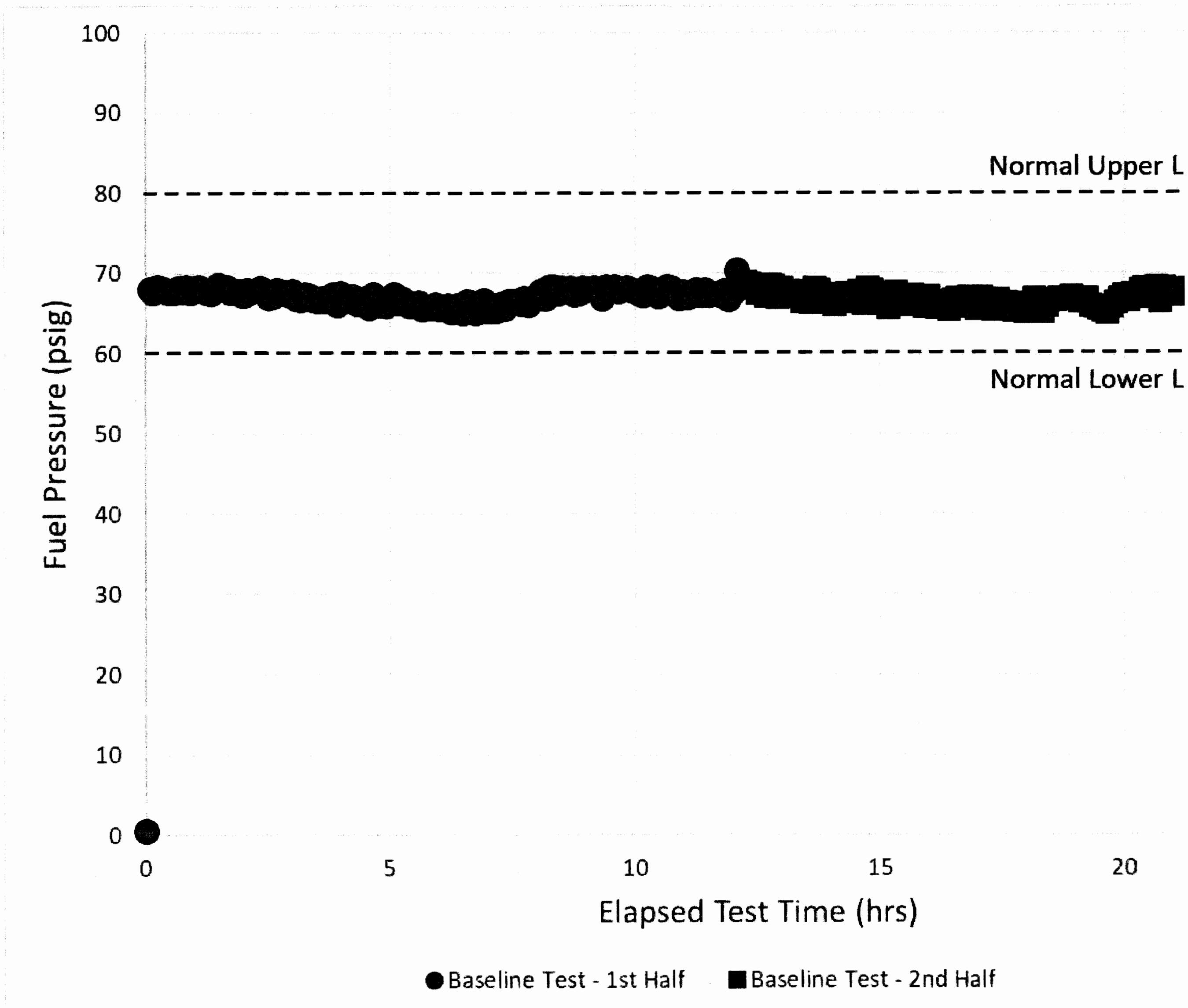

Figure 6-13. Baseline Test – Engine FO Pressure vs. Elapsed Test Time

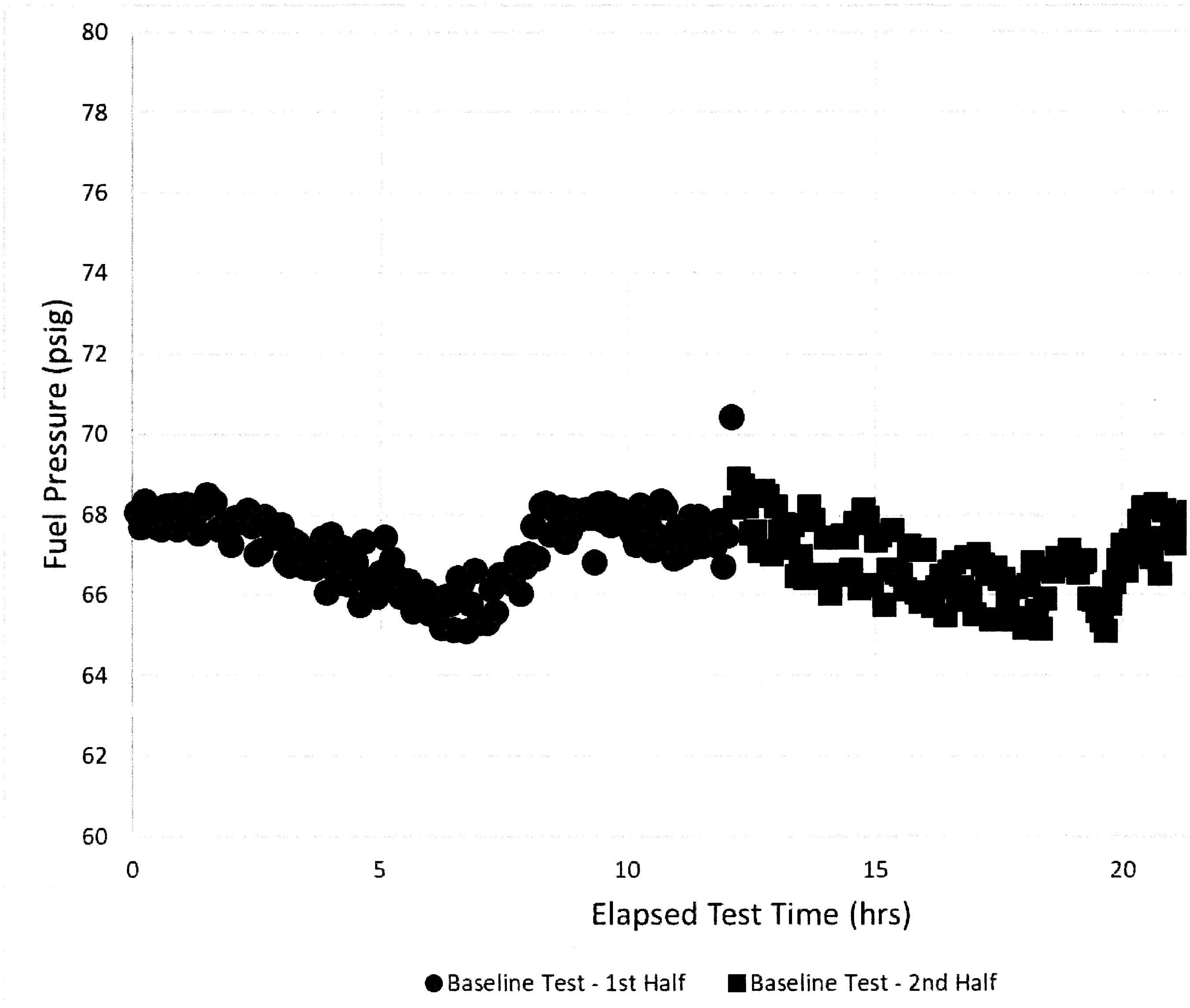

Figure 6-14. Baseline Test – Engine FO Pressure vs. Elapsed Test Time

Table 6-2. Baseline Test Engine LO Sample Analysis Results

Engine LO Sample	ASTM D3524 FO Concentration (wt.%)	ASTM D445 Viscosity, 40°C (cSt)	ASTM D445 Viscosity, 100°C (cSt)	ASTM D5185 Aluminum (ppm)	ASTM D5185 Chromium (ppm)	ASTM D5185 Copper (ppm)
Baseline Test, First Session, Shortly After Test Start	< 0.3	132.6926	14.4073	< 1	< 1	< 1
Baseline Test, First Session, ~4 Hours Elapsed	< 0.3	130.8851	14.4199	< 1	< 1	< 1
Baseline Test, First Session, ~8 Hours Elapsed	< 0.3	130.2231	14.3259	< 1	< 1	< 1
Baseline Test, First Session, ~12 Hours Elapsed	< 0.3	129.4832	14.2278	< 1	1	< 1
Baseline Test, Second Session, Shortly After Test Start	< 0.3	128.9022	14.2067	< 1	1	< 1
Baseline Test, Second Session, ~4 Hours Elapsed	< 0.3	128.6267	14.1590	< 1	1	< 1
Baseline Test, Second Session, ~8 Hours Elapsed	< 0.3	128.5886	14.1525	< 1	1	< 1
Baseline Test, Second Session, ~12 Hours Elapsed	< 0.3	128.6771	14.1715	< 1	1	2

6.3. Diluted LO Test

Following the baseline test, a diluted LO test was performed to determine the impact of an elevated and increasing FO concentration in the engine LO on the test engine's operation and performance. The diluted LO test started at 07:09:12 on December 14, 2023, and ended at 07:43:54 on December 15, 2023 (the total test duration was 24.58 hr; the test engine was loaded for 24.50 hr). Data recorded during the test are plotted and discussed in Section 6.3.2 through 6.3.12, and specifically are directly compared with the baseline test data of the same type.

Detailed results for the diluted LO test are documented in the following sections. In the plots of the diluted LO test results (Figure 6-15 through Figure 6-27), the corresponding results for the baseline test sessions are also included for direct comparison with the diluted LO test results.

6.3.1. Initial Test Conditions

Table 6-3 compares the initial test conditions for the diluted LO test with the requirements of the test plan. In summary, all initial test conditions satisfied the requirements of the test plan, except for the initial FO concentration (see Section 6.5).

Table 6-3. Diluted LO Test Initial Conditions

Test Parameter	Diluted LO Test	Test Plan Requirement
Engine LO FO Concentration (wt.%)	15.1	18.2
Engine LO/FO Mixture Temperature (°F)	59.7	40 - 127
Engine Coolant Temperature (°F)	55.3	40 - 127
Engine Intake Air Temperature (°F) [1]	54.6	≥ 40
Engine Sump LO/FO Mixture Level	~ 2 in above high-level mark on engine dipstick	Level consistent with 2B AF engine [2]
LO/FO Mixture Condition	Mixed [2]	Mixed

1. The test plan required that the temperature in the immediate vicinity of the test genset shall be ≥ 40°F. The temperature of the intake air, measured at one of the engine's four air filters, was used as a surrogate.
2. See Section 4.6.

6.3.2. FO Addition Rate

The test plan required that FO be added to the test engine at a rate of 1.09 gal/hr for the full duration of the diluted LO test. As discussed in Section 5.4, the FO addition system was calibrated to flow FO at the target rate. To confirm that this flow rate was maintained during the test, the weight of FO added to the engine was trended and used to calculate instantaneous and cumulative average flow rates. These trended rates identified that the cumulative average flow rate was at times too low or too high by a small amount. During the test, small adjustments to the pump duty cycle were made to increase/decrease the instantaneous flow rate such that the cumulative average flow rate met or exceeded the test plan requirement.

Per Reference 10, a total of 190.7 lb of FO was added to the test engine during the diluted LO test. This corresponds with a total volume of 26.8 gal of FO added to the engine. The cumulative average rate for the full diluted test was 1.09 gal/hr, which satisfied the test plan requirement.

6.3.3. Genset Speed

Figure 6-15 shows genset speed plotted as a function of elapsed time for the diluted LO test. The test plan required that genset speed be maintained within the band of 1,800 ± 36 rpm (± 2%), same as for the baseline test. As shown, genset speed was steady at approximately 1,805 rpm for the full test duration (i.e., the test plan requirement was satisfied).

6.3.4. Generator Load

Figure 6-16 shows generator load plotted as a function of elapsed time for the diluted LO test. The test plan required that the load meet or exceed the loads of the accident profile for the 2B AF engine (i.e., the load stepped downward as time progressed) at the start of the test, and thereafter meet or exceed the lowest test load for the remainder of the test duration. As shown, generator load exceeded the minimum required test plan loads at all times during the diluted LO test.

Figure 6-17 shows generator load plotted as a function of elapsed time at the start of the diluted LO test. The test plan required that the peak test load be reached within 55 sec after the start of the test, same as for the baseline test. Load was first applied approximately 30 sec after the start of the test, and the peak load was reached approximately 174 sec after the start. The delay in applying load and reaching the peak test load was similar to what occurred during both baseline test sessions, but reaching peak load took longer during the diluted LO test because of the failure of one of the load bank resistor circuits approximately 110 sec after the test start. The additional delay was the result of switching to a spare resistor circuit of the same capacity, which allowed the peak test load to be reached. The delay caused the test plan requirement for load addition to not be satisfied for the diluted LO test, same as for the baseline test. Section 6.2.3 discusses how the intent of the test plan requirement was satisfied during the baseline test because the use of a resistive load bank with discrete circuits results in step loading of the engine and transient loading of lubricated components. MPR considers that the intent of the test plan was also satisfied for the diluted LO test for the same reason.

6.3.5. Engine LO/FO Mixture Pressure

Figure 6-18 and Figure 6-19 show engine LO/FO mixture pressure plotted as a function of elapsed time for the diluted LO test. As shown, LO/FO mixture pressure was consistently lower during the diluted LO test than during the baseline test at the same elapsed time. At the start of the diluted LO test, the initial pressure was approximately 2-3 psig lower than during the baseline test. Further, while the pressure remained relatively constant during the baseline test sessions, the pressure progressively decreased slowly and consistently over the full duration of the diluted LO test at a rate of approximately 0.3 psig/hr. By the end of the test, the pressure had decreased by an additional approximate 7 psig to an average of 47 psig (over the final 30 minutes of the test). The differences in the pressure behavior between the baseline and diluted LO tests are explained by the impact of the high and increasing FO concentration on the LO/FO mixture viscosity (and density) during the diluted test. Specifically, the presence of the FO, which has a significantly lower viscosity than the LO, resulted in a significant decrease in viscosity (and a more modest decrease in density) for the LO/FO mixtures. As a consequence, the fluid pressure decreased as the FO concentration increased and the viscosity (and density) correspondingly decreased.

The test plan did not include a specific requirement for LO/FO mixture pressure other than it should always exceed the 2B AF engine trip setpoint of 10 psig. The LO/FO mixture pressure always exceeded the trip limit by a significant margin, even after the decrease in pressure that occurred during the diluted LO test. Further, the average LO/FO mixture pressure at the end of the test (47 psig) was still within the normal LO pressure range of 45-70 psig identified in Table 11-4 of Reference 3.

6.3.6. Engine LO/FO Mixture Temperature

Figure 6-20 and Figure 6-21 show engine LO/FO mixture temperature plotted as a function of elapsed time for the diluted LO test. As shown, LO/FO mixture temperature was consistently lower during the diluted LO test than during the baseline test at the same elapsed time. At the start of the diluted LO test, the initial temperature was approximately 6-9°F lower than during the baseline test. Further, toward the end of the test the temperature progressively decreased slowly and consistently at a rate of approximately 0.3°F/hr despite the generator load remaining constant (in contrast, the temperature remained relatively constant at a given generator load during the baseline test). The lower temperatures are most likely the result of increased LO/FO mixture flow because of the lower viscosity. The increased flow rate increased heat rejected by the engine LO coolers.

The test plan did not include a specific requirement for LO/FO mixture temperature (other than the initial condition identified in Table 6-3, which was satisfied).

6.3.7. Engine Coolant Temperature

Figure 6-22 and Figure 6-23 show engine coolant temperature plotted as a function of elapsed time for the diluted LO test. As shown, coolant temperature was steady and consistent for the full diluted LO test duration, and it was more consistent than during the baseline test sessions. The average coolant temperature was 167°F during the diluted LO test, which was slightly less than the temperatures recorded during the baseline test sessions.

The test plan did not include a specific requirement for engine coolant temperature other than it should not exceed the 2B AF engine trip setpoint of 205°F. The temperature during the diluted test was always below the trip limit by a significant margin.

6.3.8. Engine Intake Air Temperature

Figure 6-24 shows engine intake air temperature plotted as a function of elapsed time for the diluted LO test. As shown, intake air temperature trended upward and then downward during the test as the ambient air temperature changed, similar to what occurred during the baseline test sessions. The average intake air temperature was 74°F during the diluted LO test, which was lower than the average temperatures during both baseline test sessions.

The test plan did not include a specific requirement for intake air temperature (other than the initial condition identified in Table 6-3, which was satisfied).[5]

6.3.9. Engine Crankcase Pressure

Figure 6-25 shows engine crankcase pressure plotted as a function of elapsed time for the diluted LO test. As shown, crankcase pressure fluctuated slightly, but overall it was consistently positive at a low level. An exception was a brief excursion at approximately 23 hours elapsed time where the crankcase pressure was slightly negative and then recovered to its normal positive and fluctuating behavior. The reason for the pressure excursion is not known. Aside from the excursion, the overall pressure behavior and average pressure (0.026 psig) were both similar to what occurred during the baseline test sessions.

The test plan required that the engine crankcase be properly ventilated to mitigate excessive positive pressure; however, a specific limit or range for crankcase pressure was not specified.

6.3.10. Engine FO Pressure

Figure 6-26 and Figure 6-27 show engine FO pressure plotted as a function of elapsed time for the diluted LO test. As shown, FO pressure was steady and consistent during the diluted test with slight decreasing and increasing trends due to changes in ambient temperature, similar to what occurred during the baseline test sessions. The average FO pressure was 68 psig during the diluted test, which was slightly higher than the pressures recorded during the baseline test sessions.

The test plan did not include a specific requirement for FO pressure.

[5] The 2B AF diesel engine is located in Environmental Zone (EZ) A11. Constellation calculation BRW-01-0153-E / BYR01-068 (Reference 19) states that during the first two hours of a LOCA / LOOP, the ambient air temperature of EZ A11 could reach 140°F. The engine draws combustion intake air from EZ A8, and EZ A8 could also reach a temperature of 140°F during the first two hours of a LOCA / LOOP. The 2B AF diesel engine needs to be capable of operating under these conditions with the as-found September 2023 FO dilution of LO.

The peak intake air temperature during the diluted LO test was 93°F. Per Reference 19, the peak ambient and intake air temperatures for the 2B AF engine could be as much as 47°F higher than the peak inlet air temperature during the diluted LO test. The increased ambient and intake air temperatures result in increased lube oil and jacket water temperatures, with all driving an increase in jacket water cooling demand. The 2B AF engine jacket water cooler has substantial cooling margin; it is rated for 3.15 million BTU/hr (Reference 20) or 1,238 hp, which is more than the maximum load carried by the 2B AF engine. Typically, the jacket water cooler rejects approximately 60 percent of the engine output load (e.g., see Reference 21), so the 2B AF engine jacket water cooler has significant margin for mitigating large increases in lube oil and jacket water temperatures due to the significantly higher ambient and intake air temperatures. As a result, the lube oil and jacket water temperatures are expected to increase only a small fraction of the 47°F peak inlet air temperature difference between the 2B AF engine and the diluted LO test. The small increases in lube oil and jacket water temperatures will have minimal impact on lube oil pressure and viscosity.

6.3.11. Engine Knock Sensor Output Comparison

Two engine knock sensors attached to the side of the engine block (one sensor adjacent to cylinder 2L and the other sensor adjacent to cylinder 5L) were used to monitor for abnormal engine vibrations during the test. A significant change/increase in either knock sensor output signal would likely be indicative of damage to one or more components and ideally would be an early warning of impending failure. Figure 6-28 shows the output signal (displayed on an oscilloscope) during the baseline test at approximately five hours elapsed time. Figure 6-29 shows the output signal shortly before the end of the diluted LO test. As shown, the displayed output signals are nearly identical in form and amplitude. The lack of significant change in the output signals during the diluted test compared to the baseline test suggests that damage to engine components resulting in increased vibrations did not occur during the diluted LO test.

(Note: The date and time stamps displayed in Figure 6-28 and Figure 6-29 are not correct. The date and time were not set to the current values when the oscilloscope was set up for the tests. The image in Figure 6-28 was taken at 14:07 on December 9, 2023. The image in Figure 6-29 was taken at 07:42 on December 15, 2023.)

6.3.12. Engine Shutdown Behavior

The shutdown behavior of the test genset during the baseline and diluted LO tests was compared to understand if damage occurred during the diluted test that impacted the normal shutdown behavior. Specifically, damage to engine bearings and/or bushings, if significant, could increase friction and cause a decrease in the time required for genset speed to decrease from the peak test speed (approximately 1,800 rpm) to a dead stop. Figure 6-30 shows genset speed plotted as a function of elapsed test time at the ends of the baseline (second session) and diluted LO tests. As shown, there was no significant difference in the genset speed decrease at the end of the two tests (i.e., the shutdown times were nearly identical). This result suggests that damage to bearings or bushings resulting in a significant increase in friction did **not** occur during the diluted LO test.

6.3.13. Test Anomalies

At approximately 3.5 hours after the start of the diluted LO test, fluid was observed to be spraying onto the camera lens used to monitor the engine-mounted LO pressure, FO pressure, and coolant temperature gauges at the rear end of the right side of the engine. The fluid was initially assumed to be FO given the presumed location of the leak near the FO pressure gauge, which had developed a small leak requiring repair during the initial setup of the test engine. The nature and source of the leak could not be investigated during the test for personnel safety reasons. The leak continued for the remainder of the diluted test, and the leak rate appeared visually to remain relatively constant throughout the test. As shown in Figure 6-32 and Figure 6-32, the leak resulted in a significant amount of fluid on the test engine and surrounding surfaces. The volume of leaked fluid could not be easily measured, but visually it appeared to be multiple gallons.

The test engine was visually inspected after the diluted test to understand the nature of the leaked fluid and the potential/likely leak source(s). Upon closer inspection, the leaked fluid appeared to be a mixture of LO and FO based on its brown color and intermediate viscosity (i.e., in between the viscosities of pure LO and FO). The leaked fluid was also concentrated more around the rear end of the engine rather than the sides or front. This is consistent with the observed location of fluid spraying during the test. The visual inspection of the engine did not identify any obvious, significant sources of leakage (some very minor seepage was observed at gasketed component surfaces, but all observations combined represented only a small volume of leakage). The inspection included checking the hoses and connections for the FO system, LO sampling circuit, and FO addition system to confirm they were not the source(s) of the leakage. The FO system was also pressurized to approximately 60 psig, and no leaks were identified. By process of elimination, the crankshaft rear main LO seal was identified as the most likely source of the fluid leakage. The engine has two main LO seals, one at each end of the crankshaft, that prevent LO from leaking from the engine at the ends of the crankshaft during engine operation. The rear main seal is located behind the engine flywheel, which is located between the engine and generator. The rear main seal is normally not visible, and it could not be inspected at SwRI without significant disassembly of the test genset, including removal of the generator and flywheel. No evidence of significant leakage from the crankshaft front main LO seal was observed during the post-test visual inspection at SwRI.

Section 6.4 discusses post-test disassembly of the test engine, which included removal of the generator and engine flywheel to allow for the direct inspection of the rear main seal. The purpose of the inspection was to determine if the leakage was due to damage to and/or failure of the seal, or if the seal was intact and leakage occurred for other reasons.

No other test anomalies occurred during the diluted LO test, including no significant leaks of FO (from the FO system), intake air, or exhaust gases.

6.3.14. Post-Test Engine Sump LO/FO Mixture Level

The engine sump LO level was documented after the diluted LO test and compared with the pre-test level and the volume of FO added to the sump during the test. The purpose of the comparison was to better understand the volume of leakage that occurred during the test, and the net impact of leakage and FO addition on the sump LO/FO mixture level during the test.

As mentioned in Table 6-3, the addition of nearly 7 gal of FO to the engine sump in addition to the normal LO volume resulted in the initial LO/FO mixture level being very high on the engine dipstick (approximately 2 in above the high-level mark) at the start of the diluted LO test. At the end of the test, the LO/FO mixture level on the dipstick could not be accurately read because the viscosity of the mixture was so low and its color was lighter than normal. To obtain an accurate level, a clear tube was connected to the drain at the bottom of the lower oil pan for use as a level sight tube. With the drain open, the elevation of the fluid level inside the tube was consistent with a level of approximately 0.5 in below the high-level mark on the engine dipstick.

As noted in Section 6.3.2, a total of 26.8 gal of FO was added to the engine sump during the diluted LO test in addition to the nearly 7 gal of FO added prior to the start of the test (in the initial LO/FO mixture). The dipstick level is at the high-level mark for the normal volume of LO only without any FO. As noted above, the dipstick level at the end of the diluted test was approximately 0.5 in below the high-level mark. Per Note 4 for Table 6-1, a level difference of 0.5 in on the engine dipstick represents approximately 2.3 gal of fluid. Based on this, the total volume of LO/FO mixture decreased by approximately 36.1 gal (33.8 + 2.3 gal). The "lost" fluid is a combined result of the leakage from the engine and consumption through combustion. Based on the normal LO consumption rate from the baseline test (which should be higher for the diluted test because of the lower viscosity of the LO/FO mixture) and the amount of leaked fluid on and around the test genset, the majority of the fluid loss occurred due to consumption by combustion as opposed to leakage.

6.3.15. Engine LO/FO Mixture Sampling and Analyses

Per the test plan, engine LO samples were collected every hour during the diluted LO test and analyzed by SwRI. A total of 26 samples were analyzed (hours 0 through 24, and hour 24.5). Table 6-4 contains the results of the LO analyses. In summary:

- The viscosity of the LO/FO mixture (at both 40°C and 100°C) was significantly lower at the start of the diluted test compared to the baseline test due to the high FO concentration. The viscosity further decreased progressively during the test as the FO concentration increased. The decrease in viscosity (at both temperatures) was significant over the full test duration.
- The measured FO concentrations, as determined by ASTM D3524 (Reference 18), were consistently lower than expected based on the target starting FO concentration and the rate of FO addition during the test. The reported ASTM D3524 values are considered to be inaccurate due to FO concentrations being above the identified limit for the test. MPR's evaluation included additional scope to determine accurate FO concentrations for the diluted LO test. See Section 6.5 for further discussion.
- Wear metals were consistent at either trace levels (aluminum, chromium, copper, lead, and tin) or a normal level (iron), similar to or below the levels measured for the baseline test.

The analysis results support that the diluted LO test successfully tested the operation and performance of the test engine with a significant and increasing concentration of FO in the engine's LO. The results also support that the FO contamination did not result in significant or increased wear or other damage to any lubricated engine components during the diluted LO test. Additional evaluation of the test and test results are documented in Section 7.0.

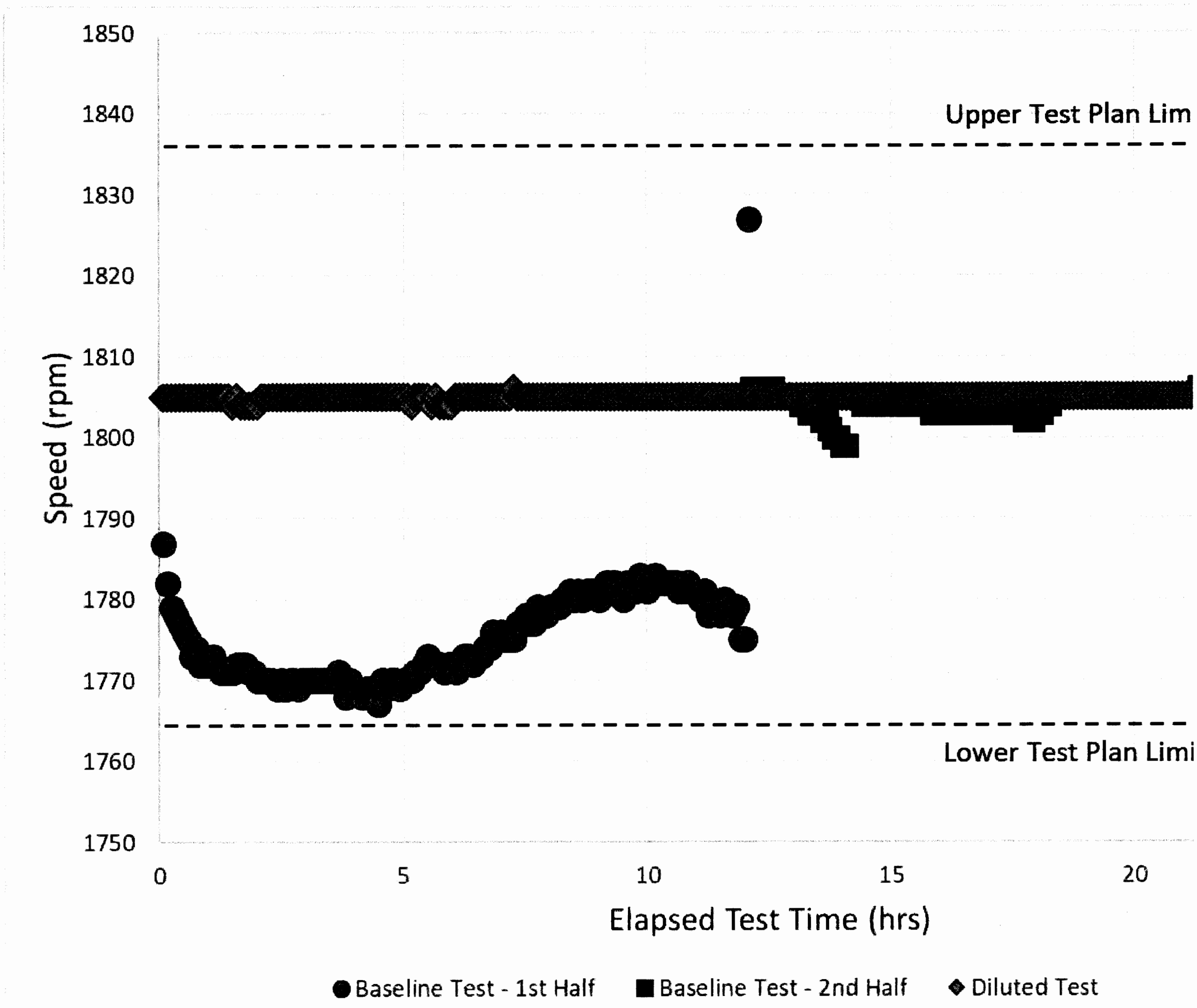

Figure 6-15. Diluted LO Test – Genset Speed vs. Elapsed Test Time

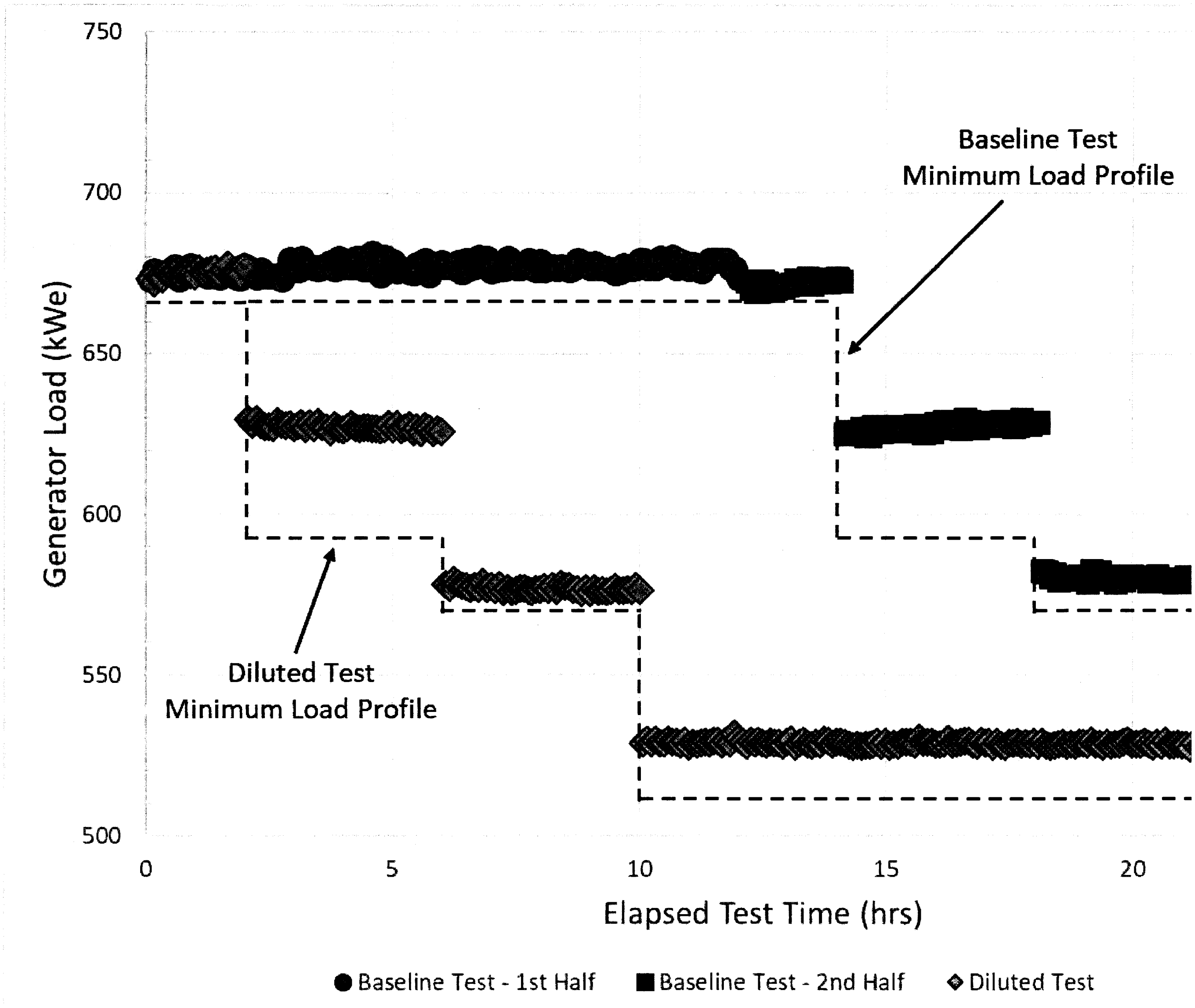

Figure 6-16. Diluted LO Test – Generator Load vs. Elapsed Test Time

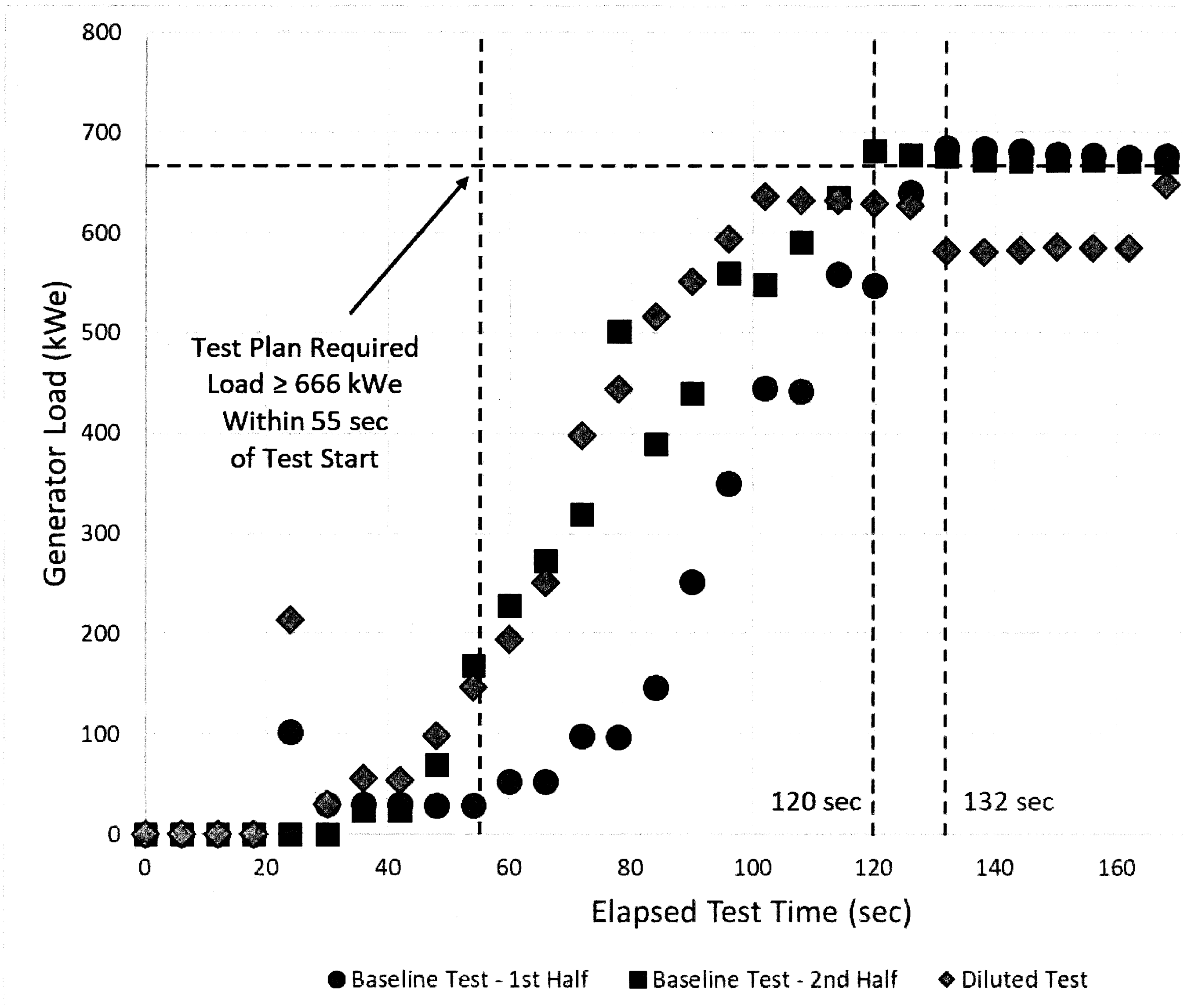

Figure 6-17. Diluted LO Test – Generator Load vs. Elapsed Test Time at Test Start

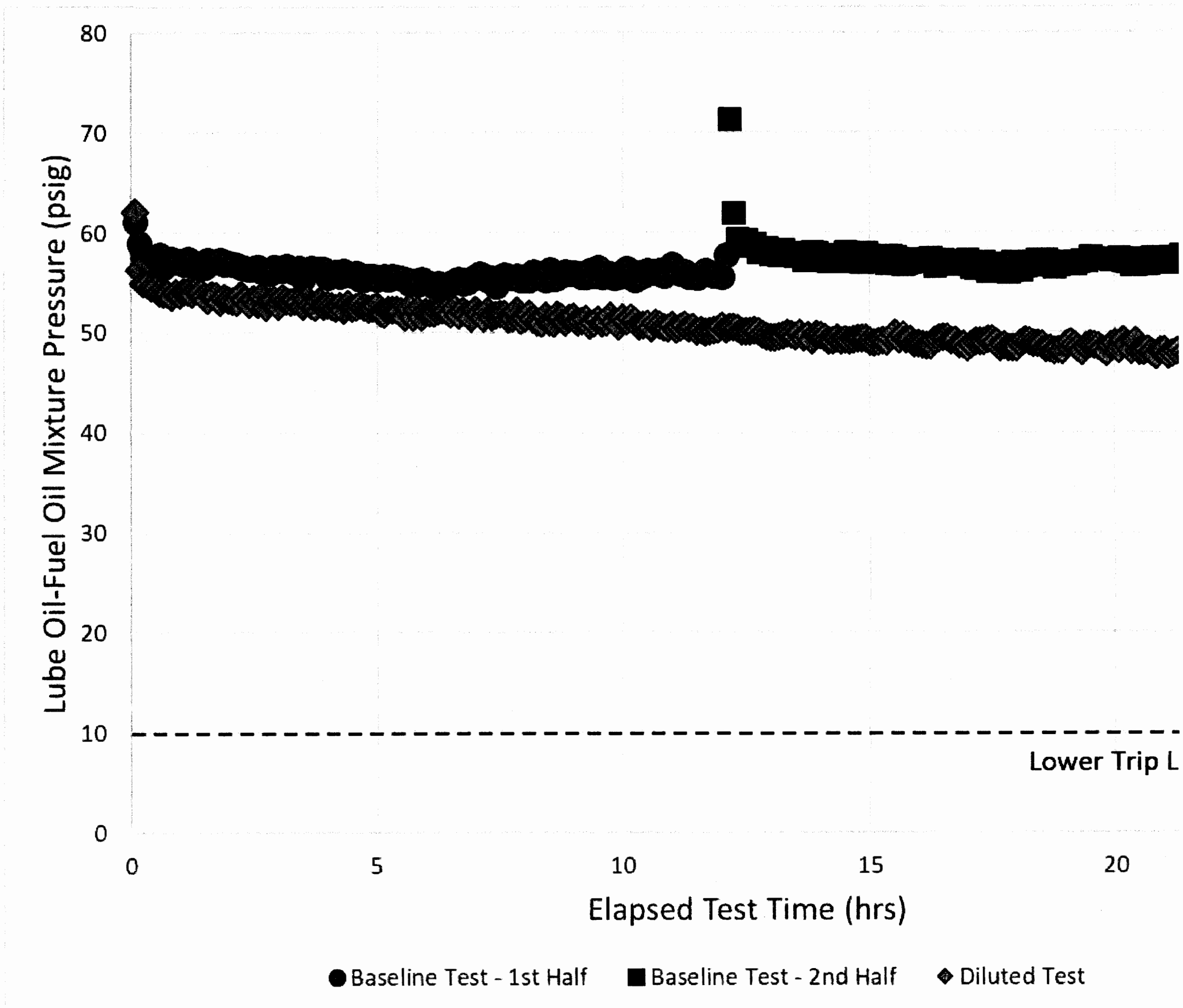

Figure 6-18. Diluted LO Test – Engine LO/FO Mixture Pressure vs. Elapsed Test Tin

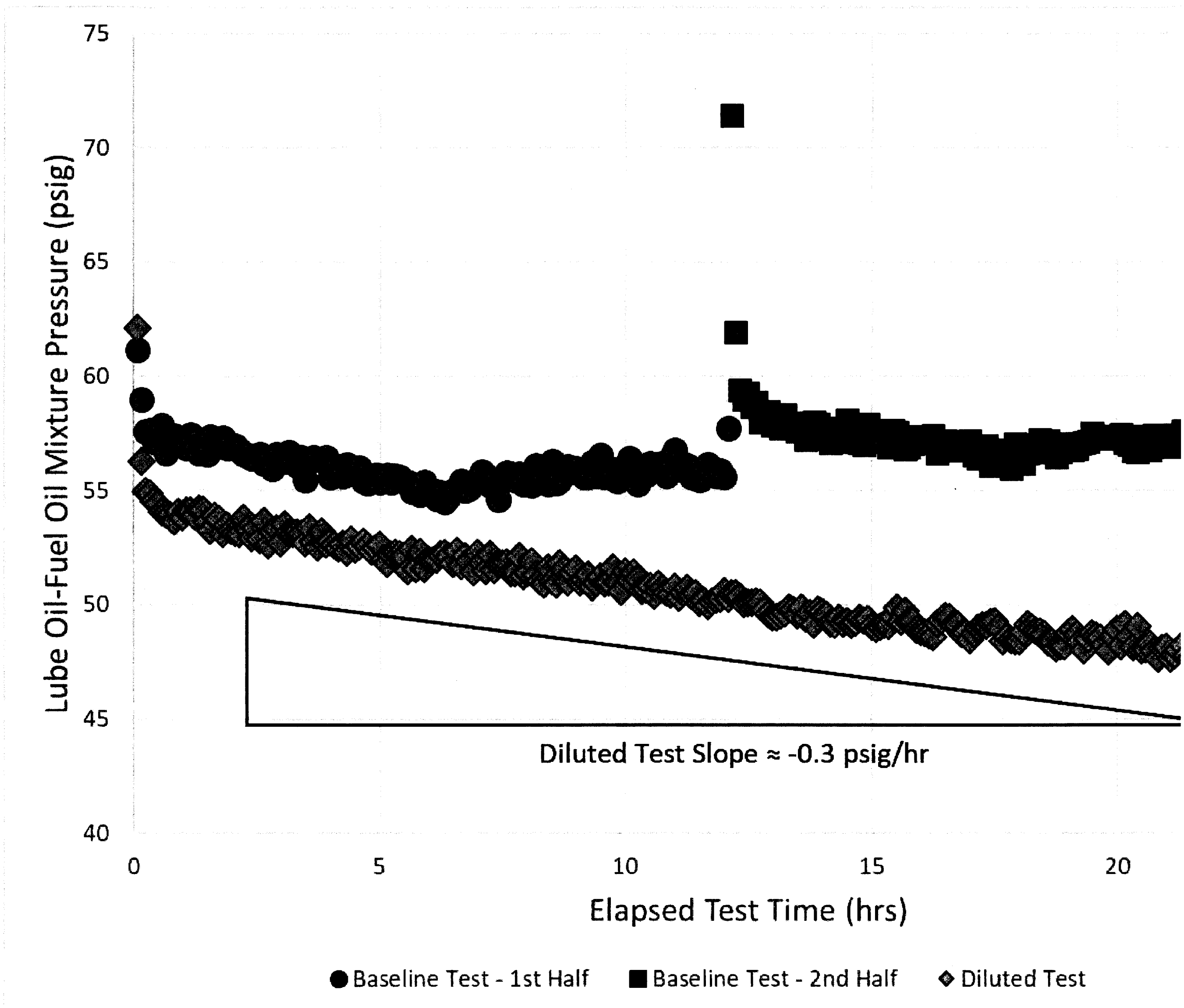

Figure 6-19. Diluted LO Test – Engine LO/FO Mixture Pressure vs. Elapsed Test Tin

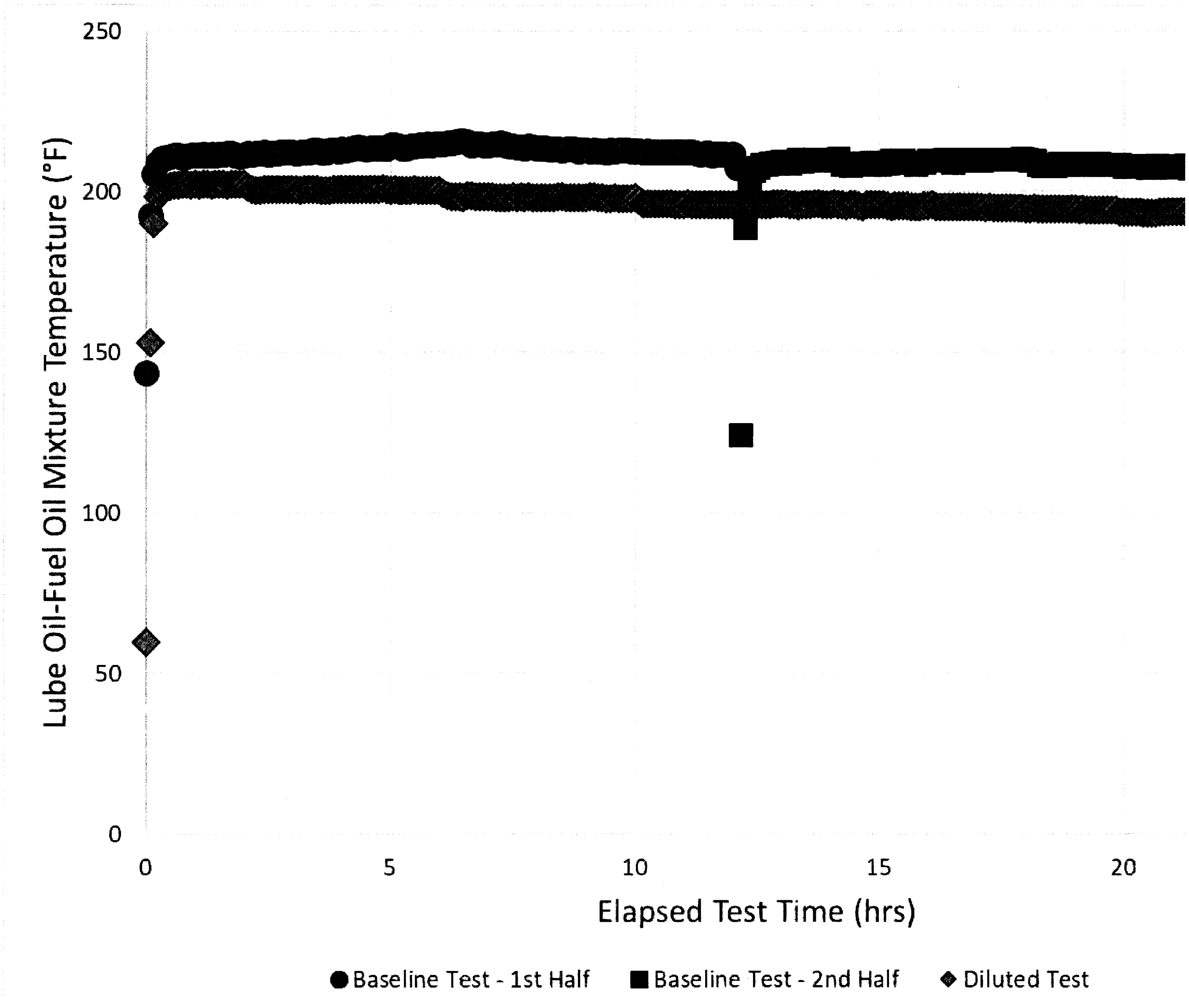

Figure 6-20. Diluted LO Test – Engine LO/FO Mixture Temperature vs. Elapsed Test T

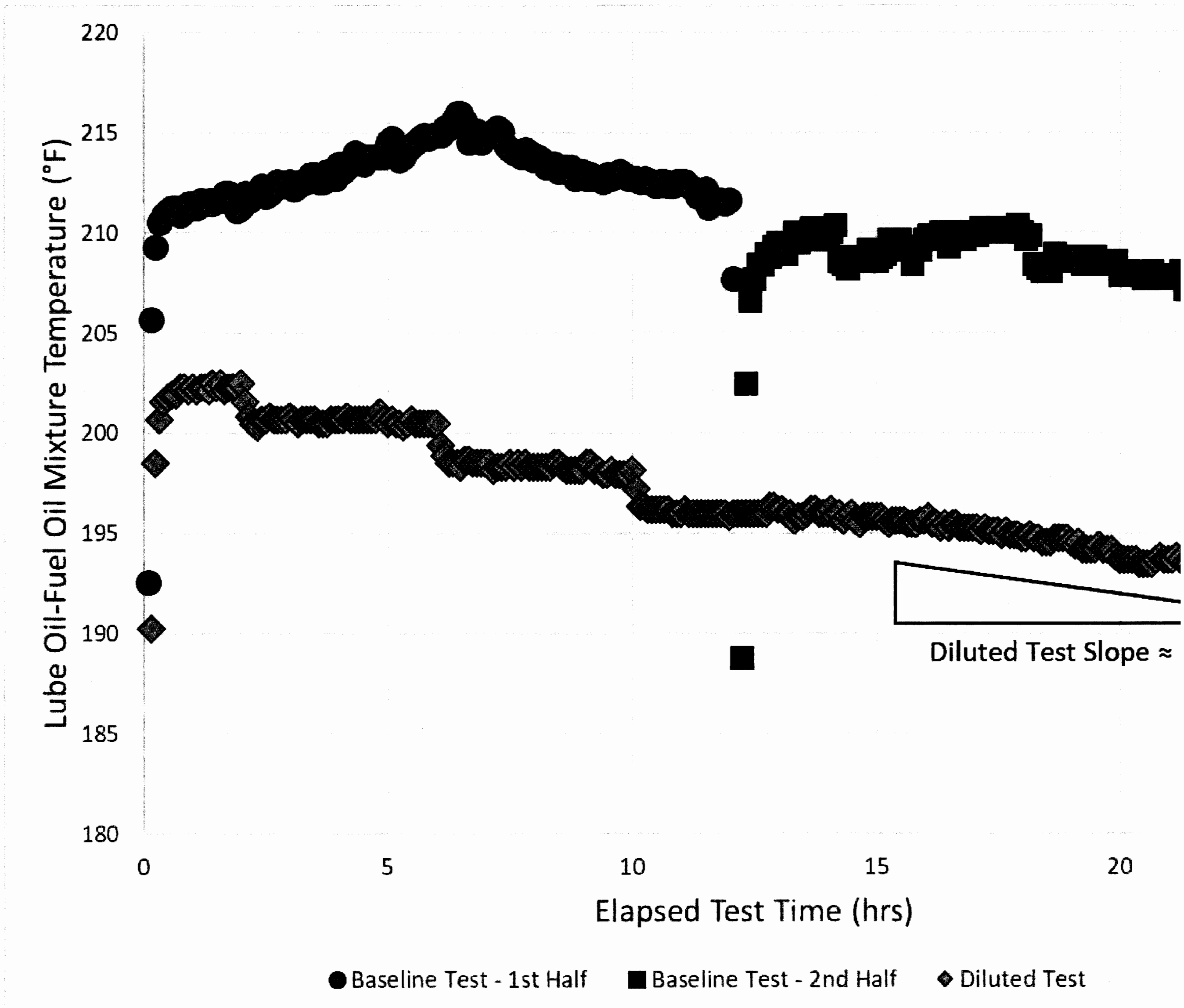

Figure 6-21. Diluted LO Test – Engine LO/FO Mixture Temperature vs. Elapsed Test T

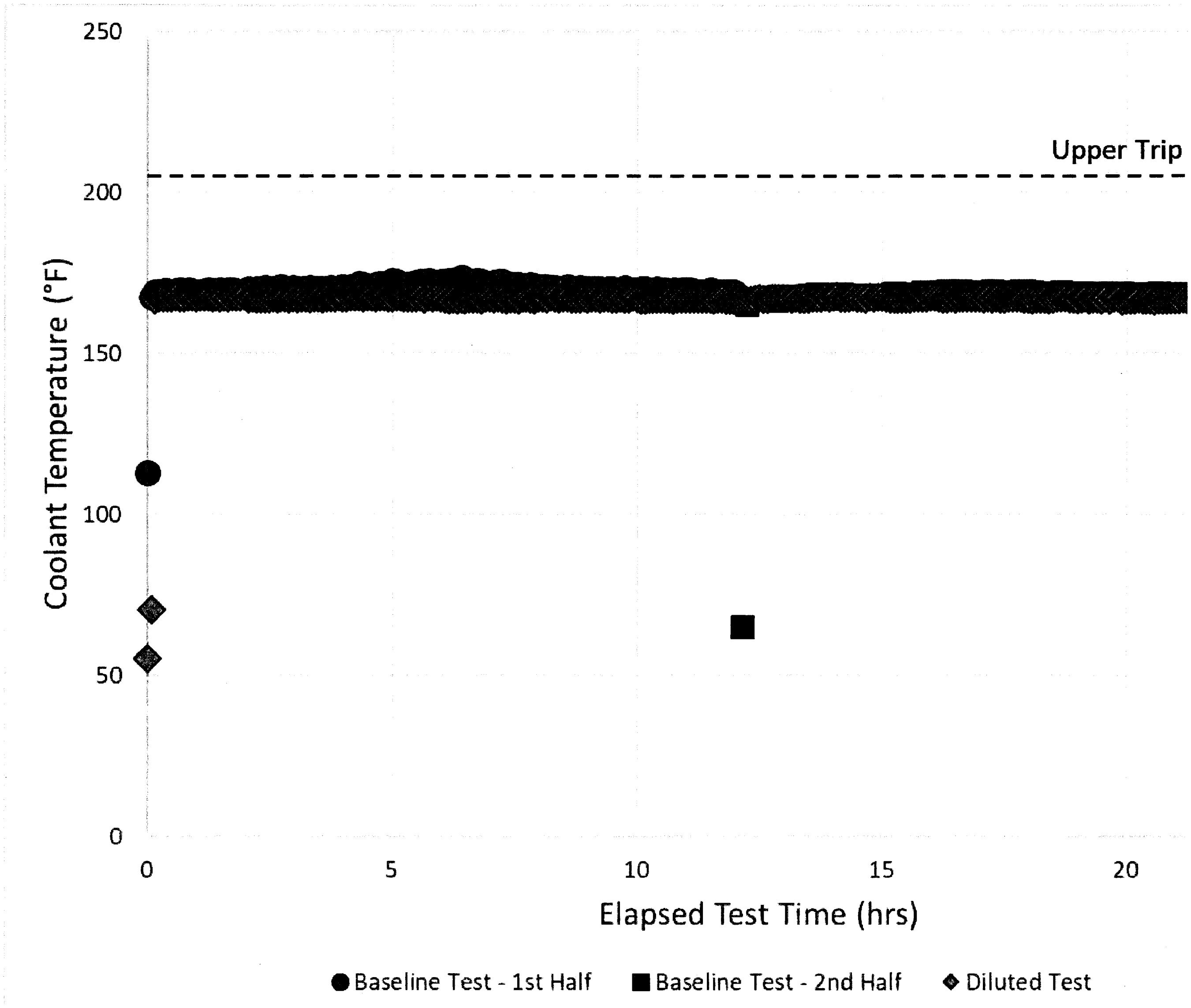

Figure 6-22. Diluted LO Test – Engine Coolant Temperature vs. Elapsed Test Time

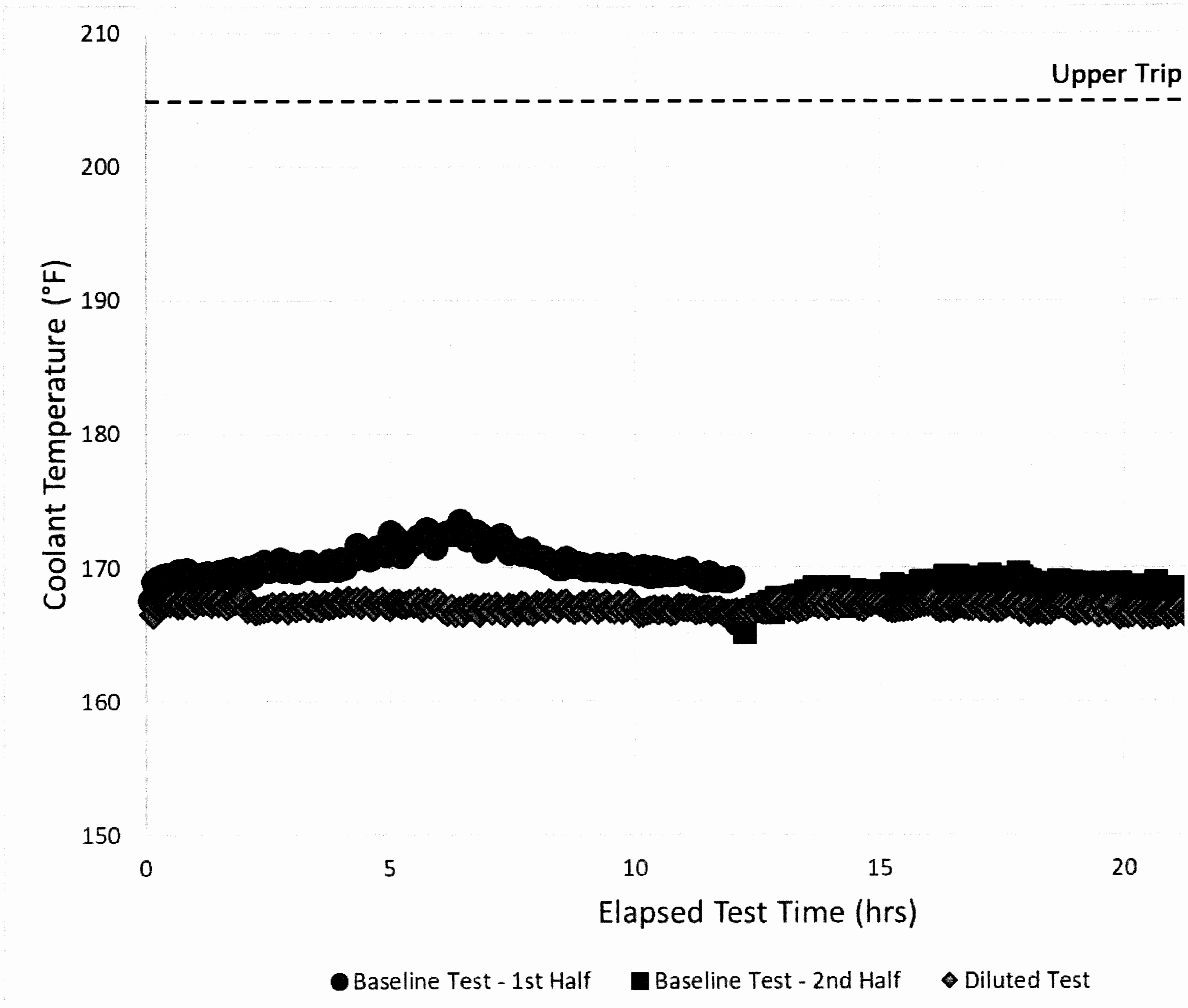

Figure 6-23. Diluted LO Test – Engine Coolant Temperature vs. Elapsed Test Time

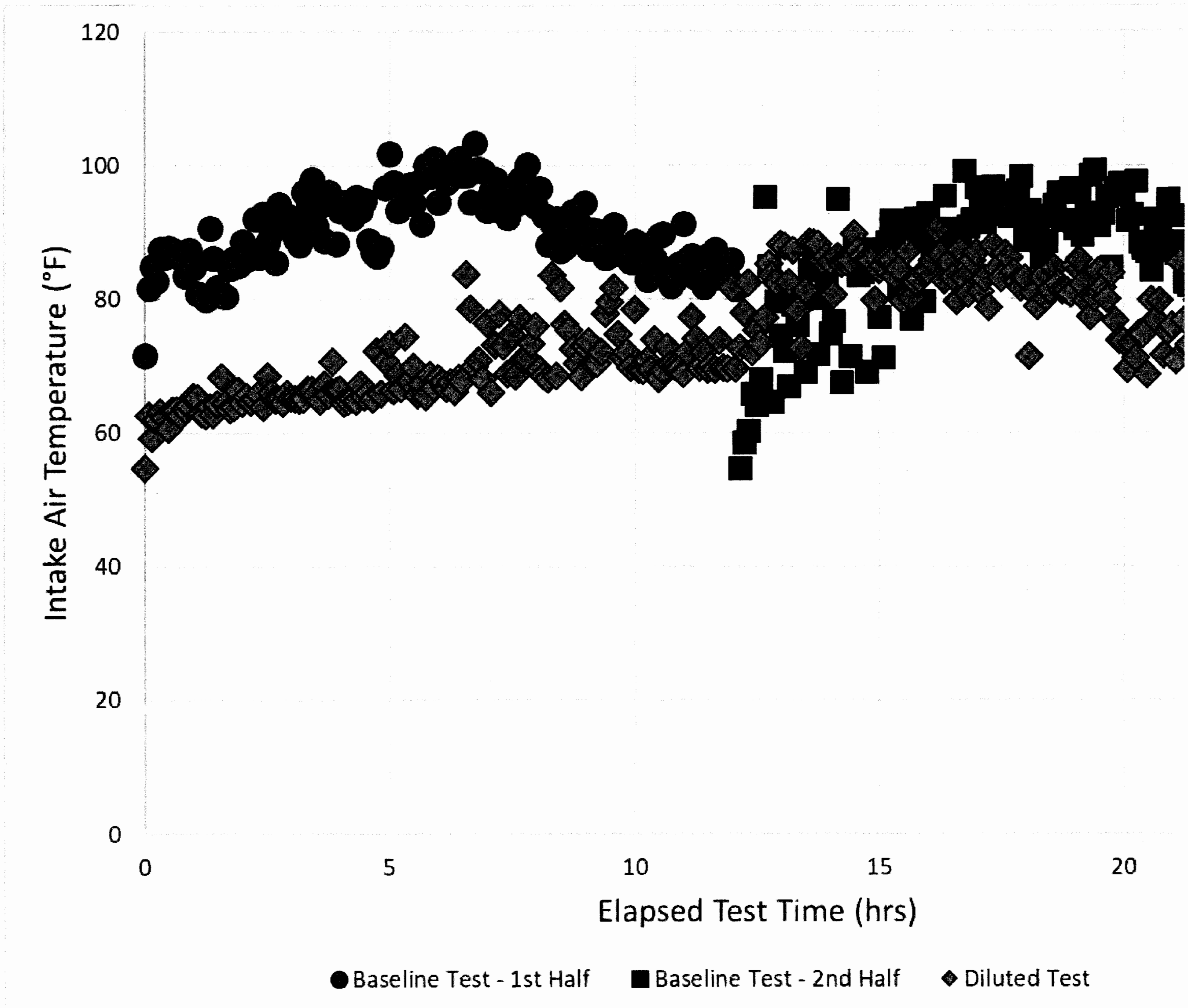

Figure 6-24. Diluted LO Test – Engine Intake Air Temperature vs. Elapsed Test Tim

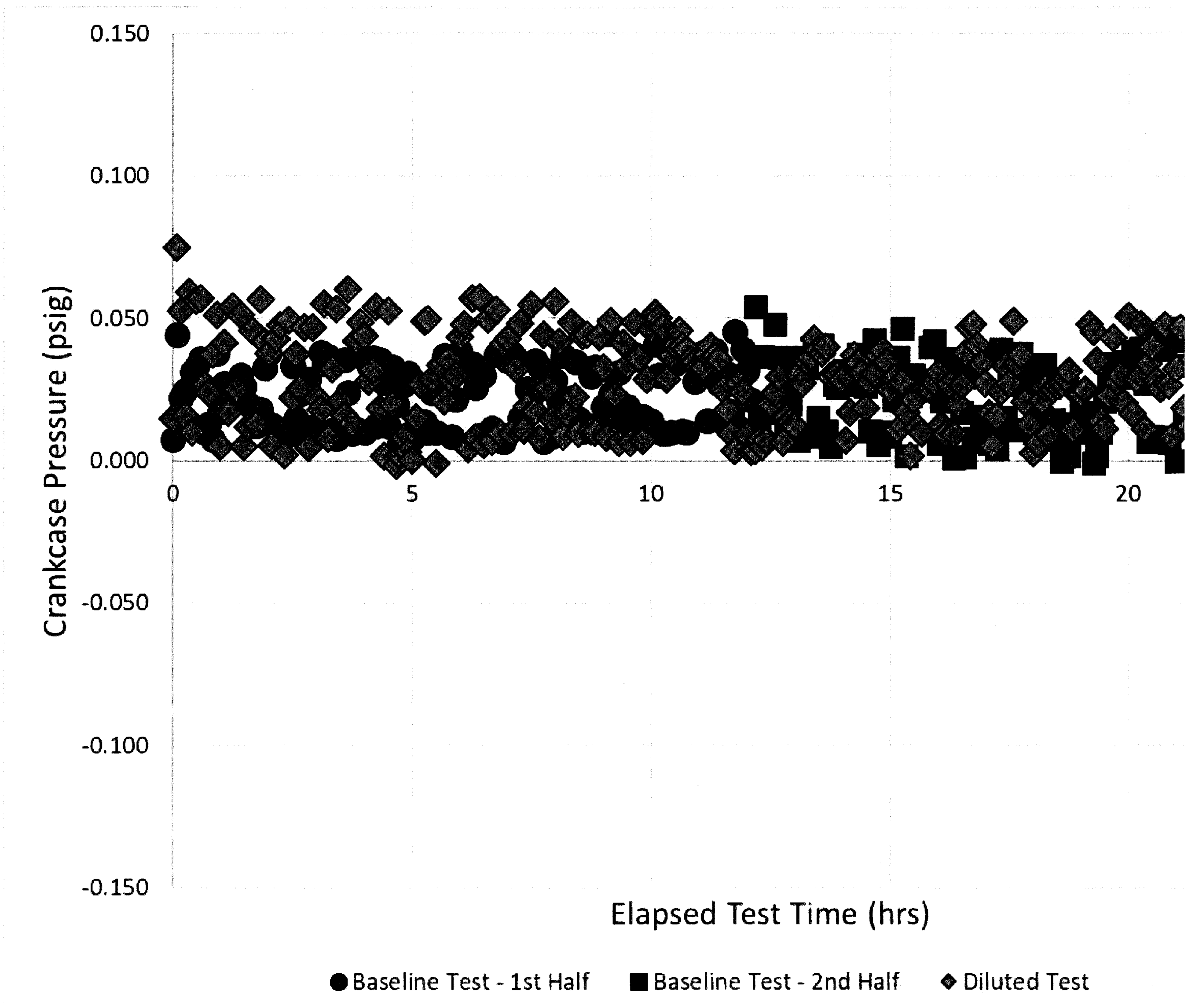

Figure 6-25. Diluted LO Test – Engine Crankcase Pressure vs. Elapsed Test Time

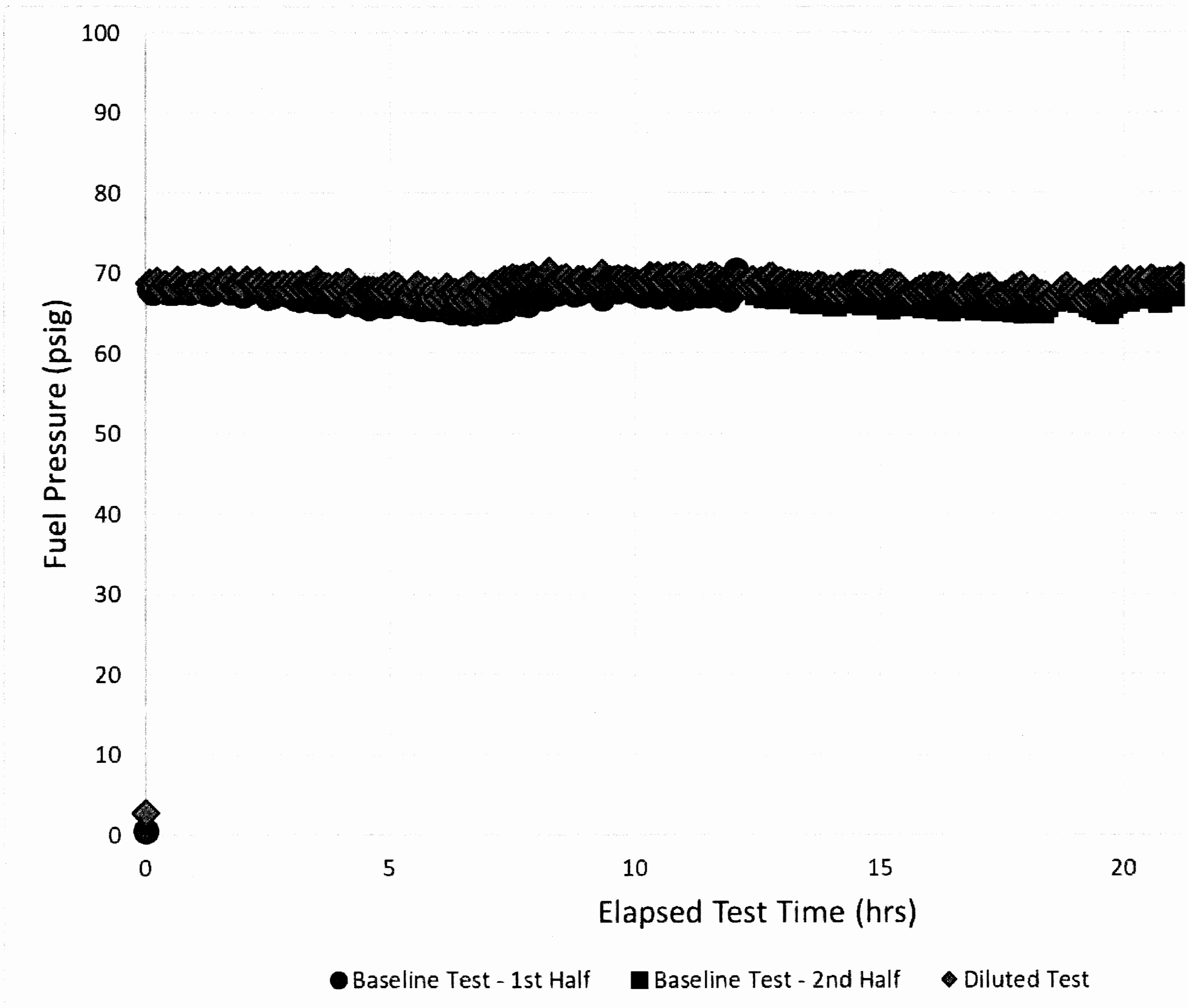

Figure 6-26. Diluted LO Test – Engine FO Pressure vs. Elapsed Test Time

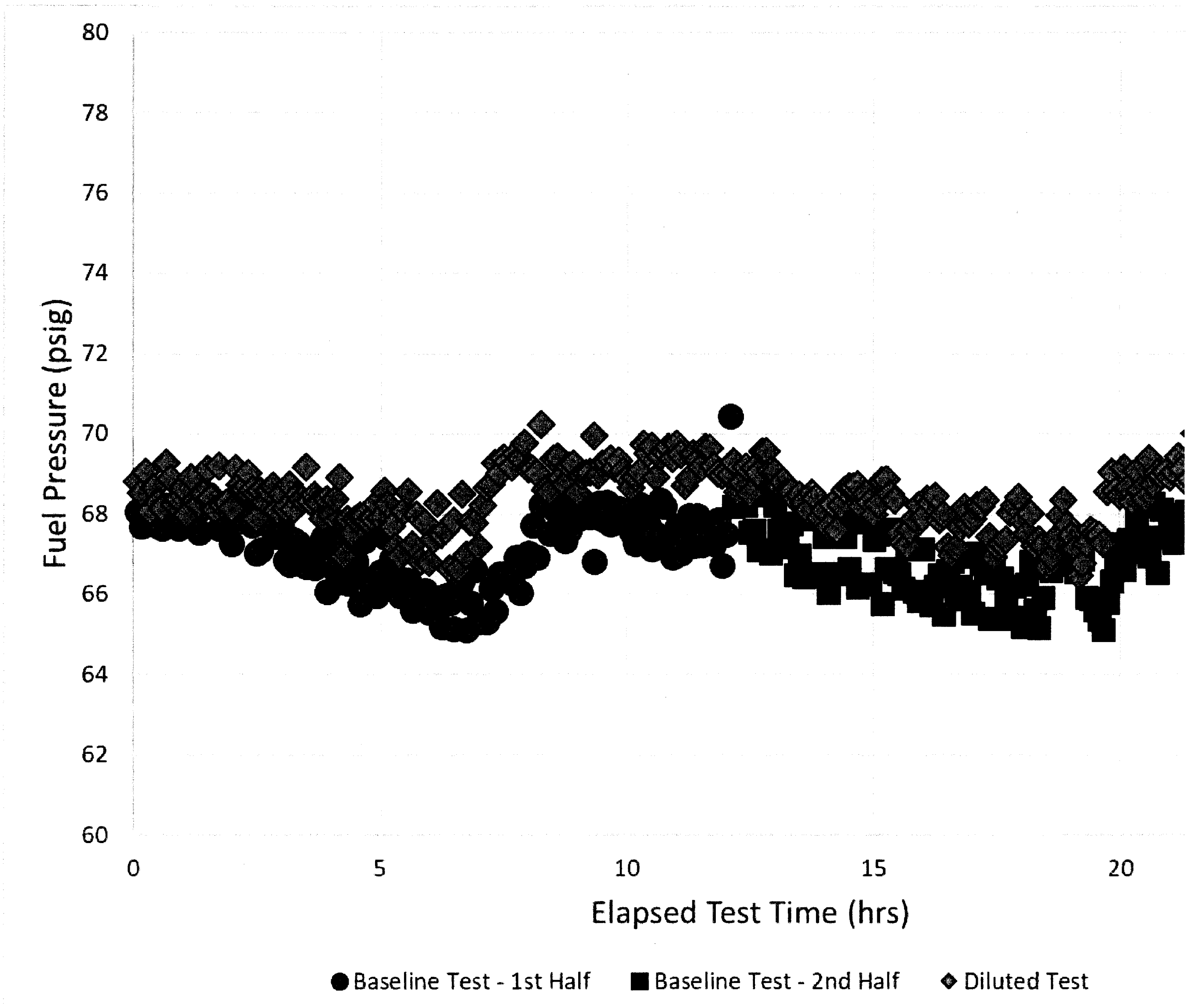

Figure 6-27. Diluted LO Test – Engine FO Pressure vs. Elapsed Test Time

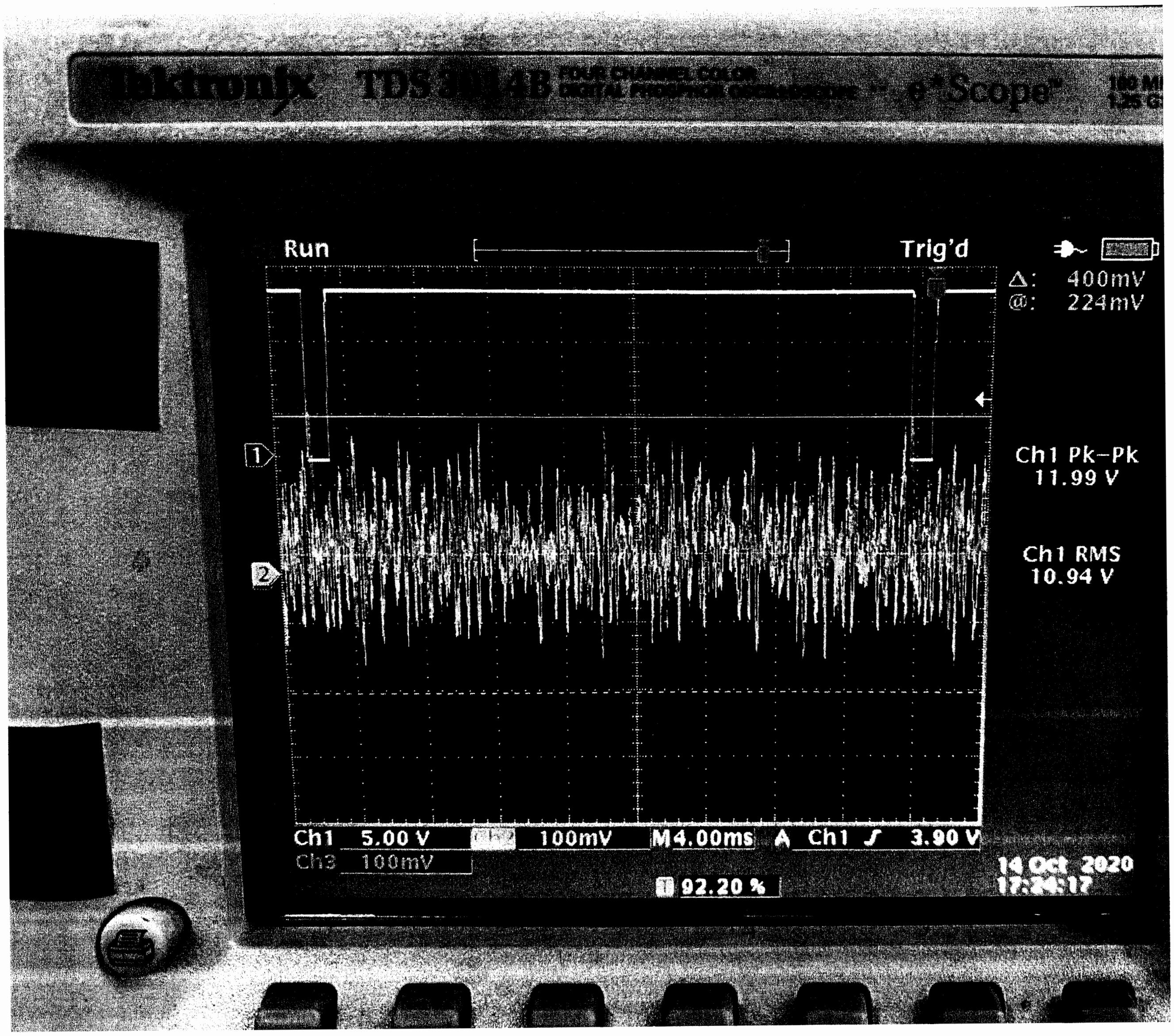

Figure 6-28. Knock Sensor Output Signal During Baseline Test (At Approximately 5 Hours Ela

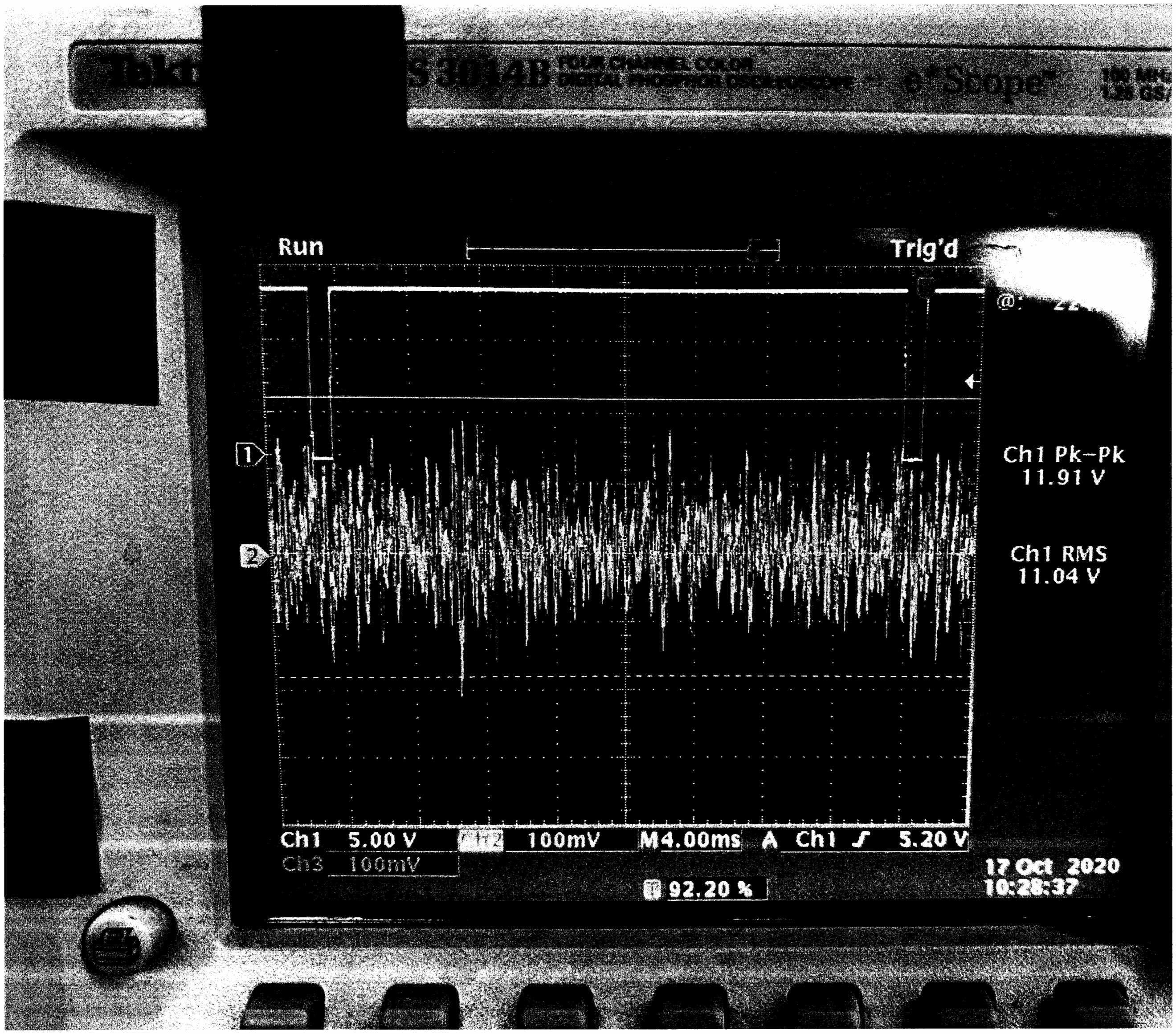

Figure 6-29. Knock Sensor Output Signal Shortly Before End of Diluted LO Test

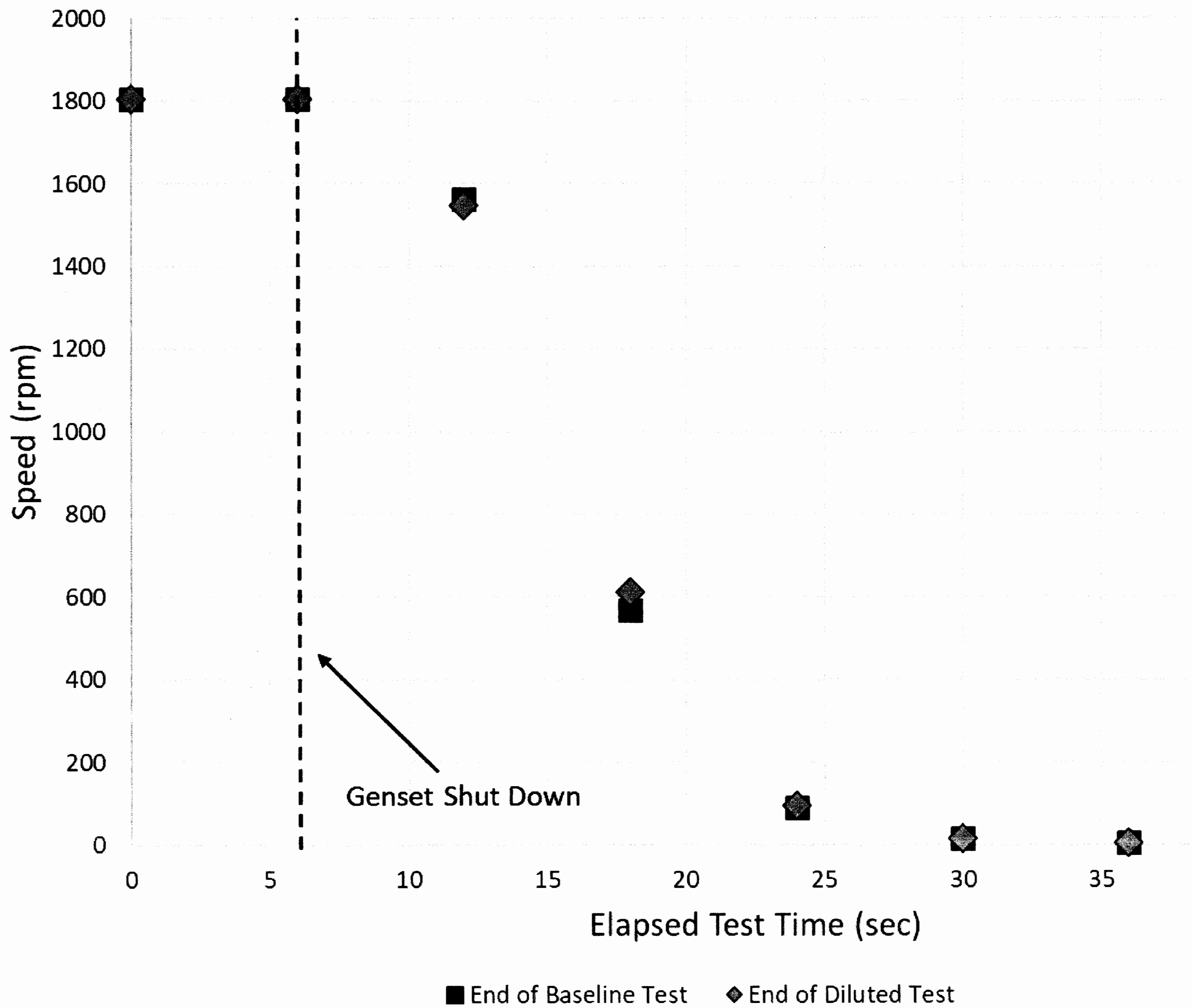

Figure 6-30. Comparison of Engine Shutdown Behavior for Baseline and Diluted LO T

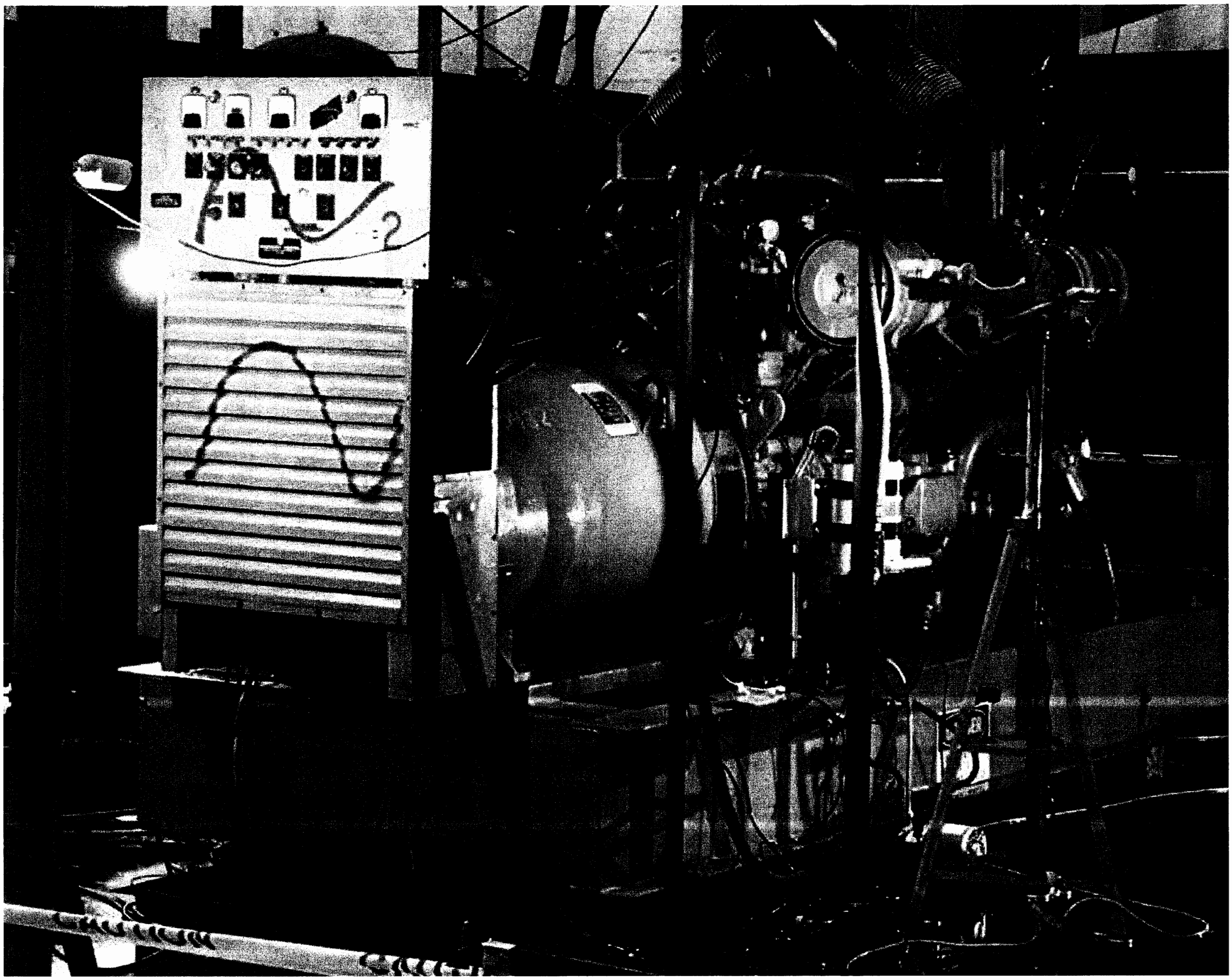

Figure 6-31. Test Genset After Diluted LO Test Showing Leaked LO/FO Mixture On/Around Test En

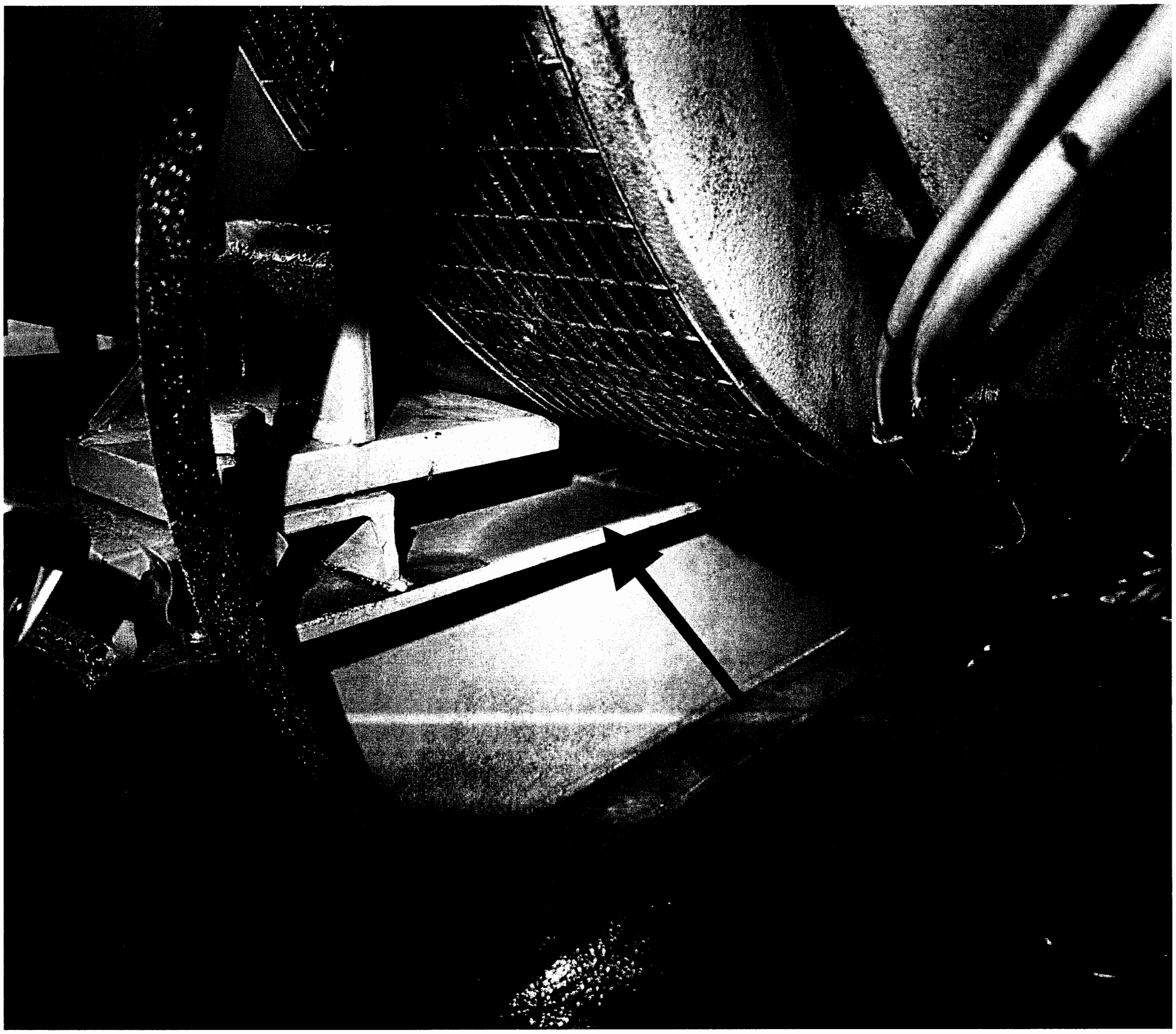

Figure 6-32. Test Genset After Diluted LO Test Showing Leaked LO/FO Mixture On/Around Test En

Table 6-4. Diluted LO Test Engine LO/FO Mixture Sample Analysis Results

Elapsed Test Time (hr)	ASTM D3524 FO Concentration (wt.%) [1]	ASTM D445 Viscosity, 40°C (cSt)	ASTM D445 Viscosity, 100°C (cSt)	ASTM D5185 Aluminum (ppm)	ASTM D5185 Chromium (ppm)	ASTM D5185 Copper (ppm)
0 (Shortly After Test Start)	8.7	54.8786	8.3650	< 1	< 1	< 1
1	8.9	52.0930	8.1538	< 1	< 1	< 1
2	10.9	49.7312	7.9313	< 1	< 1	< 1
3	10.1	47.5127	7.7161	< 1	< 1	< 1
4	10.3	45.8545	7.4970	< 1	< 1	< 1
5	11.3	43.2935	7.2296	< 1	< 1	< 1
6	11.3	41.4080	7.0101	< 1	< 1	< 1
7	11.8	39.4082	6.7837	< 1	< 1	< 1
8	12.3	37.3011	6.5347	< 1	< 1	< 1
9	13.7	35.6074	6.3594	< 1	< 1	< 1
10	13.3	34.0162	6.2015	< 1	< 1	< 1
11	14.1	31.7520	5.9953	< 1	< 1	< 1
12	14.2	30.9355	5.8199	< 1	< 1	< 1
13	14.1	29.3343	5.6551	< 1	< 1	< 1
14	15.0	28.1852	5.4756	< 1	< 1	< 1
15	14.7	26.8195	5.3400	< 1	< 1	< 1
16	15.5	25.8658	5.2212	< 1	< 1	< 1
17	16.8	25.0845	5.1339	< 1	< 1	< 1
18	16.8	24.0224	4.9211	< 1	< 1	< 1
19	17.6	23.1630	4.8272	< 1	< 1	< 1

Elapsed Test Time (hr)	ASTM D3524 FO Concentration (wt.%) [1]	ASTM D445 Viscosity, 40°C (cSt)	ASTM D445 Viscosity, 100°C (cSt)	ASTM D5185 Aluminum (ppm)	ASTM D5185 Chromium (ppm)	ASTM D5185 Copper (ppm)
20	19.0	22.2788	4.6915	< 1	< 1	< 1
21	14.1	21.3697	4.5844	< 1	< 1	< 1
22	19.2	20.7732	4.4875	< 1	< 1	< 1
23	19.9	20.2086	4.3709	< 1	< 1	< 1
24	20.4	19.4394	4.2768	< 1	< 1	< 1
24.5	21.1	19.1348	4.2175	< 1	< 1	< 1

1. The FO concentration test results are inaccurate because the sample conditions fall outside of the range identified for the ASTM further discussion.

6.4. *Post-Test Engine Inspections*

Following the diluted LO test, the test genset was shipped to Braidwood for disassembly and post-test engine inspections. The purpose of the inspections was two-fold. First, the lower main bearings removed and visually inspected prior to the baseline test were re-inspected to determine what damage, if any, occurred during the diluted LO test. Second, the crankshaft rear main LO seal was visually inspected to determine if the leakage of the LO/FO mixture from the engine during the diluted test was due to damage to and/or failure of the seal, or if the seal was intact and the leakage occurred for other reasons. The results of the post-test engine inspections are summarized in the following sections.

6.4.1. Lower Main Bearing Inspections

As discussed in Section 6.1, lower main bearings #2, #3, #6, and #7 were removed for visual inspection of overall condition prior to testing. Figure 6-1 shows the good condition of all four bearings at that time. The same four lower main bearings were removed for visual inspection following the diluted LO test. Figure 6-33 shows a comparison of the pre- and post-test conditions for lower main bearings #2 and #3. Figure 6-34 shows a comparison of the pre- and post-test conditions for lower main bearings #6 and #7. As shown, the conditions of all four bearings following the diluted LO test appeared unchanged from the pre-test conditions (other than those caused by the lighting and camera differences for the two inspections). Specific wear areas/patterns present on each bearing prior to testing are present and unchanged after testing. The pre- and post-test images also do not show any new wear areas/patterns that occurred during the testing.

The pre- and post-test inspections results support that damage did not occur to any of the inspected main bearings from the high concentration of FO in the engine LO during the diluted LO test. The inspection results are consistent with the LO/FO mixture analysis results discussed in Section 6.3.15; these analyses showed no increase in wear metal concentrations over during the diluted test. Combined, the main bearing visual inspection results and LO/FO mixture analysis results also support that other lubricated components (e.g., engine/turbocharger bearings) most likely did not suffer any significant damage during the diluted test. While the high FO concentration clearly impacted some engine operating parameters during the diluted test (e.g., the slow, progressive decrease in LO/FO mixture pressure), it appears that the FO did not cause any significant degradation of the condition of lubricated engine components during the test.

6.4.2. Crankshaft Rear Main LO Seal Inspection

Section 6.3.13 addressed the importance of determining the condition of the crankshaft rear main LO seal given the likelihood that it was the source of the leakage of the LO/FO mixture from the engine during the diluted LO test. The generator and engine flywheel were removed to allow for the visual inspection of the seal to document condition. Figure 6-35 through Figure 6-39 show the rear main seal after removal of the flywheel. The seal assembly was intact and in the correct installation position and orientation, and it appeared to be in overall excellent condition. The outermost edge of the dust shield showed minor damage in a couple of locations; this damage likely occurred during the flywheel removal, and even if present during the test, it would not have caused leakage. Other than the dust shield damage, there was no visible damage to any of the seal assembly components.

Based on the observed condition of the rear main seal, the leakage past the seal was not due to seal damage or failure of the seal. Given that the seal did not leak during the baseline test or until after a few hours into the diluted LO test, leakage past the seal occurred due to a combination of: (1) the LO/FO mixture level reaching the elevation of the seal, and (2) the decreased effectiveness of the seal due to the decreased mixture viscosity. All of the components of the seal assembly are highly resistant to diesel FO; therefore, it is unlikely that the high FO concentration during the diluted test caused any permanent damage to the seal. MPR expects that the seal in its current condition would most likely be effective again (i.e., not leak) during further operation of the engine with normal LO conditions. (Note: The rear main seal assembly on the 2B AF engine is the same as on the test engine.)

The inspection did not identify any other locations in the vicinity of the rear main seal where leakage had obviously occurred during the diluted LO test.

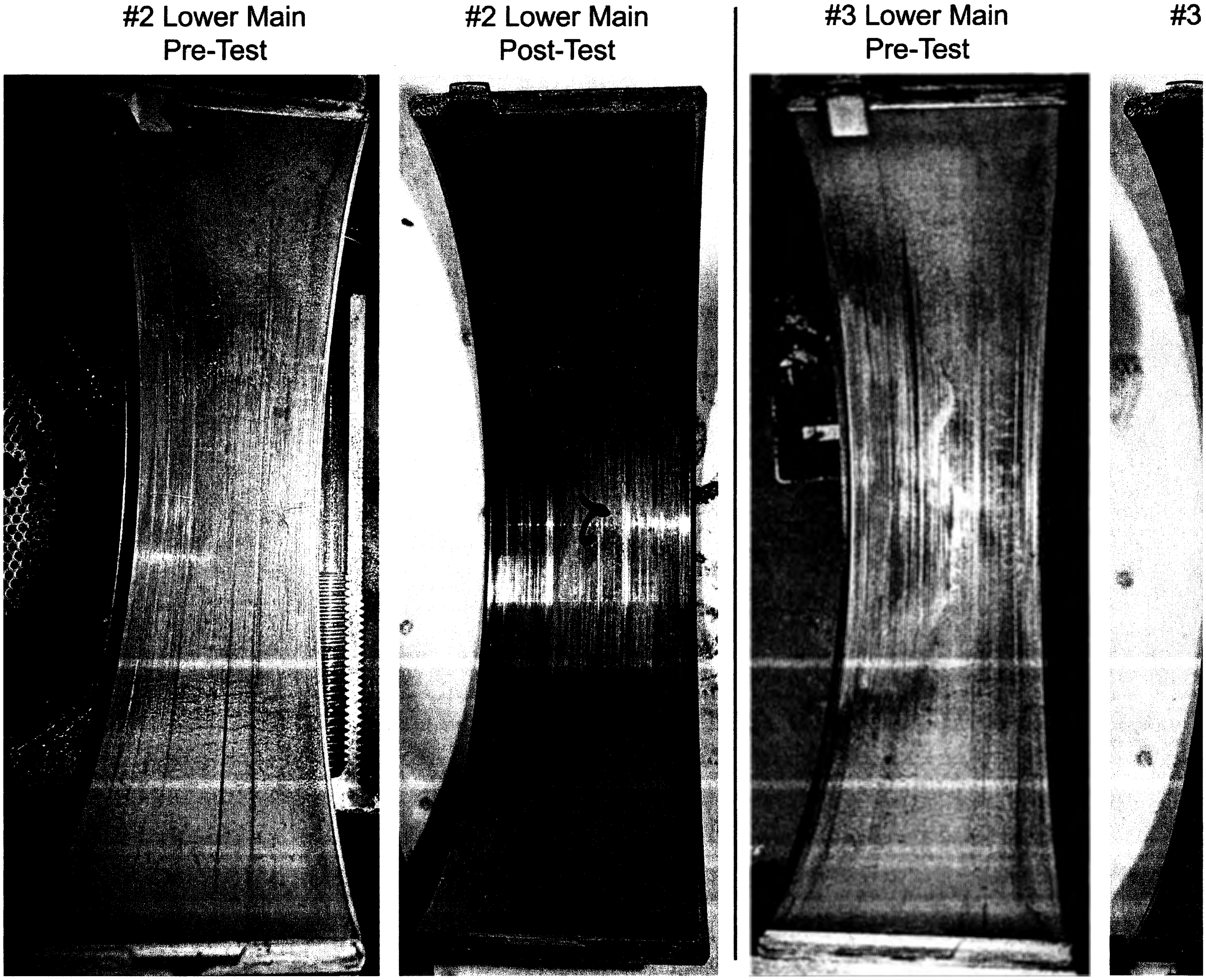

Figure 6-33. Comparison of Pre- and Post-Test Inspection Results for Engine Lower Main Bearir

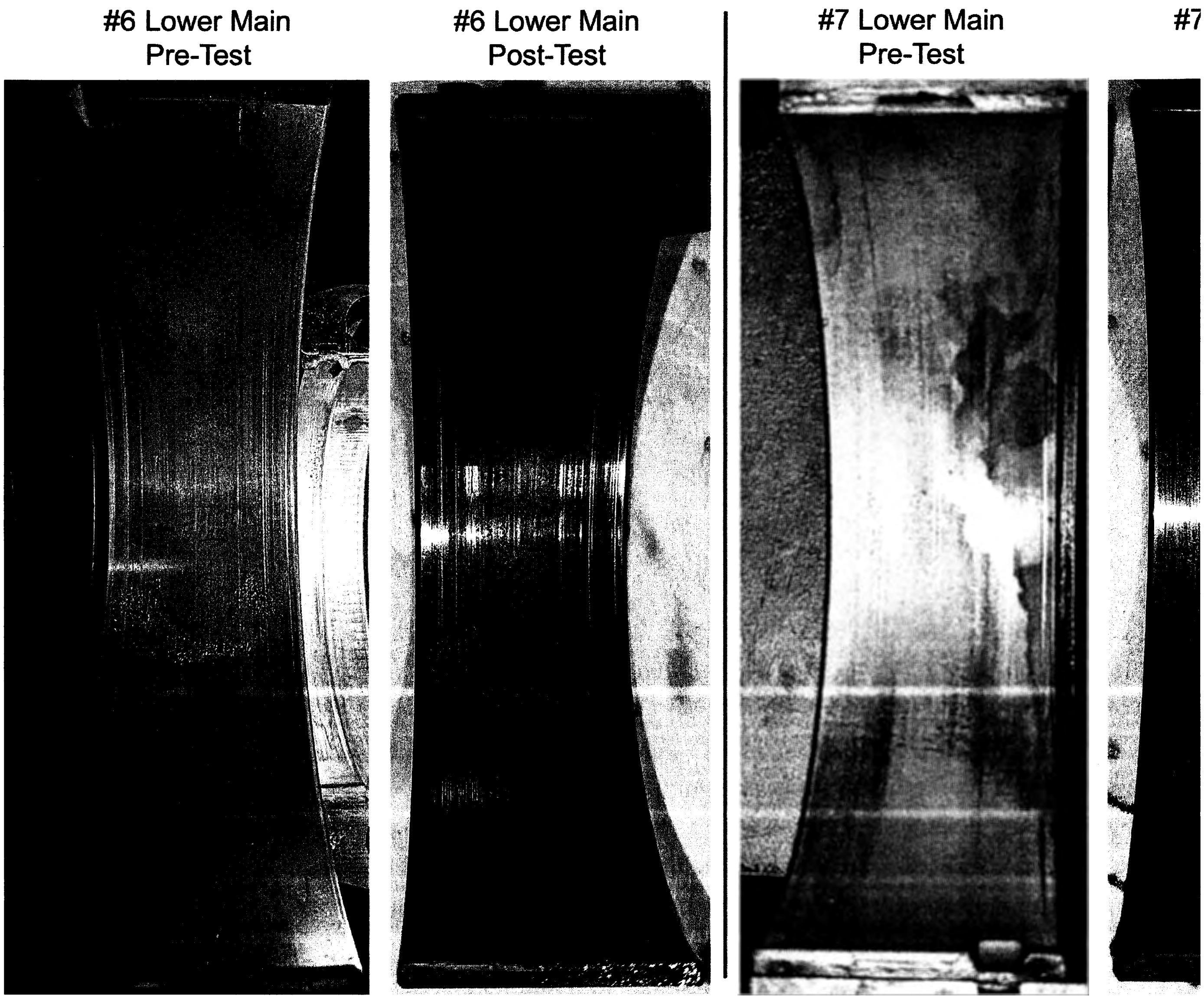

Figure 6-34. Comparison of Pre- and Post-Test Inspection Results for Engine Lower Main Bearir

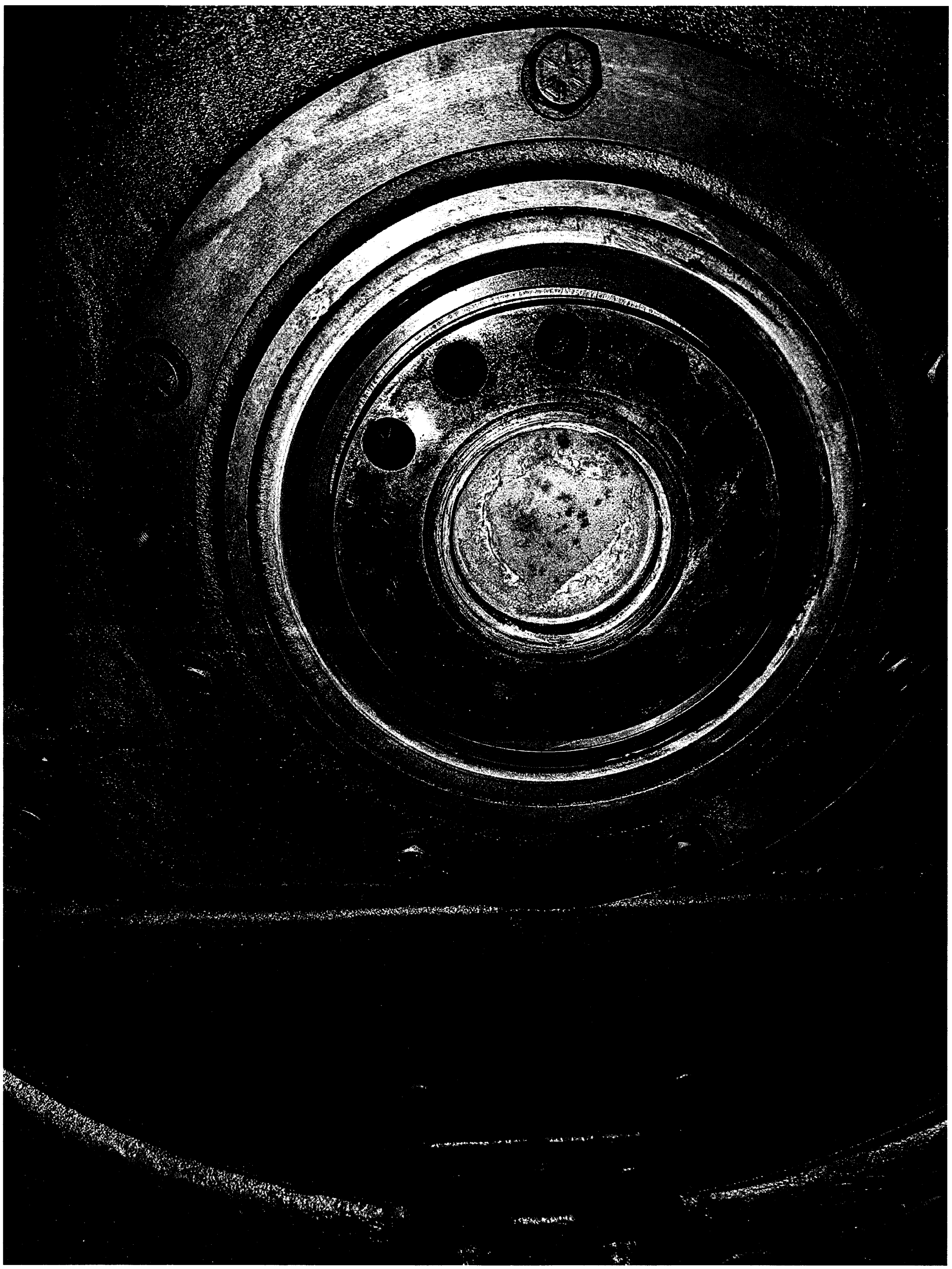

Figure 6-35. Rear Main Seal – View from Rear End

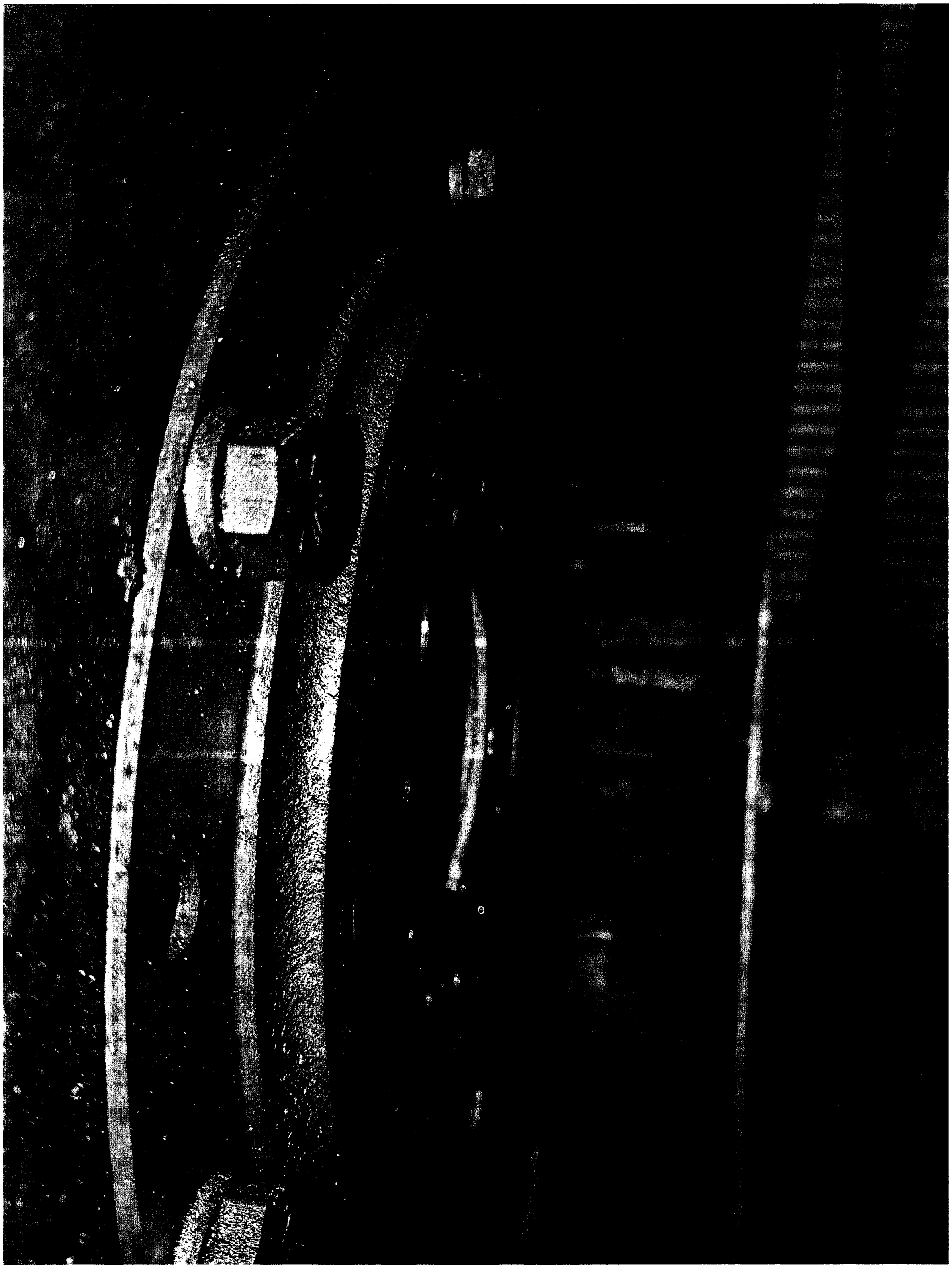

Figure 6-36. Rear Main Seal – View from Left-Bank Side

Figure 6-37. Rear Main Seal – View from Right-Bank Side

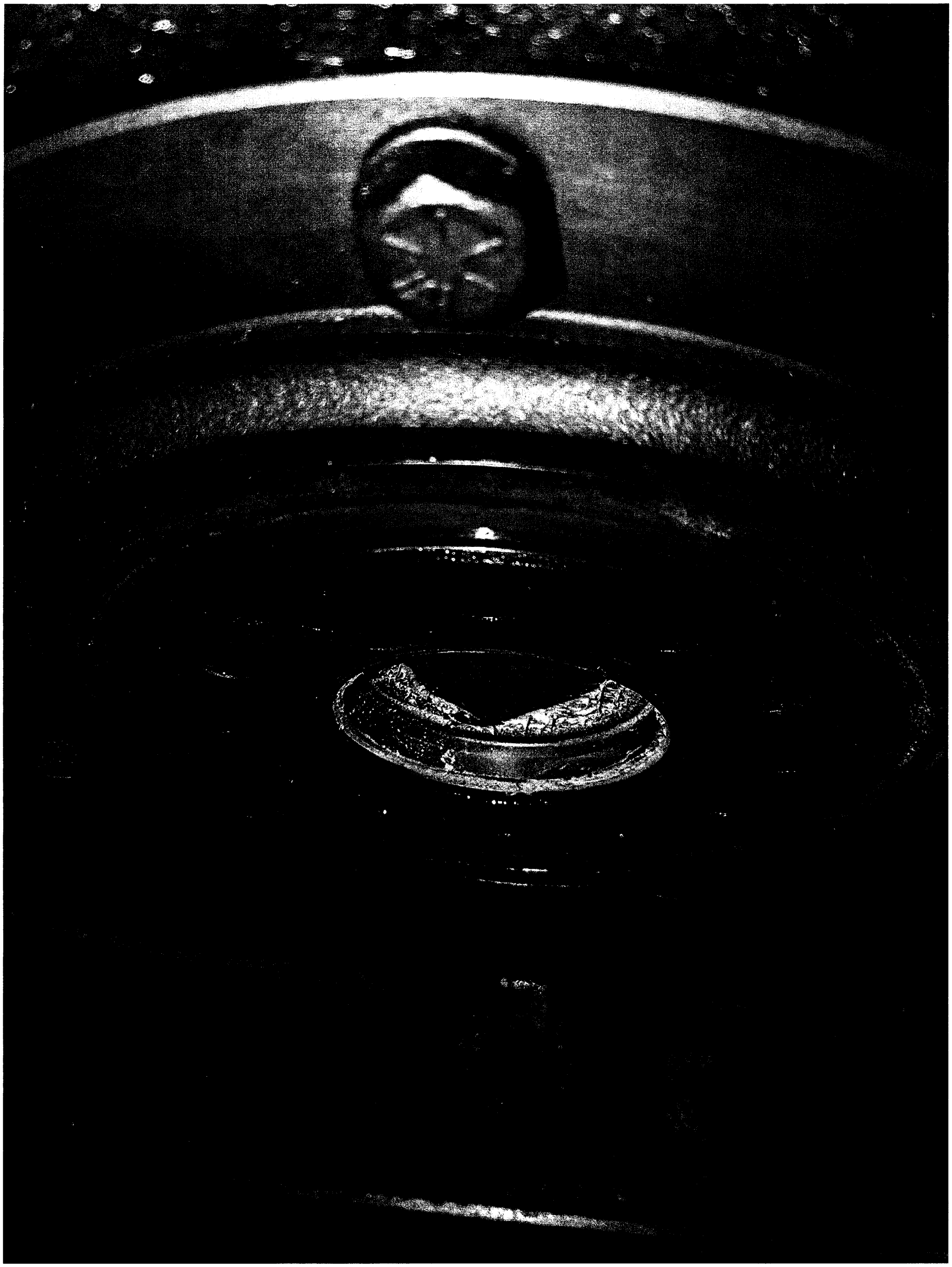

Figure 6-38. Rear Main Seal – View from Above

Figure 6-39. Rear Main Seal – View from Below

6.5. *Supplemental LO and FO Analyses*

6.5.1. Issue

As noted in Section 6.3.15, the FO concentrations reported in Table 6-4 for the diluted LO test are significantly lower than projected for the test based on the staring FO concentration and rate of FO addition during the test. Figure 6-40 shows the measured FO concentrations compared to the projected values. ASTM D3524 (Reference 18), which is the standard test method for quantifying FO concentration in LO, was used to analyze the LO/FO mixtures samples from the diluted test. The ASTM standard includes statements in its scope that the test is limited to SAE 30 oil and FO concentrations up to 12 wt.%. Both requirements were not satisfied for the diluted LO test samples. The accuracy of the ASTM D3524 test results for different grades of LO and higher FO concentrations is not known. As a result, MPR developed an alternative methodology for determining accurate FO concentrations for the diluted LO test LO/FO mixture samples.

6.5.2. Methodology

In order to determine accurate FO concentrations for the diluted test samples, MPR contracted SwRI to prepare and analyze a supplemental set of LO/FO mixture samples with known FO concentrations ranging from pure LO (0 wt.% FO) to pure FO (100 wt.% FO). The results of these analyses were used to generate calibrations that were used to identify a FO concentration for each diluted test sample.

As shown in Table 6-4, the viscosity of the LO/FO mixture decreased significantly and progressively as the FO concentration increased during the diluted LO test. LO also typically contains an additive package containing multiple elements at elevated levels (e.g., calcium, phosphorus, zinc, magnesium). The SwRI test report (Reference 10, Appendix E) includes concentrations for each of these elements for each diluted test sample. Similar to the viscosity values, the element concentrations also decreased significantly and progressively as the FO concentration increased during the diluted test. Based on these observations, MPR requested that SwRI quantify viscosity and element concentrations for each supplemental sample. MPR also requested that SwRI also perform the ASTM D3524 (Reference 18) test on each supplemental sample. SwRI prepared the supplemental samples with FO concentration on a weight basis (as opposed to a volume basis) for better accuracy and since the ASTM test results are typically reported in wt.%. MPR converted the FO concentration values to vol.% so that values in both units could be leveraged during data comparisons.

Table 6-5 contains the results of the supplemental LO/FO mixture analyses.

6.5.3. Determination of Calibrations for Determining FO Concentration

Calibrations that could be used to determine accurate FO concentrations for the diluted LO test samples were determined separately using the supplemental viscosity and element concentration data. Calibrations were prepared using both data types since each version could potentially provide different FO concentration values. The methods used to determine the calibrations are summarized in the following sections.

Viscosities

Figure 6-41 and Figure 6-42 show viscosity (at 40°C and 100°C, respectively) plotted as a function of FO concentration (wt.%) for the supplemental LO/FO mixture samples. On each plot, a smooth curve fit through the data was added so that interpolated correlations between viscosity and FO concentration could be made. In Section 6.5.4, the plots are used to determine approximate initial and final FO concentrations for the diluted LO test.

Element Concentrations

The decrease in the concentration of LO additive elements with increasing FO concentration is due to volumetric dilution.[6] As a result, it is expected that the element concentrations in a LO/FO mixture decrease proportionally with the volume of FO in the mixture (assuming a uniform distribution of each element in the sample, which is reasonable). For example, if a mixture contains 20 vol.% FO (and correspondingly only 80 vol.% LO), then the element concentrations of the mixture should be 80% of the corresponding baseline concentrations in the pure LO (no FO) sample. To confirm this expectation, the element concentrations measured for the supplemental LO/FO mixture samples were compared to the baseline values for the pure LO sample to determine the fraction (by volume) of each element in each mixture. Figure 6-43 shows the measured volume fraction of the baseline element value as a function of the target volume fraction of the baseline (for the latter, the target value is simply equal to the FO concentration divided by 100). As shown, the data for all elements fall nearly on top of one another along a line with slope of 1. This result confirms the expectation that the element concentrations in the LO/FO mixtures decrease proportionally with FO concentration. Therefore, the FO concentration (vol.%) can be determined using the following equation:

$$Fuel\ Oil\ Conc.(vol.\%) = \left(1 - \frac{Measured\ Element\ Concentration}{Baseline\ Element\ Concentration}\right) x\ 100 \quad (Eq.1)$$

Equation 1 is used in Section 6.5.4 to determine a FO concentration for each of the diluted LO test samples.

6.5.4. Determination of FO Concentrations for Diluted LO Test

FO concentrations for the LO/FO mixture samples collected during the diluted LO test were determined using both the viscosity and element concentration calibrations discussed in Section 6.5.3. These results are summarized in the following sections.

[6] It is normal for the concentration of some LO additive elements to decrease with engine operation (the elements are "consumed" as they perform their function(s)). The decrease typically occurs slowly over the course of hundreds to thousands of operating hours. This evaluation assumes that the extents of normal consumption of additive elements during the diluted LO test (i.e., during 24.5 operating hours) are negligible and do not significantly impact the FO concentrations predicted using the measured element concentrations.

Viscosities

Figure 6-44 and Figure 6-45 show viscosity (at 40°C and 100°C, respectively) plotted as a function of FO concentration (wt.%) for the supplemental LO/FO mixture samples (same plots as in Figure 6-41 and Figure 6-42). Each plot is annotated with red arrows that identify the expected FO concentrations (wt.%) at the start and end of the diluted LO test based on the measured viscosities for the initial and final samples collected. As shown, both viscosity values predict an initial FO concentration of approximately 16.5 wt.% and a final FO concentration of approximately 41 wt.%. Using the specific gravities for pure LO and pure FO identified in Section 4.7, these values correspond with 17.1 vol.% (initial) and 42 vol.% (final).

Element Concentrations

Table 6-6 contains the element concentrations measured for the LO/FO mixture samples collected during the diluted LO test. Table 6-7 contains the calculated FO concentrations for the diluted samples based on Equation 1 in Section 6.5.3. Figure 6-46 contains a plot of the calculated FO concentrations for each element as a function of elapsed time for the diluted test. For each diluted test sample, the plot also includes the average of the FO concentrations calculated based on the four elements. Finally, a polynomial regression (second-order) of the average FO concentrations is plotted to show the overall trend in the increase in FO concentration with time. The regression predicts an initial FO concentration of 15.1 vol.% and a final FO concentration of approximately 45.8 vol.% for the diluted test.

Assessment

The ranges of FO concentrations for the diluted LO test predicted based on viscosity and element concentration are similar, but slightly different. The viscosity data predict a higher initial concentration (17.1 vs 15.1 vol.%) that is closer to the target initial concentration for the test. However, the viscosity data also predict a lower final concentration (42 vs 45.8 vol.%) that is further from the target final concentration of approximately 52.5 vol.%. The reason(s) for the difference in predicted FO concentrations are not fully understood, but they are potentially related to the limitations of the ASTM test (Reference 18) discussed in Section 6.5.1. That said, MPR considers that the FO concentrations predicted based on element concentrations are more accurate based on the fundamental simplicity and soundness of how they were calculated. MPR is not aware of any mechanisms by which the element concentrations would change from the baseline value during limited duration testing, other than by the previously mentioned volumetric dilution by the FO, such that the predicted FO concentrations would be significantly affected. MPR also considers that the decreases in viscosity during the test may be influenced by other parameters than the FO concentration. It is clear that the increasing FO concentration was the principal influence on the decreasing viscosity; however, there may have been other second-order factors that had impacts on viscosity that were relatively small but significant enough to impact the predicted FO concentrations. As a result, MPR considers that it is more appropriate to use the FO concentrations based on element concentrations when evaluating the results of the diluted LO test and their comparison with the test plan requirements.

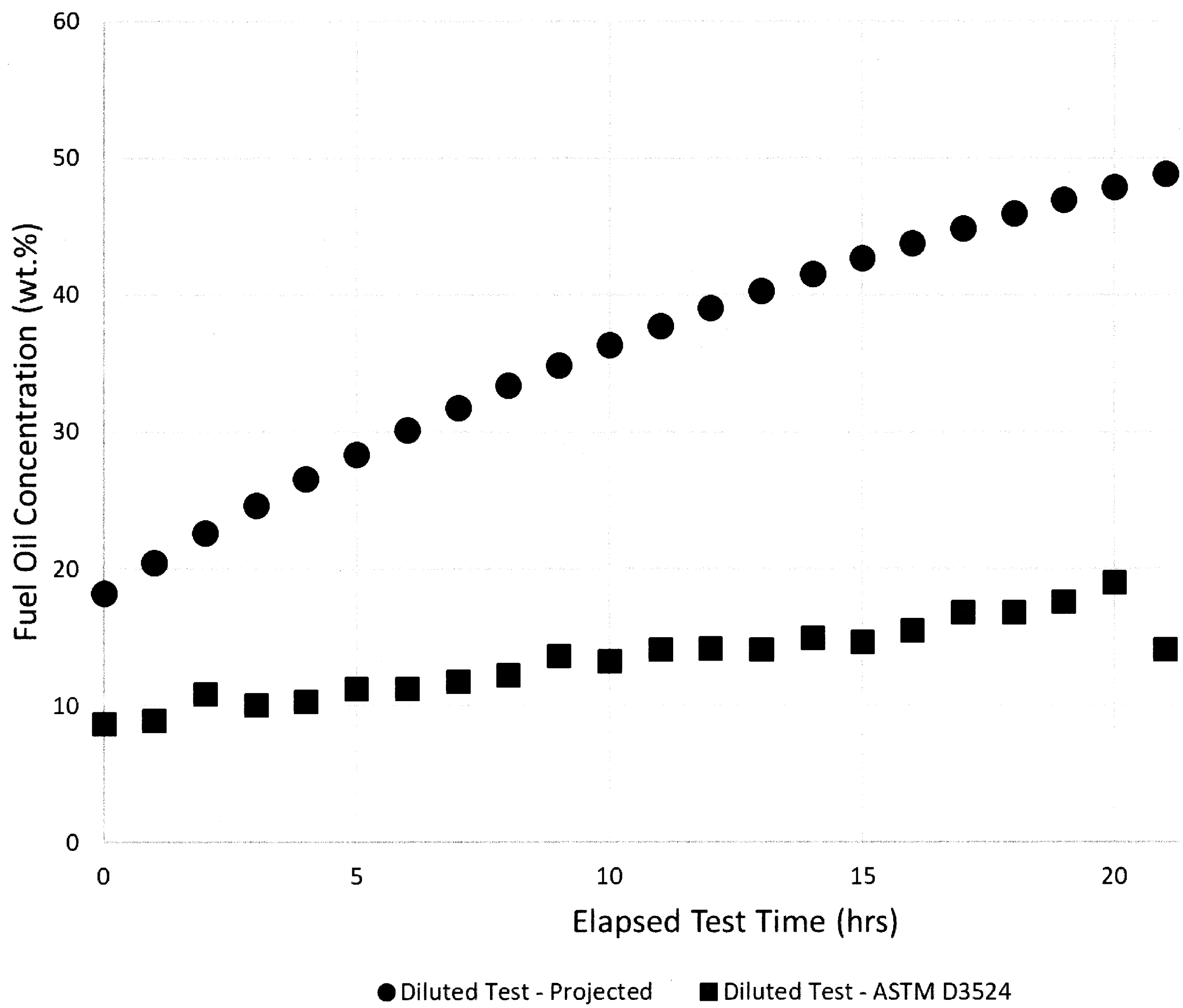

Figure 6-40. Comparison of Measured FO Concentrations (ASTM D3524) and Projected Values for

Table 6-5. Supplemental LO/FO Mixture Analysis Results

ASTM D3524 FO Concentration (wt.%)	ASTM D445 Viscosity, 40°C (cSt)	ASTM D445 Viscosity, 100°C (cSt)	ASTM D5185 Calcium (ppm)	ASTM D5185 Phosphorus (ppm)	ASTM D5185 Zinc (ppm)	ASTM D5185 Magnesium (ppm)
< 0.3	132.4181	14.4402	3556	904	989	211
2.6	100.2988	12.0908	3370	858	936	200
8.5	74.7121	9.8004	3125	796	870	186
12.1	60.5065	8.7418	2998	764	836	178
16.1	46.3297	7.5726	2812	718	787	167
27.5	29.5151	5.6387	2448	627	685	146
39.3	19.3872	4.3422	2115	534	582	125
49.1	12.9981	3.3998	1728	440	480	103
58.0	9.0259	2.6600	1411	380	394	84
68.4	6.4053	2.1062	1049	279	308	63
78.6	4.7909	1.6937	696	184	204	41
90.0	3.5910	1.3748	352	94	104	21
94.4	2.6917	1.1055	< 1	< 1	< 1	< 1

with a total weight of 100g, and the individual weights of LO and FO were varied to achieve the correct FO concentrations. For
) sample consisted of 80g LO mixed with 20g FO.

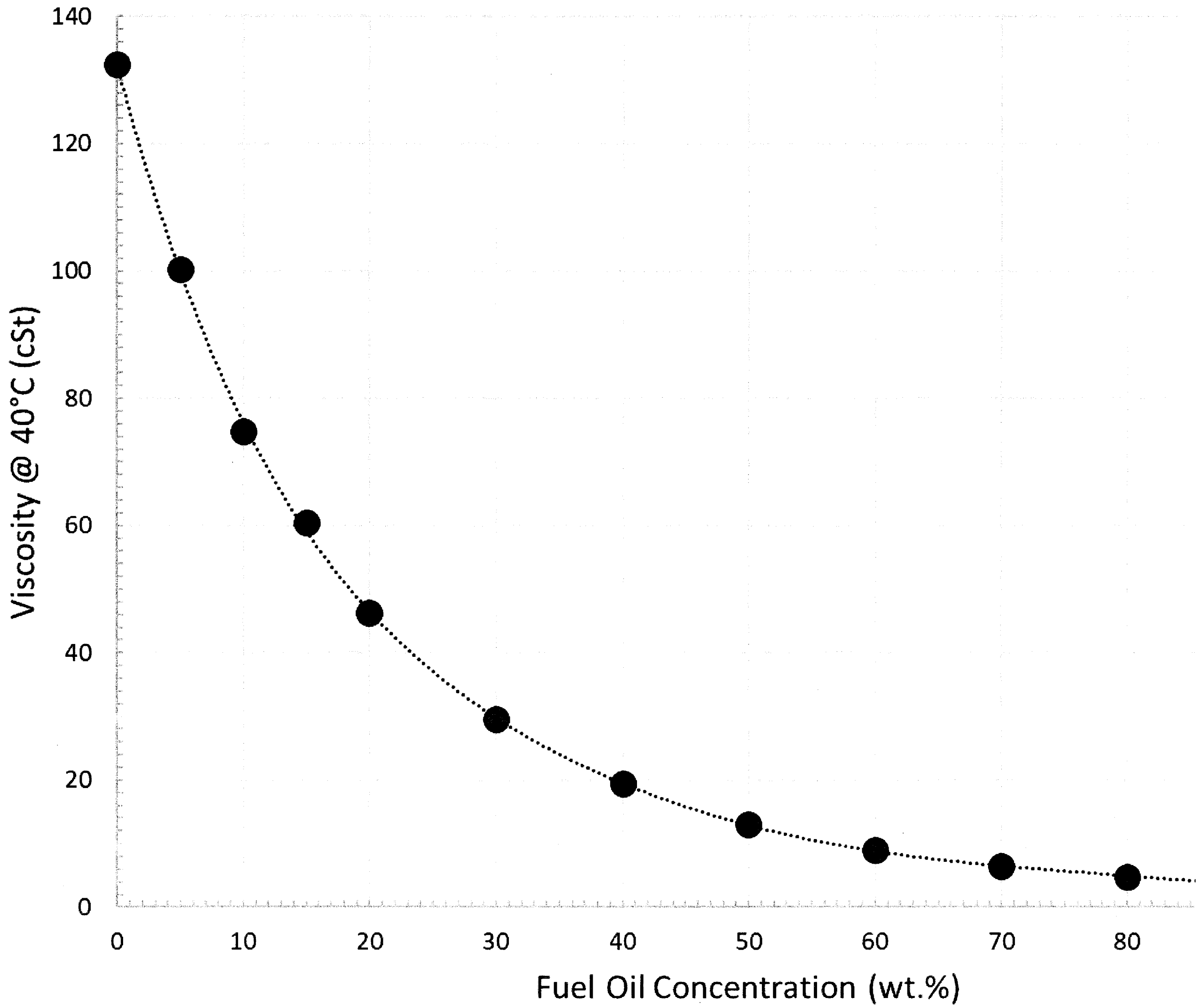

Figure 6-41. Viscosity @ 40°C vs. FO Concentration

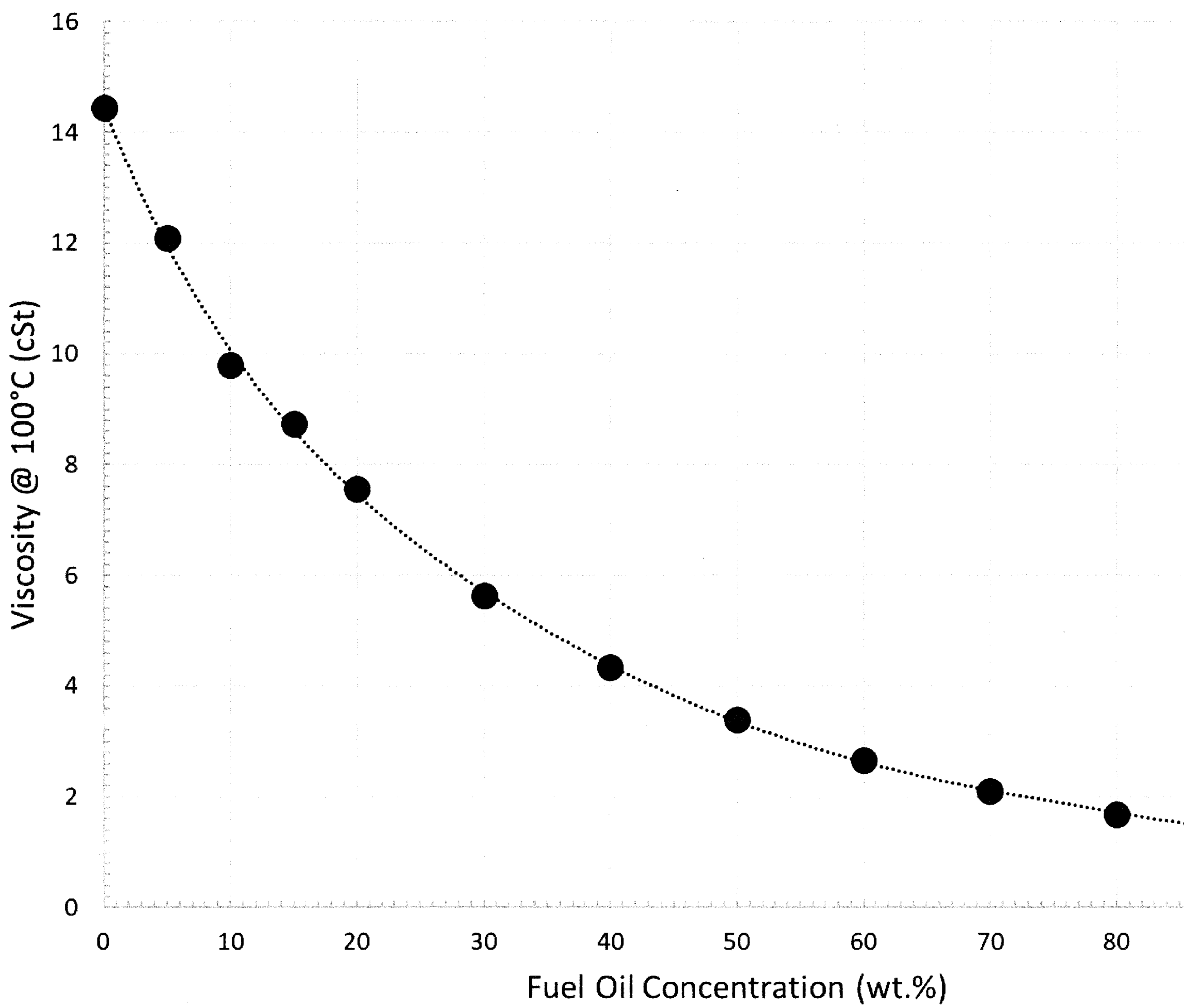

Figure 6-42. Viscosity @ 100°C vs. FO Concentration

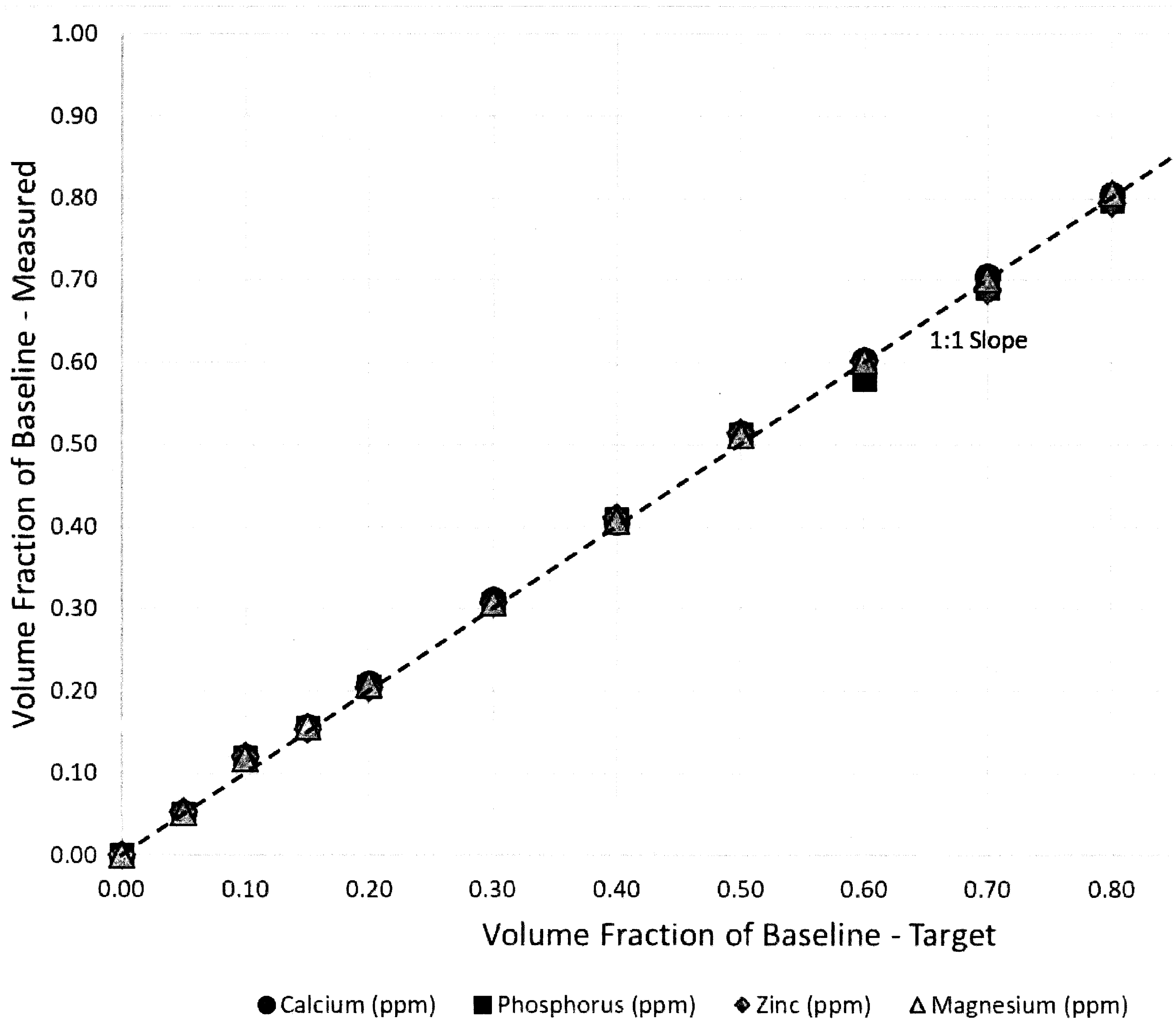

Figure 6-43. Elemental Volume Fraction of Baseline (Pure LO) Value – Measured vs. Ta

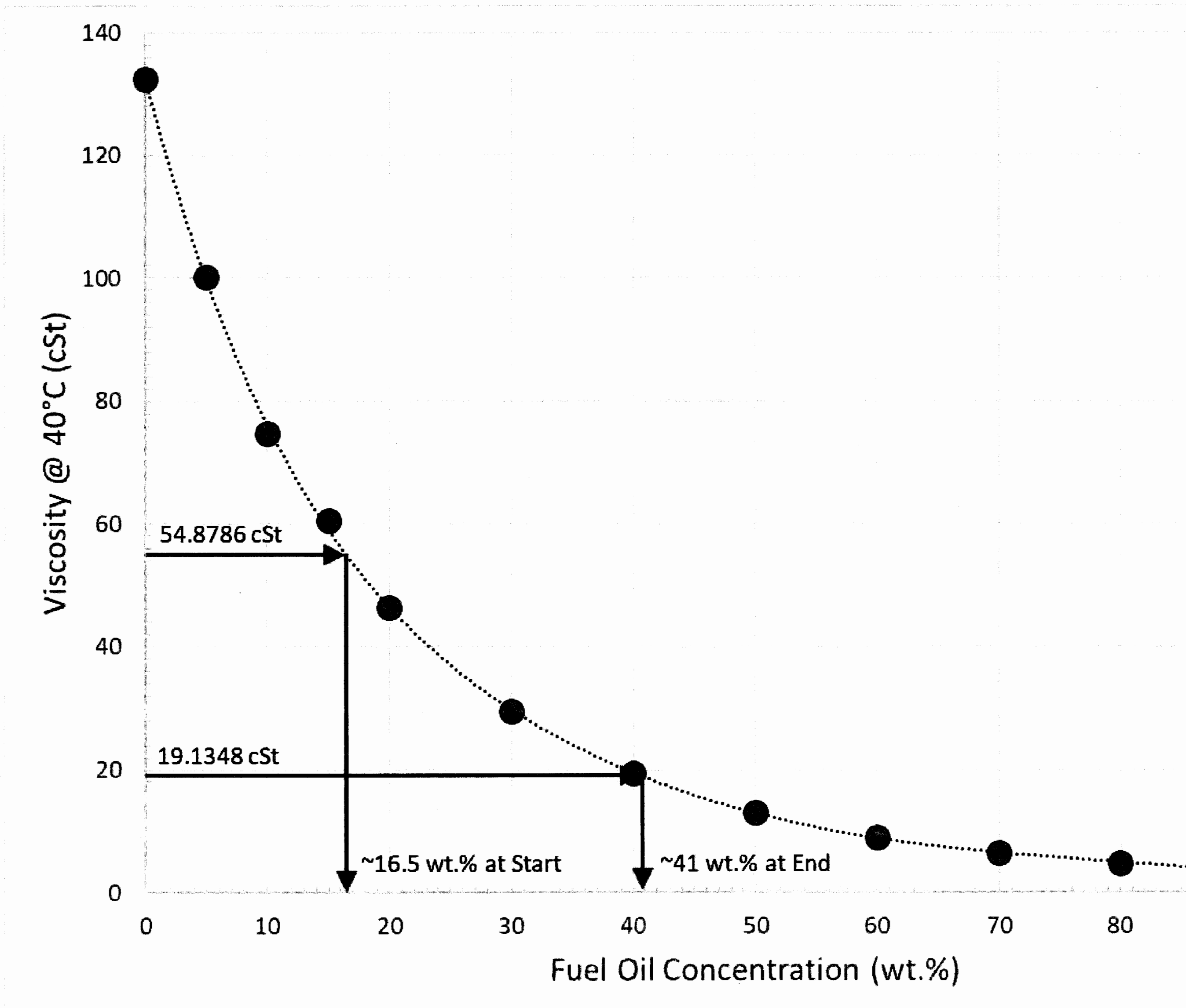

Figure 6-44. Predicted FO Concentrations for Diluted LO Test Based on Viscosity @ 40°C vs. FO

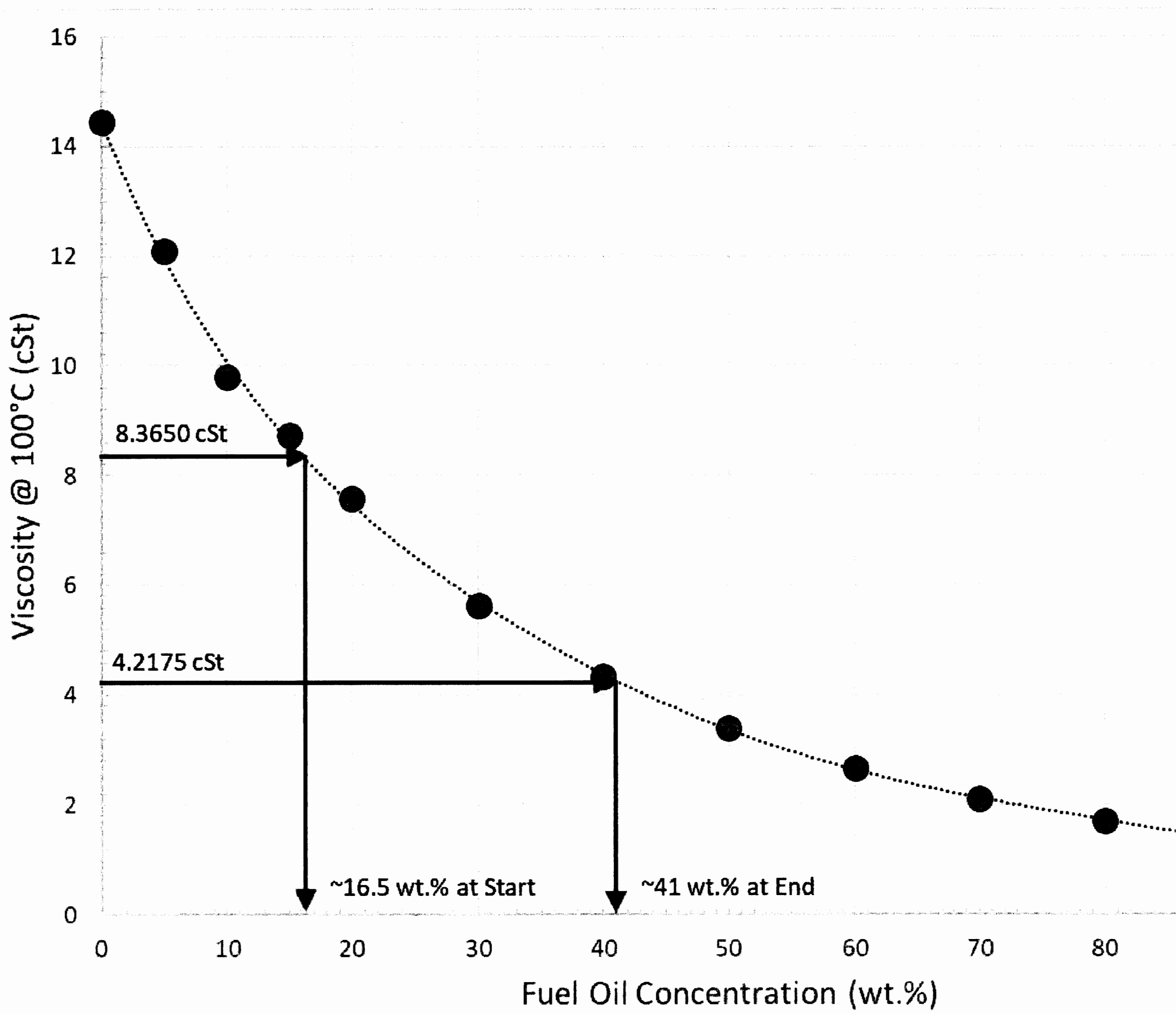

Figure 6-45. Predicted FO Concentrations for Diluted LO Test Based on Viscosity @ 100°C vs. FC

Table 6-6. Diluted LO Test Engine LO/FO Mixture Sample Analysis Results

Elapsed Test Time (hr)	ASTM D5185 Calcium (ppm)	ASTM D5185 Phosphorus (ppm)	ASTM D5185 Zinc (ppm)
0 (Shortly After Test Start)	3116	819	870
1	3042	755	846
2	2994	781	837
3	2956	772	822
4	2916	765	815
5	2863	715	798
6	2798	728	778
7	2751	718	766
8	2703	702	753
9	2669	694	744
10	2623	674	726
11	2568	661	709
12	2514	649	693
13	2479	640	720
14	2423	623	701
15	2379	609	690
16	2338	600	678
17	2289	589	663
18	2246	582	656
19	2178	562	630

Elapsed Test Time (hr)	ASTM D5185 Calcium (ppm)	ASTM D5185 Phosphorus (ppm)	ASTM D5185 Zinc (ppm)
20	2144	551	616
21	2107	540	608
22	2069	530	596
23	2021	517	579
24	1994	511	573
24.5	1974	505	568
Baseline [1]	3682	925	1032

1. The baseline value for each element is the average of the values measured for the four LO samples collected during the first bas

Table 6-7. FO Concentrations for Diluted LO Test Samples Based on Element Concent

Elapsed Test Time (hr)	FO Concentration Calcium-Basis (vol.%)	FO Concentration Phosphorus-Basis (vol.%)	FO Concentration Zinc-Basis (vol.%)	FO Concentration Magnesium-Basis (vol.%)
0 (Shortly After Test Start)	15.4	11.4	15.7	14.5
1	17.4	18.3	18.0	16.8
2	18.7	15.5	18.9	18.6
3	19.7	16.5	20.3	19.5
4	20.8	17.3	21.0	20.5
5	22.2	22.7	22.7	21.8
6	24.0	21.3	24.6	23.7
7	25.3	22.3	25.8	24.6
8	26.6	24.1	27.0	26.4
9	27.5	24.9	27.9	26.9
10	28.8	27.1	29.7	28.3
11	30.3	28.5	31.3	30.1
12	31.7	29.8	32.8	31.5
13	32.7	30.8	30.2	32.9
14	34.2	32.6	32.1	34.3
15	35.4	34.1	33.1	34.7
16	36.5	35.1	34.3	36.1
17	37.8	36.3	35.8	37.5
18	39.0	37.0	36.4	38.9
19	40.9	39.2	39.0	40.2

Elapsed Test Time (hr)	FO Concentration Calcium-Basis (vol.%)	FO Concentration Phosphorus-Basis (vol.%)	FO Concentration Zinc-Basis (vol.%)	FO Concentration Magnesium-Basis (vol.%)
20	41.8	40.4	40.3	41.1
21	42.8	41.6	41.1	42.5
22	43.8	42.7	42.2	43.4
23	45.1	44.1	43.9	44.8
24	45.8	44.7	44.5	45.3
24.5	46.4	45.4	45.0	45.7

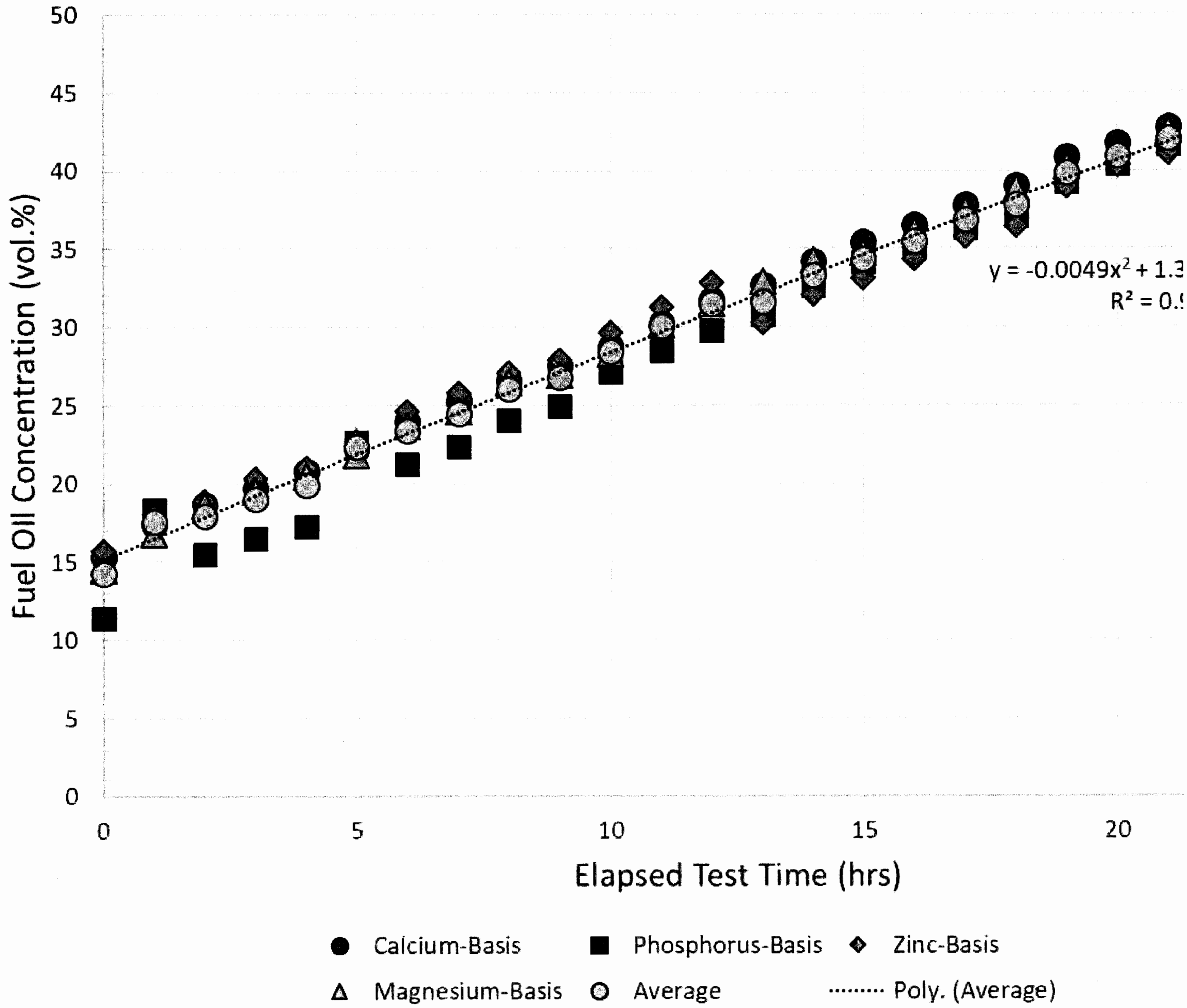

Figure 6-46. Predicted FO Concentrations for Diluted LO Test Samples Based on Element Co

7.0 Evaluation of Results

The results of the test to simulate operation of the Braidwood 2B AF diesel engine with FO-diluted LO are evaluated in the following subsections.

7.1. Performance of Test Engine During Diluted LO Test

Section 6.0 documents in detail the test engine performance during the diluted LO test. As part of this, direct comparisons are made to the performance of the engine during the baseline test. These comparisons allow for the impacts of decreasing LO viscosities due to dilution by FO during engine operation to be quantified and evaluated.

During the diluted LO test, the test engine operated for a full 24 hours, the same cumulative duration as the baseline test, plus an additional 30 minutes. Overall, the operation of the test engine was excellent and largely normal for the full duration of the diluted test. In fact, the decision to extend the test duration by 30 minutes was made based on the excellent performance of the engine and the opportunity this presented to build margin into the test results. Both MPR and Constellation requested that the test continue even longer given the performance of the engine; however, SwRI did not permit this given the uncertainty (at the time) regarding the nature and source of the leaked fluid and the potential implications on test personnel and facility safety.

The only notable differences in engine performance during the diluted LO test compared to the baseline test were as follows:

- The initial LO/FO mixture pressure was approximately 2-3 psig lower than during the baseline test. Further, while the LO pressure remained relatively constant during the baseline test, the LO/FO mixture pressure progressively decreased slowly and consistently over the full duration of the diluted LO test at a rate of approximately 0.3 psig/hr. By the end of the test, the pressure had decreased by an additional approximate 7 psig to an average of 47 psig (compared to an average pressure of 56-57 psig during the baseline test). Despite the pressure decrease, the average pressure was still within the normal 45-70 psig range for the test engine and well above the 2B AF engine trip of 10 psig. In general, the decrease in LO/FO mixture pressure will be detrimental to engine performance. Below some threshold (lower than the manufacturer recommended normal pressure range), the pressure will be insufficient to support bearing/bushing loads, and damage/failure should be expected. See Section 7.5 for further discussion.
- Similar to LO/FO mixture pressure, the initial LO/FO temperature was lower than during the baseline test (by approximately 6-9°F). Further, while the LO temperature remained relatively constant during the baseline test, the LO/FO mixture temperature progressively decreased slowly and consistently toward the end of the diluted test at a rate of approximately 0.3°F/hr despite the generator load remaining constant (in contrast, the temperature remained relatively constant at a given generator load during the baseline test). In general, the decrease in LO/FO mixture temperature is beneficial to engine performance. The lower temperature results in a higher LO/FO mixture viscosity, which increases the mixture pressure and the margin to bearing/bushing failure.

- LO/FO mixture leaked from the crankshaft rear main LO seal during the diluted LO test, but not during the baseline test. In Reference 3, Detroit Diesel states that leakage past the seal is expected under some operating conditions, e.g., if the LO level is too high. The leakage has a significant impact on the interpretation of the test results and the conclusions drawn from them. The leakage is discussed further in Sections 6.3.13, 6.3.14, 6.4.2, and 7.3.

The baseline and diluted LO tests were completed without any apparent damage occurring to any lubricated engine/turbocharger components. Detroit Diesel recommends inspecting a subset of the lower main bearings when an engine experiences a LO dilution event. The inspection of the lower main bearings prior to the baseline test and after the diluted LO test identified no change in appearance. Further, the analysis of LO and LO/FO mixture samples collected during the baseline test and diluted test, respectively, showed that there was no increase in the concentrations of any wear metals during either test. Finally, there was no significant difference in the shutdown behavior (i.e., shutdown time) of the test engine for the baseline and diluted tests. This similar behavior is consistent with lubricated components not having experienced any damage that resulted in an increase in overall engine friction between the rotating/reciprocating components and stationary components.

Overall, the test engine operated similarly during both the baseline test and diluted LO test with no apparent indications of engine/component degradation or distress. If the leakage of the LO/FO mixture had not occurred and the LO/FO mixture pressure had not been closely monitored and trended, there would have been no obvious indicators that the LO contained a high and increasing concentration of FO during the diluted LO test.

7.2. Test Engine/Turbocharger Bearing and Bushing Lubrication

The test plan requirements, or the intent of the requirements, were satisfied for all test parameters during the baseline and diluted LO tests except for the range of FO concentrations tested during the diluted test. Figure 7-1 shows the FO concentrations predicted for the diluted test based on element concentrations compared to the projected FO concentrations for the test (based on the test plan requirements). As shown, the peak FO concentration reached during the diluted test was nearly 7 vol.% lower than the peak concentration projected for the test. Section 4.6 discusses the estimation of the volume of residual pure LO inside the test engine at the start of the diluted LO test. MPR expects that the lower-than-expected range of FO concentrations during the diluted test was due to the underestimation of the residual pure LO volume. The uncertainty in the residual volume was acknowledged prior to the diluted test, and it was expected that the actual FO concentrations during the test may not exactly match the projected values.

As mentioned in Section 1.3, the primary concern (i.e., potential failure mechanism) resulting from LO containing a high concentration of FO is inadequate lubrication of engine/turbocharger bearings and bushings. The high FO concentration causes a decrease in the viscosity of the LO/FO mixture. As the viscosity decreases, the ability of the mixture to support bearing/bushing loads also decreases. In terms of how well bearings and bushings were lubricated during the diluted LO test, the specific viscosities and the range of the viscosities are of fundamental importance (FO contamination is the cause, but the impact on viscosity is the effect that can lead to failure).

Figure 6-41 and Figure 6-42 show viscosity at 40°C and 100°C, respectively, plotted as a function of FO concentration for the supplemental LO/FO mixtures analyzed by SwRI. As shown, the decrease in viscosity is not linear with FO concentration at both ASTM test temperatures. For a similar change in FO concentration (e.g., 10 vol.%), the decrease in viscosity is significantly larger at low FO concentrations than at high concentrations. For example, an increase in FO concentration from 0 vol.% (pure LO) to 10 vol.% results in decreases in viscosity of approximately 42% (at 40°C) and 30% (at 100°C) relative to the baseline viscosities of the pure LO. In contrast, an increase in FO concentration from 50 vol.% to 60 vol.% results in decreases in viscosity of approximately 3% (at 40°C) and 5% (at 100°C) relative to the baseline viscosities. At higher FO concentrations, relatively large changes in FO concentration result in relatively small differences in viscosity, and by extension relatively small differences in lubrication quality. For the difference in predicted versus projected final (highest) FO concentrations for the diluted LO test, the corresponding differences in final (lowest) viscosities are small (approximately 5% at 40°C and 7% at 100°C). It follows that the expected difference in lubrication quality at the final viscosities is similarly small. As noted earlier, the test engine performance was still excellent and effectively normal at the end of the diluted LO test with no damage to engine bearings/bushings having occurred. Based on this, MPR considers that the differences in final viscosities had no impact on the test results, in particular the ability of the engine to operate with a high and increasing concentration of FO for more than 24 hours.

Figure 7-2 and Figure 7-3 show viscosity (at 40°C and 100°C, respectively) plotted as a function of FO concentration (vol.%) for the supplemental LO/FO mixture samples. Overlaid on each plot are two boxes, one for the diluted LO test (red box) and one for the 2B AF engine (blue box), that illustrate the respective ranges of viscosity and FO concentration. The ranges for the boxes were determined as follows:

- For the diluted LO test boxes, the viscosity limits are the measured values for the initial and final LO/FO mixture samples collected during the diluted test. The FO concentration limits are the predicted values based on element concentrations for the same initial and final samples.
- For the 2B AF engine boxes, the FO concentration limits are the projected initial and peak FO concentrations for the diluted LO test (i.e., 18.82 vol.% and 52.45 vol.%, respectively). The upper viscosity limit is the measured value for the September 21, 2023, LO/FO mixture sample collected from the 2B AF engine (Reference 2). The lower viscosity limit is the value from the viscosity versus FO concentration curve corresponding with the projected peak FO concentration.

Figure 7-2 and Figure 7-3 both show that the ranges of viscosity and FO concentration largely overlap, in particular when considering their overall size and location relative to the full range of viscosity for FO concentrations from 0 vol.% (pure LO) to 100 vol.% (pure FO). Of the two parameters, viscosity is more important than FO concentration when considering the impacts on bearing/bushing lubrication. The initial viscosities for the diluted LO test and 2B AF engine were very similar (in fact, the values at 100°C, which is very close to the LO/FO mixture temperature, are nearly identical). The differences in final viscosities were larger than the differences in initial viscosities; however, they were still small and represent a relatively small difference in the quality of bearing/bushing lubrication. The overall goal of the diluted LO test was to determine if a high and increasing FO concentration impacted lubrication of the engine/turbocharger bearings and bushings sufficiently for damage and failure to occur. The figures support that the goal of the diluted LO test was satisfied despite the specific differences in FO concentration tested.

7.3. Test Engine LO/FO Mixture Level

As mentioned in Section 1.3, a second potential failure mechanism resulting from LO containing a high concentration of FO, in particular due to an active leak, is the internal LO/FO mixture level becoming too high. If the level continues to rise, at some point the internal rotating/reciprocating engine components will contact the LO/FO mixture. This is expected to have two primary effects: (1) aeration of the mixture, and (2) increased resistance to the rotating/reciprocating motion of components and frictional heating of the mixture (which further decreases the mixture viscosity). As part of the test plan development, MPR estimated that the LO/FO mixture level would rise to the lowest elevation of the internal rotating/reciprocating components approximately 8-10 hours into the diluted LO test.

Sections 6.3.13 and 6.3.14 discuss the leakage of the LO/FO mixture from the test engine during the diluted LO test starting at approximately 3.5 hours into the test. This leakage, combined with the normal consumption of the LO/FO mixture by combustion, had a significant impact on the rise in internal mixture level during the diluted test. Some contact between the internal rotating/reciprocating components likely occurred during the test based on the observation of bubbles in the samples of LO/FO mixture collected; however, these observations were intermittent and not excessive. Further, the LO/FO mixture level at the end of the test was approximately 0.5 in below the high-level mark despite the initial level being approximately 2 in above the same mark. These observations support that the LO/FO mixture level was high enough to contact the internal rotating/reciprocating components at times during the diluted oil test. However, in general the level did not get excessively high and for most of the test it was likely below the level at which contact occurred. MPR considers that the leakage of the LO/FO mixture from the test engine played a significant role in limiting the rise in the mixture level and helped mitigate the second potential failure mechanism.

In Section 6.3.13, MPR identified the crankshaft rear main LO seal as the most likely location at which the LO/FO mixture leaked from the test engine during the diluted LO test. A visual inspection of the rear main seal assembly confirmed that it was intact and without any obvious damage or failure (see Section 6.4.2). The test engine also contains a crankshaft front main LO seal. Leakage from the front end of the test engine was not observed during the diluted LO test, and a visual post-test inspection of the front of the engine showed no evidence of significant leakage in the vicinity of the crankshaft. To understand why leakage occurred at the rear main seal but not at the front main seal, MPR reviewed the design and location of both seals to identify reasons why one would be more susceptible to leakage.

The design of the front and rear main seal assemblies are the same (at least for the vintage of seals used in the test genset and 2B AF engines; the design of the front seal assembly has since been changed to include an additional exterior dust seal). However, as shown in Figure 7-4, the locations of the seals and the degrees to which they are protected from direct impingement of the LO/FO mixture are different. The rear main seal is not well protected by other internal components. LO/FO mixture that splashes onto the interior of the engine crankcase above the rear main seal will flow down to the seal without obstruction. Further, if/when the LO/FO mixture level rises above the bottom elevation of the rear crankshaft gear (which is directly adjacent to the seal), the gear will act as a pump and carry the mixture to the seal. In contrast, the front main seal is well protected by other internal components. The front of the engine contains an additional outboard bearing that also acts to support the seal. The bearing obstructs the front main seal and prevents the LO/FO mixture from direct impingement on the seal by either splashing or pumping via the front crankshaft gear. For the mixture to reach the seal, it would have to flow along a relatively long, tight and tortuous path; however, there is nothing to drive this flow. Given the noted differences, it is not surprising that significant leakage occurred past the rear main seal and not past the front main seal when the LO/FO mixture viscosity decreased sufficiently from the FO contamination. The front main seal is protected such that it is unlikely that the seal would experience any significant leakage regardless of how low the mixture viscosity decreased.

7.4. Explanation for Test Engine Performance During Diluted LO Test

The excellent performance of the test engine during the diluted LO test demonstrates that the engine/turbocharger bearings and bushings were adequately lubricated during the test despite the high concentration of FO in the engine LO. Most of the engine bearings (e.g., main bearings, connecting rod big-end bearings) and all of the turbocharger bearings (i.e., radial and thrust) are lubricated by a hydrodynamic lubrication mechanism. The engine also contains bushings (e.g., piston wrist pin bushings, rocker arm bushings) that are lubricated by boundary lubrication. The hydrodynamic engine and turbocharger bearings are more susceptible than the boundary-lubricated bushings to failure from decreased viscosities due to significant FO contamination because of: (1) high operating speeds, (2) high operating loads (in particular for the engine bearings), and (3) the importance of lubricant viscosity in achieving hydrodynamic lubrication conditions. Detroit Diesel's recommendation to inspect lower main bearings for damage if the FO concentration in the LO exceeds 2.5 vol.%, as discussed in Section 6.1 and Section 6.4.1, is consistent with the higher failure susceptibility of the hydrodynamic bearings.

Hydrodynamic bearings use relative motion to generate a high-pressure fluid film that keeps the moving and stationary surfaces physically separated. The separation of the surfaces results in a significant reduction in friction and prevents wear/damage of the surfaces. The resulting film pressure is significantly higher than the pressure of the fluid delivered to the bearing (e.g., the LO system pressure for the test engine). The film pressure increases with the difference between the speeds of the moving and stationary surface, i.e., higher operating speeds are beneficial. The hydrodynamic mechanism does not exist when there is no relative motion between surfaces. For example, when a rotating shaft is at rest, the hydrodynamic film does not exist, and the bottom of the shaft is in contact with the shaft's journal bearing. Specifically, asperities on the shaft and bearing surfaces are in contact with each other, while a partial fluid film exists in between the asperities. Initial lubrication of the shaft and bearing surfaces is provided by the partial fluid film. As the shaft begins to rotate, the relative motion creates a high-pressure wedge of fluid; the pressure of this wedge increases as the shaft speed increases. Above a threshold speed, the wedge pressure becomes sufficient to lift the shaft off of the bearing such that it "floats" within the fluid; i.e., hydrodynamic lubrication is achieved. As speed further increases, the minimum thickness of the fluid film between the shaft and bearing also increases. At relatively high speeds (compared to the threshold speed for hydrodynamic lubrication), the rotating shaft is stable and well-supported by the hydrodynamic film.

For a given lubricant quality, the highest probability of wear/damage occurring is during the initial rotation of the shaft prior to hydrodynamic lubrication being achieved. If hydrodynamic lubrication is achieved before significant wear/damage occurs, then continued rotation of the shaft without additional wear/damage is expected. Even if lubricant quality decreases thereafter, hydrodynamic bearing/bushing lubrication and continued shaft rotation without wear/damage should be expected as long as the volume, pressure (system, not fluid film) and viscosity of the supplied fluid remain adequate.

The above phenomenon explains the excellent test engine performance during the diluted LO test and why the test genset was able to operate for more than 24 hours with a high and increasing FO concentration in the test engine LO. Although the initial FO concentration was high, the volume, system pressure, and viscosity of the LO/FO mixture were still adequate for the engine/turbocharger bearings to survive the test start without any apparent wear/damage. As the test genset speed increased, the engine/turbocharger bearings/bushings quickly achieved hydrodynamic lubrication. For a high-speed diesel engine like the Detroit Diesel Series 149 engine, hydrodynamic bearing/bushing lubrication is typically achieved at a small fraction of the full operating speed, e.g., 200 rpm compared to the 1,800 rpm operating speed. This difference between the threshold and operating speeds represents a significant amount of intrinsic margin that exists relative to a decrease in lubrication quality. As the FO concentration increased during the diluted LO test and the LO/FO mixture viscosity correspondingly decreased, the speed threshold for hydrodynamic lubrication would have also increased. Although the increase in speed threshold that occurred may have been significant, the diluted LO test demonstrated that the LO/FO mixture volume, system pressure, and viscosity remained adequate for hydrodynamic lubrication of bearings to be maintained throughout the test (i.e., the threshold speed remained below the operating speed).

7.5. Expected Duration of Additional Test Engine Operation Before Failure

Given the overall excellent operation of the test engine during the diluted test, including at the moment that the test was intentionally stopped for non-engine performance reasons, MPR considers that the engine would have operated for longer if permitted. Specifically, MPR expects that the test engine would have continued to operate until significant damage to and failure of one or more hydrodynamic bearings occurred. As noted in Section 7.4, hydrodynamic lubrication of the engine/turbocharger bearings should be expected as long as the volume, system pressure, and viscosity of the LO/FO mixture remain adequate.

The volume of the LO/FO mixture decreased during the diluted LO test; however, the final volume was only slightly less than the normal peak volume (recall that the level was approximately 0.5 in lower than the high-level mark on the dipstick). The continued loss of the mixture by consumption (through combustion) and leakage through the rear seal should be expected. The addition of FO to the test engine (simulating the active FO leak) should counteract the majority of the loss and help minimize its rate; however, it is plausible that at some point the mixture volume will be inadequate (too small) to support adequate lubrication of bearings (and bushings). While the specific net rate of the mixture loss is not known, overall, it should be relatively slow. Based on what occurred during the 24.5 hours of the diluted LO test, MPR considers that then LO/FO mixture volume most likely would have remained adequate for multiple additional days of test engine operation.

The system pressure and viscosity of the LO/FO mixture are related. As observed during the diluted LO test, the system pressure decreased as the mixture viscosity decreased (due to the increasing FO concentration). Although the system pressure is not the same as the hydrodynamic film pressure that develops for hydrodynamic bearings, the system pressure is a reasonable overall indicator of whether the mixture viscosity is sufficiently high to maintain an adequate film pressure. The average mixture pressure during the final 30 minutes of the diluted test was 47 psig, which is 2 psig above the lower limit for "normal" pressure. At the recorded decreasing rate of approximately 0.3 psig/hr, the normal lower pressure limit would not have been reached for nearly 7 hours of additional operating time.

The normal lower pressure limit includes significant margin; therefore, the engine would have continued to operate with the LO/FO mixture pressure lower than the normal limit. Below some pressure threshold, bearing/bushing damage and failure will occur such that continued operation of the engine would not be possible. If the LO did not contain FO and the LO viscosity was normal, then MPR expects that the pressure could have decreased below the 10 psig trip limit before bearing damage/failure occurred (one of the goals of the trip is to prevent bearing damage/failure if LO conditions are normal except for the pressure being too low). However, for a LO/FO mixture with decreased viscosity, it is more likely that bearing damage/failure would occur at a pressure greater than the trip limit. The exact pressure threshold for bearing damage/failure is not known; however, somewhere in the 30-40 psig range is a reasonable and likely still conservative limit. For a continued pressure decrease of 0.3 psig/hr, the estimated additional test engine operating times before bearing damage/failure for this pressure threshold range are 23 hours, 40 hours, and 57 hours for pressure thresholds of 40 psig, 35 psig, and 30 psig, respectively.

For the above pressure thresholds, the estimated additional test engine operating time before bearing damage/failure occurs is close to or more than 24 hours (and represents time in addition to the 24.5-hours duration of the diluted LO test). All of these times are based on an assumption that the LO/FO mixture pressure continues to decrease at a constant rate that is the same as measured during the diluted LO test (i.e., approximately 0.3 psig/hr). In reality, it is likely that the rate of pressure decrease will not remain constant and instead the rate will decrease as the decreasing viscosity (with increasing FO concentration) asymptotically approaches the viscosity of pure FO (see Figure 6-41 and Figure 6-42). As shown in Figure 6-19, the LO/FO mixture pressure began to level off and the average pressure did not change significantly during the last couple hours of the diluted test; this is consistent with the expected asymptotic pressure behavior during additional test engine operation. Based on this, MPR considers that the estimated additional test engine operating time based on LO/FO mixture pressure are potentially significantly longer than stated above.

The leakage of the LO/FO mixture occurred for more than 20 hours during the diluted test without any detrimental impacts on the test setup or personnel/facility safety. MPR expects that continued leakage that would have occurred during any additional test time, even with an increasing (albeit slowly) FO concentration, would not have resulted in a need to prematurely end the test prior to the times estimated previously for bearing damage/failure based on LO/FO mixture volume and pressure.

Section 7.2 discusses why the peak projected FO concentration not being reached during the diluted LO test does not significantly impact the test results. Specifically, the reduction in viscosity caused by the FO contamination is most important in terms of lubrication, and the additional viscosity decrease that would have occurred between the actual and projected peak FO concentrations is small. Regardless, the FO concentration would have further increased if the diluted test had continued, and the projected peak FO concentration would have eventually been reached if the test duration were sufficiently longer. Figure 7-5 shows the predicted FO concentrations (element-basis; same data as in Figure 7-1) extrapolated out to longer elapsed test times. As shown, the duration of the diluted LO test would have needed to be approximately 30.5 hours, or 6 hours longer than the actual test duration, for the peak projected FO concentration to have been reached. All of the estimates of additional diluted test time before bearing damage/failure occurred, as discussed in this section, support that the test engine could have operated for at least an additional 24 hours (and potentially significantly longer) than the 24.5-hour duration of the test. Based on this, MPR expects that the test engine would have continued operating at the end of the diluted LO test, if the test had not been stopped, for significantly more than the approximate 6 hours required for the peak FO concentration to reach the peak projected value for the test.

7.6. Expected 2B AF Engine Performance Based on Diluted LO Test Performance

Based on all of the test parameter and other results discussed in this report, the performance of test engine during diluted LO test accurately represents the expected performance of the 2B AF engine with the LO having an initial FO concentration of 18.2 wt.% and the concentration further increasing with operating time at the projected rate. Based on the test engine performance, MPR expects the following specific behavior and performance for the 2B AF engine with the compromised LO:

- The 2B AF engine would be able to start without the damage to or failure of any engine or turbocharger bearings or bushings.
- The 2B AF engine would be able to drive all of the required loads, per the required load profile, for considerably longer than 24 hours before bearing damage/failure occurred. Based on the test engine performance, a minimum additional operating time of 24 hours (48 hours total) is reasonable and likely still conservative.
- Bearing damage/failure most likely would be the result of inadequate LO/FO mixture volume and/or pressure (depending on which occurred first).
- LO/FO mixture would leak from the 2B AF engine's crankshaft rear main seal during operation, similar to what occurred during the diluted LO test. The volume of leaked fluid would be similar to the volume that leaked from the test engine, scaled for the difference in engine size (i.e., less than a couple dozen gallons). Fluid that leaks from the 2B AF engine would flow out of a drain at the bottom of the flywheel housing and onto

the steel structure and floor underneath the engine (as opposed to spraying of the fluid by the flywheel and generator fans during the diluted test). The leaked fluid would either flow into a floor drain or remain on the structure/floor. None of the fluid would contact hot surfaces of sufficient temperature to ignite the fluid (e.g., turbochargers). The leakage would mitigate the potential for engine failure because of a too high internal fluid level (same as for the test engine).

Overall, MPR concludes that there is reasonable assurance that the 2B AF engine would have been able to perform its mission for at least 24.5 hours and is expected to be able to run considerably longer than 24 hours with its LO containing the high and increasing FO concentration.

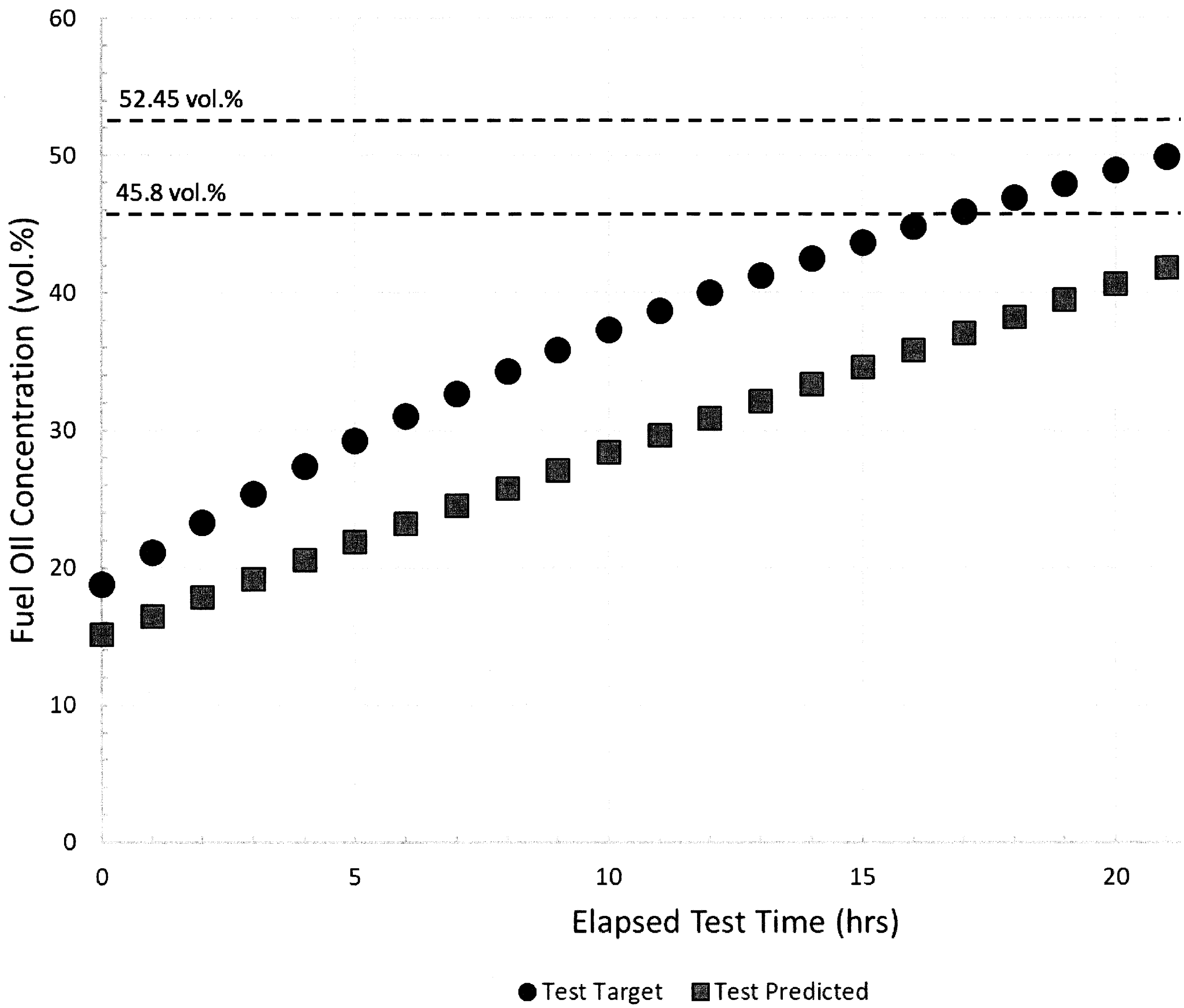

Figure 7-1. Comparison of Predicted FO Concentrations (Elements-Basis) and Projected Values fo

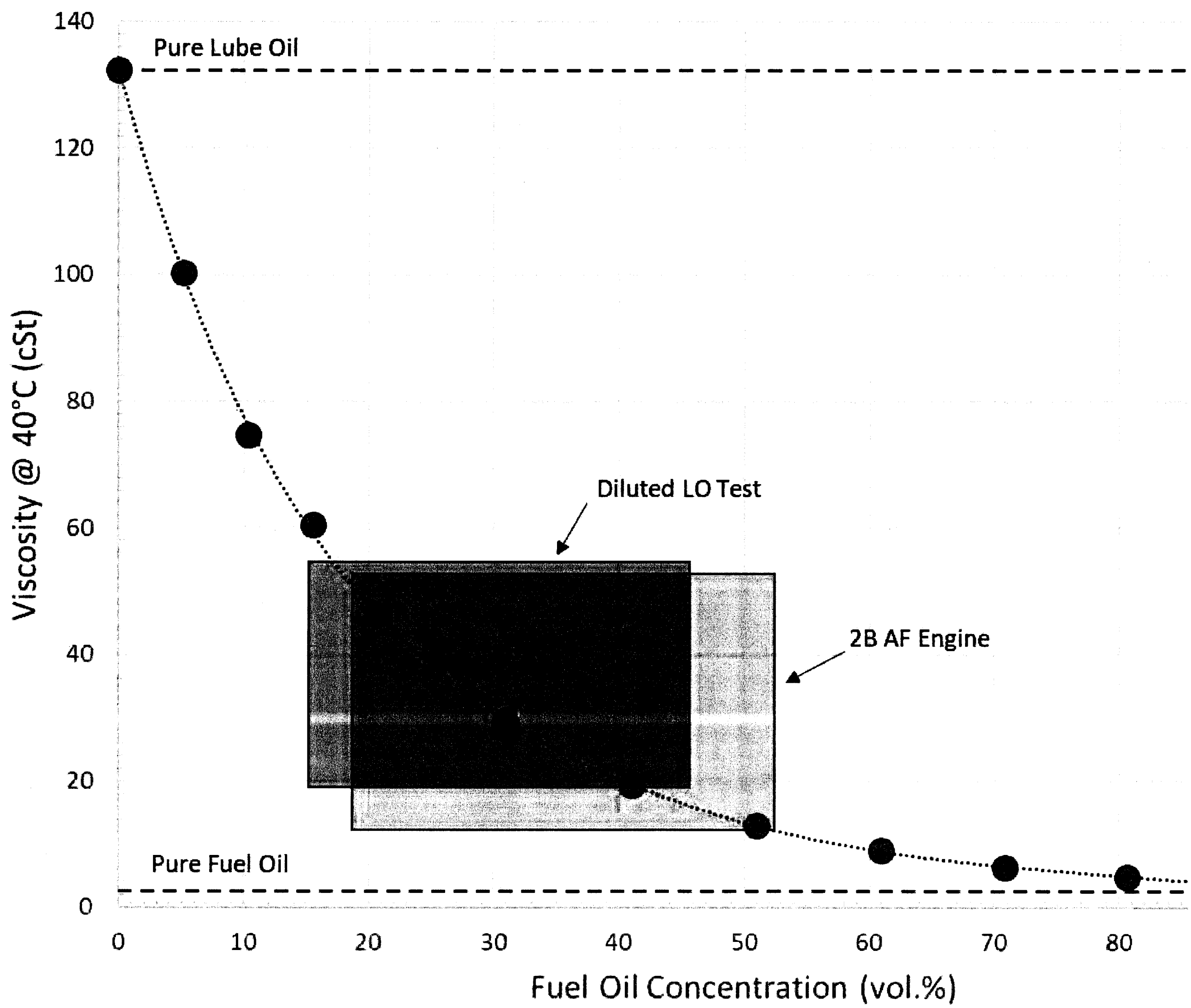

Figure 7-2. Ranges of Viscosities (at 40°C) and FO Concentrations for Diluted LO T

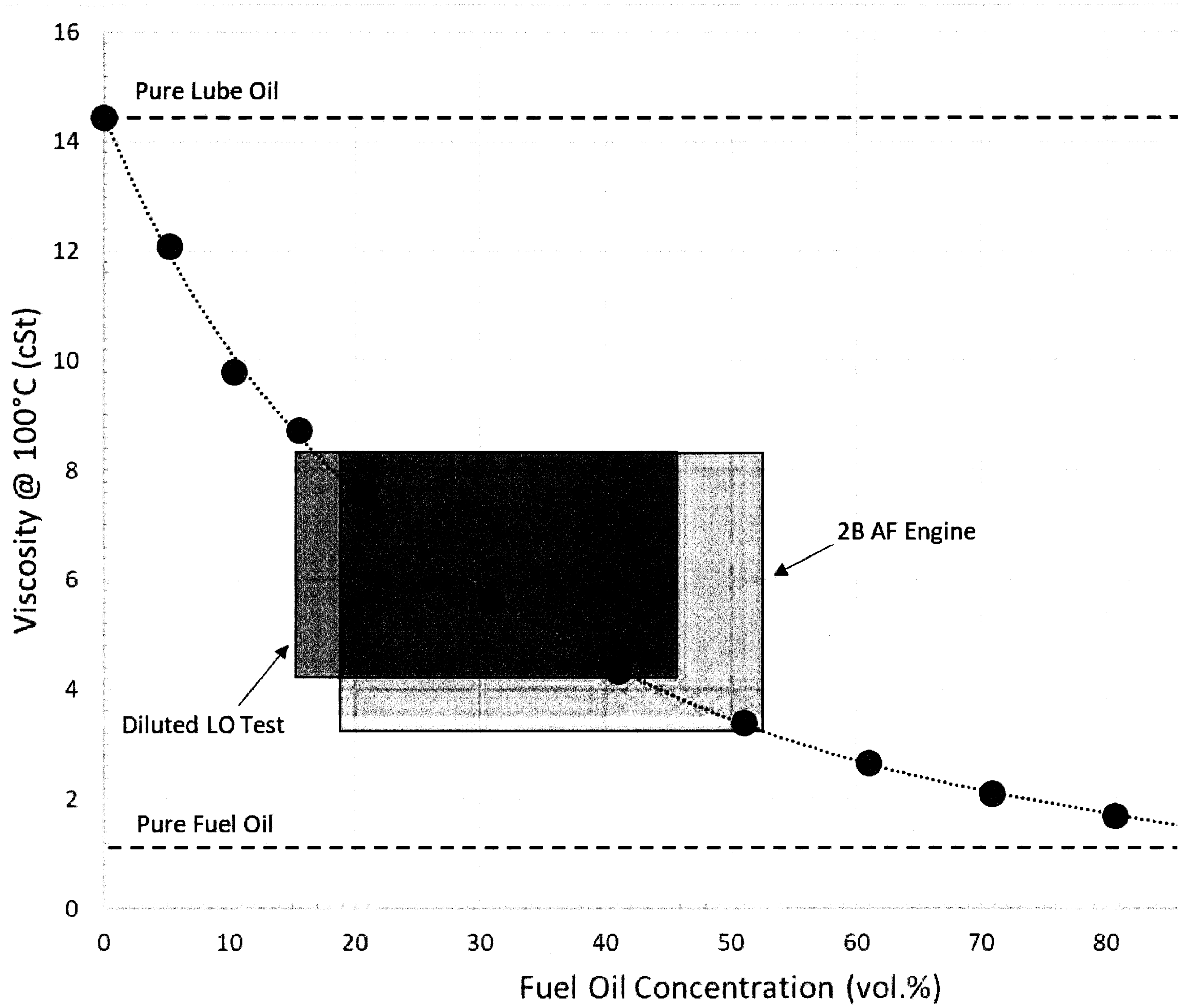

Figure 7-3. Ranges of Viscosities (at 100°C) and FO Concentrations for Diluted LO T

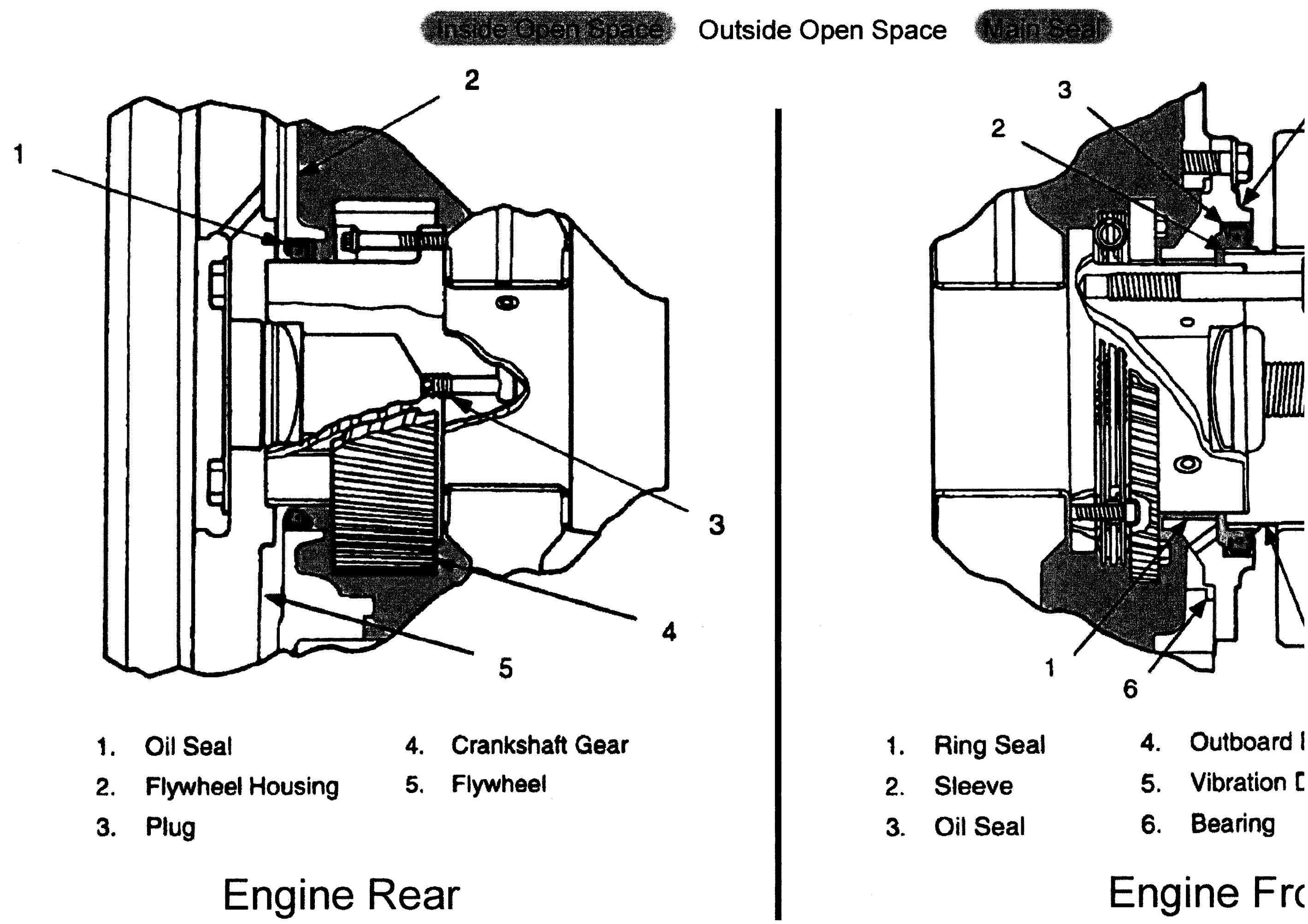

Figure 7-4. Differences Between Crankshaft Rear and Front Main LO Seals (Adapted from R

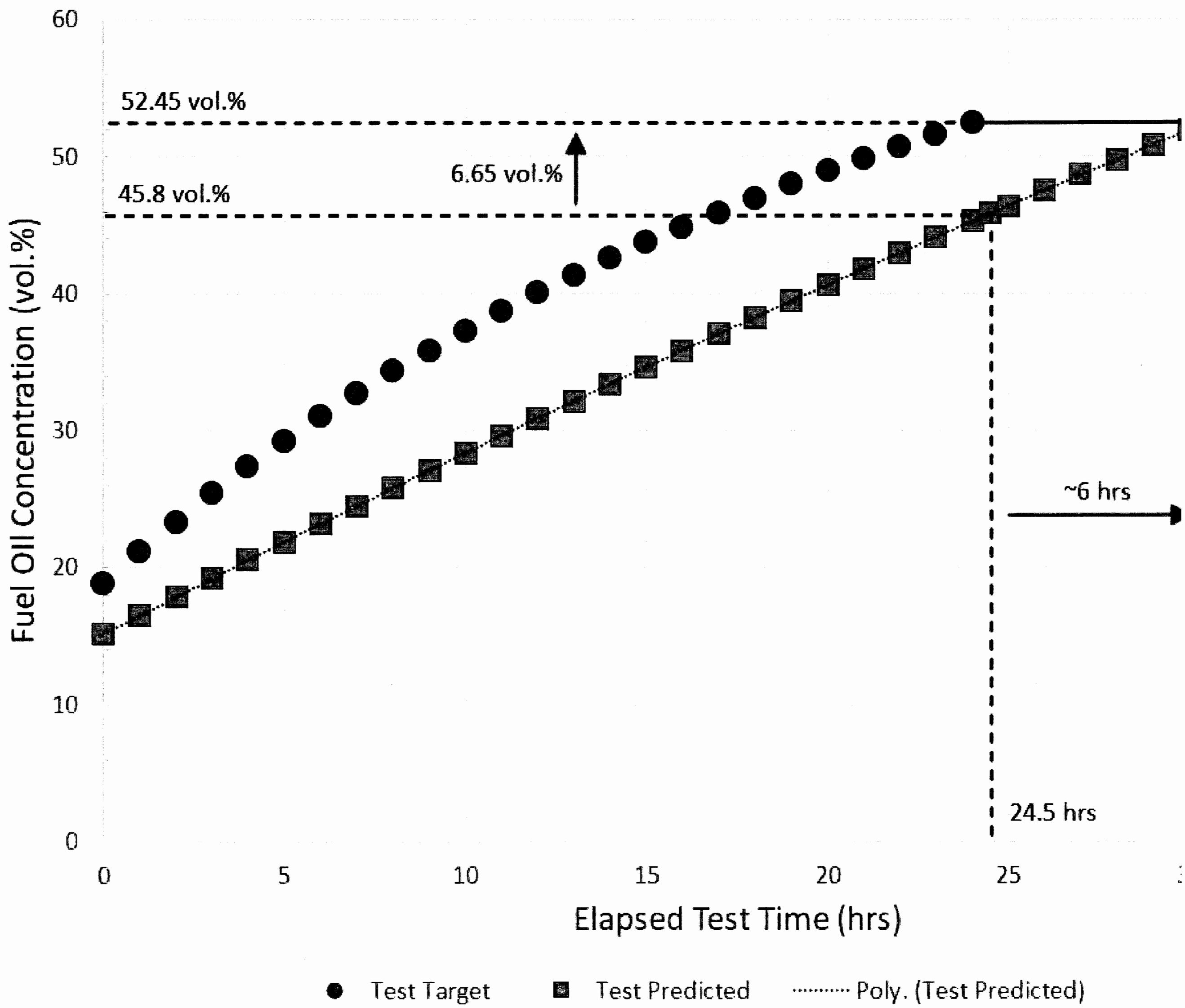

Figure 7-5. Extrapolation of Predicted FO Concentrations (Elements-Basis) and Elapsed Time for

8.0 References

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A
Similarity Evaluation of Plant and Test Engines

A.1 Purpose and Background

A.1.1 Purpose

This appendix documents the similarity evaluation performed to compare the 2B Auxiliary Feedwater (AF) Pump Drive Diesel Engine at Constellation Nuclear's Braidwood Clean Energy Center (hereinafter referred to as the plant engine) with the prime mover for the diesel generator set (hereinafter referred to as the test engine or test genset) used for testing at Southwest Research Institute's (SwRI) Locomotive Technology Center (LTC) and to compare the operating conditions of the test to those of the plant engine. Similarity between the plant engine and its operating conditions to the test genset and its operating conditions is necessary to conclude that the results of the testing performed on the test genset are representative of the results that would have occurred under the same or similar conditions for the plant engine.

A.2 Description of Plant and Test Engines

Both the plant and test engines are Detroit Diesel Series 149 diesel engines. The Series 149 engine is a Vee-configuration, two-stroke engine. The plant engine was assembled in 1978, has serial number 16E0004838, and operates within the controlled environment of the Braidwood Auxiliary Building. It is a 16V-149TI engine, which means that it has 16 cylinders and is turbocharged and intercooled. The test engine was assembled in 1980 (Reference 1), has serial number 12E0006264, and operated in the SwRI LTC Back Shop. It is a 12V-149T engine, which means that it has 12 cylinders and is turbocharged. The test engine is not intercooled. Table A-1 compares several engine parameters between the plant engine and the test engine.

Table A-1. Major Engine Parameters

Parameter	Plant Engine	Test Engine	Reference
Number of Cylinders	16	12	-
Total Displacement	2,389 cu in	1,792 cu in	2
Displacement per Cylinder	149.3 cu in	149.3 cu in	-
Engine Speed	1,795-1,845 RPM	1,800 RPM	-
Cylinder Bore	5.75 in	5.75 in	2
Stroke Length	5.75 in	5.75 in	2
Compression Ratio	15:1	16:1	2
Continuous Rating	1,500 bhp	1,130 bhp	3, 1
Continuous Rating per Cylinder	93.75 bhp	94.17 bhp	-
Number of Main Bearings	10	8	2

At the time of the diluted LO event, the plant engine had approximately 600 hours of operation (Reference 4). At the time of its purchase, the test engine had approximately 1,450 hours (Reference 5) of operation, and at the start of the diluted LO test, it had approximately 1,483 hours of operation.

The test engine was not supplied with any documentation regarding its configuration or its maintenance and operating history. Inspections and troubleshooting runs of the test genset identified that (1) the tubes in the radiator supplied with the genset were significantly plugged, (2) the lower oil pan was cracked, (3) the cylinder 4L fuel injector was not functioning properly, (4) the thermostats were faulty, and (5) the electronic governor was malfunctioning. The radiator and its engine-driven fan were removed from the test genset, and a radiator with a motor-driven fan was connected to the test genset for cooling. The lower oil pan was replaced with a new oil pan. The cylinder 4L fuel injector was replaced and the fuel control linkage was adjusted. The thermostats were replaced. The electronic governor was replaced with one from SwRI.

The test genset was run for approximately 24 hours in two 12-hour baseline runs to shake down the test system and ensure that the test genset was capable of operating for 24 hours. Mobil Delvac 1640 LO provided by Constellation was used for the baseline runs and for the diluted LO test. FO provided by Constellation was used for the diluted LO test, both as the fuel supply and the FO used to dilute the LO.

A.3 Discussion

As discussed in Section 1.3 of the main body of this report, the primary concern with FO contamination of LO is a reduction in the LO viscosity, which reduces the load carrying capability of the oil between lubricated engine parts (e.g., hydrodynamically lubricated bearings). A second concern, due to the active FO leak into the engine sump is the potential for increased volume of fluid in the engine sump and contact of rotating and reciprocating engine components (e.g., crankshaft counterweights and connecting rod bearing caps) with the fluid in the sump, which would create drag on the crankshaft, add impact loads to the engine components and heat and aerate the LO/FO mixture.

The reduced viscosity can result in metal-to-metal contact between lubricated engine parts leading to accelerated wear, seizure, and/or catastrophic failure. The plant engine and test genset use the same make and model diesel engine (Detroit Diesel Series 149), but the engines have different numbers of cylinders and some configuration and component differences.

A.3.1 Engine Components

Using Reference 6, the plant and test engine model numbers (9163-7301 and 9123-7305, respectively), and the plant and test engine options labels (Figure A-1 and Figure A-2, respectively), the as-manufactured configurations of the plant and test engines can be determined. Given the relatively low number of operating hours on the engine, it is reasonable to assume that no major engine components (such as the crankshaft; connecting rods; main, connecting rod, and camshaft bearings; cylinder heads; pistons, cylinder liners; camshafts; gear trains) have been replaced on either engine since they were manufactured.

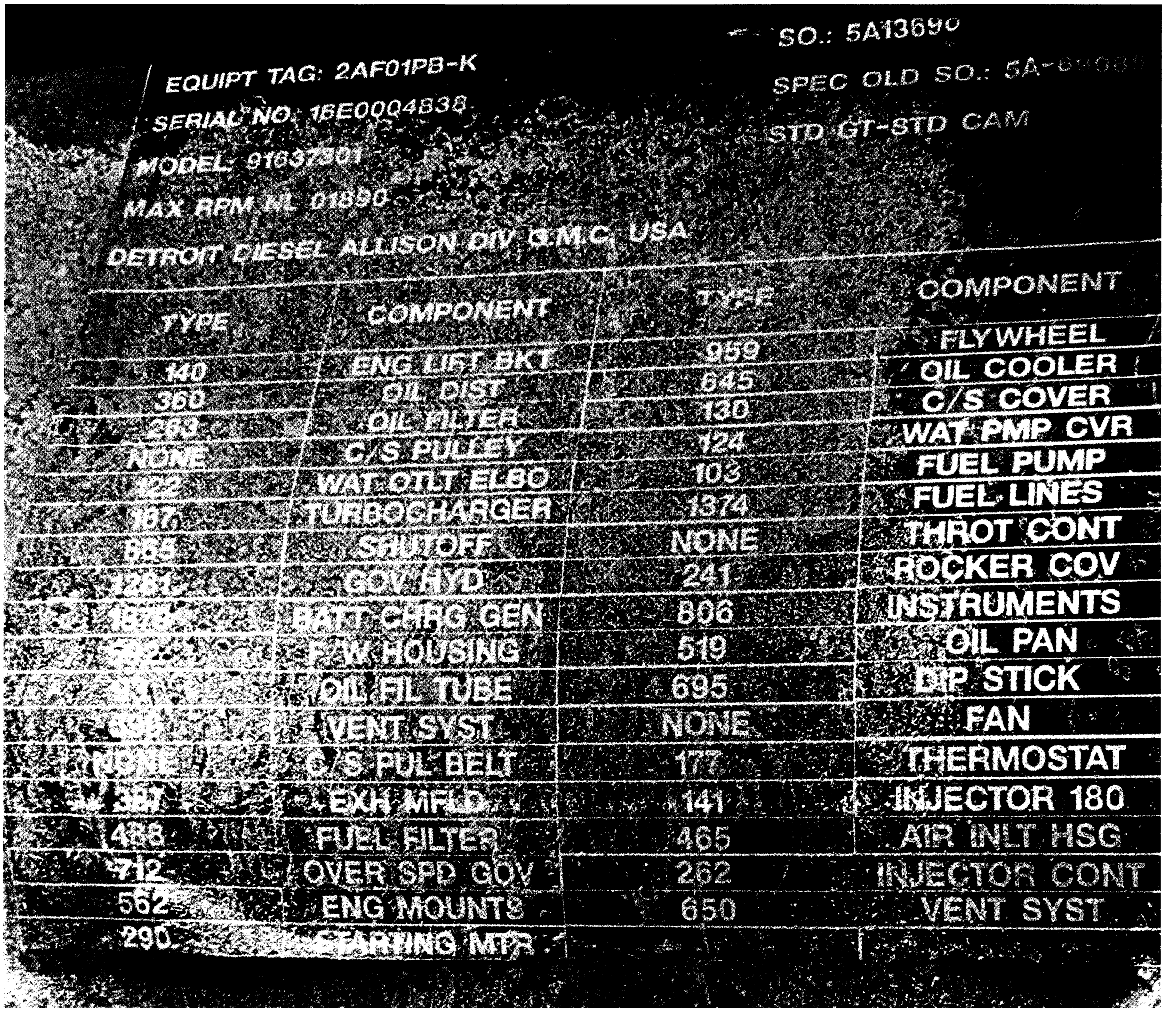

Figure A-1. Plant Engine Options Label

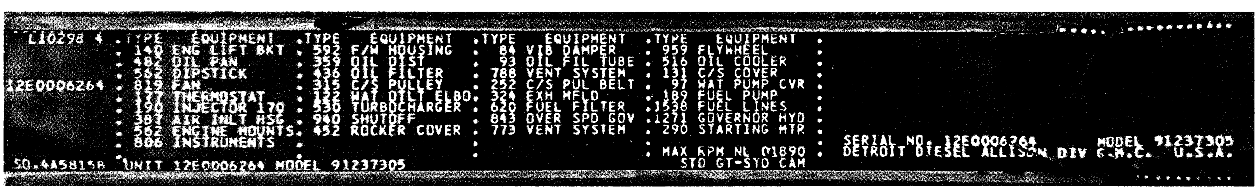

Figure A-2. Test Engine Options Label

The review of the as-manufactured configurations of the plant and test engines is documented in Table A-2. The review indicates that the following components that could be affected by LO viscosity are the same on both engines:

- Main bearings,
- Crankshaft thrust bearings,
- Connecting rod bearings,
- Camshaft bearings,

- Camshaft thrust bearings,
- Cylinder heads,
- Valve and Injector Operating Mechanisms with the exception of the exhaust valves,
- Piston skirts,
- Piston rings,
- Piston pins,
- Piston pin bushings,
- Cylinder liners,
- Front and rear crankshaft oil seals, and
- Oil pressure regulators.

The plant engine exhaust valves are stellite-coated, which is an upgrade in comparison to the uncoated test engine valves. In addition, the connecting rods, flywheels, and LO coolers on the plant and test engines are the same.

The 16-cylinder plant engine has 10 main bearings, and the 12-cylinder test engine has 8 main bearings. The plant engine has 1.6 cylinders per main bearing, while the test engine has 1.5 cylinders per main bearing. As a result, the average engine loads on the main bearings in the plant engine would be slightly (approximately seven percent) higher than in the test engine. The name plate of the test genset generator indicates that it is a single-bearing generator with a bearing at the exciter (rear) end. The other (front or engine) end of the generator is supported by the engine, and its load is carried by the bearings at the drive end of the engine. Inspections of the test engine #2, #3, #6 and #7 lower main bearing shells performed at Braidwood following the diluted LO test showed no degradation of the bearing shells when compared to pre-test inspections (see report Figure 6-33 and Figure 6-34), and LO analysis results indicated that no significant or abnormal wear occurred in the test engine during the diluted LO test.

Table A-2. Plant and Test Engine Model Index and Options Label Comparison

Component	Plant Engine		Test Engine		Discussion
	Group No.	Type	Group No.	Type	
Cylinder Block	1.1000	130	1.1000	188	Different due to number
Air Box Drains	1.1000A	194	1.1000A	194	Same.
Cylinder Head	1.2000	157	1.2000	156	Same.
Engine Lifter Bracket	1.2000A	140	1.2000A	140	Same.
Crankshaft, Oil Seals and Stabilizers	1.3000	46	1.3000	71	Crankshafts different due Main and thrust bearings same.
Crankshaft Front Cover	1.3000A	*130	1.3000A	*131	Same.
Vibration Damper	1.3000B	85	1.3000B	*84	No impact for short dura
Crankshaft Pulley	1.3000C	*NONE	1.3000C	315	Not affected by LO visco
Crankshaft Pulley Belt	1.3000D	*NONE	1.3000D	*252	Not affected by LO visco
Flywheel	1.4000A	*959	1.4000A	959	Same.
Flywheel Housing	1.5000A	*592	1.5000A	*592	Same.
Connecting Rod and Piston	1.6000	145	1.6000	198	Connecting rods, connec skirts, piston rings, pisto bushings, and cylinder li domes (crowns) are diffe ratio difference.
Camshaft and Gear Train	1.7000	104	1.7000	304	Camshafts different due Camshaft bearings and t
Valve and Injector Operating Mechanism	1.8000	89	1.8000	61	Same with exception of valves, which are stellite
Rocker Cover	1.8000A	*241	1.8000A	452	Not affected by LO visco

Component	Plant Engine		Test Engine		Discussion
	Group No.	Type	Group No.	Type	
Fuel Injector	2.1000A	*141	2.1000A	*190	Different, but not affecte viscosity.
Fuel Pump	2.2000	*103	2.2000	*189	Different due to number affected by LO viscosity
Fuel Filter and Strainer	2.3000A	*488	2.3000A	*620	Same
Fuel Manifold and/or Connections	2.4000	61	2.4000	59	Different due to number affected by LO viscosity
Fuel Lines and Fuel Cooler	2.5000A	*1374	2.5000A	*1538	Different, but not affecte
Hydraulic Governor	2.7000A	*1281	2.8000A	*1271	Different, but not affecte
Injector Controls	2.9000	*262	2.9000	175	Different, but not affecte
Throttle Controls	2.9000A	*NONE			Different, but not affecte
Air Inlet Housing	3.3000A	*465	3.3000A	*387	Different, but not affecte
Blower and Drive	3.4000	126	3.4000	163	Different due to number affected differently by LC
Blower Drive Shaft	3.4000A	38	3.4000A	37	Different due to number affected differently by LC
Turbocharger, Intercooler and Aftercooler	3.5000A	*167	3.5000A	*530	Different.
Oil Pump	4.1000A	123	4.1000A	128	Different due to number affected differently by LC
Oil Distribution System	4.1000B	*360	4.1000B	359	Different due to number affected differently by LC
Oil Pressure Regulator	4.1000C	17	4.1000C	17	Same.
Oil Filter	4.2000A	*263	4.2000A	*436	Different due to number affected differently by LC
Oil Cooler	4.4000A	*645	4.4000A	*516	Same.
Oil Filler	4.5000A	*93	4.5000A	93	Same.

Component	Plant Engine		Test Engine		Discussion
	Group No.	Type	Group No.	Type	
Dipstick	4.6000A	*695	4.6000A	*562	Different due to oil pan d by LO viscosity.
Oil Pan	4.7000A	*519	4.7000A	482	Different.
Ventilating System	4.8000A	*599	4.8000A	*773	Different due to oil pan d by LO viscosity.
Ventilating System (on Rocker Cover)	4.8000A	*650	4.8000A	*773	Different due to oil pan d by LO viscosity.
Fresh Water Pump	5.1000	189	5.1000	126	Different, but not affecte
Fresh Water Pump Cover	5.1000A	*124	5.1000A	*97	Different, but not affecte
Water Outlet Manifold and/or Elbow	5.2000A	*122	5.2000A	*122	Same.
Thermostat	5.2000B	*177	5.2000B	*177	Same. Plant engine the replaced with thermostat opening temperatures. S
Fan	5.4000A	*NONE	5.4000A	*819	Different, but not affecte
Exhaust Manifold and/or Connections	6.1000A	*387	6.1000A	*324	Different, but not affecte
Battery Charger Generator	7.1000A	*1879	7.1000A	---	Different, but not affecte
Starting Motor	7.3000A	*290	7.3000A	*290	Same.
Shutoff (Crankcase Pressure Monitoring Switch)	7.4000C	*865	7.4000C	*940	Different, but not affecte
Instruments	7.4000A	*806	7.4000A	*806	Same.
Overspeed Governor	7.4611	*712	7.4611	*843	Different, but not affecte
Engine Mounting and Base	11.1000A	*562	11.1000A	*562	Same.

Cylinder Components

For the individual cylinder components (connecting rod bearings, cylinder heads, valve and injector operating mechanisms, piston skirts, piston rings, piston pins, piston pin bushings and cylinder liners), as long as the per-cylinder load and operating conditions of the test engine are sufficiently similar to those of the plant engine, the results of the diluted LO test for those components are directly applicable to the plant engine since the components are the same.

The piston domes (crowns) are different between the plant and test engines due to the compression ratio difference for turbocharged (16:1) vs. turbocharged and intercooled (15:1) engines (Reference 2). The compression ratio is higher for non-intercooled engines. The intercooler cools the combustion air that has been compressed and heated by the turbocharger, increasing its density and increasing the mass of air in the cylinder. The swept volume (cylinder displacement) is the same in both the plant and test engines, so the average force on the piston during each revolution is the same in both engines since power is proportional to average force times swept volume (Reference 7 Equation 2.19a). As a result, the loads on the cylinder heads, pistons, piston pins, piston pin bushings, connecting rods, and connecting rod bearings will be sufficiently similar between the plant and test engines at any given load per cylinder.

Engine Components

Many components on the two engines are different due to the difference in the number of cylinders. These include:

- Cylinder blocks,
- Crankshafts,
- Camshafts,
- Blowers and blower drives,
- Fuel pumps,
- Fuel manifolds,
- Injector controls (fuel control linkage)
- Turbochargers,
- Oil pumps,
- Oil distribution systems,
- Oil pans,
- Water pumps, and
- Exhaust manifolds.

The majority of these components are either not affected by LO viscosity (e.g., the cylinder block) and/or are simply larger in the plant engine than in the test engine due to the larger number of cylinders in the plant engine and carry similar loads and stresses (e.g., the crankshaft).

Three components from this list warrant additional attention – the turbochargers, the oil pumps and the oil pans.

Turbochargers

The plant engine has four model T18A40 turbochargers, and the test engine has four model TV7101 turbochargers (Reference 6). Both turbocharger models are manufactured by Garrett Motion Inc. The turbochargers are supplied with oil by the lubricant system but do not receive coolant. Each turbocharger has two journal bearings and a thrust bearing (References 2 and 6). The rotating assemblies (turbine and compressor wheels) of the turbochargers on the test engine are physically smaller than those of the turbochargers on the plant engine as evidenced by the smaller inducer and exducer dimensions of the TV7101 turbochargers (Reference 8) as compared to the T18A40 turbochargers (Reference 9).

Turbochargers of this size used on the Series 149 engine have high operating speeds, typically in the tens of thousands of revolutions per minute. Radial and axial loads on the turbocharger rotating assemblies are balanced as much as practicable by the turbocharger designer to minimize bearing loads. At their respective rated loads, the speeds of the turbochargers on the plant and test engines are expected to be similar, and axial and radial forces on the bearings scale with the size of the turbocharger. As a result, the results and effects of the diluted LO test on the test engine turbochargers can be applied to the plant engine turbochargers.

Oil Pumps

The LO pump on the plant engine provides 150 gpm at 1,800 rpm engine speed (References 2 and 10*)*, or 9.4 gpm per cylinder. The pump on the test engine provides 120 gpm at 1,900 rpm engine speed (References 2 and 11). The LO pump is a positive-displacement gear pump, so the flow rate provided by the LO pump is proportional to engine speed, so the pump on the test engine would provide 114 gpm at 1,800 rpm engine speed, or 9.5 gpm per cylinder. The number of engine components to which LO is delivered scale roughly proportionally with the number of cylinders, so the volume of LO provided to each component should be approximately equal in the two engines.

Oil Pans

Each engine has upper and lower oil pans mounted on the bottom of the cylinder block. The plant engine has two rectangular cast upper oil pans and two flat, rectangular stamped lower oil pans. The test engine has two rectangular cast upper oil pans and one sloped, stamped lower oil pan. The capacity of the plant engine oil pans is larger than the capacity of the test engine oil pans. Braidwood personnel reported that they added 42 gallons of oil to the 2B AF engine following a maintenance window in 2023 (Reference 12). Reference 13 indicates that the oil pan capacity of the test engine is 30 gallons.

A.3.2 Test Engine Loading

The engine speed and power output are critical to ensuring that the loading on engine components such as pistons, piston pins, connecting rods, connecting rod bearings and main bearings are similar for the plant and test engines. The nominal speeds for both engines are approximately 1,800 rpm. To match loading, the test engine was operated at loads that provided equal or higher loads per cylinder as the plant engine would experience during its 24-hour PRA mission. These loads were calculated in Reference 14 and included in Reference 15.

A.3.3 Engine Operating Conditions

Engine Cooling System

The plant engine is cooled with service water through a water-to-water heat exchanger. The test engine was cooled with a radiator. The radiator supplied with the genset was found to be fouled with deposits and it and its engine-driven fan were removed from the genset. The test engine was connected to a radiator with a motor-driven fan. The cooling systems on both engines are equipped with thermostats to direct coolant to the heat exchanger (plant engine) or radiator (test engine) once coolant temperature has increased to the thermostat opening temperature. The plant engine is equipped with thermostats that fully open at 185°F or 189°F (Reference 16). The test engine was equipped with thermostats that begin to open at 170°F. Section 4.6 of Reference 2 states that the thermostats are fully open at 17°F to 20°F above the opening temperature, so the thermostats on the plant and test engines are nearly identical. Plant engine operating data (Reference 17) indicates that the plant engine coolant temperature is 160°F when warmed up, and as shown in Figure 6-23, test engine temperature varied slightly with load, but was approximately 165°F to 175°F during the baseline and diluted oil tests. Higher temperatures are conservative, as higher coolant temperatures would lead to higher LO temperatures, since the LO is cooled by the cooling water system.

The plant engine uses treated water as coolant (no antifreeze), and treated water was also used as the coolant in the test engine. The plant engine has a cooling water high temperature trip set at 205°F. The test engine also had a cooling water high temperature trip, but the set point and functionality of the trip were not known. Had cooling water temperature reached 205°F during the diluted oil test, the engine would have been shut down, since the plant engine would have automatically tripped.

Engine Lubrication System

The pressure regulator valves on both the plant and test engines are set at 50 psi (References 2 and 18). Oil pressure in the plant engine is 50 to 51 psi once the engine reaches operating temperature (Reference 17), and the test engine LO header pressure, which is measured just upstream of the pressure regulator valves, was approximately 55 to 58 psi at operating temperature during the baseline testing (see Figure 6-5 and Figure 6-6).

LO temperature in the plant engine is 185°F to 215°F once the engine reaches operating temperature (Reference 17), and the test engine LO temperature during baseline testing was approximately 205°F to 215°F (see Figure 6-8). The higher LO temperature of the test engine is more conservative, as LO viscosity decreases with increasing temperature, meaning that the lubrication conditions in the test engine were more challenging than those expected in the plant engine.

The plant engine has a low LO pressure trip set at 10 psi (Reference 19), and Section 11.3.1 of the plant engine manual (Reference 2) indicates that this is a standard low LO pressure trip set point. The test engine is equipped with a low lube oil pressure trip, and its set point was not known prior to the test. Had LO pressure fallen to 10 psi without tripping during the diluted oil test, the test engine would have been shut down, as the plant engine would have automatically tripped if its LO pressure reached 10 psi. As discussed in Section 6.3.5 of this report, LO pressure remained well above the 10 psi trip set point during the diluted oil test.

Lube Oil Dilution and Volume

As discussed in Section 4.6 of the report, it was desired to match the initial FO concentration, FO concentration increase during the diluted FO test, initial sump level and sump level during the diluted FO test between the plant and test engines. While the oil pans were different, FO concentration and sump level were to be controlled, to the extent practicable by choosing the initial test engine sump level such that the time at which rotating and reciprocating components in the test engine contact the sump fluid no later than the time at which contact was expected in the plant engine.

Intercooler

The plant engine has an intercooler, and the test engine does not. Since the compressed and heated intake air leaving the turbochargers is not cooled, the test engine likely runs with higher intake air temperatures than the plant engine. This is conservative since it would cause the cylinder temperatures in the test engine to be higher than those in the plant engine.

A.3.4 Fuel Leakage Conditions

The FO leaks in the plant engine were from supply and return lines to several fuel injectors. FO would have leaked into the cylinder heads and drained to the sump through drain passages from the heads. Replicating the leak location and leakage rate from this location would have required modifying fuel lines that are exposed to high pressure fuel during engine operation or machining one or more valve covers. These were judged to be high-risk activities that provided no gain in replicating the engine operating conditions with diluted LO, since any FO that leaked onto the cylinder heads would drain directly to the sump. Instead, FO was directly added to the engine sump through a modified access panel during the diluted oil test at a controlled and monitored rate.

A.4 Results and Conclusions

The test engine and its operating conditions are representative of the plant engine and its operating conditions such that the results of testing performed at SwRI LTC can be used to determine if the plant engine could have operated with the September 2023 as-found FO dilution of the LO and an active FO leak into the LO occurring during subsequent operation. The test engine and its operating conditions adequately simulated the plant engine and its operating conditions.

A.5 References

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3. Constellation Calculation BRW-10-014-M / BRY10-103, "AF Diesel Driven Pump Fuel Consumption and Day Tank Requirements," Revision 3, February 26, 2015.

4. Email from Matthew Fisher (Constellation) to Mark O'Connell (MPR), "RE: [EXTERNAL]Plant Engine Operating Hours," January 10, 2024.

5. Power Zone Equipment, Inc., Quotation 26942-01, "Detroit 12V-149 7300 Series," October 13, 2023, including pictures of genset provided by Power Zone.

6. Detroit Diesel Corporation Doc No. 6SP134, "Series 149 Parts Catalog," Rev 11/93.

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10. Detroit Diesel Performance Curve and Specification Sheet for Model 16V-149TI ILCC, 9163-7416, Curve No. E4-9165-32-44, Revision 9, May 22, 1996.

11. Detroit Diesel Engine Performance Curve and Engine Specification Sheet for Model 12V-149T, 9123-7300, Curve No. E4-9123-32-6, Revision 2, June 16, 1987.

12. Email from Matthew Fisher (Constellation) to Mark O'Connell (MPR), RE: [EXTERNAL]Lube Oil Volume for AFW Diesel Drive," December 1, 2023.

13. Email from Matthew Fisher (Constellation) to Mark O'Connell (MPR). "FW: [EXTERNAL]FW: Test Engine," November 30, 2023.

14. MPR Memorandum 4101-0031-MMO-001, "Evaluation of Test Load for Braidwood 2B Auxiliary Feedwater Pump Diesel Drive Test with Lube Oil Diluted by Fuel Oil," Revision 0.

15. MPR Report 4101-0031-OTHR-001, "Braidwood 2B AFW Diesel Engine Test Plan," Revision 0.

16. Exelon Generation Drawing 62241, "Spec. # L-2891 16V149TI Auxiliary Feedwater Pump Drive, Engine Cooling System, Units 1 & 2," Revision B, January 22, 1979.

17. Microsoft Excel Spreadsheet *2B AF Diesel Oil Temp Pressure and Jacket Temp.xlsx*, Uploaded to Constellation OneDrive by Matthew Fisher (Constellation) on December 14, 2023.

18. Stewart & Stevenson Services Drawing No. C-62243, "16V149TI Auxiliary Feedwater Pump Drive Engine Lube Oil Schematic," Revision A, January 22, 1979.

19. Email from Matthew Fisher (Constellation) to Mark O'Connell (MPR), "RE: Questions from yesterdays [sic] call," November 15, 2023.

B

Mobil Delvac 1640 Lube Oil Specification

Mobil

Mobil Delvac 1600 Series

Mobil Commercial-Vehicle-Lube , United States

High Performance Diesel Engine Oils

Product Description

Mobil Delvac 1630, 1640, and 1650 are high performance monograde diesel engine oils formulated from advanced technology base oils and a balanced additive system. They are recommended by ExxonMobil for use in intercooled, turbo-charged engines operating under severe on and off-highway conditions as well as a wide range of applications where a monograde lubricant is recommended.

Features and Benefits

Features	Advantages and Potential Benefits
Excellent protection against oil thickening, high temperature deposits, sludge build-up, oil degradation and corrosion	Prolonged engine life Less wear Excellent protection against ring sticking
Extended TBN reserve	Long-term deposit/wear control Controls formation of acids when using higher sulfur fuels

Applications

Recommended by ExxonMobil for use in:

- Naturally aspirated and turbo-charged diesel powered equipment
- On-highway light and heavy-duty trucking
- Off-highway industries including: construction, mining, quarrying, and agriculture

Specifications and Approvals

This product has the following approvals:	1630	1640	MOBIL DELVAC 1650
General Electric Fundamental Approval (letter on file)		X	
MTU Oil Category 2	X	X	
ZF TE-ML 04B	X	X	
ACEA E2		X	
API CF		X	
API SF		X	
MAN 270		X	

This product is recommended for use in applications requiring:	1630	1640	

This product is recommended for use in applications requiring:	1630	1640	
ACEA E2	X		
Allison C-4	X		
API CF	X		X
API SF	X		X
MAN 270	X		

Properties and Specifications

Property	1630	1640	MOBIL DELVAC 1650
Grade	SAE 30	SAE 40	SAE 50
Ash, Sulfated, mass%, ASTM D874	1.4	1.4	1.4
Density @ 15.6 C, g/cm3, ASTM D4052	0.89	0.89	0.896
Flash Point, Cleveland Open Cup, °C, ASTM D92	230	239	290
Kinematic Viscosity @ 100 C, mm2/s, ASTM D445	11.5	14.7	19.5
Kinematic Viscosity @ 40 C, mm2/s, ASTM D445	90	132	202
Pour Point, °C, ASTM D97	-30	-21	-18
Total Base Number, mgKOH/g, ASTM D2896	12	12	12
Viscosity Index, ASTM D2270	117	112	110

Health and Safety

Health and Safety recommendations for this product can be found on the Material Safety Data Sheet (MSDS) @ http://www.msds.exxonmobil.com/psims/psims.aspx

09-2021

Exxon Mobil Corporation
22777 Springwoods Village Parkway
Spring TX 77389

1-800-ASK MOBIL (275-6624)

Typical Properties are typical of those obtained with normal production tolerance and do not constitute a specification. Variations that do not affect product performance are to be expected during normal manufacture and at different blending locations. The information contained herein is subject to change without notice. All products may not be available locally. For more information, contact your local ExxonMobil contact or visit www.exxonmobil.com
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ExxonMobil

C

Analysis Report for Diesel Fuel Used in 2B AF Diesel Drive

Bureau Veritas

LABORATORY REPORT: DIESEL FUEL – ASTM D 975 2006b

Exelon Nuclear Procurement Engineering Standard PES-P-006, Rev13 April 27, 2020

ANALYSIS PERFORMED FOR: BRAIDWOOD STATION

Sample received date at Bureau Veritas: 11/29/2023

Analysis Date: 12/04/2023 Sampling Date: 11/29/2023

Sample Identification: TRUCK SAMPLE Lab Number: 09

CAB # 6 TRAILER # 101 C4 PETROLEUM TRANSPORT INC/

PO # 00806910-00301 PETROLEUM TRADERS

FINAL REPORT

PARAMETER (ASTM)	TEST RESULTS	SPECIFICATION
FUEL TYPE	#2 Diesel	#2 FUEL
Viscosity, CSt @ 40°C (D 445)	2.731	1.9 to 4.1
API Gravity @ 60°F (D 1298-99)	34.2	27 to 39
Ash, % (D 482)	<0.001	0.01 max
Color (D 1500-98)	4.0	5 max
Clear and Bright (D 4176-93)	Pass	Pass
HHV, BTU / gal (D 4809)	140,086	135,000 min
Cetane Index , Calc. (D 976)	44.4	40 min
Cetane Index, Calc. (D 4737)	44.1	40 min
Flash Point (D 93)	147°F /64°C	125 °F / 52°C min
Cloud Point (D 2500)	0°F /-18°C	5°F /-15°C max
Copper Strip Corrosion, 3 hours @ 50°C (D130)	1A	No. 3, max
Distillation Temp, 90% Recovered (D 86)	624°F /329°C	540 to 640°F / 282 to 338°C
Presence of biodiesel, %(AI method, IR)	<0.1%	Less than 0.5%
Lubricity, HFRR @ 60°C, micron (D 6079)	450	520 max
Bacteria Test	Negative	Negative
Total Particulate Concentration, mg/L (D 5452-98)	0.24	10 mg/L
Volume Fuel Oil-Filtered, Liters (D 5452-98)	3.310	--------
Ramsbottom Carbon Residue, 10% Distillation Residue, % (D 524)	0.09	0.35 max
Sulfur, % (D 4294)	N/R	0.05% max
Sulfur, % (D 5453)	0.0006%	0.0015% max
Water & Sediment, % Volume (D 2709-96e)	0	0.05 max

NOTE: ALL TESTS ARE PERFORMED PER LATEST ASTM STANDARDS IN EFFECT AT TIME OF TESTING UNLESS YEAR IS SPECIFIED ABOVE.

Sampled @ Bureau Veritas. Hoffman Estates, IL 60169 in accordance with ASTM D-4057-95 and IL LOC WI-00008 /1

Sample(s) meets ASTM Specification: XX

Sample(s) does NOT meet ASTM Specification: ____

Results reported on: 12/04/2023 by RM

Method of reporting ____phone; ____fax; ____mail; ____e-mail; XX

(A designation of "N/R" shall indicate that the test was not requested by the station)

This sample of safety related diesel fuel oil conforms to Exelon's Procurement Engineering Standard PES-P-006 and the requirements of Contract 00053484, Section 6.0, and Safety Related procurement requirements (6.1.1).

Approved: Technical Manager/Designee [signature] QA/Designee [signature]

D

Test Plan 4101-0031-OTH-001, Braidwood 2B AFW Diesel Engine Test Plan, Baseline and Diluted Lube Oil Tests, Revision 0

4101-0031-OTHR-001
Revision 0

Braidwood 2B AFW Diesel Engine Test Plan

Baseline and Diluted Lube Oil Tests

Prepared for: Braidwood 1 & 2

Preparer:	Gary Thompson	E-signed by: Gary Thompson on 2023-12-08 18:23:03
Checker:	Daniel McCray	E-signed by: Daniel McCray on 2023-12-08 18:28:33
Reviewer:	Mark O'Connell	E-signed by: Mark O'Connell on 2023-12-08 18:29:18
Approver:	Mark O'Connell	E-signed by: Mark O'Connell on 2023-12-08 18:29:38

QA Statement of Compliance

This document has been prepared, reviewed, and approved in accordance with the Quality Assurance requirements of the MPR Standard Quality Program.

MPR Associates, Inc.
320 King St. • Alexandria, VA 22314
(703) 519-0200 • www.mpr.com

Braidwood 2B AFW Diesel Engine Test Plan
Baseline and Diluted Lube Oil Tests

RECORD OF REVISIONS		
Revision Number	**Pages /Sections Revised**	**Revision Description**
0	All	Initial issue

Table of Contents

1.0 Introduction

1.1. Purpose

This test plan describes testing to simulate the operation of the diesel-driven auxiliary feedwater (AFW) pump at Constellation Nuclear's Braidwood Clean Energy Center (hereafter referred to as the "AFW diesel test" or "test"). The AFW diesel test will specifically simulate the operation of the Detroit Diesel 16V-149TI diesel engine that drives the AFW pump (and other associated loads) with lube oil that is diluted by fuel due to an active fuel leak. The test will be performed on an engine of the same model as the 2B AFW pump diesel drive, but the test engine will have 12 cylinders instead of 16 cylinders (appropriate adjustments will be made to the test to account for the different number of cylinders). Load will be applied to the engine during the test by an electrical generator. The test will start with the engine lube oil containing an elevated concentration of fuel oil to simulate the as-found 2B AFW diesel engine conditions[1]. The fuel oil concentration will be increased progressively throughout the test to simulate continued operation of the plant engine with an active fuel leak.

1.2. Background

In September 2023, Braidwood Clean Energy Center personnel identified an elevated concentration of fuel oil in the lube oil of the prime mover for the station's 2B diesel-driven AFW pump. The prime mover is a Detroit Diesel 16V-149TI diesel engine, which operates with a two-stroke mechanical cycle (one crankshaft revolution per power stroke). At the time of discovery, the engine's lube oil contained approximately 18.2 mass percent fuel oil (Reference 1). The source of the fuel oil contamination was corrected, and the lube oil was replaced.

Constellation Nuclear contracted MPR to determine if the diesel-driven AFW pump would have been able to perform its mission starting in the as-found condition with further fuel oil dilution of the lube oil occurring during operation. The primary concern with fuel oil contamination of lube oil is a reduction in the lube oil viscosity, which reduces the load carrying capability of the oil between lubricated engine parts (e.g., hydrodynamically lubricated bearings and bushings). The reduced viscosity can result in metal-to-metal contact between engine parts leading to accelerated wear, seizure and/or catastrophic failure.

MPR has subcontracted Southwest Research Institute (SwRI) to perform the testing described in this plan. SwRI has experience performing large engine tests for locomotive and stationary power applications for more than 35 years. SwRI has the capability to receive a Detroit Diesel 149-series diesel generator set (genset), connect the appropriate engine controls and instrumentation, and operate and load the genset per the requirements of this test plan.

[1] The initial concentration of fuel oil in the lube oil will be equal to the concentration determined by Constellation Nuclear based on the analysis of lube oil samples collected at the time the fuel leak was identified.

This plan documents the scope of the testing to be performed by SwRI, including responsibilities for MPR and/or Constellation Nuclear in support of the testing.

1.3. Test Objectives

The objective of the AFW diesel test is to determine if the Braidwood 2B AFW diesel drive can operate at the required loads with its lube oil diluted by fuel oil from a simulated active fuel leak (with the specific lube oil conditions consistent with the as-found conditions from the September 2023 lube oil contamination event, and the subsequent degrading conditions during operation in response to a postulated plant accident). Specifically, the testing will:

- Evaluate the ability of a similar Detroit Diesel 149-series engine to operate according to a prescribed load profile (consistent with the expected AFW diesel drive pump loads in response to a plant accident) with fuel-oil-diluted lube oil (consistent with the as-found fuel oil concentration and expected increase in the fuel oil concentration during continued engine operation).
- Monitor the engine's performance, lube oil condition, and overall health throughout the test.

2.0 Scope of Work to be Performed by SwRI

The scope of work to be performed by SwRI is discussed in the following sections. Additional details regarding the test, including other responsibilities of SwRI, MPR, and/or Constellation Nuclear are provided in later sections of this test plan.

2.1. General

2.1.1. Access to SwRI Test Facility

SwRI shall provide employees from MPR, Constellation Nuclear, and the U.S. Nuclear Regulatory Commission (NRC) access to the test facility and test system at all times during the subject test, when and where permitted in accordance with SwRI's safety requirements and plan (see Section 2.4 for additional details regarding the SwRI safety plan).

2.1.2. Communication and Coordination

SwRI shall participate in periodic phone calls and/or online meetings with MPR and Constellation Nuclear to discuss project status, challenges, and actions being taken to maintain the project schedule and quality. Any challenges that could affect the project schedule shall be brought to the attention of MPR as soon as possible. MPR shall provide technical direction and oversight of SwRI's work as required to ensure that the testing meets the test objectives.

All communications regarding the testing shall occur directly between MPR and SwRI unless otherwise noted/approved. As appropriate, MPR may request that SwRI include specific Constellation Nuclear personnel on written communications, e.g., daily status emails. Constellation Nuclear will coordinate with MPR and/or SwRI, as appropriate, on the responses to any communications requested by the NRC.

2.2. *Quality Assurance*

SwRI shall perform all work required by this test plan in accordance with SwRI's standard (non-safety related) Quality Assurance (QA) program.

2.3. *Test System Design and Fabrication*

SwRI shall design and fabricate a test system suitable for performing tests that meet the test objectives in Section 1.3 and the test system requirements in Section 3.0 (and its sub-sections). SwRI is responsible for ensuring that the test system can be controlled adequately, which includes, but is not limited to: (1) genset starting/stopping and load control, (2) metering of fuel oil additions to the engine lube oil sump, and (3) monitoring for apparent degradation of engine component(s) and impending failure (e.g., rod-knock indicative of connecting rod bearing damage/failure). Per the executed subcontract agreement between MPR and SwRI, the following actions shall be taken by SwRI as part of the test design and fabrication:

- Installation of the Detroit Diesel 12V-149T test genset at SwRI's testing facility,
- Installation of a secondary safety containment around the genset (at a minimum around the genset's engine),
- Procurement and setup of an appropriate device for loading the genset, including all required equipment for connecting the genset to the load device (e.g., a resistive load bank and appropriate electrical and signal cabling),
- Installation of a data acquisition system for collecting data from the genset's engine and/or generator,
- Procurement and installation of an appropriate exhaust system with the capability of matching the plant's engine exhaust backpressure as closely as practicable,
- Installation of a peristaltic pump (or other suitable device/method) for adding fuel oil to the engine's crankcase during the test,
- Modification of the engine's lube oil system to allow for the collection of representative lube oil samples during the test[2], and
- Identification and installation of any supplemental Instrumentation and Control (I&C) equipment required for operating the genset.

SwRI shall provide the test system design to MPR for approval. SwRI should include MPR and Constellation Nuclear in the test system design process, as much as practicable, to ensure that the system design can be finalized quickly while still meeting the required test objectives and

[2] As the genset used for the test will have a 12-cylinder, rather than a 16-cylinder, engine, some test parameters will be scaled appropriately to account for the lower number of cylinders, such that the per-cylinder conditions match for both the 16- and 12-cylinder engines. A detailed similarity evaluation of the two engines will be performed by MPR and documented separately from this test plan.

requirements. As appropriate, MPR may authorize SwRI to proceed with aspects of fabrication and assembly of the test system in advance of approval of the final test system design.

2.4. Safety Plan

SwRI shall develop an appropriate written safety plan for the test. The plan should, at a minimum, identify potential risks to personnel and property arising from a failure or accident during the test, and the actions that will be taken to minimize or mitigate these risks (e.g., fabrication and installation of the secondary safety containment around the genset/engine).

2.5. Test Documentation

SwRI shall prepare and implement written test procedures as required to meet the test objectives in Section 1.3 and the test system requirements in Section 3.0 (and its sub-sections).

2.5.1. Commissioning, Testing, and Pre-Test Inspection Procedures

SwRI shall prepare and implement written test procedures as required to describe how system commissioning and system testing are to be performed. The procedures shall be provided to MPR for review, and all review comments shall be resolved by SwRI, prior to the procedures being finalized and used for the commissioning, testing, and/or inspection activities.

2.5.2. Test Results

SwRI shall submit test results, including preliminary copies of the completed test procedures and an electronic copy of the recorded test data ("preliminary test results"), to MPR as soon as practicable after completion of the testing. The format of electronically recorded data shall be agreed upon by MPR and SwRI prior to any testing and specified in the test procedure(s), as appropriate. MPR and SwRI shall agree upon what data/format, if any, are to be recorded manually during testing, separate from the electronically recorded data.

SwRI shall review the test results for accuracy, consistency, and completeness, as well as evaluate the results to ensure that the test requirements have been satisfied. MPR shall review the preliminary test results. SwRI shall address all comments to the satisfaction of the reviewers as soon as practicable.

2.5.3. Test Report

SwRI shall prepare a report that documents the testing performed. The report shall include a description of the test facility, a test narrative, presentation of the test results, and discussion and conclusions.

3.0 Test System Overview and Setup

The test system will use a diesel engine-generator set to simulate the operation of the plant's diesel-driven AFW system following a plant accident. The genset will consist of a Detroit Diesel 12V-149T diesel engine (see Footnote 2) mated to an electrical generator that is loaded using an appropriate surrogate load (e.g., a restrictive load bank) for the plant's AFW pump and other driven loads. The test system will be designed such that the equipment and operating conditions are representative of the as-found conditions for the plant's AFW diesel engine and the subsequent safety-related mission conditions expected in response to a plant accident.

3.1. Test Equipment and Setup

The principal equipment used in the test system and the parties responsible for their procurement are identified below:

1. Diesel Engine Generator Set – The diesel genset simulates the operation of the plant's diesel-driven AFW pump and other driven loads in response to a plant accident. The engine will be mated to an electrical generator of sufficient capacity to load the diesel according to the operating load profile for the AFW pump during an accident (scaled for the test engine with fewer cylinders). The genset will include a self-contained control system for operating the genset. MPR is responsible for procuring the diesel genset and providing it to SwRI for modification and subsequent testing. The test genset is equipped with four automated trips: (1) low lube oil pressure, (2) coolant high temperature, (3) overspeed, and (4) overcrank. The set points of these trips will be adjusted to match the trip setpoints for the plant's engine, or the trips will be disabled and the test genset manually shut down if any trip conditions are reached (see Section 3.2, Item 6 for additional details).

2. Generator Loading – A resistive load bank (or acceptable equivalent load) will be connected to the diesel genset for the purpose of loading the diesel genset according to the scaled accident load profile for the AFW diesel drive. The load bank will be of sufficient capacity to accept and safely dissipate the electrical output of the genset during the test. SwRI is responsible for procuring the load bank and required connections, and for connecting the load bank to the genset.

3. Engine Lube Oil Dilution – The engine lube oil dilution system is responsible for adding fuel oil to the engine's lube oil sump to simulate the fuel leak that was identified in the plant's engine. The endurance test will begin with a specified concentration of fuel oil dilution that represents the as-found condition of the lube oil in the plant's engine. Additional fuel oil will be added to the crankcase at a fixed rate of 1.09 gal/hr (Reference 2) throughout the test to simulate the active fuel leak that the plant's engine would have experienced if it had been called to service prior to the leaking fuel components being repaired/replaced. SwRI is responsible for the design, fabrication and installation of the engine lube oil dilution system, and commissioning of the system to verify it can accurately add fuel oil at the required rate.

4. Engine Lube Oil Sampling – Throughout testing, periodic samples of engine lube oil will be taken while the engine is operating. These samples will be analyzed by SwRI to monitor lube oil dilution, wear metals, and other parameters indicative of engine health throughout testing. SwRI is responsible for making the necessary modifications to the test engine to allow for periodic oil sample collection while the genset is operating.

5. Data Acquisition Instrumentation – The diesel genset will have data acquisition instrumentation installed such that required data can be monitored and recorded throughout the duration of testing. Specific data to be recorded and the frequency of

sampling are discussed in Section 3.3. SwRI is responsible for providing and installing the necessary instrumentation, data acquisition, and data storage equipment.

Additional equipment and supplies required to perform the test are identified below:

1. Engine Lube Oil – The engine lube oil used for the test will be the same as used in the plant's engine (SAE Grade 40 Mobil DELVAC 1640). Constellation Nuclear is responsible for procuring the lube oil used for the diluted oil test and arranging for its shipment to SwRI. SwRI is responsible for: (1) receipt of the lube oil and its storage until testing, (2) adding the lube oil to the test engine, (3) removing the lube oil from the engine for final analysis, and (4) arranging for the appropriate disposal of the lube oil after test completion. SwRI is also responsible for performing lube oil changes, as appropriate, during the test (e.g., after the pre-test inspection).

2. Engine Lube Oil Filters – New engine lube oil filters that are the same or similar model(s) as used on the plant's engine will be installed on the test engine[3]. SwRI or Constellation Nuclear is responsible for procuring the lube oil filters and arranging for their shipment to SwRI (if procured by Constellation Nuclear). SwRI is responsible for installing the new lube oil filters on the test engine and the disposal of any used filters removed from the engine. The use of similar lube oil filters will have no impact on the results of the diluted oil test.

3. Engine Air Filters – New engine air filters that are the same or similar model(s) as used on the plant's engine will be installed on the test engine (see Footnote 3). SwRI or Constellation Nuclear is responsible for procuring the air filters and arranging for their shipment to SwRI (if procured by Constellation Nuclear). SwRI is responsible for installing the new air filters on the test engine and the disposal of any used filters removed from the engine. If a sufficient number of new air filters of the same or similar model(s) are not available in time to support the test, one or more existing filters on the test genset shall be inspected and used for the test if verified to be acceptable for further use based on condition. The use of acceptable used air filters, or air filters of slightly different makes or models, will have no impact on the results of the diluted oil test.

4. Diesel Fuel Oil Filters – New diesel fuel oil filters that are the same or similar model(s) as used on the plant's engine will be installed on the test engine (see Footnote 3). SwRI or Constellation Nuclear is responsible for procuring the fuel oil filters and arranging for their shipment to SwRI (if procured by Constellation Nuclear). SwRI is responsible for installing the new fuel oil filters on the test engine and the disposal of any used filters removed from the engine. The use of similar model fuel filters will have no impact on the results of the diluted oil test.

5. Diesel Fuel Oil – Diesel fuel oil that is consistent in quality and properties with the diesel fuel oil supplied to the plant's engine will be used for the test. Constellation Nuclear is responsible for procuring the diesel fuel oil and arranging for its shipment to SwRI. Constellation Nuclear is also responsible for confirming that the quality and properties of

[3] The specific model(s) of filter used may be different from the filter used on the plant's engine if there are differences for 12-cylinder vs. 16-cylinder engines.

the procured diesel fuel oil are consistent with the diesel fuel oil supplied to the plant's engine. SwRI is responsible for: (1) receipt of the fuel oil and its storage prior to and throughout testing, (2) establishing an adequate supply of fuel oil to the test engine such that the genset operates at the required loads, (3) adding the appropriate amounts of fuel oil to the test engine's lube oil sump (both the initial amount prior to test commencement and the subsequent amount at a controlled rate during the test), and (4) arranging for the appropriate disposal of the remaining fuel oil after test completion.

6. Engine Coolant – The engine shall be cooled with water with corrosion inhibitors that protect engine components against corrosion. No anti-freeze is to be used in the coolant. If the corrosion inhibitor used in the plant's engine (NALCO LCS-60) is not available, then the use of a similar corrosion inhibitor is acceptable. SwRI is responsible for: (1) procuring the engine coolant, (2) adding the coolant to the test engine, and (3) arranging for the appropriate disposal of the coolant after test completion.

7. Engine Exhaust System – SwRI is responsible for installing an appropriate exhaust system on the test engine with the capability of matching the plant's engine exhaust back pressure as closely as practicable. The target exhaust back pressure for the test engine is 15 inH_2O (1.10 inHg) at the continuous rating of the test genset. Reference 3 states that the plant engine's exhaust back pressure limit is 1.2 inHg. The exhaust system installed by SwRI shall maintain a back pressure of 12.2 inH_2O (0.90 inHg; 81.5% of 15 inH_2O) at a load of 666 kWe (81.5% of the test engine continuous rating of 1130 hp including the assumed generator efficiency of 97%).

8. Engine Crankcase Ventilation – Engine crankcase ventilation serves to mitigate excess positive pressure from the crankcase to reduce the risk of oil leaks through various seals, and in the extreme case, provide ventilation to reduce the risk of a crankcase explosion. SwRI is responsible for inspecting the test engine and making any necessary modifications to the engine crankcase ventilation system such that adequate ventilation is provided for explosion prevention, and fluids that may be expelled through the vent are appropriately captured.

9. Engine Safety Containment – Due to the nature of the testing and the potential for significant or catastrophic engine failure, additional containment surrounding the test engine is prudent to contain leaked fluids and ejected engine component(s) in the event of an engine failure. SwRI is responsible for designing, fabricating, and installing an adequate safety containment system around the test genset/engine. SwRI is also responsible for providing fire-fighting equipment (e.g., extinguishers of the appropriate class, fire blankets).

3.2. Test System Design Requirements

The test system shall meet the following requirements:

1. Initial Lube Oil Level – The test engine lube oil sump shall have the correct initial lube oil level, as specified in Section 5.1.1 or Section 5.2.1 (depending on the specific test being performed). The initial lube oil level shall be set based on post-run conditions including oil drainback to the sump from the lube oil system. For the diluted lube oil test, the initial lube oil level shall be set prior to the addition of the appropriate amount of fuel oil.

2. Initial Fuel Oil Concentration – For the diluted lube oil test, the engine lube oil sump shall contain the correct initial fuel oil concentration, as specified in Section 5.2.1. The appropriate amount of fuel oil needed to achieve the specified concentration shall be added to the lube oil sump after the specified initial lube level is set. The initial fuel oil concentration in the engine lube oil shall be 18.2% by mass.

3. Initial Lube Oil and Coolant Temperatures – The test engine lube oil and coolant shall be at the correct initial temperatures, as specified in Section 5.1.1 or Section 5.2.1 (depending on the specific test being performed).

4. Rate of Fuel Addition – The test engine shall have the ability for fuel oil to be added to the lube oil sump at a specific, controlled rate (either continuously or in periodic, discrete additions), as specified in Section 5.2.2.

5. Genset Load – The test system shall include the ability to load the genset according to the load or load profile specified in Section 5.1.2 or Section 5.2.2 (depending on the specific test being performed).

6. Test Genset Trips – The functionality and set points of the test genset trips are not currently known. The test genset generator control panel contains indication lights for overcrank (duration), overspeed, coolant high temperature, and lube oil low pressure trips. The plant engine has the same four trips, with set points of 55 seconds, 1,900 rpm, 205°F, and 10 psig (Reference 4), respectively. Since the trips on the plant engine are not disabled during emergency operation, the test genset trip set points must be incorporated into the diluted lube oil test. The test engine trips will be addressed as follows:
   - The overcrank trip shall be disabled, as the engine will be started under local control, and any start attempt can be manually discontinued.
   - The overspeed trip shall not be disabled for personnel safety and asset protection purposes. SwRI shall verify that the overspeed trip does not actuate during test engine starts.
   - The coolant high temperature trip shall be disabled, as engine outlet coolant temperature will be monitored during the test, and the test engine can be manually shut down without damaging the engine should coolant temperature reach the plant's trip set point of 205°F. The coolant high temperature trip shall not be disabled until after commissioning testing is complete.
   - The low lube oil pressure trip shall be disabled, as it could trip spuriously or have a set point above the nominal 10 psi set point of the plant engine's low lube oil pressure trip. The low lube oil pressure trip shall not be disabled until after commissioning testing is complete.

3.3. Test System Monitoring Requirements

The test system shall include instrumentation and other equipment that allow for the following monitoring during the test:

1. Lube Oil Pressure – Lube oil pressure shall be monitored and recorded both electronically (every six seconds using SwRI-installed sensor(s)) and manually (every 10 minutes, or more frequently as needed, using the existing engine-mounted gauge). If

the existing engine-mounted gauge is non-functional or provides erroneous indication, the SwRI-installed sensor is sufficient documentation of lube oil pressure.

2. Lube Oil and Fuel Oil Sump Temperature – Lube/fuel oil sump temperature shall be monitored and recorded electronically (every six seconds using SwRI-installed sensor(s)) and manually (every 10 minutes, or more frequently as needed, using the existing engine-mounted gauge). If the existing engine-mounted gauge is non-functional or provides erroneous indication, the SwRI-installed sensor is sufficient documentation of lube/fuel oil sump temperature.

3. Engine Outlet Coolant Temperature – Engine outlet coolant temperature shall be monitored and recorded both electronically (every six seconds using SwRI-installed sensor(s)) and manually (every 10 minutes, or more frequently as needed, using the existing engine-mounted gauge). If the existing engine-mounted gauge is non-functional or provides erroneous indication, the SwRI-installed sensor is sufficient documentation of engine outlet coolant temperature.

4. Genset Speed/Generator Output Frequency – Generator output frequency shall be monitored and recorded manually (every 10 minutes, or more frequently as needed) using the existing panel-mounted gauge or the load bank frequency indication.

5. Genset Load – Genset load shall be monitored and recorded manually (every 10 minutes, or more frequently as needed) using the load bank display.

6. Fuel Oil Addition Rate – The rate of fuel oil addition to the lube oil sump shall be monitored. If additions are performed continuously (e.g., by peristaltic pump), then parameters that govern the volumetric flow rate shall be recorded manually (every 5 minutes, or more frequently as needed). If additions are performed by periodic, discrete additions, then the volume and timing of each addition shall be recorded manually.

7. Lube Oil Quality – Representative samples of engine lube/fuel oil shall be collected from the test engine sump hourly during the test and subjected to the following analyses:

   - Viscosity at 40°C and 100°C per ASTM D445
   - Viscosity Index per ASTM D2270
   - Fuel dilution per ASTM D3524
   - Wear metals per ASTM D5185
   - Sulfur per ASTM D5185
   - Distillation per ASTM D86

8. Engine Health – The health of the test engine shall be monitored by appropriate transducers to detect changes in engine vibration and/or sound indicative of the degradation of internal engine or generator components (e.g., bearing/bushing failure).

9. Video Monitoring – The test genset and its installed gauges shall be monitored by videography during testing. Videography of the gauges shall be of sufficient resolution to permit the gauge readings to be read and manually recorded. Any videos should include time stamp information that can be traced back to engine operating time.

SwRI shall include in its test procedure(s) any proposed additional instrumentation or other equipment for the purpose of monitoring engine and/or operating parameter(s) during the test.

4.0 Commissioning

Commissioning tests shall be performed to verify that the genset, load bank, lube oil dilution system, lube oil sampling system, and the existing and added data acquisition and monitoring equipment are functioning correctly prior to the start of the test. Any operation of the test engine during commissioning shall be performed with the engine lube oil filled according to manufacturer's recommendations (i.e., no fuel oil should be introduced into the lube oil for commissioning).

4.1. Genset Receipt Inspection

SwRI shall perform a walkdown and visual inspection of the test genset upon receipt and prior to operation of the genset. SwRI shall inform MPR immediately if any obvious quality issues that could potentially impact the test schedule and results (e.g., broken or missing components) are observed.

4.2. Engine Pre-Test Inspection

An engine inspection and partial engine tear down, as necessary, of select components shall be performed prior to operation of the genset. The tear down and inspection activities shall be performed by qualified Constellation Nuclear personnel and/or other subcontracted personnel with experience with the Detroit Diesel 149-series engine (e.g., Stewart & Stevenson). All components that are identified as degraded and are judged by MPR to potentially impact the test result shall be replaced (or repaired, if possible) prior to operation of the genset. Constellation Nuclear is responsible for procuring all required replacement parts, with assistance from MPR and SwRI as needed for identifying appropriate options.

4.3. Test System Assembly Verification

SwRI shall visually inspect the assembled test system (test genset, load bank, and added systems and monitoring equipment) to verify that all equipment is installed in the correct locations and orientations, is attached by appropriate means (e.g., electrical cables between the generator and load bank, fuel supply hoses), and overall meets all design requirements identified in this test plan. SwRI shall correct all identified issues prior to performing the baseline and diluted lube oil tests in Section 5.1 and Section 5.2, respectively.

4.4. Test System Operation Verification

SwRI shall verify that all sub-systems of the test system are operational and able to perform their intended function(s), including correctly receiving and executing control signals, prior to performing the baseline or diluted lube oil tests in Section 5.1 (as possible) and Section 5.2, respectively. Sub-systems that require the test genset to be operating (e.g., load bank) may be verified during the baseline test described in Section 5.1. SwRI shall correct all identified issues prior to performing the diluted lube oil test in Section 5.2.

4.5. Test Data Verification

SwRI shall verify that all test system components that generate test data or other direct/indirect test results are operational, calibrated, and provide consistent, accurate data prior to performing the baseline or diluted lube oil tests in Section 5.1 (as possible) and Section 5.2, respectively. Components that require the test genset to be operating (e.g., genset speed, engine lube oil pressure) may be verified during the baseline test described in Section 5.1. SwRI shall correct all identified issues prior to performing the diluted lube oil test in Section 5.2. SwRI shall provide up-to-date calibration records for all calibrated components stating the calibration scope, results and dates (both performed and due dates) for each component.

5.0 Testing

The AFW diesel test will consist of two phases: (1) a "baseline test" for demonstrating that the test system is fully operational and that the test engine is capable of reliable operation for an extended period with normal lube oil conditions, and (2) a "diluted lube oil test" for determining the impact of an elevated and increasing fuel oil concentration in the engine lube oil on engine performance, reliability, and longevity. The two test phases shall be performed sequentially in the order listed. Details for both tests are discussed below.

5.1. Baseline Test

SwRI shall perform a baseline test to demonstrate that the test system is fully operational and reliable under normal engine lube oil conditions for a cumulative period of up to 24 hours. The test may be performed in multiple sessions to accommodate personnel schedules and/or to minimize noise impacts on the residential neighborhood surrounding the test location. The baseline test session(s) should be performed such that the number of times the test engine is stopped and re-started is minimized as much as practicable. See Section 5.1.2 for additional requirements regarding the duration and genset loading for the baseline test.

The baseline test will also serve to "break-in" the engine lube oil so that its condition more accurately represents the used condition of the lube oil in the plant's engine at the time the fuel leak was identified. Engine lube oil samples will be collected at four-hour intervals during the baseline test and analyzed to monitor oil conditioning and the health of lubricated engine components.

As noted in Section 4.4 and Section 4.5, verification of proper operation of some test sub-systems and components may require the test genset to be operating. SwRI may perform the verification of these components during the baseline test.

The initial (prior to starting) and operating conditions, and the termination and restart criteria for the baseline test are identified in the following sections.

5.1.1. Initial Conditions

Following are the required initial conditions for the baseline test:

- The engine sump lube oil level shall be at the high-level mark on the engine dipstick.

- The engine lube oil shall contain no fuel oil (above trace levels).
- The engine lube oil temperature shall be ≥40°F.
- The engine coolant temperature shall be ≥40°F.
- The temperature in the immediate vicinity of the test genset shall be ≥40°F.

5.1.2. Operating Conditions

Following are the required operating conditions for the baseline test:

- The genset operating speed shall be 1,800 rpm +/- 36 rpm.
- The genset shall be operated consistent with the engine OEM's requirements prior to loading.
- The genset shall be loaded to a minimum of 666 kWe within 55 seconds of the initial start signal.
- The test duration shall be up 24 hours of cumulative, loaded operation consistent with the loading schedule below. The test may be performed in multiple sessions. SwRI may adjust the session and/or total test durations with prior approval by MPR and Constellation Nuclear. The genset shall be loaded according to the following
    - Hours 0 through 12 – A minimum of 666 kWe (equivalent to approximately 77 engine bhp/cylinder)
    - Hours 12 through 14 – A minimum of 666 kWe (equivalent to approximately 77 engine bhp/cylinder)
    - Hours 14 through 18 – A minimum of 593 kWe (equivalent to approximately 68 engine bhp/cylinder)
    - Hours 18 through 22 – A minimum of 570 kWe (equivalent to approximately 66 engine bhp/cylinder)
    - Hours 22 through 24 – A minimum of 511 kWe (equivalent to approximately 59 engine hp/cylinder).

  Note: If the total duration of the baseline is to be less than 24 hours, the duration of the first load step (hours 0 through 12) shall be reduced accordingly. The baseline test shall finish by completion of the full accident load profile for the plant engine (i.e., the last four load steps; hours 12 through 24).
- The engine lube oil temperature shall be ≤230°F.

[4] The load profile for hours 13-24 of the baseline test matches the load profile for the first 12 hours of the diluted oil test. Loads for each period were calculated by scaling Braidwood 2B AFW loads in Reference 5 as documented in Reference 6.

- The engine coolant temperature shall be 160-185°F once stable operating conditions are achieved.
- The engine lube oil pressure shall be ≥65 psig.
- The temperature in the immediate vicinity of the test genset shall be ≥40°F.

5.1.3. Termination Criteria

Following are the criteria for terminating the baseline test prior to completing the required duration:

- The SwRI test manager may terminate the test for any safety reason(s).
- Any of the required operating conditions in Section 5.1.2 are not met (with the required action(s) taken after discussion and agreement by Constellation, MPR, and SwRI, as appropriate depending on the condition(s) not met).
- Any test system component fails.
- The performance of any test system component becomes degraded such that its failure and/or the failure of another component is imminent.
- Any test system component develops a significant fluid leak that cannot be contained or otherwise managed safely or will impact the test results.
- Any test system component catches fire.
- The test engine and/or generator experience a significant change in noise type and/or increase in level consistent with the degradation of internal engine components.
- The test engine and/or generator experience a significant increase in vibration consistent with the degradation of internal engine components.
- There is a significant change in oil analysis results consistent with degradation of internal engine components.
- The overspeed limit is reached, but the automated trip does not actuate.
- The engine coolant outlet temperature increases to 205°F or lube oil pressure decreases to 10 psi, as the plant engine would have automatically tripped should either of these conditions occur.

Note that the above criteria are intended to protect the test system so that issues can be corrected and the test system used for the diluted lube oil test in Section 5.2.

5.1.4. Restart Criteria

Restarting of the test genset may be required if the baseline test is terminated prematurely (manually or by automated trip). If this occurs, SwRI shall not restart the test genset without first determining the reason(s) for the termination and receiving approval to restart from MPR and Constellation Nuclear.

5.2. *Diluted Lube Oil Test*

SwRI shall perform a diluted lube oil test to determine if a Detroit Diesel 149-series diesel engine can operate at the required loads with its lube oil diluted by fuel oil from a simulated active fuel leak. The test duration shall be at least seven hours unless the test engine experiences a failure or the test is terminated prematurely for safety reasons (see Section 5.2.3). If seven hours of operation is achieved, Constellation Nuclear shall determine for how much longer the test system should be operated before the test is terminated (assuming no test engine failure or other safety issues prior to). The health of the engine and lubricated internal components will be monitored, in part, through the analysis of lube oil analysis samples collected hourly.

The initial (prior to starting) and operating conditions, and the termination and restart criteria for the diluted lube oil test are identified in the following sections.

5.2.1. Initial Conditions

Following are the required initial conditions for the diluted lube oil test:

- The engine sump lube oil level, prior to the addition of fuel oil, shall be at a level consistent with the plant engine oil level prior to initiation of the fuel oil leak.
- The engine lube oil shall contain 18.2% fuel oil (by mass). Note: The addition of the fuel oil to the test engine sump may raise the lube oil level above the high-level mark on the engine dipstick.
- The combined lube oil and fuel oil in the engine sump shall be mixed.
- The temperature of the combined lube oil and fuel oil in the engine sump shall be 40°F-127°F.
- The engine coolant temperature shall be 40°F-127°F.
- The temperature in the immediate vicinity of the test genset shall be ≥40°F.

5.2.2. Operating Conditions

Following are the required operating conditions for the diluted lube oil test:

- The genset operating speed shall be less than 1,800 rpm +/- 36 rpm.
- The genset shall be loaded to a minimum of 666 kWe within 55 seconds of the initial start signal.
- The genset shall be loaded according to the following load profile (based on the load profile for the plant's engine, but scaled for a 12-cylinder engine; see Footnotes 2 and 4):
    - <u>Test start through 2 hours</u> – A minimum of 666 kWe (equivalent to approximately 77 engine bhp/cylinder)
    - <u>Hours 2 through 6</u> – A minimum of 593 kWe (equivalent to approximately 68 engine bhp/cylinder)

    - Hours 6 through 10 – A minimum of 570 kWe (equivalent to approximately 66 engine bhp/cylinder)
    - Hour 10 through End/Termination of Test – A minimum of 511 kWe (equivalent to approximately 59 engine hp/cylinder).
- The amount of fuel oil in the engine lube oil shall increase at a continuous (or equivalent stepped) volumetric rate of 1.09 gal/hr.
- The test duration shall be a minimum of 7 hours, and a maximum to be determined by Constellation Nuclear.

5.2.3. Termination Criteria

Following are the criteria for terminating the diluted lube oil test prior to completing the required duration:

- The SwRI test manager may terminate the test for any safety reason(s).
- Any of the required operating conditions in Section 5.2.2 are not met, such that the test results will not be valid or useful.
- Any test system component fails.
- Any test system component develops a significant fluid leak that cannot be contained or otherwise managed safely or a leak that will impact the test results occurs.
- Any test system component catches fire.
- The test engine and/or generator experience a significant change in noise type and/or increase in level consistent with an imminent catastrophic failure.
- The test engine and/or generator experience a significant increase in vibration consistent with an imminent catastrophic failure.
- The overspeed limit is reached, but the automated trip does not actuate.
- The engine coolant outlet temperature increases to 205°F or lube oil pressure decreases to 10 psi, as the plant engine would have automatically tripped should either of these conditions occur.

Note: In general, the diluted lube oil test should be allowed to progress until completion or significant/catastrophic failure (without compromising test facility and personnel safety).

5.2.4. Restart Criteria

In the event of a premature termination of the diluted lube oil test, the test genset shall not be restarted until after a thorough evaluation is performed and all parties (Constellation Nuclear, MPR and SwRI) are in agreement. Depending on the reason(s) for the termination, a restart of the test system may not be required.

6.0 Test Documentation

SwRI shall provide the following documentation for the AFW diesel test prior to commencement of the test:

- Details of the test system design,
- Commissioning, Testing and Pre-Test Inspection procedures,
- Details for all test system components and equipment to be used (e.g., manufacturer, model number, serial number), and
- Calibration records for calibrated test system components and equipment.

SwRI shall provide the following documentation for the AFW test during the performance of the test:

- Lube oil analysis reports (provided on an expedited basis as close to real time as practicable)

SwRI shall provide the following documentation for the AFW test upon completion of the test:

- Copies of completed test procedures,
- Log sheets and/or electronic copies (as appropriate) of all data recorded during the test, and
- A comprehensive report summarizing the scope and results of the test.

7.0 References

1. Bureau Veritas Oil Condition Monitoring Lube Oil Analysis Management System Report for Braidwood 2AF01PB-K-PMPA-01PB-E15-K (Braidwood 2B AFW Diesel Drive Lube Oil), October 4, 2023.
2. MPR Calculation 4101-0031-CALC-001, "2B AFW Diesel Engine Test Fuel Leakage Rate," Revision 1, December 8, 2023.
3. Exelon Generation Braidwood Station Drawing 62240-1, "Installation Drawing – 16V-149TI Auxiliary Feedwater Pump Drives," Revision D.
4. Exelon Generation Braidwood Station Procedure No. BwOP AF-7, "Auxiliary Feedwater Pump _B(Diesel) Startup on Recirc," Revision 55.
5. Constellation Calculation BRW-10-0146-M /BYR10-103, "AF Diesel Driven Pump Fuel Consumption and Day Tank Requirements, Revision 3, February 26, 2015.
6. MPR Memorandum 4101-0031-MMO-001, from Mark O'Connell (MPR) to Matt Fisher (Constellation), "Evaluation of Test Load for Braidwood 2B Auxiliary Feedwater Pump Diesel Drive Test with Lube Oil Diluted by Fuel Oil," Revision 0, December 4, 2023.

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Southwest Research Institute Test Report

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POWERTRAIN ENGINEERING DIVISION

January 19, 2024

LOCOMOTIVE TECHNOLOGY CENTER
A Department of SwRI

Mark O'Connell
MPR Associates, Inc.
320 King Street
Alexandria, VA 22314
moconnell@mpr.com

Subject: SwRI Project 03.28462 Final Report - "12V-149 GENSET 24-Hour Test with Fuel Dilution of the Lubricating Oil"

MPR Associates' client, Constellation Energy, experienced an internal Diesel fuel leak on one of their Detroit Diesel Corperation (DDC) 16V - 149 Series engines. When the leak was identified, the fuel dilution of the engine oil was reported to be 18.2% (mass based). If the leak had not been found before the engine was pressed into 24-hour operation, as part of an emergency shutdown event, there was concern about the engines ability to operate at 18.2% and higher fuel dilution levels. The goal of this project was to demonstrate the effects of 18.2% and higher levels of fuel dilution in the engine oil on a similar DDC 149 Series engine.

A used Diesel-powered generator (Genset), fitted with a DDC 12V - 149 Series engine, was purchased by MPR for this project. Figure 1 shows the name plate of the DDC 149 Series engine in the Genset purchased by MPR Associates.

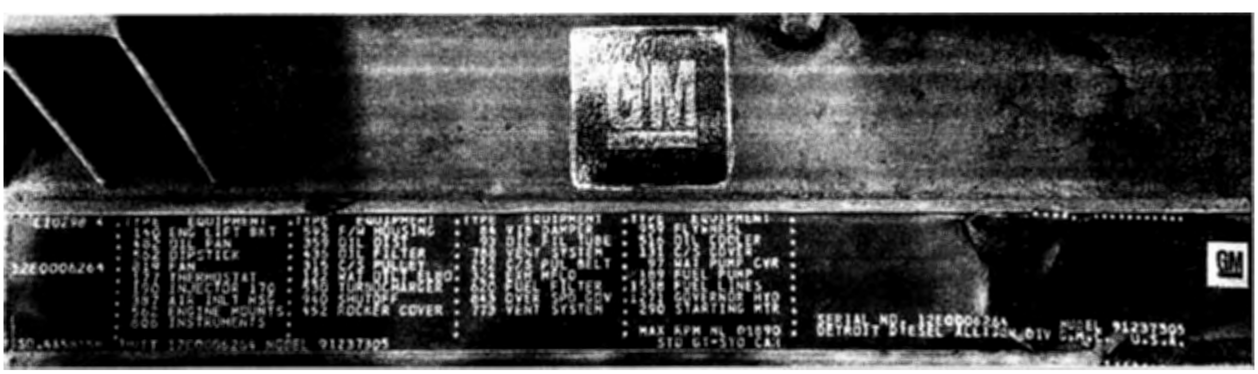


Figure #1 DDC 12V – 149 Series Engine Name Plate

At the start of the project SwRI received MPR Associate's test plan and SwRI prepared an appropriate test procedure (as required by the test plan). SwRI executed the tests described in this report in accordance with these documents. Additionally, SwRI prepared a safety plan that was used to inform / train the visitors from MPR, Constellation Energy, and Nuclear Regulatory Commission (NRC) about the project's safety requirements.

The Genset was delivered to Southwest Research Institute's (SwRI) Locomotive Technology Center (LTC) on 17-Nov-23 and installed in the "Back Shop" at the LTC. This location was chosen because the facility had:

- 30-ton overhead crane.
    - Required for off-loading, positioning, and reloading of the 10 (+) ton Genset.
- Secondary containment under the Genset.
- 1" steel plate wall to protect SwRI staff and visitors from MPR, Constellation Energy, and NRC that witnessed the tests, in the advent that there was a catastrophic engine failure.
- Location for the load bank and fuel storage outside of the test cell.
- Secondary building inside the Back Shop for SwRI staff and visitors to assemble during the test, near the test cell.
    - This building also held all the data acquisition and test cell camera displays.

Genset Modifications

After the Genset was delivered, several modifications to the Genset were needed to get the engine in good operating condition. The first modification was the removal of the radiator because the radiator coolant passage tubes were internally plugged as shown in Figure 2. The Genset radiator was replaced by a SwRI provided external radiator system that used an electric motor driven fan. The external radiator was mounted at the front of the Genset as shown in Figure 3. The fan was powered by the 480 Volt, 3-phase, electrical power generated by the Genset. The power used to drive the radiator fan was accounted for in the Genset power calculations.

Figure #2 Original Genset Radiator Tubes Viewed from Bottom of Radiator

Figure #3 Location of External Radiator Relative to the Genset, Locations of Current and Voltage Sensors, and Exhaust Pipe with Backpressure Throttle

When the external radiator was installed, several modifications to the engine's coolant system were required. These included building a custom jacket water outlet manifold, shown in Figure 4. This manifold was used to combine the two outlets from the engine's thermostat housings to a single pipe flange needed to connect to the external radiator. Additionally, the inlet to the engine's water pump had to be adapted to accommodate a different flange fitting (Figure 5), on the suction line between the external radiator and the water pump.

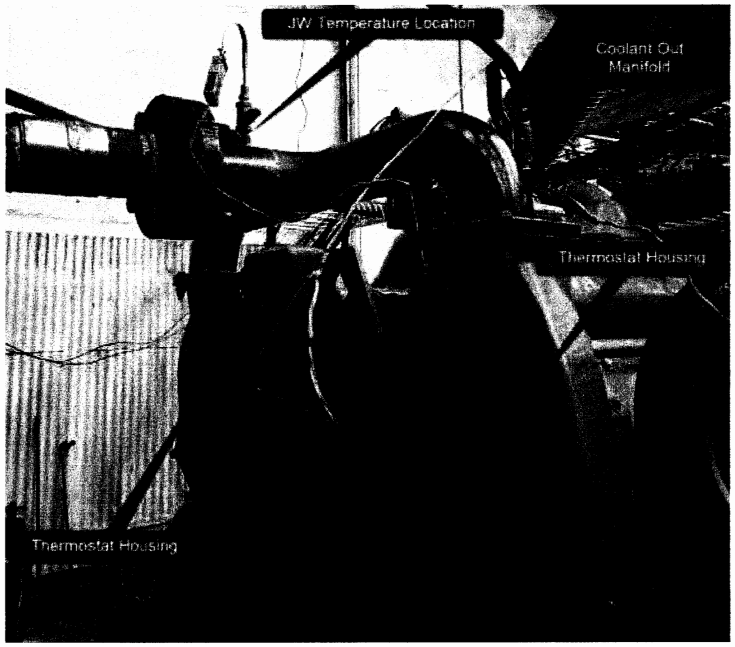


Figure #4 Jacket Water Outlet Manifold, Thermostat Housings, and Location of Jacket Water Temperature TC

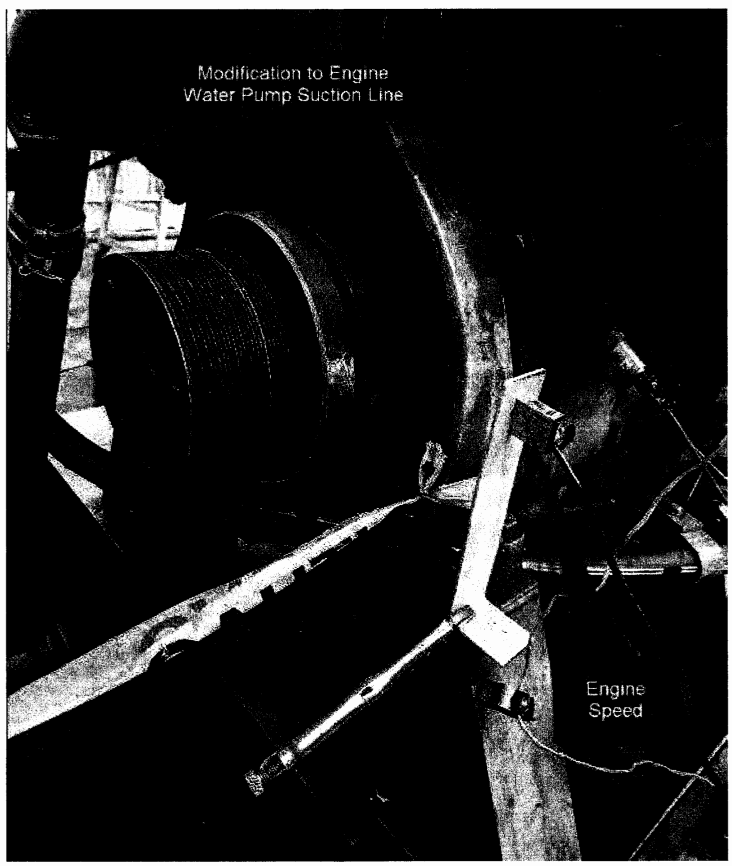


Figure #5 Water Pump Inlet Modifications and Engine Speed Sensor

The engine was delivered with passive (thermosyphon) block heaters. However, because the DDC 149 engines at the Constellation power plant did not use block heaters, the block heater system on the test Genset was left in the coolant system but were not powered.

In early operation of the Genset, the engine's jacket water operating temperature was higher than expected. It was determined that the thermostats needed to be replaced (Figure 4 shows the location of the thermostat housings). Six new 170°F thermostats were purchased from Stewart and Stevenson (S&S), the local DDC / MTU Dealership. Prior to the installation of the new thermostats, the Genset was operated for about 15 minutes post removal of two of the old thermostats. For this engine operation, the suction and return lines were run to a 330-gallon tote of water to flush the engine of any loose debris to prevent plugging of the external radiator. Once the engine was flushed, the new thermostats were installed, and the engine was connected to the external radiator.

The engine was filled with softened water and Dober TR81160 water treatment in a ratio recommended by the manufacturer. Dober TR81160 is formulated for use in heavy-duty on-highway, off-road, marine, and in locomotive engine cooling systems. Water treatment was used because the engines at the Constellation's power plant also operate on treated water (not anti-freeze) so the coolant used by this project offered similar heat capacity to the cooling system on Constellation's DDC engines.

An exhaust pipe was added to the Genset's exhaust system to route the exhaust outside the Back Shop as shown in Figure 3. A support was built at the front of the Genset to support the exhaust pipe so that added weight of the exhaust pipe was not put on the four turbochargers. Additionally, the pipe was fitted with a back pressure throttle and the back pressure on the exhaust was set at just over 13 inches of water at rated power.

During early operation of the Genset, it was determined that the analog fuel pressure gauge at the top of the fuel filter housing had failed. This was replaced with a glycerin filled analog gauge and a pressure transducer, as shown in Figure 6. The output from the pressure transducer was connected to the Campbell datalogger used to acquire all the pressure, temperature, power, and speed signals.

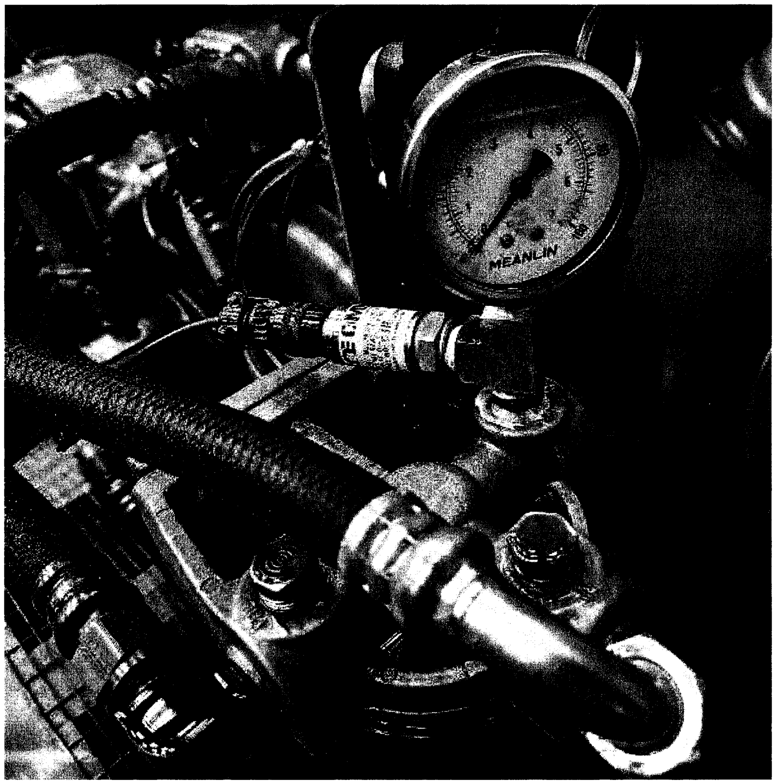


Figure #6 Fuel Pressure Gauge and Transducer

The oil drain plug in the bottom of the oil pan was replaced to allow the installation of the oil sampling system and for easy draining of the engine oil. During the installation of this system a crack in the bottom of the oil pan was found. A replacement oil pan was purchased, but the new oil pan had an incorrect bolt pattern on the upper lip of the pan. A new set of bolt holes were drilled in the new oil pan so that it could be mounted on the engine. There were four new bolt holes that overlapped with the old bolt holes and these four locations leaked after the initial installation. However, additional gasket sealer was installed around these overlapping bolt holes and the leak was stopped for the duration of the project.

At the end of the first 12-Hours of Baseline testing, the Barber Colman governor controller (Figure 7), caused the engine speed became less stable and the project was unable to further tune the controller. A replacement Barber Colman controller was located at SwRI's Main Campus, and it was installed and tuned. This replacement controller was used for the second 12-hour Baseline test and the 24.5-hours of operation during the fuel Dilution test. At the end of the project, the original Barber Colman controller was reinstalled on the Genset, and the replacement controller was returned to SwRI.

Figure #7 Barber Colman Governor Controller

To allow for remote oil sampling, an oil circulation loop was installed on the engine to draw oil from the bottom of the engine oil pan, near the engine's oil pump pickup strainer, and returned to the upper oil pan approximately two inches below the top surface of the oil in the engine as shown in Figure 8. This system used a stainless-steel rotary vane pump, shown in Figure 9, that was rated at 35 GPH to circulate the engine oil into the Hut where the samples could be safely taken. The ½" hose between the pump and the sample point was 35-foot long and held ~0.36 Gallons of engine oil. At a flow rate of 35 GPH, the oil would transfer between the vane pump and the sample point in the Hut (shown in Figure #10) in ~0.62 minutes.

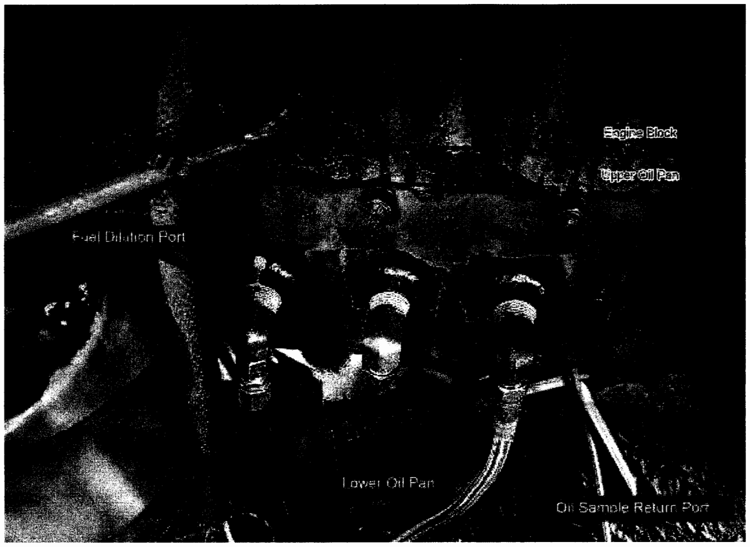


Figure #8 Return Location for Oil Sample System and Location for Fuel Dilution Port

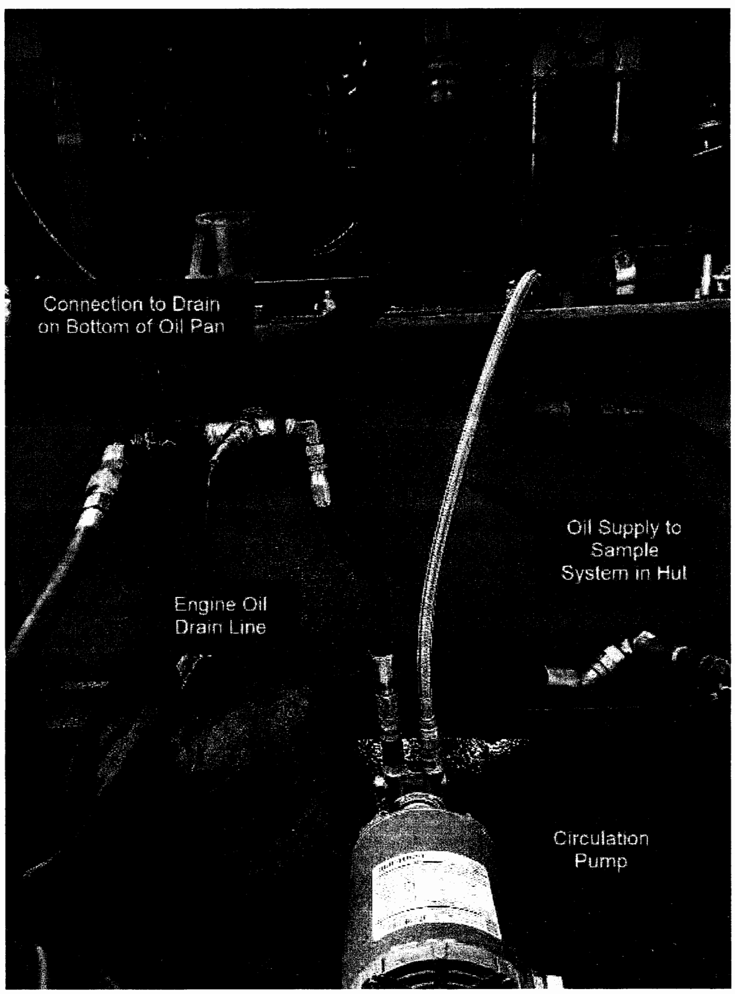


Figure #9 Oil Sample Circulation Pump and Engine Oil Drain Port

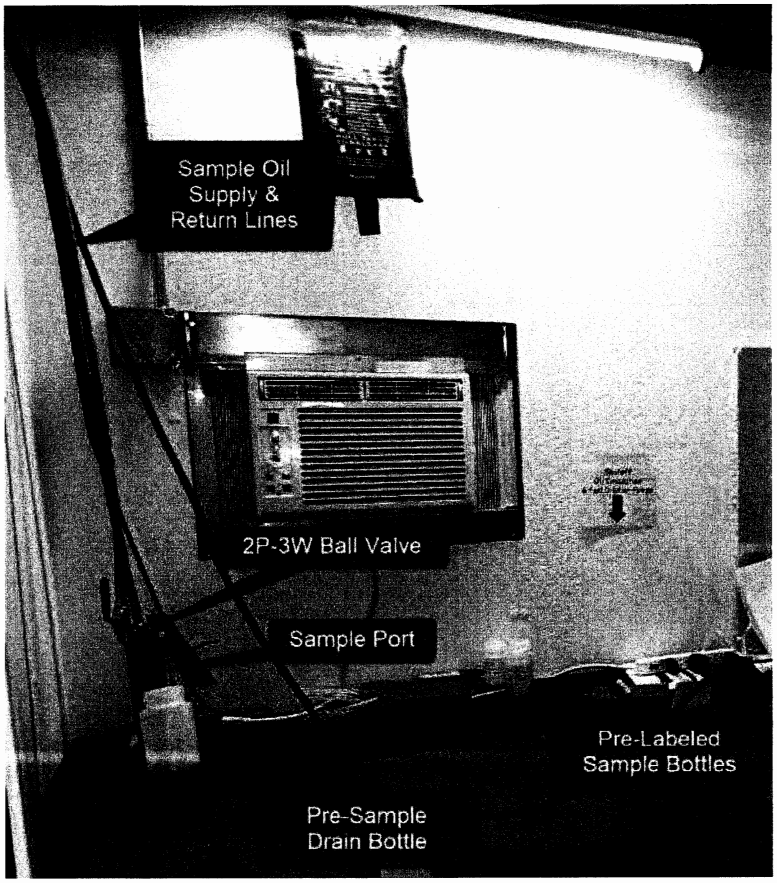


Figure #10 2P – 3W Ball Valve and Oil Sample System Inside the Hut

Prior to the Baseline tests, S&S was hired by MPR Associates to inspect the engine. A few of the main and rod bearings were removed and inspected. Constellation Energy Staff determined that the condition of the bearings was acceptable, and the engine was reassembled by S&S, using the original bearings.

During the Genset's initial operation, it was found that the engine was unable to pull full power. Using IR temperature readings on the exhaust manifold, it was determined that Cylinder 4L had lower than expected exhaust temperature, suggesting that it was producing lower than expected power. S&S staff returned and installed a new injector in this cylinder. The used injector from Cylinder 4L, shown in Figure 11, appeared to have burnt hydrocarbons on the outside of the injector body. Once this injector was replaced, the static timing on all injectors was set and fuel injector racks (shown in Figure 12) were adjusted to DDC specifications. After this modification the Genset was able to pull full power.

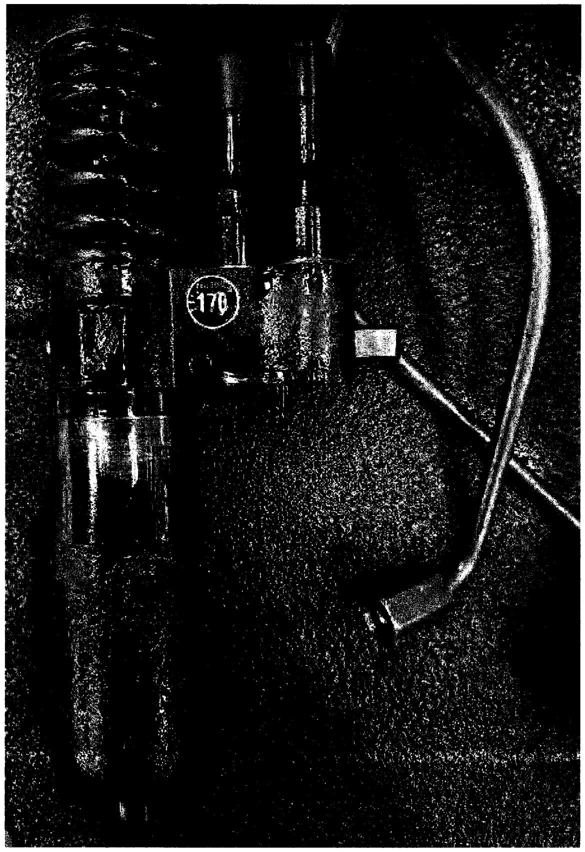


Figure #11 Injector Removed from Cylinder 4L

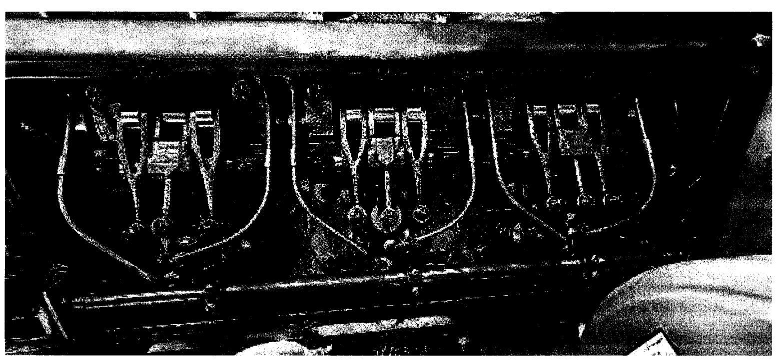


Figure #12 Overhead View of Injectors and Fuel Rack on Left Rear Quadrant of Engine

Preparation of Engine Oil System

Because this project focused on the potential degradation of the engine oil, by adding diesel fuel to the sump, several steps were taken to assure that the engine's oil system was prepared as thoroughly as possible. Before the initial start of the testing, the engine oil was drained along with the oil filters. The engine was then pre-lubed at a port on the left side of the engine block (Figure 13) with about 10 gallons of locally purchased Mobil Delvac 1640 - 40wt engine oil to flush the engine. After the pre-lube flush, the pre-lube oil was drained and discarded. The engine was then filled with the locally purchased Mobil Delvac 1640 - 40wt engine oil so that the engine could be thoroughly purged before the Constellation supplied Mobil Delvac 1640 engine oil was put into the engine. The purge oil and original filters were used while debugging the Genset.

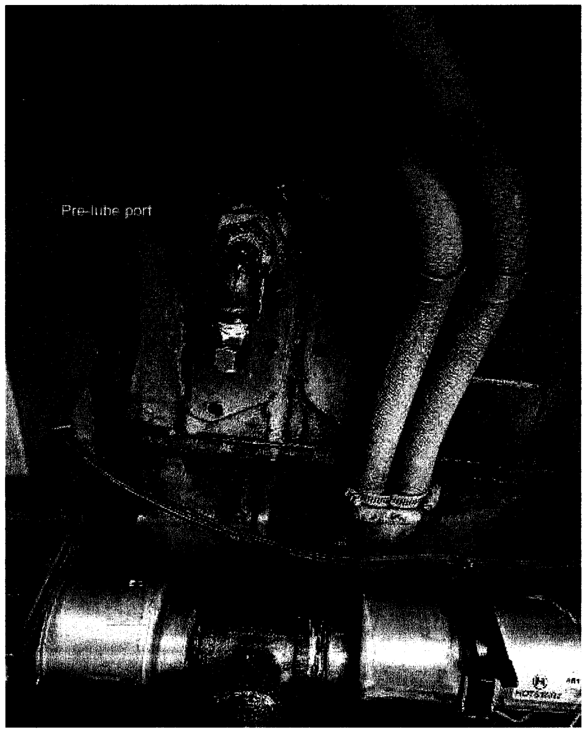


Figure #7 Location of Pre-Lube Port

Before the 24-hour Baseline tests, the engine was thoroughly drained of the purge Delvac 1640 engine oil, and all the oil, fuel, and air filters were replaced. The engine was then filled with the appropriate amount of Constellation supplied Mobil Delvac 1640 engine oil in preparation for the Baseline test.

Before the start of the fuel Dilution test, the engine and filters were drained, and then the engine was filled with the appropriate ratio of Constellation supplied Mobil Delvac 1640 engine oil and Constellation supplied Diesel fuel. At the end of the fuel Dilution test the engine and filters were drained again, in preparation for shipping the Genset.

Instrumentation

The backbone of the data acquisition system was a Campbell Scientific datalogger, Model CR3000 Micrologger®. The CR3000 was designed for stand-alone operation in harsh, remote environments, which worked well for the projects test environment. The CR3000 was programed to acquire the data at a rate of 0.166 Hz (once every 6 seconds or 10 times a minute). The CR3000 was located on top of the load bank controller, which is shown in Figure 14, that was located outside of the Hut, but the datalogger display was in the building housing the data acquisition and test cell camera displays as shown in Figure 15.

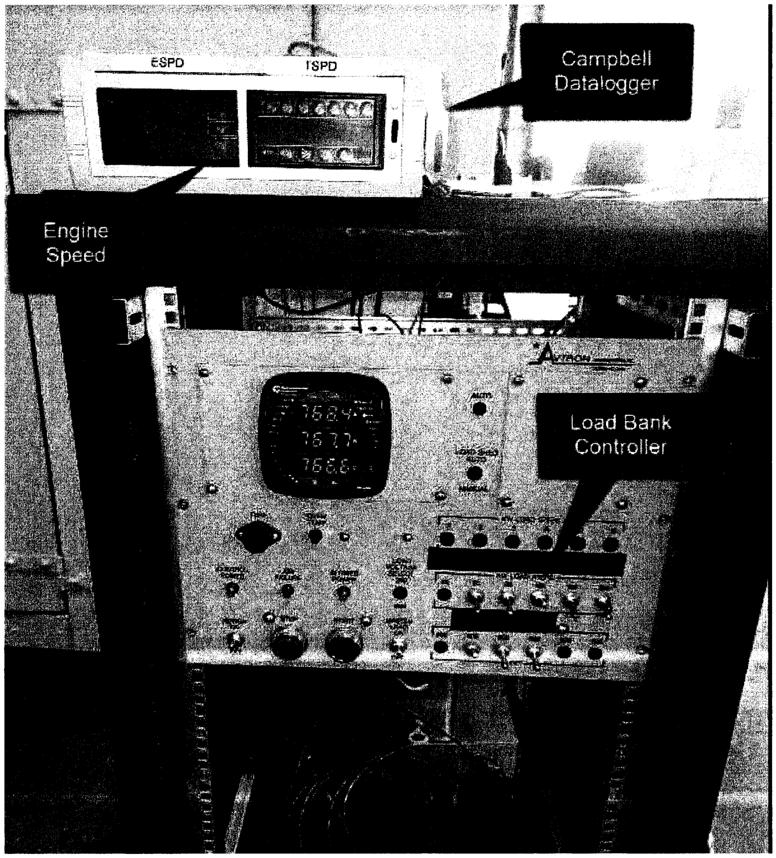


Figure #14 Location of Campbell Datalogger, Load Bank Controller, and Engine Speed Display

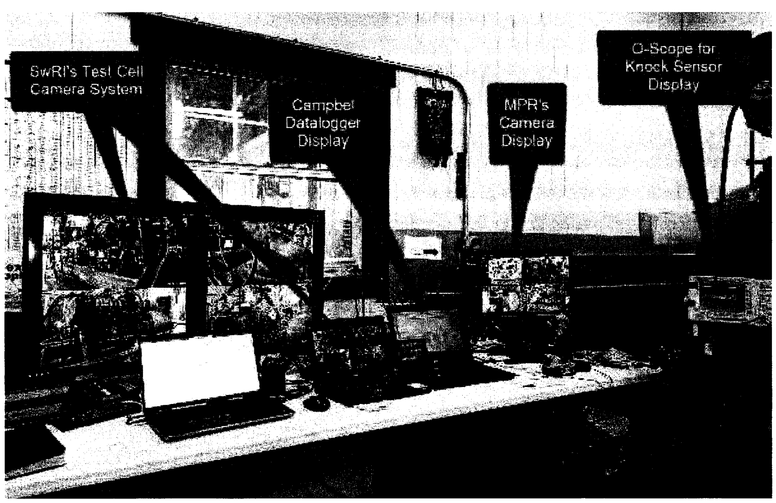


Figure #15 Campbell Datalogger Display, Camera Displays, and Knock Sensor O-Scope

The signals collected by the Campbell datalogger were:

- Temperatures
  - Ambient
    - Mounted at the back of Campbell CR3000 datalogger, next to the Hut.
    - Figure 14
  - Intake air
    - Mounted in Left Rear air filter.
    - Figure 16 & 18
  - Oil Sump
    - Located in the left side of the new, lower oil pan.
    - Figure 17
  - Coolant
    - At the outlet of the Jacket water manifold.
    - Figure 4
- Pressures
  - Oil
    - Left front corner of the engine block.
    - Figure 18
  - Fuel
    - Mounted on top of fuel filter housing.
    - Figure 6
  - Crankcase
    - Tapped into the front of the engine, on the gear cover.
    - Figure 19
- Power
  - Volts & Amps
    - Inside rear of alternator
    - Figure 3
- Engine Speed
  - RPM
    - On crankshaft harmonic balancer.
      - Optical system utilizing reflective tape on balancer.
    - Figures 5 and 14

The exhaust back pressure was not monitored by the Campbel CR3000. A Dwyer 15 In H_2O Magnehelic, shown in Figure 16, was used to set and monitor the back pressure during the test. Once the back pressure was set, it was not adjusted again.

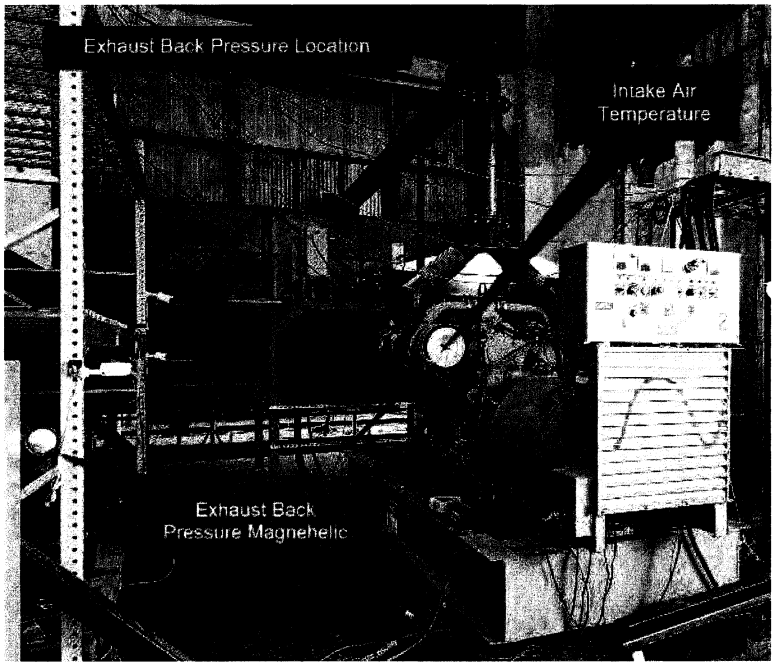


Figure #16 Location of Intake Air Temperature Sensor and Exhaust Back Pressure

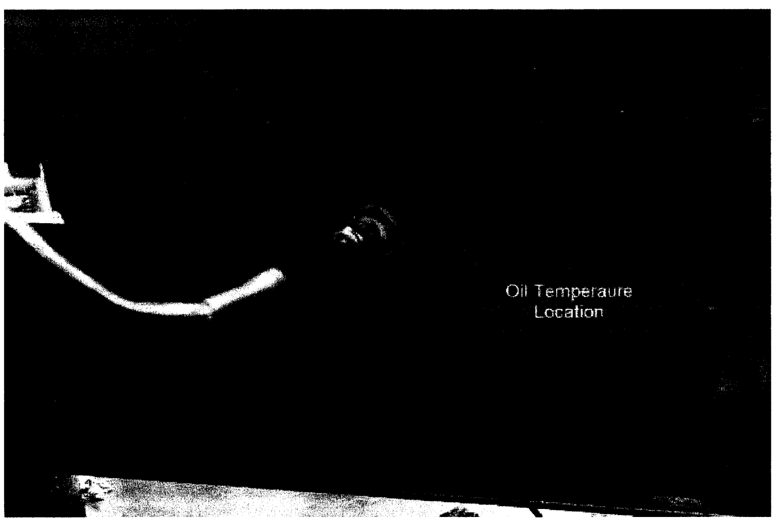


Figure #17 Location of Oil Sump Temperature Sensor

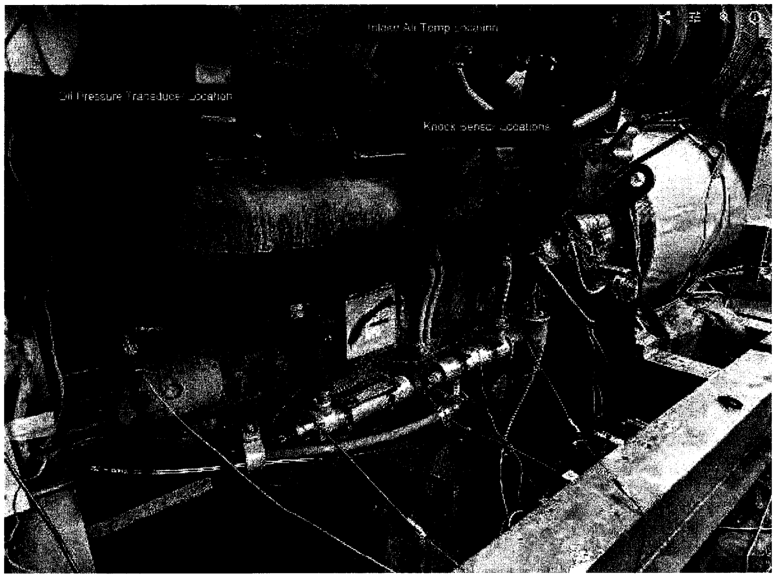


Figure #18 Location of Oil Pressure Sensor, Knock Sensors, and Intake Air Temperature

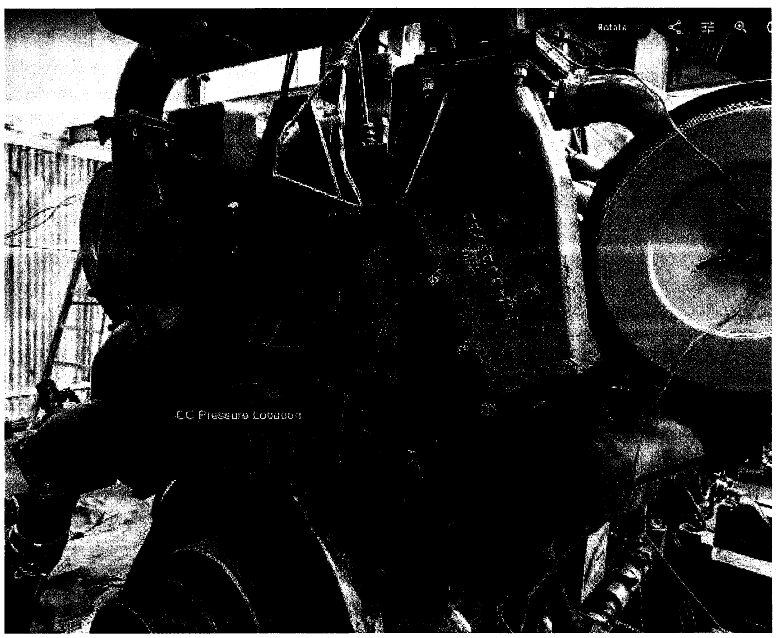


Figure #19 Crankcase Pressure Location

To visually track the changes in oil temperature and oil pressure, thought to be critical indicators to the health of the engine, the values were streamed on an hour-long digital strip chart on the Campbell CR3000 display so that trends could easily be identified. The location of the display is shown in Figure 15 and a photo of the display is shown in Figure 20.

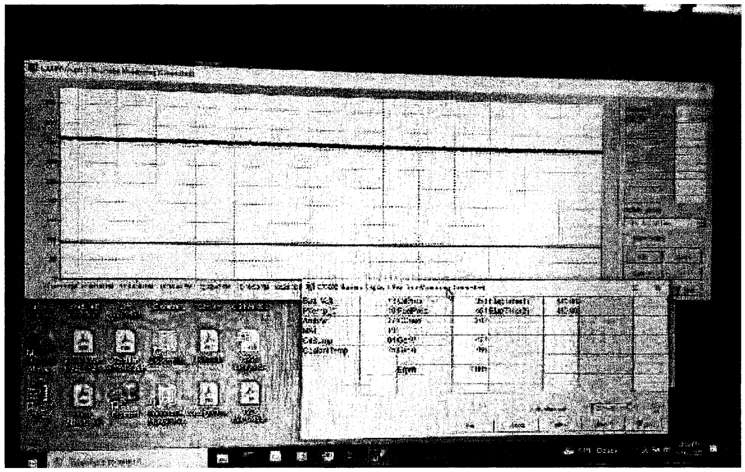


Figure #20 Campbell Datalogger Display with 1-Hour Digital Strip Chart

To help identify any signs of early engine damage, two knock sensors were installed on the left side of the engine block as shown in Figure 18. These were installed in two ½" – 13 bolt holes already drilled and tapped in the engine block. The knock sensors required an adaptor to gap between the ½" – 13 threaded holes in the block and the 5/16" bolt that fit the knock sensors.

The outputs of the knock sensors were run to a 4 channel Oscilloscope (O-scope). A triggering signal from the engine RPM system was introduced on Channel 1 (O-scope was triggered off of Channel 1) and the input from the two knock sensors were on Channels 2 and 3. The signal intensity of 400 mV was determined to be the threshold of concern for the knock sensor output on Channels 2 and 3. This level of signal intensity was selected based on the knock sensor signal level witnessed during the 24-hour Baseline test. Figure 15 shows the location of the O-Scope relative to the other displays and Figure 21 shows a closeup of the display while running the Dilution test.

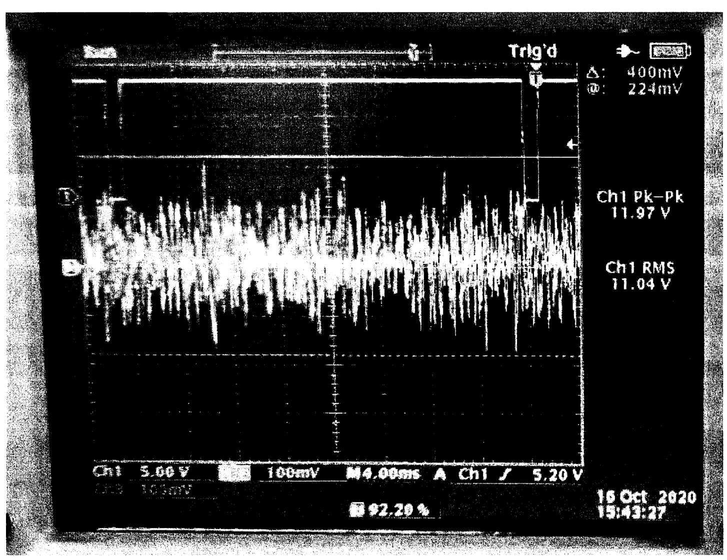


Figure #21 Knock Sensor Output on O-Scope Display

A significant effort was invested on calibrating the pump that supplied the Diesel fuel to the engine sump during the Dilution test. The pump selected was a Walchem metering pump, Model EWN-B21VCUR, that was rated at 1.6 GPH and had a maximum output of 60 PSI. For this project, the target dilution Diesel flow rate was 1.09 GPH and the Walchem metering pump had the ability to adjust the flow by changing the duty cycle (cycle rate) and the length of stroke of the pump. By adjusting the duty cycle, the pump was able to hit the target flow rate at 53.0% duty cycle as shown in Figure 22.

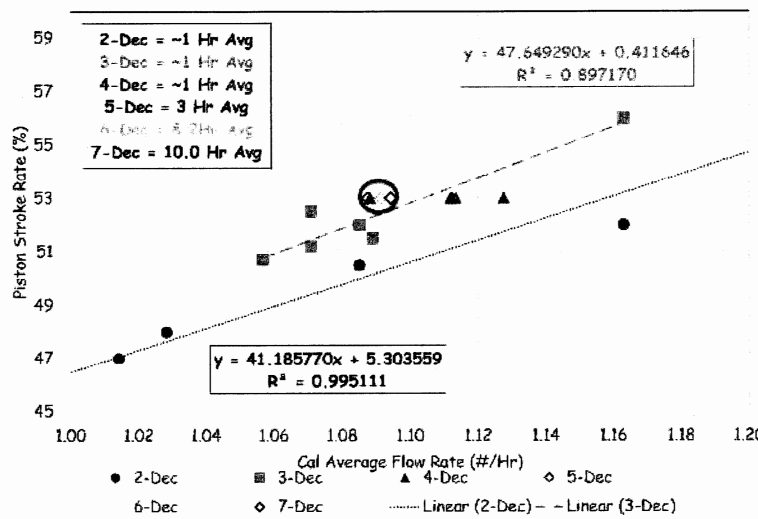


Figure #22 Walchem Metering Pump Calibration Percent Stroke Rate vs Fuel Flow

For the Dilution test, the dilution fuel supply line was connected to the crankcase at the same general location of the oil sample return line, on the left rear side of the upper oil pan (see Figure 8). This connection was ~2" below the surface of the oil in the sump at the start of the Dilution test and more liquid head was generated as more fuel was added to the engine's oil pan.

Baseline Test

24-hour Baseline test was broken into two 12-hour test days. For the 1st 12-hour Baseline test, the engine load was constant and for the 2nd 12-hour Baseline test there were four load steps at specific times, as called for in the test plan.

During the 1st 12-hour Baseline test, it was noted that the engine was consuming more fuel than expected and there was concern that the project would not have enough Constellation provided Diesel fuel to complete 24 hours of operation targeted for the Dilution test. Because the primary focus of this project was the fuel Dilution test, and the 24-hour Baseline test was to determine the Gensets capability to complete the Dilution test, it was imperative that the Dilution test operated exclusively on Constellation provided Diesel fuel. To assure that there was enough Constellation provided Diesel fuel for the Dilution test, the second 12-hour Baseline test was completed using Diesel fuel sourced in the San Antonio, Texas area. Because of the unique blend of the Constellation Diesel fuel, there was no attempt to match the Constellation fuel blend.

The engine speed became intermittently unstable during the last ~20 minutes of the 1st 12-hour Baseline test while the Genset load remained constant, as shown in Figure 23. However, during the 1st Baseline test session, the Genset speed always met the test plan requirements. At the end of the 1st test, the Barber Colman Governor was replaced to correct the unstable speed control, as discussed in the section titled "Genset Modifications". During the second 12-hour Baseline test the Genset power continued to hit the target power and the engine speed was stable, as shown in Figure 24.

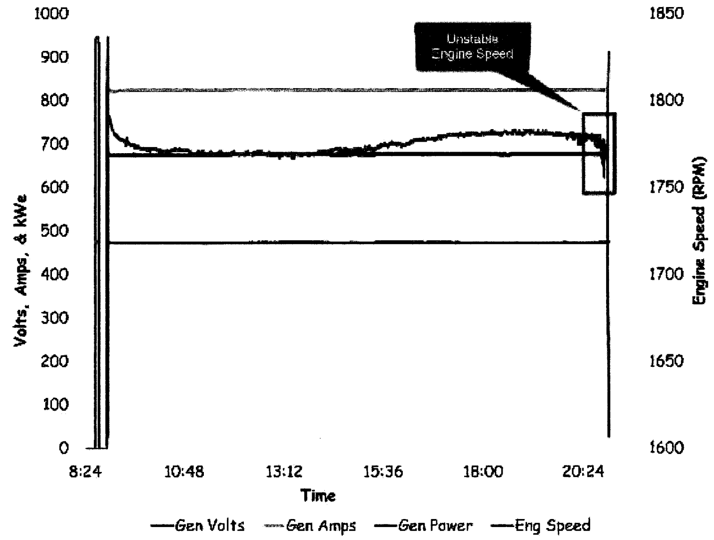


Figure #23 Engine Speed and Generator Power During the 1st 12-Hour Baseline Test

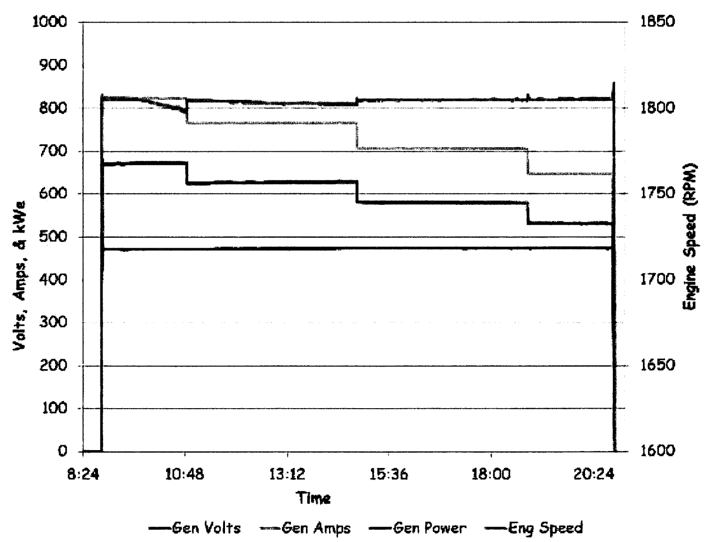


Figure #24 Engine Speed and Generator Power During the 2nd 12-Hour Baseline Test

During the two 12-hour Baseline tests, the monitored engine pressure and temperatures were deemed to meet the requirements of the test plan and are shown in Figures 25 through 28.

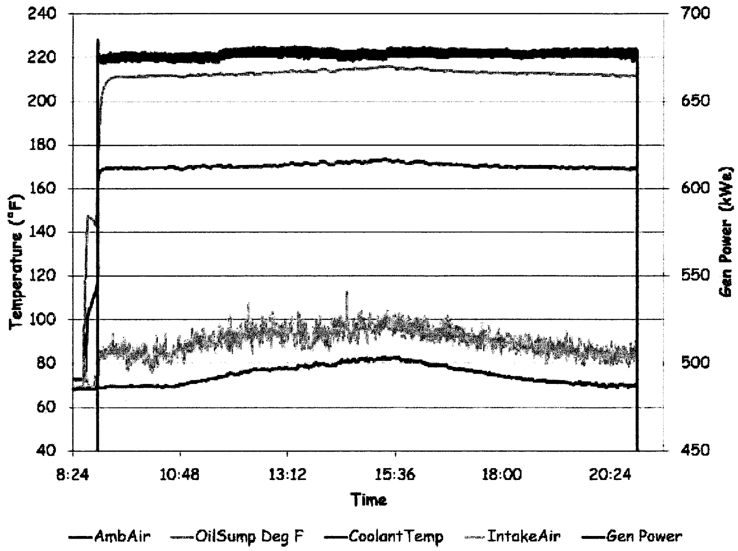


Figure #25 Engine Temperatures During the 1st 12-Hour Baseline Test

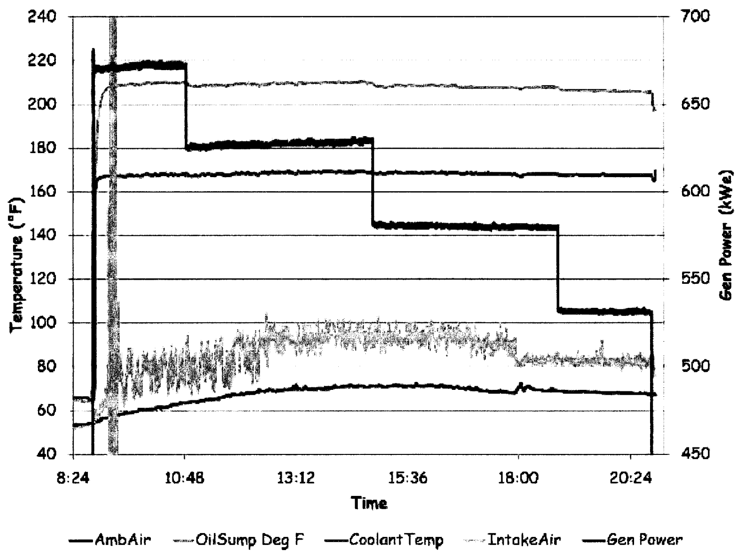


Figure #26 Engine Temperatures During the 2nd 12-Hour Baseline Test

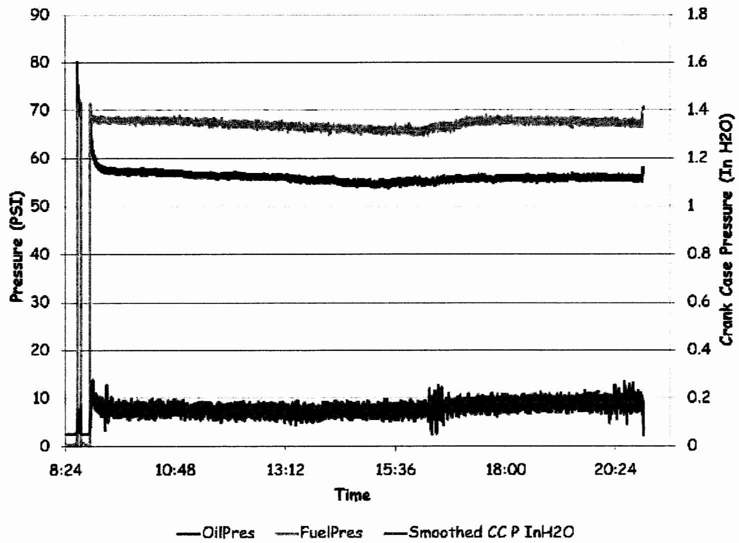


Figure #27 Engine Pressures During the 1st 12-Hour Baseline Test

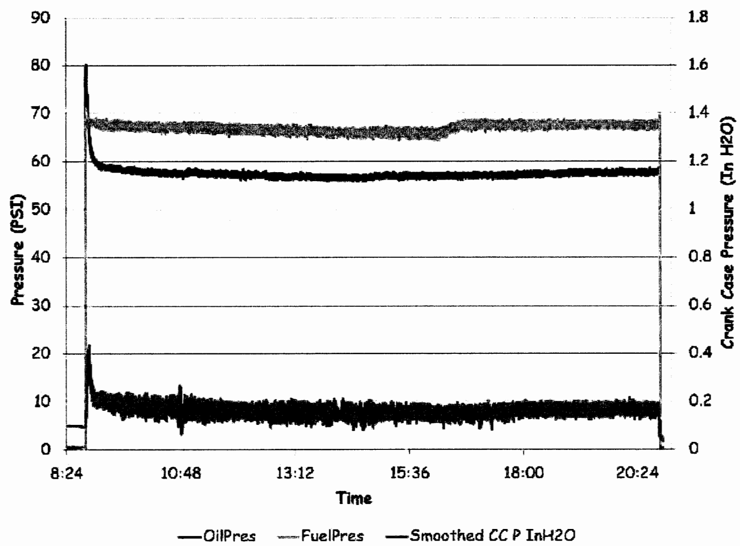


Figure #28 Engine Pressures During the 2nd 12-Hour Baseline Test

Over the duration of the Baseline tests, the engine oil was sampled every 4 hours to assure that there were no issues with the engine wear or unexpected fuel dilution and the sample analysis results are shown in Table 1. The oil analysis results showed that there were no engine issues that would prevent the project moving forward with the fuel Dilution test.

Table #1 Oil Analysis Results from Baseline Tests

Test	Description	Fuel	Date	Sample #	Time	Total Time	D445 @40°C	D445 @100°C	D3524 Fuel Dilution	D5185 Metals													D5185 - Sulfur
					(Clock)	Hours	cSt	cSt	WT%	Al	Sb	Ba	Cr	Cu	Fe	Pb	Ni	Ti	Ca	P	Zn	Mg	WT%
Baseline	1st 12-Hrs	Plant provided	9-Dec-23	0	9:01	0.00	132.7	14.4	<0.3	<1	<1	<1	<1	<1	4	<1	<1	<1	3685	925	1029	216	0.792
				1	12:58	3.95	130.9	14.4	<0.3	<1	<1	<1	<1	<1	4	<1	<1	<1	3678	930	1034	216	0.791
				2	16:58	7.95	130.2	14.3	<0.3	<1	<1	<1	<1	<1	4	<1	<1	<1	3681	927	1038	218	0.790
Baseline	2nd 12-Hrs		10-Dec-23	3	8:55	12.00	129.5	14.2	<0.3	<1	<1	<1	1	<1	5	<1	<1	<1	3685	916	1027	220	0.792
Baseline	2nd 12-Hrs	Shop fuel	12-Dec-23	3A	8:55	12.00	128.9	14.2	<0.3	<1	<1	<1	1	<1	6	1	<1	<1	3652	922	1029	214	0.817
				4	12:50	15.92	128.6	14.2	<0.3	<1	<1	<1	1	<1	6	1	<1	<1	3658	926	1033	225	0.817
				5	16:50	19.92	128.6	14.2	<0.3	<1	<1	<1	1	<1	5	<1	<1	<1	3642	917	1027	224	0.819
				6	20:50	23.92	128.7	14.2	<0.3	<1	<1	<1	1	2	6	2	<1	<1	3622	912	1015	215	0.818

Fuel Dilution Test

For the start of the fuel Dilution test, the engine and oil filters were drained and was refilled with a mix of fresh Constellation provided Mobil Delvac 1640 engine oil and Constellation provided Diesel fuel to target initial fuel dilution of 18.2% by mass. The mixture was supervised by MPR staff and was measured by both mass and volume. However, there was an assumption of the amount of engine oil that remained in the engine. Once the fuel / oil mixture was placed in a clean 55-gallon drum, it was thoroughly mixed using an air driven drum stir, and then pumped into the engine crankcase.

The Dilution test was started at 07:12 Hours on 14-Dec-23 and ended 24.5-hours later at 07:42 Hours on 15-Dec. Over the duration of the test, Constellation provided Diesel fuel was pumped into the crankcase of the DDC 149 engine at an average rate of 1.09 Gallon per Hour (GPH), as shown in Table 2. Over the duration of the Dilution test a total of 190.7 pounds or 26.8 Gallons of Diesel fuel was added to the crankcase.

During the Dilution test a couple of adjustments were made to increase the flow rate of Diesel fuel into the crankcase to maintain the targeted 1.09 GPH flow rate. While the starting point was a duty cycle of 53.0% on the pump, by the end of the test the duty cycle had been increased to 55.0%.

Table #2 Fuel Added to the Engine Crankcase During Dilution Test

Pail number	Time	Delta Hrs	Pail weight	Change pail weight	Change gallons	Gal/Hr
1	7:11	0.00	37.95	0.00	0	--
	10:39	3.47	11.20	-26.75	3.8	1.08
2	10:41	0.00	39.00	0.00	0	--
	13:44	3.05	15.40	-23.60	3.3	1.09
3	13:45	0.00	37.90	0.00	0	--
	16:48	3.05	15.40	-22.50	3.2	1.04
4	16:39	0.00	37.10	0.00	0	--
	19:13	2.57	17.05	-20.05	2.8	1.10
5	19:14	0.00	37.80	0.00	0	--
	21:57	2.72	16.40	-21.40	3.0	1.11
6	21:57	0.00	37.55	0.00	0	--
	0:37	2.67	16.60	-20.95	2.9	1.10
7	0:37	0.00	36.85	0.00	0	--
	3:17	2.67	15.95	-20.90	2.9	1.10
8	3:17	0.00	38.50	0.00	0	--
	5:34	2.28	20.55	-17.95	2.5	1.10
9	5:35	0.00	31.80	0.00	0	--
	7:42	2.12	15.25	-16.55	2.3	1.10
			Totals =	-190.7	26.8	--
					Average =	1.09

During the Dilution test the engine load profile matched the targets identified in MPR's test plan. The load profile and the engine speed are shown in Figure 29. The recorded engine temperatures and pressures are graphically shown in Figures 30 and 31, respectively.

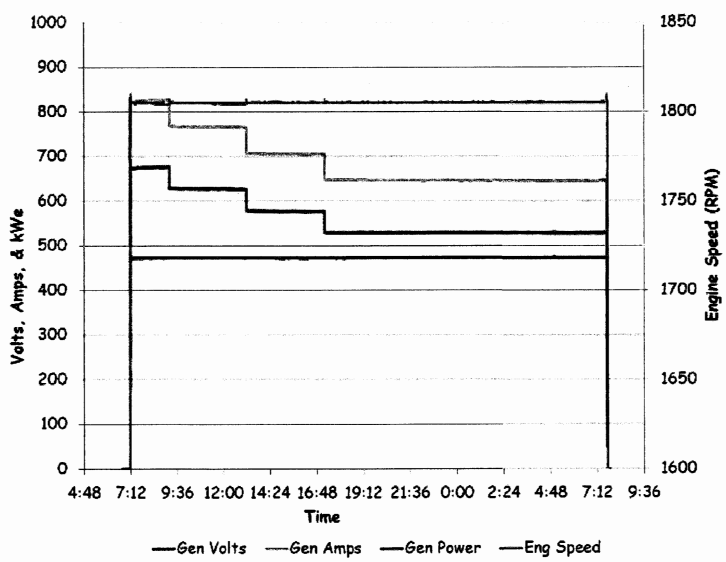


Figure #29 Engine Speed and Genset Power During Dilution Test

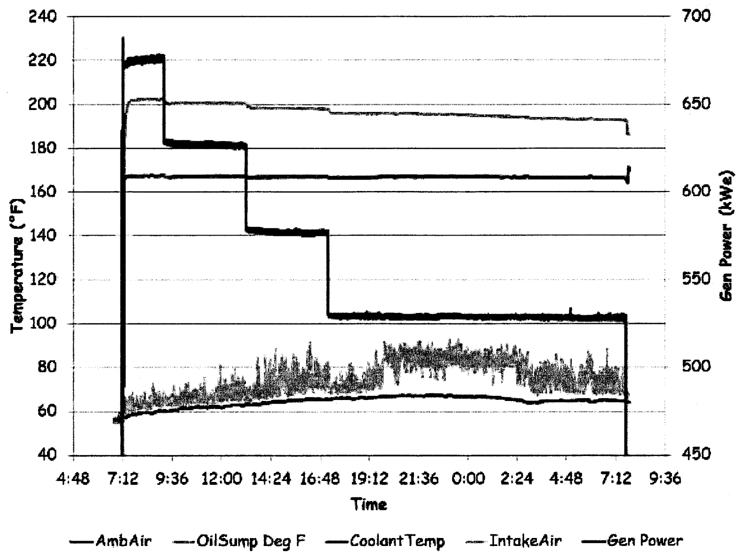


Figure #30 Engine Temperatures During Dilution Test

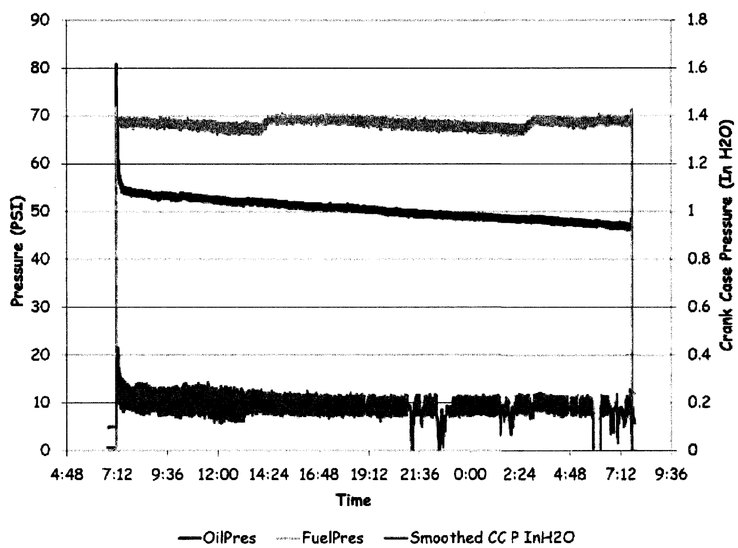


Figure #31 Engine Pressures During Dilution Test

During the Dilution test the knock sensor display was visually monitored to determine if there were any changes to the impact energy that was being transferred into the engine block. At the EOT, there was no detectible changes to knock sensor output on the O-Scope display, indicating that there was no significant increase in the mechanical noise generated by the engine.

Oil samples for the test were taken shortly after the engine was started and every hour during the test, and again at the end of test (EOT) after 24.5 hours of operation. The results of the oil sample analysis are shown in Table 3 and show no significant changes in the wear metals in the engine oil during the Dilution test.

Table #3 Oil Analysis Results from Dilution Test

Test	Description	Fuel	Date	Sample #	Time	Total Time	D445 @40°C	D445 @100°C	D3524 Fuel Dilution	D5185 Metals													D5185 - Sulfur
					(Clock)	Hours	cSt	cSt	WT%	Al	Sb	Ba	Cr	Cu	Fe	Pb	Ni	Ti	Ca	P	Zn	Mg	WT%
Dilution		Plant provided	14-Dec-23	0	7:12	0.00	54.9	8.37	–	<1	1	<1	<1	<1	2	<1	<1	<1	3116	819	870	186	0.739
				1	8:12	1.00	52.1	8.15	–	<1	<1	<1	<1	<1	2	<1	<1	<1	3042	755	846	181	0.729
				2	9:11	1.98	49.7	7.93	–	<1	<1	<1	<1	<1	2	<1	<1	<1	2994	781	837	177	0.710
				3	10:10	2.97	47.5	7.72	–	<1	<1	<1	<1	<1	2	<1	<1	<1	2956	772	822	175	0.702
				4	11:10	3.97	45.9	7.50	–	<1	1	<1	<1	<1	2	<1	<1	<1	2916	765	815	173	0.689
				5	12:10	4.97	43.3	7.23	–	<1	1	<1	<1	<1	2	<1	<1	<1	2863	715	798	170	0.677
				6	13:10	5.97	41.4	7.01	–	<1	1	<1	<1	<1	2	<1	<1	<1	2798	728	778	166	0.667
				7	14:10	6.97	39.4	6.78	–	<1	2	<1	<1	<1	2	<1	<1	<1	2751	718	766	164	0.654
				8	15:10	7.97	37.3	6.53	–	<1	<1	<1	<1	<1	2	<1	<1	<1	2703	702	753	160	0.642
				9	16:10	8.97	35.6	6.36	–	<1	1	<1	<1	<1	2	<1	<1	<1	2669	694	744	159	0.632
				10	17:10	9.97	34.0	6.20	–	<1	1	<1	<1	<1	2	<1	<1	<1	2623	674	726	156	0.621
				11	18:10	10.97	31.8	6.00	–	<1	<1	<1	<1	<1	2	1	<1	<1	2568	661	709	152	0.605
				12	19:10	11.97	30.9	5.82	–	<1	<1	<1	<1	<1	2	<1	<1	<1	2514	649	693	149	0.597
				13	20:10	12.97	29.3	5.66	–	<1	<1	<1	<1	<1	2	1	<1	<1	2479	640	720	146	0.588
				14	21:10	13.97	28.2	5.48	–	<1	<1	<1	<1	<1	2	1	<1	<1	2423	623	701	143	0.575
				15	22:10	14.97	26.8	5.34	–	<1	1	<1	<1	<1	2	<1	<1	<1	2379	609	690	142	0.564
				16	23:10	15.97	25.9	5.22	–	<1	1	<1	<1	<1	2	1	<1	<1	2338	600	678	139	0.555
			15-Dec-23	17	0:10	16.97	25.1	5.13	–	<1	<1	<1	<1	<1	2	<1	<1	<1	2289	589	663	136	0.545
				18	1:10	17.97	24.0	4.92	–	<1	<1	<1	<1	<1	2	1	<1	<1	2246	582	656	133	0.537
				19	2:10	18.97	23.2	4.83	–	<1	1	<1	<1	<1	2	<1	<1	<1	2178	562	630	130	0.512
				20	3:10	19.97	22.3	4.69	–	<1	<1	<1	<1	<1	2	<1	<1	<1	2144	551	616	128	0.500
				21	4:10	20.97	21.4	4.58	–	<1	1	<1	<1	<1	2	<1	<1	<1	2107	540	608	125	0.491
				22	5:10	21.97	20.8	4.49	–	<1	2	<1	<1	<1	2	<1	<1	<1	2069	530	596	123	0.483
				23	6:10	22.97	20.2	4.37	–	<1	<1	<1	<1	<1	2	1	<1	<1	2021	517	579	120	0.473
				24	7:10	23.97	19.4	4.28	–	<1	<1	<1	<1	<1	2	1	<1	<1	1994	511	573	119	0.467
				24.5	7:42	24.50	19.1	4.22	–	<1	1	<1	<1	<1	2	1	<1	<1	1974	505	568	118	0.462

At the end of the testing, the engine was prepared for shipment to Constellation Energy's facility in Illinois. On 21-Dec-23, the Genset was placed on a truck, chained down, and tarped before it departed the LTC.

Determining Fuel Dilution of Engine Oil

ASTM Test D3524 is a "Standard Test Method for Diesel Fuel Diluent in Used Diesel Engine Oils". While this is an industry standard to determine fuel dilution, the test is "limited to SAE 30 oil" and is not accurate at fuel concentrations above 12% (by mass). Because the Dilution test was conducted at levels well above 12% and used an SAE 40 engine oil, the ASTM D3524 test is not a suitable for determining the fuel dilution levels in the engine oil.

To overcome this limitation, MPR Associated had SwRI blend fresh Constellation supplied engine oil and Constellation supplied Diesel fuel at the follow mass ratios (Diesel / oil):

- 0%
- 5%
- 10%
- 15%
- 20%
- 30%
- 40%
- 50%
- 60%

- 70%
- 80%
- 90%
- 100%

These mixed ratios were analyzed to determine the change of the critical oil additive concentrations [Calcium (Ca), Magnesium (Mg), Potassium (P), and Zinc (Zn)] and the resulting calculated fuel dilution based on the change to the oil additive concentrations are shown in Figure 32. Averaging concentrations of these four different oil additive metals, as shown in Figure 33, offers a strong correlation between the calculated average dilution and the dilution of the sample mixture.

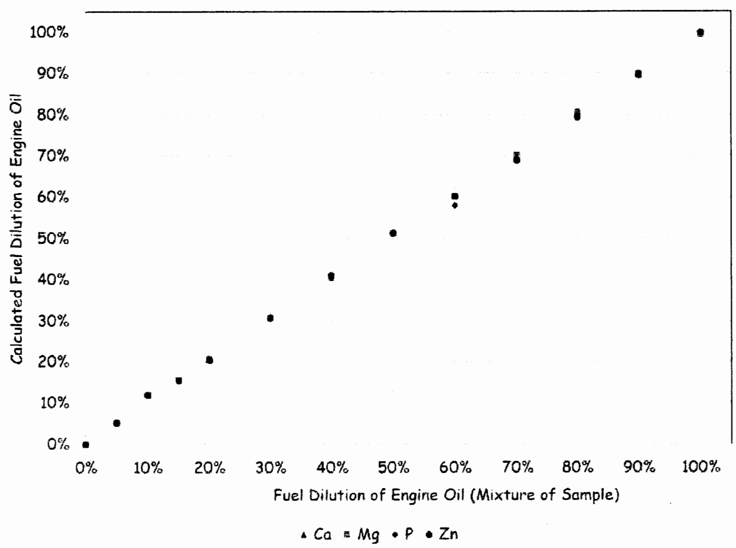


Figure #32 Oil Additive Concentrations for Different Levels of Dilution

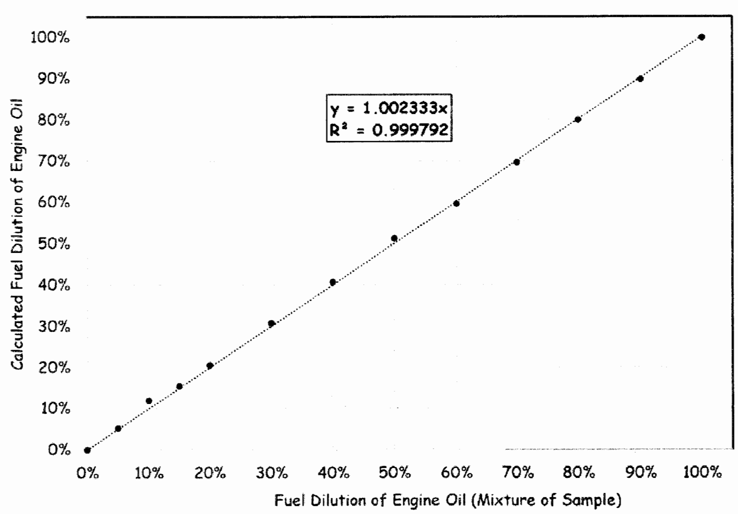


Figure #33 Average of Oil Additive Concentrations for Different Levels of Dilution

By using the average of the Baseline test oil additive concentrations shown in Table 1, and the individual oil sample additive levels shown in Table 3, the dilution of each of the oil additives was calculated and are shown in Figure 34. Using the average of the calculated dilution of the oil additives (the same approach shown in Figure 33), the calculated fuel dilution of the engine oil samples is shown in Figure 35.

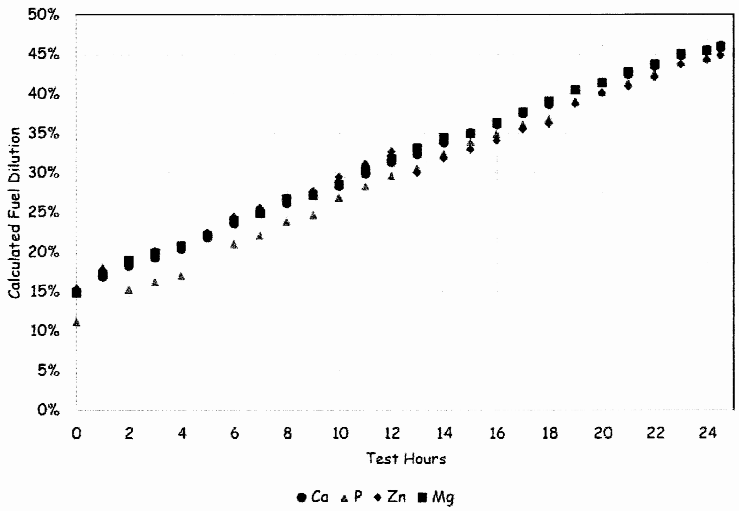


Figure #34 Calculated Fuel Dilution Based on Change in Each Oil Additive

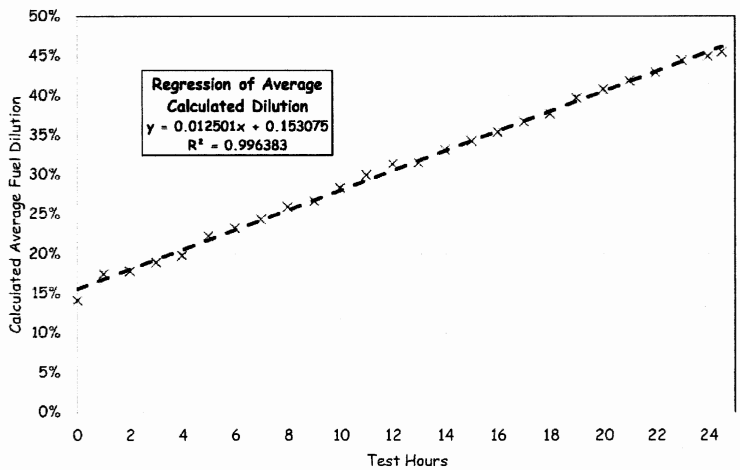


Figure #35 Calculated Average Fuel Dilution

Based on this analysis, and assuming the fuel added to the engine oil was a constant over the duration of the test, the fuel dilution of the engine oil at the start of the test was calculated to be 15.3%. At the EOT, after 24.5 hours of operation, the dilution was calculated to be 45.9%.

Dilution Test Observations

During the Dilution test, there was a significant amount of liquid leakage from the engine. At that time, it was assumed to be a nuisance fuel leak from the engine's fuel plumbing because:

- The coolant system level remained constant over the duration of the test.
- There were no other fluids plumbed into or stored in the test cell.
- There were no signs of a significant engine oil leak during the 24-hours of operation during the Baseline tests.

At the EOT, lube oil from the engine sump and lube oil filters was drained into a 55-gallon drum in preparation for shipping the Genset. The liquid height in the drum was 18 5/8" inches, as shown in Figure 36. Based on this measurement, the calculate volume of liquid in the drum is ~32.1 gallons (at ~50°F and de-gassing for >96 hours), as shown in Table 4.

Figure #36 Liquid Height in 55-Gallon Drum Post Engine and Oil Filter Drain

Table #4 Calculated Volume of Fuel / Oil Mixture from Engine and Filters

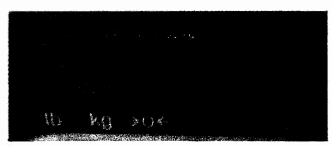
ID	22.5	Inch
Liquid Height	18.625	Inch
Volume	7405.4	Inch^3
	32.1	Gallons
Sample Jugs	0	
Total Gallons	**32.1**	

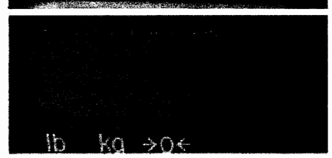
The total weight of the 55-gallon drum was 264.8 pounds and the empty drum weight was 35.2 pounds providing a Tare weight of 229.6 pounds of fuel/oil mix in the drum (includes filter drain oil). The four drained oil filters were weighed and compared to new clean filter weights, and it was calculated (Table 5) that the four filters contained 4.57 pounds of fuel / oil mixture. Adding this to the drum weight, the total fuel/oil mix weight is ~234.2 pounds.

Table #5 Calculated Fuel/Oil Mixture Remaining in Wet Oil Filters

Estimate for amount of Diluted test oil in filters.

ET weight of 3 new filters =		8.05 Pounds
Numb of filters =		3
Est weight per new filter =		2.68 Pounds
Filter weight wet =		
	A&B	7.65 Pounds
	C&D	7.65 Pounds
	Wet weight per filter =	3.825 Pounds
	Oil residual per filter =	1.14 Pounds
	Total residual oil in filters =	**4.57 Pounds**





At the end of the Dilution test, there was some concern that the dilution fuel supply line to the engine might be the source of the hydrocarbon leak. This would have reduced the amount of fuel dilution in the engine oil and could have been the source of the hydrocarbon leak. An inspection of the line and all the fittings between the pump and the engine crankcase showed no signs of leak, indicating that all the pumped dilution fuel ended up in the engine crankcase.

To determine if there was a fuel leak from the engine plumbing, after the Dilution test the fuel system was pressurized with ~60 PSI of air and no leaks in the fuel system were identified. Additionally, the hydrocarbons in the test cell appeared too viscous to be only fuel and was brown in color, like the engine oil, in place of the red color of the Diesel fuel. This suggested that it was a combination of fuel / oil mix that was leaked from the rear of the engine. The engine was shipped to Constellation Energy to determine the location of the fuel / oil leak.

While taking oil samples during the Dilution test, the aeration of the oil was noted. This was visible when the 125 ml sample bottles were filled, lid tightened, and the captured sample would start to degas, as shown in Figure 37. The first time that this phenomenon was noted was around 00:10 hours on 15-Dec-23

The change in viscosity of the oil was quite visible between the first and last sample of the Dilution test. This difference in viscosity was observable by shaking two separate sample bottles and the more diluted samples flowed more freely in the bottles.

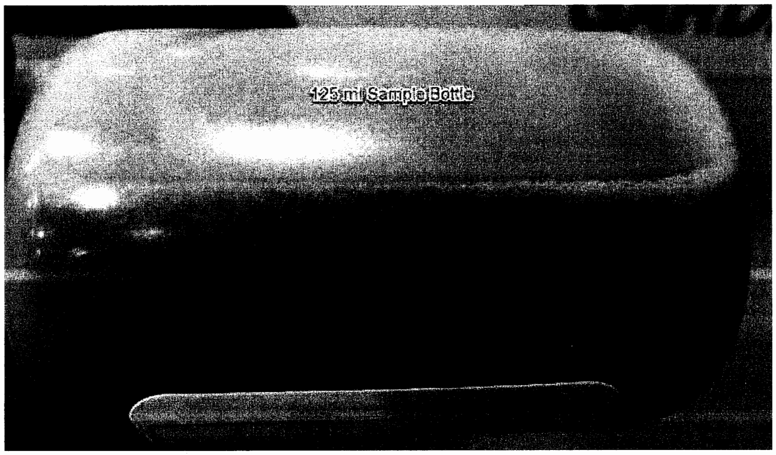


Figure # 37 Example of Degassing of Oil Sample

Conclusions

This project demonstrated that a DDC 12V 149 Series engine could operate, over the targeted test cycle, with very high levels of fuel dilution of the engine oil. Additionally, the engine was able to complete the 24.5 hours of operation without excessive wear, as documented by the lack of change to the wear metal levels in the oil samples taken during the Dilution test.

Prepared by:

John Hedrick, Principal Analyst
Locomotive Technology Center
Powertrain Engineering

Approved by:

Steven G. Fritz, P.E., Sr. Manager
Locomotive Technology Center
Powertrain Engineering

/mfr

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Power Zone Equipment, Inc. Quotation 26942-01

46920 County Rd. E Center, CO 81125
Phone: 719-754-1981 Fax: 719-754-1982

October 13, 2023

Southwest Research Institute
9503 West Commerce
San Antonio, TX 78227

Subject:	Detroit 12V-149 7300 Series
Quote Number:	26942-01
Attn:	Michael Ross

Part/Stock No.	Make & Model	Qty	Price Ea.	Line Total
60482	Detroit 12V-149 7300 Series Description: Used Detroit 12V-149 7300 series engine Generator with following features: • 800 HP • 1800 RPM • V-12 Cylinder • 146 mm (5.75 in) Bore • 146 mm (5.75 in) Stroke • 29.39 L (1792 in3) Displacement • Generator model Marathon Magna one • S/N KM-92430-11/24-1 • 1800 RPM • 750 KW • 938 KVA • 277/480 Volts • Weight 20,000 lbs • Dims 186"LX72"Wx96"H. We do not have the muffler for this. Sold as is.	1	$29,000.00	$29,000.00
			Total Price:	**$29,000.00**

Regards,

Drew Hoffstaetter
Power Zone Equipment, Inc.
(719) 754-1981
drew@powerzone.com

Power Zone Equipment, Inc.
Terms and Conditions of Sale

Applicability and Acceptance

The terms and conditions set forth herein shall exclusively govern the sale of goods and services by Power Zone Equipment, Inc. (Seller) to Buyer. Acceptance of this offer or of the goods furnished pursuant to this order is expressly limited to the terms contained herein. All contracts or sales orders for Seller's products are accepted, and all shipments of goods are made, on the express understanding that the Terms and Conditions set forth herein shall be applicable thereto, and shall supersede any provision on Buyer's purchase order or other documents accepted by Seller which are at variance with or in addition to these Terms and Conditions. No changes or additions to these Terms and Conditions shall be binding upon Seller unless expressly agreed to in writing, executed by an authorized officer of Seller. Buyer may issue a purchase order for administrative purposes only. Additional or different terms and conditions contained in any such purchase order or other offer will be null and void. No course of price dealings between the parties and no usage of trade will be relevant to determine the meaning of these Terms and Conditions.

Delivery and Risk of Loss

Delivery is F.O.B. place of origin of shipment. Buyer assumes all risk of loss or damage to goods in transit. Seller will use its best efforts to deliver as scheduled, but Buyer acknowledges that delivery schedules are approximate only. Seller shall not be liable for any damages, consequential or otherwise, which may be claimed by Buyer to arise from late delivery. When partial shipments are made, each such shipment shall be invoiced and paid for separately in accordance with these Terms and Conditions.

Scope of Supply

Only the material detailed within these documents (i.e. quotation, invoice, etc.) is being offered. No assumption should be made that anything not specifically defined is included.

Force Majeure

Neither Buyer nor Seller will be liable for delay or non-performance due to governmental regulations, strikes, hostile actions, weather, acts of God, supply delays or any other cause beyond the reasonable control of either party (any and all of which causes re referred to herein as "Force Majeure"). Force Majeure will not, however, affect liabilities assumed or payments due before declaration of Force Majeure.

Security Interest

Buyer hereby grants to Seller a security interest in the goods being sold and in all proceeds from such goods to secure performance of all of Buyer's obligations in connection with the purchase of said goods, and if requested by Seller, Buyer shall execute and deliver such separate documents as may be necessary to evidence such security interest or enable Seller to perfect such security interests.

Taxes

Prices are exclusive of all taxes and duties, however designated, including sales, use, import and excise taxes (but excluding taxes on Seller's net income). These taxes and all other taxes measured in whole or in part by gross receipts applicable to Buyer's order shall be borne by Buyer. If Buyer claims exemption from any of these taxes, Buyer shall promptly furnish satisfactory proof of exemption and shall indemnify Seller for all or any loss, cost and damage, including attorney's fees, incurred by such taxes.

Payment Terms

A down payment from the Buyer to the Seller is required before any work commences. The down payment will be a percentage of the total sale price, ranging from 25% up to 50% and detailed in the quote, depending on the circumstances of the sale, and is non-refundable. Installment payments may be required by the Seller depending on the total sale price and the estimated delivery schedule. The full balance must be paid by the Buyer to the Seller before Seller releases the equipment, unless otherwise agreed upon in writing in the product price quote, by an authorized Seller's representative. Buyer expressly waives any right of set-off and shall make no deductions from payment due hereunder or for any damages of any type claimed by Buyer against Seller.

Quote Currency and Validity

Unless stated otherwise in writing by Seller, regardless of destination all prices quoted are in U.S. Dollars. Quotes, Proposals, or Bids are valid for thirty (30) days from issue date, unless otherwise indicated by Seller.

Equipment Repair Work

Seller will process the Buyer's repairs as per the Buyer's written instructions. If no instructions are provided, Seller will use industry standard methods to complete the repairs.

Design

Seller does not recommend materials. The responsibility for selection and approval of materials rests solely on the owner of the equipment or the owner's representative. From time to time, Seller may suggest materials at the request of the equipment owner or the owner's representative, but Seller accepts no liability for their suitability for the intended purpose or other service. In the event that design work has been performed by Seller, the design is warranted only for the conditions supplied in the process data sheets or other information supplied by the Buyer. If a discrepancy exists in the information supplied by the customer, time is of the essence and it is the sole responsibility of the Buyer to promptly clarify the discrepancy in writing.

Buyer Inspection and Acceptance

Within ten (10) days after tender of delivery to or receipt of Buyer of any shipment, Buyer shall inform Seller in writing if the goods are found defective or short in any respect. Failure to so inform Seller or any use of the goods by Buyer shall constitute conclusive evidence that Buyer waives any right to reject such goods without the prior written authorization of Seller.

Returned Goods

No product may be returned to Seller for credit except upon written authorization. A request for authorization must be submitted in writing. All returned goods will be subject to restocking charges and all freight will be prepaid by the Buyer. The return goods policy of the supplier from whom Seller obtained the goods will be the basis for whether to authorize, and the conditions of authorization for, the return of goods from a Buyer. Unauthorized returns will not be accepted. Goods returned without authorization will be returned to the Buyer at its own expense. Goods damaged by the Buyer will not be authorized for return or credit.

Limited Warranty

Seller warrants that new goods and repairs supplied to the Buyer shall be free from defects in material, workmanship, and title. Warranty does not cover problems or circumstances arising from:

- Goods that have been modified by the Buyer or Buyers representative
- Swapping of components between different pieces of equipment
- Improper storage, handling, installation, operation, or maintenance.
- Plant or system design
- Misapplication of materials or technology
- Goods used for purposes other than described in the original quote

Seller does not warranty suitability of purpose or damage from misuse or abuse.

Seller does not warranty parts requiring replacement due to normal wear and tear

- Unless otherwise specified, warranty terms shall be as follows:
- All new equipment warranty shall be covered by their respective OEM manufacturer on the OEM manufacturers Terms. The warranty time-frame on all new equipment shall be from the date of shipment from the OEM, and not from the date of shipment from Power Zone Equipment Inc.
- All refurbished equipment warranties shall expire (90) days after delivery of goods.

Used equipment is sold "AS-IS", unless otherwise agreed upon by an authorized Seller's representative. Seller warrants that information provided to the Buyer regarding the nature of the equipment is accurate. No other warranty is implied.

Any claims against Seller for defects in workmanship or materials must be verified by an authorized agent of Seller before any deductions in charges are taken. No credit will be allowed unless Seller has agreed to it in advance of taking such credit. Seller must be offered the chance to repair the defective product prior to any work being done to it by others.

Seller is not responsible for work done by others unless Seller has agreed to it beforehand in writing.

Buyer is responsible for all costs related to the removal and re-installation, as well as freight to and from Seller's shop or OEM facility.

This warranty is limited to the costs of repair or replacement of the goods or repairs only.

EXCEPT AS SET FORTH HEREIN OR ANY STATEMENT OF WORK THAT EXPRESSLY AMENDS SELLER'S WARRANTY, SELLER HEREBY EXPRESSLY DISCLAIMS ALL OTHER WARRANTIES, EITHER EXPRESS OR IMPLIED, INCLUDING WITHOUT LIMITATION ANY WARRANTIES OF MERCHANTABILITY OR FITNESS FOR A PARTICULAR PURPOSE. THERE ARE NO OTHER WARRANTIES (PROVIDED BY SELLER) THAT EXTEND BEYOND THE DESCRIPTION ON THE FACE HEREOF.

LIMITED LIABILITY

UNDER NO CIRCUMSTANCES AND NOTWITHSTANDING THE FAILURE OF ESSENTIAL PURPOSE OF ANY REMEDY SET FORTH HEREIN WILL SELLER, OR ITS EMPLOYEES OR AGENTS BE LIABLE FOR:

(A) ANY INCIDENTAL, INDIRECT, SPECIAL, PUNITIVE OR CONSEQUENTIAL DAMAGES INCLUDING BUT NOT LIMITED TO, LOSS OF WORK, PRODUCTION, OR PROFITS, EVEN IF SELLER HAS BEEN ADVISED OF THE POSSIBILITIES OF SUCH DAMAGES, OR IF SUCH DAMAGES ARE OTHERWISE FORESEEABLE: IN EACH CASE, WHETHER A CLAIM FOR ANY SUCH LIABILITY IS PREMISED UPON BREACH OF CONTRACT, WARRANTY, NEGLIGENCE, STRICT LIABILITY OR OTHER THEORY OF LIABILITY;

(B) ANY CLAIMS, DEMANDS OR ACTIONS AGAINST BUYER BY ANY THIRD PARTY;

(C) ANY LOSS OR CLAIM ARISING OUT OF OR IN CONNECTION WITH BUYER'S IMPLEMENTATION OF ANY PRODUCT, CONCLUSIONS OR RECOMMENDATIONS BY SELLER BASED ON, RESULTING FROM, ARISING OUT OF OR OTHERWISE RELATED TO THE PRODUCTS OR SERVICES; OR

(D) ANY UNAVAILABILITY OF THE PRODUCT FOR USE OR ANY LOST, DAMAGED OR CORRUPTED PRODUCT OR ASSOCIATED EQUIPMENT OR SYSTEMS.

IN THE EVENT OF ANY LIABILITY INCURRED BY SELLER OR ANY OF ITS AGENTS, THE ENTIRE LIABILITY OF SELLER AND ITS AGENTS FOR DAMAGES FROM ANY CAUSE WHATSOEVERWILL NOT EXCEED THE LESSER OF: (A) THE DOLLAR AMOUNT PAID BY BUYER FOR THE PRODUCT(S) GIVING RISE TO THE CLAIM OR THE SPECIFIC SERVICES GIVING RISE TO THE CLAIM; OR (B) $50,000.00.

Disputes

If a dispute arises out of or relates to a sale of goods or services by Seller to Buyer, the parties shall endeavor to settle the dispute through direct discussion. If the dispute between the Buyer and Seller cannot be resolved by direct discussion, both parties agree first to try in good faith to settle the dispute by mediation administered by the American Arbitration Association under its Commercial Mediation Procedure before resorting to any other form of dispute resolution. The parties shall select the mediator within fifteen (15) days of the request for mediation. Engaging in mediation is a condition precedent to any form of binding dispute resolution. Unless the parties mutually agree otherwise, any controversy or claim not settled by direct discussion or mediation shall be settled by arbitration administered by the American Arbitration Association in accordance with its Commercial Arbitration Rules, including the Optional Rules for Emergency Measures of Protection, and judgment on the award rendered by the arbitrator(s) may be entered in any court having jurisdiction thereof. A written demand for arbitration shall be filed with the American Arbitration Association and the other party to the sale/purchase within a reasonable time after the dispute or claim has arisen, but in no event after the applicable statute of limitations for a legal or equitable proceeding has run. The arbitration award shall be final. This agreement to arbitrate shall be governed by the federal Arbitration Act and judgment upon the award rendered by the arbitrator(s) may be entered in any court having jurisdiction thereof.

Cost of Dispute Resolution

The cost of any mediation proceeding shall be shared equally by the parties participating. The prevailing party in any dispute that goes beyond mediation arising out of or relating to an order between Buyer and Seller shall be entitled to recover from the other party reasonable attorney's fees, costs, and expenses incurred by the prevailing party in connection with such dispute.

Entire Understanding

These terms and conditions shall supersede all prior written or oral proposals, statements, and agreements relating to the matters covered hereby of any kind whatsoever made by Seller or its representatives and cannot be modified or terminated except by a writing signed by both parties.

Law Governing Disputes

These Terms and Conditions shall be construed and enforced in accordance with the laws of the State of Colorado.

Buyer Solvent

Buyer represents that, at the time of signing and accepting this order, Buyer is not insolvent within the meaning of the UCC or bankruptcy laws of the United States and that there have been no material adverse changes with respect to Buyer's financial condition since such time as Buyer has provided such financial information in its credit application.

Assignment and Delegation

The rights and obligations of Buyer under this agreement may not be assigned or delegated without the prior written consent of Seller.

Severability

If any of these terms or conditions is found to be illegal and/or unconscionable by a court of competent jurisdiction, the remaining terms and conditions will remain in full force and effect.

Termination

Either party may terminate performance of a performance or a Statement of Work for cause if the other party fails to cure a material default in the time period specified herein. Any material default must be specifically identified in a written notice of termination. After written notice, the notified party will, subject to the provision of warranties herein, have thirty (30) days to remedy its performance except that it will only have ten (10) days to remedy any monetary default. Failure to remedy any material default within the applicable time period provided for herein will give cause for immediate termination, unless such default is incapable of being cured within the time period in which case the defaulting party will not be in breach (except for Buyer's payment obligations) if it used its reasonable efforts to cure the default. In the event of any termination of the performance or a Statement of Work, Buyer will pay Seller for all Services performed and expenses incurred up to and including the date of termination plus any termination fee if one is set forth in the applicable Statement of Work. In such event Buyer will also pay Seller for any out-of- pocket or other direct costs resulting from termination. Upon termination, all rights and obligations of the parties under this Agreement will automatically terminate except for any right of action occurring prior to termination, payment obligations, and obligations that expressly or by implication are intended to survive termination (including, but not limited to, limitation of liability, indemnity, confidentiality, or licensing of work Product and this survival provision).

Confidential Information

All information and proprietary materials provided or developed in whole or in part by Seller, including but not limited to, all trade secrets, drawing, and specifications are confidential ("Confidential Information") whether or not identified as such. Buyer agrees that it shall not, without written consent from Seller, use or disclose any Confidential Information except as necessary to utilize the service or product for Buyer's own intended use. Buyer shall protect Seller's Confidential Information by limiting access to such information to its employees or agents who have a "need to know" and where such personnel have agreed to comply with the confidentiality obligations in these Terms and Conditions. At the request of Seller, Buyer agrees to promptly (i) return to Seller all Confidential Information; and (ii) destroy or permanently erase all Confidential Information in whatever form it is recorded.

Publicity

Buyer agrees that Seller may identify Buyer as a client and describe, in writing and/or through video/photography, the Deliverables and Services in any marketing materials, advertisements, and presentations by Seller. Buyer agrees that Seller has the right to incorporate, in a tasteful manner, the Seller logo tile in the Final Deliverables. In the case of a non-disclosure agreement, Seller will protect the identity of the client, project details, and other confidential and private information related to the service, project or Buyer. The Buyer may request, in writing within 30 days of the initial purchase order acknowledgment, additional regulations for the use of the Buyer's name, project, or service provided on any marketing materials, advertisements, and presentations by Seller. Seller reserves the right to accept or deny additional regulations submitted by the Buyer. Payments made to Seller will not be reimbursed as a result of the Buyer's termination of the contract as a result of denial to additional regulations as outlined above.

Anti-bribery

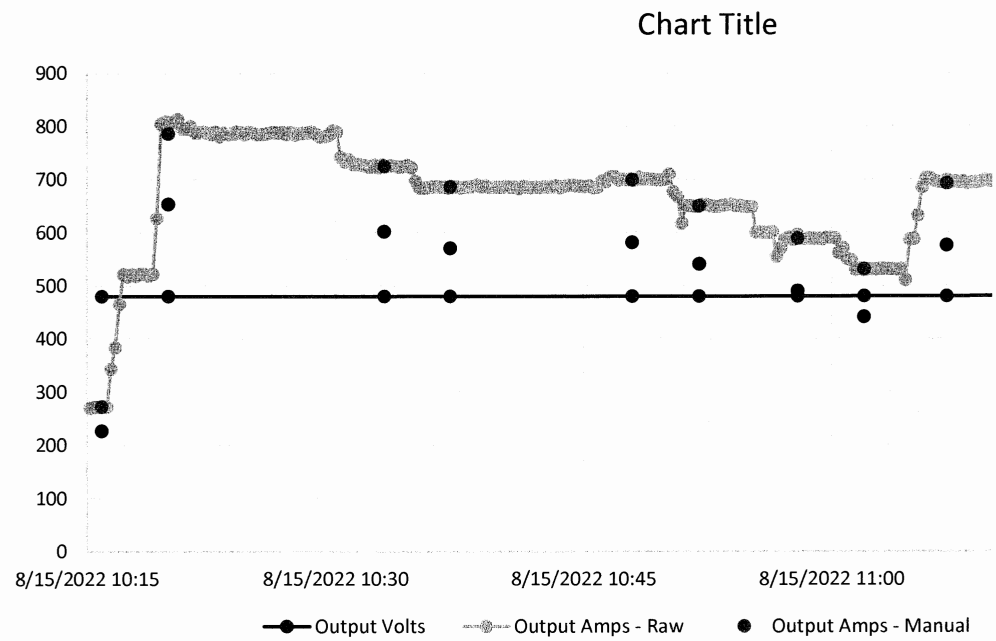
Both Buyer and Seller shall act in accordance with the principles described in the Convention on Combating Bribery of Foreign Public Officials in International Business Transactions, signed in Paris on December 17, 1997 ("the Convention"), and the Convention's Commentaries (collectively "the OECD Principles"), and shall comply with all applicable laws implementing the OECD Principles (including the U.S. Foreign Corrupt Practices Act of 1977), as well as any applicable local laws related to anti-corruption, anti-kickbacks, and anti-money laundering. The parties agree not to take or fail to take any action that might cause the other party to be in violation of any such laws. In connection with this Agreement, neither Party nor any of its respective direct or indirect owners, directors, officers, employees, or agents has or will pay, offer, promise to pay or authorize the payment, offer or promise to pay, directly or indirectly, any monies or anything else of value to any current or former government official, political party or official of a political party, or any candidate for public office in order to obtain or retain business, direct business to another person or entity, or to obtain an improper advantage or to any third party knowing, believing, or suspecting that such third party will give the payment, or any portion thereof, to any of the foregoing persons in order to obtain or retain business, or for any other improper purpose. The Parties agree and acknowledge that, for purposes of this Agreement, a "government official" is (i) any officer or employee of a government or any department, agency, or instrumentality of a government; (ii) an officer or employee of a public international organization such as the United Nations or the World Bank; (iii) an individual acting in an official capacity for or on behalf of a government agency, department, instrumentality or of a public international organization; (iv) any officer or employee of a company owned or controlled by a government; or (v) a member of a royal family who may lack formal authority but who may otherwise be influential, including by owning or managing state-owned or controlled companies.

Economic Sanctions and Export Controls

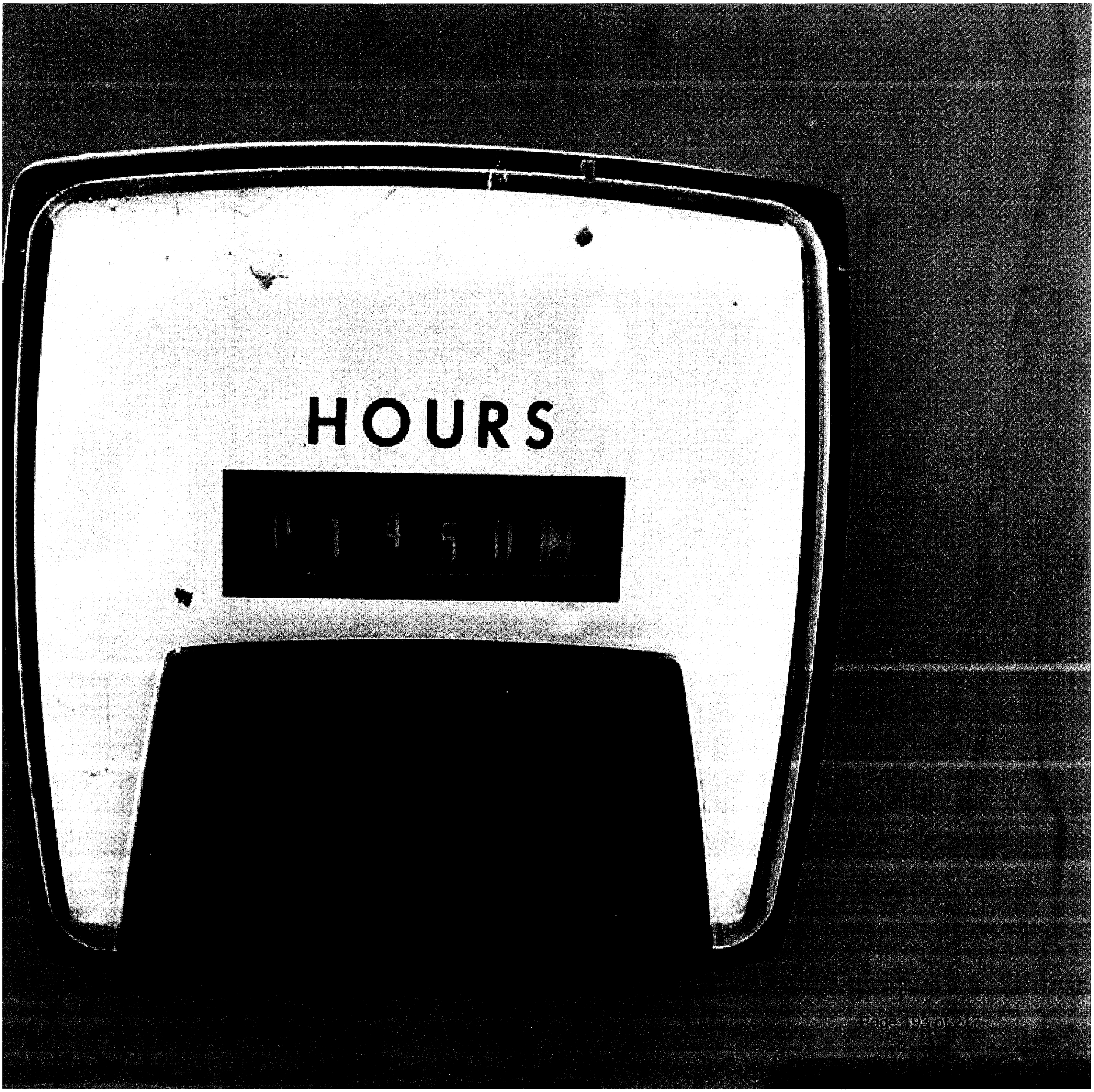
Buyer, Seller, and all their representatives, officers, agents and assigns warrant to fully comply with all applicable economic sanctions and export control laws and regulations, including those regulations maintained by the U.S. Commerce Department's Bureau of Industry and Security and the U.S. Treasury Department's Office of Foreign Assets Control. In addition, Buyer, Seller, and all their representatives, officers, agents and assigns shall not, directly or indirectly, sell, provide, export, re-export, transfer, divert, loan, lease, consign or otherwise dispose of any equipment, product, services, software, source code, technical data or technology to or via any person, entity or destination, or for any activity or end-use restricted by the laws or regulations of the United States or any other applicable jurisdiction (including nuclear, missile, chemical or biological weapons proliferation, military, or money laundering activities) without first obtaining all required government authorizations.

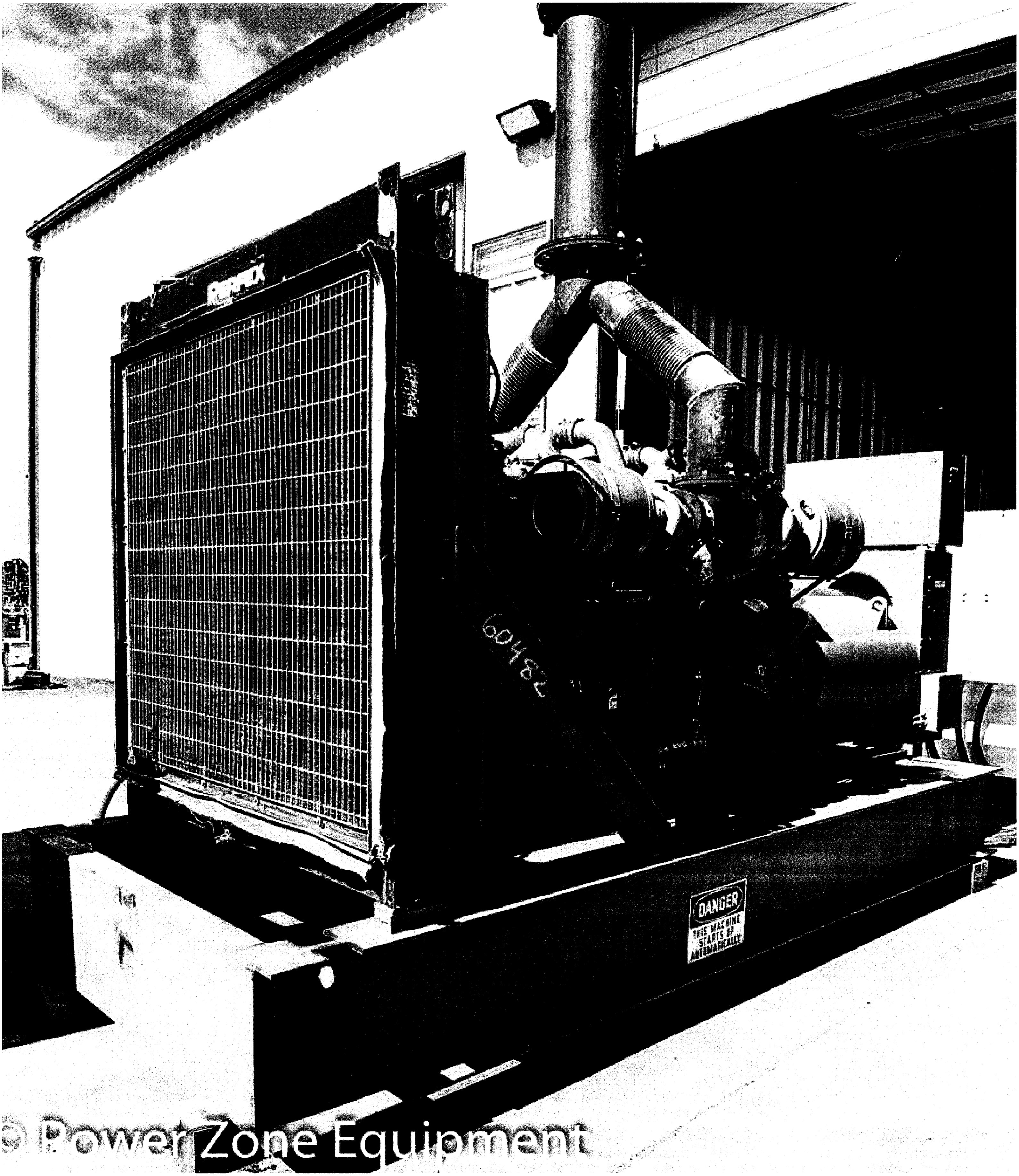
Generator Test Results

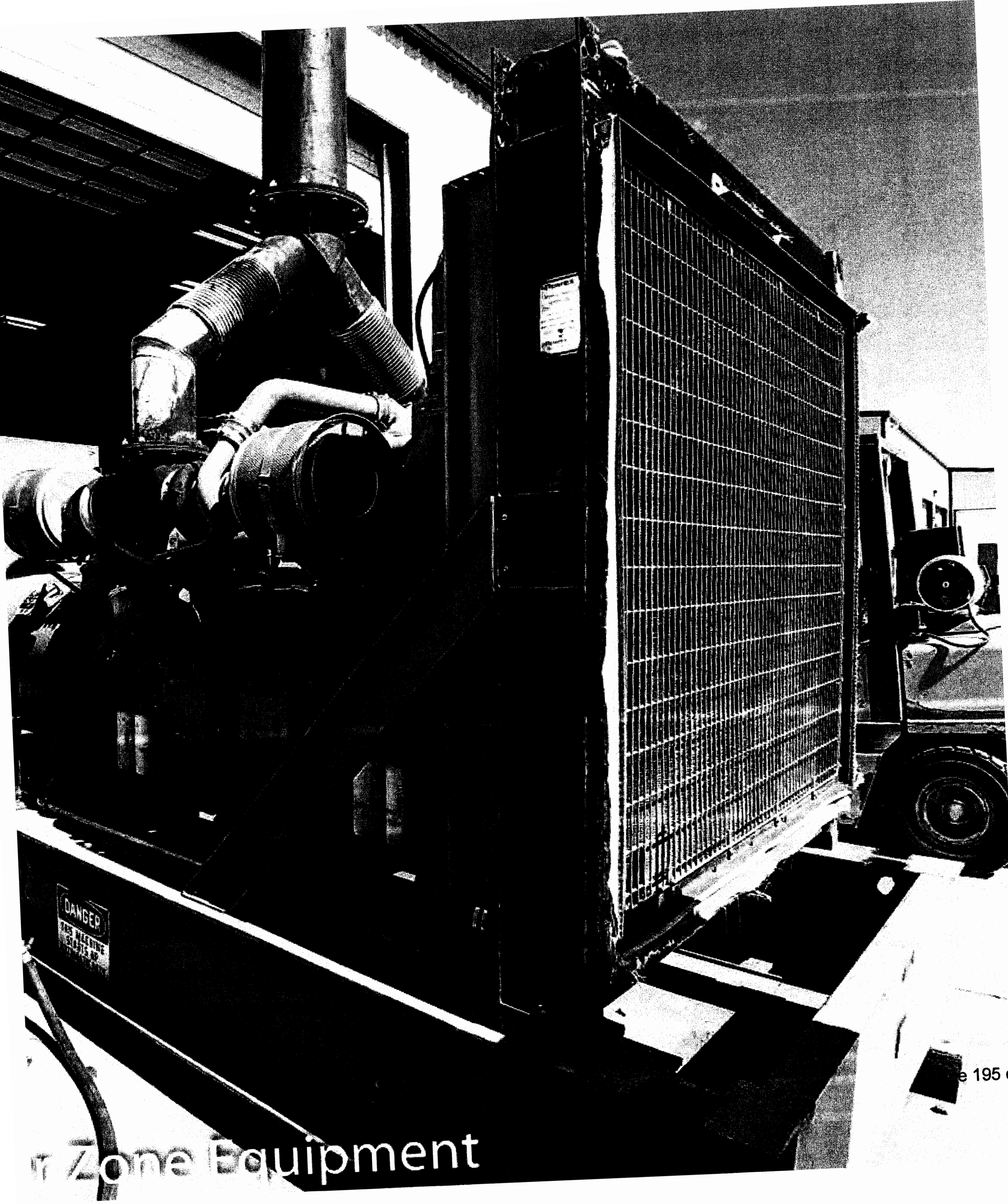
Date/Time	Output Volts	Output Amps	Output kVA
8/15/2022 10:16	480	272	226.1
8/15/2022 10:20	480	785.9	653.4
8/15/2022 10:33	480	724.2	602.1
8/15/2022 10:37	480	685.7	570.1
8/15/2022 10:48	480	698.5	580.7
8/15/2022 10:52	480	649.9	540.3
8/15/2022 10:58	480	588.5	489.3
8/15/2022 11:02	480	530.8	441.3
8/15/2022 11:07	480	692.1	575.4
8/15/2022 11:20	480	794.3	660.3
8/15/2022 11:23	480	528	439

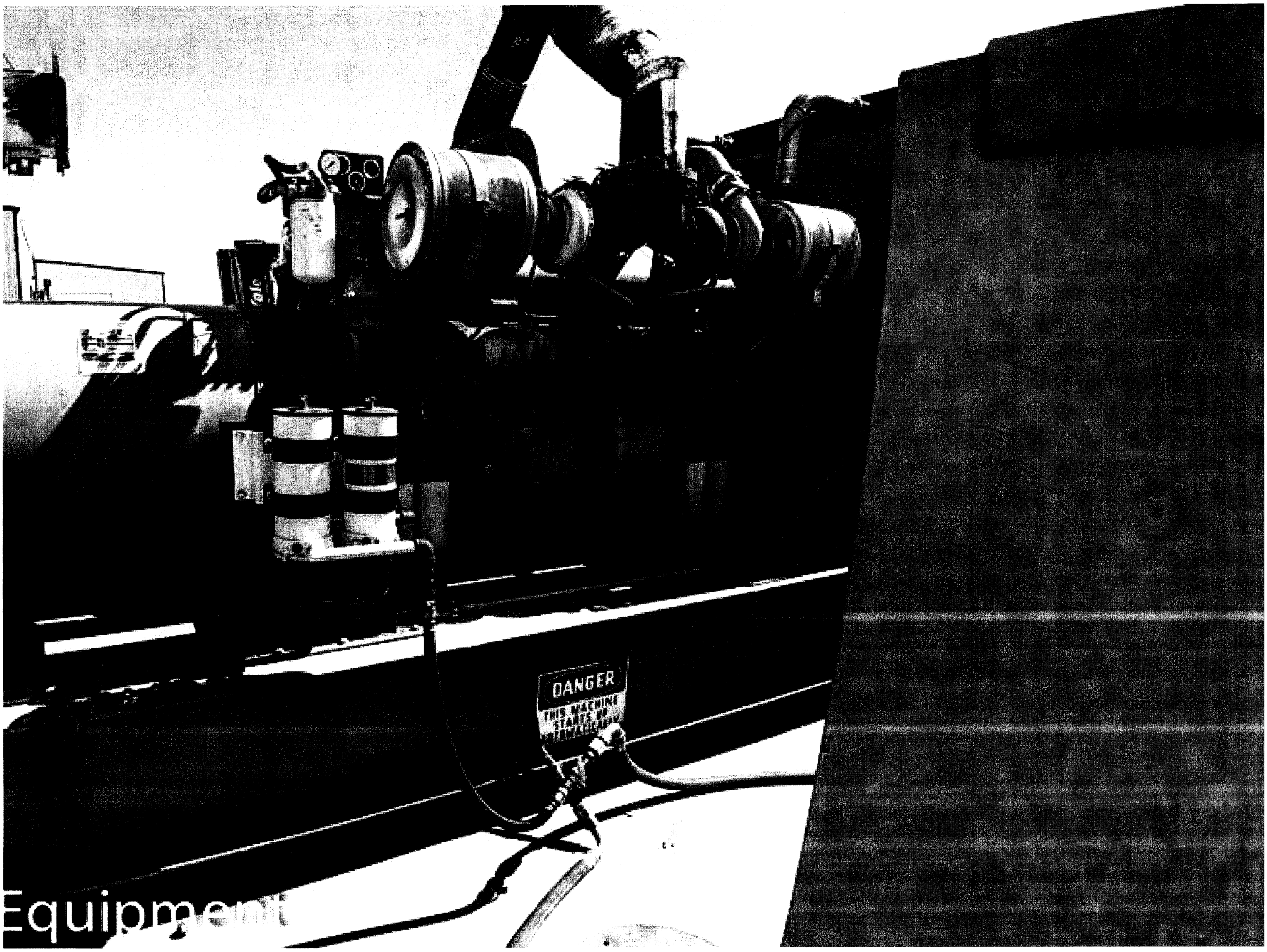


This generator set was tested under load on August 15, 2022 at Power Zone pump testing facility. The pump that was being used as the load c 3x10DA-9 which required 700 HP at full flow. Due to the pump performance characteristics it was not possible to load the generator more than The maximum output capacity may not have been reached on the generator during this test. The test was conducted at 7600 ft elevation at 78 de very well, and the exhaust was clean, with no visible smoke. The reason for the fluctuations in the output amperage and overall power was due t run a full pump performance test.


HOURS


DANGER
THIS MACHINE STARTS AUTOMATICALLY
60482
© Power Zone Equipment


DANGER
Zone Equipment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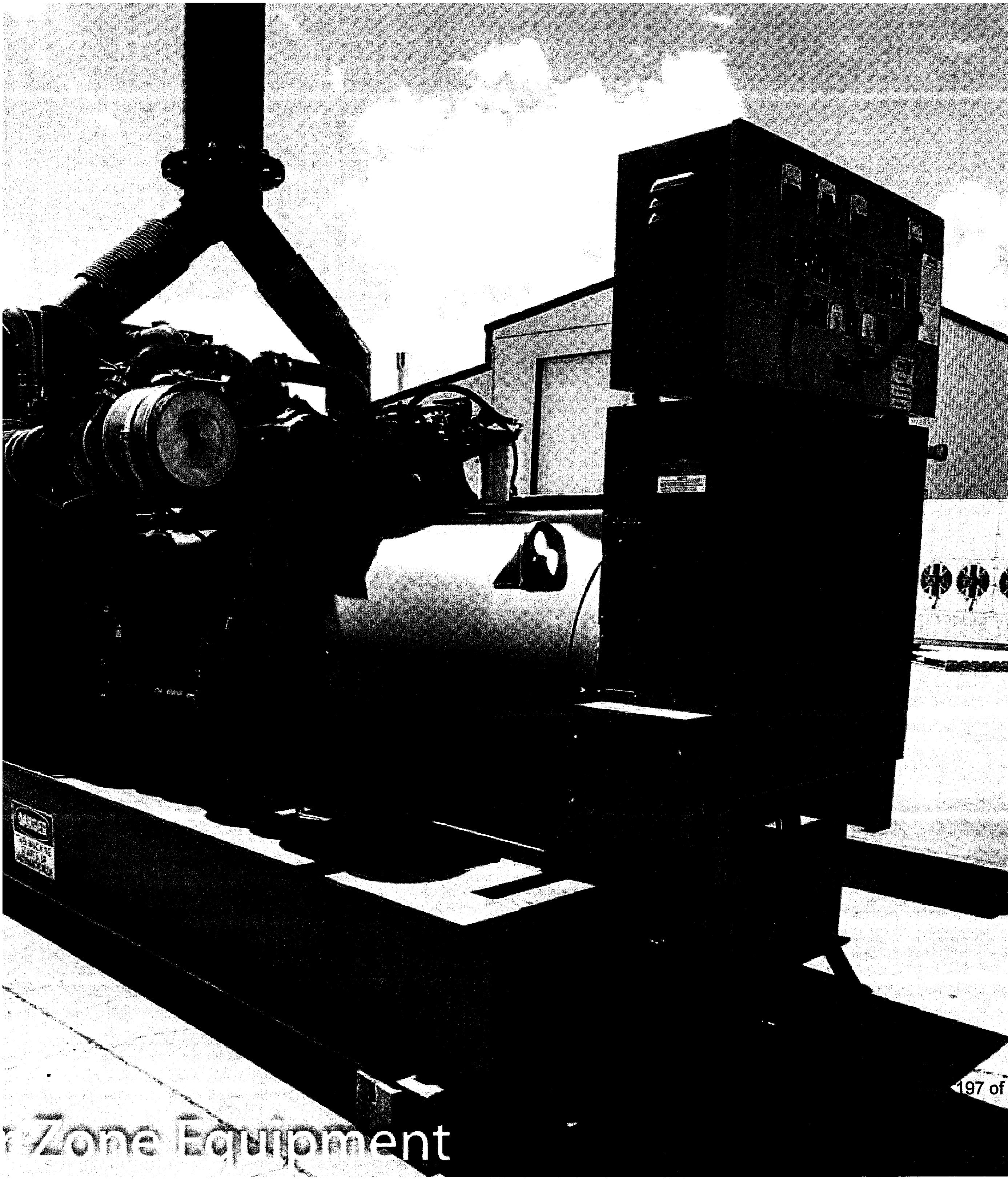
Equipment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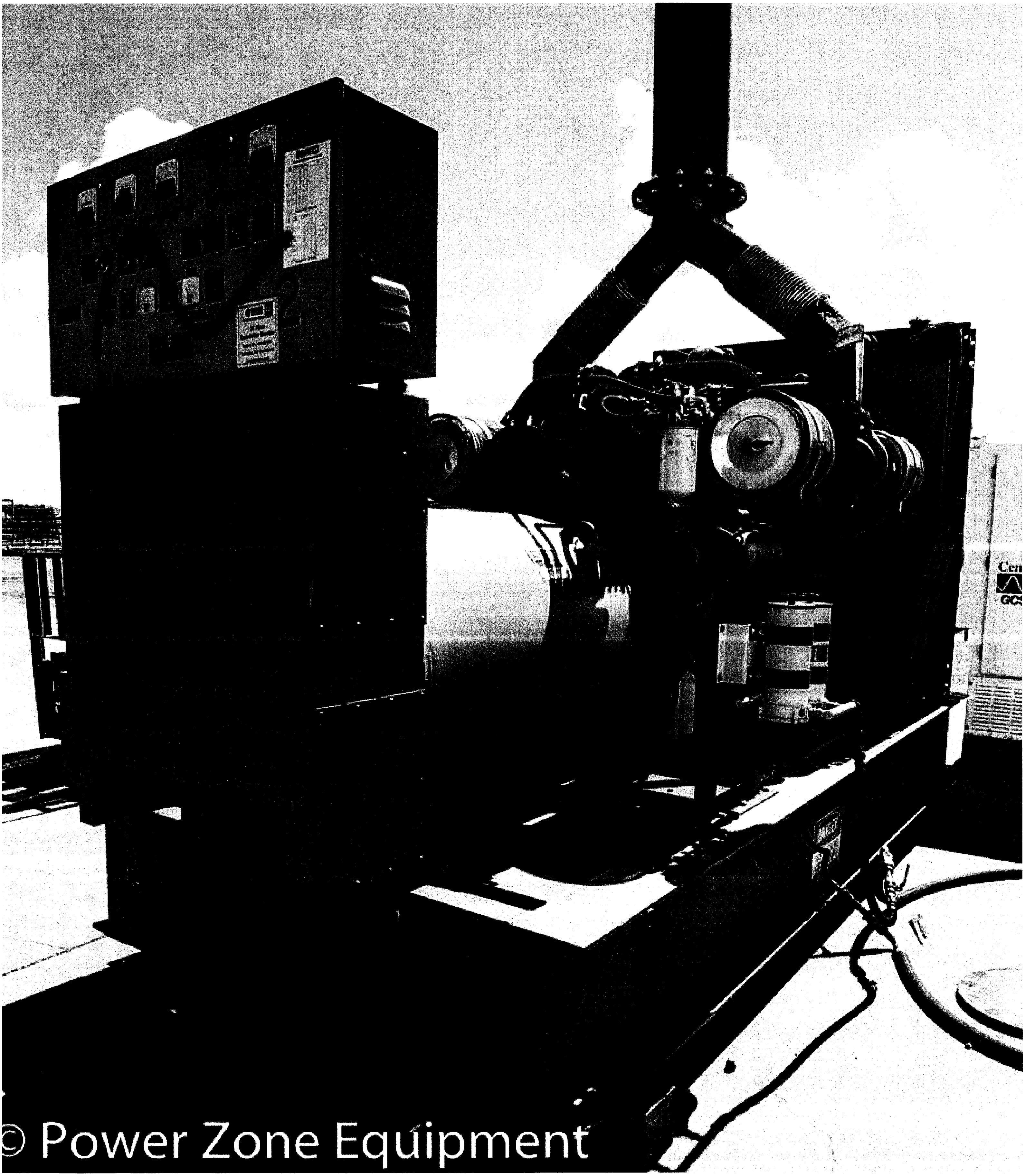
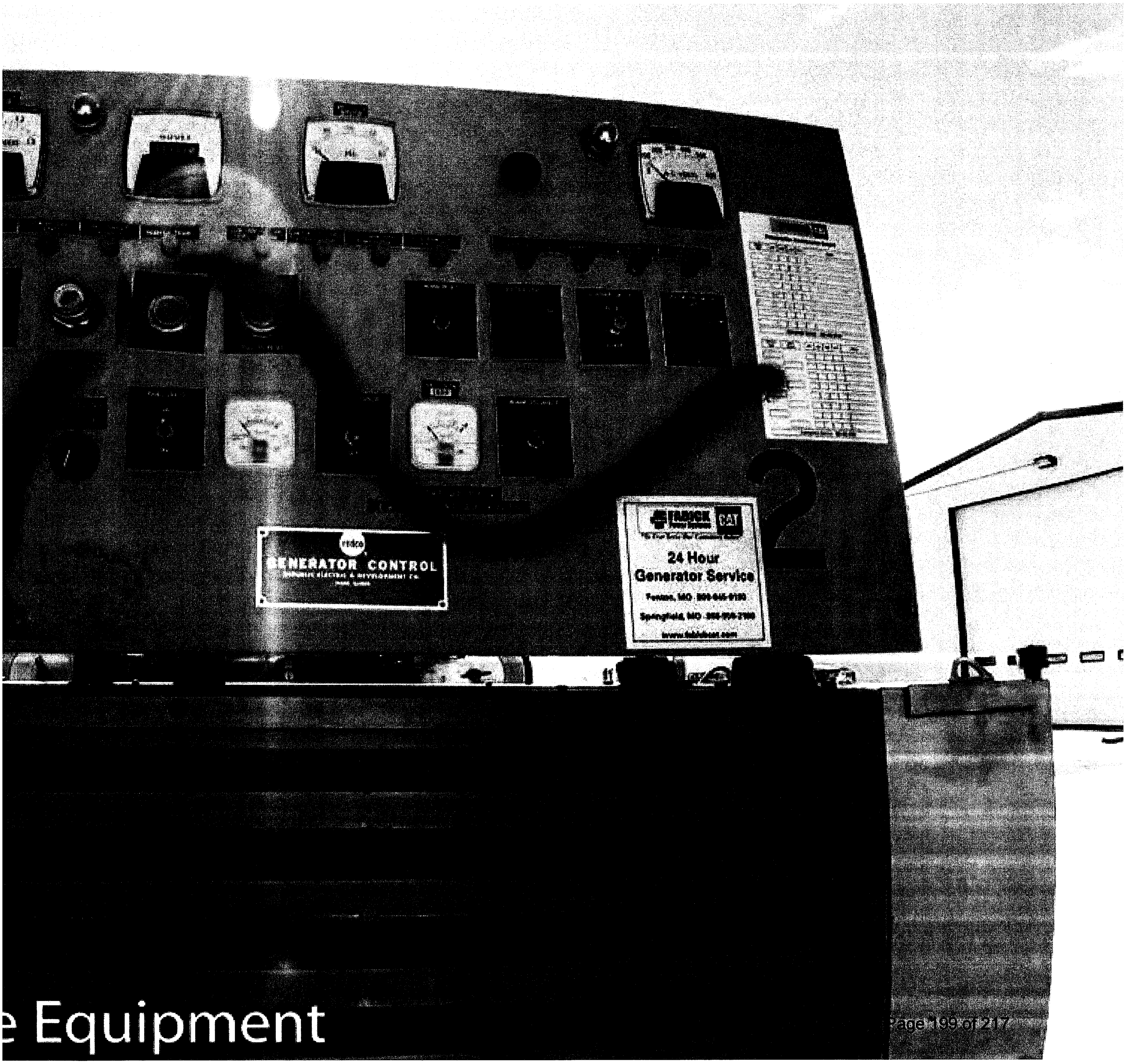
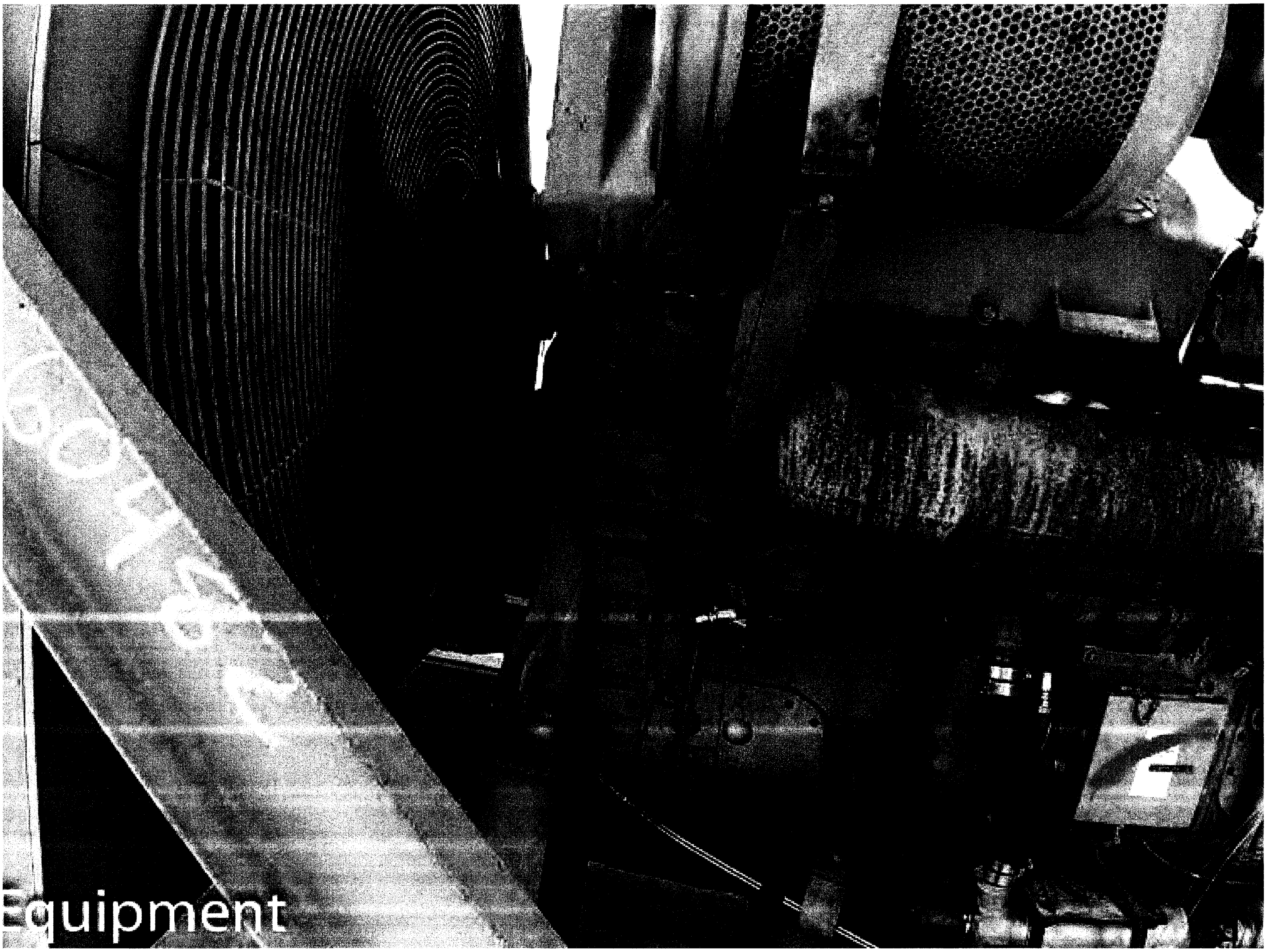

© Power Zone Equipment



e Equipment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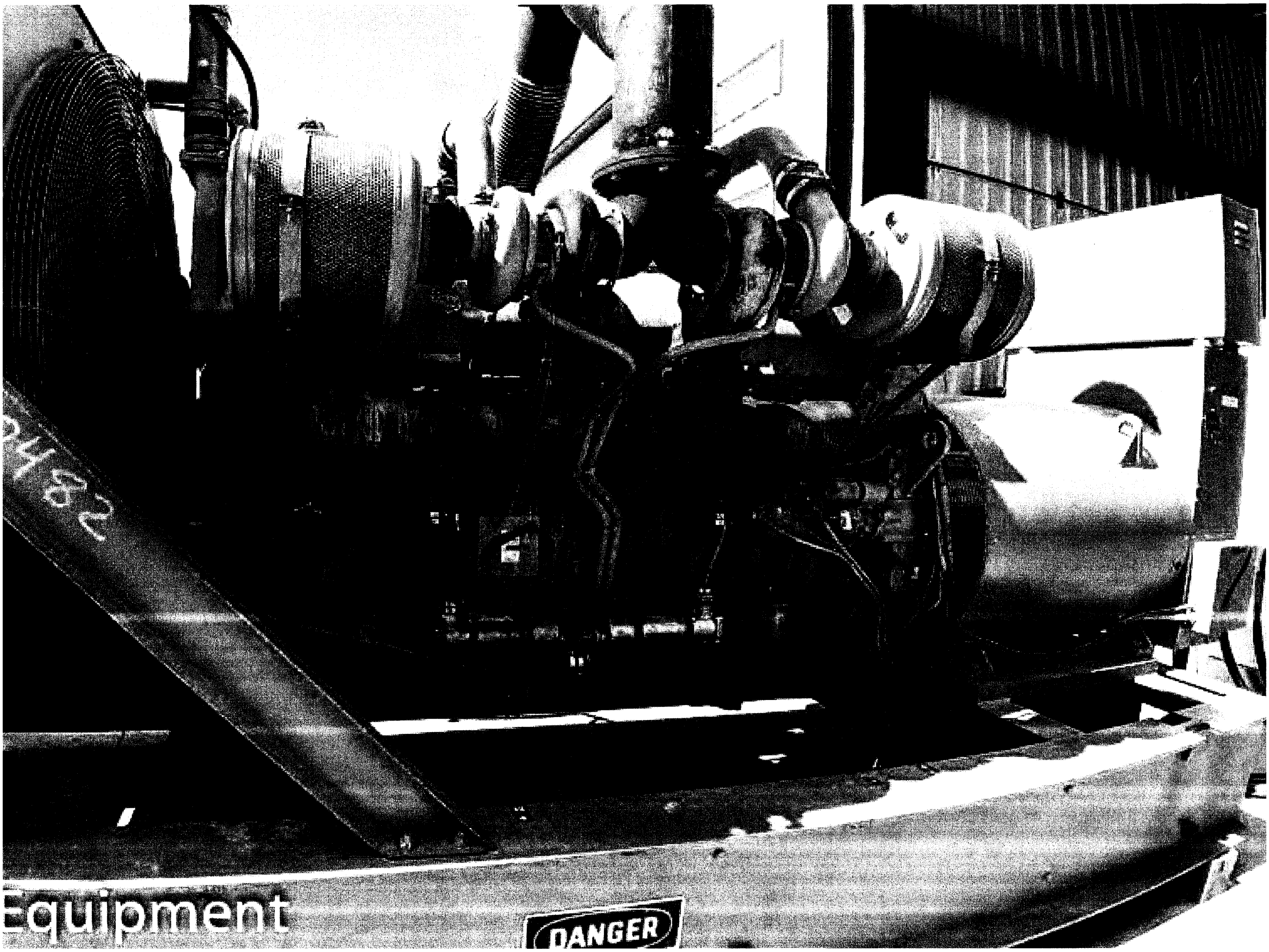
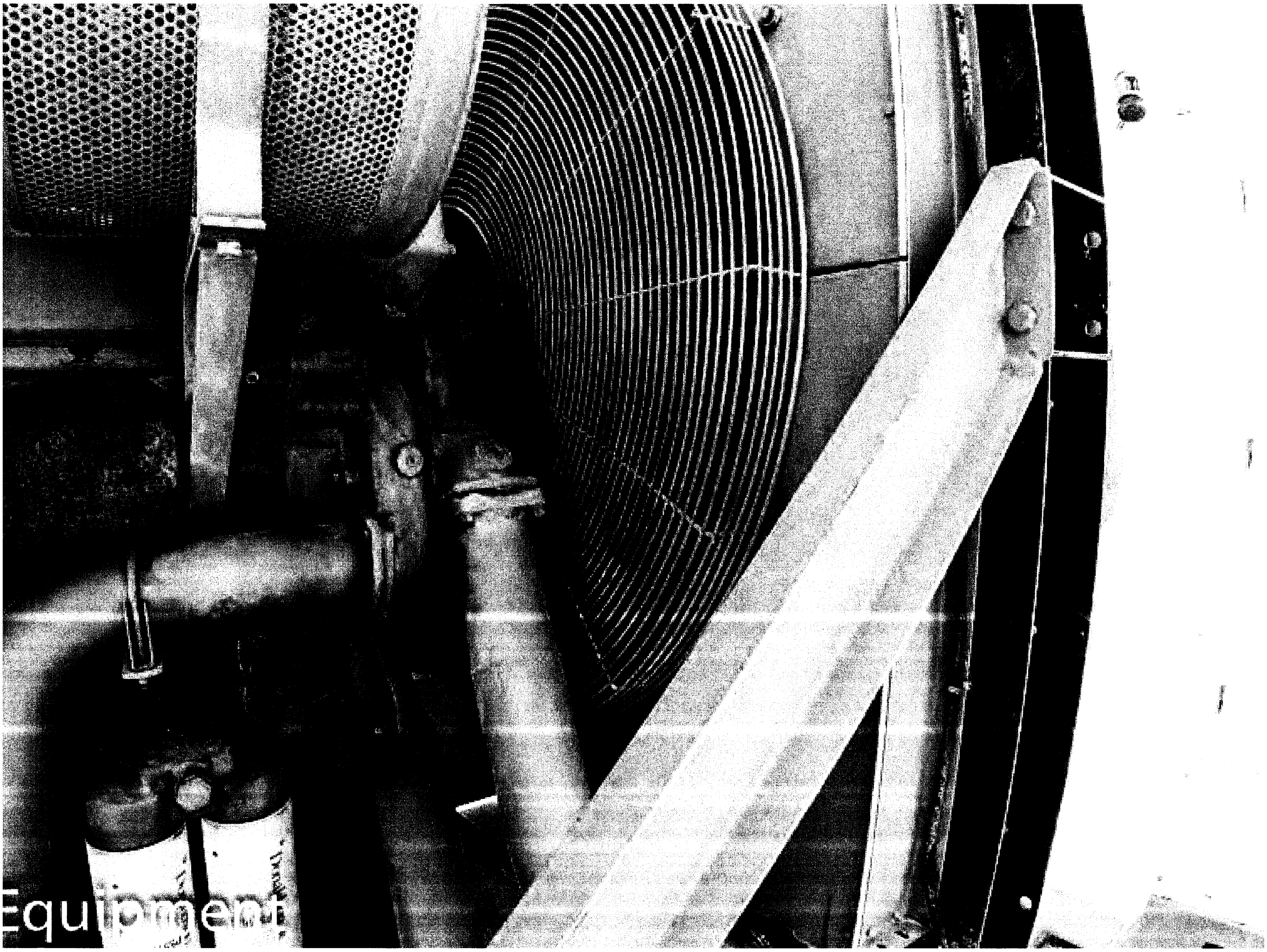

482
Equipment
DANGER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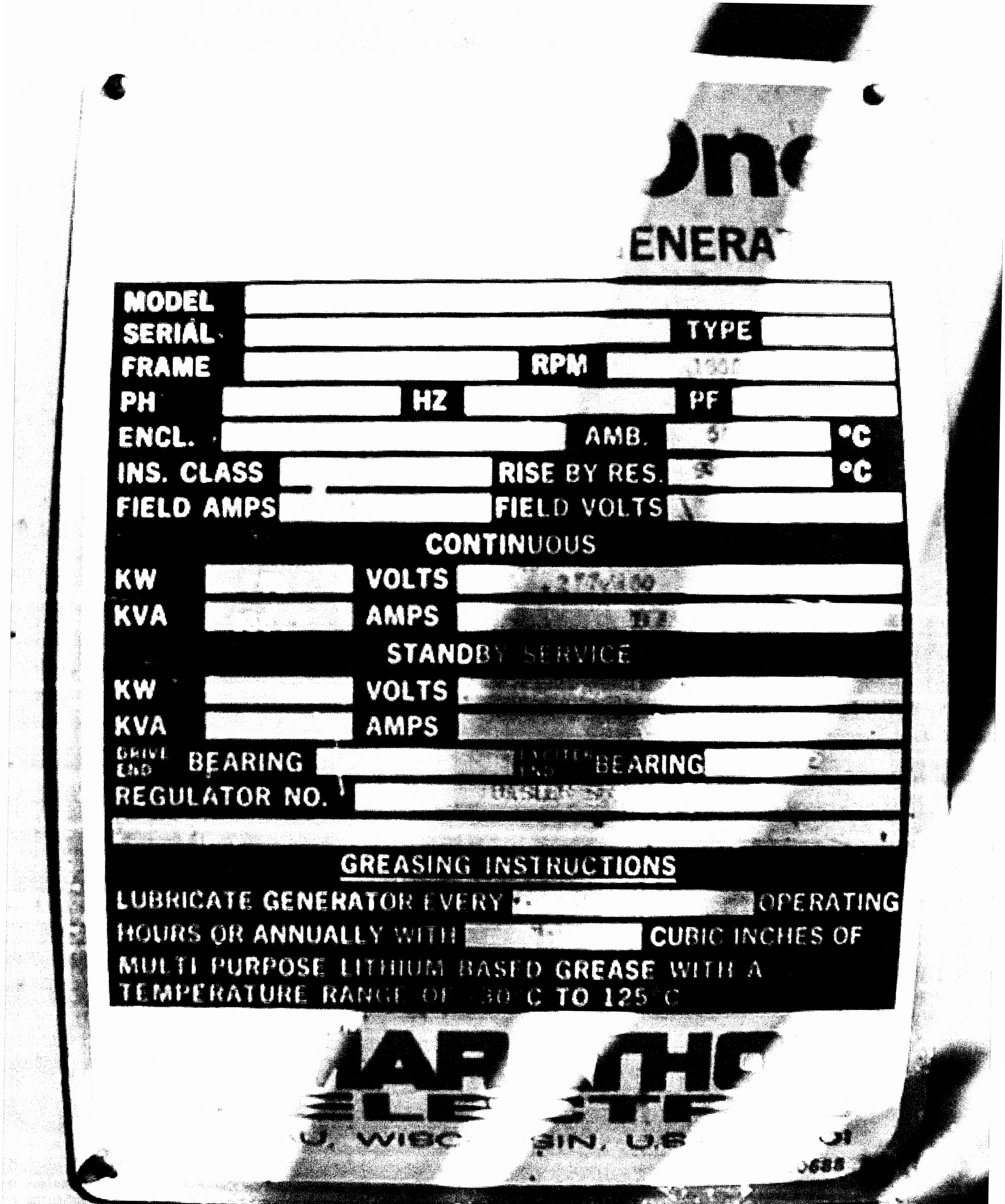
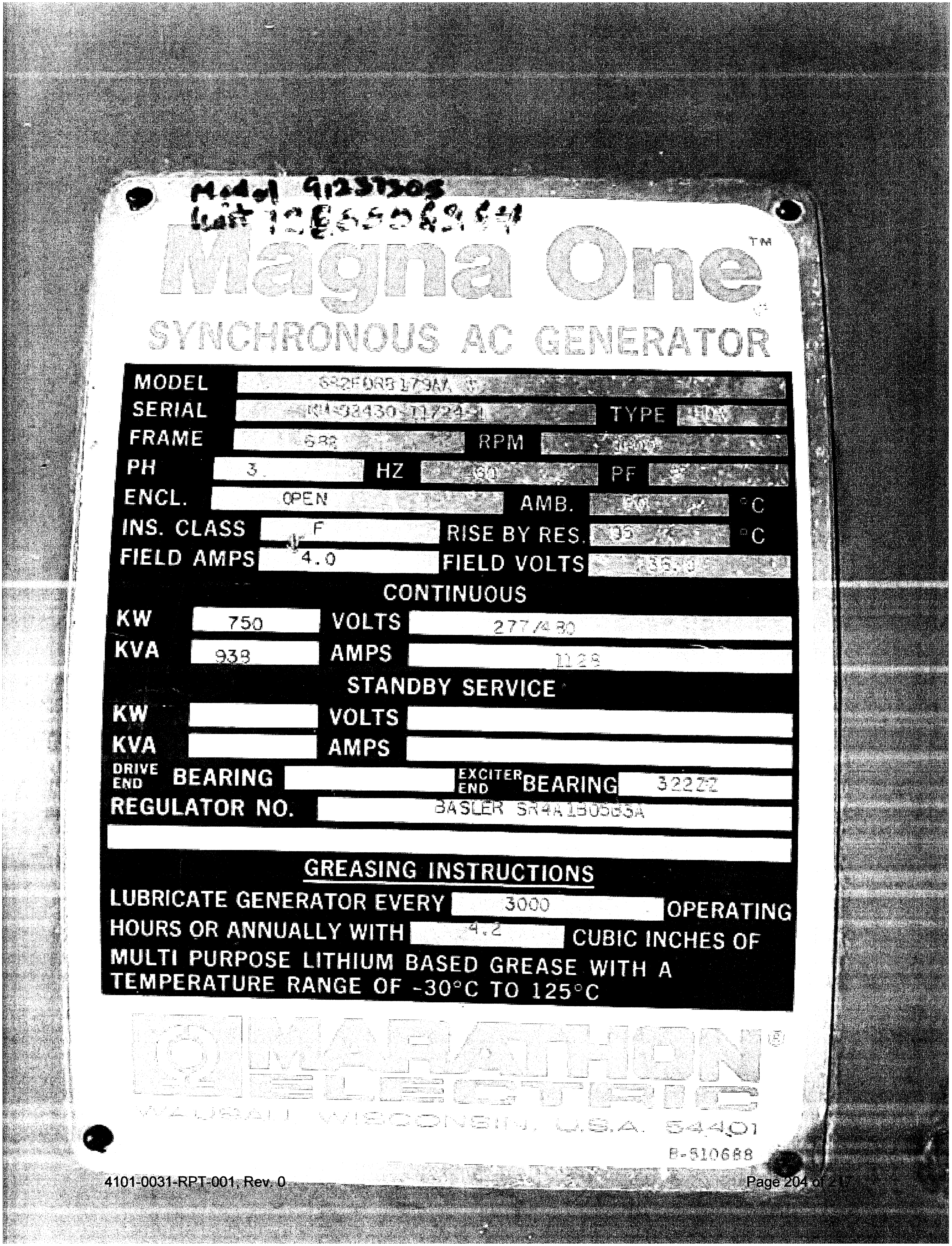


4101-0031-RPT-0


Magna One
SYNCHRONOUS AC GENERATOR
MODEL
SERIAL
TYPE
FRAME
RPM
PH 3
HZ
PF
ENCL. OPEN
AMB. °C
INS. CLASS F
RISE BY RES. °C
FIELD AMPS 4.0
FIELD VOLTS
CONTINUOUS
KW 750
VOLTS 277/480
KVA 939
AMPS 1128
STANDBY SERVICE
KW
VOLTS
KVA
AMPS
DRIVE END BEARING
EXCITER END BEARING 3222Z
REGULATOR NO. BASLER SR4A1B0588A
GREASING INSTRUCTIONS
LUBRICATE GENERATOR EVERY 3000 OPERATING HOURS OR ANNUALLY WITH 4.2 CUBIC INCHES OF MULTI PURPOSE LITHIUM BASED GREASE WITH A TEMPERATURE RANGE OF -30°C TO 125°C
MARATHON ELECTRIC
WAUSAU WISCONSIN U.S.A. 54401
B-510688

G

MPR Memorandum 4101-0031-MMO-001, "Evaluation of Test Load for Braidwood 2B Auxiliary Feedwater Pump Diesel Drive Test with Lube Oil Diluted by Fuel Oil," Revision 0

MPR

December 4, 2023
4101-0031-MMO-001, Revision 0

MEMORANDUM

To: Matt Fisher (Constellation Nuclear)

From: Mark O'Connell

Subject: Evaluation of Test Load for Braidwood 2B Auxiliary Feedwater Pump Diesel Drive Test with Lube Oil Diluted by Fuel Oil

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1.0 Purpose

This memorandum documents the scaled load profile to be used for the Braidwood 2B auxiliary feedwater (AFW) pump diesel drive test with lube oil diluted by fuel oil (this test will be performed with a 12-cylinder Detroit Diesel series 149 engine rather than a 16-cylinder engine, as is used at Braidwood). The scaled load profile is based on the loading calculated by Constellation (Reference 1). It is desired to match the per-cylinder loading of the test engine to the per-cylinder loading of the Braidwood AFW pump diesel so that the loads and forces on the components of the two engines are matched as closely as practicable.

2.0 Background

The Braidwood 2B AFW diesel drive drives three connected components – the shaft-driven AFW pump, a shaft-driven cubicle cooler fan and a shaft-driven SX booster pump. The diesel drive is a Detroit Diesel 16V-149TI diesel engine rated at 1,500 hp (Reference 2). The rated per-cylinder output of the Braidwood diesel drive is 93.8 horsepower per cylinder.

Fuel consumption is calculated in Reference 2 by determining the loads on the engine during three periods of AFW pump operation (hot standby, cooldown and soak). The loads are calculated from the AFW pump curves provided by the AFW pump manufacturer assuming the maximum surveillance procedure limit for pump speed and the corresponding maximum limit for flowrate. Flow rates are adjusted for recirculation, and pumping power is adjusted for speed increases due to the governor droop setting. The total load is adjusted for the AFW pump speed increaser (gear box), cubicle cooler fan load (constant 80 hp) and the shaft-driven SX pump load (constant 20 hp). The Braidwood 2B AFW diesel drive pump loads from Reference 1 are shown in Table 2-1.

Table 2-1. Braidwood 2B AFW Diesel Drive Pump Loads

Period	Duration	Load	% of Rating
1	120 min	1,222 hp	81.5
2	240 min	1,087 hp	72.5
3	60 min	1046 hp	69.7
4	180 min	1046 hp	69.7
5	840 min	939 hp	62.6

The units of the above load values are brake horsepower, meaning they are the horsepower developed by the engine at the engine output shafts. The fuel dilution test will be run on a diesel generator set, and generator output will be controlled to load the engine.

It is desired to run the test engine using a load profile that applies the same percentage of the engine rating to the test engine as the Braidwood AFW diesel drive would experience under accident conditions.

3.0 Discussion

The test diesel generator set consists of a 12V-149T engine with a continuous rating of 1130 hp attached to a generator with a continuous rating of 750 kWe (Reference 3). The per-cylinder output of the test diesel generator set is 94.2 hp per cylinder, which is slightly higher than that of the Braidwood engine. Determining the test load profile using a percentage of the continuous rating is conservative, as it applies a slightly higher per-cylinder load to the test engine to account for the slightly higher rating per cylinder. The brake powers for the test engine corresponding to the same percentages of engine rating as the AFW pump diesel drive carries are show in Table 3-1.

Table 3-1. 12-Cylinder Test Engine Brake Horsepower

Period	Duration	% of Rating	Brake Power
1	120 min	81.5	921 hp
2	240 min	72.5	819 hp
3	60 min	69.7	788 hp
4	180 min	69.7	788 hp
5	840 min	62.6	707 hp

Typical generator efficiencies at rated load are approximately 96% (e.g., see Reference 4). A higher generator efficiency is conservative, as it results in a higher test genset load. A generator efficiency of 97% is assumed for the test genset. Brake horsepower is converted to brake kilowatts (by multiplying 0.746) and then multiplied by the generator efficiency (0.97) to determine the corresponding generator output. The resulting equivalent generator output powers are shown in Table 3-2.

Table 3-2. 12-Cylinder Test Generator Set Loads in Kilowatts

Period	Duration	Brake Power	Brake Power	Generator Output
1	120 min	921 hp	687 kWb	666 kWe
2	240 min	819 hp	611 kWb	593 kWe
3	60 min	788 hp	588 kWb	570 kWe
4	180 min	788 hp	588 kWb	570 kWe
5	840 min	707 hp	527 kWb	511 kWe

4.0 References

1. Email from Matt Fisher (Constellation) to Mark O'Connell (MPR), "FW: Engine Loading Computation.xlsx," November 30, 2023.

2. Constellation Calculation BRW-10-0146-M /BYR10-103, "AF Diesel Driven Pump Fuel Consumption and Day Tank Requirements, Revision 3, February 26, 2015.

3. Email from Theodore Ellison (Interstate Power Systems) to Mark O'Connell (MPR), "RE: Test Engine," November 13, 2023.

4. Letter from Mark M. Anderson (Dresser-Rand Electric Machinery) to Larry Hajous (PSEG), "EM Sale: 89-2950, Your P.O.: P1-322809," October 3, 1989.

H

MPR Calculation 4101-0031-CALC-001, "2B AFW Diesel Engine Test Fuel Leakage Rate," Revision 1

2B AFW Diesel Engine Test Fuel Leakage Rate

Prepared for: Braidwood 1 & 2

Preparer:	Daniel McCray	E-signed by: Daniel McCray on 2023-12-08 18:09:58
Checker:	Edward McCarty	E-signed by: Edward McCarty on 2023-12-08 18:11:52
Reviewer:	Gary Thompson	E-signed by: Gary Thompson on 2023-12-08 18:16:36
Approver:	Mark O'Connell	E-signed by: Mark O'Connell on 2023-12-08 18:17:27

QA Statement of Compliance

This document has been prepared, reviewed, and approved in accordance with the Quality Assurance requirements of the MPR Standard Quality Program.

MPR Associates, Inc.
320 King St. • Alexandria, VA 22314
(703) 519-0200 • www.mpr.com

2B AFW Diesel Engine Test Fuel Leakage Rate

RECORD OF REVISIONS		
Revision Number	**Pages /Sections Revised**	**Revision Description**
0	All	Initial Issue
1	Sections 2.0, 5.0, and 6.0	Incorporates client comments

Table of Contents

1.0 Introduction

1.1. Purpose

This calculation determines the fuel leakage rate required to achieve the as-found and projected future concentrations of fuel oil in the lube oil system of the Braidwood 2B AFW pump diesel engine. This calculation also determines the scaled fuel leakage rate required to achieve the same initial and future concentrations of fuel oil in the lube oil system of a smaller test engine. The test engine will be used to investigate the effects of the fuel oil contamination on the operation and reliability of the AFW pump diesel engine.

1.2. Background

In September 2023, Braidwood Clean Energy Center personnel identified an elevated concentration of fuel oil in the lube oil of the prime mover for the station's 2B diesel-driven AFW pump. The prime mover is a Detroit Diesel 16V-149TI diesel engine, which operates with a two-stroke mechanical cycle (one crankshaft revolution per power stroke). At the time of discovery, the engine's lube oil contained approximately 18.2 mass percent fuel oil (Reference 1). The source of the fuel oil contamination was corrected, and the lube oil was replaced.

Constellation Nuclear contracted MPR to determine if the diesel-driven AFW pump would have been able to perform its mission starting in the as-found condition with further fuel oil dilution of the lube oil occurring during operation. As part of this effort, MPR and Southwest Research Institute (SwRI; as a subcontract to MPR) are performing a test using a Detroit Diesel 12V-149T diesel engine. During the test, fuel oil will be added to the test engine's lube oil sump at a controlled rate to achieve a fuel oil concentration in the lube oil that is consistent with the calculated fuel concentration for the plant's engine. This calculation determines the fuel leakage rate required to achieve the as-found and projected future concentrations of fuel oil in the plant engine's lube oil. The calculation also determines the scaled fuel leakage rate required to achieve the same initial and future concentrations of fuel oil in the smaller test engine (the test engine has 12 cylinders versus 16 cylinders for the plant's engine).

2.0 Summary of Results and Conclusion

The fuel leak rate for the plant engine, given an initial lube oil volume of 42 gallons and a fuel oil concentration of 18.2 % by mass after 6.39 hours, is 1.524 gal/hr. The corresponding fuel leak rate for the test engine, with an initial lube oil volume of 30 gallons, is 1.089 gal/hr.

3.0 Methodology

The fuel leak rate required for testing is determined by calculating the volumetric flow rate required to achieve specific concentrations of fuel oil after specific amounts of engine operating time for a given initial volume of lube oil for the plant's engine. This flow rate is then scaled (based on the fractional relationship between the initial lube oil volume in the plant and test engines) to identify the equivalent volumetric flow rate of fuel oil for the test engine.

4.0 Assumptions

4.1. Assumptions with a Basis

This calculation contains the following assumptions with a basis:

1. The leakage of fuel into the plant engine (and also into the test engine) occurs at a constant rate and only during engine operation.
2. Lube oil and/or fuel oil does not leak out of the plant or test engines through seals and gaskets during engine operation.
3. The volume of lube oil consumed by the test engine during the test will result in the test conditions being conservative.

4.2. Assumptions without a Basis

This calculation contains no assumptions without a basis.

5.0 Design Inputs

The fuel leakage rate and resulting fuel oil concentrations are functions of the initial volume of lube oil. Per Reference 2, the initial lube oil volume for the plant engine is 42 gal. Per Reference 3, the initial lube oil volume for the test engine oil will be 30 gal. Table 5-1 contains the initial lube oil volumes for the two engines.

Table 5-1. Initial Lube Oil Volume Inputs

Input	Value	Basis
Plant Engine Lube Oil Volume, $V_{0,\,plant}$	42 gal	Reference 2
Test Engine Lube Oil Volume, $V_{0,\,test}$	30 gal	Reference 3

Per Reference 4, the fuel oil concentration in the plant engine's lube oil was 18.2% by mass after 6.39 hours of engine operation. The fuel oil and lube oil have different specific gravities; therefore, the fuel oil concentration by volume is different than the fuel oil concentration by mass. Table 5-2 contains the specific gravity for the lube oil and the API gravity for the fuel oil used in the plant and test engines. API gravity is a parameter that indicates the relative gravity or density with respect to water and is defined as:

$$API = \frac{141.5}{SG} - 131.5$$

where SG is the specific gravity at 60 °F.

Table 5-2. Percent Oil by Volume Calculation Inputs

Input	Value	Basis
Fuel, API_F	34.2	Reference 5
Lube, SG_L	0.89	Reference 6
Dilution % by Mass, $P_{init,\,mass}$	18.2%	Reference 1

Eq. 1 is used to convert API gravity to specific gravity.

$$SG_F = \frac{141.5}{131.5 + API_F} \qquad \textbf{Eq. 1}$$

$$SG_F = \frac{141.5}{131.5 + 34.2}$$

$$SG_F = 0.854$$

Eq. 2 converts fuel concentration by mass to fuel concentration by volume.

$$P_{init,vol} = \frac{\frac{P_{init.mass}}{SG_F}}{\frac{P_{init.mass}}{SG_F} + \frac{1 - P_{init,mass}}{SG_L}} \qquad \textbf{Eq. 2}$$

The initial test volumes for the plant and test engines are calculated using Eq. 3.

$$V_{start} = \frac{V_0}{1 - P_{init,vol}} \qquad \textbf{Eq. 3}$$

Table 5-3 tabulates the necessary inputs for determining the fuel leak rate and contains the plant and test lube oil system start volumes.

Table 5-3. Leakage Rate Calculation Inputs

Input	Value	Basis
Run Time to Discovery, t_{pre}	6.39 h	Reference 4
Dilution Percent by Volume, $P_{init, vol}$	18.82%	Eq. 2
Test Start Volume Plant, $V_{start, plant}$	51.74 gal	Eq. 3
Test Start Volume Test, $V_{start, test}$	36.95 gal	Eq. 3

6.0 Calculations and Results

Eq. 4 is used to calculate the required leak rate (Q_{plant}) to achieve the known fuel oil concentration in the plant engine's lube oil (18.82% by volume) over 6.39 hours of engine operation.

$$P_{init,vol} = \frac{t_{pre} * Q_{plant}}{V_{0,plant} + t_{pre} * Q_{plant}} \qquad \textbf{Eq. 4}$$

Rearranging Eq. 4 to solve for Q_{plant} yields the following:

$$Q_{plant} = \frac{V_{0,plant} * P_{init,vol}}{t_{pre} - t_{pre} * P_{init,vol}}$$

$$Q_{plant} = \frac{42\ gal * 18.82\%}{6.39\ h - 6.39\ h * 18.82\%}$$

$$Q_{plant} = 1.524\ \frac{gal}{h}$$

The equivalent leak rate for the smaller test engine is calculated using Eq. 5, which scales the leak rate for the plant engine by the fractional relationship between the initial lube oil volumes for the test and plant engines.

$$Q_{test} = \frac{V_{0,test}}{V_{0,plant}} Q_{plant} \qquad \textbf{Eq. 5}$$

$$Q_{test} = \frac{30\ gal}{42\ gal} * 1.524\ \frac{gal}{h}$$

$$Q_{test} = 1.089\ \frac{gal}{h}$$

7.0 References

1. Bureau Veritas Oil Condition Monitoring Lube Oil Analysis Management System Report for Braidwood 2AF01PB-K-PMPA-01PB-E15-K (Braidwood 2B AFW Diesel Drive Lube Oil), October 4, 2023.
2. Email from Matthew Fisher (Constellation) to Mark O'Connell (MPR). "Re: [EXTERNAL] Lube Oil Volume for AFW Diesel Drive," December 1, 2023.
3. Email from Jonathan Meyn (Interstate Power Systems) to Mark Mikoff (Constellation), "Re: [EXTERNAL] Fw: Test Engine," November 30, 2023.
4. Email from Matthew Fisher (Constellation) to Mark O'Connell (MPR). "Preliminary Detroit Diesel Information," November 2, 2023.
5. Bureau Veritas Laboratory Report: Diesel Fuel – ASTM D 975 2006b for Braidwood Doc No. 120423-12042023171938 (Braidwood 2B AFW Diesel Drive Fuel Oil), December 4, 2023.
6. Specification for Mobil Delvac 1600 Series Mobil Commercial-Vehicle-Lube, September 29, 2023.

IDENTIFY THE APPLICABILITY OF THE FOLLOWING TO THE DESIGN CHANGE. **WHEN** A TOPIC IS DETERMINED TO BE APPLICABLE, **THEN PLACE** THE APPLICABLE TOPIC INFORMATION IN THE DESIGN CHANGE. **IF** THE INFORMATION IS INSTALLATION-RELATED, **THEN PLACE** THIS INFORMATION IN THE INSTALLER INSTRUCTIONS (ATTACHMENT C IN CC-AA-103-100). **IF NOT** INSTALLATION-RELATED**, THEN PLACE** THE TOPIC INFORMATION IN A SEGREGATED DESIGN CONSIDERATION SECTION, OR WITHIN THE DOCUMENTATION REQUIRED BY THE PROCEDURES GOVERNING A PARTICULAR ATTRIBUTE. OPTIONAL FIELDS "TRACKING OF ACTION" AND "REFERENCES" ARE AVAILABLE FOR NOTATION BY THE PREPARER IF DESIRED TO ASSIST THE PREPARER IN MANAGING THE ACTIVITY.

Engineering Change Number: 640630		**Revision Number: 000**		
Section	**Design Change Attribute**	**Applicable**	**Tracking of Action**	**References (optional)**
4.1.4.1	IDENTIFY Basic SSC Functions	☒		See DCS
4.1.4.2	IDENTIFY Configuration Change safety classification.	☒		See DCS
4.1.4.3	IDENTIFY Seismic Classification of the SSC.	☒		See DCS
4.1.5	PROVIDE the performance requirements and design conditions (including margin) of the SSC needed to evaluate the change from the existing to the modified systems, structures, or components.	☒		See Eval Details
4.1.6	DETERMINE the design requirements necessary to facilitate periodic surveillance testing and acceptance testing that is necessary for the Configuration Change being considered.	☐		
4.1.7	DETERMINE the Codes, Standards, and Regulatory Requirements applicable to the Configuration Change.	☐		
4.1.8	IDENTIFY PWR Sump GL 2004-02 Program impacts PWR sites only	☐		
4.1.9	DETERMINE changes required to existing Design Analysis or new parameters that require new calculations or calculation revisions that are used to assess the acceptability of a system or a component function in meeting various physical requirements.	☐		
4.1.10	If Redundancy, Diversity and Separation requirements are identified or affected, then REVIEW the original design basis as well as any subsequent modifications.	☐		
4.1.11	IDENTIFY any Failure Effects requirements. (See CC-AA-102 Attachment 12)	☐		

Engineering Change Number: 640630		**Revision Number: 000**		
Section	**Design Change Attribute**	**Appli cable**	**Tracking of Action**	**References (optional)**
4.1.12	IDENTIFY Fire Protection and Appendix R Safe Shutdown requirements, by using the "Screening for Approved Fire Protection Program (AFPP) Impact", CC-AA-102-F-02. NFPA 805 Units - IDENTIFY the impact on NFPA 805 requirements by using CC-AA-102-F-02, "Screening for Approved Fire Protection Program (AFPP) Impact".	☐		
4.1.13	DETERMINE any Material requirements, such as material grade, product form, compatibility with existing or other new materials, galvanic interaction between dissimilar metals, special welding material requirements, critical properties, performance characteristics, alternative materials as well as any Material Suitability requirements such as compatibility, electrical insulation properties, protective coating, corrosion resistance, mechanical insulation etc. necessary for the Configuration Change.	☐		
4.1.14	Determine environmental conditions and impacts. Also see EN-AA-103.	☐		
4.1.15	DETERMINE if Environmental Qualification (EQ) of equipment is affected. (see CC-AA-102-F-03)	☐		
4.1.16	REVIEW the Operating Experience databases through the INPO Internet Site or equivalent in accordance with PI-AA-115:	☒		See DCS
4.1.17	DETERMINE if the configuration change may affect the existing INPO Consolidated Data Entry (CDE) database.	☐		
4.1.18	DETERMINE if the Configuration Change may affect the existing Probabilistic Risk Assessment (PRA), Mitigating System Performance Index (MSPI) Basis Document PRA content, and shutdown risk models by using the screening checklist in CC-AA-102-F-04. NFPA 805 Units - In addition to CC-AA-102-F-04, PERFORM a review of the configuration change for impact on the NFPA 805 using CC-NE-102-F-15.	☐		
4.1.19	EVALUATE if System Operational Requirements have changed.	☐		

Engineering Change Number: 640630		Revision Number: 000		
Section	**Design Change Attribute**	**Applicable**	**Tracking of Action**	**References (optional)**
4.1.20	IDENTIFY any Human Factors requirements.	☐		
4.1.21	IDENTIFY procedure changes per direction in CC-AA-102-F-09.	☐		
4.1.22	IDENTIFY any changes or additional training requirements for various departments, per direction in CC-AA-102-F-09.	☐		
4.1.23	CONSIDER the functional and physical system interface requirements, including the effect of cumulative tolerances between the subject system or component and adjacent or related support systems, structures, and components that may have been affected by the Configuration Change.	☐		
4.1.24	DETERMINE specialized layout and arrangement requirements.	☐		
4.1.25	DETERMINE if the Radiation Protection/ALARA programs are affected by review of changes that affect any of the following during normal or post accident conditions: Radiation sources; changes affecting controlled radiation areas; primary coolant fluid systems (Cobalt Materials); contaminated systems; radiation monitoring systems; HVAC Systems which could transport airborne contaminants; change or alter shielding. (see CC-AA-102-F-05)	☐		
4.1.26	DETERMINE the need for walkdowns to look at accessibility to the work area(s) and any special installation considerations that need to be addressed during design development.	☒		Mikoff/Broda/Fisher were onsite for testing
4.1.27	DETERMINE Accessibility for maintenance, repair and In-Service Inspection (ISI) and In-Service Testing (IST), and the conditions under which these activities will be performed.	☐		
4.1.28	DETERMINE handling, storage, cleaning, and shipping requirements, as well as transportability requirements for items which require special handling during transit from supplier to site, from site to vendor (for repair), or from site receiving to final placement in the plant.	☐		

Engineering Change Number: 640630		Revision Number: 000		
Section	**Design Change Attribute**	**Appli cable**	**Tracking of Action**	**References (optional)**
4.1.29	DETERMINE the effect of the Configuration Change on existing Emergency Plan or environmental and discharge monitoring that are used to prevent undue risk to public health and safety.	☐		
4.1.30	DETERMINE Industrial Safety requirements such as restricting the use of dangerous materials, hazardous chemicals, escape provisions from enclosures, pertinent OSHA requirements, and grounding of electrical systems.	☐		
4.1.31	DETERMINE impact on nuclear fuel, core components, core design, reactivity management, criticality control and accountability of nuclear materials as well as transient and / or accident analysis, by using CC-AA-102-F-06.	☐		
4.1.32	DETERMINE Load Path requirements for installation, removal, and repair of equipment and replacement of major components.	☐		
4.1.33	IDENTIFY Mechanical System Characteristics where design limits are placed on the mechanical properties of a system or components.	☒		See DCS
4.1.34	IDENTIFY Chemistry requirements where limits are placed on the chemical properties of a system or component based upon safety, reliability, ALARA, economics, or other considerations.	☐		
4.1.35	IDENTIFY Electrical requirements where limits are placed on the electrical properties of a system or component.	☐		
4.1.36	IDENTIFY Instrument and Control requirements, including digital technology requirements.	☐		
4.1.37	IDENTIFY Security requirements such as site monitoring, alarm systems, vehicle barrier systems, security and security lighting.	☐		
4.1.38	IDENTIFY Civil/Structural requirements where design limits are placed on the structural properties of a SSC such as equipment foundations and component supports.	☐		

Engineering Change Number: 640630		Revision Number: 000		
Section	**Design Change Attribute**	**Appli cable**	**Tracking of Action**	**References (optional)**
4.1.39	If the Configuration Change adds, relocates, or alters Seismic Category I mechanical and/or electrical components then ENSURE that the Seismic Dynamic Qualification (SD/Q) of the components has been addressed per CC-AA-320-001.	☐		
4.1.40	DETERMINE Personnel Requirements and Limitations such as the need for trade specialists and engineering experts as well as support personnel, such as Radiation Chemistry technicians, welding technicians with special expertise, use of specific contractor or station procedures for installation or the need for mock-ups for training, installation, or operation.	☐		
4.1.41	LIST special procedures and installation specifications that apply, but are not part of the normal installation procedural direction.	☐		
4.1.42	DETERMINE Interfacing Department impact of the Configuration Change, such as Operations, Plant Engineering, Training (including Plant Simulator), Maintenance, Reactor Engineering, Radiation Protection and others. (see CC-AA-102-F-10A through 10H)	☐		
4.1.43	CONSIDER the impact on the License Renewal.	☐		
4.1.44	REVIEW the proposed changes for conformance with requirements of any applicable Nuclear Electric Insurance Limited (NEIL) Insurance Standard, or other appropriate insurance standards.	☐		
4.1.45	DETERMINE the impact of the design change on System Vulnerability.	☐		
4.1.46	IDENTIFY changes to the plant, both permanent and temporary, that potentially impact the switchyard or the interconnected transmission system. Communication and coordination of these plant changes with the applicable transmission entities is a requirement of the mandatory NERC Reliability Standards.	☐		
4.1.47	IDENTIFY potential impacts on safety related motor operated valves and the Constellation MOV Program.	☐		

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Section	**Design Change Attribute**	**Appli cable**	**Tracking of Action**	**References (optional)**
4.1.48	DETERMINE the effect of the Configuration Change on Dry Cask Storage.	☐		
4.4	Configuration Control Activities- Use of CC-AA-102-F-07	☐		
4.5	Determination of Program Impact - Use of CC-AA-102-F-08	☐		