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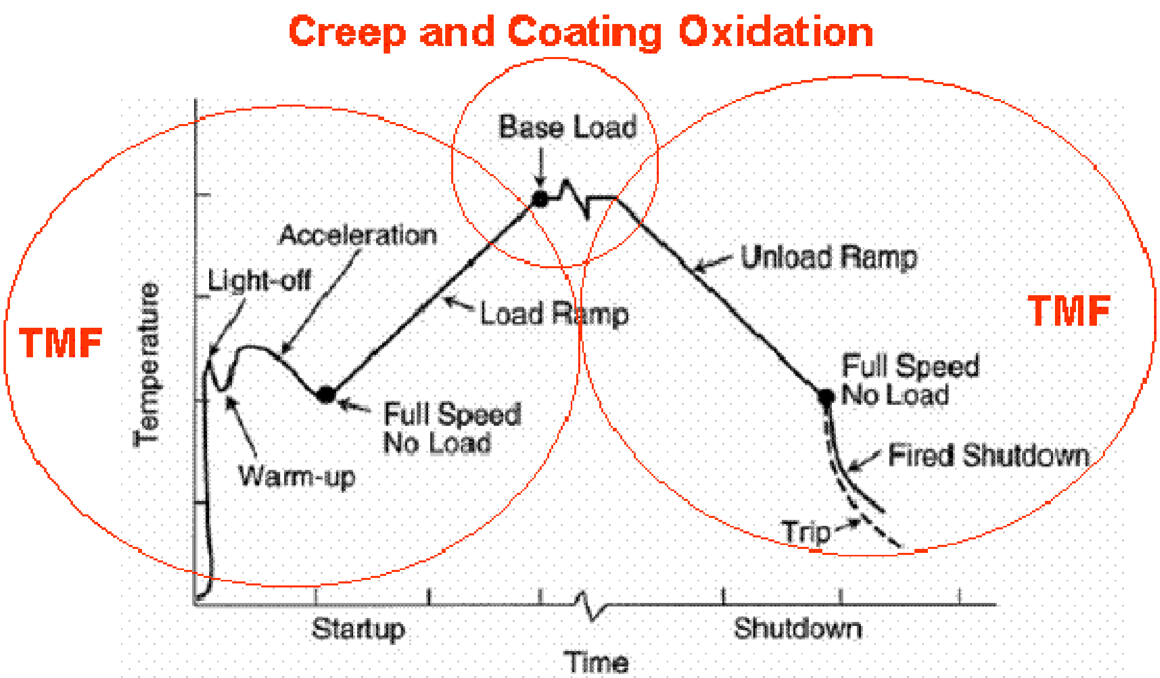
Hot Section Maintenance Interval Estimation for General Electric Combustion Turbines

1011484



Hot Section Maintenance Interval Estimation for General Electric Combustion Turbines

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Technical Update, January 2005

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Cosponsor

U.S. Department of Energy

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ABSTRACT

Development of a comprehensive Combustion Turbine Health Management (CTHM) System will play a critical role in reducing the cost of electricity by improving reliability, availability, and maintainability. EPRI and the US Department of Energy (DOE) National Energy Technology Laboratory have jointly sponsored development of a series of real-time health management technologies including sensor validation, performance diagnostics and prognostics, vibration diagnostics, and critical component remaining life assessments. This report describes the initial design of a remaining life module (RLM) – a low-cost, easy-to-use software program for calculating the remaining life of the hot section components of General Electric (GE) heavy frame combustion turbines (CTs). The spreadsheet-based RLM incorporates the remaining life formulas described in GE's GER-3620J technical report. It also incorporates the Hot Section Life Management Platform algorithms EPRI has developed for the GE 7FA+ first stage buckets. These two methods for estimating remaining life will allow CT operators to plan maintenance actions in a manner that reduces overall life cycle costs. RLM features automated access to CT operating data, which allows the actual operating history of the engine to be factored into the remaining life calculations.

CONTENTS

1 INTRODUCTION

The overall objective of the EPRI Hot Section Life Prediction Project (P79.003) is to provide CT owners with a technically objective basis for improving hot section maintenance intervals. While each OEM has developed its own conventions such as "factored hours" or "equivalent operating hours (EOH)", CT owners are often surprised by the actual versus predicted component life. Furthermore, it is not readily apparent from the OEM formulations which specific component location, e.g. first row blade tip, leading edge, trailing edge platform is indeed the weak link driving the maintenance action. This underlying uncertainty can result in high repair fallout rates or possible lost production time. In some cases, the OEM issues maintenance advisories overriding its stated maintenance interval conventions. In other cases, the maintenance interval may be too conservative leading to premature parts retirement. This state of uncertainty is further confounded with such practices as repaired part pooling.

EPRI has been developing the tools and knowledge to re-examine the OEM maintenance interval conventions. The general concept, as shown in **Figure 1-1**, is to employ 3-D aero-thermal stress analysis supplemented by service-aged component data and materials degradation data. This approach is referred to as the HSLMP (Hot Section Life Management Platform) evaluation. It is of comparable rigor to the OEM design tools but with additional features for modeling degradation. The results of the HSLMP analysis are translated into a form that can be readily compared with the OEM convention and automatically driven by the machine process data. Initially the goal of the HSLMP-derived maintenance interval is to identify the component-specific and location-specific 'weak-link' with a clear engineering basis without commercial bias. The ultimate goal is to tie in the inspection data taken periodically between outages to further validate or adjust the HSLMP projections.

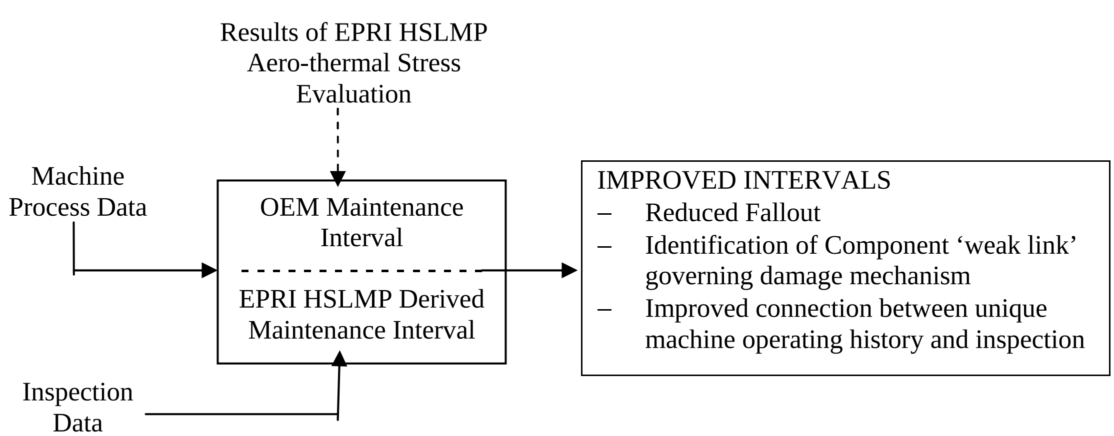


Figure 1-1

General EPRI Maintenance Interval Concept

Figure 1-2 indicates the current status of the on-line maintenance interval development for the GE models. Software is available for implementation covering the GE3620 only calculation as this is not typically supplied by the OEM. There are three ongoing model-specific HSLMP projects to develop the EPRI maintenance interval estimations. This report describes the development of the GE3620 formulation and the HSLMP-derived alternative for the 7FA+ (7231) first stage bucket. The plan is to extend these results to the most current 7FA+e (7241) complete hot section. Parallel activities for the 9FA and 7EA are proceeding and will use the same basic software. Similar projects are also underway for the S-W501F and VX4.3A machines.

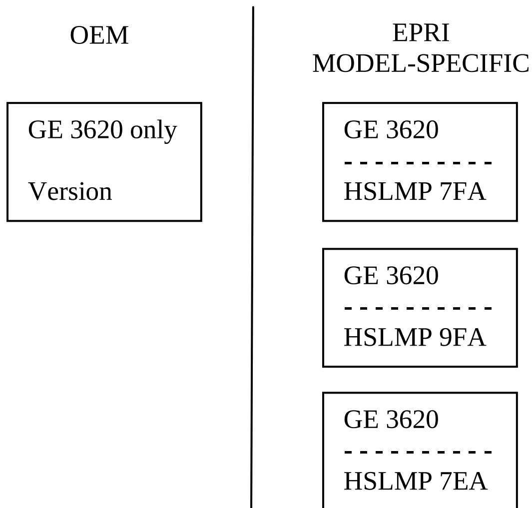


Figure 1-2
Current Status of EPRI Maintenance Interval Estimator for GE Models

Remaining Life Module (RLM) Development

The EPRI Remaining Life Module (RLM) is a spreadsheet that predicts the safe useable remaining hot section life or intermediate maintenance/refurbishment interval for a GE heavy-duty gas turbine via two methods: EPRI's Hot Section Life Management Platform (HSLMP) algorithms [1] and GE's standard algorithms [2] described in GER-3620J. The HSLMP algorithms are currently only applicable to the first stage rotating blade of the GE 7FA+ (MS7231) combustion turbine. The GER-3620J algorithms can be used for all of GE's heavy duty combustion turbines.

Important features of the RLM spreadsheet include:

- Operates as a spreadsheet with macros in Microsoft's Excel (version 97 or later)
- Runs under the Windows NT/98/2000 operating systems
- Comes with an installation routine developed using InstallShield
- Uses data calculated by EPRI's CTPFDM spreadsheet for performance monitoring of combustion turbines
- The familiar Excel "Chart" feature can be used to trend the RLM output

- Capable of predicting the remaining hot section life of GE heavy-duty gas turbines using GE's GER-3620J algorithms
- Capable of predicting the remaining hot section life of GE 7FA+ gas turbines using EPRI's HSLMP algorithms

RLM Calculation Overview

The RLM calculations can be carried out in two different modes: initialization and run-by-run. In the initialization mode, the user manually enters the current operating history of an engine in terms of fired hours, number of starts, number of trips, etc. Where necessary, the user will input estimates to characterize the nature of the operating history (e.g., percentage of total hours operated in part-load, base-load and peak-load). The GER-3620J calculations are carried out to define the current equivalent (a.k.a. factored) run hours and starts for the hot section, the rotor, and the combustor. This will then form the basis for future calculations on a run-by-run basis using either the 3620J algorithms or the EPRI algorithms.

The run-by-run mode can be used after the initialization calculations have been executed. When a run (i.e., a complete start-stop cycle) has ended, the user can enter the approximate start and stop times and a macro will extract the specified data from a PI data historian supplied by OSI Software, Inc. The macro then "marches" through the run data on an hour-by-hour basis to calculate the equivalent operating hours and starts incurred during the run. If the run-by-run calculations are carried out on a GE 7FA+, the HSLMP algorithms will also be calculated.

Note that it is possible for a user to forego the initialization calculation if an on-line PI database contains information on each run that the turbine has executed. In such a case, the user can enter the start and stop times for each run, one-by-one, and calculate the contribution of each run to the cumulative factored hours and starts total.

2
THEORY AND MODULE DEVELOPMENT

GER-3620J Algorithms

The GER-3620J algorithms provide an hours-based maintenance interval and a starts-based maintenance interval for inspection and replacement of the hot section parts of a CT. Typically starts may be related to the accumulated damage caused from thermal mechanical fatigue (TMF) cycles, and hours may be related to coating degradation and/or creep damage accumulated over time.

The 3620J algorithms assume there is no interaction between the starts-based and hours-based intervals. The maintenance action should be carried out if either interval is exceeded. This philosophy is shown visually in **Figure 2-1**.

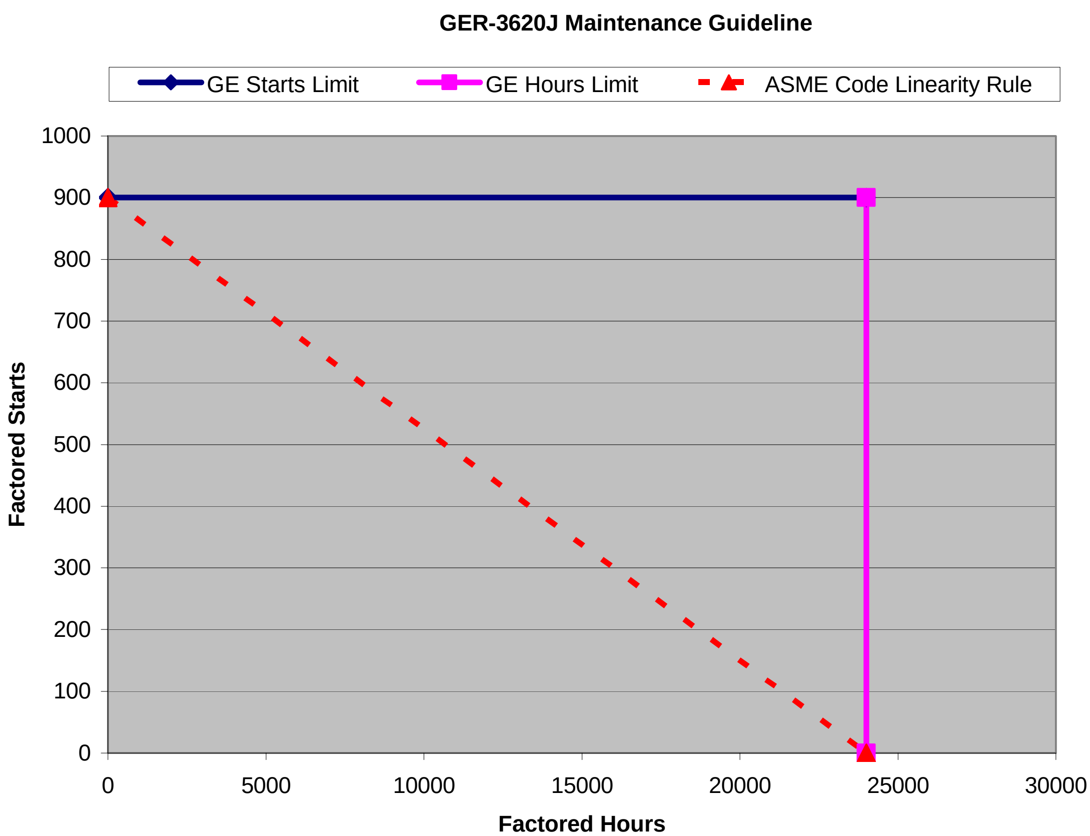


Figure 2-1
Hot Gas Path Maintenance Interval Criteria for a GE "F" Class Turbines based on GER-3620J.

The term "factored starts" used in the figure means that actual starts are referenced to a baseline start referred to as a normal base load start or NB in the starts-based portion of the GER-3620J formula. To account for damage accumulated for different types of starts or trips, factors are applied to the normal base-load start-stop cycle (NB), reflecting GE's opinion of their relative severity. For example, a "fast load start" is given a severity factor of two, meaning one fast load start counts as two factored starts. Similarly, the term "factored hours" means actual operating hours are referenced to a baseline of base-load operation with natural gas and no water or steam injection. Note that based on the GE criteria, an F class CT could have 899 normal starts and 23,999 base load fired hours and not need a hot section overhaul, but if it had 1 normal start and 24,001 baseload fired hours it would need a hot section overhaul.

Creep Fatigue Interaction

The assumption that there is no interaction between starts (fatigue) and operating hours (creep) is not supported by experts outside of GE. There is a large body of evidence that shows creep-induced damage will reduce the fatigue life of a metal and that fatigue-induced damage will reduce the metal's creep life. The ASME Boiler and Pressure Vessel Code Section III, Case N-47 addresses the interaction between fatigue and creep. It recommends using a linear combination of remaining creep life and remaining fatigue life to determine a materials remaining life. The least conservative assumption is that:

% Remaining Life = (% Remaining Fatigue + % Remaining Creep Life) – 100%

This is known as the "linearity rule". It is also shown in **Figure 2-1**. Actual tests on different metals have shown that the interaction between fatigue and creep is often stronger than that described by the linearity rule [3].

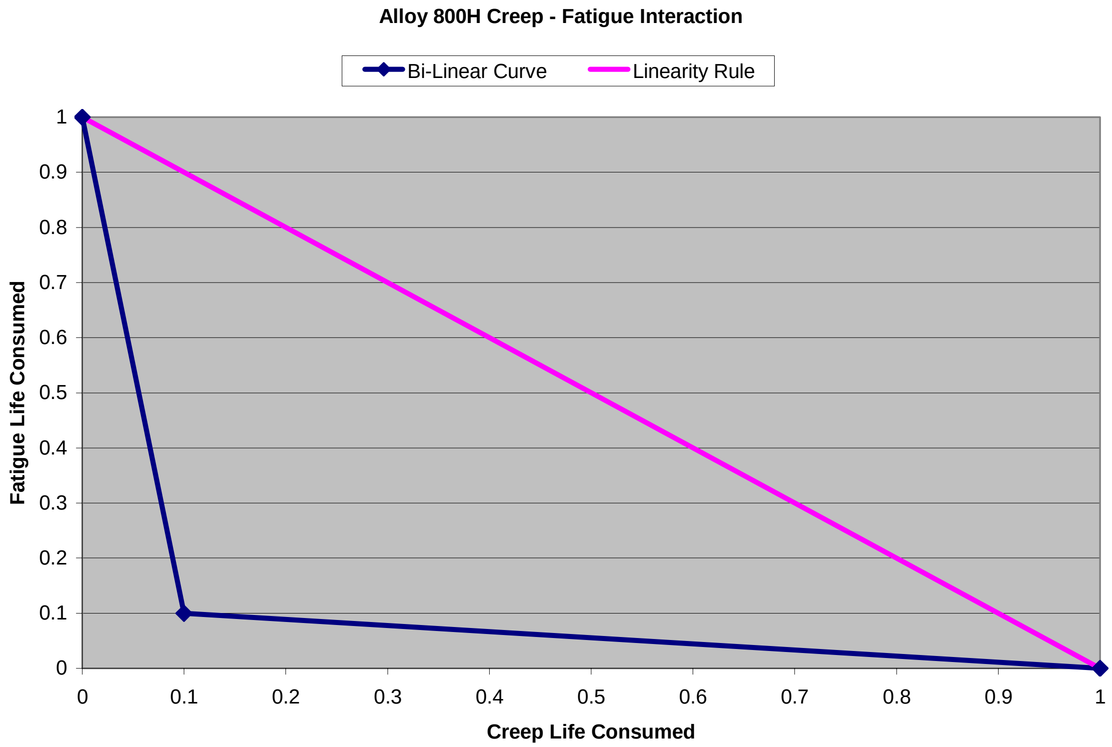


Figure 2-2
Bi-Linear Creep-Fatigue Interaction Curve for Alloy 800H from Ref. 3 compared to ASME Section II Code Case N-47 Linearity Rule.

An example of a stronger creep-fatigue interaction is shown in the "bi-linear" curve of **Figure 2-2** that was derived from experimental data for Alloy 800H. It shows that when 10% of the creep life of 800H has been consumed, the material will fail if more than 10% of its fatigue life is expended.

Even GE's own published data indicate there is a strong interaction between starts and hours, at least for the combustion liner and transition piece of the PGT10 [4]. An example of that data is shown in **Figure 2-3**, which shows the "maintenance line" for the transition piece. The maintenance line represents the locus of points at which 2/3rds of the engines surveyed had experienced transition piece failures. The data in **Figure 2-3** strongly suggest a linear relationship between fatigue and creep. This directly contradicts the assertion made in GER-3620J.

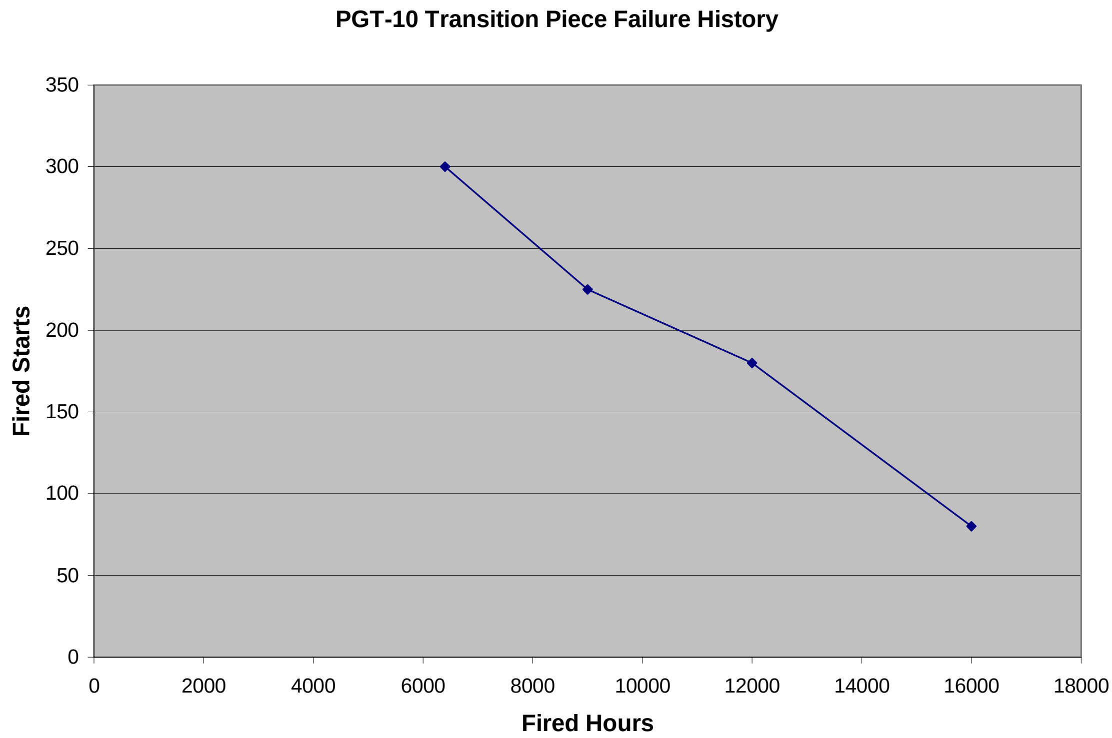


Figure 2-3
GE PGT-10 Transition Piece "Maintenance Line" based on the failure history of multiple engines surveyed by GE.4

Without additional data it is not known if the maintenance intervals recommended for an F class CT in GER-3620J represent a conservative simplification of the creep-fatigue linearity rule or an unconservative simplification. The unconservative possibility is represented by **Figure 2-1**. It would suggest that hot section failures could occur in CTs that accumulate a combination of hours and start cycles which fall within GE's 24,000 hour and 900 starts limit.

The conservative possibility is represented by **Figure 2-4**. If that figure represents the actual situation, then it implies that CTs that operate many hours with few cycles could go far beyond GE's 24,000 factored hour limit. Also, turbines that experience many cycles but few hours could withstand more than 900 factored starts before encountering hot section failures.

Whether the GE criteria are conservative or unconservative, either scenario represents a potential for unnecessary maintenance expenses. If the criteria are overly conservative, CT owners will be replacing parts too soon and therefore spending too much money on hot section spares. In addition, the units will be shutdown for overhauls more frequently than necessary which represents a loss in revenue.

If the GE criteria are unconservative, CT owners will experience hot section failures that could cause additional damage to downstream parts. In addition the unplanned outages caused by the failures may mean that replacement parts will not be available right away, which will extend the length of the outage and cause additional revenue loss.

Clearly there is an incentive to improve upon the GER-3620J remaining life algorithms. That was the motivation for the EPRI Hot Section Life Management Platform.

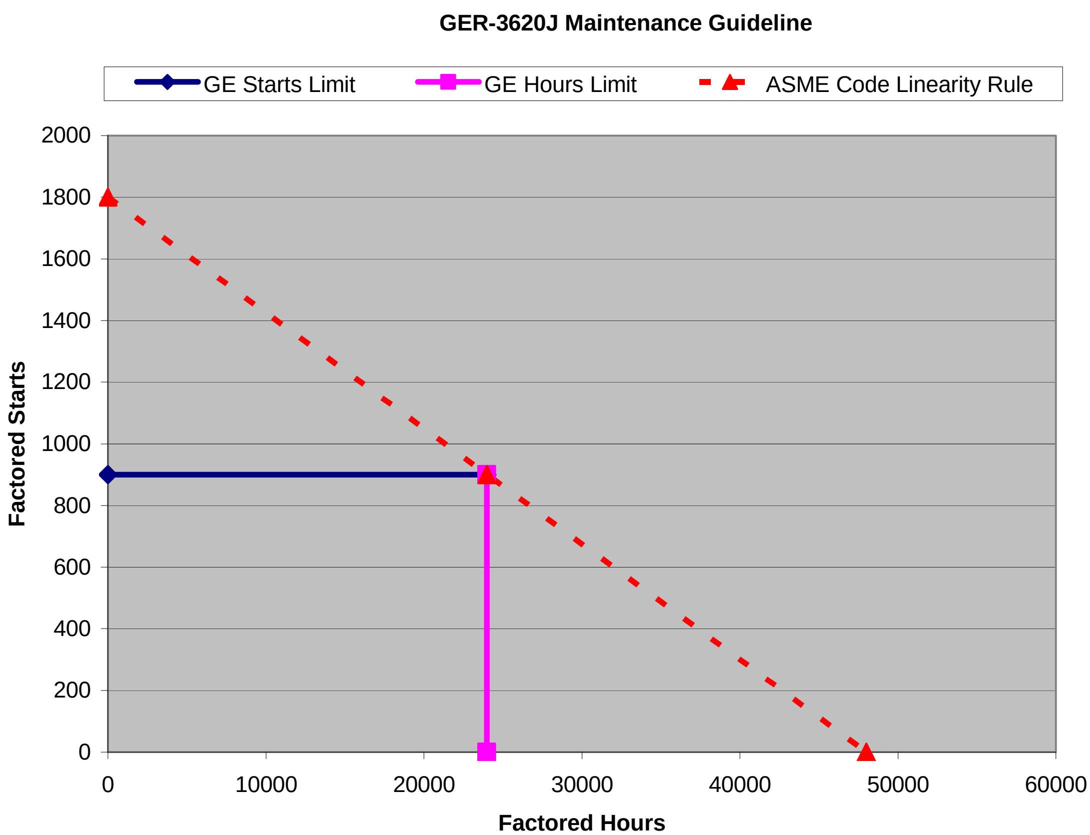


Figure 2-4
"Conservative" Simplification of Creep-Fatigue Linearity Rule.

EPRI's Hot Section Life Management Platform

Unlike the GER-3620J approach, EPRI's Hot Section Life Management Platform (HSLMP) algorithms do assume there is interaction between the various damage mechanisms that occur in a CT hot section. The algorithms consolidate the damage caused for different types of events as a basis to establish when the equivalent maintenance interval is reached. The algorithms are based on aerothermal modeling and tests carried out to estimate the strain induced at specific locations by specific operating conditions such as an emergency trip from full-load. This information is then used to calculate a severity factor for each condition or event.

In the initial version of RLM, HSLMP algorithms for only the GE 7FA+ series 1st stage bucket (i.e., rotating airfoils) are incorporated. The current OEM inspection limits for the 7FA+ 1st stage bucket are set at 900 starts maximum and/or 24,000 hours, whichever comes first. Replacement limits are 1800 factored starts and 48,000 factored hours.

Results of a hypothetical calculation of an interval using both the OEM approach (GER-3620J) and the HSLMP approach are presented in **Figure 2-5**. In the example, on a 7FA+ 1st stage bucket, a trip at 40% load is considered by GER-3620J to be 4.2 times as damaging as a normal base load start-stop cycle. As reflected in the figure, the HSLMP factor would produce 50% less life consumption (2.1 times an NB start-stop cycle). It should be noted that the actual factors used in HSLMP are different from those shown in **Figure 2-5**.

Factored Starts	Annual Starts	OEM Factor	HSLMP Adjusted
Normal Base Load S-S	**90**	**1.0**	**1.0**
Part Load S-S (<60%)	0	0.5	0.3
Peak Load S-S	0	1.3	0.7
Fast Load Starts	2	2.0	1.0
Trip Severity @ 25%	0	2.6	1.3
Trip Severity @ 40%	4	4.2	2.1
Trip Severity @ 60%	0	6.0	3.0
Trip Severity @ 80-100%	0	8.0	4.0
Emergency Start	1	20.0	10.0

Actual Starts	97	97
Factored Starts	131	110.4
Maximum Specified Starts	900	900
Maintenance Interval =	**667**	**791**
Maintenance Factor	**1.35**	**1.14**

Life Consumed	14.5%	12.3%
Life Remaining	85.5%	87.7%

Note: HSLMP factors in example are hypothetical, used for illustration purposes only

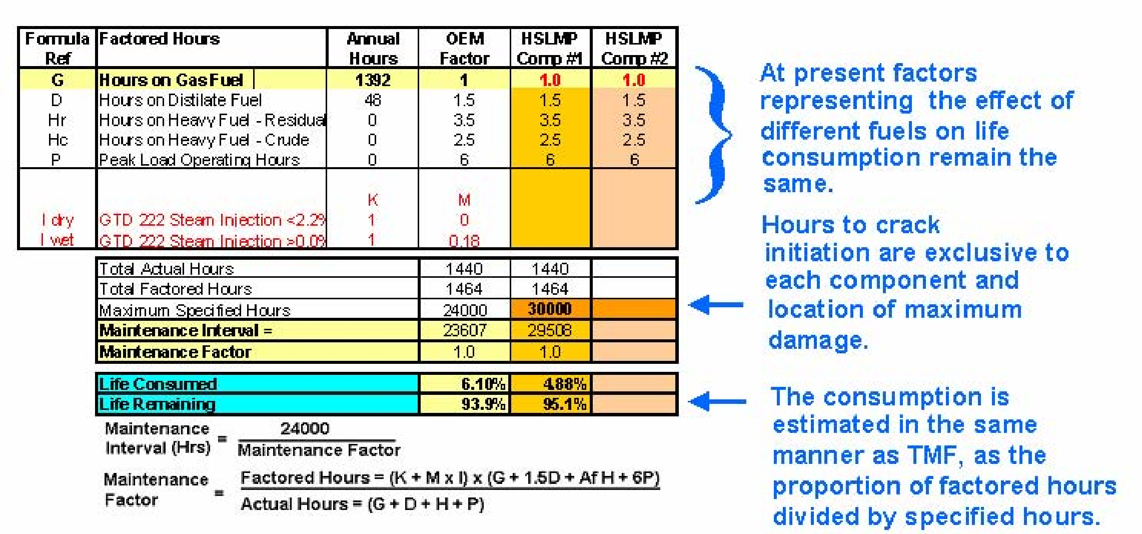
- The adjusted factors reflect the relative damage at specific locations based on the equivalent strain ranges produced from the aero thermal analysis.
  - They reflect the relative severity of each additional type of cycle as predicted by the HSLMP.
- In this example, the maximum specified NB type starts used to establish the proportion of life consumption is kept at 900.
- As a consequence, the lower factors produce a slightly lower rate of life consumption.

Figure 2-5
Formulation of Life Consumption for Start-Based Criterion

As reflected in **Figure 2-5**, the HSLMP provides an opportunity to independently compare and assess the OEM interval estimates. In the calculation using the OEM factors, the starts are reflected as a portion of the total life consumed to date and proportion of life remaining. From the hypothetical record of 131 factored starts, it infers that nearly 14.5% of the total life has been consumed. The independent calculation produced from factors that are adjusted to reflect proportional damage accumulation for each of the referenced events provided by the HSLMP reflects a life consumption of 12.3%. However, this is based on the damage caused to a specific location on the 1st stage bucket, attributable to TMF only.

The treatment of life consumption due to creep and/or coating life in the HSLMP is treated in a similar fashion, as shown in **Figure 2-6**. Note that in this example a different baseline interval assumed in the HSLMP calculations (30000 vs. 24000 hours).

The linear damage rule is used to take into account the interaction between creep and fatigue damage and the result is reported as a “combined” remaining life parameter.



Formula Ref	Factored Hours	Annual Hours	OEM Factor	HSLMP Comp #1	HSLMP Comp #2
G	**Hours on Gas Fuel**	**1392**	**1**	**1.0**	**1.0**
D	Hours on Distilate Fuel	48	1.5	1.5	1.5
Hr	Hours on Heavy Fuel - Residual	0	3.5	3.5	3.5
Hc	Hours on Heavy Fuel - Crude	0	2.5	2.5	2.5
P	Peak Load Operating Hours	0	6	6	6
		K	M		
I dry	GTD 222 Steam Injection <2.2%	1	0		
I wet	GTD 222 Steam Injection >0.0%	1	0.18		
	Total Actual Hours		1440	1440	
	Total Factored Hours		1464	1464	
	Maximum Specified Hours		24000	**30000**	
	Maintenance Interval =		23607	29508	
	Maintenance Factor		1.0	1.0	
	Life Consumed		**6.10%**	**4.88%**	
	Life Remaining		**93.9%**	**95.1%**	

$$\text{Maintenance Interval (Hrs)} = \frac{24000}{\text{Maintenance Factor}}$$

$$\text{Maintenance Factor} = \frac{\text{Factored Hours} = (K + M \times I) \times (G + 1.5D + Af\,H + 6P)}{\text{Actual Hours} = (G + D + H + P)}$$

Figure 2-6
Formulation of Life Consumption for Hours-Based Criterion

The principal distinction between the HSLMP results and the OEM approach is that the HSLMP derives its estimates of proportional damage directly for each of the respective locations where maximum temperatures, stresses and strains are predicted to occur. Rate of damage for each principal mechanism is based on the properties obtained by controlled tests of materials and coating samples independently performed by EPRI. This means that the final result is specific to:

a. the part (and/or the particular design iteration that is installed),
b. the operating conditions of the unit (whether in a heat recovery scheme or as a stand alone unit),
c. the location on the part (where it is most susceptible to a particular type of damage) and
d. the operating record (reflected in measurements by the units' automated data tracking system).

Comparisons made with factors obtained from the HSLMP have indicated in certain situations that the OEM life formulation produced a more conservative interval for inspection and replacement because it lacks the specificity provided by the HSLMP. Conversely, damage caused by certain modes of operation is apparently being underestimated by the OEM's formulas. In this regard, the appearance of cracks in regions such as the trailing edge cooling hole of the 1st stage bucket was predicted by HSLMP for start intervals below the OEM factored allowable, based on the stresses and temperatures that were being calculated in this region. These predictions were subsequently confirmed by examples obtained from the field. A recent TIL (1186-2r1) has reduced the inspection interval for 7FA+ parts to 350 starts, with guidance as to what maximum crack sizes are allowable.

Module Development

EPRI's contractor for the development of the HSLMP was Turbine Technology, Inc. (TTI) of Rochester, NY. As part of the RLM project, TTI created a Dynamic Link Library (DLL), which contained the HSLMP algorithms for the 7FA+ 1st stage buckets. A DLL can be thought of as a compiled subroutine that can be called by a Windows-based program.

It was determined that the best way to implement the HSLMP calculation was in a "batch-wise" fashion at the end of each CT run (start-stop cycle). The HSLMP algorithms account for events that occur over the complete course of a start-stop cycle and therefore are not conducive to being used in a real-time mode during a CT run.

Instead, the DLL was designed to be called at the end of each CT run. Input parameters to the DLL included the three % remaining life values (TMF-based, Creep-based, and combined) before the run started and various parameters that describe the severity of the run such as fuel type, peak firing temperature, and whether an emergency trip occurred. A full description of the inputs can be found in Chapter 4. The outputs from the DLL were the three remaining life parameters, updated to reflect the impact of the run.

A simple Excel spreadsheet was initially developed to allow testing of the HSLMP DLL. The spreadsheet required all of the DLL inputs to be manually entered in cells of the spreadsheet. The DLL was called by a macro, which was invoked by clicking a button in the spreadsheet. TTI tested this simple spreadsheet and confirmed that the DLL was operating correctly.

This simple spreadsheet was then expanded to include the GER-3620J calculations and automatic retrieval of CT operating data to support both the 3620J calculations and the HSLMP calculations. In addition, the macro that called the HSLMP DLL was automatically linked to the macro that implemented the run-by-run 3620J calculations.

As described in Chapter 1, the RLM calculations can be carried out in either an initialization mode or a run-by-run mode. The initialization calculations use only the GER-3620J calculations to determine the remaining life of the hot section. Details of how these calculations are carried out are provided in Chapter 3.

The run-by-run calculations always follow the GER-3620J algorithms and also use the HSLMP DLL if the CT type is a 7FA+. A description of how the run-by-run calculations are implemented is found in Reference [4].

3
INITIALIZATION CALCULATIONS

Inputs

The initialization calculations are set up on the RLM.xls worksheet named "Initialization Inputs". The user must specify information on the combustion turbine being evaluated. This information includes:

- CT model type (e.g., MS6B, MS7FA+, etc.)
- Fuel type corresponding to the primary and secondary liquid fuel flow meters
- 2nd and 3rd stage turbine nozzle material (GTD-222 or FSX-414)
- Whether compressor bleed heating is used to pre-heat inlet air
- What NO_x control method is used (e.g., DLN combustor, water injection, steam injection)

Also, the user must enter the values of the following counters from the CT's operating history or can optionally define formulas in the cells to extract the values from a PI database (using the Excel add-in PI DataLink):

- Total Fired Starts, L30CFS
- Total Fast Starts, L30CFLS
- Total Emergency Trips, L30CES
- Total Fired Hours, L30FT_T
- Total Peak Hours, L30FT_P
- Total Gas Fuel Fired Hours, L30FT_G
- Total Primary Liquid Fuel Fired Hours, L30FT_L
- Total Secondary Liquid Fuel Fired Hours, L30FT_L2

In addition to the counters, the user must also enter estimates that describe the operating history of the CT. For example, the user is asked to estimate the percentage of total starts that were part-load (i.e., <60% load) starts and the percentages of starts that were fired on gas fuel, on the primary liquid fuel and on the secondary liquid fuel.

The spreadsheet has some built-in error-checking to ensure that the user enters a consistent set of data. For example, if the sum of the gas fired, primary liquid fired, and secondary liquid fired hours does not equal the total fired hours, the cells for the three fuel-based hours counters will be highlighted in red (see **Figure 3-1**).

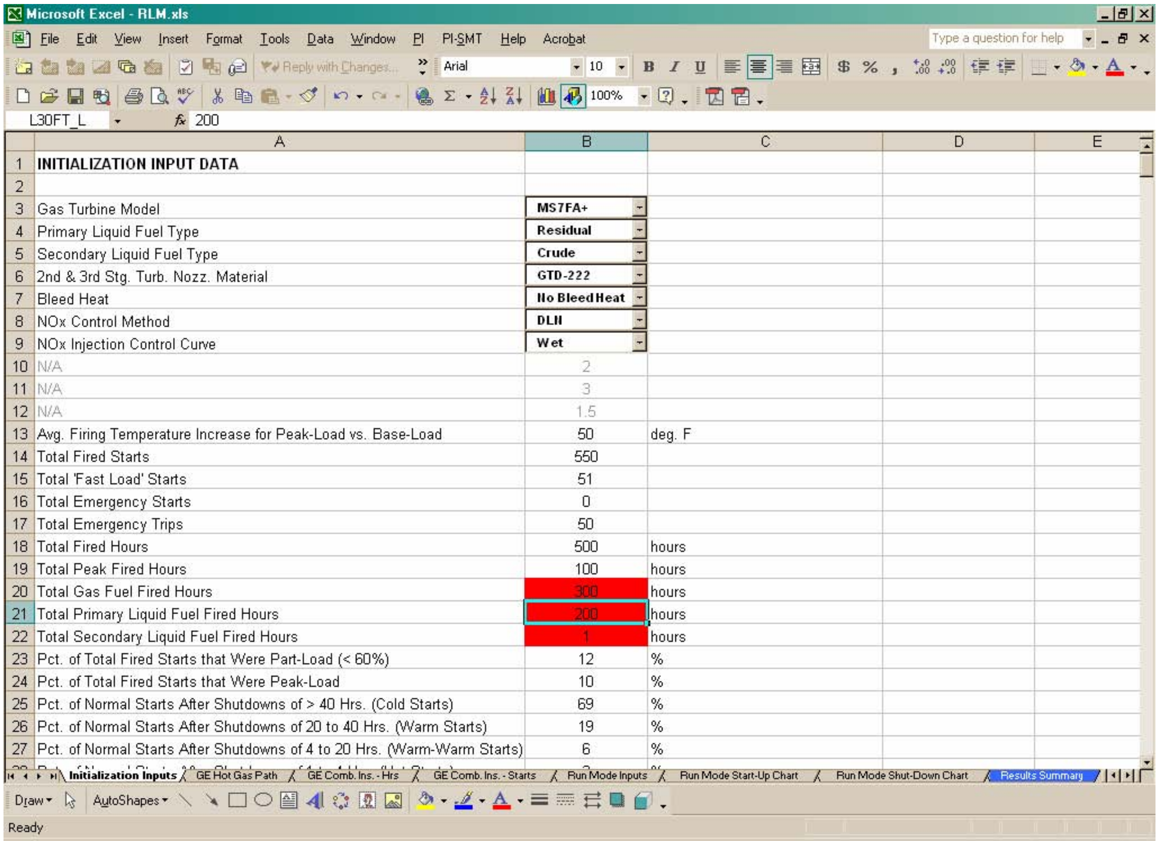


Figure 3-1
Example of Error Checking on Initialization Inputs Worksheet

Results

Using the user-entered inputs, the following parameters are calculated based on the GER-3620J formulas:

- Hot Gas Path Inspection
  - Factored Starts
  - Maintenance Factor – Starts Based
  - Maintenance Interval – Starts Based
  - % of Starts Based Maintenance Interval Remaining
  - Factored Hours
  - Maintenance Factor – Hours Based
  - Maintenance Interval – Hours Based
  - % of Hours Based Maintenance Interval Remaining
- Rotor Life
  - Factored Hours
  - Maintenance Factor – Hours Based
  - Maintenance Interval – Hours Based

  - % of Hours Based Maintenance Interval Remaining
  - Factored Starts
  - Maintenance Factor – Starts Based
  - Maintenance Interval – Starts Based
  - % of Starts Based Maintenance Interval Remaining
- Combustion Inspection
  - Factored Hours
  - Maintenance Factor – Hours Based
  - Maintenance Interval – Hours Based
  - % of Hours Based Maintenance Interval Remaining
  - Factored Starts
  - Maintenance Factor – Starts Based
  - Maintenance Interval – Starts Based
  - % of Starts Based Maintenance Interval Remaining

These results, along with details of the calculation, are displayed on three results worksheets: GE Hot Gas Path, GE Comb. Ins. – Hrs, and GE Comb. Ins. – Starts (see **Figure 3-2**, **Figure 3-3**, and **Figure 3-4**). These three worksheets are automatically updated whenever a change is made to the initialization inputs. If the user wants to save the results shown on these sheets and use them as the starting point for subsequent run-by-run calculations, the button labeled "Use Results to Initialize Future Remaining Life Calculations" should be clicked. Note that even though this button exists on all three worksheets, it is not necessary to click all three buttons. Clicking the button on any of one of the worksheets will save the complete set of results from all three worksheets.

After the results are saved, the Results Summary worksheet is displayed and the user should again check the results reported there. If satisfied with the results, initialization of the current gas turbine can be considered complete and further runs for the turbine can be analyzed using the individual run calculations discussed in Chapter 5. Otherwise, the user may return to the Initialization Inputs worksheet to modify the data there, then re-initialize the gas turbine, overwriting the previous results.

Whenever the user attempts to re-initialize a gas turbine, a warning message will be displayed informing the user of 1 or 2 existing files. If the gas turbine being re-initialized is a GE 7FA+, the first warning message to be displayed will inform the user that an existing Results.csv (HSLMP results) file has been detected. If the user is certain that they want to overwrite the previous HSLMP initialization results, they should click on the "Yes" button. If unsure about re-initializing, the user should click on the "No" button to abort the initialization. The second warning message to be displayed (or first, in the case of non-GE 7FA+ gas turbines) will inform the user that an existing 3620J.csv (GER-3620J results) file has been detected. If the user is certain that they want to overwrite the previous GER-3620J initialization results, they should click on the "Yes" button. If unsure about re-initializing, the user should click on the "No" button to abort the initialization.

The user must be careful when re-initializing. Completing the re-initialization process (i.e., saving the results to file) results not only in the loss of all previous initialization results, but also the loss of all previous run results if the turbine has already been analyzed for individual runs.

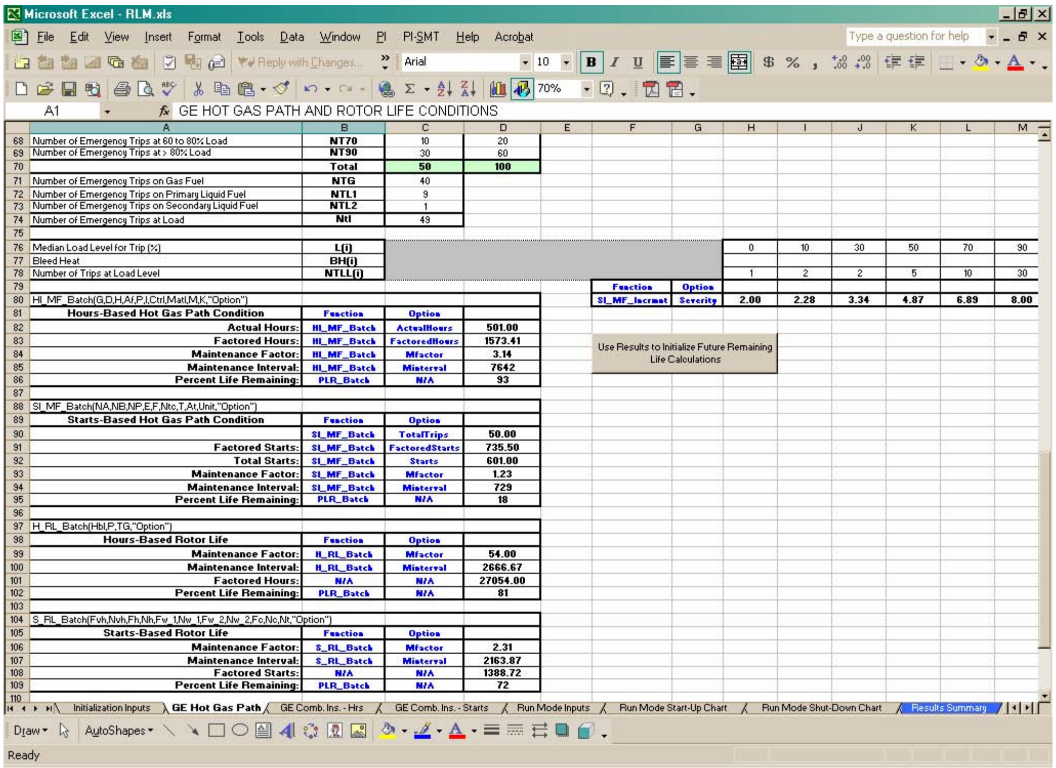
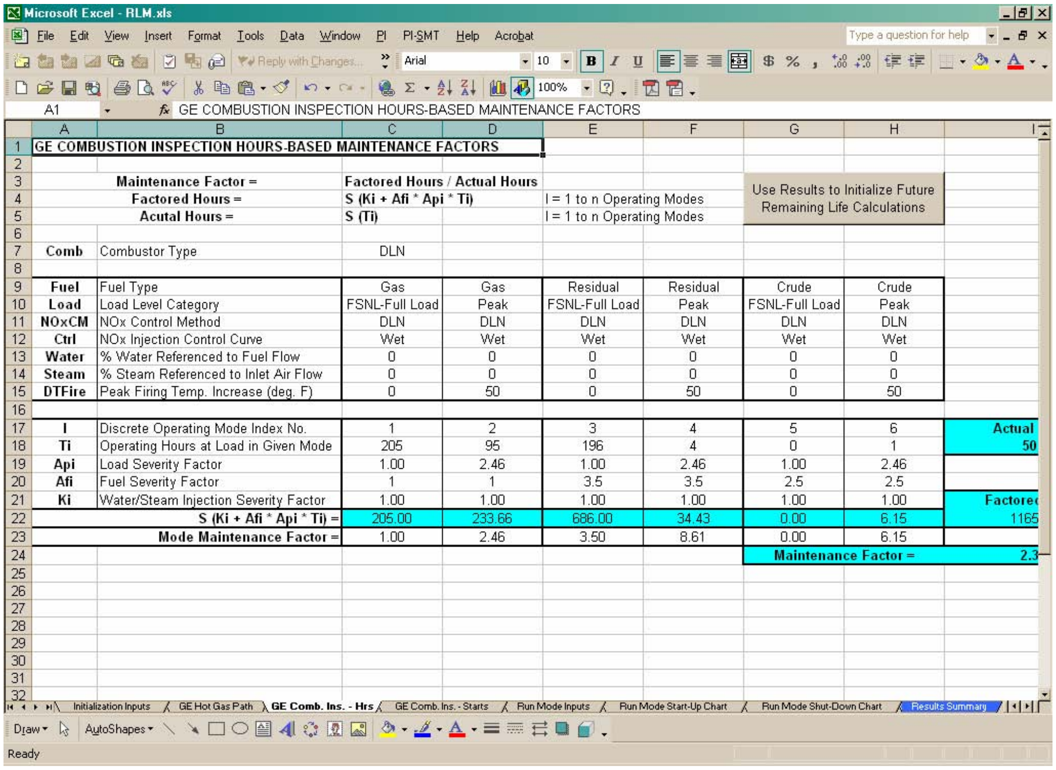
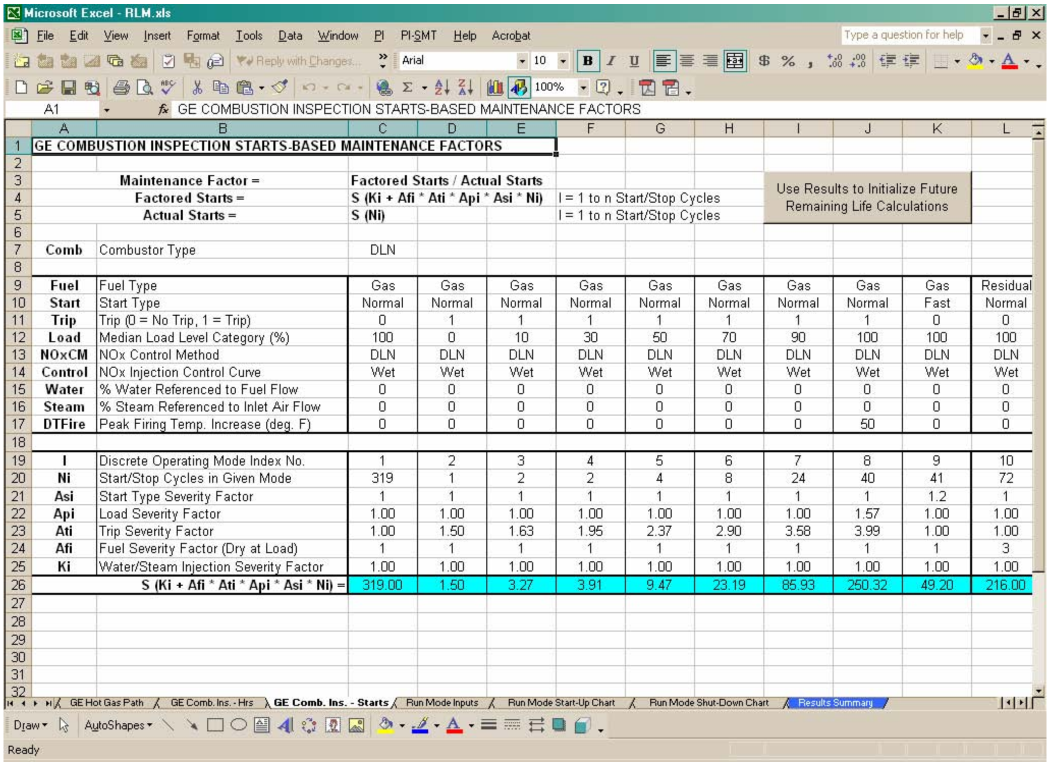


Figure 3-2
Example of Initialization Results for Hot Gas Path and Rotor Life Calculations



	A	B	C	D	E	F	G	H	I
1	GE COMBUSTION INSPECTION HOURS-BASED MAINTENANCE FACTORS								
3		Maintenance Factor =	Factored Hours / Actual Hours				Use Results to Initialize Future Remaining Life Calculations		
4		Factored Hours =	S (Ki + Afi * Api * Ti)		I = 1 to n Operating Modes				
5		Acutal Hours =	S (Ti)		I = 1 to n Operating Modes				
7	Comb	Combustor Type	DLN						
9	Fuel	Fuel Type	Gas	Gas	Residual	Residual	Crude	Crude	
10	Load	Load Level Category	FSNL-Full Load	Peak	FSNL-Full Load	Peak	FSNL-Full Load	Peak	
11	NOxCM	NOx Control Method	DLN	DLN	DLN	DLN	DLN	DLN	
12	Ctrl	NOx Injection Control Curve	Wet	Wet	Wet	Wet	Wet	Wet	
13	Water	% Water Referenced to Fuel Flow	0	0	0	0	0	0	
14	Steam	% Steam Referenced to Inlet Air Flow	0	0	0	0	0	0	
15	DTFire	Peak Firing Temp. Increase (deg. F)	0	50	0	50	0	50	
17	I	Discrete Operating Mode Index No.	1	2	3	4	5	6	Actual
18	Ti	Operating Hours at Load in Given Mode	205	95	196	4	0	1	50
19	Api	Load Severity Factor	1.00	2.46	1.00	2.46	1.00	2.46	
20	Afi	Fuel Severity Factor	1	1	3.5	3.5	2.5	2.5	
21	Ki	Water/Steam Injection Severity Factor	1.00	1.00	1.00	1.00	1.00	1.00	Factorec
22		S (Ki + Afi * Api * Ti) =	205.00	233.66	686.00	34.43	0.00	6.15	1165
23		Mode Maintenance Factor =	1.00	2.46	3.50	8.61	0.00	6.15	
24							Maintenance Factor =		2.3

Figure 3-3
Example of Initialization Results for Hours-Based Combustion Inspection Interval



	A	B	C	D	E	F	G	H	I	J	K	L
1	GE COMBUSTION INSPECTION STARTS-BASED MAINTENANCE FACTORS											
3		Maintenance Factor =	Factored Starts / Actual Starts						Use Results to Initialize Future Remaining Life Calculations			
4		Factored Starts =	S (Ki + Afi * Ati * Api * Asi * Ni)			I = 1 to n Start/Stop Cycles						
5		Actual Starts =	S (Ni)			I = 1 to n Start/Stop Cycles						
7	Comb	Combustor Type	DLN									
9	Fuel	Fuel Type	Gas	Gas	Gas	Gas	Gas	Gas	Gas	Gas	Gas	Residual
10	Start	Start Type	Normal	Normal	Normal	Normal	Normal	Normal	Normal	Normal	Fast	Normal
11	Trip	Trip (0 = No Trip, 1 = Trip)	0	1	1	1	1	1	1	1	0	0
12	Load	Median Load Level Category (%)	100	0	10	30	50	70	90	100	100	100
13	NOxCM	NOx Control Method	DLN	DLN	DLN	DLN	DLN	DLN	DLN	DLN	DLN	DLN
14	Control	NOx Injection Control Curve	Wet	Wet	Wet	Wet	Wet	Wet	Wet	Wet	Wet	Wet
15	Water	% Water Referenced to Fuel Flow	0	0	0	0	0	0	0	0	0	0
16	Steam	% Steam Referenced to Inlet Air Flow	0	0	0	0	0	0	0	0	0	0
17	DTFire	Peak Firing Temp. Increase (deg. F)	0	0	0	0	0	0	0	50	0	0
19	I	Discrete Operating Mode Index No.	1	2	3	4	5	6	7	8	9	10
20	Ni	Start/Stop Cycles in Given Mode	319	1	2	2	4	8	24	40	41	72
21	Asi	Start Type Severity Factor	1	1	1	1	1	1	1	1	1.2	1
22	Api	Load Severity Factor	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.57	1.00	1.00
23	Ati	Trip Severity Factor	1.00	1.50	1.63	1.95	2.37	2.90	3.58	3.99	1.00	1.00
24	Afi	Fuel Severity Factor (Dry at Load)	1	1	1	1	1	1	1	1	1	3
25	Ki	Water/Steam Injection Severity Factor	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
26		S (Ki + Afi * Ati * Api * Asi * Ni) =	319.00	1.50	3.27	3.91	9.47	23.19	85.93	250.32	49.20	216.00

Figure 3-4
Example of Initialization Results for Starts-Based Combustion Inspection Interval

Details on the calculation algorithms for each maintenance interval are provided in the following sub-sections.

Hours-Based Hot Section Calculation

Since the GE fuel-based run hour counters do not distinguish between base and peak load operation, RLM uses the following modified version of the GER-3620J formula for factored hours:

$$\text{Factored Hours – Gas} = (K + M * I)_g * (G + 6 * P_g)$$

$$\text{Factored Hours – Distillate} = (K + M * I)_d * (1.5 * D + 6 * P_d)$$

$$\text{Factored Hours – Residual} = (K + M * I)_r * (3.5 * H + 6 * P_r)$$

$$\text{Factored Hours – Crude} = (K + M * I)_c * (2.5 * H + 6 * P_c)$$

Total Factored Hours = Sum of the four fuel-based factored hours

where the subscripted Ps indicate the number of peak run hours on the various fuel types: gas, distillate, residual, and crude. This breakdown is found by multiplying the total peak hours by the user-entered percentages. The base-load hours (G and D) are calculated from:

$$G = \text{L30FT\_G} – P_g$$

$$D = \text{L30FT\_L} – P_d, \text{ etc.}$$

The subscripted (K + M * I)s represent the water/steam injection factors corresponding to operation on the various fuel types.

Starts-Based Hot Section Calculation

First, the number of normal starts is calculated:

NN = L30CFS – L30CFLS

Then the normal starts are broken down into part-load, base-load and peak-load starts using the user-entered percentages.

Next, the number of trips that occurred at the various load ranges is calculated based on the user-entered percentages. The trip severity factor for each of the load ranges is then calculated using the median value of each range as the load level (e.g., 30% for the range 20% to 40%).

Hours-Based Rotor Life

First, total base-load hours is calculated:

Hrl = L30FT_T – L30FT_P

Total time on turning gear is estimated by the formula:

$$TG = K62CD * L30CFS$$

where K62CD is the cool-down sequence timer length

Then the maintenance factor is calculated based on the formula in GER-3620J.

Starts-Based Rotor Life

Using the number of normal starts, NN, calculated for the Hot Section Interval, the normal starts are broken down into the various shutdown length categories based on the user-entered percentages.

Then the fast starts are broken down into the various shutdown lengths based on the user-entered percentages for fast starts. The formula for maintenance factor (MF) is:

$$MF = [(Fh * Nh + Fw1 * Nw1 + Fw2 * Nw2 + Fc * Nc)_{normal} + (Fh * Nh + Fw1 * Nw1 + Fw2 * Nw2 + Fc * Nc)_{fast} + Ft * Nt] / [(Nh + Nw1 + Nw2 + Nc)_{normal} + (Nh + Nw1 + Nw2 + Nc)_{fast}]$$

$$Nh_{normal} = NN * \%Hot_{normal} / 100$$

$$Nh_{fast} = NN * \%Hot_{fast} / 100$$

where $\%Hot_{normal}$ is the user-entered percentage of normal starts that were considered hot starts and $\%Hot_{fast}$ is the user-entered percentage of fast starts that were considered hot starts. Similar formulas are used for the "w1", "w2", and "c" start categories.

The "F" factors can be found in the table in Figure 45 of GER-3620J.

Hours-Based Combustion Inspection

The following operating modes are considered:

1. Gas-Fired, FSNL to Full Load
2. Gas-Fired, Peak
3. Primary Liquid-Fired, FSNL to Full Load
4. Primary Liquid-Fired, Peak
5. Secondary Liquid-Fired, FSNL to Full Load
6. Secondary Liquid -Fired, Peak

The water/steam injection severity factors are calculated for each operating mode based on the user-entered values for average steam or water injection flows for each fuel type.

The fuel severity factors are based on the values in GER-3620J and the user-entered information on whether a DLN combustor is present.

The peak load severity factors are based on the user-entered value for the peak firing temperature increase.

The number of operating hours in each mode has previously been calculated for the hot section maintenance factor evaluation (G, P_g, etc.).

Starts-Based Combustion Inspection

A total of 27 types of start/stop cycles are considered:

- Gas-Fired
  - Normal Start
    - Up to Base Load
      - No Trip
      - Trip
        - FSNL
        - FSNL to 20% Load
        - 20 to 40%
        - 40 to 60%
        - 60 to 80%
        - >80%
    - Peak Load
  - Fast Start
- Primary Liquid-Fired
  - Normal Start
    - Up to Base Load
      - No Trip
      - Trip
        - FSNL
        - FSNL to 20% Load
        - 20 to 40%
        - 40 to 60%
        - 60 to 80%
        - >80%
    - Peak Load
  - Fast Start
- Secondary Liquid-Fired
  - Normal Start
    - Up to Base Load
      - No Trip
      - Trip
        - FSNL
        - FSNL to 20% Load
        - 20 to 40%
        - 40 to 60%
        - 60 to 80%
        - >80%
    - Peak Load
  - Fast Start

For each fuel type, it is assumed that the water/steam injection severity factor will be identical for all start types. The value is based on the user-entered values for average steam or water injection flow and control curve type.

The fuel severity factor is based on the GER-3620J values and the user-entered specification of DLN or non-DLN.

The trip severity factor for each of the load ranges is based on the median value of the range (e.g., 30% for the range 20% to 40%).

The load severity factor for peak starts is based on the user-entered value for the peak firing temperature adder.

4
INDIVIDUAL RUN CALCULATIONS

User Inputs

The inputs for individual run calculations are entered on the Run Mode Inputs worksheet.

The user should manually enter or select the following information:

- Run Number
- Date and Hour that Run Started
- Date and Hour that Run Ended
- Date and Hour that Previous Run Ended (normally will automatically be filled with the date and hour from a previous run calculation)
- CT Engine Model
- Primary Liquid Fuel Type (distillate, residual, or crude)
- Secondary Liquid Fuel Type (distillate, residual, or crude)
- 2^{nd} & 3^{rd} Stage Nozzle Material
- NO_x Control Method (water, steam, DLN, or none)
  - If water or steam, then NO_x Control Curve Type (wet or dry)
- Base Load Firing Temperature (deg. F)

Also, the user must enter the PI database tag names for the parameters listed in the lower-left section of the worksheet beginning in cell "C17" (see **Figure 4-1**). Note that some of the parameters are normally not available from the Mark V (or Mark VI), but are calculated by EPRI's Combustion Turbine Performance and Fault Diagnostics Module (CTPFDM.xls). Therefore, CTPFDM should be set up to execute calculations during a run and to export the required parameters to the PI database. This assumes the user has available, unused PI tagnames, which CTPFDM will use to store parameter values.

Once all the inputs have been set, the user should click the button labeled "Retrieve Run Data and Run Remaining Life Calculations". That button initiates a macro that retrieves, via PI DataLink function calls, one minute data for the HP turbine shaft speed (TNH) from 30 minutes before the user-entered starting time to 30 minutes after the start and from 30 minutes before the user-entered ending time to 30 minutes after the end. For example if the user entered:

Date & Time that Run Started: 2/2/04 13:30
Date & Time that Run Ended: 2/4/04 23:05

The data would be retrieved for every minute from 13:00 to 14:00 on 2/2/04 and from 22:35 to 23:35 on 2/4/04.

Table 4-1
Parameters Required from PI Database

Parameter Description	Mark V Tag
Peak Fired Time Counter	L30FT_P
Total Fired Time Counter	L30FT_T
Time Unit Fired on Gas Fuel	L30FT_G
Time Unit Fired on Liquid Fuel	L30FT_L
Steam Injection Flow, lbs/sec	WQJA
NOx Injection Water Flow, lbs/sec	WQJ
Compressor Inlet Air Flow, lbs/sec	AFQ
Gas Fuel Flow, lbs/sec	FQG
Primary Liquid Fuel Mass Flow, lbs/sec	FQLM1
Second. Liquid Fuel Mass Flow, lbs/sec	FQLM2
Fired Starts Counter	L30CFS
Total Starts Counter	L30CTS
‘Fast Load’ Starts Counter	L30CFLS
Emergency Trips Counter	L30CES
Firing Temperature (from CTPFDM.xls), deg. F	Tfire
% Load (from CTPFDM.xls)	Load
HP Turbine Shaft Speed, rpm	TNH
Bleed Heat (On/Off)	CSRIHOUT
GT Inlet Air Flow (from Mark VI or CTPFDM.xls), lbs/sec	WIN

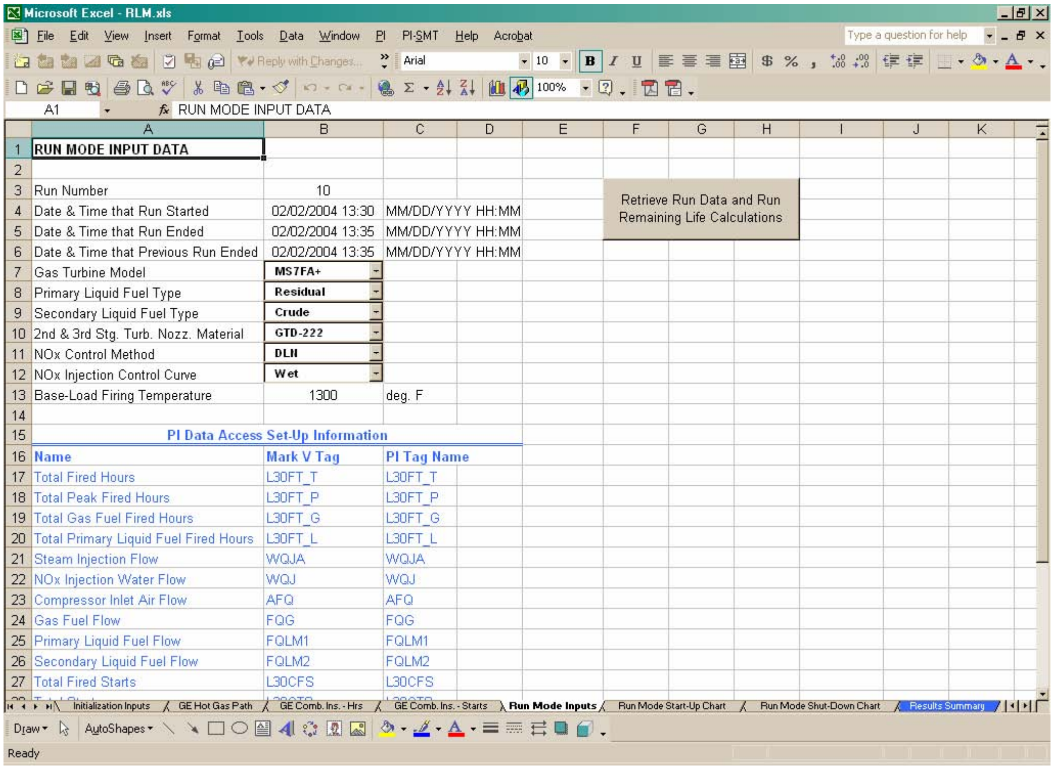


Figure 4-1
Example Run Mode Inputs Worksheet

The macro also creates a trend chart of HP turbine speed versus time for the retrieved data around the starting time. A message box pops up asking the user, "Do you wish to modify the date and/or hour that the run started?" If the user selects the button labeled "Yes", then the view switches back to the Run Mode Inputs worksheet and the macro ends. The user can then modify the start date or time and re-run the retrieve data macro. This feature is included as an aid for determining the exact starting time of a run. In the example shown in **Figure 4-2**, it is clear from the plotted data that the turbine was not running during the specified period, and the user should click "Yes" and enter a new starting time.

If the user selects the button labeled "No" when viewing the TNH plot around the starting time, the macro then creates a trend chart of TNH versus time from the retrieved data around the ending time. Another message box pops up asking the user "Do you wish to modify the date and/or hour that the run ended?" If "Yes" is selected, then the macro returns the user to the Run Mode Inputs worksheet. Otherwise, if the user selects "No", the macro continues with the main data extraction via PI DataLink for each hour of the run, and performs the GER-3620J calculations (and the EPRI HSLMP calculations if the CT model is a 7FA+).

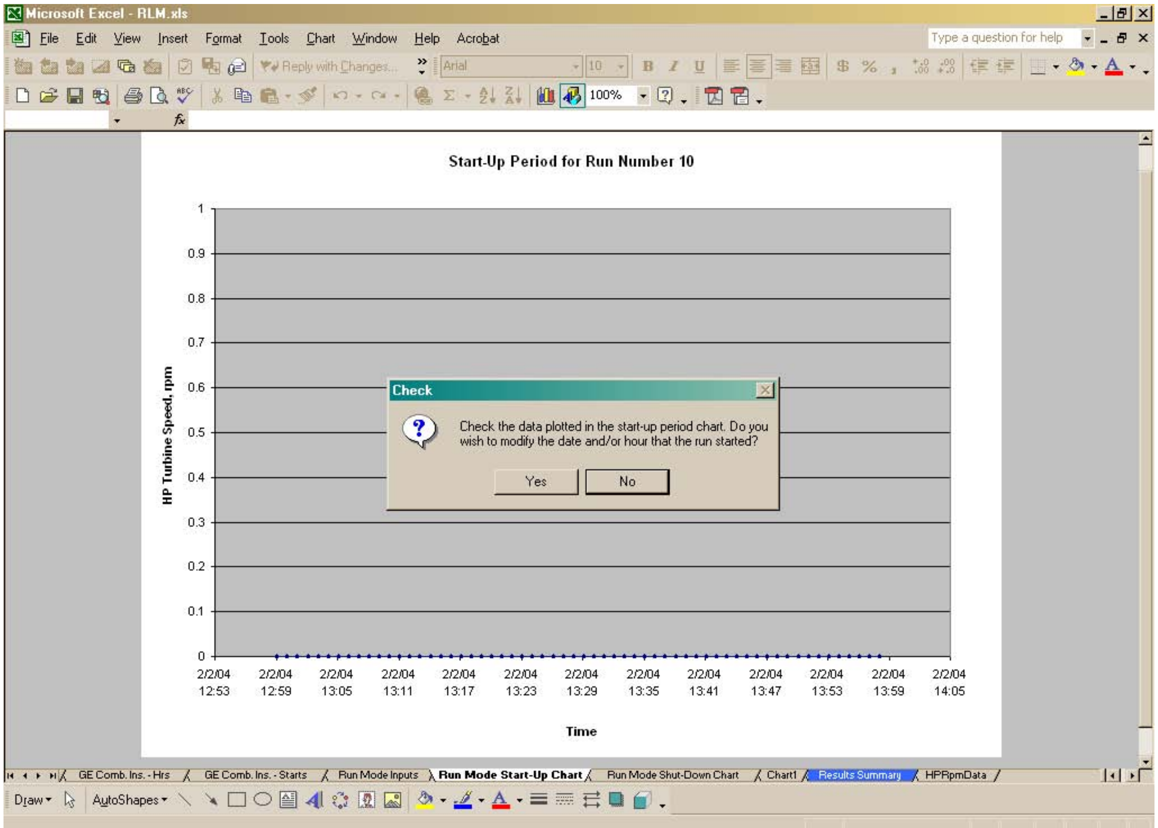


Figure 4-2
Trend Chart of HP Turbine Speed (TNH) around the Period of the User-Specified Run Start Time

Results

Once the user has accepted the starting and ending times for the run mode input data, RLM begins analyzing each hour of retrieved run period data using the GER-3620J algorithms. If the CT model is a GE MS7FA+, the macro also uses the HSLMP algorithms for the first stage rotating blades to calculate the % of maintenance interval remaining based on creep (comparable to GER-3620J hours-based calculation), TMF (comparable to GER starts-based calculation), and the % of maintenance interval remaining based on the combined effects of creep and TMF (no comparable GER-3620J calculation). Then, after RLM has completed processing all run period hours, a message box will pop up displaying a brief summary of the calculated results: Hot Gas Path Factored Hours and Factored Starts, Rotor Life Factored Hours and Factored Starts, and Combustion Inspection Factored Hours and Factored Starts for the run (see **Figure 4-3**). If the CT model is a 7FA+, Remaining Creep Life, Remaining Thermal Mechanical Fatigue, and Remaining Combined Life percentages are also displayed.

In the pop-up message box, the user is given the option to either accept or reject the results. If the user accepts the results by clicking the "Yes" button, the GER-3620J results are written to a new line in a separate comma separated value (CSV) format file named 3620J.csv. Each line in 3620J.csv represents an individual turbine run (start/stop cycle). The data in the CSV file is also imported to the 3620J.csv worksheet where it can be used for generating trend charts. (Charts can be created by the user.) The end date and time for the current run is also written to the input cell for "Date & Time that Previous Run Ended" (cell "B6") to prepare for the next run calculation.

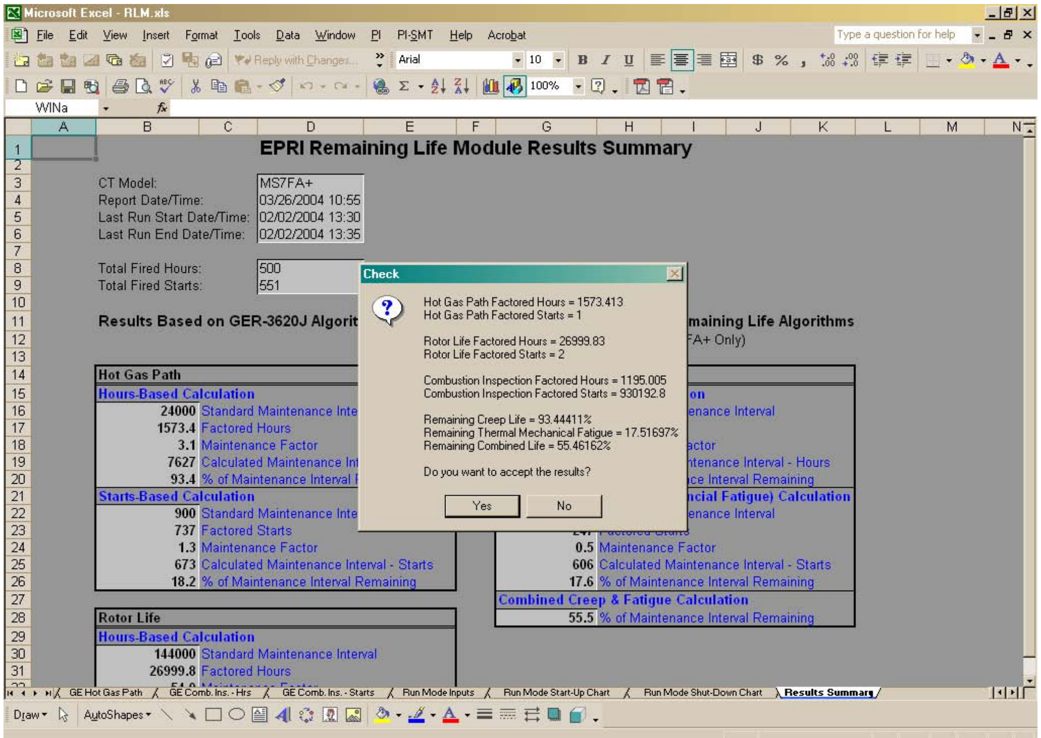


Figure 4-3
Pop-Up Window on Results Summary Worksheet that Appears after Run Mode Calculations are Completed

The data written to 3620J.csv includes:

- Run Number
- Date & Time that Run Started (stored in days since 1/1/1900 format)
- Date & Time that Run Ended (stored in days since 1/1/1900 format)
- Total Cumulative Hours on Turning Gear
- Actual Hours for the Run
- Hot Gas Path Hours-Based Results
  - Factored Hours for Run
  - Maintenance Factor for the Run
  - Cumulative Factored Hours
  - Cumulative Maintenance Factor
  - Maintenance Interval
  - % of Maintenance Interval Remaining

- Hot Gas Path Starts-Based Results
  - Factored Starts for Run
  - Cumulative Factored Starts
  - Cumulative Maintenance Factor
  - Maintenance Interval
  - % of Maintenance Interval Remaining
- Rotor Life Hours-Based Results
  - Factored Hours for Run
  - Maintenance Factor for the Run
  - Cumulative Factored Hours
  - Cumulative Maintenance Factor
  - Maintenance Interval
  - % of Maintenance Interval Remaining
- Rotor Life Starts-Based Results
  - Factored Starts for Run
  - Cumulative Factored Starts
  - Cumulative Maintenance Factor
  - Maintenance Interval
  - % of Maintenance Interval Remaining
- Combustion Inspection Hours-Based Results
  - Factored Hours for Run
  - Maintenance Factor for the Run
  - Cumulative Factored Hours
  - Cumulative Maintenance Factor
  - Maintenance Interval
  - % of Maintenance Interval Remaining
- Combustion Inspection Starts-Based Results
  - Factored Starts for Run
  - Cumulative Factored Starts
  - Cumulative Maintenance Factor
  - Maintenance Interval
  - % of Maintenance Interval Remaining

If the user accepts the results by clicking the "Yes" button in the pop-up message box and the CT being analyzed is a GE 7FA+, the HSLMP results will also be saved to a separate CSV file named Results.csv and to a Results.csv worksheet. The worksheet data can then be used to generate charts showing the historical trend in % life remaining. (Charts can be created by the user.)

After the "Yes" button in the pop-up message box has been clicked to accept the results and the data has been saved to the CSV file(s) and worksheet(s), the message box is closed and the calculated results are displayed on the Results Summary worksheet.

If the user chooses to reject the results by clicking the "No" button in the message box, the results are neither saved to file(s) nor saved to worksheet(s), but the results are displayed on the Results Summary worksheet. The user can then review the results and/or return to the Run Mode Inputs worksheet where the input data can be modified before retrieving the run data and running the remaining life calculations once again.

Results Summary

A summary of all of the life calculations is displayed in the Results Summary worksheet. An example of a portion of the summary screen is shown in **Figure 4-4**.

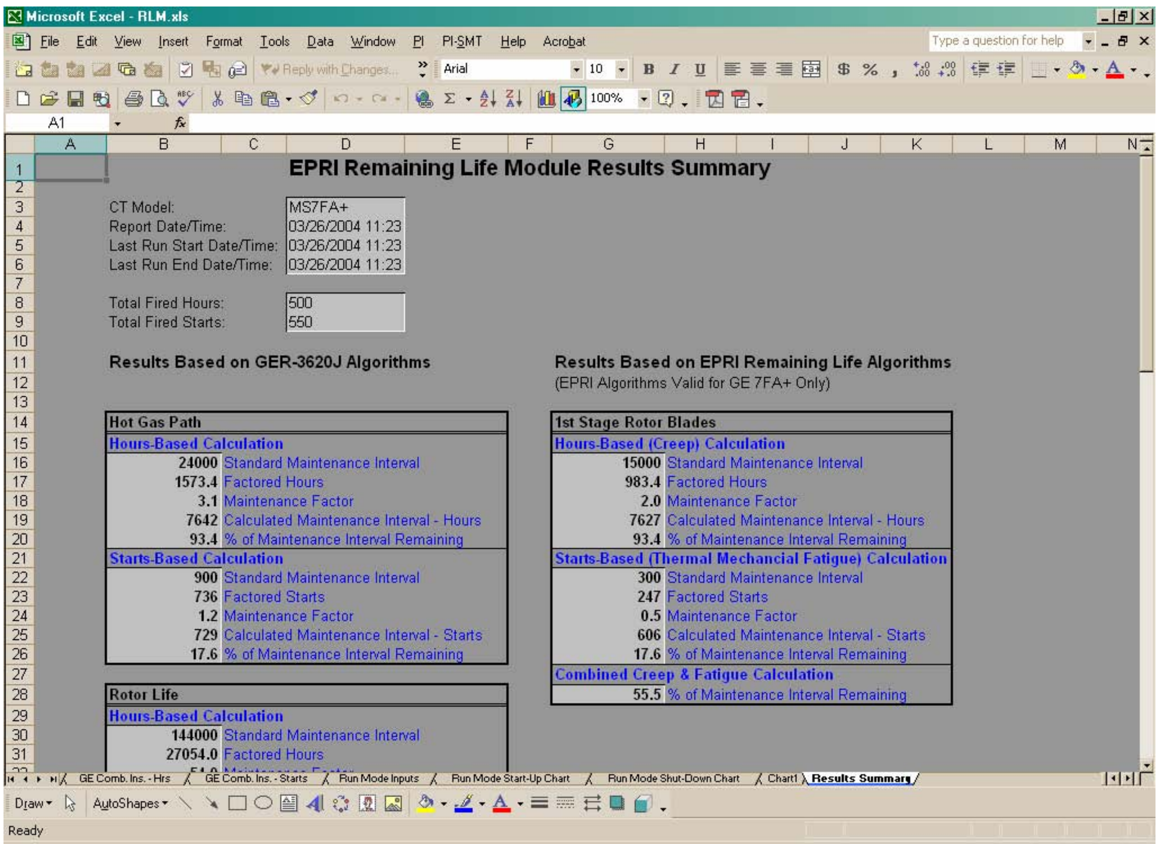


Figure 4-4
Example of Results Summary Worksheet

5 REFERENCES

[1] Robert Dewey, “Combustion Turbine F Class Life Management: Maintenance Life Tracking”, EPRI Report 1004364, Dec. 2002.

[2] Robert Hoeft, Jamison Janawitz, and Richard Keck, “Heavy-Duty Gas Turbine Operating and Maintenance Considerations”, GE Power Systems Report GER-3620J, Atlanta, GA, Jan. 2003.

[3] “Specialists' meeting on heat exchanging components of gas-cooled reactors Duesseldorf (Germany) 16-19 Apr 1984”, International Atomic Energy Agency, International Working Group on Gas-Cooled Reactors, Vienna (Austria) IWGGCR--9, pp:377-388

[4] Fabio, G., and F. Carlevaro, “Gas Turbine Maintenance Policy: A Statistical Methodology to Prove Interdependency between Number of Starts and Running Hours”, ASME Technical Paper GT2002-30281, presented at Turbo Expo 2002, Amsterdam, June 2002.

A
Appendix

Installation

Hardware & Software Requirements

Table A-1 lists the minimum hardware requirements for running the RLM spreadsheet. In addition, the PC must have Microsoft Excel 97 (or later) and OSI Software PI DataLink 2.0 (or later) installed. Finally, if the user wishes to view an electronic version of this User's Guide, Adobe Acrobat Reader 5.0 (or later) must be installed on the PC. Acrobat Reader is available free of charge on the Adobe Systems Web site at http://www.adobe.com.

Table A-1
Minimum Hardware Requirements

Hardware	Minimum Requirement	Recommended
Processor	333 MHz Pentium III	Same
Operating System	Windows 95/98/2000/NT 4.0/XP	Same
RAM	256 MB	512 MB
Available Hard Disk Space	10 MB	>20 MB

How to Install

1. Start Windows 95, 98, 2000, NT, or XP. Make sure that no other application is running while RLM is being installed.
2. The RLM installation disk(s) may consist of either a single CD or multiple 3½-inch diskettes. Insert the RLM installation CD or 1st diskette into the appropriate disk drive of your computer. For diskettes, this is usually drive A:\.
3. Select the "**Start**" button from the taskbar at the bottom of the screen and then "**Run**…". The "**Run**" dialog box appears.
4. For diskettes, type "A:\Setup.exe" in the Command Line text box. If installing from a CD or diskette drive other than A:\, substitute the appropriate letter for that source drive.
5. Select "**OK**". A welcome dialog box appears.

6. Select "**Next**" to go to the next screen.
7. A message box appears and asks where to install the RLM files (C:\Program Files\RLM is the default path). If desired, change the default name and destination of the RLM directory (folder).

   The installation program will then install the program in the specified directory. If installing from diskettes, you will be prompted to change disks. The installation program will also add RLM to the "**Programs**" menu option found under the "**Start**" button in the taskbar at the bottom of the screen. When you receive an on-screen message that the installation is complete, remove the CD or final diskette from its drive.
8. To start the RLM program, select the "**Start**" button from the taskbar, select the "**Programs**" submenu, click on **RLM,** then click on the Excel spreadsheet icon labeled **RLM**. Excel will start and load the RLM.xls spreadsheet. A dialog box will appear stating that the spreadsheet contains macros and asking if you want to enable or disable the macros (see Figure 6-1). Click "**Enable Macros**" and the spreadsheet will finish loading.

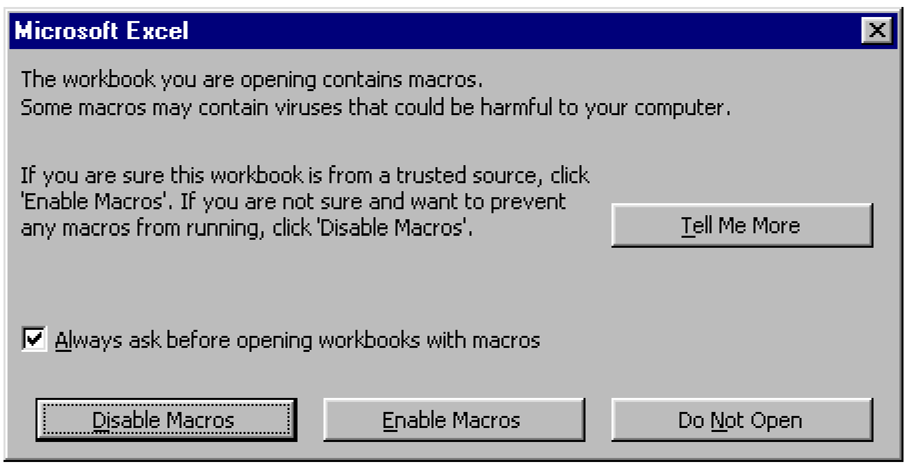


Figure 5-1
Example of Dialog Box that Appears Each Time the RLM.xls Spreadsheet Is Loaded

How to Uninstall

1. From the Windows 95, 98, 2000, NT, or XP desktop, click on the "**My Computer**" icon to open the "My Computer" window.
2. From the "My Computer" window, click on the "**Control Panel**" icon to open the "Control Panel" window.
3. From the "Control Panel" window, click on the "**Add/Remove Programs**" icon to open the "Add/Remove Programs" window.
4. Select the RLM software from the list of currently installed programs, then click the "**Add/Remove**" button ("**Change/Remove**" button in Windows 2000).
5. A message box will appear asking for confirmation of the removal of the program

and its components. If you are certain that you want to uninstall RLM, click the "**Yes**" button and RLM will be removed.

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