TURBINE GENERATOR LIFE ASSESSMENT/EXTENSION

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Dr. Jhansale joined the Advanced Technology Center of Allis-Chalmers in 1977, as a Specialist in Fatigue and Fracture Mechanics. From 1972-1977, he was Visiting Assistant Professor of Theoretical and Applied Mechanics at the University of Illinois, where he taught and conducted research in fatigue and fracture mechanics. At Allis-Chalmers, Dr. Jhansale has been responsible for the development of automated fatigue and fracture mechanics test and analytical capabilities. Also, he has been responsible for organizing inhouse educational seminars/workshops, and also in various successful practical applications of fatigue and fracture mechanics. Presently he is involved in life evaluation of turbogenerator components.

Dr. Jhansale has authored over thirty articles and reports in ASME, ASTM, and ASCE journals and several conference proceedings. He reviews technical articles for ASME and ASTM journals, and proposals for NSF. He is a member of the ASTM and SESA and a past chairman of SESA-Milwaukee chapter. He is also an active member of the technical committees, ASTM E-09 on Fatigue, ASTM E-24 on Fracture Testing, SAE Fatigue Design and Evaluation Committee, and SESA fatigue and fracture mechanics committees.

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Prior to being Manager of Marketing, he was Senior Project Manager of the Power Generation Section, Equipment Services Division, Allis Chalmers Corporation and was involved in major projects in the turbine generator aftermarket, including three life expectancy projects for Wisconsin Electric Power Company.

ABSTRACT

The approach and methodology to life assessment/extension are described. Items considered are nondestructive testing, material testing, flaw sizing, stress analysis, fracture mechanics

analysis and cumulative damage analysis. Examples are provided to illustrate specific aspects of the study.

INTRODUCTION

Life assessment/extension of a turbine generator unit is necessary for economic evaluation of the power plant. Proper maintenance and operation, although essential for long life of turbine generator components, will not disclose certain material degradation that occurs with time until the component is near failure. These items include cumulative damage and flaw growth due to both creep and fatigue. Creep is caused by steady state stress at high temperature, and fatigue is caused by startup and shutdown thermal and mechanical transient stresses. Fracture mechanics techniques are used to perform flaw growth due to fatigue, creep and stress corrosion cracking and evaluate observed flaws. Hence, analytical engineering techniques and inspection methods provide assurance that components will successfully perform during their planned life. If these techniques reveal problem areas, then a plan can be developed to find the most cost effective corrective measures. The purpose of a life assessment/extension study, therefore, is to evaluate the present condition of the turbine generator unit in terms of expended life, and to estimate when various components will require future inspections, repair, modifications or replacement, based on projected usage, so that the economical operation of the unit can be optimized.

The manufactcurer's involvement in the life studies covers only the turbine generator unit. Auxiliary components such as boiler, piping, heaters, motors, pumps, etc., are not included in the study. The majority of the turbine components are nondestructively inspected, and there is analytical evaluation of components such as high pressure (HP), intermediate pressure (IP) and low pressure (LP) turbine spindles, HP and IP inner, and outer cylinders, blade rings, main and reheat stop valves, intercept valves, dump valves, steam chests, steam strainer, inlet and reheat pipe bends, generator rotor, and generator retaining rings. Furthermore, both the generator rotor and stator are subjected to a series of electrical tests.

OPERATIONAL DATA

Past operational records such as inspection and maintenance reports should be reviewed and summarized, and a chronology should be prepared, if it is not already available. A questionnaire is sent to the customer to aid with collecting data that are required in order to perform the analytical evaluations. Information required includes past operating hours in specific ranges of temperatures, the number of cold, warm and hot starts and load changes per year for all years of operation. In addition, information regarding turbine operating data (temperature, pressure, rpm, MW, steam flow) should be defined as a function of time for cold, warm and hot starts, for shutdowns and for load changes. Typical cold start data are shown in Figure 1. These data are used to develop the various startup transients which are required for the thermal and stress analyses. It is preferred to have the cumulative damage calculations completed for all components, if at all possible, before the outage. This allows components with high damage to be investigated more closely, and, if necessary, replicas can be made to determine the condition of the material or samples can be removed for testing.

If the life assessment/extension study is being conducted on an Allis- Chalmers unit, internal records are also reviewed to obtain the maximum amount of information on the unit.

NONDESTRUCTIVE TESTING

The turbine and generator components that are normally inspected during a life study are tabulated in Figure 2, together

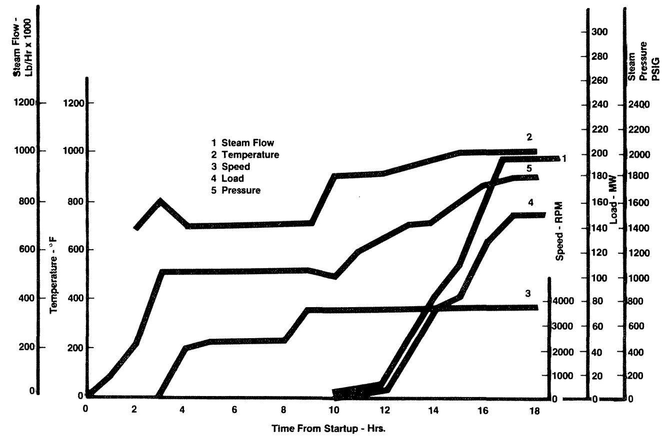

Figure 1. Cold Startup Transient Data.

with appropriate inspection methods. These methods include dimensional (Dim), visual (VT), magnetic particle (MT), penetrant (PT), ultrasonic (UT) and eddy current (ET). A detailed inspection plan is developed so that no components are missed. Component sketches are provided which show exactly where dimensions are to be measured to determine if extensive wear or creep deformation has occurred.

Component	Dim.	VT	MT	PT	UT	ET
Main Stop Valves	X	X	X	X		
Inlet Valves	X	X	X	X	X	
Steam Chests	X	X	X			
Steam Strainers	X	X	X			
Intercepting Valves	X	X	X	X		
Reheat Stop Valves	X	X	X	X		
Main Steam Pipe	X	X	X			
Hot Reheat Pipe	X	X	X			
Outer Cylinder	X	X	X			
Piping Nozzles	X	X	X			
Nozzle Chests & Blocks	X	X	X			
Inner Cyl. & Blade Rings	X	X	X			
Spindles	X	X	X		B	
Bearings	X	X		X	X	
Gland Casing	X	X	X			
Bolting	X	X	X		X	
Crossunder Piping		X		X		
Gen. Rotor		X	X		B	
Gen. Stator		X				
Gen. Retaining Rings		X		X	X	X

B - Bore Inspection

Figure 2. Typical Field Inspection NDE Requirement for Turbine and Generator Components.

All turbine spindles and generator rotors are boresonic (ultrasonic inspection from the bore) examined at this time, if recent inspection results within the last five years are not available for analysis. Furthermore, if it is known that a spindle/rotor contains numerous ultrasonic indications and the data are in a format that cannot be analytically evaluated by computer, then another boresonic inspection is requested with the appropriate data acquisition equipment.

Electrical tests of the generator rotor and stator are also undertaken at this time. Rotor tests include 500V DC megger test, impedance test, DC resistance test and exploring coil test. Stator tests include 2500V DC megger test, core test, winding step test, slot discharge and corona probe test, power factor test and Doble bushing test. Generator rotor retaining rings are also thoroughly inspected, utilizing ultrasonic, eddy current and penetrant techniques.

MATERIAL TESTING

Material tests could include one or more of the following: tensile properties, chemical analysis, Charpy V-notch impact tests and fracture appearance transition temperature (FATT), state-of-the-art fracture toughness tests (K_{Ic} or J_{Ic}), elevated temperature creep and stress rupture tests, cyclic stress-strain and strain based fatigue crack initiation life tests, fatigue crack growth property tests, chemical analysis, and metallurgical studies for embrittlement and cause of cracks. Since only small samples of material are available from the operating components, special built-up specimens are fabricated for mechanical tests. Samples obtained from the rotors are either radial or axial trepans from the outer diameter (OD) or ring samples removed from the ends or from the bore as part of an overbore operation.

The most important and useful tests for remaining life prediction by fracture mechanics are the tensile, the Charpy impact and the fracture toughness tests. These tests will provide the actual material properties. In the absence of the actual properties, lower bound conservative values based on the population database of all vintage rotors will be used. More importantly, if the material samples are obtained from the potential embrittled region (exposed to 600 to 900°F), these tests will provide the current embrittled fracture toughness of the material.

A typical fabrication of a bend test specimen for either Charpy or fracture toughness test from a radial trepan sample is shown in Figure 3. Two attachments of a material similar to the sample are electron beam welded to minimize the heat affected zone to eliminate any influence on the sample material properties. This also allows the sample to be appropriately oriented in order to measure the toughness in the radial-axial plane of the rotor.

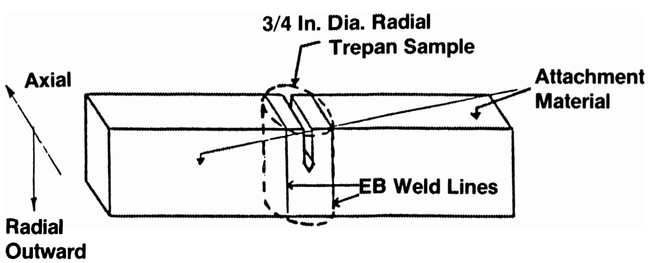

Figure 3. Fracture Toughness Test Specimen.

Fracture toughness tests are usually performed following ASTM Standard E-813 for J_{Ic} using the single specimen automated unloading compliance method. A typical load *vs* mid-span displacement plot obtained during such a test of a rotor steel is shown in Figure 4. The applied J- integral *vs* crack growth data derived from the load *vs* displacement data of Figure 4 is shown in Figure 5. As shown in Figures 4 and 5, the material exhibited excellent ductility and fracture toughness.

Depending on the number of samples available, Charpy and fracture toughness tests are performed at one or more temperatures. These data are compared with the existing database, and appropriate conservative values as a function of temperature are chosen after due consideration for measured values and expected scatter.

TURBINE SPINDLE/GENERATOR ROTOR CRACK SIZE ANALYSIS

Since startup and steady state stresses are highest at the bore surface and decrease with radial distance from the bore, axial-radial flaws within 3.0 in of the bore are the most harmful with respect to a burst failure for rotating components. Therefore,

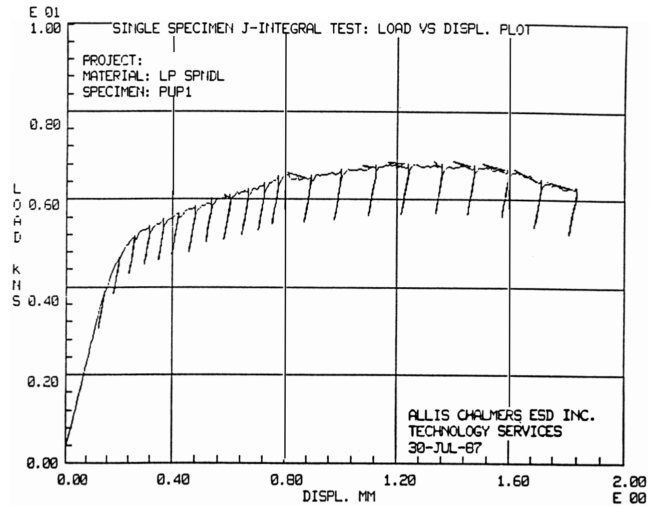

Figure 4. J_{Ic} Test Load vs *Displacement Test.*

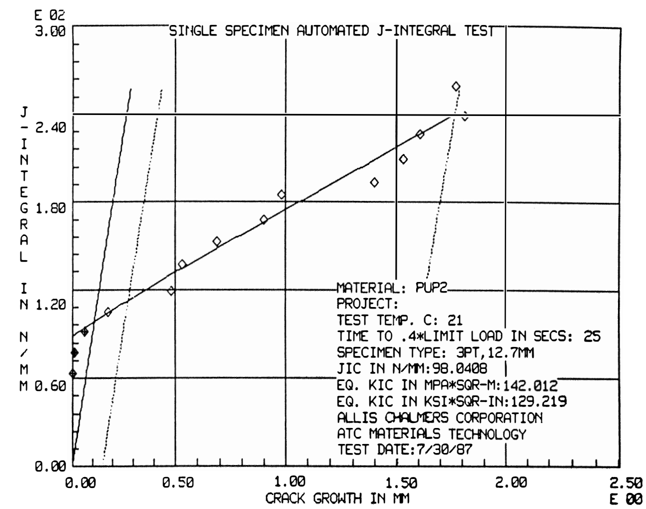

Figure 5. J_{Ic} Test J-Integral vs *Crack Growth Plot.*

nondestructive inspection methods are employed to detect axially oriented surface and subsurface flaws around the bore. These inspection methods include visual, magnetic particle and ultrasonic techniques.

Surface flaw sizes are estimated from visual and magnetic particle indications by assuming a flaw depth to surface length ratio of 0.5.

Subsurface flaw sizes and additional surface flaw sizes are derived by performing a "3-D Computer Linkup Analysis" of the boresonic inspection data. The linkup analysis essentially calculates the 3-D distances between neighboring boresonic indications. All those indications closer to each other than a specified length criterion are considered to be linked-up to form a larger hypothetical flaw. The results include a listing of all linkup flaws, their coordinate locations and sizes. Although individual ultrasonic indications usually show a relatively small amplitude, it is possible for larger flaws to be present due to reflection uncertainty associated with flaw shape and orientation. Furthermore, it is possible to have ligament yielding between indications without being detected. The critical linking distance is, in general, a function of the size of the neighboring indications, the stress level and the yield strength of the material. A conservative value of 0.3 in is generally used as the criterion. To further assist with the evaluation of flaw size, plots of the ultrasonic data are made as follows: axial location *vs* circumferential location; axial location *vs* radial location and circumferential location *vs* radial location. Specific linkup flaws can also be plotted on expanded scales to assist in determining whether the flaw is a planar (crack) defect or a cluster (nonmetallic inclusions, porosity, etc.) defect.

A typical linkup output is shown in Figure 6. For each potential flaw, the number of ultrasonic indications that constitute the flaw, its location and its size are tabulated. The DTHETA dimension, which is the circumferential width of the flaw, is used to determine whether the flaw is planar (DTHETA $\leq 20°$) or cluster (DTHETA $> 20°$). For example, for the fracture mechanics analysis, Linkup 5 would be considered as a buried crack, 0.21 in deep × 0.22 in long, centered 1.43 in from the bore, and Linkup 46 would be considered as surface crack, 0.28 in deep × 0.56 in long.

		POSITION					
		AXIAL, IN.		CIRCUM. DEG.		RADIAL, IN.	
LINKUP NO.	NUMBER OF PTS	X START	DX DIFF	THETA START	DTHETA DIFF	R START	DR DIFF
1	3	23.72	0.00	71.00	2.00	3.03	0.03
2	4	26.27	0.00	45.00	2.50	0.01	0.00
3	3	29.10	0.00	230.00	4.60	1.42	0.22
4	3	33.02	0.00	265.90	1.90	1.57	0.01
5	12	37.50	0.22	160.00	3.10	1.32	0.21
6	4	38.32	0.00	262.90	2.90	1.50	0.00
7	4	40.65	0.00	263.70	3.90	1.73	0.17
8	3	42.65	0.00	45.00	2.00	0.61	0.23
9	10	101.60	0.14	236.00	3.10	0.44	0.20
10	4	140.47	0.00	193.70	2.90	1.62	0.03
11	3	147.47	0.20	11.70	1.10	1.25	0.00
12	3	140.27	0.00	40.00	1.90	1.72	0.19
13	5	182.23	0.40	191.00	2.50	4.21	0.25
[illegible]	3	193.07	0.00	42.00	3.00	1.17	0.10
		[illegible]	0.00	110.00	3.10	1.76	0.10
29	[illegible]		[illegible]	127.20	1.50	1.62	0.20
30	9	239.23	[illegible]		[illegible]	0.44	0.30
31	4	240.03	0.04	[illegible]		[illegible]	0.26
32	4	241.03	0.20	309.00	11.10	[illegible]	
33	4	240.03	0.00	223.20	4.70	1.99	[illegible]
34	14	254.03	0.40	295.00	16.50	1.25	0.49
35	3	250.03	0.00	294.00	3.30	1.40	0.15
36	4	259.03	0.00	304.60	2.40	1.42	0.30
37	4	261.23	0.04	220.20	3.00	2.10	0.43
38	3	261.43	0.00	235.20	1.60	2.31	0.13
39	4	261.43	0.00	237.10	3.00	1.75	0.24
40	10	261.47	0.16	221.50	7.40	1.57	0.46
41	3	261.03	0.00	239.60	1.40	2.90	0.00
42	4	264.23	0.00	249.70	3.00	2.59	0.46
43	8	264.27	0.20	234.00	11.50	2.46	0.36
44	3	265.67	0.00	343.20	4.70	0.62	0.23
45	5	270.43	0.04	105.30	4.90	0.30	0.13
46	16	280.03	0.40	290.10	15.70	0.06	0.22
47	11	287.23	0.20	66.40	14.00	0.15	0.34
48	6	292.43	0.04	221.70	0.00	1.40	0.21

Figure 6. Results of Linkup Analysis.

THERMAL AND STRESS ANALYSES

The ANSYS [1] computer code is a large scale, general purpose finite element analysis package that is used to conduct the thermal and stress analyses for the rotating and non-rotating components. The ANSYS analysis capabilities include statics and dynamics; elastic, plastic, creep and swelling; buckling; small and large deflections; steady-state and transient heat transfer, electrostatics, magnetostatics and fluid flow. The program employes the matrix displacement method of analysis based on finite element idealization.

Transient and steady state heat transfer coefficients on the surface of the component are first calculated with an in-house computer program. These data completely define the thermal boundary conditions for each load step as required by the ANSYS computer program. Transient and steady state thermal analyses are conducted to obtain temperature profiles throughout the component. Both wet (condensation) and dry steam conditions are considered. These data, together with pressure or centrifugal load, are used to determine stress profiles. Complete temperature and stress contour plots are provided for all transients in the report.

Typical circumferential stress contours developed in a HP-IP spindle several hours after a cold start are shown in Figure 7. Note that maximum bore stresses are developed under the LP balance piston (45.4 ksi) and in the center of the IP section (64.5 ksi). Stresses decrease rapidly with radial distance from the bore surface. Steady state stresses would be lower, since the transient thermal stress becomes smaller during steady state operation.

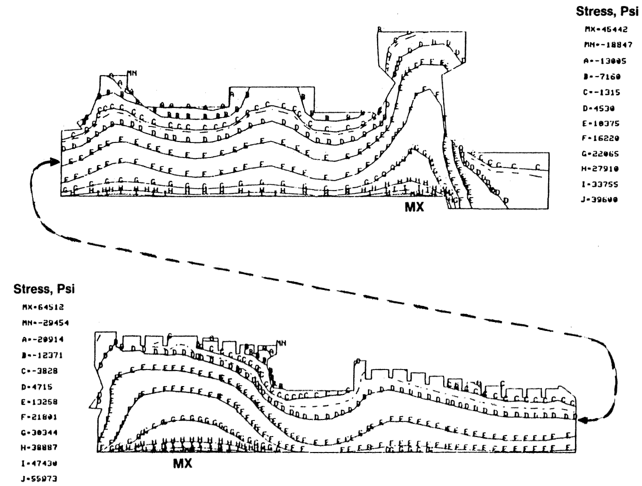

Figure 7. Circumferential Stress Contours, Cold Start.

For the HP and IP spindles, the worst case condition during cold startup is determined at the time when the fracture toughness/stress (K_{Ic}/σ) ratio is a minimum, since that is when the critical crack size is the smallest. This is accomplished using a postprocessor, which calculates K_{Ic}/σ ratio along the bore at any transient time to locate the minimum ratio. K_{Ic} is the fracture toughness corresponding to the appropriate temperature at the bore. Stresses due to the combined effect of thermal plus mechanical (centrifugal) loading are determined.

For safe operation of HP and IP spindles, it is desirable to have the K_{Ic}/σ ratio greater than 1.25 at all spindle locations. This ratio will provide a relatively large critical crack size as illustrated later. If the ratio is lower than 1.25, the cold start procedure is generally changed, so as to increase bore temperature while reducing the thermal stress.

Another postprocessor is used to calculate the alternating stress intensities from multiaxial stress components in accordance with the ASME Boiler and Pressure Vessel Code [2]. The extreme values of the range of these alternating stress intensities are used for the fatigue damage calculations.

For creep damage calculations, either the von Mises stress or the ASME crotch primary membrane stress intensity [3] is used. The ANSYS program also has the ability to analyze stress relaxation with time about the bore.

FRACTURE MECHANICS ANALYSIS

This analysis usually pertains to turbine spindles, generator rotors and generator retaining rings. Although the magnetic particle and ultrasonic indications may not be as serious as real cracks, they are usually considered to be cracks for fracture mechanics analysis, unless other analyses shows otherwise. This is a conservative approach.

Critical Crack Size

The burst condition for the spindle/rotor occurs when the stress intensity factor, K_I, corresponding to the present crack, is equal to or exceeds the current fracture toughness of the material, K_{Ic} The crack size corresponding to this situation is said to be critical. The stress intensity factor is a function of the applied stress and crack size and increases with either of these values. The critical crack size, a_{cr} is a function of the ratio of the fracture toughness to the applied stress. The fracture toughness is a function of the temperature and generally increases with it.

The bore circumferential stress, σ, fracture toughness, K_{Ic} and critical crack depth, a_{cr} change with time (or temperature) during a cold start, as illustrated in Figure 8. Note that $a_{cr}$is proportional to the square of the $K_{Ic}/$ratio and that both σ and K_{Ic} increase with temperature, but at a different rate. Furthermore, the stress reaches a peak value and then decreases to the steady state condition. Note that a_{cr}starts at a high value, decreases to a minimum and then rises again. The time at which the minimum occurs and its value are dependent upon the thermal stress and bore temperature. Normally a rapid start will produce a smaller a_{cr} than a slow start.

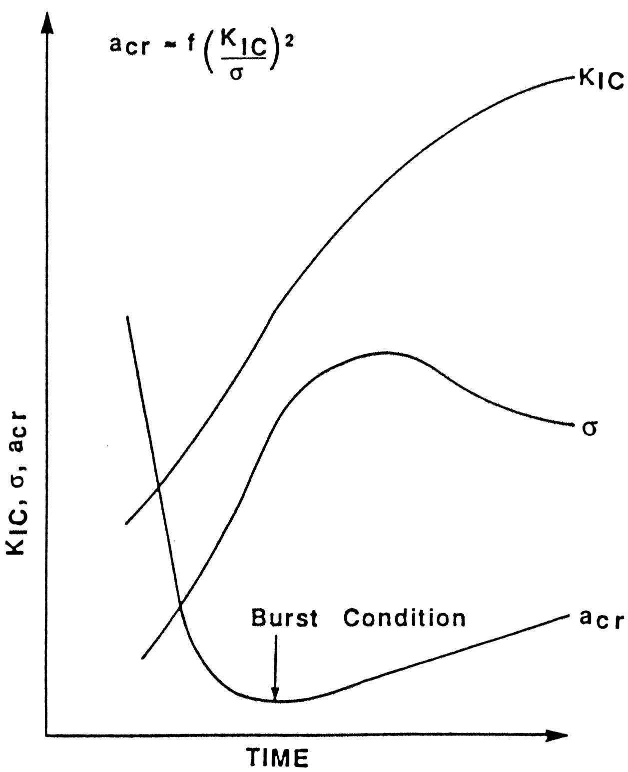

Figure 8. K_{Ic} σ a_c VS Time During a Cold Start.

The K_{Ic}/σ ratio *vs* critical crack depth, a_{cr} for a surface crack with a depth/length ratio of 0.5 is plotted in Figure 9 for two methods. One method utilizes the actual stress profile about the bore. Note that for the same K_{Ic}/σ ratio, the constant stress method predicts a much smaller crack depth than the stress profile method. Hence, the constant stress approach is much too conservative. A K_{Ic}/σ ratio of 1.25 indicates a critical crack depth of about 0.85 in and 2.0 in, respectively, for the two methods.

If the current stress intensity factor is less than the fracture toughness, then the current crack size is subcritical. However, this subcritical crack could grow by fatigue due to start-stop cyclic operation of the spindle/rotor and/or creep due to steady operation at sufficiently high temperature. By performing a crack growth analysis, the remaining life to reach the burst condition is estimated.

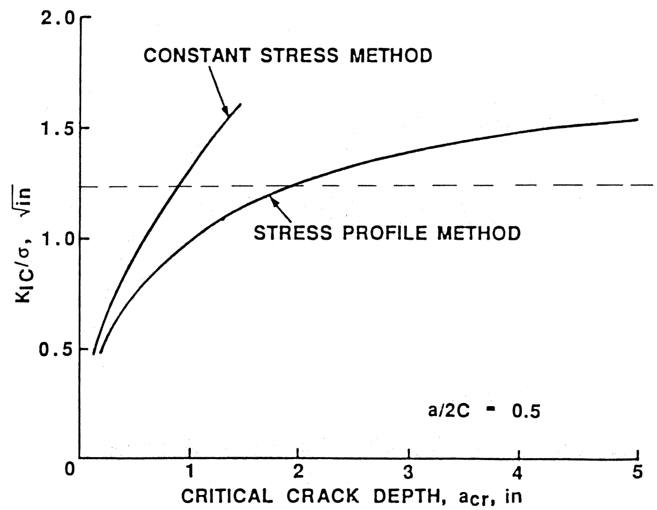

Figure 9. K_{Ic} Ratio vs *Critical Crack Depth.*

Fatigue Crack Growth

The BIGIF [4] computer program is used to calculate the stress intensity factors and the number of start-stop cycles or load blocks required to grow a subcritical surface or buried crack to critical size. BIGIF is an acronym for boundary integral equation generated influence function. This program utilizes prior stress analysis of the uncracked structure, previously developed crack stress intensity solutions and a straightforward elastic superposition technique to calculate the cracked induced redistribution of the elastic stress field.

A load block normally consists of a number of cold starts, hot starts, load changes and overspeed tests. Since the BIGIF program allows stress profiles as input, this program is especially suited to spindle/rotor bore analysis. Upper bound fatigue crack growth rate data are used for the calculations, and it is considered that the spindle/rotor will fail during an overspeed test. To account for uncertainty in the analysis, the number of calculated start-stop cycles or load blocks is reduced by a factor of ten. The BIGIF program is also enhanced inhouse to include the effects of a buried crack approaching the bore surface and finite wall thickness on stress intensity factor and crack growth.

If the calculated number of load block cycles is not acceptable, either the flaws are removed by overboring and/or the startup procedure is changed to increase the minimum K_{Ic}/σ ratio.

The inspection interval between boresonic examinations of a spindle/rotor is based on an allowable number of elapsed start-stop cycles or operating hours, whichever comes first. Consider a bore surface crack, 0.3 in deep $\times$ 0.6 in long, in the main body portion of a generator rotor. This crack size, along with the stress profiles for running speed and ten percent overspeed, a load block consisting of ten start-stop cycles and one overspeed test, and the fatigue crack growth rate data were all input to the BIGIF fatigue crack growth program. A partial output, shown in Figure 10, tabulates crack sizes, stress intensity factors and load blocks for small increments of crack growth. If the fracture toughness for the burst condition is about 50 ksi $\sqrt{in}$, then the critical crack size is 0.92 in deep $\times$ 2.02 in long, and it will take 2576 load blocks, or 25760 start-stop cycles, to reach critical size, as shown by Figure 10. A safety factor of ten is applied to these cycles, and the allowable start-stop cycles for the next inspection is established at 2576 cycles. It is company policy, however, to limit the inspection interval to no more than 2000 start-stop cycles.

Crack Dim., In. Depth	Length	K_I, ksi√in	Cumulative Load Blocks
0.30	0.60	33.4	0.0
0.35	0.71	36.0	355
0.41	0.85	38.0	712
0.49	1.05	41.4	1072
0.57	1.20	44.2	1437
0.67	1.42	46.9	1807
0.79	1.70	49.7	2186
0.92	2.02	52.2	2576
1.08	2.40	54.6	2982
1.25	2.85	57.3	3406
1.47	3.39	60.4	3853
1.72	4.04	63.5	4325
2.02	4.80	67.0	4823
2.37	5.71	70.5	5350
2.80	6.79	74.2	5471

Figure 10. Results of Fatigue Crack Growth Analysis.

CUMULATIVE DAMAGE

Cumulative damage of steam turbine components that are subjected to steady state and transient stresses can be estimated from a knowledge of past and projected usage, operating stresses and material properties. Damage is defined as the fraction of life that has been expended as of a certain time and a certain number of startup, shutdown and load change cycles. Total cumulative damage, D_t, is defined as the linear sum of damage due to creep and low cycle fatigue:

$$D_t = D_c + D_f$$

$$D_t = \sum \frac{t_i}{T_f} \text{ Creep} + \sum \frac{n_i}{N_f} \text{ LCF}$$

Where t_i and n_i are actual time and cycles, respectively, and T_f and N_f are the time to creep rupture and cycles to fatigue crack initiation, respectively.

When the total damage reaches a value of 0.5 for creep and for fatigue in regions free of stress concentrators, or 1.0 for fatigue in regions with stress concentrators, it is considered that a warning point has been reached. This means that cracks may initiate, and/or severe creep deformation may occur. This does not imply that the component need be replaced, but only that inspection is required.

Creep Damage

An inhouse computer program, which utilizes mean and lower bound stress rupture data for a number of materials, is used to calculate the past creep damage and future yearly creep damage. The program can handle a number of stress levels and a variety of times for each temperature of interest.

Low Cycle Fatigue Damage

Transient temperature conditions caused by startup, shutdown and load changes produce an alternating stress condition that produces fatigue damage. The damage is expressed as:

$$D_f = \left(\frac{n_i}{N_f}\right)_{\text{Cold}} + \left(\frac{n_i}{N_f}\right)_{\text{Warm}} + \left(\frac{n_i}{N_f}\right)_{\text{Hot}} + \left(\frac{n_i}{N_f}\right)_{\text{Load Change}}$$

An inhouse computer program, which utilizes appropriate temperature cyclic stress-strain and strain-life data, is used to calculate past and future fatigue damage based on a knowledge of the nominal stress, the stress concentration factor and the number of start-stop cycles. The Neuber [5] rule approach is used to account for any plasticity that may arise from stress concentration effects. To account for uncertainty in the fatigue properties, only ten to 30 percent of the estimated fatigue life is used for the damage analysis depending on the presence or absence of creep.

The past creep damage and future yearly creep damage are also input to this program, so that the output data displays a year by year tabulation of damage for creep and fatigue. The year at which the warning point is reached can then be easily identified.

Cumulative damage calculations are important, since they pinpoint problem areas in components before the problems become unmanageable. Consider a steam chest from a unit which is rated at 2400 psig and 1050°F inlet steam conditions. The historical time-pressure-temperature data are established, and past creep damage is calculated from mean and lower bound stress-rupture data. By using both lower bound and mean data, a range for creep damage is established. After the creep damage has been calculated, the fatigue damage is determined, and it is added to the creep damage. Consider that the unit has encountered 150 cold starts, 327 warm starts and 43 hot starts to date while the number of load changes has been negligible. Future planning mandates about six cold, 12 warm, and two hot starts, with approximately 6600 hours of operation per year. This startup information, the transient stress amplitudes, and past and future creep damages are used to calculate creep damage, fatigue damage and total damage on a year by year basis. This is illustrated in Figure 11, where the results of calculations are shown for the lower bound creep damage condition and for fatigue damage at a location in the steam chest that has a stress concentration factor of two. The warning points for creep damage and total damage will be reached in the years 1989 and 2008, respectively. However, if the mean stress-rupture properties are used, then the warning point for creep is not reached until 2011, and the warning point for total damage is not reached until after the year 2015, as illustrated in Figure 12. Thus, the steam chest will require inspection in the future, and it is recommended that replicas be taken periodically after the year 1989, to determine if creep damage is as high as predicted. Replication consists of producing an imprint of a highly polished and acid etched metallic surface using cellulose acetate replicating tape and an appropriate solvent, which temporarily softens the tape, so that an impression of the microstructure can be obtained. The replica is then viewed at high magnifications to determine whether metallurgical changes have occurred and/or cracks have initiated. If the lower bound creep data calculations had revealed a warning point beyond the year 2015, then replication would not be necessary.

REPORT

A final report is issued, which documents the entire study of the turbine-generator unit. It includes a general summary of the life assessment findings and provides recommendations regarding life extension. It also contains a component by component summary, followed by field service inspection reports, all nondestructive examination (NDE) data including boresonic results, dimensional data, electrical test data, historical operation data and transient starting information, a summary of mainte-

CREEP AND LOW CYCLE FATIGUE DAMAGE ANALYSES

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COMPONENT: STOP VALVE
MATERIAL: 2.25CR-1MO      ( 2)         PLACED IN SERVICE ,YR: 1961
                                       ANALYSIS THROUGH YR:   2014
NOMINAL STRESSES:                       USAGE     PAST   FUTURE(YEARLY)
KT=  2.0  D.R.= 0.1                     HOURS  150561.    6600.
STRESS, KSI    AMP       MEAN          STARTS
  COLD:       10.00      0.00           COLD:    150.      6.00
  WARM:        7.20      0.00           WARM:    327.     12.00
  HOT:         5.60      0.00            HOT:     43.      2.00
             LD CHG:(SEE TEXT)         LD CHG:     0.      0.000
```

CUMULATIVE DAMAGE FROM 1961 THROUGH YEAR INDICATED BELOW

YEAR	CREEP	LOW CYCLE FATIGUE				TOTAL
		COLD	WARM	HOT	LDCHG	
1984	0.415	0.057	0.034	0.002	0.000	0.500
1985	0.433	0.059	0.035	0.002	0.000	0.529
1986	0.450	0.062	0.036	0.002	0.000	0.550
1987	0.467	0.064	0.037	0.002	0.000	0.571
1988	0.485	0.066	0.039	0.002	0.000	0.591
1989	0.502	0.068	0.040	0.002	0.000	0.612
1990	0.519	0.071	0.041	0.002	0.000	0.633
1991	0.537	0.073	0.042	0.002	0.000	0.654
1992	0.554	0.075	0.044	0.002	0.000	0.675
1993	0.571	0.078	0.045	0.002	0.000	0.696
1994	0.589	0.000	0.046	0.002	0.000	0.717
	[illegible]	0.082	0.047	0.002	0.000	0.738
2000	[illegible]		[illegible]	0.002	0.000	0.759
2001	0.710	0.096	[illegible]	[illegible]	[illegible]	0.780
2002	0.727	0.098	0.056	0.003	0.000	
2003	0.744	0.100	0.057	0.003	0.000	0.905
2004	0.762	0.103	0.058	0.003	0.000	0.926
2005	0.779	0.105	0.060	0.003	0.000	0.947
2006	0.796	0.107	0.061	0.003	0.000	0.968
2007	0.814	0.110	0.062	0.003	0.000	0.989
2008	0.831	0.112	0.063	0.003	0.000	1.010
2009	0.848	0.114	0.065	0.003	0.000	1.030
2010	0.866	0.116	0.066	0.004	0.000	1.051
2011	0.883	0.119	0.067	0.004	0.000	1.072
2012	0.900	0.121	0.068	0.004	0.000	1.093
2013	0.918	0.123	0.069	0.004	0.000	1.114
2014	0.935	0.126	0.071	0.004	0.000	1.135

Figure 11. Cumulative Damage Using Lower Bound Stress-Rupture Data.

CREEP AND LOW CYCLE FATIGUE DAMAGE ANALYSES

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COMPONENT: STOP VALVE
MATERIAL: 2.25CR-1MO      ( 2)         PLACED IN SERVICE ,YR: 1961
                                       ANALYSIS THROUGH YR:   2014
NOMINAL STRESSES:                       USAGE     PAST   FUTURE(YEARLY)
KT=  2.0  D.R.= 0.1                     HOURS  150561.    6600.
STRESS, KSI    AMP       MEAN          STARTS
  COLD:       10.00      0.00           COLD:    150.      6.00
  WARM:        7.20      0.00           WARM:    327.     12.00
  HOT:         5.60      0.00            HOT:     43.      2.00
             LD CHG:(SEE TEXT)         LD CHG:     0.      0.000
```

CUMULATIVE DAMAGE FROM 1961 THROUGH YEAR INDICATED BELOW

YEAR	CREEP	LOW CYCLE FATIGUE				TOTAL
		COLD	WARM	HOT	LDCHG	
1984	0.237	0.057	0.034	0.002	0.000	0.329
1985	0.247	0.059	0.035	0.002	0.000	0.343
1986	0.257	0.062	0.036	0.002	0.000	0.356
1987	0.266	0.064	0.037	0.002	0.000	0.370
1988	0.276	0.066	0.039	0.002	0.000	0.383
1989	0.206	0.060	0.040	0.002	0.000	0.396
1990	0.296	0.071	0.041	0.002	0.000	0.410
1991	0.306	0.073	0.042	0.002	0.000	0.423
1992	0.316	0.075	0.044	0.002	0.000	0.437
1993	0.326	0.078	0.045	0.002	0.000	0.450
1994	0.335	0.000	0.046	0.002	0.000	0.464
1995	0.345	0.082	0.047	0.002	0.000	0.477
1996	0.355	0.084	0.048	0.002	0.000	0.491
1997	0.365	0.087	0.050	0.003	0.000	0.504
1998	0.375	0.089	0.051	0.003	0.000	0.518
1999	0.385	0.091	0.052	0.003	0.000	0.531
2000	0.395	0.094	0.053	0.003	0.000	0.544
2001	0.405	0.096	0.055	0.003	0.000	0.558
	0.414	0.098	0.056	0.003	0.000	0.571
2008	[illegible]	[illegible]	0.057	0.003	0.000	0.505
2009	0.483	0.114	[illegible]	[illegible]	[illegible]	0.598
2010	0.493	0.116	0.066	0.004	[illegible]	
2011	0.503	0.119	0.067	0.004	0.000	0.693
2012	0.513	0.121	0.068	0.004	0.000	0.706
2013	0.523	0.123	0.069	0.004	0.000	0.719
2014	0.533	0.126	0.071	0.004	0.000	0.733

Figure 12. Cumulative Damage Using Mean Stress-Rupture Data.

nance reports, the recommended generator inspection procedures, and the analytical procedures and detailed results (tabulations and plots) for each component that was evaluated.

CONCLUSIONS

The principles expressed herein have been successfully applied to over 170 turbine spindles and generator rotors, the majority of which were from non-company units, and b) to life assessment/extension studies on 13 units. None of the spindles or rotors were retired by the company, but several were overbored or bottlebored to remove large subcritical flaws.

The company considers the life assessment of 1050°F main steam units with over 140,000 hr of operation most important to provide a long service life. Next in order of priority are the 1000°F units with large numbers of start-stop cycles (all types). It is recommended that all units rated at ten megawatt or greater have the spindle and rotor bores inspected and analyzed at least once, at a minimum, to assess their serviceability regardless of age or operation temperature.

REFERENCES

1. ANSYS available from Swanson Analysis Systems, Houston, PA.
2. ASME Boiler and Pressure Vessel Code, Section III, Div. 1, Subsection NB-3545, American Society of Mechanical Engineers, New York, New York (1983).
3. ASME Boiler and Pressure Vessel Code, Section III, Div. 1, Subsection NB-3216, American Society of Mechanical Engineers, New York, New York (1983).
4. BIGIF, Electric Power Research Institute, Palo Alto, California.
5. Topper, T. H., Wetzel, R. M., and Morrow, J., "Neuber's Rule Applied to Fatigue of Notched Speciments," Journal of Materials, ASTM JMLSA 4, 200-209 (1969).