Diagnostic Indicators for Shipboard Mechanical Systems Using Non-Intrusive Load Monitoring

by

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Submitted to the Department of Mechanical Engineering in Partial Fulfillment of the
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and
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ABSTRACT

This thesis examines the use of Non-intrusive Load Monitoring (NILM) in auxiliary shipboard systems, such as a low pressure air system, to determine the state of equipment in larger connected systems, such as the main propulsion engines.

Using data collected on previously installed NILM's at the Naval Surface Warfare Center, Philadelphia DDG-51 Land Based Engineering Site (LBES), major event changes were analyzed and diagnosed using power data collected from the in-service low pressure air compressor (LPAC) and the in-service fuel oil pump. Events investigated include main propulsion engine starts and loadings, gas turbine generators starts, major electrical load shifts, and leak insertions into the low pressure air system.

An additional NILM was installed on the General Electric LM2500 Universal Engine Controller (UEC) in order to assist in the diagnosis of various state changes. The UEC provides the appropriate interfaces to monitor and control each LM2500 GTM. The UEC controls the application of starter air, ignition power, and fuel to the engine while also receiving feedback of engine parameters from sensors on the engine.

Using the combined data received by the LPAC, fuel oil pump, and UEC, a diagnosis system is derived that can detect major events in the engineering plant described above.

Thesis Supervisor: Steven B. Leeb
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Chapter 1 Introduction

1.1 Motivation for Research

1.1.1 *Integrated Power Systems*

In the past several decades, the United States Navy has pushed the designs of its ships and associated subsystems, from propulsion to weapons, more and more into forms that require increasingly large amounts of electrical power for usage. These increasingly electrified naval loads in turn have directed the course of much naval research into better and more efficient ways to generate and distribute this electrical power. The current solution to this problem for modern naval vessels is an Integrated Power System (IPS). An Integrated Power System permits the operator to distribute power between propulsion and other electrical loads as desired. This allows for increased power available for non-propulsion uses, higher levels of automated control, greater flexibility in arrangement of internal spaces, increased opportunity for modular design, and the ability to distribute electrical power between subsystems on command [1].

Traditional ship engineering plant designs generate power for two basic purposes – main propulsion engines that mechanically drive propeller shafts, and electrical generators. The generators provide the necessary electrical power to operate the vast majority of equipment onboard a vessel. As modern ship designs include more and more items with larger and larger electrical requirements, and larger motor designs become more and more advanced, ships are being designed with electric drives. This is a major keystone in the overall arch of benefits provided by an IPS. With *all* power requirements onboard a vessel met by electrical generators, naval vessels can now use this "pool of electricity" to conduct all necessary operations, both combat and general service, via a switching architecture [1].

1.1.2 *Reduced Manning*

In 1995, the Chief of Naval Operations requested that the National Research Council's Naval Studies Board conduct an 18-month examination of the impact of technology on the form and capability of the naval forces until the year 2035. A Panel on Human Resources was convened to address specific issues of the overall inquiry. One of the topics of scrutiny for the Panel on Human Resources was the idea of reducing the manning of ships at sea [2].

Fiscal requirements stimulate the Navy to build ships with smaller crews that can still perform the same or a larger number of operational missions. Implicitly, ships of the future must have an increased capability to conduct these operations. Fortunately, technological advances make the fulfillment of both these objectives, reduced manning on an increasingly capable platform, possible. The Navy has had success throughout the past several decades in accomplishing these requirements, as seen in Figure 1-1 below.

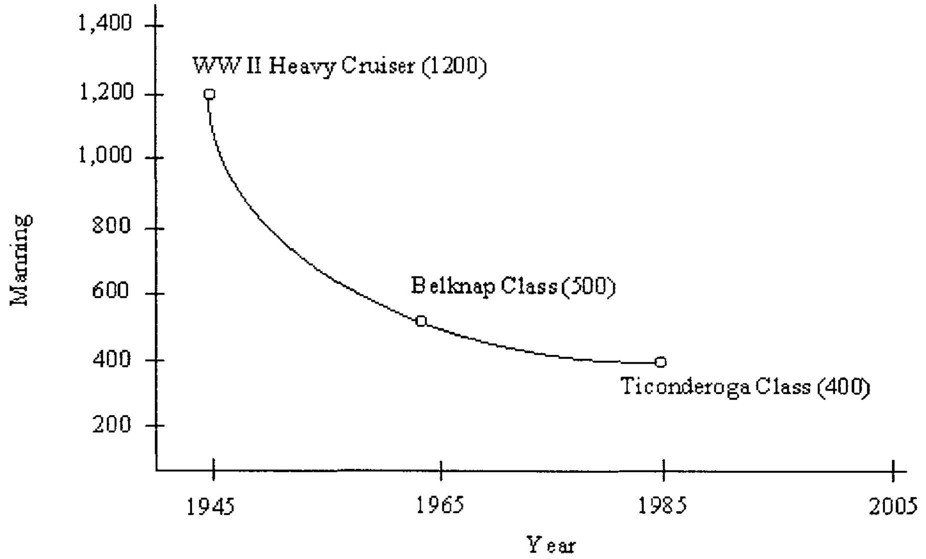

Figure 1-1: Manning Levels on a 10,000 ton Cruiser, 1945-1985.[1]

It is expected that the Navy can reduce manning on a 10,000 ton cruiser to roughly 325 personnel by approximately 2005 [2]. An important part of reducing manning is automation. Military operations of the future will require decision and information superiority. Knowledge-based computerized aids will help sailors make the right decision at the right time. "The Navy will have little choice other than to automate functions because the reaction times necessary can only be accomplished by machines (the human will be the least reliable and the slowest part of the system)"[3].

---

[1] SOURCE: Adapted from Glover, CAPT Greg, U.S. Naval Sea Systems Command (PMS 400 FSS), and Robert Bost, Naval Surface Warfare Command, Carderock Division, "Smart Ship," briefing to Panel on Technology, August 5, 1996.

1.1.3 *Condition Based Maintenance*

The reduction in manpower onboard naval vessels is expected to require maintenance providers to accelerate their repair processes and to enhance the reliability of the systems for which they are responsible. To assist in this endeavor, the Navy has begun to shift its maintenance policy from a Preventative Maintenance System (PMS) to one of Condition Based Maintenance (CBM). In a preventative system, maintenance is performed at regular intervals to help ensure that equipment does not fail by conducting repair, service, or component exchange. In a condition based system, the need for maintenance is not determined strictly by schedule, but by examining the equipment and making a determination if maintenance is required or not. This type of system lends itself to the use of automation to assist in the examination of equipment [4].

The first step in this shift is the development and fielding of the Integrated Condition Assessment System (ICAS) already in use on multiple vessels in the US fleet. ICAS is a monitoring system that uses the CBM methodology to reduce the amount of preventative maintenance operations required by the ship crews themselves while simultaneously providing data to shore-based maintenance providers. The shore-based providers can then individually tailor their maintenance plans to suit the needs of vessels. The success of this system depends largely upon the reliable information gathered from individual sensors installed on the vessel's equipment.

1.1.4 *The Non-Intrusive Load Monitor as Part of the Solution*

As a result of the above considerations, a possible solution to part of this combined need is the Non-Intrusive Load Monitor (NILM), which is a device that can determine the operating schedule of all of the major loads on an electrical service. The main utility of the NILM is that it can use its electrical measurements to assess the state of many electromechanical loads. Additionally, the NILM can perform numerous supervisory control functions [5], [6], [7].

1.2 Non-Intrusive Load Monitoring Onboard Ships

The Non-Intrusive Load Monitor (NILM) was developed at the Massachusetts Institute of Technology (MIT) Laboratory for Electromagnetic and Electronic Systems (LEES). The NILM uses the voltage and current supplied to the target item to calculate power envelopes for that item. These envelopes are time-varying estimates of frequency content and have been used for power system monitoring and diagnostics for several years. Spectral envelopes are defined formally as:

$$a_m(t) = \frac{2}{T}\int_{t-T}^{T} x(\tau)\sin(m\omega\tau)d\tau \qquad (1)$$

$$b_m(t) = \frac{2}{T}\int_{t-T}^{T} x(\tau)\cos(m\omega\tau)d\tau \qquad (2)$$

These equations are Fourier-series analysis equations evaluated over a moving window of length T. The coefficients $a_m(t)$, $b_m(t)$ contain time-local information about the frequency content of the quantity $x(t)$. In a steady-state AC power system, these coefficients have a very useful physical interpretation as real, reactive, and harmonic power when $x(t)$ is the measured current and the basis terms $\sin(m\omega\tau)$ and $\cos(m\omega\tau)$ are synchronized with the voltage [8]. By examining the transient behaviors in the spectral envelopes, spectral envelope features can be correlated to the specific physical function or task that the item is performing, and thus the envelopes can be used to identify individual loads. An example of this is shown in Figure 1-2.

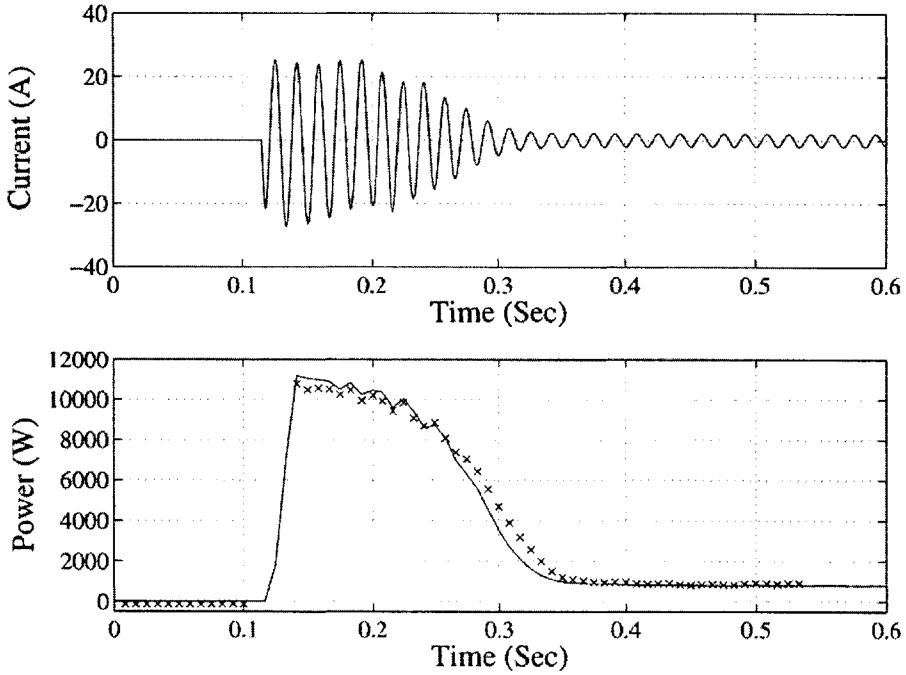

Figure 1-2: Measured current and computed power during the start of 1.7hp vacuum pump motor. Also shown in the power plot is a section of the template that has been successfully matched to the observed transient behavior.

Placement of a NILM at an aggregate location allows for analysis of multiple transients, and thus can "fingerprint" multiple loads. The NILM, installed in only a single point at an upstream feed, can detect and classify multiple loads downstream of the feed, such as lights and motors [9], [10]. When installed in an automobile, the NILM can identify the use of electromechanical equipment from measurements made at the alternator alone [11].

The NILM can be easily adapted for shipboard uses. The NILM itself is constructed of a relatively few, commercially available components, thus making it very inexpensive. Because it has the potential to differentiate and diagnose multiple loads downstream of the entry point, it can reduce the number of sensors required in a system. Fuel oil pumps, air compressors, sewage pumps, reverse osmosis plants and seawater pumps have all been targeted by NILM's [5-7]. The diagnosis of these systems via the NILM has yielded encouraging results. The NILM has had success as a detector for the state or status of various electrical loads (pump on/off, etc.). An example is shown in Figure 1-3.

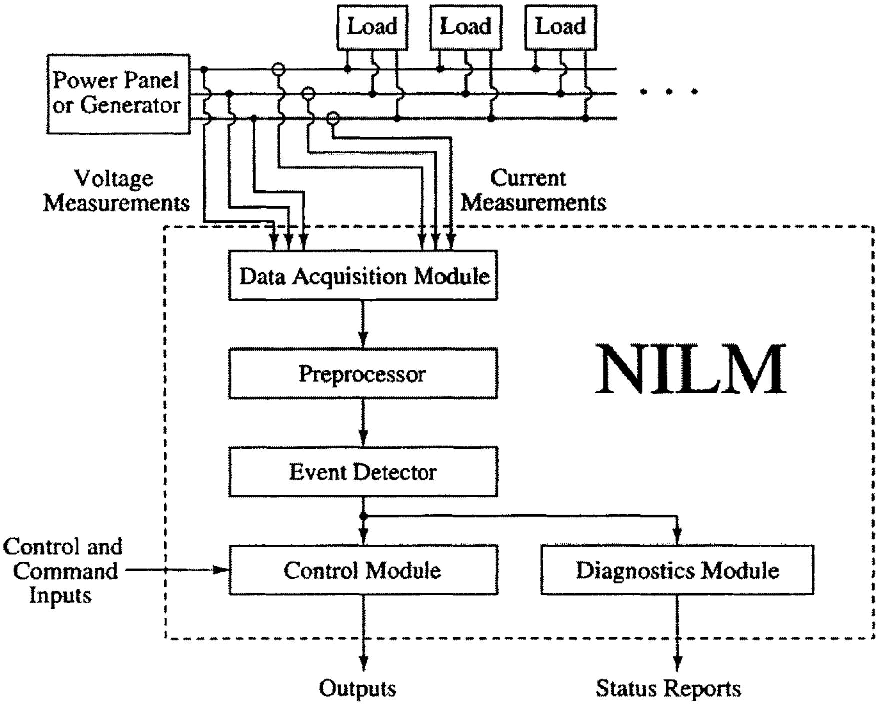

Figure 1-3: Diagram showing the fundamental signal flow path in a NILM. The status report generated by the diagnostics module is sent electronically to the ship's Engineering Officer.

1.3 The NILM as a System Diagnostic Tool

The capability of a NILM should not be limited simply to determining the on/off status of various electrical loads however. Additional diagnosis and analysis of status changes among targeted electrical loads yields even more information about their combined operation and can be utilized to detect the status or condition of not just *individual* components and loads, but an entire *system*, such as leaks in a sewage piping and components [6], [16].

This thesis will explore the capability of a NILM to act as a diagnostic tool of integrated systems in a naval engineering plant. Three NILM's installed in the US Navy's DDG-51 engineering test site in Philadelphia, Pennsylvania were used to diagnose and to determine state changes of various large shipboard components. Through a relative few entry points in components in the engineering plant, the capability may exist to determine status of systems mechanically connected to the NILM-targeted equipment, but with no direct electrical connections.

Chapter 2 Shipboard Systems

Currently, several NILM devices are installed at the Navy's DDG-51 Land Based Engineering Site (LBES) located at the Navy's Surface Ship Engineering Complex in Philadelphia, Pennsylvania. Using these devices, testing and development of a NILM can be conducted in an environment that very much approximates an actual ship.

2.1 The Land Based Engineering Site (LBES)

The LBES, which is housed in a former naval aircraft assembly building, consists of a full-scale replica of part of the engineering plant of a DDG-51 class destroyer (Figure 2-1 and Figure 2-2). This facility is primarily used as a testing and evaluation platform for new equipment and software, and it is also used to conduct routine crew training certifications [5]. Effectively, the LBES provides both engineering support and overall life cycle management for in-service US Navy destroyers.

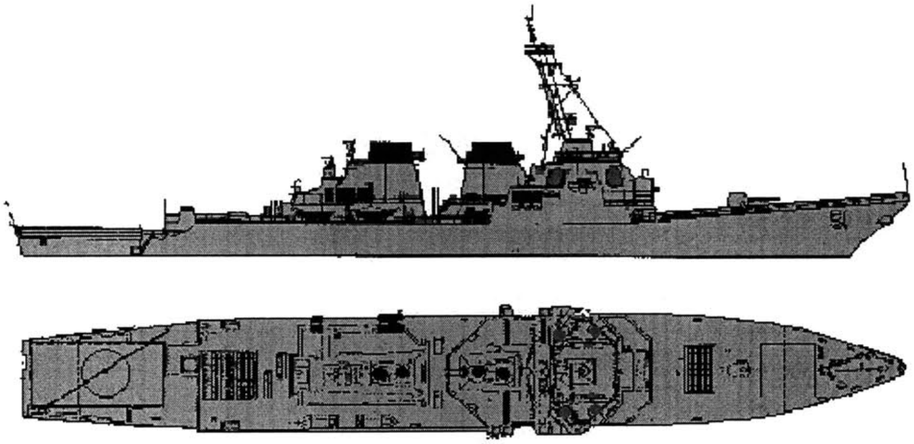

Figure 2-1: US Navy DDG-51 Arleigh Burke-Class Destroyer

The LBES replicates the equipment and operations of the Number Two Main Engine Room of a US Navy DDG-51 Flight I (ARLEIGH BURKE Class) Destroyer. Thus, the LBES consists of multiple levels constructed in the same scale as an actual engine room onboard a ship. Major pieces of equipment pertinent to this research include the following:

- Two LM2500 Gas Turbine propulsion engines (GTM's)
- Three Gas Turbine Generators (GTG's)

- Auxiliary systems to include fuel oil, lube oil, low pressure air, and cooling water
- A full zonal electrical distribution system
- Main reduction gear, shafting, and bearings

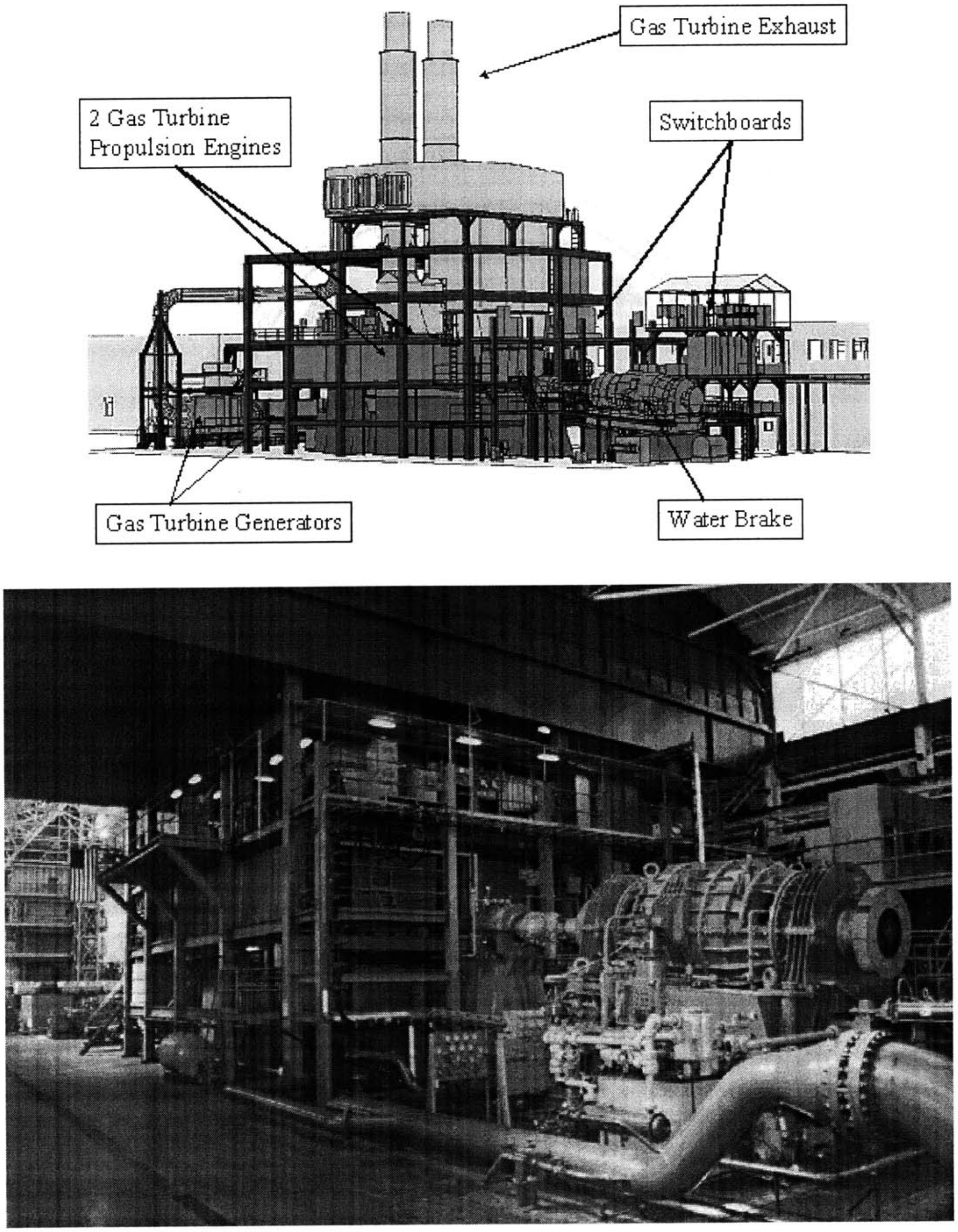

Figure 2-2: DDG-51 Land Based Engineering Site (LBES)

There are several notable differences between the LBES and a typical DDG-51 engineering plant. For instance, A DDG-51 class destroyer has four propulsion engines and two shafts. By contrast, the LBES supports two engines and one shaft. Due to its land-based nature, the LBES has no propeller mounted on the end of its shaft; instead, a 50,000 horsepower waterbrake provides the necessary mechanical load. For electrical power, the LBES is supplied by a regional utility, thus preventing the facility from needing to obtain all of its electricity from its own GTG's. Also, any shipboard systems that normally rely on seawater for cooling instead use shore-based fresh water. Additionally, high pressure air systems are not in place at the LBES. Various habitability and support systems are likewise non-existent at LBES, such as refrigeration, sewage, fire main, etc.

The LBES is arranged on five platforms. The platform names and the major features on these platforms are indicated in Table 2-1. Remaining auxiliary and support features (e.g. piping, cabling, etc.) are distributed among the platforms.

Table 2-1: LBES Equipment by Platform

Platform Name	Major Features and Equipment
Ground Level (or Pad Level)	Waste Oil Collection and #1 and #3 GTG's
7-foot Level	Fuel and Lube Oil Pumps
14-foot Level	Both GTM's, #2 GTG, Air Compressors
23-foot Level	Shaft and Propulsion Control Station
32-foot Level	Major Switchboards and Breakers

Control stations at the LBES are established in various locations. Central Control, which is located inside the LBES administrative building, contains control stations for the electric distribution system (e.g. the Electric Plant Control Panel (EPCP)) and the main propulsion system (e.g. the Propulsion Plant and Auxiliaries Control Panel (PPAC)). The features provided at these two stations allow operators to control the GTM's, the GTG's, the main electrical distribution breakers, and the waterbrake system. Additionally, the EPCP and PPAC indicate the status of many other systems throughout the LBES. In the LBES plant itself, a Shaft Control Unit (SCU) is located on the 23-Foot Level. Although this station allows control of only the GTM's and the waterbrake, it still indicates the status of all of the same sensors and systems as the PPAC. The SCU does not allow an operator to control the GTG's or any other electrical distribution system equipment. Finally, each GTG has a Full Authority Digital Control (FADAC) unit, which is a touch-screen panel located on the exterior of the turbine module. This allows a local operator to perform control functions for the GTG itself, but not any other electrical distribution system equipment. A summation of this control equipment is indicated in Table 2-2.

Table 2-2: LBES Main Control Stations

Control Station	Function	Location
Propulsion Plant and Auxiliaries Control (PPAC)	Control and indications for both GTM's	Central Control
Electric Plant Control Panel (EPCP)	Control and indications for the electrical distribution system, associated breakers, and all GTG's	Central Control
Shaft Control Unit	Control and Indications for both GTM's	23-Foot Level
Full Authority Digital Control Units (FADAC's)	Control and indication for individual GTG	At each GTG

2.2 Main Propulsion Engines

The DDG-51 LBES houses two General Electric LM2500 Propulsion Gas Turbine Modules (GTM's). Some basic specifications for the LM2500 Propulsion GTM's are given in Table 2-3. The primary purpose of these GTM's is to generate mechanical power and to transmit it through a high speed flexible coupling shaft (HSCS) to the LBES's main reduction gearbox (MRG) and shaft [12]. As shown in Figure 2-3, the GTM's at the DDG-51 LBES include four major components. These components are the following:

- The Base Enclosure Assembly (BEA)
- Gas Turbine Assembly (GTA)
- Lube Oil Storage and Conditioning Assembly etc
- Interim Integrated Electronic Control (replaced by a Universal Engine Controller at the LBES)

Table 2-3: LM2500 Propulsion Gas Turbine Module

Model	LM2500 Propulsion Gas Turbine Module
Manufacturer	General Electric
Full Power Rating	26,250 BHP
Power Turbine Speed	3600 RPM
Max Specific Fuel Consumption	0.40 lb/bhp-hr

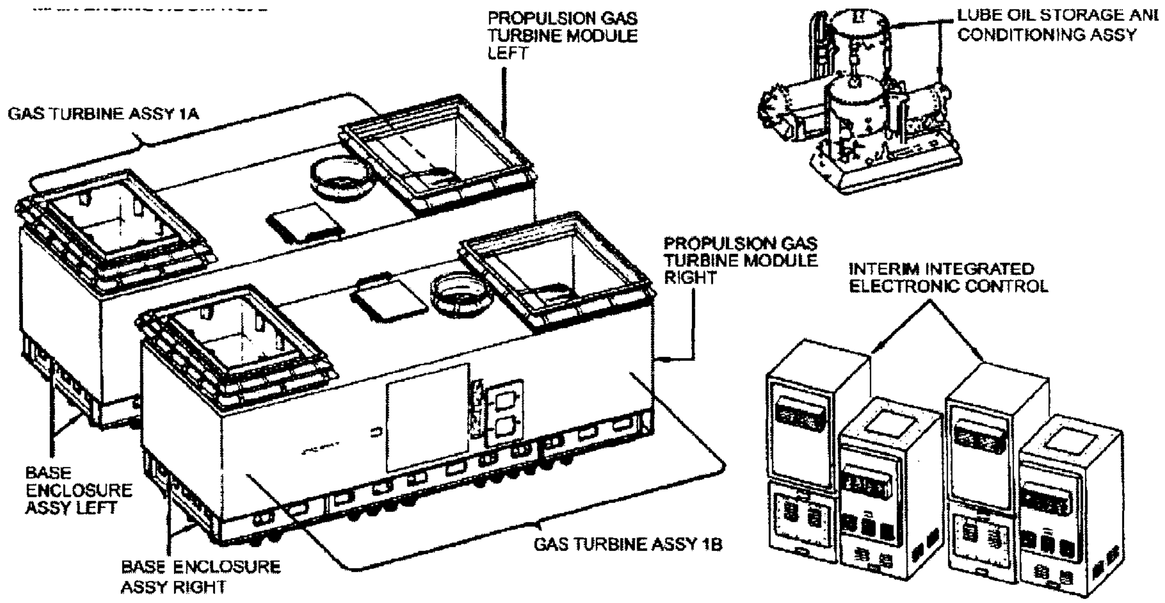

Figure 2-3: LM2500 Gas Turbine Module General Arrangement from Reference 12

The Base Enclosure Assembly (BEA) provides physical support and thermal and acoustic isolation for the Gas Turbine Assembly (GTA), as well as connections for electrical, liquid cooling, fire extinguish, etc. The GTA is the prime mover for the overall GTM, providing the mechanical power needed to drive the shaft. A photograph of the GTA is shown in Figure 2-4 and a cutaway view is shown in Figure 2-5.

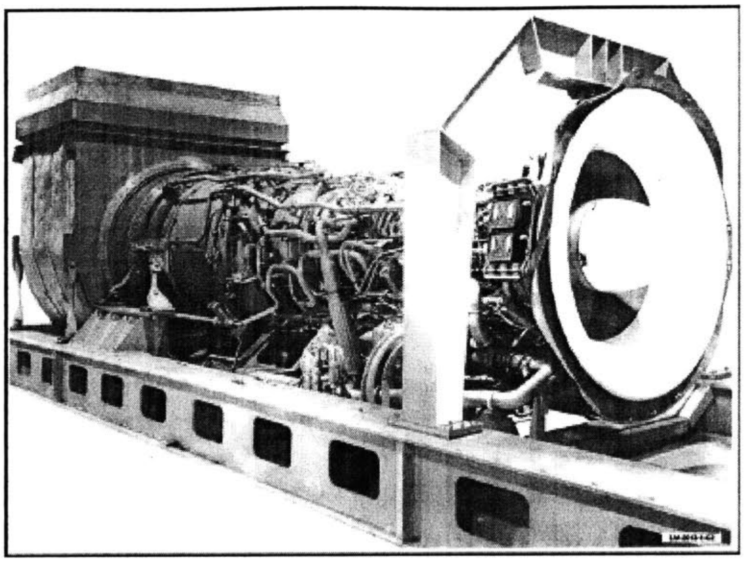

Figure 2-4: LM2500 Gas Turbine Assembly (Exterior View) from Reference 12

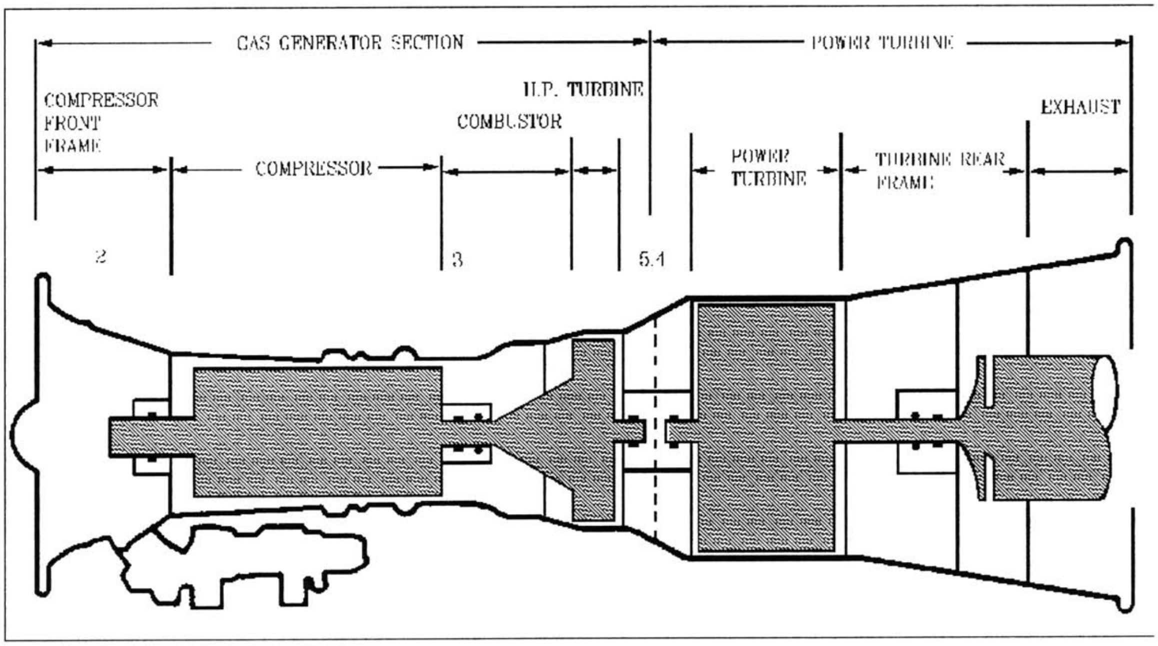

Figure 2-5: LM2500 Gas Turbine Assembly (Cutaway View) from Reference 12

Various minor support functions for the GTM, such as internal cooling, require pressurized air. An easy method to acquire this air is to "bleed" it from the GTA itself. Bleed Air valves are located on the 8th, 9th, 13th and 16th stages of the GTM compressor. When open, these valves allow pressurized air to vent off the compressor. The valves for the 8th, 9th and 13th stages supply air for use inside the GTM. Air from the 16th stage can be directed to the Bleed Air header.

The Lube Oil Storage and Conditioning Assembly (LOSCA) provides cooled lube oil for proper operation of the GTA. The Universal Engine Controller (UEC) replaces the Interim Integrated Electronic Control at the LBES, yet still performs the same functions as the Interim Integrated Electronic Control. The UEC provides command, control, status, protection, alarm and test features for the GTM's. An example of how these items are integrated physically and functionally is shown below in Figure 2-6.

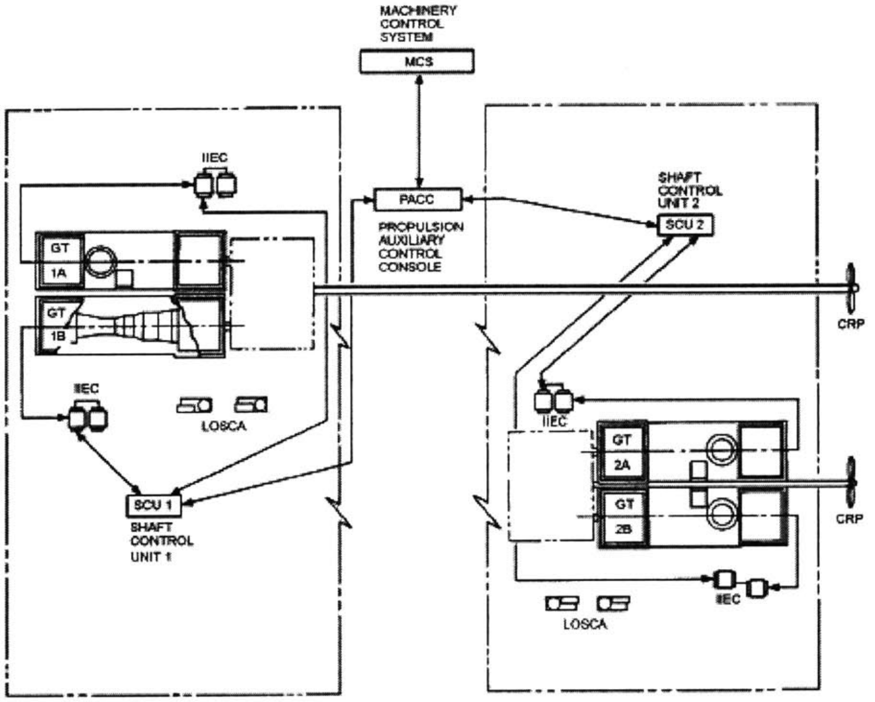

Figure 2-6: GTM Equipment and System Integration from Reference 12

As indicated above in Figure 2-6, two LM2500 GTM's provide power for one shaft. The LBES, because it is designed to replicate Engine Room Number Two on an actual ship, refers to its two GTM's as "2A" and "2B". They are arranged at the LBES on the 14-Foot Level as indicated above (i.e., side by side).

2.2.1 *Universal Engine Controller (UEC)*

The UEC is essentially the "nervous system" for the GTM. As noted above, each GTM has its own UEC. The UEC provides the appropriate interfaces to monitor and control each

LM2500 GTM from a single location (see Figure 2-7). Using information provided from the numerous sensors that monitor the status of the engine, the UEC can automatically control the application of starter air, ignition power, and fuel. The UEC interfaces with the Shaft Control Unit (SCU) in order to provide real-time engine status information and to accept operator input commands [13].

The UEC receives 115VAC power (both single phase and 3-phase) from the LBES power distribution system. A power module inside the unit converts the 3-phase AC input into various AC and DC voltages. These output busses provide power to several key actuators associated with the GTM, including the igniter and many solenoid-controlled valves. For example, a 28V DC bus generated by the UEC's power module is used to operate various solenoids in the GTM system. The key bus voltages in the UEC are given in Table 2-4.

Table 2-4: Universal Engine Controller Data

Manufacturer	Lockheed Martin
Primary Input Power Source	115VAC, 60 Hz, 3-phase
Internal Power Supplies	+5VDC, ±15VDC, +28VDC

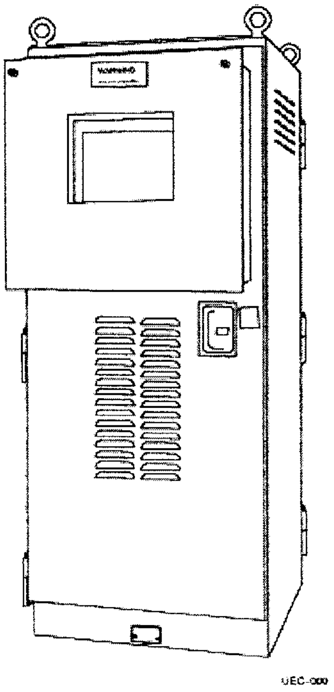

Figure 2-7: Universal Engine Controller (Exterior View) from Reference 13

2.3 Electrical Power Generators

To simulate shipboard electrical power generation and distribution, the LBES supports three gas turbine generators (GTG's). These GTG's are housed in modules similar to the GTM's. GTG locations and types are indicated below in Table 2-5.

Table 2-5: Gas Turbine Generators at the LBES

GTG Label	Location	Gas Turbine Engine Type	Generator Manufacturer and Rating
#1 GTG (Unit 9140)	Ground Level	Allison 501-k34	Kato 3000 KW
#2 GTG (Unit 9130)	14-Foot Level	Allison 501-k34	Kato 2500 KW
#3 GTG	Ground Level	Allison 501-k17	Stewart Stevens 2500 KW

Similar to the GTM's, the GTG's have bleed air valves. These valves are located on the 5th, 10th, and 14th stages of the GTG compressor. They are used to prevent stalls during a start sequence by venting air out of the compressor. Additionally, air from the 14th stage supplies the Bleed Air header.

Onboard an actual ship, the output of the generators feeds directly into the shipboard electrical distribution system (as these GTG's are the sole electrical power source for the ship). However, at the LBES, the output of the GTG's is directed to 4,000 KW load banks to simulate the electrical loads found onboard a ship. The power for the LBES electrical system comes from a standard utility. This allows the LBES to conduct testing of various pieces of equipment and equipment lineups without relying on operation of the GTG's to provide the necessary electrical power.

The #3 GTG is used only infrequently. The majority of operations requiring GTG's are conducted with #1 and #2 GTG's. The #1 and #2 GTG's are often referred to as Unit 9140 and Unit 9130, respectively. The difference between units 9130 and 9140 is not just their generator ratings, as indicated above. Another major feature that distinguishes the two is the installment of a Rapid Independent Mechanical Starting System (RIMSS) on Unit 9140.

2.3.1 *Gas Turbine Generator Start Systems*

The RIMSS has been developed fairly recently (in the past decade or so) to assist in providing a safer and more efficient method for starting GTG's. In earlier designs, the GTG's and GTM's are both started using a "Start Air" system that supplies pressurized air at approximately 75 psig to motor and start the GTG's and GTM's. This start air is supplied from cooled bleed air, which in turn is supplied via Bleed Air valves on the GTM's and GTG's, as shown in Figure 2-8. As discussed above, the valves that supply the Bleed Air header are located on the 16th stage for GTM's and on the 14th stage for GTG's. If no turbines (either GTG's or GTM's) are in operation to provide this air, then start air is supplied by an Auxiliary Power Unit (APU) located above each GTG module [14]. The APU is a miniature gas turbine engine whose pressurized gas output is directed to the bleed air header.

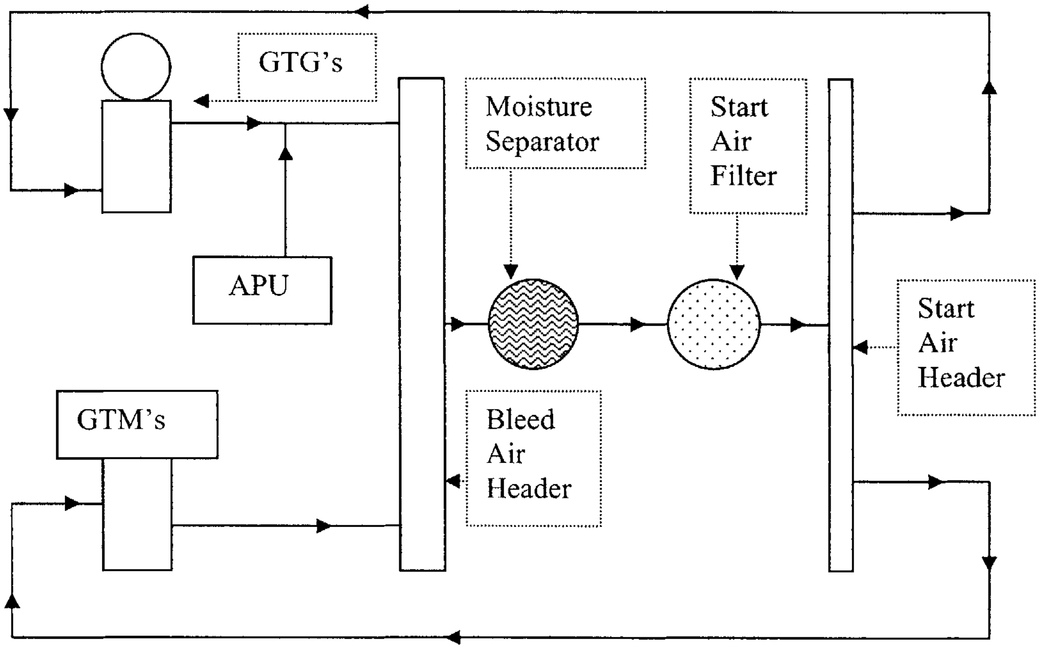

Figure 2-8: Bleed and Starter Air Block Diagram

For overall reliability and increased efficiency, it was decided to remove the requirement for the GTG's to use air to start. Thus, the RIMSS was designed. The RIMSS consists of a small gas turbine engine housed within the GTG module. The power to start the RIMSS is supplied by a DC voltage source, and the mechanical output of this RIMSS engine is linked to the shaft of the GTG engine, as shown in Figure 2-9. At the LBES, this DC voltage source is a battery supply located outside the Unit 9140 module. Upon starting a GTG with the RIMSS, the operating GTG in turn supplies bleed air that can be used to start all other gas turbine engines (GTG's and GTM's). The advantage of the RIMSS lies in its independence from an air system to start a GTG as seen above. In case of a ship casualty that resulted in a large leak in the bleed/start air system, GTG's can still be brought online and used to generate electrical power.

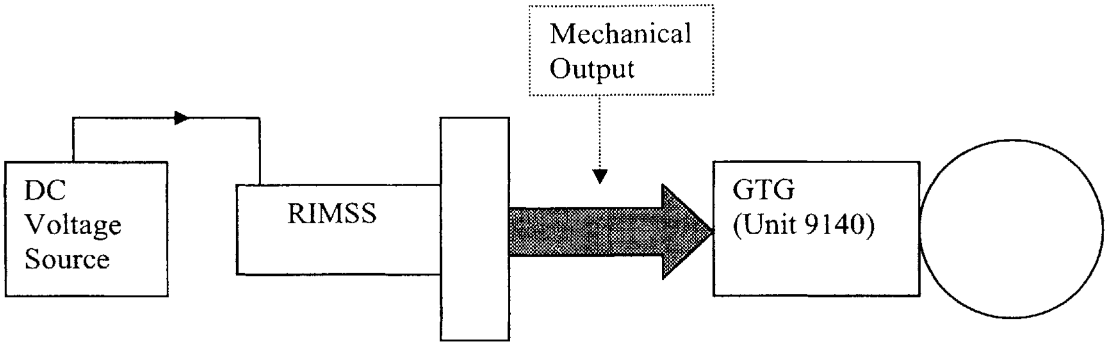

Figure 2-9: Block Diagram of GTG Start Using a RIMSS

2.4 Low Pressure Air System

The low pressure air system at the LBES provides clean, dry, low pressure air throughout the plant for service, control, and pneumatic power [5]. The LBES can generate this low pressure air via two methods:

1. A building facility low pressure air generation system with associated air flasks, referred to as "shop air" or "facility air", which maintains approximately 95-110 psig.
2. Low Pressure Air Compressors (LPAC's) installed in the LBES similar to those installed on a ship which maintain approximately 110-125 psig. Figure 2-11 indicates associated components of the LPAC.

The two systems are cross-connected, but can be isolated if desired. A simplified schematic of the relation between shop air, the LP air system, and the bleed/start air system is shown in Figure 2-10. A full schematic of the LBES air systems is shown in Appendix D.

For typical operations at the LBES, shop air is aligned to supply the Start Air header, and Bleed Air isolation valves for the GTM's and GTG's are shut. In this configuration, shop air is in parallel with the LP air system, and thus can supply LP air as well if pressure drops too low and cannot be maintained by the LPAC. Note that when the Start and Bleed Air systems are fed directly from shop air, they operate at shop air pressure: 95-110 psig. This is different than onboard an actual ship, where bleed air from turbines is regulated down to approximately 75 psig.

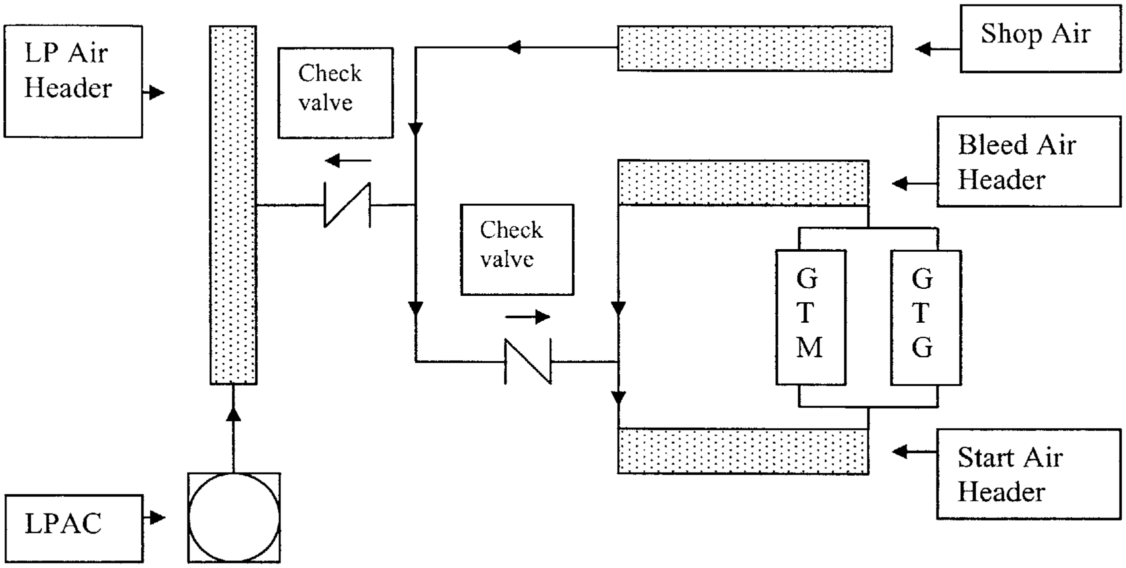

Figure 2-10: Low Pressure Air system relationships at the LBES. Shop air typically operates at 95-110 psig, and the LPAC maintains the LP Air header at 110-125 psig.

When shop air is isolated, the Bleed Air isolation valves are opened and Bleed Air regulating valves maintain Bleed Air header pressure at 75 psig. The Bleed Air header then provides start air as discussed in Section 2.3.1 above. Note that due to check valves, the LP air system cannot supply the Bleed/Start Air system, and the Bleed/Start Air system cannot supply the LP air system.

There exists a subsystem of the LP air system termed "control air". Control air is used to provide pneumatic power to operate various valves throughout the LBES. The specific components of interest in this thesis that use control air are:

- GTM Bleed Air regulating valves
- GTG Bleed Air regulating valves
- GTM Motor regulating valve (to be discussed in Section 2.6.2)

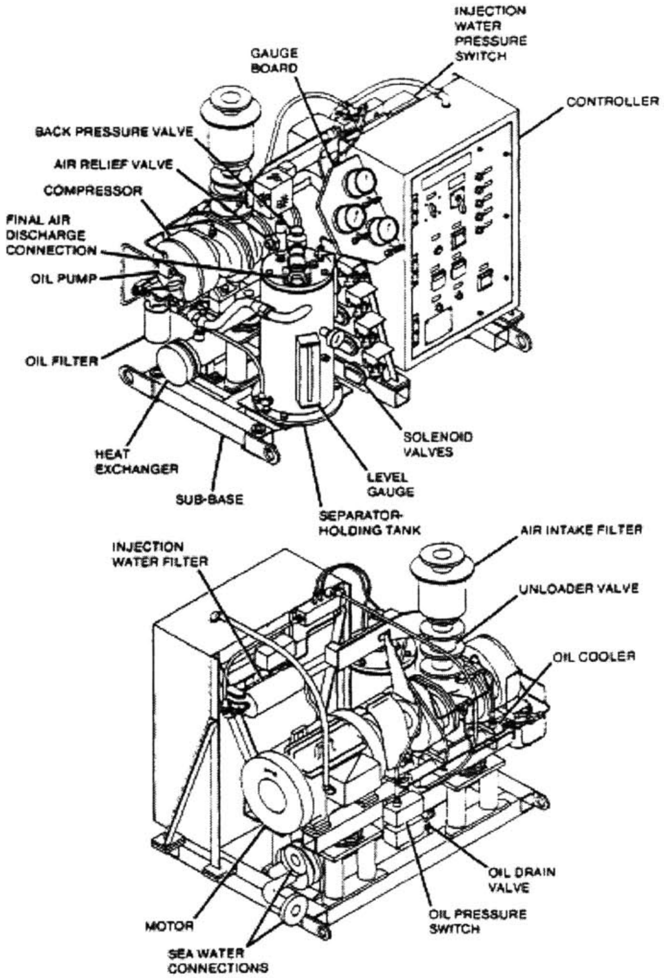

Figure 2-11: LBES Low Pressure Air Compressor from Reference 15

The general flow path for the system while an LPAC is in operation is as follows [14]:

1. The LPAC takes suction on the atmosphere via the system air intake on the 14-Foot Level, in the vicinity of the compressor itself.
2. The air is charged up to approximately 125 psig, and then discharged to the low pressure air service header.
3. The pressurized air passes through a dehydrator which removes moisture and particulate matter.
4. Downstream of the dehydrator is an air receiver that acts as a surge volume to maintain a constant supply of low pressure air for various pneumatic loads.

Reference data for the compressor and its associated motor are listed below in Table 2-6 and Table 2-7 [15].

Table 2-6: Air Compressor Reference Data

Nomenclature	Low Pressure Air Compressor
Model	NAXI 100-4A
Manufacturer	Ingersoll-Rand
Inlet Capacity	100 CFM
Discharge Pressure Settings	115/120/125
Brake Horsepower	28.8 Maximum
Motor Speed	3600 rpm

Table 2-7: Air Compressor Motor Reference Data

Power Requirements	440V, 3-phase, 60 Hz, 35A Full Load
Horsepower	35
Rotor	Squirrel Cage
Speed Class	Constant
RPM Synchronous	3600
RPM Full Load	3535
Torque Class	Design B
Current Class	Design B

Typically, when testing requires the use of an LPAC, only one of the two installed is actually operated. The LPAC is set to automatically maintain header pressure between 110 and 125 psig in the following manner [15]:

1. With the discharge pressure selector switch set to "AUTOMATIC-125 PSIG", the ON/OFF selector is placed in ON.
2. When compressor discharge pressure reaches 125 psig, the compressor will be automatically unloaded by a combination of throttling the air intake and redirecting compressed air from the compressor discharge back to the intake as follows (see Figure 2-12 below):

  a. When the compressor discharge pressure reaches 125 PSIG, the discharge pressure switch actuates the solenoid-operated unloader valve. The solenoid valve opens to recycle discharge air through a bypass line back to the compressor inlet to prevent the continued build-up of pressure in the air receiver.
  b. The opening of the solenoid valve also applies discharge air pressure to the air cylinder operator. The air cylinder piston extends to mechanically shut the butterfly valve located in the compressor intake pipe. Shutting off the air intake to the compressor effectively unloads the unit.
3. The compressor will operate for 10 minutes unloaded and then automatically shut down.
4. When discharge pressure drops below 110 psig, the compressor will automatically be reloaded if the unit is operating unloaded or automatically be restarted and loaded if the unit is shut down.

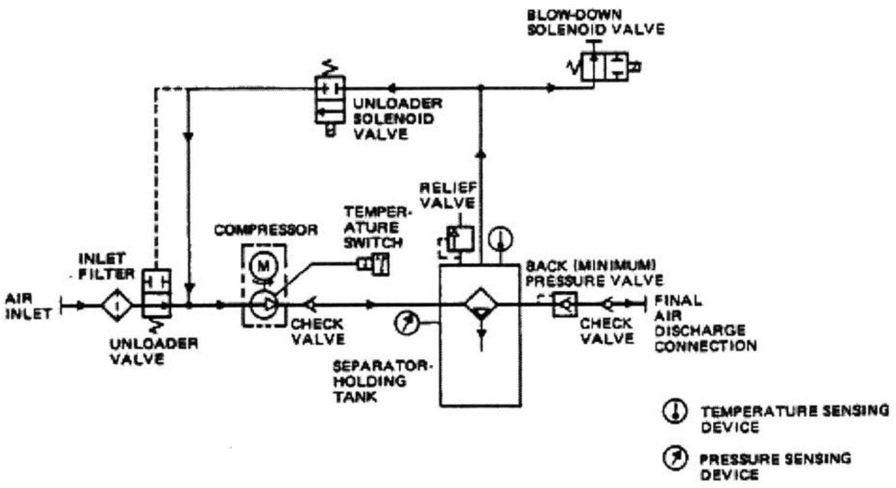

Figure 2-12: Air Compressor Flow Diagram and Unloader System from Reference 15

2.5 Fuel Oil System

The DDG-51 Fuel Oil System installed at the LBES is designed to deliver clean and filtered fuel oil to the GTM's and GTG's at the proper pressures and temperatures. A full schematic of the LBES fuel oil system is shown in Appendix D. The general flow path for the system is as follows [14]:

1. The Fuel Oil Pumps take suction on the 5000 gallon Fuel Service Tank and discharge to the fuel supply header.

2. A pneumatic pilot operated fuel oil unloader valve located downstream of the pump discharge maintains a supply header pressure of 35 psig by sending fuel back through a recirculation line to the Service Tank.
3. Fuel passes through a heater and pre-filters to remove sediment and filter/separators to remove water from the fuel.
4. Fuel is then supplied to the GTM's and the Fuel Oil Gravity Feed Tank. This Gravity Feed Tank supplies the fuel for the GTG's, and any overflow from the Gravity Feed Tank is directed to the fuel oil return header and back to the Service Tank.

Pressure for the fuel oil system is provided by two motor operated pumps, labeled 2A and 2B. Reference data for the pumps and their motors is given below in Table 2-8 and Table 2-9 [17].

Table 2-8: Fuel Service Pump Reference Data

Pump Type	Sliding Vane, Positive Displacement
Capacity	36 GPM in Slow/ 72 GPM in Fast
Pump Speed	~260 rpm in Slow/ ~530 rpm in Fast
Pump Brake Horsepower	2.6
Discharge Pressure	105 psig

Table 2-9: Fuel Service Pump Motor Reference Data

Motor Type	Squirrel Cage Induction
Power Requirements	440V, 3-phase, 60 Hz
Motor Horsepower	3.75 HP in Slow/ 7.5 HP in Fast
Motor Speed	~890 rpm in Slow/ ~1780 rpm in Fast

Typical operation at the LBES requires use of one pump in run with the other in standby, one heater, one pre-filter and one filter/separator. However, a second pump will start when required according to the following logic [14]:

1. With the lead pump in low speed: if header pressure drops below 20 PSIG for two seconds, the standby pump cycles in fast.

2. With pump(s) in high: if header pressure does not recover, or stays below 20 PSIG for 5 seconds, both pumps are commanded to off (this is to remove the pressure source in case of a fuel oil rupture).
3. With pumps in local control, pump logic is disabled.

2.6 Integrated Plant Operations

A naval engineering plant consists of multiple systems, many of which are connected either mechanically, electrically, or both. The main systems of concern for this thesis are listed above. To detect various events that occur in the plant, it is useful to get an understanding of the specific relations and interactions that take place between these systems during certain operations. The specific operations of interest in this thesis are:

- Main Propulsion Engine (GTM) start (i.e. the engine is started but not used to provide propulsion power)
- Main Propulsion Engine (GTM) being placed online (i.e. the engine provides propulsion power to the main reduction gear and shafting)
- Main Propulsion Engine (GTM) motoring (the turbine is spun with air and fuel may be purged)
- Main Propulsion Engine (GTM) normal stop
- Gas Turbine Generator (GTG) start

As stated above in Section 2.1, there are two main locations to control the GTM's: in Central Control with the Propulsion Plant and Auxiliaries Control panel (PPAC) and on the 23-Foot Level at the Shaft Control Unit (SCU) panel. Both panels are almost identical. Commands to the GTM's are performed by pressing illuminated buttons to initiate certain sequences (start, stop, motor, online, fuel purge, etc.) or by adjusting a throttle lever to answer propulsion demands ("bell orders"). In addition, various indications and alarm lights are displayed at the two panels. A simplified diagram of the control buttons is indicated below in Figure 2-13. The dashed boxes indicate labels, and not actual buttons. The solid boxes indicate actual buttons on the SCU or PPAC. Detailed explanations of operations will be discussed later, but a simple example can be given here: to start a GTM, the operator, having ensured all pre-start checks for the GTM were completed, presses the ON button. The UEC and associated control circuitry send the necessary signals to conduct a start sequence for the GTM.

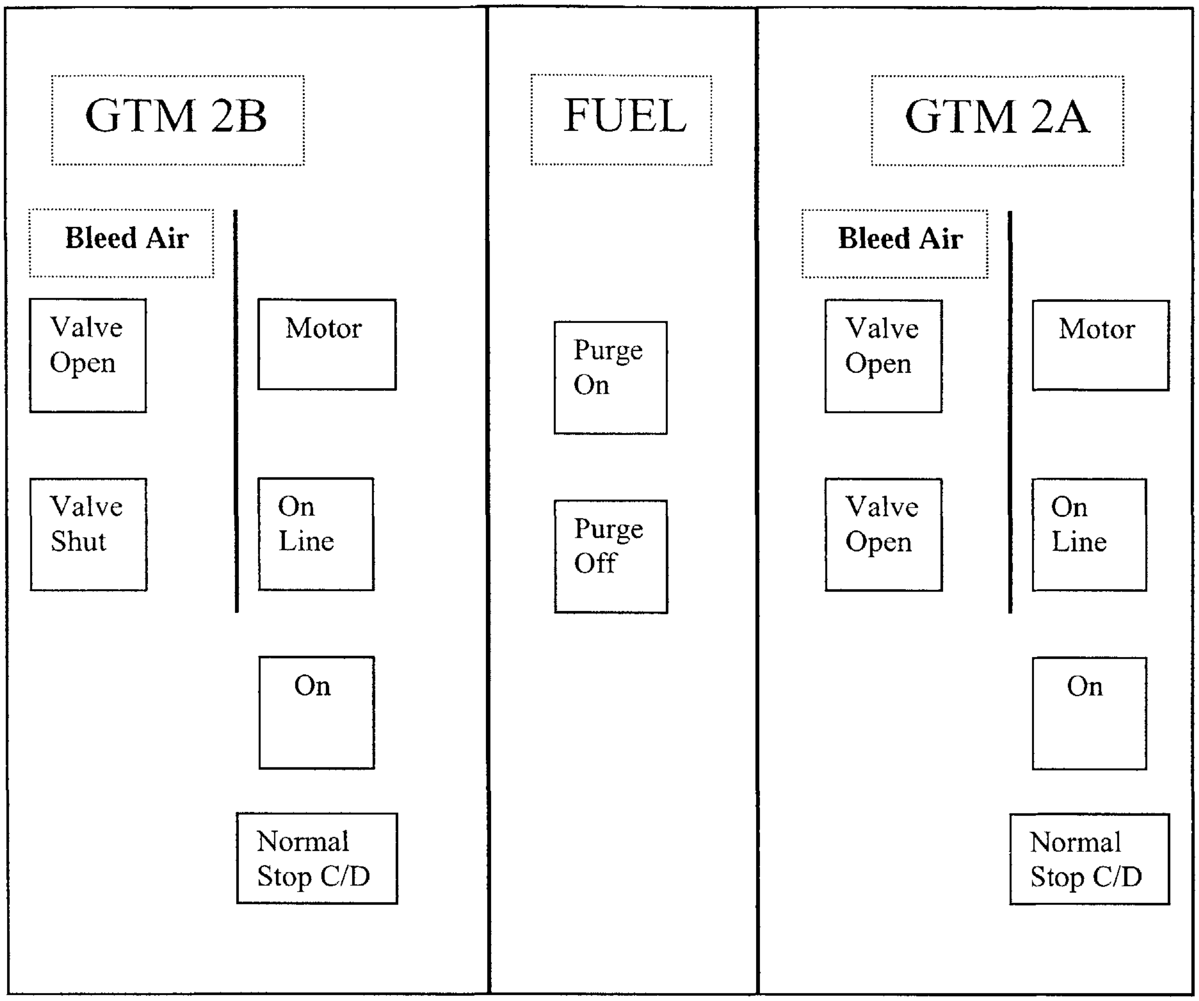

Figure 2-13: Simplified PPAC Panel

Bleed valves were discussed in Section 2.2. The 16th stage bleed valve supplies air to the Bleed Air header. An isolation valve can be actuated to prevent this bleed air from passing to the Bleed Air header. The appropriate buttons on the PPAC control this Bleed Air isolation valve by sending a signal to the UEC. The UEC in turn sends a signal to a 28V DC motor to shut the Bleed Air isolation valve. The Bleed Air isolation valves for the GTM's are normally shut, as discussed in Section 2.4. Recall that Bleed Air isolation valves and Bleed Air regulator valves are two separate components in the Bleed Air system. The remaining GTM functions – Motor, On Line, On, Normal Stop, and Fuel Purges – will be discussed later.

Panel layout and operation for the GTG's are similar. The Electric Plant Control Panel has a display representing the DDG-51 electrical distribution system ("mimic bus") and its associated main breakers and main switchboards. A schematic of this system is given below in Figure 2-14. Standard electric plant operations, such as opening and shutting breakers, or adjusting voltage and frequency, can be conducted using the mimic bus. Additionally, GTG operations similar to those of the GTM's can be conducted at the EPCP, such as start and stop sequences. Controls for all three GTG's are located at the EPCP, but only one is used in the simplified diagram below, Figure 2-15. This is not a diagram of electric plant controls, but simply the GTG controls.

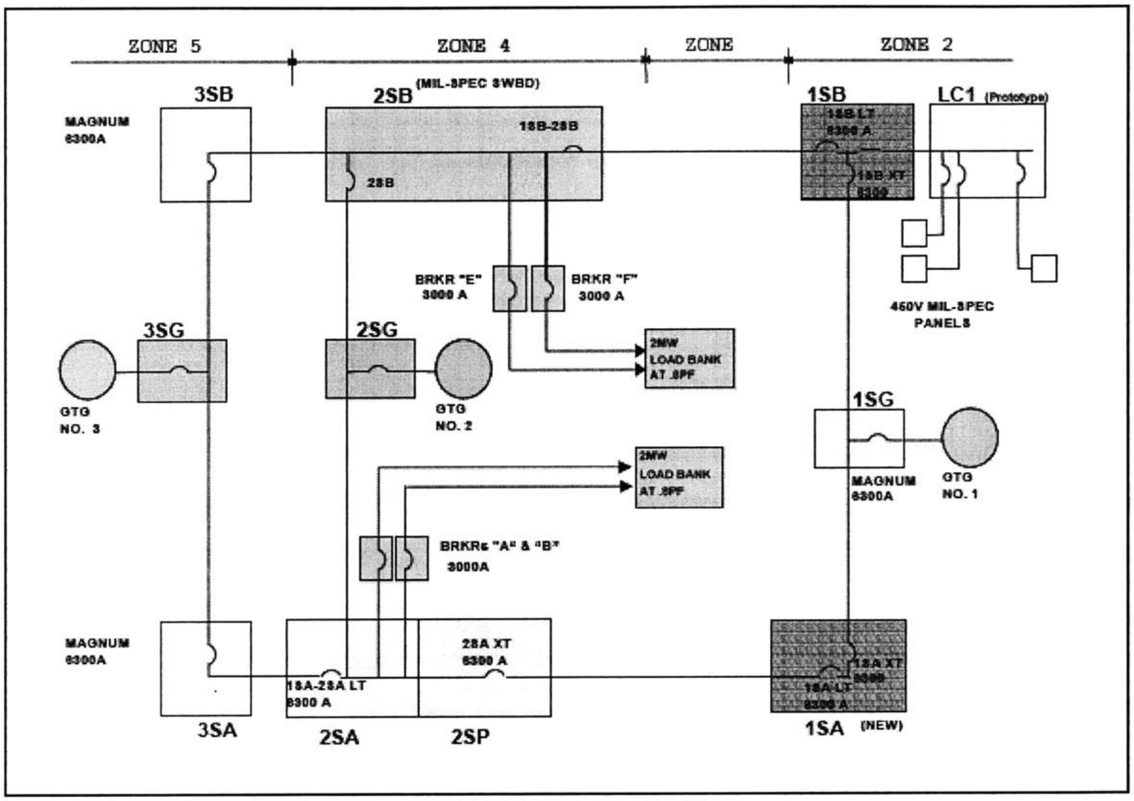

Figure 2-14: LBES Electrical Distribution System

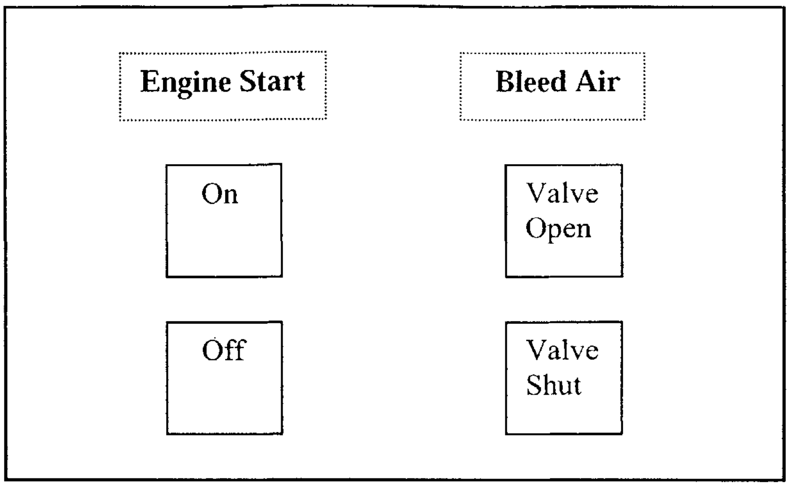

Figure 2-15: Simplified GTG Controls at the EPCP

The Bleed Air valve buttons function similar to the GTM Bleed Air valve buttons for the GTM's. They control the opening and closing of a Bleed Air shutoff valve. Again, the GTG Bleed Air shutoff valves are normally shut as discussed in Section 2.4.

2.6.1 *Main Propulsion Engine (GTM) Start*

The following is a general description of the LM2500 GTM start sequence [12], [18]. It is assumed that the GTM is in proper working condition, all pre-start checks have been completed satisfactorily, and all required auxiliary systems (cooling fans, etc.) are working properly. Expected actions and operations in related systems will be described where applicable.

1. The operator at either the SCU or PPAC presses the appropriate (either 2A or 2B) ON button. The ON pushbutton indicator illuminates momentarily.
2. The UEC receives the ON signal.
3. The UEC energizes the Starter Air Regulating Valve, admitting compressed air into a pneumatic starter in the following manner (see Figure 2-16):
   a. Air from the Start Air header at approximately 95-110 psig continually passes to the inlet of the Starter Air Regulating Valve, and vents through the solenoid switcher ambient vent.
   b. The UEC passes a 28V DC signal to the solenoid switcher, which repositions to shut the ambient vent and port air to the proper side of the Starter Air Regulating Valve diaphragm, opening the valve.

    c. The diaphragm of the Starter Air Regulating Valve positions the valve to maintain 35-41 psig to the inlet of the pneumatic starter.
4. The GTM turbine starts rotating.
5. The UEC starts the following timers:
    a. 20 seconds to reach 1,200 RPM
    b. 45 seconds for engine lube oil pressure to reach 10 psig
    c. 90 seconds to reach 4,500 RPM
    d. If times are exceeded, the UEC will initiate an automatic shutdown. Note: a typical time for the turbine to reach 4,500 RPM is about 50 seconds after the start is initiated.
6. At 1,200 RPM, the UEC commands the following:
    a. Igniters on. A contact closes to send 115V AC single phase power from the UEC (Note this is not the same as the input power to the UEC) to the igniters located in the combustion chamber of the turbine.
    b. Fuel Shutoff valves open. The UEC sends a 28V DC signal to two electrically actuated Fuel Shutoff valves (positioned in series) which open to pass fuel to the GTM fuel nozzles.
    c. If the UEC receives indications of a fuel ignition failure, it will initiate an automatic shutdown.
7. At 4,500 RPM, the following occurs:
    a. The UEC de-energizes the igniters by opening a contact and thus removing 115V AC single phase power.
    b. The UEC shuts the Starter Air Regulating Valve by stopping the 28V DC signal powering the Starter Air Regulating Valve solenoid.
    c. The pneumatic starter disengages.
8. The GTM turbine will now approach idle speed (approximately 5,000 RPM) but its control is disconnected from the throttle. Note that a typical time for the turbine to reach idle speed is 60 seconds after the start is initiated.

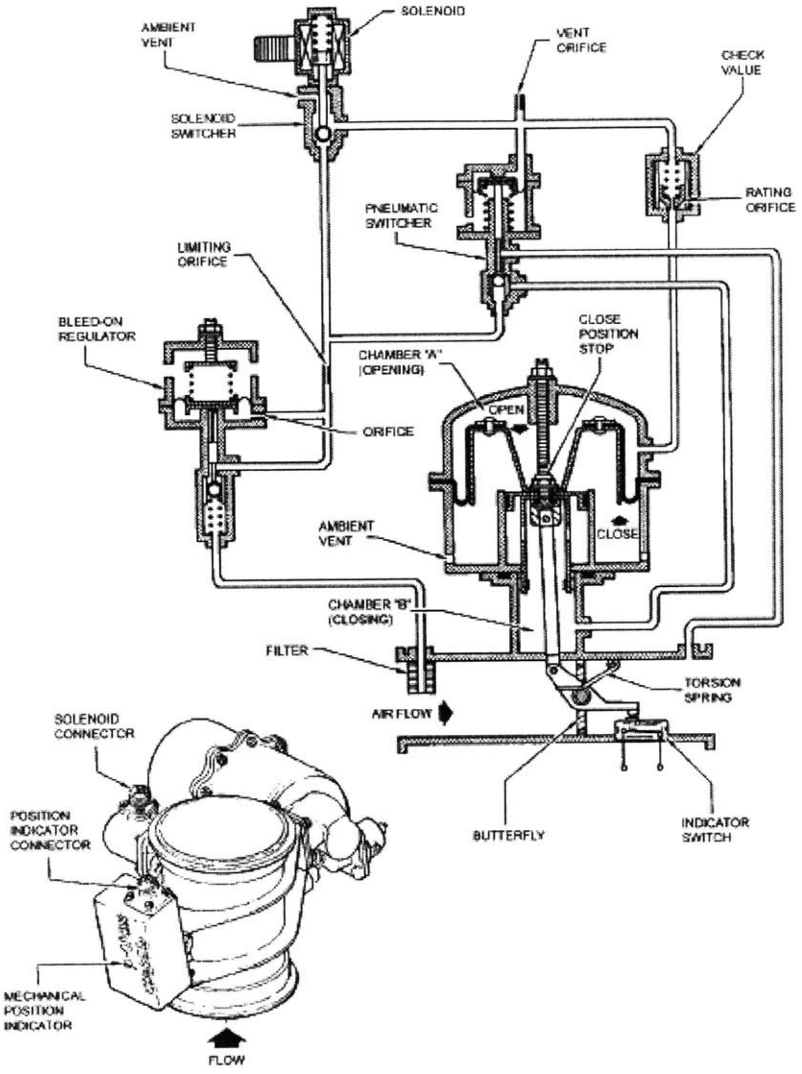

Figure 2-16: Starter Air Regulating Valve from Reference 12

2.6.2 *Main Propulsion Engine (GTM) Motoring/Fuel Purging*

Motoring (fuel purging) is an operation typically performed either for maintenance or when a Gas Turbine Engine has been shut down for more than 14 days [12]. A fuel purge removes approximately three gallons of low temperature fuel from the fuel lines. It is assumed that all pre-start checks have been completed satisfactorily.

1. The operator at either the SCU or PPAC presses the appropriate (either 2A or 2B) MOTOR button. The MOTOR pushbutton indicator illuminates momentarily.
2. The UEC receives the MOTOR signal.

3. The SCU sets air pressure at the inlet of the Starter Air Regulating Valve to 20-22 psig as follows:
    a. A 28V DC signal is sent to the Motor Regulating Valve solenoid, actuating it using control air and directing air from the Starter Air header through a Motor Air Regulating Valve, which uses Control Air (i.e. LP air) to maintain 20-22 psig at the inlet of the Starter Air Regulating Valve. The Motor Regulating Valve is a normally open valve (see Figure 2-17).
4. The operator presses the FUEL PURGE ON button, which illuminates momentarily.
5. The UEC receives the FUEL PURGE ON signal and sends a 28V DC signal to the solenoid-actuated Fuel Purge valve, which opens and purges approximately 3 gallons of fuel.
6. The Fuel Purge valve shuts and the FUEL PURGE OFF button illuminates.
7. The UEC opens the Starter Air Regulating Valve per Section 2.6.1 sending 20-22 psig air to the pneumatic starter. When inlet pressure (~21 psig) to the Starter Air Regulating Valve is less than desired outlet pressure (~35 psig from Section 2.6.1 above), the Starter Air Regulating Valve positions to fully open.
8. The GTM turbine starts spinning, and reaches approximately 1,800 RPM.
9. After 3 minutes, the operator presses the NORMAL STOP button, and the following occurs:
    a. The UEC shuts the Starter Air Regulating Valve by removing the 28V DC signal to the solenoid.
    b. The SCU fully opens the Motor Regulating Valve by removing the 28V DC signal to the solenoid. This operation stops the flow of control air to the Motor Regulating Valve.

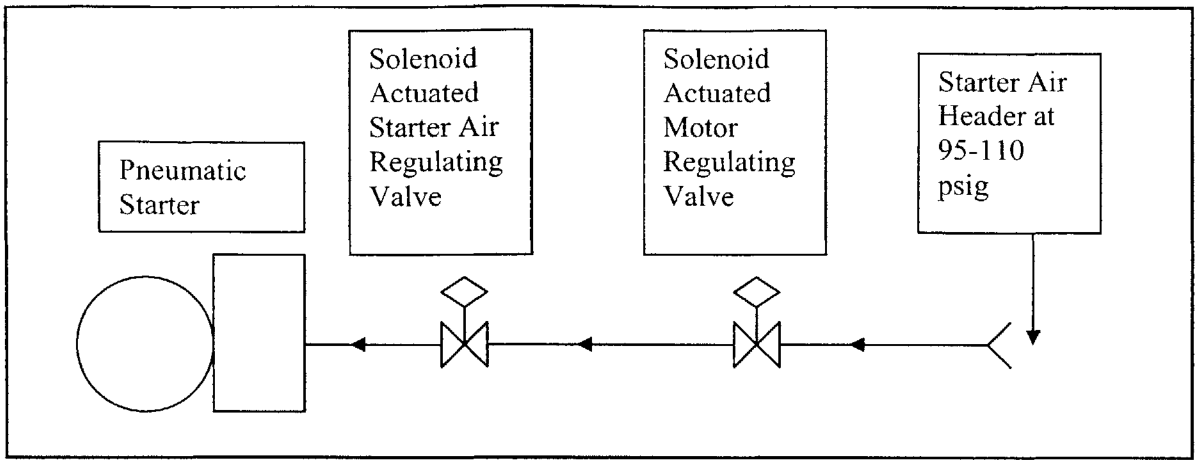

Figure 2-17: Starter and Motor Regulating Valve Locations

Note that fuel purges as written above are not normally performed at the LBES, but they are performed onboard actual ships. At the LBES, the turbines are typically motored with no fuel purging. Motoring effectively lubricates bearings with oil and warms up the turbine for full operation. Motoring operations are typically performed for 1, 2, or 3 minutes as determined by the operator. The motoring procedure is the same as the motor/fuel purge procedure above, except steps 4, 5, and 6 are removed. For future discussions in this thesis, the term "motor" or "motoring" will indicate a motor operation without fuel purging. A motor operation *with* fuel purging will be termed "motor/purge" [12].

2.6.3 *Main Propulsion Engine (GTM) Online*

After being started, a GTM operates at idle speed (4,900-5,100 RPM) but does not provide any mechanical work to the main reduction gear (MRG). In order to accomplish this, the GTM must be placed "online". The SCU sends a command signal to remove a hydraulic brake from the GTM's power turbine, allowing it to accelerate to the power setting determined by the UEC, which is in turn determined by the throttle setting. A synchronized self-shifting clutch system engages the mechanical output of the power turbine to the MRG [14].

The power turbine brake is located between the GTM and the MRG. It is a 1" thick steel rotor with two sets of brake calipers. The brake is actuated by oil and pressurized by low pressure air. The power turbine brake is released when an operator presses the appropriate ON LINE button at either the PPAC or SCU. A mode change from ON LINE to ON will not apply the power turbine brake.

A combined operation known as an "online start" may also be performed. A GTM can be placed online directly from a shutdown status by pressing the ON LINE button without first conducting the start sequence of Section 2.6.1. When conducting this online start, the start procedure of Section 2.6.1 and the online action listed above are combined, and the UEC and SCU automatically carry out both sequentially.

2.6.4 *Main Propulsion Engine (GTM) Normal Stop*

A normal stop occurs any time a GTM is brought to idle speed for a period of 5 minutes for cooldown, and then secured [14]. It is assumed that the GTM has been taken offline and is operating at idle speed.

1. The operator at either the SCU or PPAC presses the appropriate (either 2A or 2B) NORMAL STOP C/D button. The NORMAL STOP C/D pushbutton indicator illuminates momentarily.
2. The UEC receives the normal stop command. The UEC starts a 300 second timer.
3. After 300 seconds have elapsed, the UEC shuts the Fuel Shutoff valves per Section 2.6.1 above.
4. The GTM decelerates.
5. The power turbine brake will be applied automatically when power turbine speed decreases below 500 RPM and various fuel pressure parameters are met.

2.6.5 *Gas Turbine Generator (GTG) Start*

The starting procedure for the GTG's is similar to that for the GTM's. GTG #1 (Unit 914) can be started either with the RIMSS (described in Section 2.3.1) or with Start air and a pneumatic starter similar to the GTM. GTG #2 and GTG #3 can only be started with Start air.

Instead of a UEC, the GTG's have a 301 sequencer which is a micro-processor control unit. The sequencer initiates and oversees engine operations such as starts and shutdowns, monitors system parameters, and initiates alarms and shutdowns when required [14]. The general start sequence is listed below.

1. The operator presses the ON button.
2. If the turbine is being started by the RIMSS, power is applied to the RIMSS from the DC voltage source as discussed in Section 2.3.1. If the turbine is being started by Start air, the Start air valve opens and powers a pneumatic starter.

3. The GTG turbine accelerates.
4. At 2,200 RPM
    a. Fuel valves open.
    b. Igniters energize.
5. At 7,500 RPM, the igniters de-energize.
6. At 9,100 RPM
    a. The low pressure start air valve closes.
    b. The pneumatic starter disengages.
7. The GTG reaches normal operating speed at 14,340 RPM.

2.6.6 *Gas Turbine Generator (GTG) Transient Load Sensor*

A specific protection function that prevents a GTG casualty condition caused by electrical load shifts is the Transient Load Sensor. When the electrical load on a GTG is greater than 1000 kW, a Transient Load Sensor will close the Bleed Air isolation valve when the electrical load on the GTG increases by 500 kW or more [18]. The Bleed Air isolation valve will remain closed for three minutes, and then re-open. This prevents the GTG from experiencing an over-temperature shutdown. The Transient Load Sensor will also close the Bleed Air isolation valves on the remaining GTG's if one of the GTG's is shutdown with the associated generator breaker (1SG, 2SG, or 3SG) closed. This prevents an over-temperature shutdown of the remaining GTG's [14].

Chapter 3 NILM Applications

The DDG-51 LBES provides a multitude of possibilities for installation and evaluation of the capabilities of a NILM. Previous MIT students have installed NILM's at locations in the LBES, with two installations left permanently in-place. Another NILM was permanently installed in the course of this research. These permanently installed NILM's were used to investigate the possibility of using the data provided to diagnose and analyze some of the events discussed in Section 2.6 above.

3.1 NILM Installations at the LBES

Previous research conducted at the DDG-51 LBES resulted in the permanent installation of two NILM's targeting the LPAC and Fuel Oil Service Pump #2A. Throughout the course of conducting research for this thesis, a single additional NILM targeting the UEC's for both GTM's was installed permanently at the LBES. The location and target of each NILM is summarized in Table 3-1.

Table 3-1: NILM Targets and Locations at the LBES

NILM Target	NILM Location
Low Pressure Air Compressor	7-Foot Level
Fuel Oil Service Pump #2A	14-Foot Level
GTM 2A and 2B UEC's	32-Foot Level

A NILM installation consists of:

- A NEMA-type enclosure to house the power supply, transducers, and other components for measuring voltage and current
- A Pentium-class computer, keyboard, and monitor with software for recording and storing data
- A data acquisition card (PCI 1710) installed in the computer
- An uninterruptible power supply (UPS)
- All associated cabling

Specific reference data for the LPAC and Fuel Oil pump NILM's is listed below in Table 3-2 and Table 3-3 [5].

Table 3-2: NILM Configuration for LPAC

NILM Channel	Measurement	Resistors	Reference Resistors	Transducers	Current Transducer Conversion
1	Voltage	180Ω (pins 34-68)	62Ω (pins 24-26)	LEM LV-25P	2500/1000
2	Current	36Ω (pins 33-67)	62Ω (pins 33-26)	LEM LA-305S	1/2500

Table 3-3: NILM Configuration for Fuel Oil Service Pump 2A

NILM Channel	Measurement	Resistors	Reference Resistors	Transducers	Current Transducer Conversion
1	Voltage	180Ω (pins 34-68)	62Ω (pins 24-26)	LEM LV-25P	2500/1000
2	Current	62Ω (pins 33-67)	62Ω (pins 33-26)	LEM LA-55P	1/1000

3.1.1 *The Universal Engine Controller (UEC) NILM Installation*

Because the UEC is so vital to the operation sequences discussed in Section 2.6, it was decided to construct and install a NILM to target it. To determine where to attach the NILM entry points, the UEC power supply was examined. A simplified diagram of electrical and cable interfaces for a single UEC, SCU and GTM are shown below in Figure 3-1 below.

Cable J9 (from Figure 3-1) carries 115V AC/ single phase power to the UEC. Cable J10 carries the 115V AC/3-phase power. Within the UEC, these two forms of supply power are converted to various other AC and DC ratings and subsequently used for various operations (such as those described in Section 2.6). However, because the ultimate power for most of the operations discussed in Section 2.6 is supplied via J10, the NILM voltage sensing lines and current transducers were installed on the 115V AC/ 3-phase 60 Hz power feed to the UEC's.

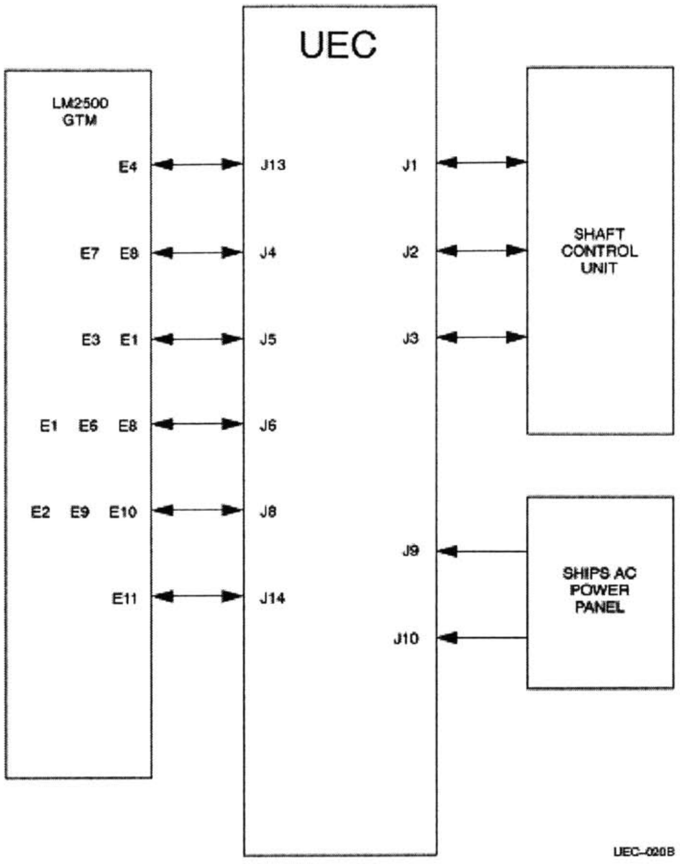

Figure 3-1: Simplified UEC Interface Schematic

There are two engine controllers at the LBES, one for each GTM (as previously discussed in Section 2.2.1). The 115VAC /3-phase power supplying each UEC is distributed from LBES power panel 1-282-1. Because the voltages supplied to each UEC are effectively identical, only one voltage sensing connection was made, specifically to phases B and C of the 2A GTM UEC. Current transducers were attached to phase A of both 2B and 2A GTM UEC's (see Figure 3-2). The specific installation procedure is indicated in Appendix A and was performed on February 23, 2006. The UEC NILM was configured as follows:

Table 3-4: NILM Configuration for Universal Engine Controller

NILM Channel	Measurement	Resistors	Reference Resistors	Transducers	Current Transducer Conversion
1	Voltage	80Ω	51Ω	LEM LV-25P	2500/1000
2	Current	160Ω	51Ω	LEM LA-55P	1/1000
3	Voltage	Jumped from CH 1	Jumpered from CH 1	Jumpered from CH 1	Jumpered from CH 1
4	Current	160Ω	51Ω	LEM LA-55P	1/1000

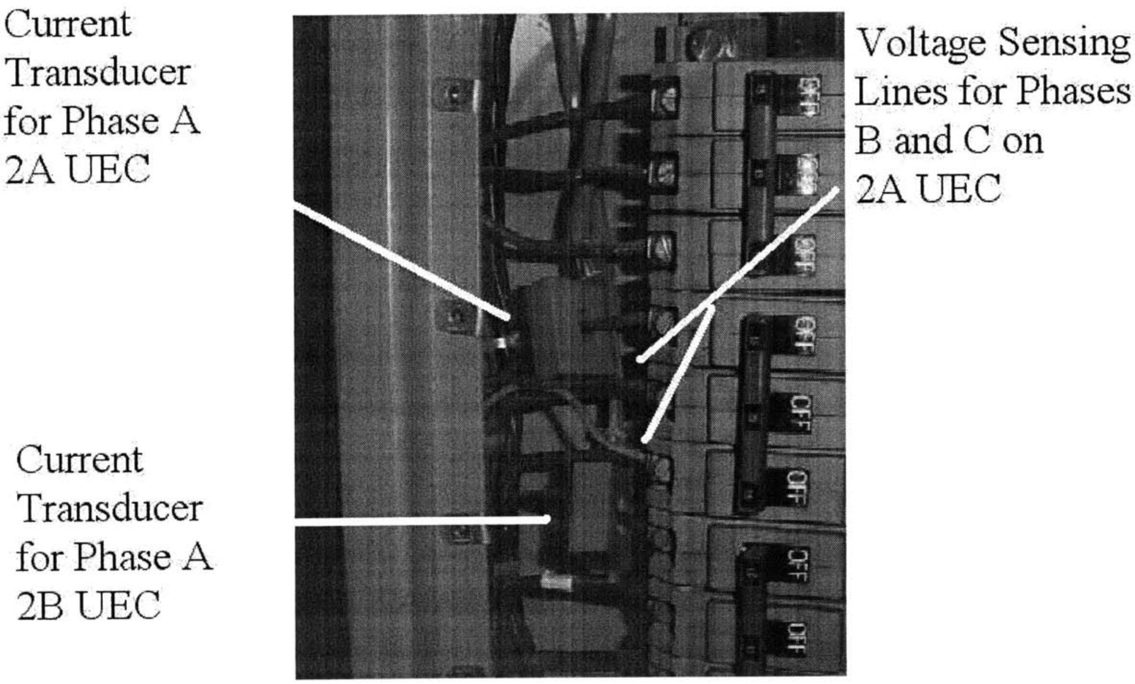

Figure 3-2: UEC current and voltage sensors in power panel 1-282-1

3.2 The LPAC NILM

The software installed on a NILM computer automatically collects spectral envelope data (see Section 1.2) in hour-long blocks termed "snapshots". Recording for a snapshot is stopped and a new recording is started each hour using Greenwich Mean Time (GMT) as a time reference. For the work in this thesis, the fundamental information of interest is the spectral envelope $a_l(t)$, which is an estimate of the real power delivered to the targeted device. A plot of this quantity yields valuable information about the operational state of the device. For example, one can use it to determine when the LPAC is loaded or unloaded (from Section 2.4). Figure 3-3 below shows real power during three cycles of the LPAC operating in Automatic 125 PSIG mode [5]. While the state of the LPAC (loaded vice unloaded) is valuable information, we can further analyze this data to determine information about the state of the low pressure air *system* itself.

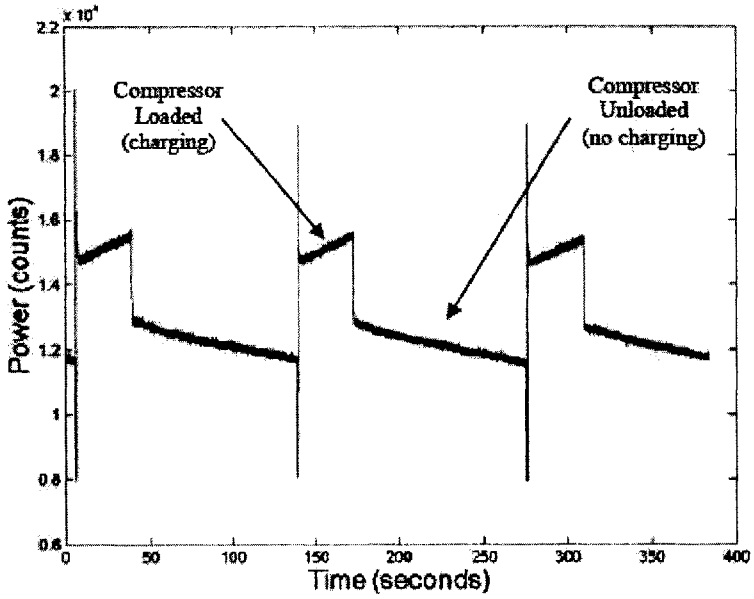

Figure 3-3: LPAC in Automatic 125 PSIG Operation

A MATLAB script (Appendix B.1) is used to calculate several values of interest. First, the actual "Load" and "Unload" time intervals for each compressor cycle are calculated and stored. These are the lengths that the compressor is in a loaded state and an unloaded state. Second, the time that a load or unload cycle is completed relative to the start of the hourly snapshot is recorded as well. Thus, if the Load-Unload Script is run on an LPAC snapshot, it is possible to get the following information:

- How many load cycles the compressor underwent in the hour
- How many unload cycles the compressor underwent in the hour

- How long each of these load/unload intervals lasted
- When each of these intervals ended relative to the start of the hour (e.g. 32 minutes after start)

Using these new quantities calculated by the Load-Unload Script, one can view the behavior of the LPAC by examining the load and unload cycle intervals throughout the course of an hour, or a day.

A specific example is as follows. The operator logs for April 22, 2005 indicated an air start of Unit 9130 (#2 GTG) occurred between 7:00 a.m. and 8:00 a.m. As discussed above, during periods when the compressor is operating under load, the real power it draws increases by a large amount. The NILM identifies this change, as well as the decrease in real power that accompanies the unloading of the compressor. Figure 3-4 indicates the change in the load interval for this specific event. The Load-Unload Script determines these intervals, and generates a time history of the compressor's loaded and unloaded times.

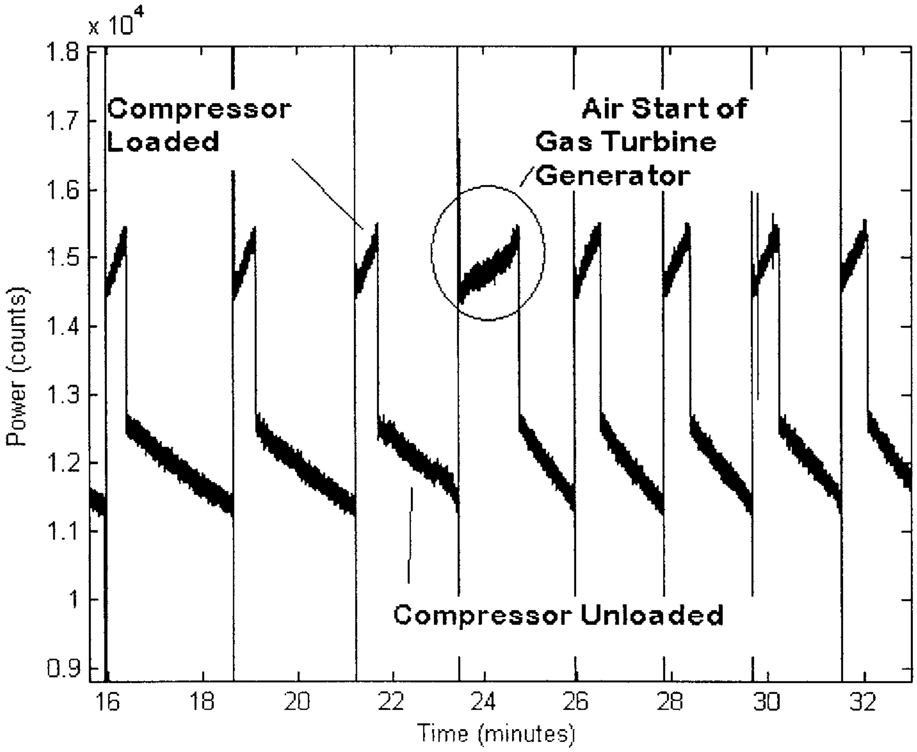

Figure 3-4: Plot of the real power drawn by the LPAC before, during, and after an air start of Unit 9130 (#2 Gas Turbine Generator). The units of real power are shown here to be counts, and they reflect the scale factors introduced by our instrumentation. The power can be converted into Watts by determining the appropriate multiplicative scale factor to apply to the data.

The time histories of the loaded and unloaded times computed by the NILM can be used to determine a vast amount of information about the purely mechanical elements that are affected by the operation of the compressor. For instance, Figure 3-5 shows how the loaded and unloaded intervals change for the LP air start of Unit 9130. Such an operation places a much heavier air load on the compressor, causing loaded times to increase and unloaded times to decrease. Note that the plots shown in Figure 3-5 were created using the data shown in Figure 3-4. During the initial starting phase, there is a dramatic increase in the loaded time due to actuation of pneumatically powered ventilation dampers, and this is clearly visible in both the plot of the real power and in the plot of the loaded time. The unloaded time intervals steadily decrease as the overall system volume becomes larger during the general plant startup, wherein various legs of LP air piping are un-isolated.

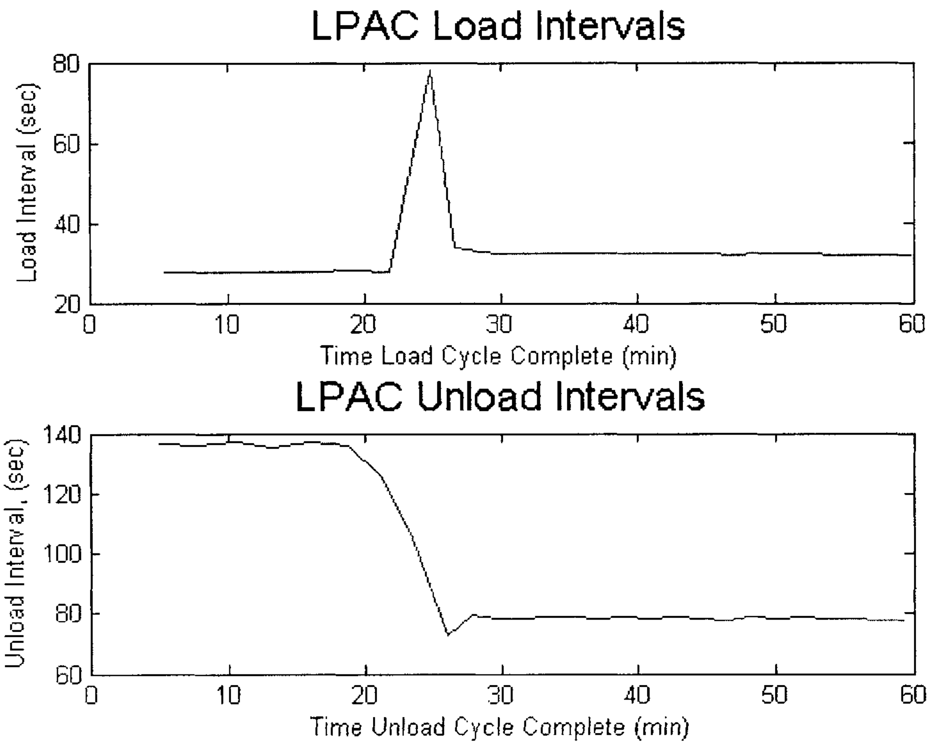

Figure 3-5: Loaded and unloaded times before, during, and after an air start of Unit 9130 (#2 Gas Turbine Generator) between 7:00 a.m. and 8:00 a.m. on April 22, 2005.

3.3 The Fuel Oil Pump NILM

The NILM targeting the #2A Fuel Oil Pump records data in the exact same manner as the LPAC NILM. Again, information concerning the pump power can be obtained, such as off/on status, as shown in Figure 3-6. However, just as in the case of the LPAC above, once the pump is actually on, observations can be made about the *system* by observing the behavior of the pump alone. Using the operator logs as a guide, we examined the pump's electrical input power in order to determine if specific GTM events cause any noticeable changes. Any distinguishable and repeatable features in the pump power plots that may have indicated a GTM event were noted. GTG events were excluded from this analysis because the GTG's rely on a gravity feed tank to supply their fuel pressure, not a fuel service pump, as discussed in Section 2.5.

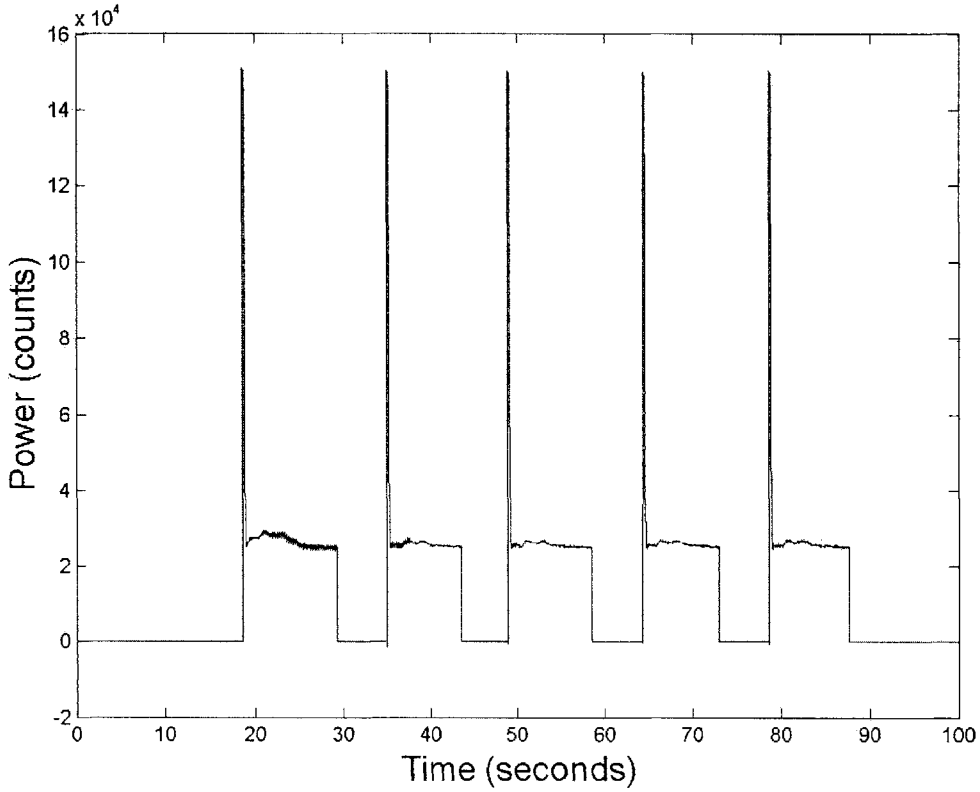

Figure 3-6: 2A Fuel Oil Service Pump Starts in Low Speed

An example of the effect of GTM operation is indicated in Figure 3-7. To assist in the identification of features, the data was first processed using the low-pass finite impulse response (FIR) filter whose coefficients are listed in Appendix B.2. The operator logs state that the 2B

GTM was started at 2:46 p.m. on April 18, 2005. In the filtered data stream, it is clear that something altered the behavior of the pump at approximately 2:48 p.m. This 2 minute delay is consistent with the sequence described in Section 2.6.1. GTM starts, motors, motor/purges, online events, online starts, and shutdowns were all examined in a similar fashion.

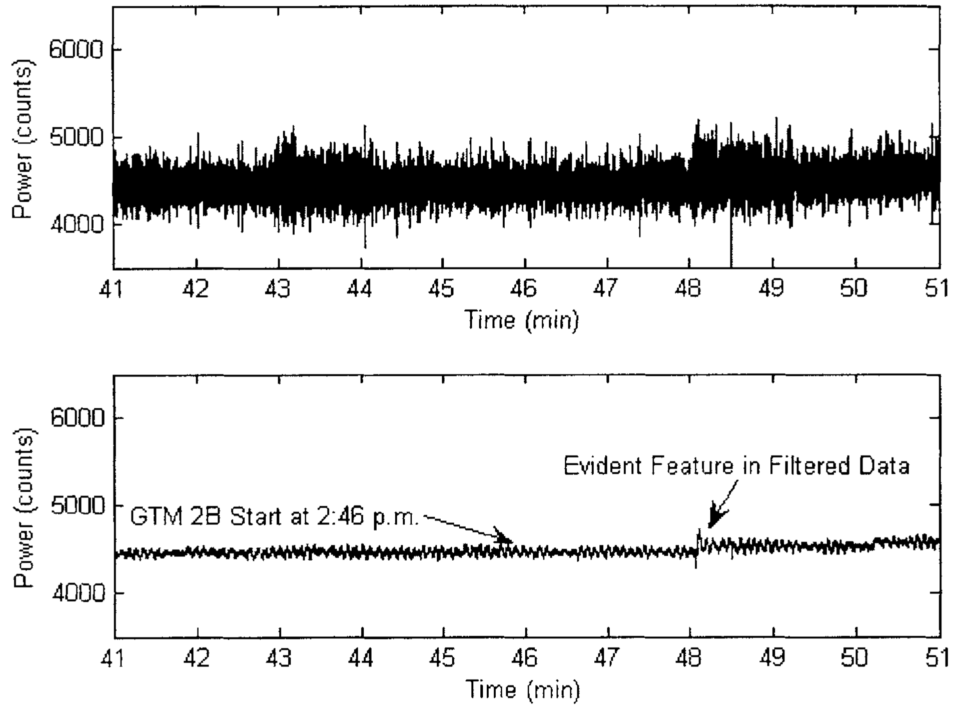

Figure 3-7: Unfiltered (top) and filtered (bottom) power data from the fuel oil pump NILM. GTM 2B was started at 2:46 p.m. per operator logs. A noticeable feature appears in the filtered data two minutes afterwards.

3.4 The UEC NILM

Similar to the Fuel Oil pump NILM, the UEC NILM provides information about the power supplied to the UEC. As discussed in Section 2.2.1, multiple command and control signals are generated in the UEC, but not using 115V AC/3-phase power directly. For example, a significant number of command signals used in the operations discussed in Section 2.6 require 28V DC power. However, because the UEC NILM is placed at an aggregate location, it captures information on many of these signals solely through changes in the 115V AC/3-phase power. An example of power data recorded by the UEC is shown in Figure 3-8.

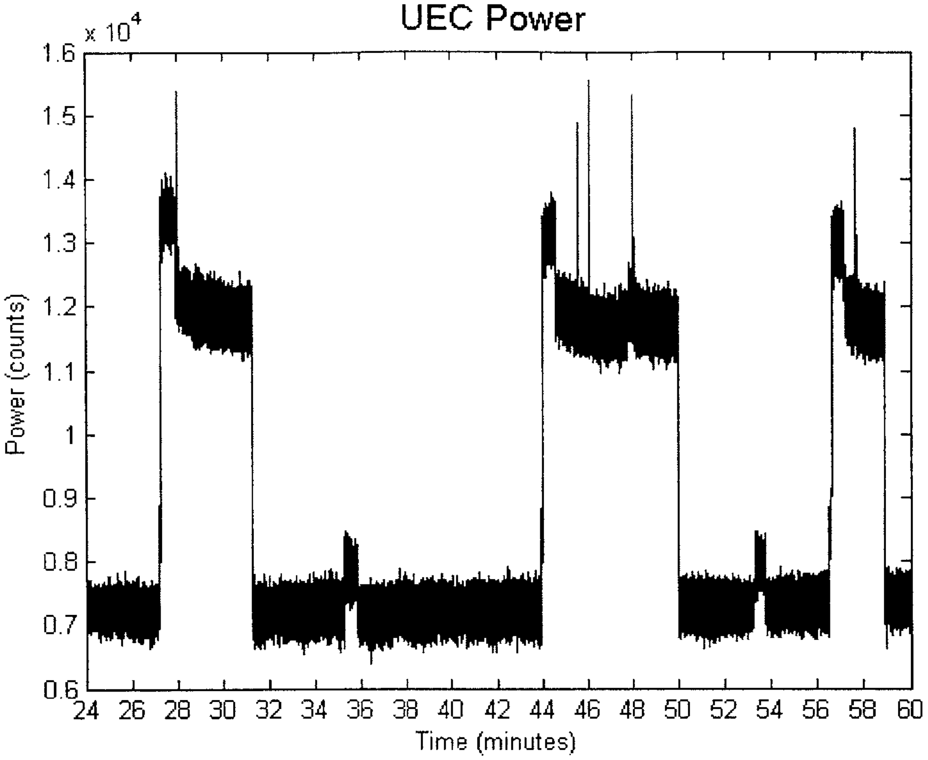

Figure 3-8: Unfiltered power data from the UEC NILM

Figure 3-8 is generated from unfiltered UEC power data recorded during GTM testing between 9:00 a.m. and 10:00 a.m. on April 25, 2006. We can see that three similar events occurred at approximately 9:27, 9:44, and 9:57. Two events of a different sort occurred at approximately 9:35 and 9: 53.

To help determine what caused these features, the operator logs were examined. Logs indicated GTM 2A starts occurred at 9:26, 9:43, and 9:56. The 2A GTM was motored at 9:34 and 9:52 for 30 seconds each instance. As part of the test procedure, an automatic shutdown of the GTM was initiated by violating a protective interlock specific to the test procedure. These shutdowns were generated at 9:30, 9:49, and 9:57. Thus, we can annotate Figure 3-8 and generate Figure 3-9. The small differences in time are most likely due to differences in the NILM computer clock and the clock used by the operators to record events.

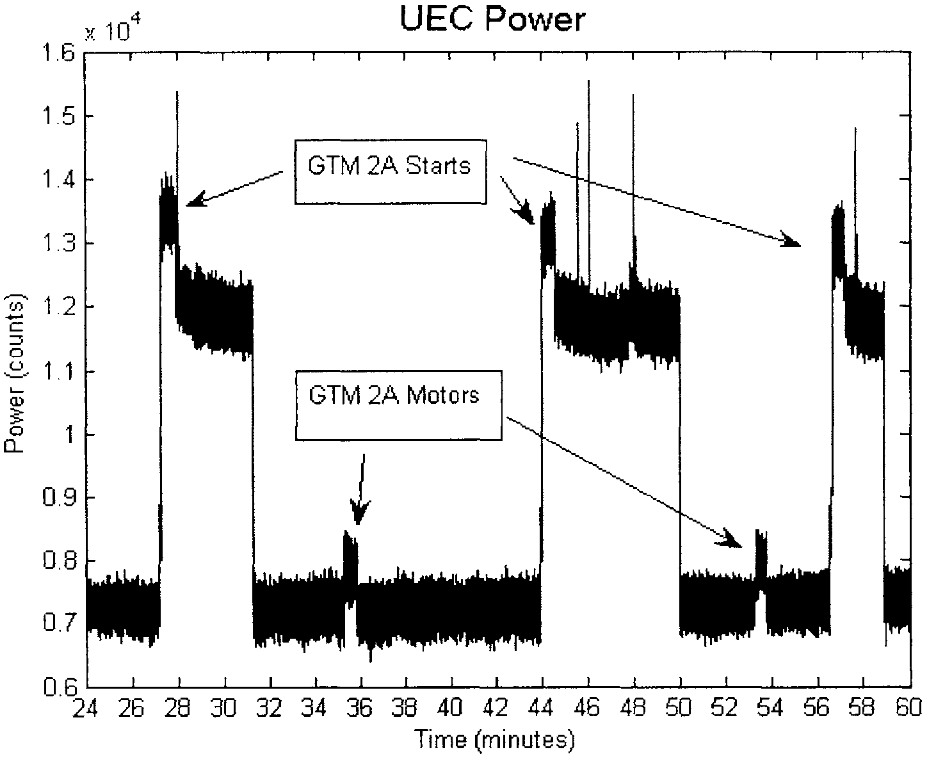

Figure 3-9: UEC NILM data annotated using information from operator logs.

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Chapter 4 Event Analyses and NILM Relations

As discussed in Chapter 1, the NILM can detect and classify various loads in certain electromechanical systems. In this chapter, the underlying relations required for this task will be examined. Using combinations of the three NILM data analysis techniques discussed in Chapter 3, the systems detailed in Chapter 2 will be examined to determine if the NILM's can provide data that relates to the specific events described in Section 2.6. For the data recorded during the period April 18, 2005 through April 22, 2005, shop air was *not* aligned, and thus the Start Air header was supplied via bleed air, not shop air.

4.1 Main Propulsion Engine (GTM) Start

Based on the GTM start sequence discussed in Section 2.6.1, several system relations can be noted that should evidence themselves in the data recorded by the three NILM's. A GTM start requires air from the Start Air header. However, as mentioned in Section 2.4, load changes in the Start Air header should not affect the LP air system based on check valves located between the two (see Figure 2-10). Thus, while there is a large amount of low pressure air used for a GTM start, it should not evidence itself in the LPAC Load-Unload plots.

A GTM start causes the Fuel Shutoff valves to open, supplying fuel from the Fuel Service header into the GTM. This opening of the valves should result in a momentary drop in system pressure. The fuel unloader valve is pneumatically operated from LP air and may reposition after the opening of the Fuel Shutoff valves, but this pneumatic adjustment may not be a large enough load to impact the LPAC behavior. However, the fuel oil service pump itself may be affected by this overall system change, requiring more work from the pump to maintain system pressure once the Fuel Shutoff valves are open.

Figure 4-1 and Figure 4-2 show plots of both LPAC Load-Unload data and Fuel Oil pump data recorded during multiple GTM 2B events that happened within a short time of each other on April 18 and April 19, 2005. The figures provide examples of separate GTM events, but the reader's attention is called to the features generated by the GTM starts at 2:46 p.m. on April 18 in Figure 4-1 and 12:40 p.m. on April 19 in Figure 4-2. The LPAC Load-Unload intervals are not affected, but the Fuel Oil pump power is. This specific relation in the behavior between the LPAC Load-Unload intervals and the Fuel Oil pump power is repeated for multiple GTM starts recorded between April 18 and April 22, 2005.

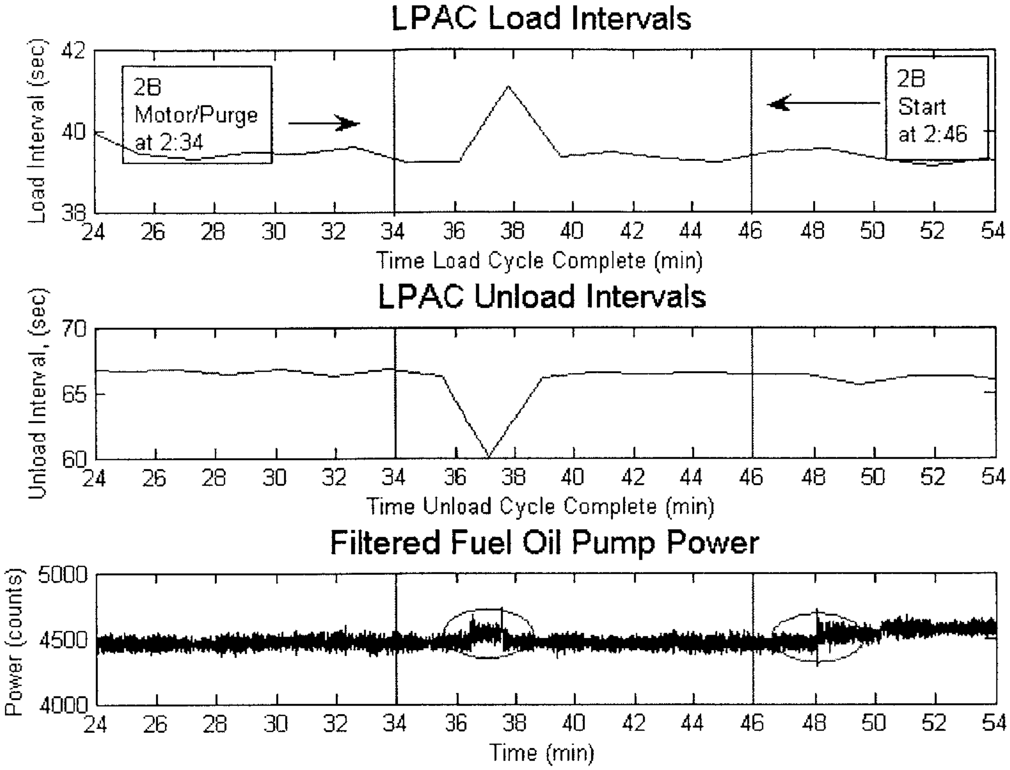

Figure 4-1: Combined NILM data from LPAC Load-Unload plot and filtered Fuel Oil pump data for a GTM start and Motor/Purge. The data was recorded between 2:00 and 3:00 p.m. on April 18, 2005. The GTM start impacts the Fuel Oil pump behavior, but not the LPAC.

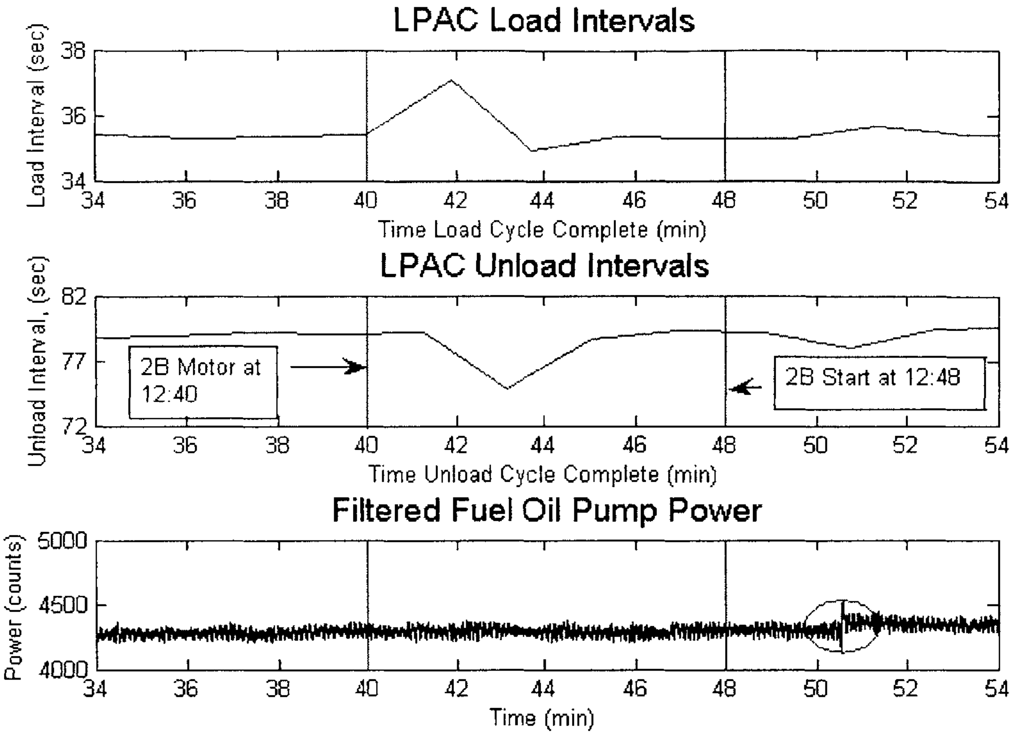

Figure 4-2: Combined NILM data from LPAC Load-Unload plot and filtered Fuel Oil pump data for a GTM start and Motor/Purge. The data was recorded between 12:00 and 1:00 p.m. on April 19, 2005. The GTM start impacts the Fuel Oil pump behavior, but not the LPAC.

Based on data collected between April 18 and April 22, 2005, a relationship was observed: GTM starts do not cause significant changes in the Load-Unload behavior of the LPAC, but do cause perceptible features in the Fuel Oil pump power. The relation between the GTM starts and features in LPAC Load-Unload data and Fuel Oil pump data for the period April 18 through April 22, 2005 are summarized in Table 4-1.

Table 4-1: LPAC and Fuel Oil Pump Behavior due to GTM Starts

Data Type	Total Number of Logged Events	Total Number of Times Relation Observed
LPAC Load-Unload Intervals	28	27
Fuel Oil Pump Power*	14	14
Combined LPAC and Fuel Oil Pump	14	14

*** The number of events analyzed using Fuel Oil pump power differs from the number of LPAC events because in some instances the 2B Fuel Oil Pump was running (not the 2A), and thus no Fuel Oil Pump power data exists for those events.**

The UEC NILM provides another approach to detecting GTM starts. Figure 3-9 from the previous chapter provides good examples of three individual start sequences of GTM 2A as seen via examination of UEC power data. Figure 4-3 is a more detailed view of an individual start of GTM 2A that occurred at approximately 9:27 a.m. on April 25, 2006, and is annotated with probable command signals from the sequence discussed in Section 2.6.1. The shutdown that is indicated was initiated as part of the test procedure the LBES operators were following on that day. Note that igniters are not indicated on the Figure 4-3 because they are on a circuit *not* monitored by the UEC NILM (i.e. they are on the 115V AC/ single phase supply).

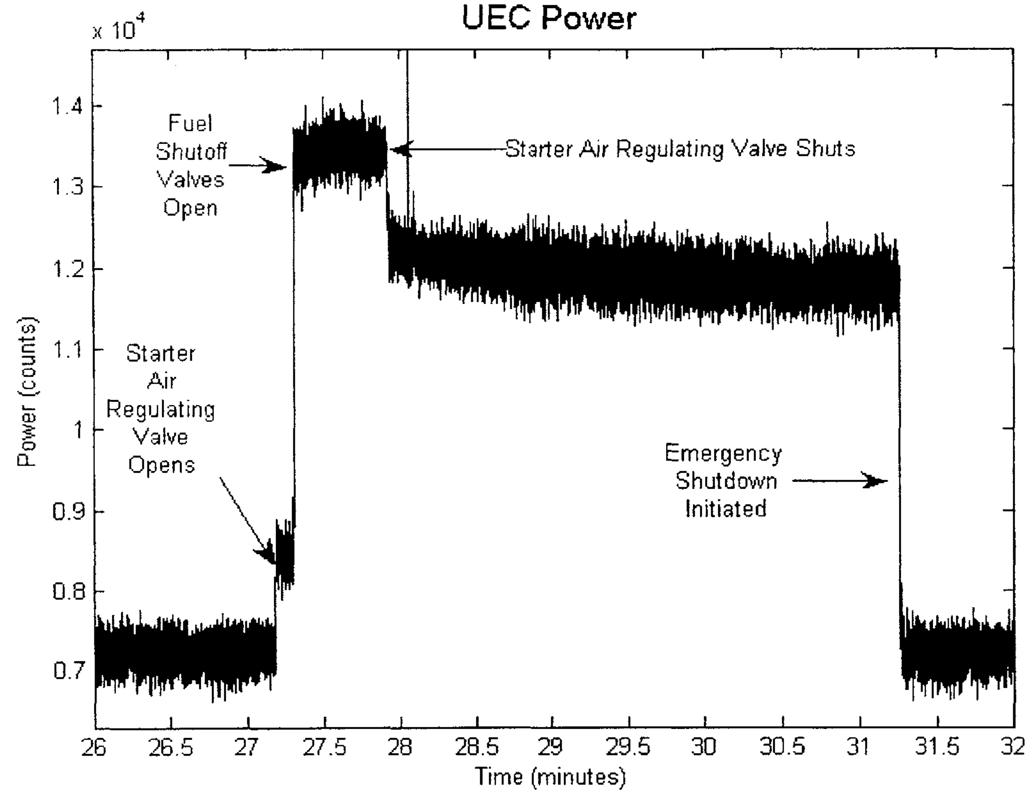

Figure 4-3: UEC power during GTM 2A start sequence annotated with probable command signals generated by the UEC. Section 2.6.1 indicates that a typical GTM start requires the Starter Air Regulating Valve to be open for approximately 50 seconds. This plot indicates the Starter Air Regulating Valve was open for approximately 45 seconds.

The UEC data for GTM starts is very useful because it provides a more exact "fingerprint" of a start than the combined LPAC-Fuel Oil pump data. While the combined LPAC-Fuel Oil pump data is capable of indicating a GTM start occurred (and when it occurred), the UEC data can provide additional specifics about the start sequence itself, such as when various commands were triggered by the UEC or *if* they were triggered. The sequence can be resolved to a series of finite states that are indicative of starts. Figure 4-4 provides a simplified example of the finite states for a start sequence. Each state transition requires a certain amount of power, and the NILM can use that information to recognize events, e.g. from Figure 4-3, "State A" (the opening of the Starter Air regulating valve) might require 8500 counts (or the equivalent in Watts) [19].

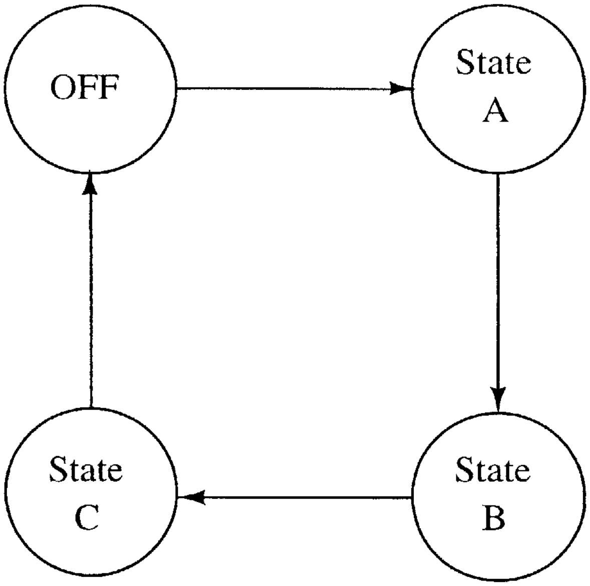

Figure 4-4: Finite states for a UEC start sequence. Using Figure 4-2 as a basis, the states can be labeled as follows: (A) Starter Air regulating valve opens (B) Fuel Shutoff valves open (C) Starter Air regulating valve closes. At this point the GTM is "on". To return to the "off" state, the Fuel Shutoff valves must close.

The UEC information further allows one to possibly detect problems with a start sequence. Figure 4-5 is an instance of a failed start attempt on April 25, 2006 at approximately 10:33 a.m. Based on operator logs, the GTM suffered a "flameout shutdown" caused by either of two things: fuel pressure supplied to the turbine was less than 50 psig, or turbine exhaust temperature was below 400±10 °F. Because either of the two parameter thresholds was not met, the UEC initiated an automatic shutdown followed immediately by an automatic, one minute motoring period [12]. The same finite state analysis can be applied to the failed start as with the proper start of Figure 4-3, and thus the NILM can recognize the specific state transitions that indicate a failed start.

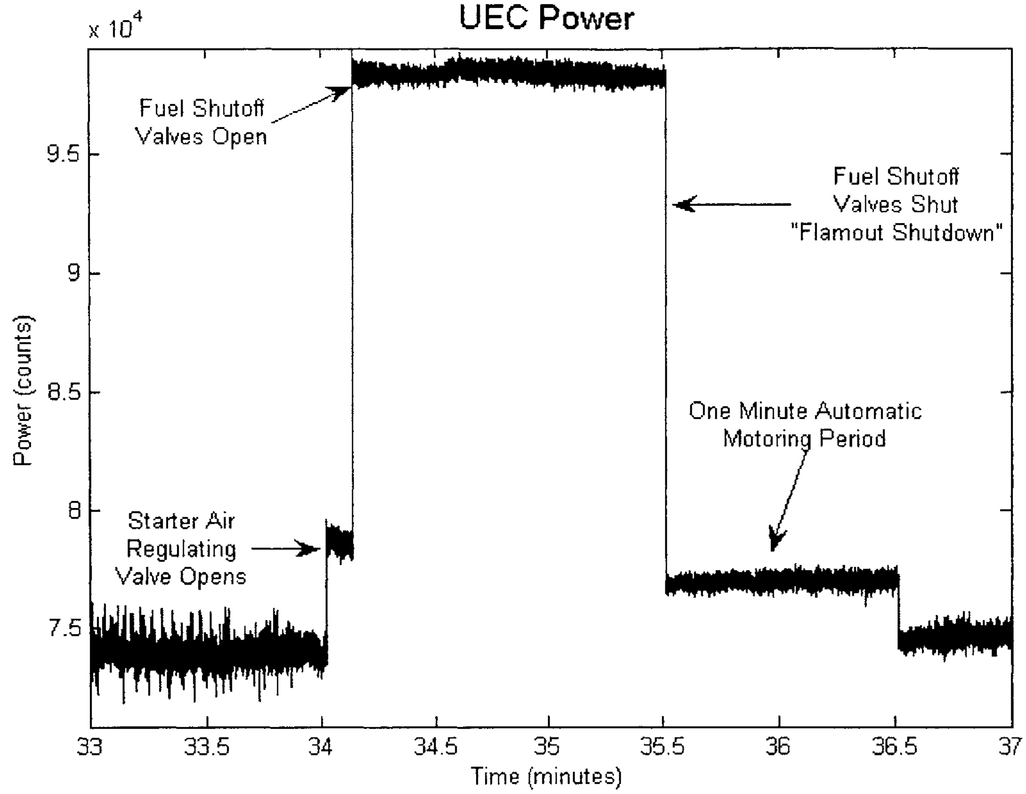

Figure 4-5: UEC power during a failed start attempt of GTM 2B between 10:00 and 11:00 a.m. on April 25, 2006.

4.2 Main Propulsion Engine (GTM) Motor/Purge

The same methods used to analyze the GTM start sequence are applied to the GTM motor or motor/purge sequence. Both operations again require air from the Start Air header for the main physical power to rotate the turbine and to conduct the motor event itself. Just as with a GTM start, the injection of high pressure air into the pneumatic starter should not affect the LPAC behavior for the same reasons – check valves prevent pressure changes in the Start Air header from affecting the LP air system. Figure 4-1, however, indicates that motors and motor/purges *do* alter the LPAC behavior. This is because the Motor Regulating valve uses Control air (i.e. LP air) to operate, and this particular valve is only operated for the GTM motor and motor/purge events, *not* GTM starts. When in operation, the valve effectively acts as a load or leak on the LP air system.

The fuel oil system is affected depending on which specific type of motoring event occurs. A motor/purge, based on the sequence described in Section 2.6.2, involves opening the fuel purge valve, thus causing a drop in pressure in the fuel oil system. This may have a noticeable effect on the Fuel Oil pump power. For a motor, the Fuel Purge valves are not actuated, thus the fuel oil system should not be affected, nor should the Fuel Oil pump. Figure 4-6 contrasts the two types of motoring events (motor/purges and motors). Both events generate effects in the LPAC Load-Unload intervals, and only the motor/purge impacts the Fuel Oil pump power. This is also evidenced in both plots of Figure 4-1 and Figure 4-2.

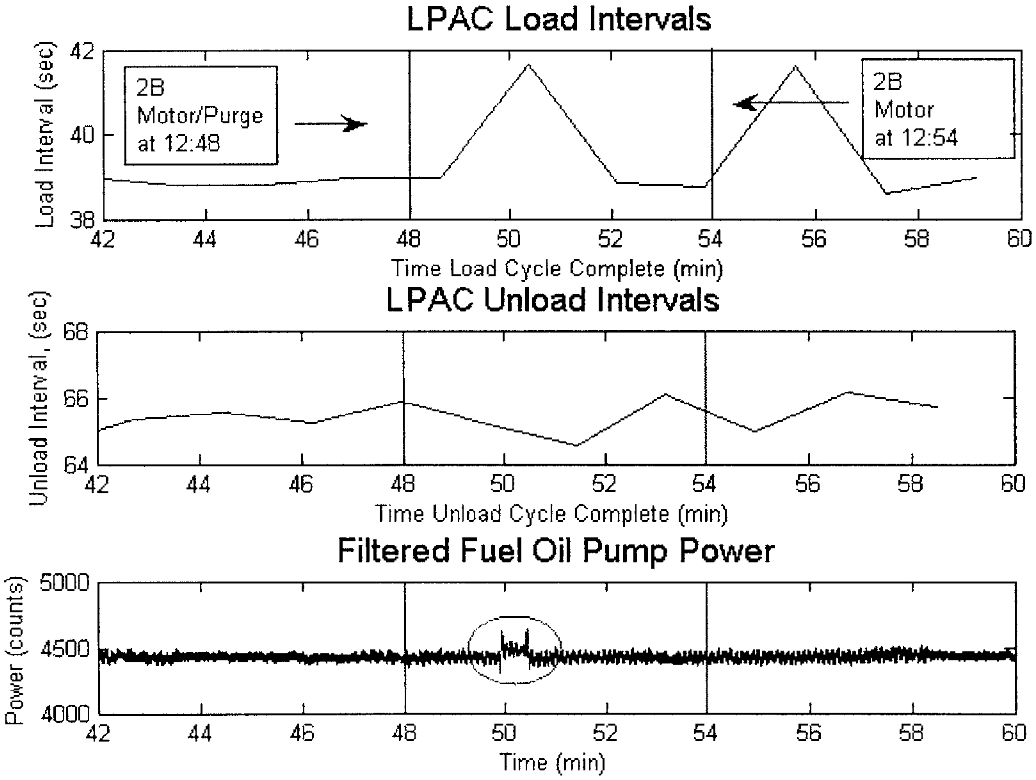

Figure 4-6: A motor/purge event is contrasted with a motor event. These events occurred between 12:00 and 1:00 p.m. on April 18, 2005. Both motoring events affect the LPAC via the Motor Regulating valve, but only the motor/purge affects the fuel oil system, and thus the Fuel Oil pump.

Based on data collected between April 18 and April 22, 2005, GTM motors or motor/purges can generate increases in the LPAC load and/or decreases in the LPAC unload intervals. Based on the same data, motor/purges cause changes in the Fuel Oil pump power, while motors alone do not. The relation between the GTM motor events and features in LPAC Load-Unload data and Fuel Oil pump data for the period April 18 through April 22, 2005 are summarized in Table 4-2 and Table 4-3. The relation between the events and the expected Load-Unload (L/U) behavior did not correspond exactly. The most likely cause is if a motor or motor/purge is short (e.g. 60 seconds), and occurs at the start of an unload cycle of the LPAC, the entire event may only slightly impact the unload cycle alone (typical unload cycles are greater than 60 seconds), and possibly never generate a spike or other feature in the Load-Unload intervals.

Table 4-2: LPAC and Fuel Oil Pump Behavior due to GTM Motor/Purges

Data Type	Total Number of Logged Events	Total Number of Times Relation Observed
LPAC Load-Unload Intervals	7	6
Fuel Oil Pump Power*	2	2
Combined LPAC and Fuel Oil Pump	2	2

Table 4-3: LPAC and Fuel Oil Pump Behavior due to GTM Motors

Data Type	Total Number of Logged Events	Total Number of Times Relation Observed
LPAC Load-Unload Intervals	8	6
Fuel Oil Pump Power*	7	7
Combined LPAC and Fuel Oil Pump	7	7

*** The number of events analyzed using Fuel Oil pump power differs from the number of LPAC events because in some instances the 2B Fuel Oil Pump was running (not the 2A), and thus no Fuel Oil Pump power data exists for those events.**

The UEC NILM can also be used to detect motor events. Recalling Figure 3-9, the motor events are clearly visible against the baseline power data of the UEC. The evident feature that corresponds to the motor event is most likely the command signal from the UEC to the motor regulating valve ordering it to actuate.

4.3 Main Propulsion Engine (GTM) Online

The GTM online sequence is fairly simple compared to GTM starts or motors. The GTM is typically already at an idle speed (approximately 4500 RPM), and the only event of interest within the overall sequence is the release of the power turbine braking mechanism. This requires the use of LP air, and thus may cause an increase in the LPAC load interval and/or a decrease in the unload interval. The fuel oil pump behavior may or may not be affected depending on the power level of the GTM at the time the online button is pushed at either the SCU or PPAC. For example, if a GTM is started, then placed online while the throttle setting for the GTM's is set at a high shaft speed, the GTM may require more fuel to increase its mechanical output fairly rapidly. However, if the throttle setting is at a low shaft speed, and the GTM does not have to provide much more power than idling power, the GTM may not require more fuel, and thus the fuel pump power may not change noticeably. Figure 4-7 shows two online events on April 19, 2005. The LPAC behavior is clearly affected by the online events, but the fuel oil pump power may or may not be affected.

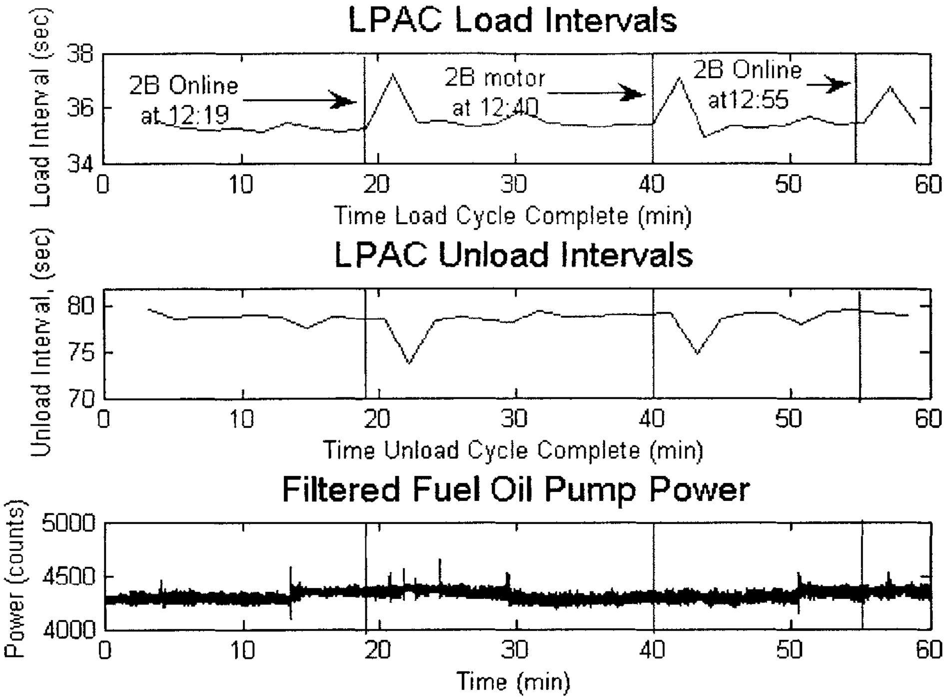

Figure 4-7: Combined NILM data from LPAC Load-Unload plot and filtered Fuel Oil pump data for GTM online events between 12:00 and 1:00 p.m. on April 19, 2005. Behavioral changes in the LPAC Load-Unload intervals are clearly evident, but any changes in Fuel Oil pump power require closer examination to detect.

Based on data collected between April 18 and April 22, 2005, GTM online sequences may generate increases in the LPAC load and/or decreases in the LPAC unload intervals. Based on the same data, online sequences may cause changes in the Fuel Oil pump power. The relation between the GTM online sequences and features in LPAC Load-Unload data and Fuel Oil pump data for the period April 18 through April 22, 2005 are summarized in Table 4-4. The relation between the events and the expected Load-Unload (L/U) behavior did not correspond exactly. The best estimate for this is the same as for the GTM motor events – the brake release sequence may not be long enough to impact the LP air system in all cases. The relation between the events and the expected Fuel Oil pump behavior did not correspond exactly. This is possibly due to power settings being very similar before and after the online sequence was initiated, as discussed above.

Table 4-4: LPAC and Fuel Oil Pump Behavior due to GTM Online Sequences

Data Type	Total Number of Logged Events	Total Number of Times Relation Observed
LPAC Load-Unload Intervals	32	24
Fuel Oil Pump Power*	14	8

*** The number of events analyzed using Fuel Oil pump power differs from the number of LPAC events because in some instances the 2B Fuel Oil Pump was running (not the 2A), and thus no Fuel Oil Pump power data exists for those events.**

Because of the lack of consistency of observed relations between the online sequences and individual NILM behavior, it is not beneficial to consider identifying relations using combined LPAC and Fuel Oil pump data.

4.4 Main Propulsion Engine (GTM) Stop

Recalling Section 2.6.4, a GTM is typically already offline and at idle speed (approximately 4500 RPM) when a normal stop command is ordered. Operators at the LBES log two events for a GTM stop:

1. "NSI" – Normal Stop Initiated. The command to stop is given by pressing the stop button for the appropriate turbine. Per Section 2.6.4, the UEC starts a 300 second (5 minute) timer.
2. "NSC" – Normal Stop Complete. The Fuel Shutoff valves close and the turbine decelerates rapidly after the 5 minute wait period is complete. Note the turbine is not completely stopped when this log entry is made.

As with previous events, the associated systems and their relations are examined to determine if the stop sequence can affect the LP air system or the fuel oil system. The initiation of the stop command does not require a large change in any LP air loads, thus it is not expected that the initiation of the stop command will affect LPAC behavior. Upon completion of the stop sequence, the power turbine brake is applied. Because this brake is powered by LP air, it is possible that the LPAC behavior may be affected during this part of the stop sequence. The fuel oil system may be affected by the completion of the stop sequence when the Fuel Shutoff valves close. This change in fuel oil system pressure may alter the power of the Fuel Oil pump. Figure 4-8 is an example of a stop sequence ordered on April 19, 2005.

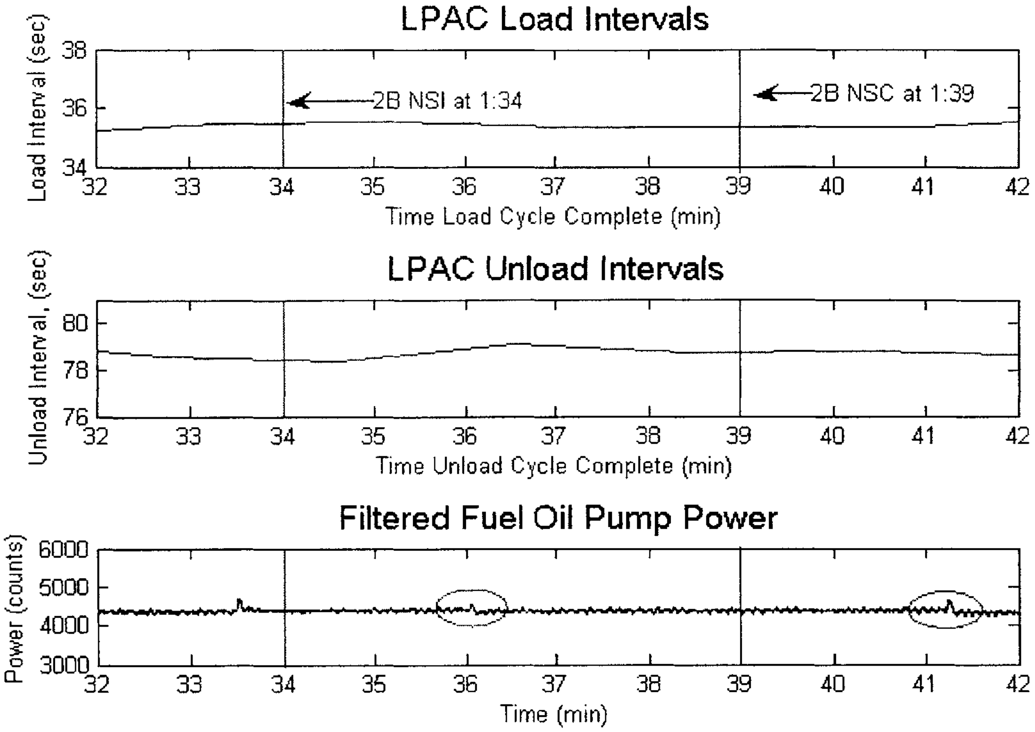

Figure 4-8: Combined NILM data from LPAC Load-Unload plot and filtered Fuel Oil pump data for GTM normal stop between 1:00 and 2:00 p.m. on April 19, 2005. Two features in the filtered Fuel Oil pump power data are evident after the stop is initiated (NSI) and completed (NSC). No discernable features are visible in the LPAC plots.

Based on data collected between April 18 and April 22, 2005, it is not clear that either the initiation or completion of GTM starts affect the behavior of the LPAC as determined by the load-unload intervals. Although the application of the power turbine brake near the completion of the stop requires the use of LP air, it may not be a large enough or sudden enough change in pneumatic load to affect the LPAC. Fuel Oil pump behavior is consistently affected by both initiation and completion of the GTM start sequence. While it is unclear why the *initiation* of the stop sequence affects the fuel oil system enough to change the fuel oil pump power, the *completion* of the stop sequence most likely affects the Fuel Oil pump power via the closing of the Fuel Shutoff valves. In both portions of the stop sequence, the Fuel Oil pump consistently experiences a drop in power, as shown in Figure 4-8. The relation between the GTM stop sequences and features in Fuel Oil pump data for the period April 18 through April 22, 2005 are summarized in Table 4-5.

Table 4-5: Fuel Oil Pump Behavior due to GTM Stop Sequences

GTM Event	Total Number of Logged Events Serviced by 2A Pump	Number of Times Fuel Oil Pump Relation Observed
Stop Initiated	23	18
Stop Completed	16	12

Table 4-5 does not include any information from LPAC Load-Unload plots because the Load-Unload information did not yield any significant relationship between LPAC behavior and GTM stop sequences. The total number of stop sequences examined was equal to the total number of stop sequences that occurred with the 2A Fuel Oil pump running (vice the 2B pump). The number of stops *completed* does not equal the number of stops *initiated* for various reasons:

- An emergency procedure was used to stop the GTM after the normal stop was initiated
- The stop sequence was cancelled and the GTM was left idling
- The stop sequence was cancelled and the GTM was placed online

4.5 Gas Turbine Generator (GTG) Start

Of the three NILM's installed at the LBES, only one can currently provide the capability to detect transients from the GTG's – the LPAC NILM. As discussed in Section 2.5, the GTG's receive their fuel from the Fuel Oil Gravity Feed Tank. By acting as a large surge volume with gravity as the motive force, the Gravity Feed Tank prevents the Fuel Oil pump from receiving any feedback from changes in GTG behavior. The UEC does not provide any command and control functions for the GTG's, and thus the UEC NILM does not detect any GTG behavior changes. GTG operational events, such as starts, can still be detected and identified however, as they will cause changes in the LP air system. GTG #1 (Unit 9140) can be started either via RIMSS or Start air. GTG's #2 and #3 can be started only via Start air. Since the RIMSS does not require pressurized air to conduct a start sequence, a RIMSS start initially was not expected to affect LPAC behavior. Similar to the GTM's, a GTG started with Start air was not expected to affect the LPAC either. However, ventilation dampers in the GTG module *do* require LP air to open. According to LBES test engineers, on some starts (via either RIMSS or Start air) the vent dampers will open, causing a sudden increase in load on the LP air system and possibly affecting LPAC Load-Unload intervals [18]. The opening of the vent damper depends on the temperature of the module and ambient atmospheric temperature. Examples of a RIMSS start of GTG #1 and an air start of GTG #2 are shown below in Figure 4-9 and Figure 4-10.

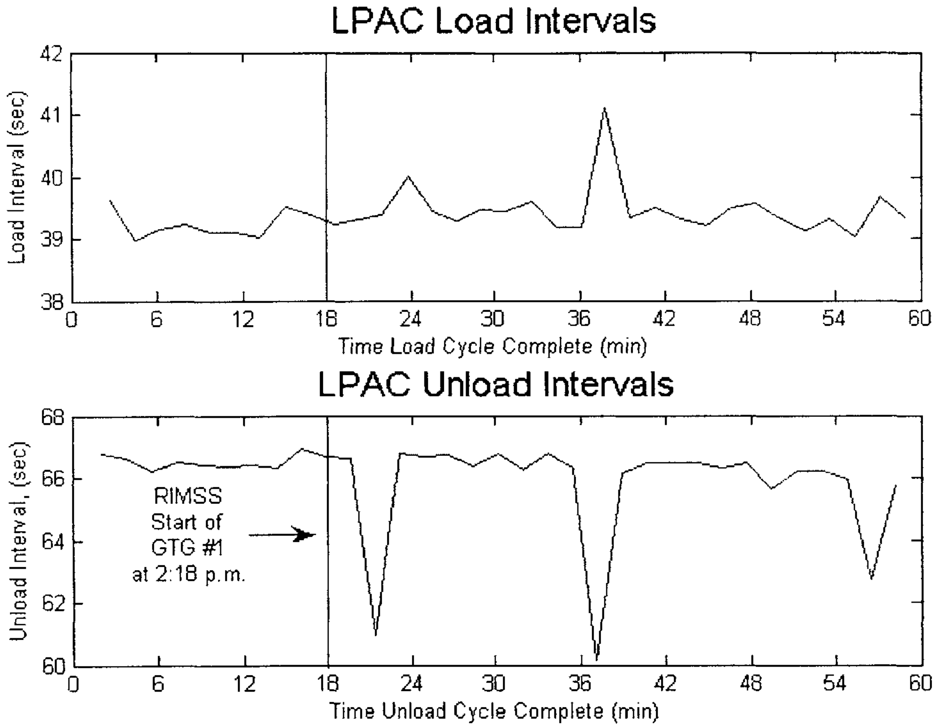

Figure 4-9: LPAC Load-Unload data for a RIMSS start of GTG #1 on April 18, 2005. The event generated a feature in the unload interval, but not the load interval.

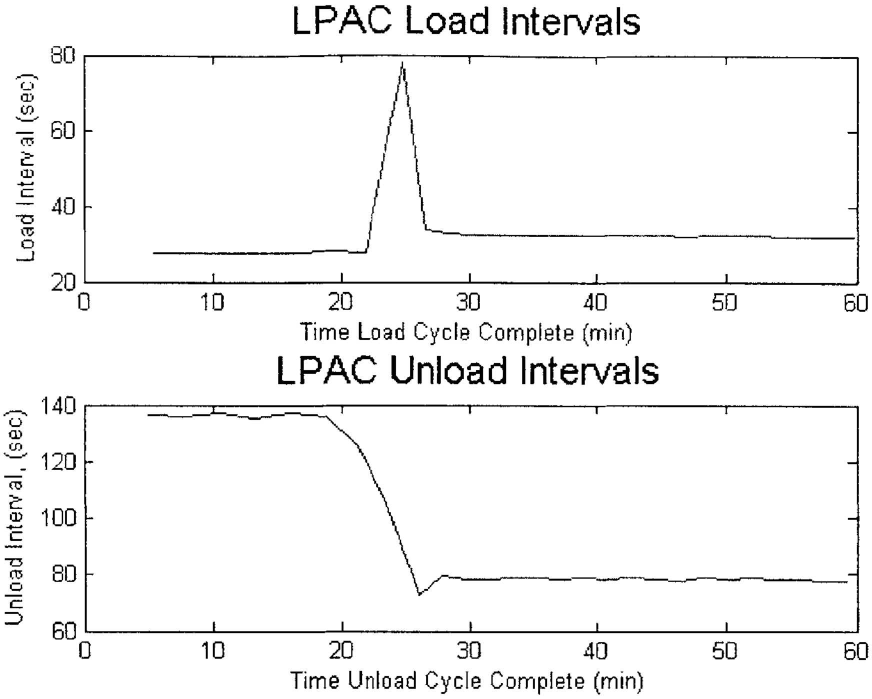

Figure 4-10: LPAC Load-Unload data before, during, and after an air start of Unit 9130 (#2 Gas Turbine Generator) between 7:00 a.m. and 8:00 a.m. on April 22, 2005. The slow decrease in unload intervals is most likely due to engineroom startup, and the various associated minor loads that entails. The large spike in load interval time is indicative of the actual GTG start.

Based on data collected between April 18 and April 22, 2005, GTG starts via either RIMSS or Start air can generate increases in the LPAC load and/or decreases in the LPAC unload intervals. The specific reason for which currently is believed to be due to the vent damper operation described above. The relation between the GTG starts and features in LPAC Load-Unload data for the period April 18 through April 22, 2005 are summarized in Table 4-6. The relation between the starts and the expected Load-Unload (L/U) behavior did not correspond exactly. As stated above, the exact damper operation is dependent on temperature, and thus it is possible for some starts not to require operation of the damper (e.g. if the damper was already open).

Table 4-6: LPAC Load-Unload Behavior Due to GTG Starts

GTG Event	Total Number of Logged Events	Number of Times L/U Relation Observed
RIMSS Start GTG #1	7	6
Air Start GTG #2	3	3

4.6 Gas Turbine Generator (GTG) Load Shifts

Similar to GTG starts, GTG load shifts are not expected to evidence themselves in any data other than possibly in LPAC Load-Unload data, and for the same reasons. A Navy ship's electric plant allows for the possibility of a multitude of different electric plant shifts, all depending on the state (open or shut) of various breakers, the number of operating generators, and the loading of the generators. The LBES is no different. Between April 18 and April 22, 2005, the LBES electric plant was manipulated into a large number of different permutations, but one particular permutation appeared to affect the LPAC Load-Unload intervals.

Figure 4-11 displays the effects of this particular electric plant operation – the opening of the 1SG breaker causing GTG #2 to carry the entire electric load. This behavior was observed once on April 18, 2005, and 8 times on April 21, 2005. In all cases, the electric load was placed entirely upon GTG #2.

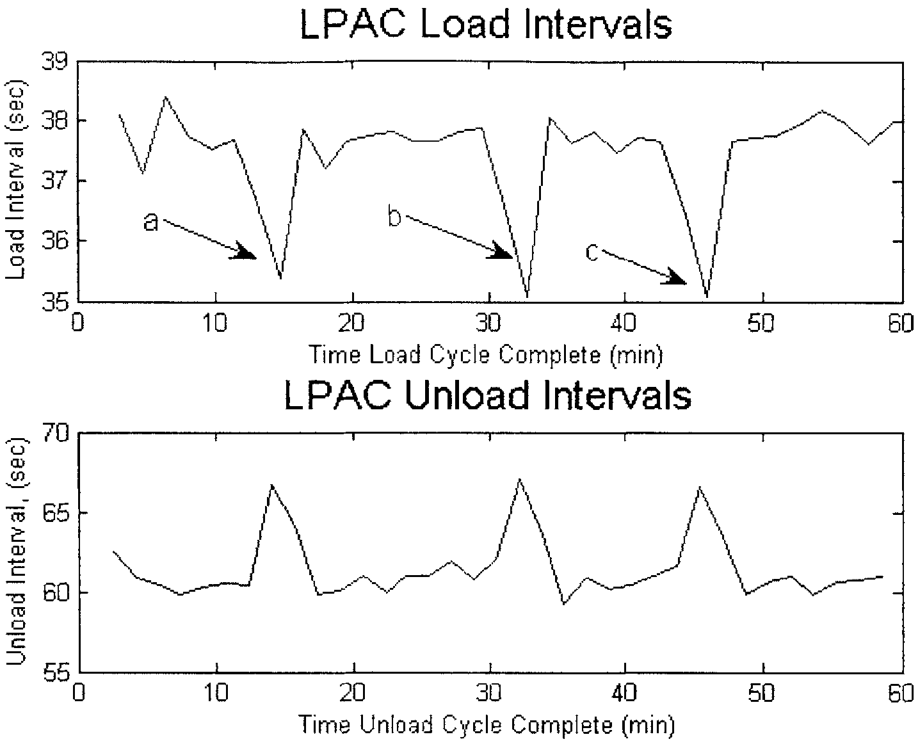

Figure 4-11: LPAC Load-Unload data for April 21, 2005 between 1:00 p.m. and 2:00 p.m. The spikes labeled a, b, and c correspond with operator log remarks of "Open 1SG, all load to #2 [GTG]".

The reason for the change in behavior of the LPAC is likely a change in position of the Bleed Air regulating valve, which relies on LP air for operation. In turn, the reason the Bleed Air regulating valve changes position for this particular event is not known either, but a possible candidate is the Transient Load Sensor of Section 2.6.6. When a GTG is "block loaded" as described in Section 2.6.6, the Bleed Air isolation valve for the loaded GTG shuts. The isolation valve is located inside the GTG module, upstream of the regulating valve, and thus the regulating valve loses its air supply. This may cause the regulating valve to reposition itself to either full open or full close. If the final position requires *little* or *no* pneumatic power to maintain that position, then the load on the LP air system will have dropped, thus causing the observed behavior in the LPAC Load-Unload intervals. There are no technical references available at this time to determine what the final position of the regulating valve is in this situation.

4.7 Leaks in the Low Pressure Air System

Short-term events, such as specific turbine operations (either GTM or GTG) are short enough in duration that they can be detected and diagnosed using hour-long snapshot data. Long-term trends, such as leaks in the low pressure air system, require inspection using a longer time frame. During the period of April 18, 2005 through April 22, 2005, a 12.5 SCFM leak was inserted into the low pressure air system using a manually operated flow valve. The leak was inserted every day during the research, and the exact time it was inserted was recorded [5]. After concatenating all the snapshot data for each day, the Load-Unload Script was run on the day-long files, and the load-unload intervals were again analyzed to look for evidence of the leak insertion. An example of a result of this analysis is shown below in Figure 4-12. The Load-Unload interval plots for each day from April 18 through April 22 are included in Appendix C.

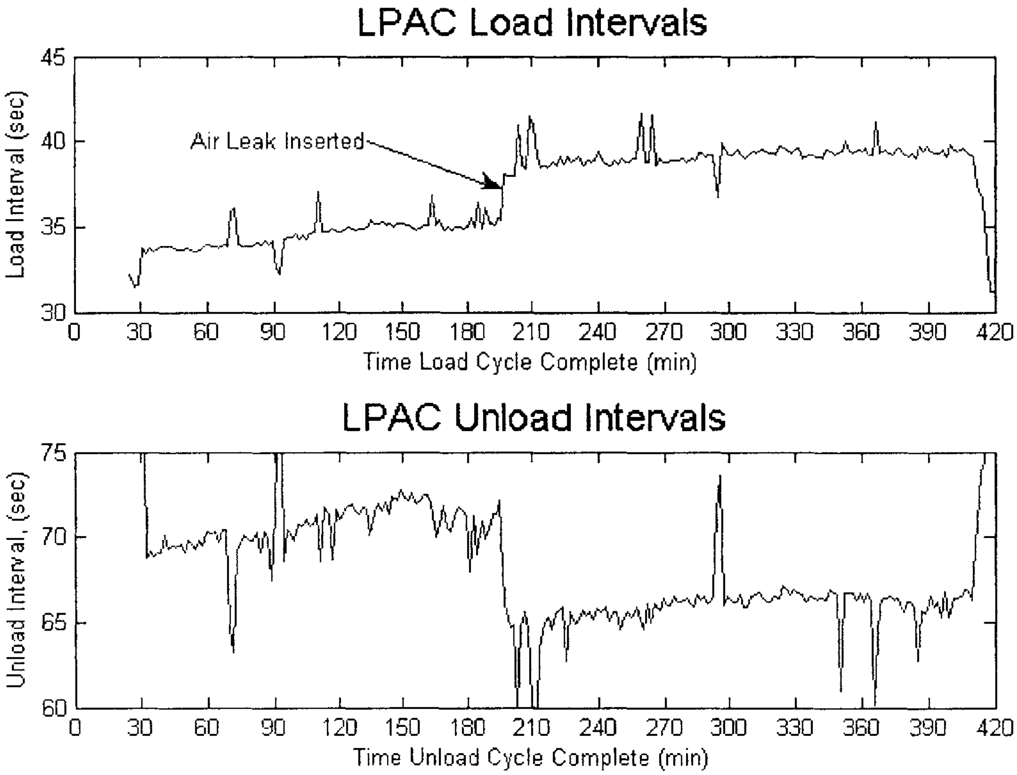

Figure 4-12: LPAC Load-Unload data for April 18, 2005. All hour long snapshots have been concatenated and then passed through the Load-Unload Script. The exact time of the air leak insertion was recorded during previous research.

The air leak insertion does not generate a spike behavior, such as those distributed throughout previous LPAC Load-Unload plots, but it does create a noticeable long-term effect in both the load and unload intervals. As expected, the leak causes an increase in the average load time and a decrease in the average unload time. This effect can be detected using an FIR filter-based change-of-mean detector.

Another instance of a long-term leak appearing in the system is the operation of the Bleed Air header itself. As stated at the beginning of this chapter, shop air was not used to supply the Start Air header during the period April 18 through April 22, 2005, and the Bleed Air header was utilized. The Bleed Air regulating valves require continuous LP air for operation (sometimes referred to as "control air"). Thus, by opening up the Bleed Air isolation valves and placing the Bleed Air regulating valves on service throughout the day, a leak effect was generated in the LP air system. An example of this effect is shown in Figure 4-13 .

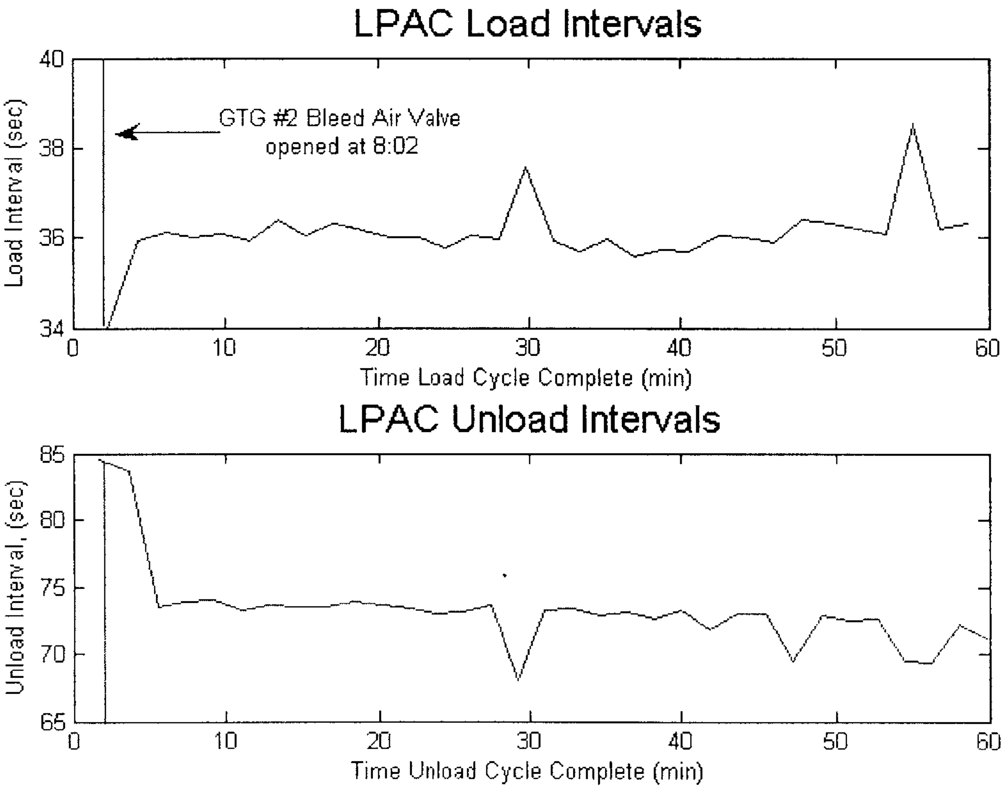

Figure 4-13: LPAC Load-Unload interval data evidencing the leak effect generated by placing the Bleed Air header on service. The data is from the period between 8:00 and 9:00 a.m. on April 19, 2005.

The leak-detection ability of the NILM can be enhanced and automated. The NILM has shown the capacity to detect large, instantaneous leaks. Given the ability to generate logs, the NILM can identify all major step changes in pneumatic load, such as those shown for the leak insertion and Bleed Air valve operation. These logs generated by the NILM can indicate any events that do not correspond to previously identified changes. An alert can then be sent to the operators warning of a possible leak.

Chapter 5 Conclusions and Further Research

Using the basic relationships between LBES system events and observed behaviors in NILM data, a method of detection, identification, and diagnosis can now be attempted. Chapter 4 examined specific LBES events and found corresponding relationships in various NILM data. Here we examine the NILM data and then develop a method to isolate and identify specific LBES events that have occurred.

5.1 Detection

The UEC NILM, combined with further data from future NILM installations, can be used to conduct initial detections for various GTM and GTG events. The UEC NILM provides a very detailed description of the UEC power during various GTM events. Because of this detail, the UEC NILM currently can determine what specific operation occurred (e.g. GTM start vice a GTM motor). Further research can expand upon the basis already developed. The data provided by the UEC NILM does not yield information that helps detect, identify, or diagnose GTG events. This can be corrected by a similar NILM installation on the GTG controller - the 301 sequencer. Together, the two NILM's (installed on the GTM UEC and the GTG sequencer) can theoretically provide detection, identification, and diagnostics for many of the standard operations performed by those two large pieces of machinery. The Fuel Oil pump and LPAC NILM data can then be used to confirm the detection and identity of these events. This combined UEC/301 sequencer data can generate logs and detect a larger array of events for both the GTM's and GTG's.

To further assist in the detection and identification of events, several additional NILM installations may prove beneficial. For example, another excellent target for NILM monitoring is the LBES lube oil system. Behavioral relations between a lube oil pump and GTM/GTG events most likely follow the same trends as the fuel oil system. Thus, starts and stops of the GTM's and GTG's may cause large enough changes in system pressure to affect pump power, which in turn can be detected and analyzed by a NILM. Other possible NILM locations and targets include:

- 115V/3-phase power to the SCU
- 115V/ single phase power to the GTM igniters (via the UEC)

- 115V/3-phase power to the 301 sequencer controlling GTG operations
- 115V/3-phase power upstream of *both* SCU and UEC (power panel 1-282-1)

5.2 Diagnostics

The combined data drawn from the above NILM installations can be used not only to determine what events happened and when, but also may be used to diagnose problems with the events. For example, the UEC data can immediately indicate an improper start of a GTM, as shown in Figure 4-5. However, the exact source of the problem is not readily apparent from just UEC data.

The UEC data can be augmented with data from the Fuel Oil pump during the failed start. This is shown in Figure 5-1. The additional data provided by the Fuel Oil pump (or Lube Oil pump, LPAC, etc.) may provide insight into what caused the fault. For example, the behavior of the Fuel Oil pump power in Figure 5-1 may indicate that fuel oil pressure did not change as is typical for GTM starts. This may be important to operators trying to decide between spending valuable time and assets troubleshooting the fuel oil system or the UEC itself or some other system (e.g. Lube Oil).

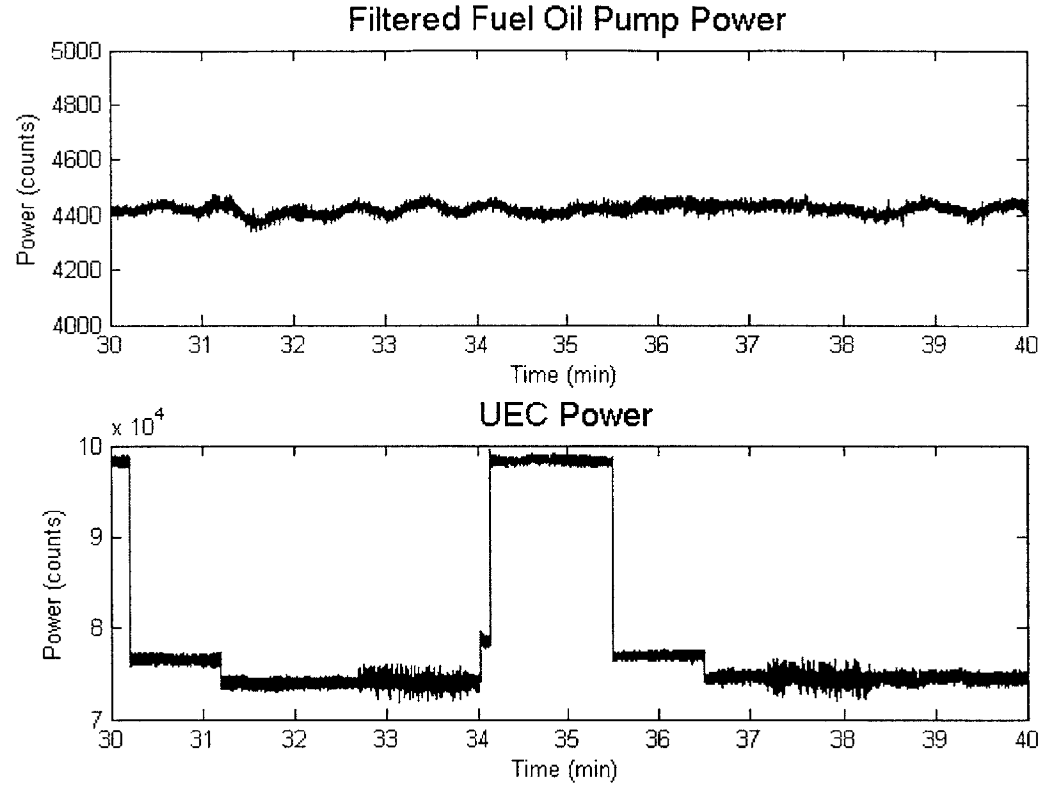

Figure 5-1: Filtered Fuel Oil pump power and UEC power during a failed GTM 2B start at approximately 10:30 a.m. on April 25, 2006. The Fuel Oil pump power remains unaltered during the failed start. This may indicate a fault in the Fuel Oil system vice the UEC, SCU, etc.

Leaks, as discussed in Section 4.7, can also be examined and diagnosed with greater detail using a combined NILM scheme. With a multitude of systems effectively monitored, the location of a leak may be pinpointed to a specific system (e.g. LP air) as opposed to a collection of hydraulic-pneumatic systems (LP air, Lube Oil, Fuel Oil, etc.). Additionally, the onset of the leak and securing of the leak may also be noted.

5.3 Future Research

To begin developing the combined NILM scheme at the LBES, several key steps must first be taken.

1. Additional data should be collected. The highest priority candidates are the Lube Oil pumps and the GTG 301 sequencers.

2. NILM automation and management must be enhanced. This involves improving the software of the NILM's to correctly identify GTM and GTG events. Furthermore the proper location and number of NILM's to be used must be determined. An example question that addresses this concern is: should the number of NILM's be increased, or should their locations be altered instead?
3. Further analysis of the LP air system must be conducted. A detailed analysis of the LP air system, including accurate pressure data during various GTM and GTG events, will assist in clarifying many inconsistencies that have developed using the LPAC Load-Unload interval data.

Ultimately, the NILM has the potential to provide large amounts of useful information while relying on only a few key penetration points into the complex electro-mechanical systems onboard US Navy ships. This is of significant value when viewed in light of the Navy's drive towards ship designs that use electricity for an increasingly larger number of functions. The information, data, and analysis discussed in this thesis provide a short example of the power of the NILM. From simple penetrations into the power feeds of the LBES LPAC, Fuel Oil pump, and UEC, data was recorded and analyzed that in turn led to the detection of state changes of systems electrically isolated from the initially targeted equipment. With additional information from future NILM installations, a vast array of events can be identified and diagnosed.

List of Acronyms

APU	Auxiliary Power Unit
BEA	Base Enclosure Assembly
EPCP	Electric Plant Control Panel
FIR	Finite Impulse Response
FSM	Finite State Machine
GTA	Gas Turbine Assembly
GTG	Gas Turbine Generator
GTM	Gas Turbine Module
LBES	Land Based Engineering Site
LPAC	Low Pressure Air Compressor
MRG	Main Reduction Gear
NILM	Non-Intrusive Load Monitor
PPAC	Propulsion Plant and Auxiliaries Control
RIMSS	Rapid Independent Mechanical Starting System
SCU	Shaft Control Unit

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Appendix A. LBES Test Plan for Installment of UEC NILM on February 23, 2006

A. OBJECTIVE:

Evaluate the use of the non-intrusive load monitor (NILM) in detecting propulsion turbine 2A/2B control signals. The NILM will be left in place to allow for the collection of long term normal operating data.

B. BACKGROUND:

Following experiments on board the USCG *Seneca* and at the DDG-51 LBES, the NILM has been shown to be able to diagnose state changes in various mechanical systems. The power feed to the Universal Engine Controller (UEC) may contain information relevant to the diagnosis of specific control signals sent from the UEC to individual main propulsion turbines 2A and 2B, and thus be able to determine state changes in the propulsion turbines.

C. PREREQUISTES:

1. Ensure NILM sensing box (NEMA-style enclosure) is constructed to monitor 115VAC / 3-phase power.

D. PRELIMINARY:

1. Read through the procedure in its entirety prior to beginning the test.

E. PROCEDURE:

1. Open breakers for 115 VAC / 3-phase power supplying Propulsion Turbine 2A UEC (labeled 'IIEC') at power panel 1-282-1. Danger Tag Open.
2. Open breakers for 115 VAC / 3-phase power supplying Propulsion Turbine 2B UEC (labeled 'IIEC') at power panel 1-282-1. Danger Tag Open.
3. Remove cover plate at power panel 1-282-1.
4. Lift the lead for one phase of Propulsion Turbine 2A UEC power. Thread the power cable through current transformer (type LM-55), and replace the lead.
5. Attach NILM voltage leads to remaining two phases of Propulsion Turbine 2A UEC power. This voltage sensing cable is rated for 600V.
6. Lift the lead for one phase of Propulsion Turbine 2B UEC power. Use the same phase (A, B or C) as in step (4) above. Thread the power cable through current transformer (type LM-55), and replace the lead. This is a second and identical, but separate transformer than the one used in step (4) above.

7. Route the two current transformer cables (steps 4 and 6) and the voltage sensing cable (step 5) through existing cutouts in the top of power panel 1-282-1 and into the NILM NEMA sensing box.

8. Connect current transformer and voltage cables in the NILM sensing box.

9. Close NILM sensing box.

10. Re-install cover plate for power panel 1-282-1.

11. Remove Danger Tags from breakers for 115 VAC / 3-phase power for Propulsion Turbine 2A and 2B UEC at power panel 1-282-1.

12. Shut breakers for 115 VAC / 3-phase power for Propulsion Turbine 2A and 2B UEC at power panel 1-282-1.

13. Plug in associated NILM PC and NILM sensing box to standard 120 VAC power outlet and start NILM acquisition software.

14. The NILM system is now ready to record data.

Appendix B. MATLAB Analysis Scripts

B.1 Load-Unload Calculation Script

```
%LOAD/UNLOAD CALCULATOR
%DUNCAN MCKAY
%APRIL 19, 2006
%
%This code utilizes four functions:
%on_off_detector.m
%nilmconst_lpac.m
%event_lpac.m
%lu_computer.m
%
%This code will calculate load and unload times from a snapshot and then it
%will plot them.

%This is the executable script

raw=load('20050418-160001.txt');
[events1,on_times1,off_times1]=on_off_detector(raw);
[L1,U1]=lu_computer(events1);

subplot(2,1,1)
plot(on_times1*(1/120),L1*(1/120));
subplot(2,1,2);
plot(off_times1(1:length(off_times1)-1)*(1/120),U1*(1/120));
```

```
function [events] = on_off_detector(x)

y = medfilt1(x,3);
x=y;
clear y;

nilmconst_lpac;
b = fir1(FILTER_LENGTH,FILTER_CUTOFF);
thresh = 1200; %GETEVENTS_THRESHOLD
[ev,z] = event_lpac(x,b,thresh)

if (mean(x(1:40))>=thresh)
    ev = ev(2:length(ev))
end

events = zeros(2,length(ev));

ev;

for j = 1:1:length(ev)
    change = mean(x(ev(j)+10:ev(j)+20))-mean(x(ev(j)-20:ev(j)-10))   ;
    if (change < 0)
        events(2,j) = -1;
        events(1,j) = ev(j);
    else
        events(2,j) = 1;
        events(1,j) = ev(j);
    end
end

new = [];
for j=1:1:length(ev)
    if j == 1
        if events(2,j) == 1
            new = [new events(:,j)];
        else
            if (events(1,2)-events(1,1)) > 1000
                new = [new events(:,j)];
            end
        end
    else
        if events(2,j) == 1 && events(2,j-1) == -1
            %j
            if (events(1,j) - events(1,j-1)) < 1000
             new = [new events(:,j)];
            end
        end
        if events(2,j) == -1 && events(2,j-1) == 1
            j;
```

```
            new = [new events(:,j)];
        end
    end
end
events =  new;

function [L,U] = lu_computer(events)
    L = [];
    U = [];
    y=diff(events(1,:));
    if events(1,2) == 1
        for i=1:1:length(y)
            if (rem(i,2) ~= 1)
                L = [L y(i)];
            else
                U = [U y(i)];
            end
        end
    else
        for i=1:1:length(y)
            if (rem(i,2) == 1)
                L = [L y(i)];
            else
                U = [U y(i)];
            end
        end
    end

end
```

```
% Elementary Event Detector - Uses a simple FIR filter designed using fir1

%
% Mark events in the incoming stream y.
%
function [e,y] = event(y,b,thres)

  nilmconst_lpac;

  if columns(y) > rows(y)
    y = y';
  end;

  fy = filter(b,1,y);
  dy = y - fy;

  % find events -> make indicator variables.
  ify = find(abs(diff(abs(dy)>thres)) == 1);
  if (isempty(ify) == 1)
    e = [];
    y = [];
    return;
  end;

  % cluster
  e = ify(1);    % Initializing e to first event location
  le = ify(1);   % Last event location
  ee = 0;

  for i=2:length(ify)
    %if ify(i) > length(y)-100
        % If an event is within the last 100 points, return a vector that
        % contains all of the points that follow it
        %y = y(ify(i):length(y));
        %ee = 1;
        %break;
        %end;
    if ify(i) > le+GETEVENTS_SKIP
      % Mark an event only if a change is observed at least 50 points after
      % the last event.
      e = [e ify(i)];
      le = ify(i);
    end;
  end;

  if ee == 0
    y = [];
  end;
```

```
%
% (C)opyright 1998, Steven R. Shaw
%

%
% This file contains all the constants relative to the NILM.
% The purpose is to make Octave and C code have uniform effects.
%

%%%%%%%%%%%%%

global FINDAB_N CLAIM_APERATURE FILTER_LENGTH FILTER_CUTOFF STAGE_LENGTH ...
    OFFSET_RANGE MAX_SUBSECTIONS MAX_SUBSECTIONS GETEVENTS_SKIP
GETEVENTS_LOCKOUT GETEVENTS_THRESHOLD ...
    N_DD N_EP N_HIT N_RECORD

FINDAB_N = 20;
CLAIM_APERATURE = 15;
FILTER_LENGTH = 32;
FILTER_CUTOFF = .1;
STAGE_LENGTH = 1000;

%%%%%%%%%%%%%
OFFSET_RANGE = 5;
MAX_SUBSECTIONS = 10;

%%%%%%%%%%%%%
GETEVENTS_LOCKOUT = FILTER_LENGTH;
GETEVENTS_SKIP = 50;
GETEVENTS_THRESHOLD = 400;

%%%%%%%%%%%%%
N_DD = 400;
N_EP = 4000;
N_HIT = 100;

%N_RECORD = 256;
N_RECORD = 600;
%DC_NAMES = [ 'FINDAB_N'; 'CLAIM_APERATURE'; 'FILTER_LENGTH';  %
%          'STAGE_LENGTH'; 'GETEVENTS_LOCKOUT'; 'GETEVENTS_SKIP'; 'N_DD' ; %
%     'N_EP'; 'N_HIT'; 'N_RECORD'; 'GETEVENTS_THRESHOLD'; %
%     'MAX_SUBSECTIONS'; 'OFFSET_RANGE'];
```

B.2 Fuel Oil Pump Filter Script

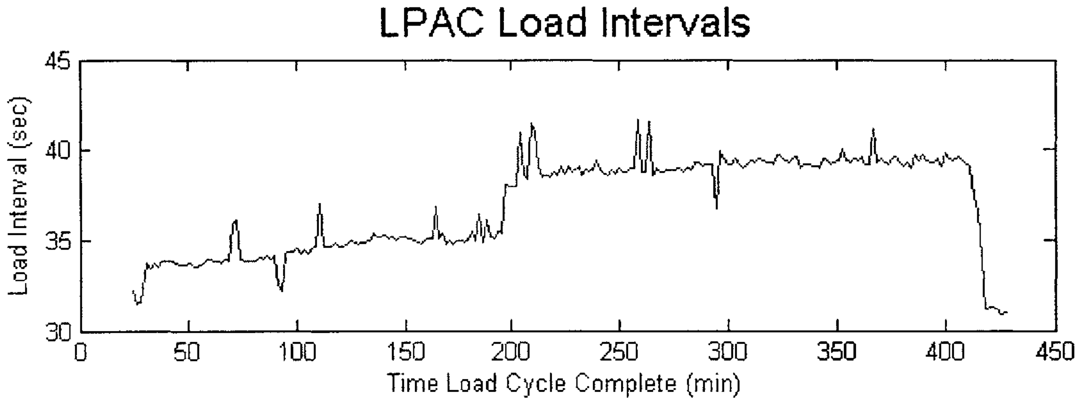
```
%SNAPSHOT DATA PLOTTING CODE
%DUNCAN MCKAY
%AUGUST 22 2005
%
%This code will plot pre-processed ("prep") data,
%either the snapshots themselves, or load/unload times
%extracted from the snapshots.  This version contains elements to filter
%data.
%
%This is the executable script
clear;
format compact;
s=120; %Sampling frequency for pre-processed data
a=load('fo-20050418-190001.txt');
load b.mat;
x=1:length(a);
%For ease of plotting, an examination point is used.  The examination point
%is the time, in minutes, when a specific event (motor, start, etc.)
%occurred.
ep=46; %Examination point
subplot(2,1,1);
plot(x/(s*60),a);%unfiltered
xlabel('Time (min)');
ylabel('Power (counts)');
axis([ep-5 ep+5 3500 6500]);
y=filter(b,1,a);
subplot(2,1,2);
plot(x/(s*60),y);%filtered
xlabel('Time (min)');
ylabel('Power (counts)');
axis([ep-5 ep+5 3500 6500]);
```

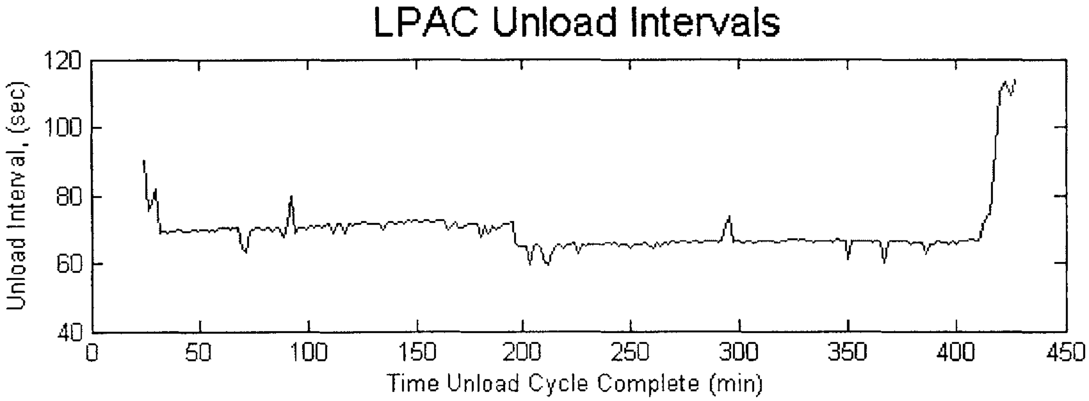
```
    elements of b.mat

     0.0002                                      0.0913
     0.0002                                      0.0880
     0.0002                                      0.0817
    -0.0001                                      0.0730
    -0.0006                                      0.0624
    -0.0014                                      0.0508
    -0.0025                                      0.0389
    -0.0038                                      0.0276
    -0.0052                                      0.0174
    -0.0064                                      0.0089
    -0.0071                                      0.0022
    -0.0069                                     -0.0026
    -0.0055                                     -0.0055
    -0.0026                                     -0.0069
     0.0022                                     -0.0071
     0.0089                                     -0.0064
     0.0174                                     -0.0052
     0.0276                                     -0.0038
     0.0389                                     -0.0025
     0.0508                                     -0.0014
     0.0624                                     -0.0006
     0.0730                                     -0.0001
     0.0817                                      0.0002
     0.0880                                      0.0002
     0.0913                                      0.0002
```

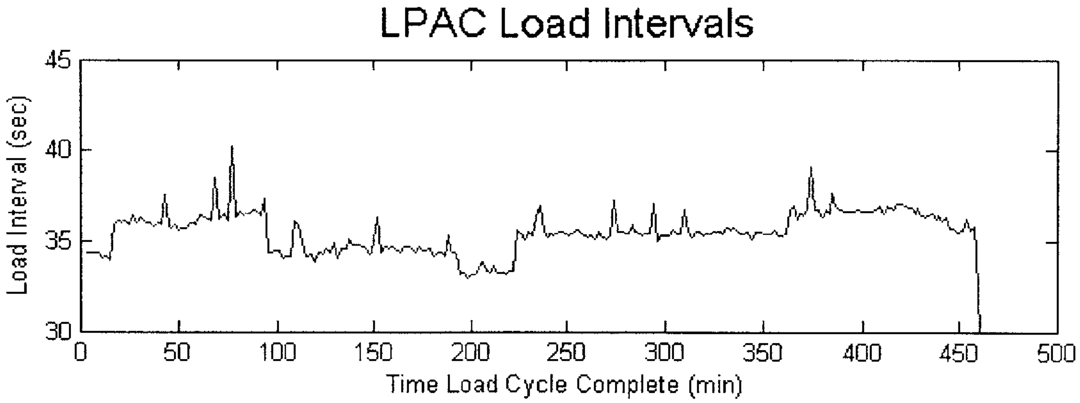
Appendix C. Daylong LPAC Load-Unload Interval Plots (April 18, 2005 – April 22, 2005)

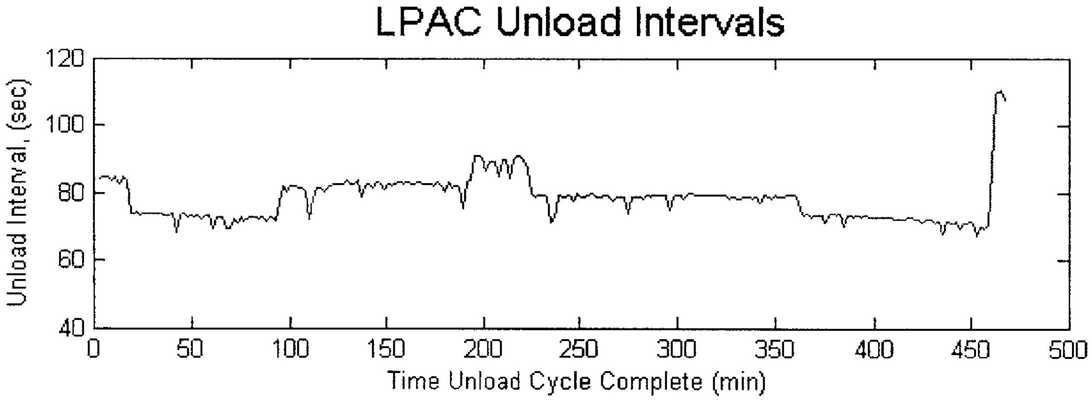
April 18, 2005



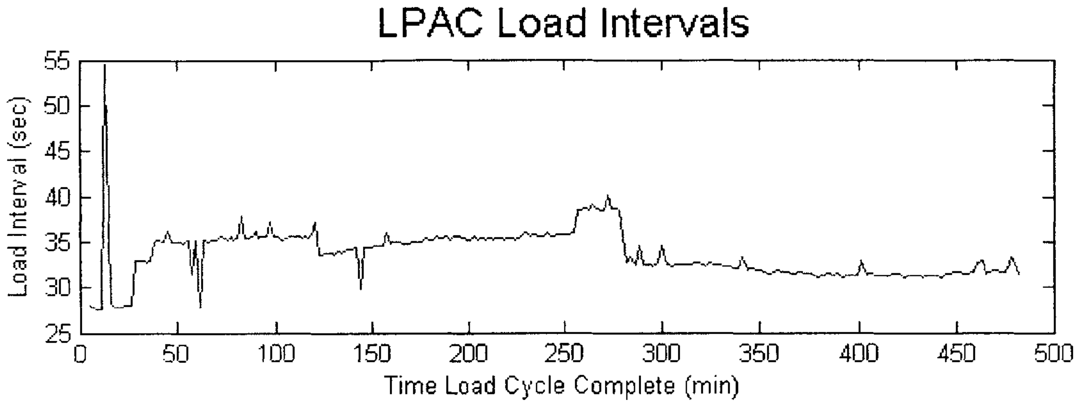


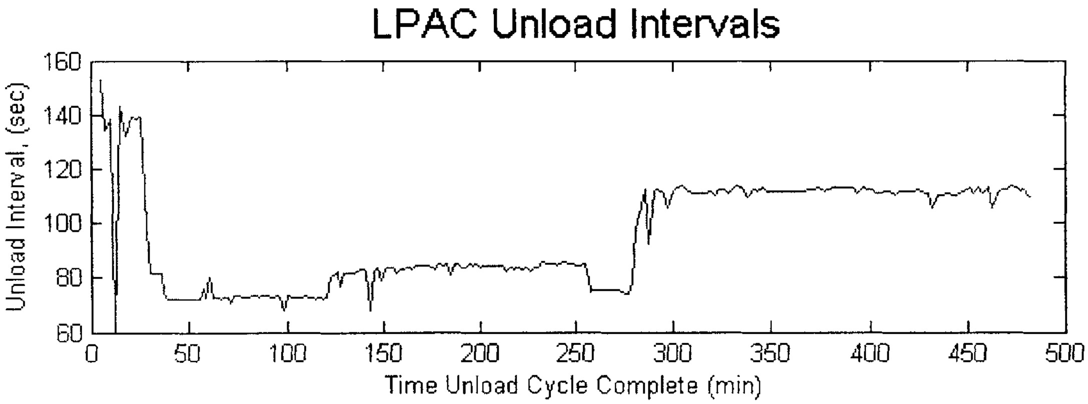
April 19, 2005


LPAC Load Intervals

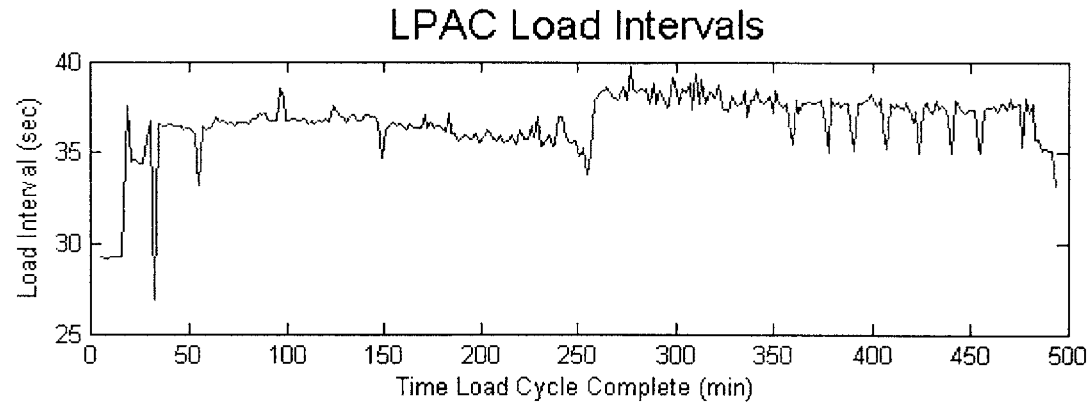

LPAC Unload Intervals

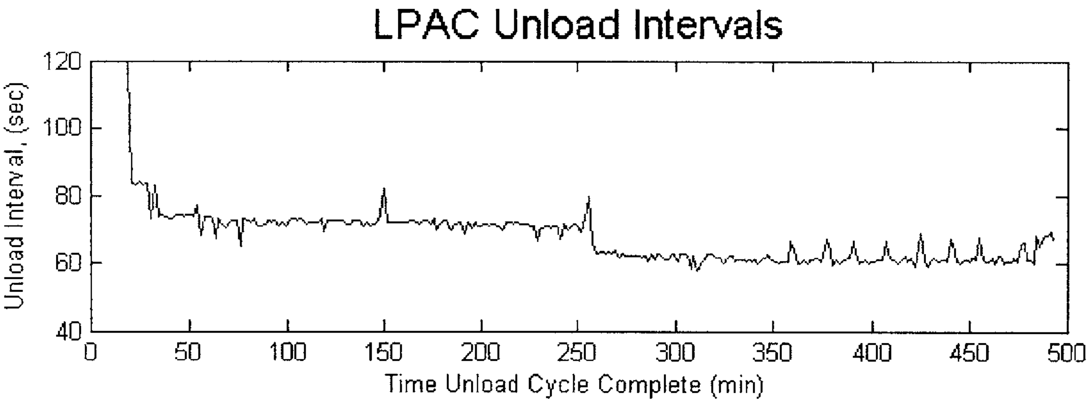
April 20, 2005


LPAC Load Intervals

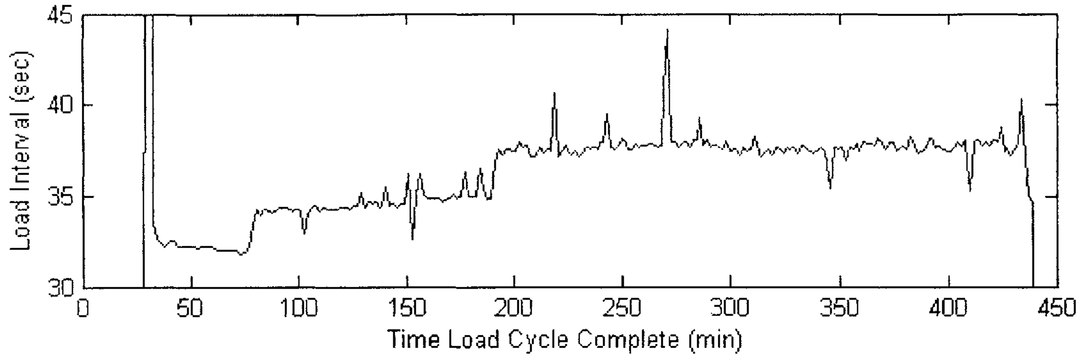

LPAC Unload Intervals

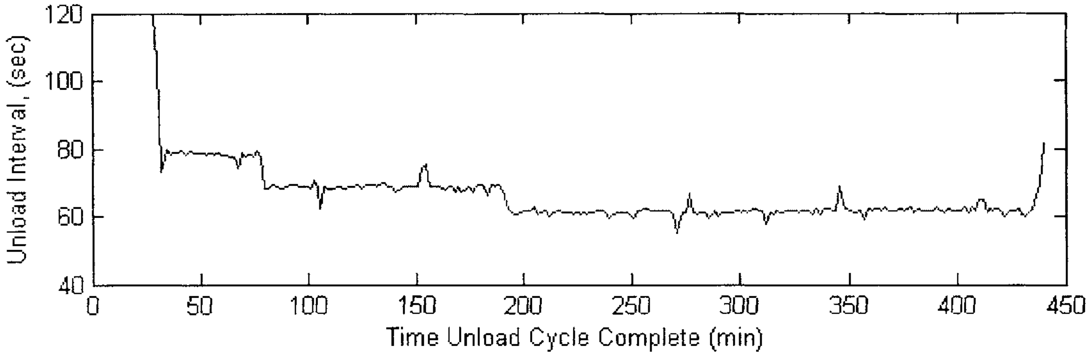
April 21, 2005



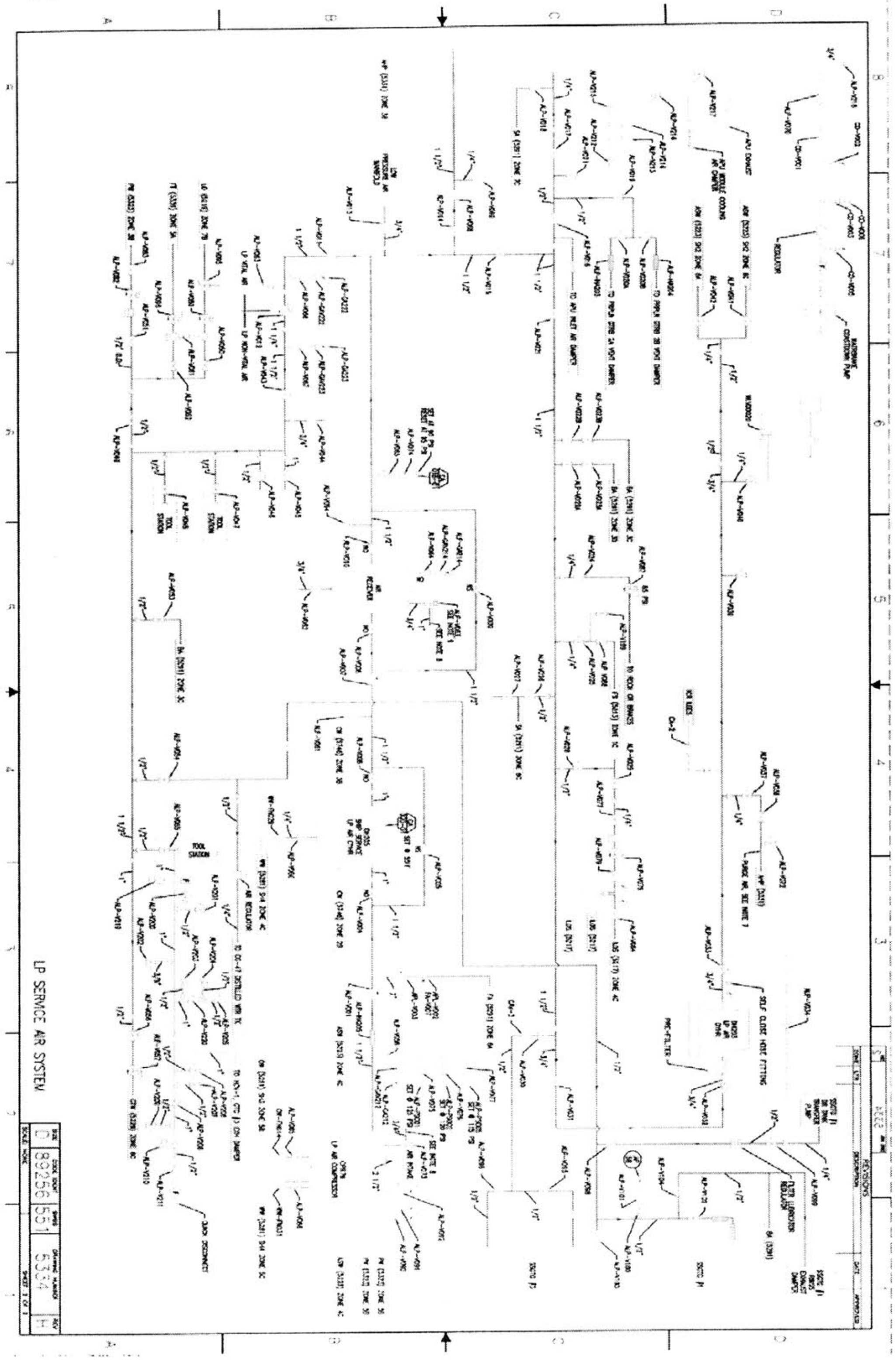


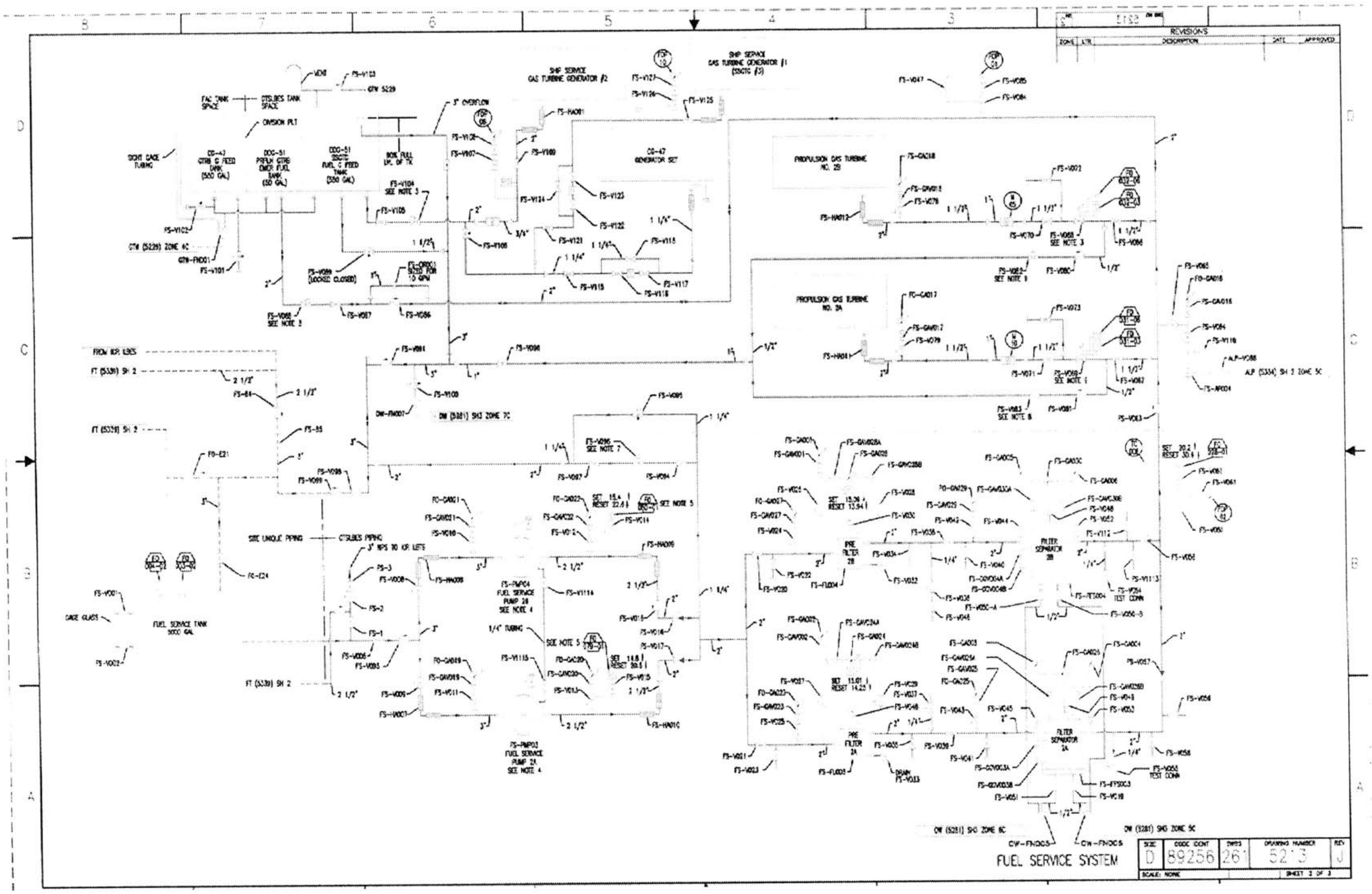
April 22, 2005


LPAC Load Intervals

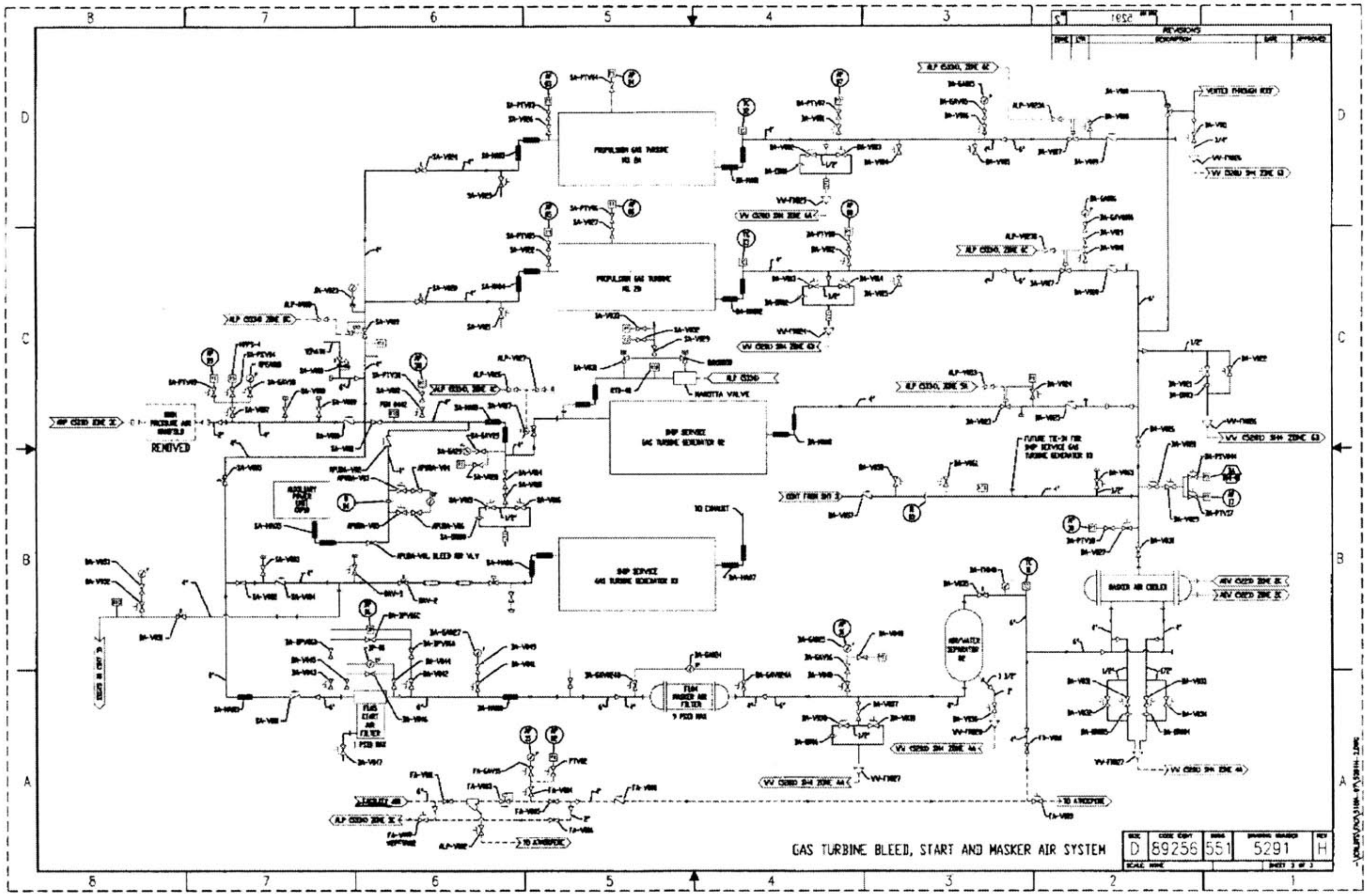

LPAC Unload Intervals

Appendix D. LBES System Schematics





FUEL SERVICE SYSTEM


PROPULSION GAS TURBINE
PROPULSION GAS TURBINE
SHIP SERVICE GAS TURBINE GENERATOR
SHIP SERVICE GAS TURBINE GENERATOR
REMOVED
AUXILIARY POWER UNIT
MASKER AIR COOLER
AIR/WATER SEPARATOR
GAS TURBINE BLEED, START AND MASKER AIR SYSTEM
D
89256
551
5291
H
REVISIONS
8
7
6
5
4
3
2
1
D
C
B
A

Appendix E. LBES Points of Contact

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