
**Pacific Northwest
National Laboratory**

Operated by Battelle for the
U.S. Department of Energy

Engine Removal Projection Tool, Version 1.0, User Guide, Administrator Manual, Technical Documents

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PACIFIC NORTHWEST NATIONAL LABORATORY

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BATTELLE

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Engine Removal Projection Tool

Version 1.0

User Guide Administrator Manual Technical Documents

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Prepared for: NAVSEA Marine Gas Turbine
Information System (MGTIS) Program

Prepared by:
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I. Overview

A. Introduction and Background

The US Navy has over 3500 gas turbine engines used throughout the surface fleet for propulsion and the generation of electrical power. The US Navy, Naval Sea Systems Command (NAVSEA) Marine Gas Turbine Information System (MGTIS) Program archives engines' historical operating and removal data for use in logistics and lifecycle planning. One analysis conducted by the MGTIS Program is to project the number of engine removals for the next ten years and determine engine down times between removals. To support this effort, NAVSEA currently uses a software program, implemented in FORTRAN in the early 1970s. The program runs on a mainframe computer and is inconvenient to use. In addition, because it does not account for certain important factors (such as decommissioning), various manual manipulations and subjective judgments are needed to make the program fit the current needs of the MGTIS program. Finally, the underlying statistical methods employed by the FORTRAN program are not well documented or understood. Thus there was a need for a new program that is more convenient to use and that is based on a defensible scientific methodology. This program is the result of the research and development conducted by Pacific Northwest National Laboratory to develop algorithms to forecast engine replacements and the implementation of a new user-friendly software program to enable the NAVSEA user to formulate forecasts that support their logistics needs. Benefits of this program are the following:

- i. The algorithms are defensible, well-documented and outperform the existing algorithms.
- ii. The software can extend the forecasting algorithm work to present a variety of information based on the data analysis and forecast.
- iii. The software presents intuitive displays, is easy to run with minimal training, and can run under Windows as a Web-based application.

B. Project funded by Naval Sea Systems Command (NAVSEA), Naval Surface Warfare Center (NSWC)

C. Section II – User Manual and Help

Section III – Administrator Manual and Help

Appendix A – Paper presented/published at 2005 ASNE Intelligent Ship Symposium

Appendix B – Database Schema

D. Conclusions and Summary

This software demanded the merger of good mathematical statistical science and computer science to create an effective tool to support NAVSEA's logistics needs. The initial implementation of the ERP Tool is on the collection of 3100 Gas Turbine Engines. The ERP Tool algorithm results in approximately a 10% improvement over the current practice. This will help guard against purchasing in advance of demand and, in addition, will help avoid the more serious situation--a shortfall. The software uses the *best* algorithm in combination with user-friendly interfaces and intuitively understandable displays. The user can select a specific engine type, forecast time period, and op-tempo. Graphical displays and numerical tables present forecasts and uncertainty intervals. The technology developed for the project is applicable to other logistic forecasting challenges any where improved forecasting and/or user-friendly software tools could help the logistics tasks.

E. Points of Contact

NAVSEA Concerns/Issues - NAVSEA Project Manager, Ed Hilferty (HilfertyEL@nswccd.navy.mil)

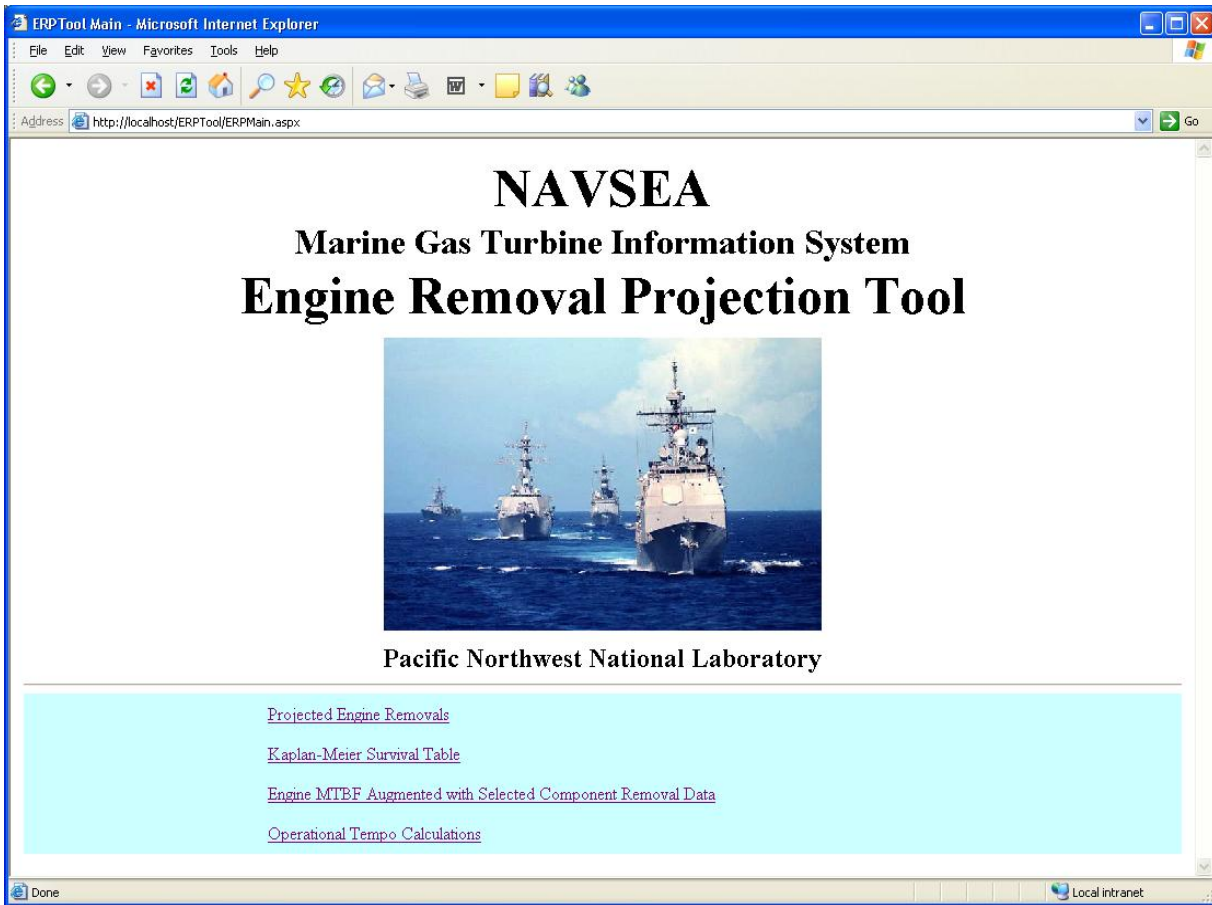
Technical Concerns/Issues - PNNL Principal Investigator, Tom Ferryman (tom.ferryman@pnl.gov)

PNNL Project Manager, Frank L. Greitzer (frank.greitzer@pnl.gov)

User Manual and Help

II. User Manual and Help

Main Menu



1. Main Menu

The Engine Removal Projection (ERP) Tool was developed at Pacific Northwest National Laboratory to forecast gas turbine engine replacements for the U.S. Navy. This page serves as the starting point of the program and must be returned to in order to navigate the different functions of ERP. The different functions of ERP include the following:

- Operational Tempo Calculations
- Engine MTBF Augmented with Selected Component Removal Tool
- Kaplan-Meier Survival Table
- Projected Engine Removals
 - Projected Engine Removal Table
 - Projected Engine Removal Graph
 - Cumulative Projected Engine Removal Graph (Multiple Years)
 - Cumulative Projected Engine Removal Graph (Single Year)

A. Click on any one of the underlined phrases to select that function

Operational Tempo Calculations

Operational Tempo Calculations

Begin Date: 05 / 2000
 End Date: 04 / 2004

[Return to Main](#)
☐ Show Actual Calculated Hours

Class	Desc	Engine	Peacetime	Multiplier	Wartime Calculated
1 DD	501-K17 COMPRESSOR		200.00	1.33	266.00
1 DD	501-K17 TURBINE		200.00	1.33	266.00
1 DD	LM2500 GAS GENERATOR PAIRED BLADE		130.00	1.33	172.90
1 DD	LM2500 POWER TURBINE		130.00	1.33	172.90
10 MCM	T-1302S SOLAR GAS GENERATOR		10.00	1.00	10.00
3 FFG	LM2500 GAS GENERATOR PAIRED BLADE		115.00	1.75	201.25
3 FFG	LM2500 POWER TURBINE		115.00	1.75	201.25
4 CG	501-K17 COMPRESSOR		195.00	1.50	292.50
4 CG	501-K17 TURBINE		195.00	1.50	292.50
4 CG	LM2500 GAS GENERATOR PAIRED BLADE		125.00	1.50	187.50
4 CG	LM2500 GAS GENERATOR SINGLE SHANK		125.00	1.50	187.50
4 CG	LM2500 POWER TURBINE		125.00	1.50	187.50
6 DDG	501-K34 COMPRESSOR		185.00	1.15	212.75
6 DDG	501-K34 TURBINE		185.00	1.15	212.75
6 DDG	LM2500 GAS GENERATOR SINGLE SHANK		105.00	1.45	152.25

2. Operational Tempo Calculations

This page displays the expected operational tempo for all engines for both peacetime and wartime conditions. It also calculates the actual hours of use during a selected time period. The page also allows the user to modify the wartime multiplier for each engine.

A. Select the time period

- i. Select the begin date.
- ii. Select the end date.

Note: The end date cannot occur before the begin date.

- B.** Check the box marked “Show Actual Calculated Hours” to show the actual number of hours the engine was used for the time period. Leave the box unmarked to skip this calculation.
- C.** Click the “Update Table” button to save the wartime multipliers and update the calculated values.
- D.** To return to the previous menu, click the underlined phrase Return to Main.

Engine/Component MTBF

TAN Record	TAN	Name	Removals	MTBF
14	D110	INLET GEARBOX ASMBY	1	758,951
15	D120	TRANSFER GEARBOX	0	----
16	D125	TRANSFER GEARBOX SP	2	379,475
17	D130	PUMP FUEL MAIN	5	151,790
18	D140	FUEL CONTROL MAIN	51	14,881
19	D145	CIT SENSOR	40	18,974
20	D150	PNEUMATIC STARTER	52	14,595
21	D160	ACTUATOR PWR LVL AGL	200	3,795
22	D170	PUMP LUBE SCAVENGE	9	84,328
23	D180	COMPRESSOR ROTOR ASY	0	----
24	D180A	DISC STG 1	0	----
25	D180B	DISC STG 2	0	----

3. Engine/Component MTBF

This page displays the mean time between failures for a selected engine during a selected time period. The table also shows the TAN Record, removal count, and the mean time between failures for individual components of a selected engine.

A. Select the engine type.

B. Select the time period

i. Select the begin date.

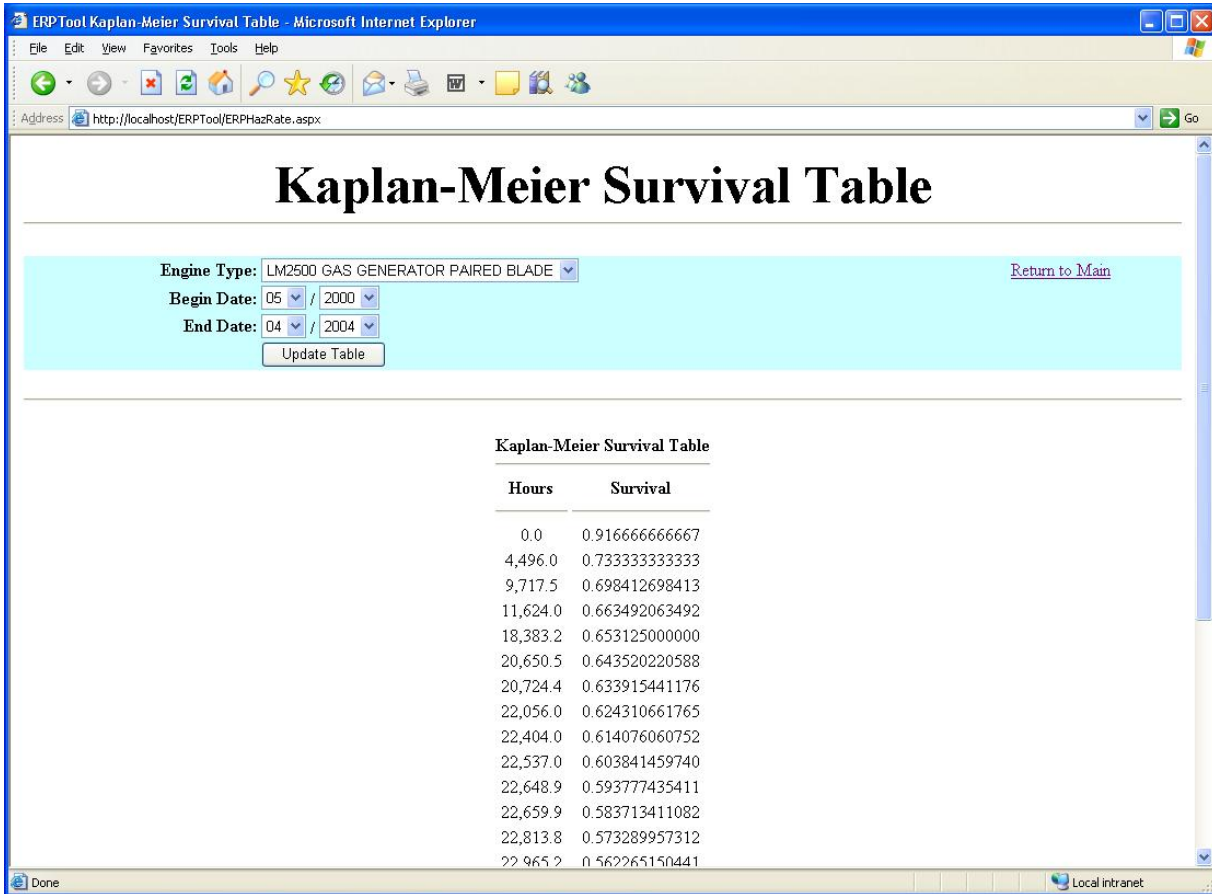
ii. Select the end date.

Note: The end date cannot occur before the begin date.

C. Click the “Update Table” button to display the results of your selections.

D. To return to the previous menu, click the underlined phrase Return to Main.

Kaplan-Meier Survival Table



4. Kaplan-Meier Survival Table

This page displays the survival table for a selected engine during a selected time period. The table shows the percentage of survival for the selected engine based on hours in use.

- A. Select the engine type.
- B. Select the time period
 - i. Select the begin date.
 - ii. Select the end date.

Note: The end date cannot occur before the begin date.

- C. Click the "Update Table" button to display the results of your selections.
- D. To return to the previous menu, click the underlined phrase Return to Main.

Projected Engine Removals Menu



5. Projected Engine Removals Menu

This page serves as the starting point for the Projected Engine Removal function. The different features of this function include the following:

- Projected Engine Removal Table
- Projected Engine Removal Graph
- Cumulative Projected Engine Removal Graph (Multiple Year)
- Cumulative Projected Engine Removal Graph (Single Year)

A. Click on any one of the underline phrases to select that function.

B. To return to the main menu, click the underlined phrase Return to Main.

Engine Removal Projection Table

ERPTool Engine Removal Projection Table - Microsoft Internet Explorer

Address: http://localhost/ERPTool/ERPProjTable.aspx

Projected Engine Removals

Engine Type: LM2500 GAS GENERATOR PAIRED BLADE [Return to Projection Menu](#)

Historical Begin Date: 05 / 2000

Historical End Date: 04 / 2004

Projection Begin Date: 05 / 2004

Projection End Date: 09 / 2008

☐ Use Wartime Multipliers

Projection Period	Engine Operating Hours	Installed Engines	Expected Removals	Upper 90% Bound	Avg. Expected Removal Age	Projected MTBR (Hrs)	Stable MTBR (Hrs)
200405 - 200409	109,550	178 (117*)	6	9	23,679	19,408	28,286
200410 - 200509	262,920	178 (117*)	13	18	23,563	19,702	28,286
200510 - 200609	262,920	178 (117*)	13	18	24,204	20,418	28,286
200610 - 200709	262,920	178 (117*)	12	17	26,296	21,249	28,286
200710 - 200809	262,920	178 (117*)	9	13	32,215	28,426	28,286

* = "Live" Engines

6. Engine Removal Projection Table

This page allows the user to display the projected engine removals for a selected engine during a selected historical time period and a selected projection time period.

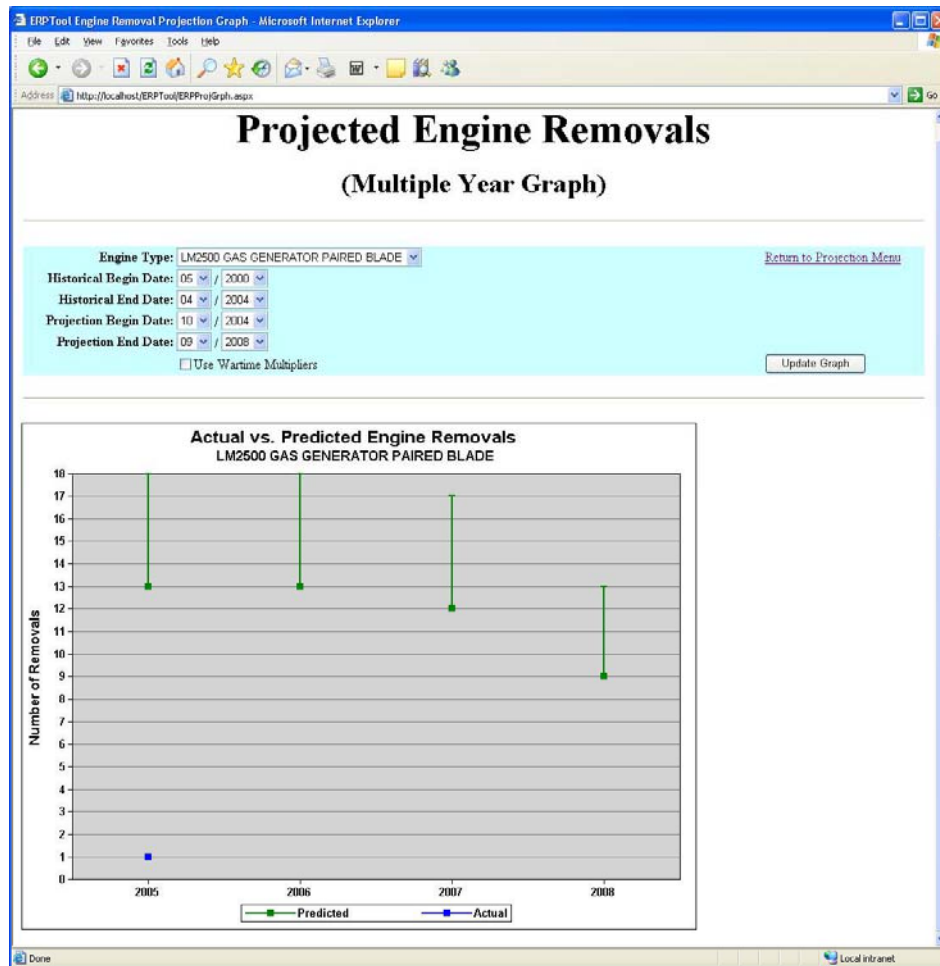
- A. Select the engine type.
- B. Select the historical time period
 - i. Select the historical begin date.
 - ii. Select the historical end date.

Note: The historical end date cannot occur before the historical begin date.
- C. Select the projection time period.
 - i. Select the projection begin date.
 - ii. Select the projection end date.

Note: The projection end date cannot occur before the projection begin date.

Note: The projection end date cannot occur before the historical end date.
- D. Check the box marked "Use Wartime Multipliers" to determine the engine removal projection during wartime. Leave the box unchecked to determine the engine removal projection during peacetime.
- E. Click the "Update Table" button to display the results of your selections in tabular format.
- F. To return to the previous menu, click the underlined phrase Return to Projection Menu.

Engine Removal Projection Graph



7. Engine Removal Projection Graph

This page allows the user to display the projected engine removals in graphical format for a selected engine during a selected historical time period and a selected projection time period.

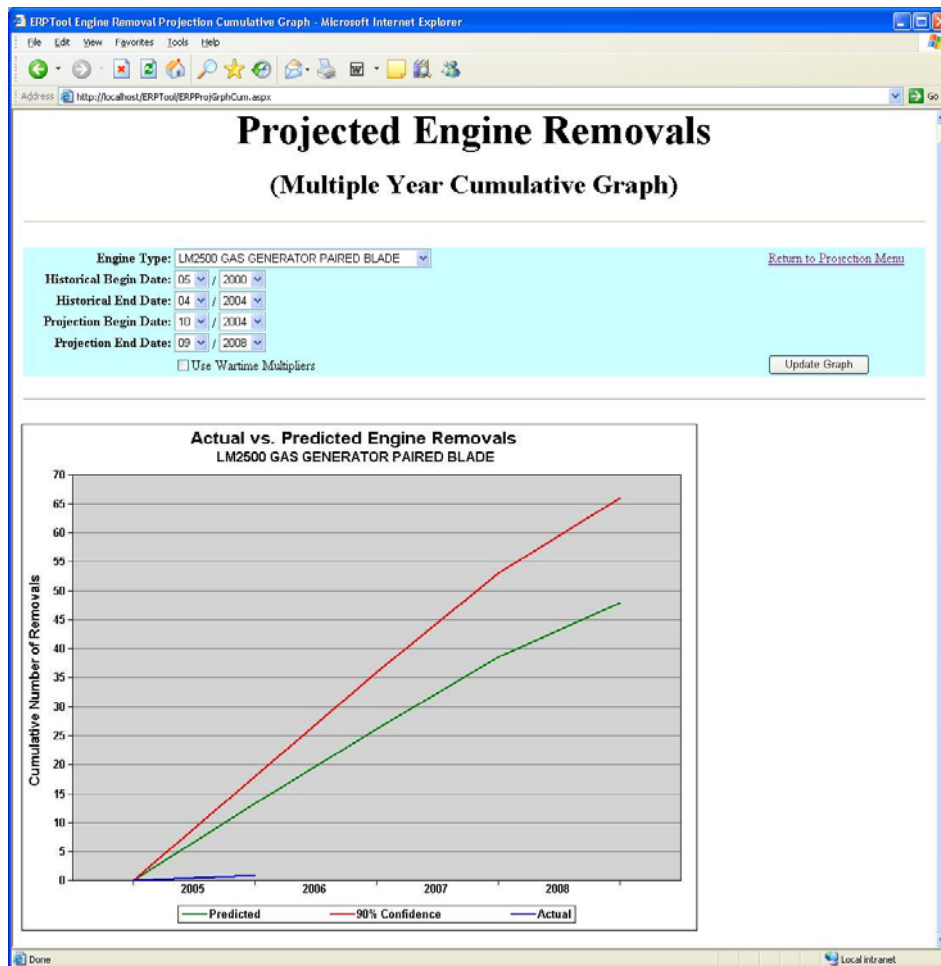
- A. Select the engine type.
- B. Select the historical time period
 - i. Select the historical begin date.
 - ii. Select the historical end date.

Note: The historical end date cannot occur before the historical begin date.
- C. Select the projection time period.
 - iii. Select the projection begin date.
 - iv. Select the projection end date.

Note: The projection end date cannot occur before the projection begin date.

Note: The projection end date cannot occur before the historical end date.
- D. Check the box marked “Use Wartime Multipliers” to determine the engine removal projection during wartime. Leave the box unchecked to determine the engine removal projection during peacetime.
- E. Click the “Update Graph” button to display the results of your selections in graphical format.
- F. To return to the previous menu, click the underlined phrase Return to Projection Menu.

Engine Removal Projection Cumulative Graph (Multiple Year)



8. Engine Removal Projection Cumulative Graph (Multiple Year)

This page displays a multiple year graph of the projected engine removals for a selected engine during a selected historical time period and a selected projection time period.

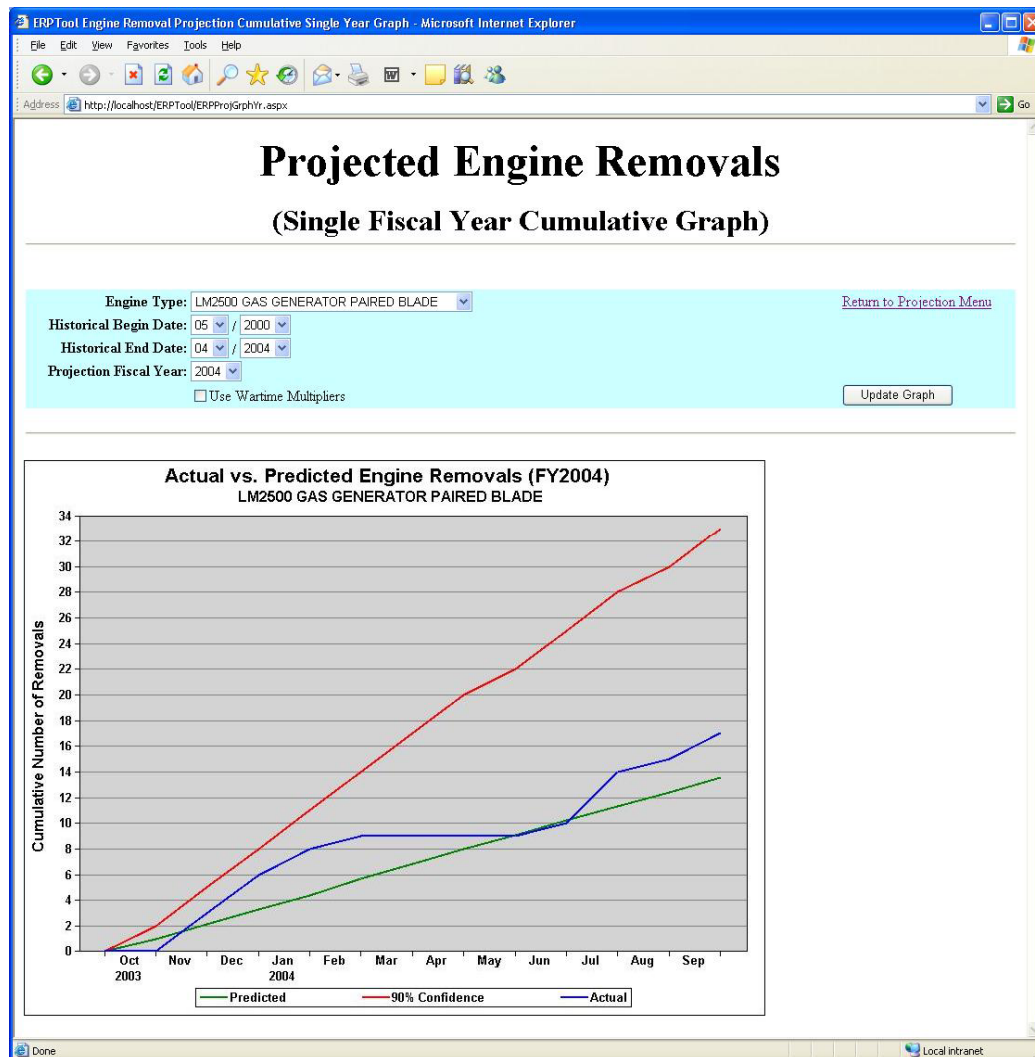
- A. Select the engine type.
- B. Select the historical time period
 - i. Select the historical begin date.
 - ii. Select the historical end date.

Note: The historical end date cannot occur before the historical begin date.
- C. Select the projection time period.
 - i. Select the projection begin date.
 - ii. Select the projection end date.

Note: The projection end date cannot occur before the projection begin date.

Note: The projection end date cannot occur before the historical end date.
- D. Check the box marked “Use Wartime Multipliers” to determine the engine removal projection during wartime. Leave the box unchecked to determine the engine removal projection during peacetime.
- E. Click the “Update Graph” button to display the results of your selections in graphical format.
- F. To return to the previous menu, click the underlined phrase Return to Projection Menu.

Engine Removal Projection Cumulative Graph (Single Fiscal Year)



9. Engine Removal Projection Cumulative Graph (Single Fiscal Year)

This page displays a single year, multiple-month graph of the projected engine removals for a selected engine during a selected historical time period and a selected projection fiscal year.

- Select the engine type.
- Select the historical time period
 - Select the historical begin date.
 - Select the historical end date.

Note: The historical end date cannot occur before the historical begin date.
- Select the projection fiscal year.
- Check the box marked "Use Wartime Multipliers" to determine the engine removal projection during wartime. Leave the box unchecked to determine the engine removal projection during peacetime.
- Click the "Update Graph" button to display the results of your selections in graphical format.
- To return to the previous menu, click the underlined phrase Return to Projection Menu.

Administrator Manual and Help

III. Administrator Manual and Help

The following section describes the installation of the ERP Tool and outlines the requirements and procedures to correctly configure the application. In order for the application to be installed successfully, the directions must be followed exactly and in the same order. The ERP Tool was written in C# with ASP.NET by John Wilson (john.wilson@pnl.gov). In addition, John Wilson wrote the installation instructions and may be contacted regarding any issues installing the application.

A. Hardware/Software Requirements

1. Microsoft Windows XP
2. ERP Tool Program Files
3. Microsoft Internet Information Services (IIS)
4. Microsoft .NET Framework Version 1.1
5. SQL Server 2000 Database

Complete the following steps to make sure these components are installed and configured properly:

1. ERP Tool program files

- a. Simply copy all the files (*.aspx, *.cs, etc.) from the ERPTool into a directory (folder) on your hard drive. This can be named anything you like. We will refer to this as the “Program Directory”.
- b. The “Program Directory” will contain two subdirectories (bin and Images). bin will contain two files: ERPTool.dll and ERPTool.pdb. Images will contain one file: Ships.jpg.

2. Microsoft Internet Information Services (IIS)

- a. IIS is the Windows program that serves up Web Pages.
- b. To see if IIS is installed and working, go to Start / Control Panel / Administrative Tools and see if Internet Information Services is present. If installed, continue with step 3, if not follow these instruction to install.
 - i. Go to Start / Control Panel / Add or Remove Programs
 - ii. Click on Add/Remove Windows Components at the left
 - iii. On the Windows Components Wizard, check the Internet Information Services (IIS) box and press the “Next” button.
 - iv. Follow the instructions. You will need your Windows XP Installation disk(s).

3. Microsoft .NET Framework version 1.1

- a. Check for the presence of Microsoft .NET Framework 1.1 by going to the web site: http://msdn.microsoft.com/netframework/downloads/framework1_1/
- b. Follow the instruction on the web site to install if not already installed.

4. SQL Server 2000 Database

- a. If you have previously installed ERPTool and want to remove your old database files, follow these steps:
 - i. Start up your SQL Server Enterprise Manager. (Start / All Programs / Microsoft SQL Server / Enterprise Manager)
 - ii. Drill down to Microsoft SQL Servers / SQL Server Group / (local*) / Databases. *Note (local*) may be your machine name followed by (Windows NT) or (local); it is usually the only entry under your SQL Server Group.*
 - iii. Right-click on gtlog (if it exists) and select Delete. Click the OK button.
 - iv. Right-click on lcac (if it exists) and select Delete. Click the OK button.
- b. To set up a new Login, follow these steps (if you have already setup a Login, you do not need to repeat this step):

- i. In the SQL Server Enterprise Manager, drill down to Microsoft SQL Servers / SQL Server Group / (local*) / Security / Logins.
 - ii. Right-click on Logins and choose New Login.
 - iii. In the Name box, type a user name, like “john”
 - iv. Select the “SQL Server Authentication” radio button
 - v. Type a password in the Password box, like “wilson”
 - vi. The Default Database and Language can be left as they are.
 - vii. Press the OK button
 - viii. Retype your password from step v (e.g. wilson)
 - ix. Press the OK button
- c. To install the new data files, follow these steps:
 - i. Copy the *.MDF and *.LDF files to the “C:\Program Files\Microsoft SQL Server\MSSQL\Data” folder (may be different depending on how you installed SQL server).
 - ii. Start up your SQL Server Enterprise Manager. (Start / All Programs / Microsoft SQL Server / Enterprise Manager).
 - iii. Drill down to Microsoft SQL Servers / SQL Server Group / (local). Right click on the (local) node and choose Properties.
 - iv. On the security tab of the Properties dialog, make sure the “SQL Server and Windows” radio button is selected for Authentication
 - v. Press the OK button
 - vi. In SQL Server Enterprise Manager drill down to: Microsoft SQL Servers / SQL Server Group / (local) / Databases
 - vii. Right-click on Databases. Choose All Tasks / Attach Database
 - viii. Select the file (using the “...” button) to find the gtfleet_data.MDF file you copied to your hard drive (in step “4.c.i” above).
 - ix. Click the Verify button to make sure everything is okay.
 - x. The “Attach as:” box should say “gtlog”
 - xi. In the “Specify database owner:” box, you can choose your Login (e.g. “john”). If you do this, it will create a “dbo” (database owner) account with your login and you will not need to complete step “d” below.
 - xii. Click the OK button.
 - xiii. Right-click on Databases again. Choose All Tasks / Attach Database
 - xiv. Select the file (using the “...” button) to find the lcac.mdf file you copied to your hard drive (in step “4.c.i” above).
 - xv. Click the Verify button to make sure everything is okay.
 - xvi. The “Attach as:” box should say “lcac”
 - xvii. In the “Specify database owner:” box, you can choose your Login (e.g. “john”). If you do this, it will create a “dbo” (database owner) account with your login and you will not need to complete step “d” below.
 - xviii. Once this is accomplished, you should see “gtlog” and “lcac” under Databases.
- d. If you did not choose your login name in steps “4.c.xi and 4/c.xvii” above, you will need to set up user accounts to allow you to log in. To create user accounts on the databases, follow these steps:
 - i. Open the Databases / gtlog tag
 - ii. Right click on Users tag. Select New Database User.
 - iii. From the Login Name drop list, select your login name (e.g. “john”).
 - iv. Enter a User Name in the box. It can be the same as the login name (e.g. “john”).
 - v. Make sure public and db_owner boxes are checked.
 - vi. Press the OK button.
 - vii. Open the Databases / lcac tag
 - viii. Right click on Users tag. Select New Database User.
 - ix. From the Login Name drop list, select the user you created in step r i above (e.g. “john”)
 - x. Enter a User Name in the box. It can be the same as the login name (e.g. “john”).
 - xi. Make sure public and db_owner boxes are checked.

- xii. Press the OK button.

5. Setup Web Site (complete this step if the Web Site has NOT been previously set up).

- a. Open the IIS (by going to Start / Control Panel / Administrative Tools / Internet Information Services).
- b. Drill down to (local computer) / Web Sites / Default Web Site.
- c. Right-click on Default Web Site and choose New / Virtual Directory
- d. In the Virtual Directory Creation Wizard, press the Next button.
- e. In the Alias box, type ERPTool. Press the Next button.
- f. In the Directory box, type (or better yet, use the browse button) to enter the Program Directory from step 1. Press the Next button.
- g. Make sure the Read and Run scripts boxes are checked. Press the Next button.
- h. Click the Finish button. (If you get a message saying that the Virtual directory name is not unique, this means that you have already set up the web site. If so, choose Cancel.)

6. Configure Web.config

- a. In order for the ERPTool program to access your database, you will need to make an adjustment to the Web.config file.
- b. Open the Web.config file (using Notepad, or your favorite text editor) and change the line that begins: <add key="SQLConnection"... (should be about the 6th line from the top).
- c. Change the part that says uid=john to uid=yourname, where yourname is the user name you selected in step "4.b.iii".
- d. Change the part that says pwd=wilson to pwd=password, where password is the password you selected in step "4.b.v".
- e. Repeat steps b, c, and d for the line in Web.config that begins: <add key="SQLConnectionLCAC"...
- f. Save and close Web.config.

7. Run ERPTool

- a. Open your favorite browser, such as Internet Explorer.
- b. In the address line, type in the address: <http://localhost/ERPTool/ERPMain.aspx> and press the "go" button or hit enter to make your browser go to that page
- c. There should be a delay of about 30 seconds while the program does some pre-processing of data. If there is no delay, that probably means the program didn't execute (see Trouble-Shooting notes below).
- d. If you want, you can add this page to your "Favorites" list to provide quick access in the future.

Trouble Shooting Notes:

- A. If program does not execute properly, it could be that the IIS web site isn't configured to process ASP.NET scripts.
 - A. To see if the IIS web site can process ASP.NET scripts, open the IIS (by going to Start / Control Panel / Administrative Tools / Internet Information Services).
 - B. Drill down to (local computer) / Web Sites / Default Web Site/ERPTool
 - C. Right-click on ERPTool and choose Properties.
 - D. On the Properties dialog, click the Configuration button.
 - E. Look to see if the extension .aspx is defined. If it is, your web site should be able to process ASP.NET scripts. If not, follow the steps below.
 - F. If your web site cannot process ASP.NET scripts, either the Microsoft .NET Framework 1.1 was not properly installed, or the Framework was installed before IIS was turned on.

G. When the .NET Framework is installed, it automatically configures your IIS. However, if the Framework was installed before IIS was turned on, you will need to manually configure IIS for .NET. To manually configure, follow these steps:

- i. Run the following program (either from Start / Run or from a command prompt window):
- ii. c:\Windows\Microsoft.NET\Framework\v1.1.4322\aspnet_regiis.exe -i (Be sure to include the -i switch. NOTE: your path may be slightly different, depending on how Windows and the .NET Framework were installed).
- iii. Re-check steps a-e above, to confirm that the configuration was successful.

B. If the program runs, but seems to lack data, it could be that the program is not accessing the database properly.

- A.** Start up your SQL Server Enterprise Manager
- B.** Drill down to Microsoft SQL Servers / SQL Server Group / (local) / Databases / gtlog / Tables
- C.** You should be able to see a lot of tables in the right-hand pane of the Enterprise managers: sys*, BLADE_HOURS, ...WAR_MULT
- D.** If you don't find gtlog or any tables, the database wasn't properly installed. See step 4 above.
- E.** If the tables are present, but the program can't access them, one or more of the following might be occurring:
 - i. A database user wasn't properly established for access. See steps 4 o-z above.
 - ii. SQL Server Authentication may not be turned on. See step 4 c above.
 - iii. Web.config wasn't properly adjusted. See step 6 above.

C. Special Note. The original databases lack certain tables necessary for the operation of ERPTool. These files were added by PNNL. For the gtlog database, these extra files and their column definitions are as follows:

A. ENGINE_DEF

- i. **ENGINE_TYPE** **varchar** **40**
- ii. **CI** **varchar** **3**
- iii. **TAN_RECORD** **numeric** **9(10,0)**
- iv. **COMP_TYPE** **numeric** **5(1,0)**

B. HRS_PROJECTED

- i. **SHIP_CLASS** **varchar** **6**
- ii. **ENGINE_TYPE** **varchar** **40**
- iii. **PROJ_HRS** **decimal** **5(3,0)**

C. REMOVAL_NON

- i. **REMV_RECORD** **numeric** **9(18,0)**
- ii. **DESCRIPT** **char** **18**

D. WAR_MULT

- i. **SHIP_CLASS** **varchar** **6**
- ii. **ENGINE_TYPE** **varchar** **40**
- iii. **MULTIPLIER** **float** **8**

E. SHIP_PROJ

- i. **SHIP_CLASS** **varchar** **6**
- ii. **CLASS_NAME** **varchar** **6**
- iii. **HULL** **varchar** **10**
- iv. **NAME** **varchar** **40**
- v. **MAIN_RECORD** **varchar** **9(10,0)**
- vi. **UIC** **varchar** **8**
- vii. **OP_DATE** **datetime** **8**
- viii. **TAN_RECORD** **decimal** **9(10,0)**
- ix. **ENGINE_TYPE** **varchar** **40**
- x. **QTY** **int** **4**

For the lcac database, these extra files and their column definitions are as follows:

a. ENGINE_DEF

i. ENGINE_TYPE	varchar	40
ii. CI	varchar	3
iii. TAN_RECORD	numeric	9(10,0)
iv. COMP_TYPE	numeric	5(1,0)

If any of these tables exists, but have a different definition, they need to be adjusted to match these tables above.

IV. Appendix A

Engine Removal Projection Tool¹

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Engine Removal Projection Tool

ABSTRACT

This paper presents results of R&D associated with creating a new algorithm and software program to predict engine removals/down time for US Navy surface ships. The US Navy has over 3500 gas turbine engines used throughout the surface fleet for propulsion and generation of electrical power. Historical data are used to forecast the number of engine removals for the next ten years and determine engine down times between removals. To update and improve current prediction methods, we tested over 60 techniques on twenty years of Navy data from over 3100 engines and 120 ships. Among the techniques investigated were moving averages, empirical negative binomial, generalized linear models, Cox regression, and Kaplan Meier survival curves. Our approach was to apply the *best* algorithm based on its performance on real-world data, and to implement the selected algorithm in a new software program that allows the user to select a specific engine type, forecast time period, and op-tempo. Graphical displays and numerical tables present forecasts and uncertainty intervals. The technology developed for the project is applicable to other logistic forecasting challenges.

SPONSOR CLEARANCE

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INTRODUCTION and BACKGROUND

The US Navy has over 3500 gas turbine engines used throughout the surface fleet for propulsion and the generation of electrical power. The US Navy, Naval Sea Systems Command (NAVSEA) Marine Gas

Turbine Information System (MGTIS) Program archives engines' historical operating and removal data for use in logistics and lifecycle planning. One analysis conducted by the MGTIS Program is to project the number of engine removals for the next ten years and determine engine down times between removals. To support this effort, NAVSEA currently uses a software program, implemented in FORTRAN in the early 1970s. The program runs on a mainframe computer and is inconvenient to use. In addition, because it does not account for certain important factors (such as decommissioning), various manual manipulations and subjective judgments are needed to make the program fit the current needs of the MGTIS program. Finally, the underlying statistical methods employed by the FORTRAN program are not well documented or understood. Thus there was a need for a new program that is more convenient to use and that is based on a defensible scientific methodology.

This paper presents results of the research and development conducted to develop algorithms to forecast engine replacements and the implementation of a new user-friendly software program to enable the NAVSEA user to formulate forecasts that support their logistics needs. Requirements for this work included the following: The algorithms need to be defensible, well-documented and outperform the existing algorithms. The software needs to extend the forecasting algorithm work to present a variety of information based on the data analysis and forecast. It must present intuitive displays, be easy to run with minimal training, and run under Windows as a Web-based application.

FORECAST ALGORITHM DEVELOPMENT

We tested over 60 techniques on almost 20 years of data collected from over 3100 gas turbine engine

¹ Ferryman, T. A., BD Matzke, JE Wilson, J Sharp, FL Greitzer, and E Hilferty. (2005) Engine Removal Projection Tool. *ASNE Intelligent Ship Symposium VI*, June 1-2, 2005, Villanova, PA.

assemblies and 120 U.S. Navy ships. Among the techniques investigated as the forecast basis were moving averages, empirical negative binomial, general linear models, Cox regression, and Kaplan-Meier curves, most of which are documented in engineering, medical, and scientific research (Lawless 1982). We applied these techniques to the data and used test set validation to quantify the accuracy of each method and choose the best algorithm.

The Kaplan-Meier estimate is defined as follows: suppose that there are n engines and that there are k ($k \leq n$) distinct times $t_1 < t_2 < \dots < t_k$ at which removals occur. The possibility of there being more than one removal at t_j is allowed, and we let d_j represent the number of removals at t_j . In addition to the lifetimes t_1, \dots, t_k , there are also censoring times L_i for engines whose lifetimes are not observed. The product-limit estimate of $S(t)$ is defined as

$$\hat{S}(t) = \prod_{j: t_j < t} \frac{n_j - d_j}{n_j}$$

where n_j is the number of engines at risk at t_j , that is, the number of engines running and uncensored just prior to t_j (Lawless 1982).

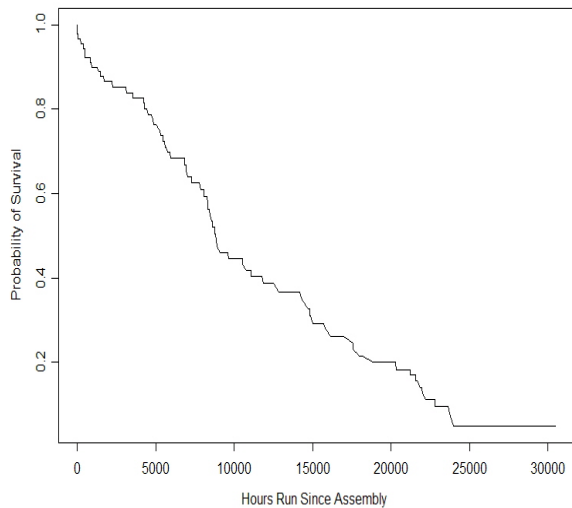


Figure 1. Example of Kaplan-Meier estimates

Figure 1 shows an example where t_1, \dots, t_k are plotted versus $\hat{S}(t)$. This shows a step function

where $\hat{S}(t)$ decreases as the values of t_1, \dots, t_k increase. It is logical to assume that each engine has some non-zero chance of failing at any point in time when we are using this distribution for forecasting purposes, and in reality, $S(t)$ should be continually decreasing as time increases. Therefore, we modified the method to smooth values of $\hat{S}(t)$ between removal times.

To compute $\hat{S}(t)$ for time values not equal to one of the values t_1, \dots, t_k we assumed the hazard rate between two consecutive values of t_1, \dots, t_k is a non-zero constant unique to times between those two points. For example, let's say there are two removal times from the original data, t_a and t_c , where the probability of survival for the Kaplan-Meier estimate is unchanged between the two points, and we wish to compute an estimated probability of survival for a time t_b that falls between times t_a and t_c . $S(t)$ for t_b is computed as follows:

$$\hat{S}(t_b) = \hat{S}(t_a) * \left(\frac{\hat{S}(t_c)}{\hat{S}(t_a)} \right)^{(t_b - t_a) / (t_c - t_a)}$$

Another issue is how to compute forecast probabilities of survival when time values approach or exceed the highest removal time in the data. For this case, we assume that hazard rates are constant beyond a time where there are r values of t_1, \dots, t_k exceeding this time in the data. We would assume a constant hazard for the time value that achieves the mean Kaplan-Meier estimate of the t_{k-r} and t_{k-r-1} removal times where $1 < r \leq k$. The mean Kaplan-Meier estimate of the t_{k-r} and t_{k-r-1} removal times occurs at a time t_{radj} computed as follows

$$t_{radj} = t_{k-r} + \frac{\ln \left(\frac{\hat{S}_{k-r} + \hat{S}_{k-r-1}}{2 * \hat{S}_{k-r-1}} \right)}{\ln \left(\left(\frac{\hat{S}_{k-r}}{\hat{S}_{k-r-1}} \right)^{\frac{1}{t_{k-r} - t_{k-r-1}}} \right)}$$

Let $totalhrs_{radj}$ be the total number of hours and the total number of removals from the n engines that exceed t_{radj} , and $totalrems_{radj}$ be the number of removals that occur at times greater than t_{radj} . $S(t)$ is then computed as follows when $t > t_{radj}$

$$\hat{S}(t | t > t_{radj}) = \hat{S}(t_{radj}) * \left(1 - \frac{totalrems_{radj}}{totalhrs_{radj}}\right)^{t-t_{radj}}$$

To compute projected removals for future months, projected operating hours for all engines are totaled. Assemblies in each ship class are assumed to operate at the average rate of the class's operating history. Using the average operating rate for all assemblies, assemblies are stepped through the ages they would reach each month. At each step, the installed population in each interval is subjected to the probability of being removed. Removed assemblies accumulated as expected removals are replaced by zero-timed assemblies for the next iteration².

EXPERIMENTAL RESULTS ASSESSING THE FORECAST ALGORITHMS' EFFECTIVENESS

The algorithms were evaluated on 12 different engine types using an iterative approach where we retrieved the first few years of data, applied the algorithm, and predicted the next year's removals. For the next iteration, we would drop the earliest year's data we used in the previous iteration, and add the next year's data. This was repeated until we had predicted the most recent year's removals. For each engine type, a residual analysis was performed on these results to evaluate how well each method performed. Many summary statistics and plots were used in our evaluation. Table 1 shows an example of a few of the summary statistics used in our evaluations.

Table 1. Summary of Test Results for 4 of the 60 Algorithms Tested

Algorithm	Mean Absolute Difference	Root MSE	Correlation
Kaplan-Meier	4.42	5.53	0.51
Cox PH	10.48	11.86	-0.22
GLM	6.14	8.59	-0.07
Negative Empirical	4.77	5.87	0.45

² Methodology for MTBR and Removal Projections was based on notes provided by NAVSEA.

Binomial			
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The Kaplan-Meier estimate method with the modifications we have described performed better than other methods when there were at least several removals in the data. A simple constant hazard rate based on removals per hour worked consistently well when there were only a few removals in the data used to compute the distribution. The method implemented uses the constant hazard for low numbers of removals, and the modified Kaplan-Meier estimate when a minimum number of removals are present in the test set data.

ERP TOOL, USER-FRIENDLY SOFTWARE WORKSTATION

The algorithm chosen as most effective is a core part of the ERP Tool. Other key characteristics are important to allow it to function in the NAVSEA environment:

- Web-based, running on a windows operating system.
- Use .NET technology and the C# language.
- The ERP Tool and all MGTIS data remain on the NAVSEA server. Raw data will not be passed to the client workstation.
- The ERP Tool accesses the MGTIS ORACLE database on the NAVSEA server to acquire user-specified data (e.g., data for the past three years) to be used by the ERP analysis. Input data include Ship ID, Engine ID, dates, operating hours, engine failure codes, selected component failure codes, and projected operating schedules.
- Outputs displays
 - Engine Hazard Rate and Reliability Summary table
 - Projected Engine Removals table
 - Charts of actual versus predicted removals by engine type and year in accordance with a user specified prediction period.
 - Charts of actual cumulative removals versus projected removals by engine type and month for a selected fiscal year.

- Aggregated chart of engine removals by year including historical data and projected data (e.g., out to ten years).
- Graph of removal rates for a selected time period.
- Bar charts broken out by engine type of MTBF values by date
- Engine MTBF values augmented for relevant components.
- Component MTBF.
- Projections based on user-selectable Peacetime Operational Tempo and/or Wartime Operational Tempo.

Many of these capabilities are illustrated below.

Data Issues

Data for the prediction tool is extracted from MGTIS database, which is a relational database stored and managed by Microsoft's SQL Server 2000.

The data needed for the prediction tool is categorized as follows:

- Monthly Engine Operating data
- Engine Removal data
- Projected Engine Operating Hours
- Current Engine Location

On start-up, the prediction tool gathers historical operating data into a single file to provide quick access for the various prediction functions. This includes organizing Monthly Engine Operating data to show "operating hours since removal" and "operating hours since new" for each month. Removals are also associated with the monthly operating records.

The current engine location data is used to determine the inventory of engines to be used for engine removal predictions. This location information is combined with projected engine operating hours data (and optionally with wartime multiplier data) to determine the number of engine and operating hours for the prediction periods. Historical operating and removal data are used to establish removal rates. Those removal rates are used with the operating hours for prediction periods to predict engine removals.

User Interface

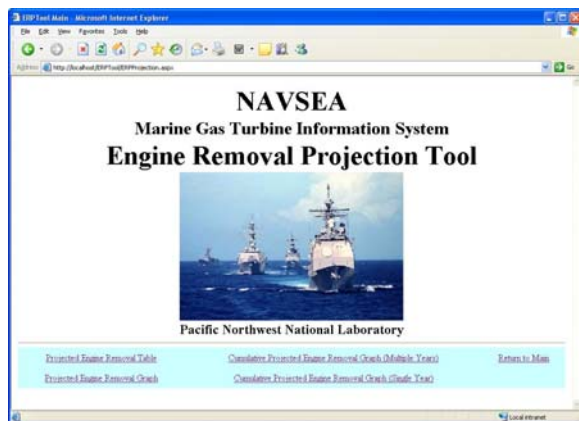
The user interface is a series of "Web pages" generated by the ERP-Tool program, which is an

ASP.NET program that resides on a server. The ERP-Tool program interacts with the MGTIS data through Microsoft SQL Server 2000. The Web pages are sent to the user through the Microsoft Internet Information Services (IIS).



The Main menu is a page that provides links to other pages. Each page represents a particular function. The following is a tree of the various functions and menus in the ERP-Tool program:

- Main Menu
 - Kaplan-Meier Survival Table
 - Engine MTBF Augmented with Selected Component Removal Data
 - Historical Operating Hour and Installation Summary
 - Operational Tempo Calculations
 - Projected Engine Removals Menu
 - Projected Engine Removal Table
 - Projected Engine Removal Graph
 - Cumulative Projected Engine Removal Graph (Multiple Years)
 - Cumulative Projected Engine Removal Graph (Single Year)



A synopsis of each function follows.

Kaplan-Meier Survival Table

This provides the table of survival values versus operating hours that are used to predict removals.

Hours	Survival
0.0	0.916666666667
4,496.0	0.88276049383
9,717.5	0.860648148148
11,624.0	0.849633074935
18,303.2	0.821594099814
20,650.5	0.822652138542
20,724.4	0.813710367471
21,162.0	0.804669342277
22,056.0	0.794734856270
22,814.0	0.786327819885

Engine MTBF Augmented with Selected Component Removal Data

This provides a list of components for a selected engine and the mean time between failures (MTBF) for each of those components during the chosen operating period. Additionally, it provides the overall MTBF for the engines which includes component failures.

TAN	Removal TAN	Name	Removals	MTBF
14	D110	DIFF. GEARBOX ASSEMBLY	3	433,425
15	D120	TRANSFER GEARBOX	0	0
16	D125	TRANSFER GEARBOX SP	0	0
17	D130	PUMP FUEL MAIN	4	325,069
18	D140	FUEL CONTROL MAIN	23	56,534
19	D145	CTT SENSOR	16	81,267
20	D150	FIRMSMART STARTER	24	54,178
21	D160	ACTUATOR FUEL LVL AG	181	7,184
22	D170	PUMP LOBE SCAVENGE	5	260,055

Historical Operating Hour and Installation Summary

This provides a list of operating hours and number of engines that operated during the chosen period, broken down into hour intervals (chosen by the user). It also includes the number of removals that occurred in the various intervals.

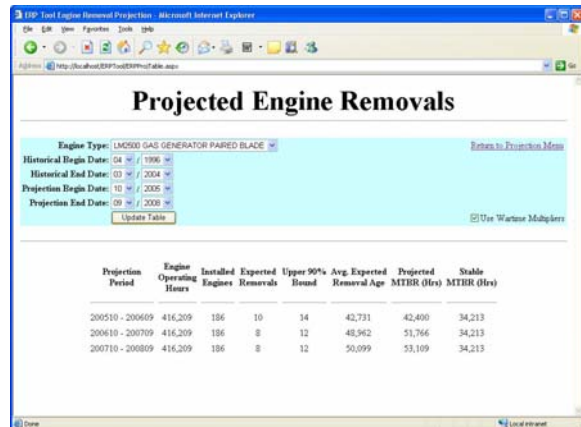
Operational Tempo Calculations

This provides a means for the user to change the multipliers to be used for projected monthly operating hours during wartime conditions. There is a different multiplier used for each engine type on each class of ship where the engine is used. Each user has a separate set of multipliers that persists during the current web session (cleared when the user exits the Web browser). The underlying peacetime operation hour projections as well as the default wartime multipliers are stored in tables in the database, and are changed outside the ERP Tool program.

Class Desc	Engine	Peacetime Multiplier	Wartime Calculated
1 DD	501-K17 COMPRESSOR	200.00	173
1 DD	501-K17 TURBINE	200.00	173
1 DD	LM2500 GAS GENERATOR FAIRLED BLADE	180.00	173
1 DD	LM2500 POWER TURBINE	180.00	173
10 MCM	T-1302S SOLAR GAS GENERATOR	10.00	100
3 FFG	LM2500 GAS GENERATOR FAIRLED BLADE	115.00	175
3 FFG	LM2500 POWER TURBINE	115.00	175
4 CG	501-K17 COMPRESSOR	195.00	160
4 CG	501-K17 TURBINE	195.00	160
4 CG	LM2500 GAS GENERATOR FAIRLED BLADE	125.00	160
4 CG	LM2500 GAS GENERATOR SINGLE SHAFT	125.00	160
4 CG	LM2500 POWER TURBINE	125.00	160

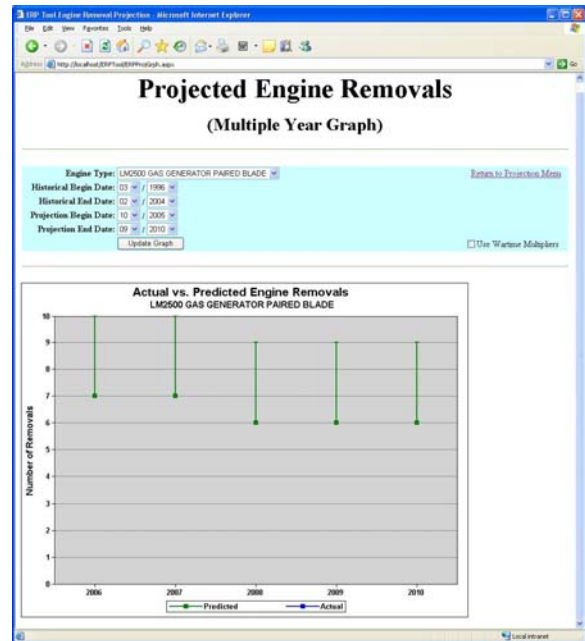
Projected Engine Removal Table

This predicts the number of engine removals for a selected period based upon the removals that occurred in a selected historical period. If sufficient removals occurred in the historical period, a Kaplan-Meier prediction method is used; if not, then a simple rate prediction method is used. The number of predicted removals along with an upper 90% confidence limit, mean time between removals (MTBR), and average removal age are all displayed in tabular format.



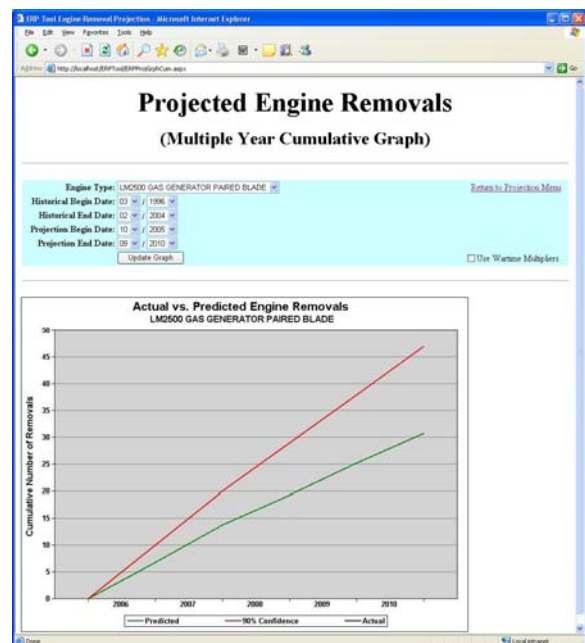
Projected Engine Removal Graph

This function operates basically the same as the Projected Engine Removal Table, except that the projected number of removals and upper 90% confidence are plotted on a graph. If part or all of the prediction period occurs in the past where historical data is available, actual removals are also plotted on the graph. Other predicted variables like MTBR and average removal age are not plotted.



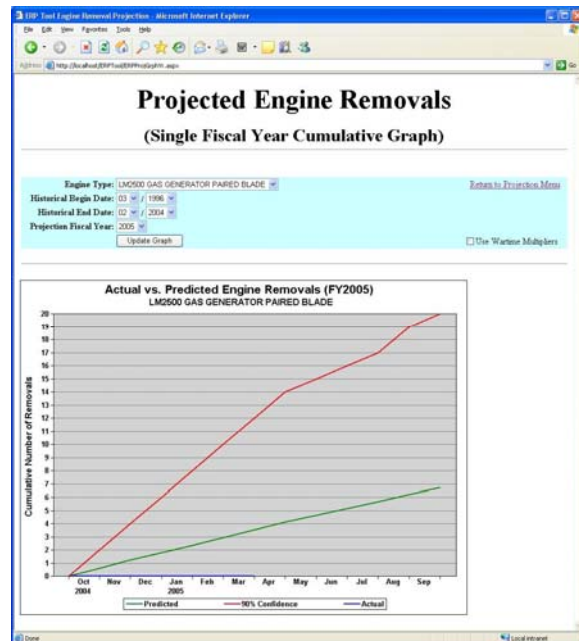
Cumulative Projected Engine Removal Graph (Multiple Years)

This function operates basically the same as the Projected Engine Removal Graph, except that the plotted removals are accumulated from one time period to the next.



Cumulative Projected Engine Removal Graph (Single Year)

This function operates basically the same as the Cumulative Projected Engine Removal Graph (Multiple Years), except that the prediction period is limited to a single fiscal year.



CONCLUSIONS

This project demanded the merger of good mathematical statistical science and computer science to create an effective tool to support NAVSEA's logistics needs. The initial implementation of the ERP Tool is on the collection of 3100 Gas Turbine Engines. The ERP Tool algorithm results in approximately a 10% improvement over the current practice. This will help guard against purchasing in advance of demand and, in addition, will help avoid the more serious situation--a shortfall. The software uses the *best* algorithm in combination with user-friendly interfaces and intuitively understandable displays. The user can select a specific engine type, forecast time period, and op-tempo. Graphical displays and numerical tables present forecasts and uncertainty intervals.

The technology developed for the project is applicable to other logistic forecasting challenges any where improved forecasting and/or user-friendly software tools could help the logistics tasks

REFERENCE

J.F. Lawless, Statistical Models and Methods for Lifetime Data, John Wiley & Sons, New York, 1982.

ACKNOWLEDGEMENTS



Thomas Ferryman is a Battelle Chief Scientist at the Pacific Northwest National Laboratory with over 30 years of experience in system engineering and mathematics/statistics. He has developed prognostic tools for use on gas turbine engines. He leads the technical development of aviation safety data analysis tools for NASA (numeric, categorical and/or text data). Prior to coming to Battelle, Dr. Ferryman was Chief Systems Engineer for Lockheed leading a major weapon system modification (AC130H Gunship) and Senior Operations Research Analyst for the U.S. Navy.



Brett Matzke is a Battelle Research Scientist at the Pacific Northwest National Laboratory. His research

interests include statistical modeling, multivariate analysis, experimental design, and automation of analyses. He has previously served as a Senior Product Line Manager of Quantitative Analysis for Reader's Digest, and a Senior Statistical Consultant for CAMO, Inc. He has an M.S. degree in Statistics.



John E. Wilson is a Battelle Research Scientist at the Pacific Northwest National Laboratory. His research interests include desktop software development, graphic user interface development, and process automation and visualization. He is the lead programmer of the Visual Sample

Plan software, a sample planning software package, used by thousands of users worldwide. He previously served as Computer Services Manager and software engineer for the Grand Junction Office of Oak Ridge National Laboratory for over 10 years.



Julia Sharp is a doctoral student in Statistics at Montana State University in Bozeman, Montana. Her research interests include statistical modeling, experimental design, and bio-statistics. Ms. Sharp recently held a summer internship position at Pacific

Northwest National Laboratory. She has an M.S. degree in Statistics from Montana State University and a B.S. in Mathematics from the University of Evansville in Evansville, Indiana.



Frank L. Greitzer is a Battelle Staff Scientist at the Pacific Northwest National Laboratory with 30 years of experience in user-centered design and development of advanced technology software systems, including performance

support/training systems and information technology systems to augment human performance. Currently managing the R&D effort in support of the work reported here, Dr. Greitzer has also managed seminal research developing an onboard, proof-of-concept prototype system (REDI-PRO Real-time Engine Diagnostics-PROgnostics) to diagnose and predict faults in Army gas turbine engines.



Ed Hilferty has been an Engineering Statistician with the Naval Surface Warfare Center-Ship System Engineering Station, Philadelphia PA for 15 years. He has held various positions including project manager and senior programmer for the Navy's Marine

Gas Turbine Reliability and Maintainability OPHR program and currently is also the project manager in the development, implementation, and management of the new Marine Gas Turbine Information System (MGTIS) and Autolog. He is the station's senior statistician with responsibility for generating and reviewing much of metrics for the Propulsion and Power Systems Department. Ed holds an M.S. degree in Applied Statistics.