Proceedings of IJPGC'01
2001 ASME International Joint Power Generation Conference
June 4–7, 2001, New Orleans, Louisiana, USA

JPGC2001/PWR-19163

CREEP LIFE PREDICTION OF GAS TURBINE COMPONENTS UNDER VARYING OPERATING CONDITIONS

Zhimin Liu,[*] Dimitri N. Mavris,[†] and Vitali V. Volovoi,[‡]
Georgia Institute of Technology, Atlanta, Georgia 30332-0150

ABSTRACT

A simplified model for creep life prediction of gas turbine components under varying operating conditions is provided. Response Surface Equations are used to connect operating conditions with nodal creep life that is calculated using nodal stresses and temperatures. Then the accumulation of creep rule is applied to determine total creep life. While the present paper is limited to deterministic examples and creep life only, the methodology is expected to be particularly useful for probabilistic prediction of life where the degradation due to both creep and fatigue is taken into account.

INTRODUCTION

Prediction of creep life of gas turbine components is a very complex task. Even the most elaborate and time consuming Finite Element (FE) procedures provide results that are not always satisfactory. Currently, in industrial practice, life of a given part is predicted under some "normal" operating conditions, even though operating conditions vary significantly for each engine or power plant in service and this variation causes significant variation in life. Engineers use a hefty safety factor in order to avoid a part failure that could lead to catastrophic consequences. Such safety factors ensure a failure-free operation even under the worst case scenario conditions. Alternatively, the most adverse combination of operating condition is used as a design point. Both approaches result in discarded parts that still have significant residual lives when operating conditions are "normal" or even "lighter" than "normal".

The prime reason for not accounting for variation in the operating conditions stems from the fact that the calculations are computationally very expensive. Traditional FE methods, (see, for example (Penny and Marriott, 1971), (Becker et al., 1994) and (Pawlik and Saff, 1999)) effectively consider the following problem:

$$F = [K]\delta - [B]^T[D]\varepsilon_c \tag{1}$$

here F is the external force vector, δ is the nodal displacement vector, $[B]$ is a matrix based on geometric parameters, $[D]$ is the elastic property matrix and ε_c is creep strain. Since both terms in the right hand side of Eq.1 are unknown, the solution of Eq.1 requires a costly iteration using either a forward difference (Euler) scheme or something equivalent. It should be noted that there are usually several approximations that are commonly employed in creep life estimation:

1. Creep data for uniaxial loading is extrapolated to a general 3-D loading condition (using some equivalent stress, such as Von-Mises stress)
2. Creep data for constant loading is applied to variable loading. The simplest, and the most commonly used way to account for such variable loading is "life fraction" or Robinson's rule (Hurst, 1984), also known as accumulation of creep (AC) rule. This rule is particularly convenient since it accounts for degradation from the combined effects of creep and fatigue (Danzer, 1992)

[*]Graduate Research Assistant, School of Aerospace Engineering
[†]Boeing Professor for Advanced Aerospace Analysis, School of Aerospace Engineering
[‡]Research Engineer, School of Aerospace Engineering

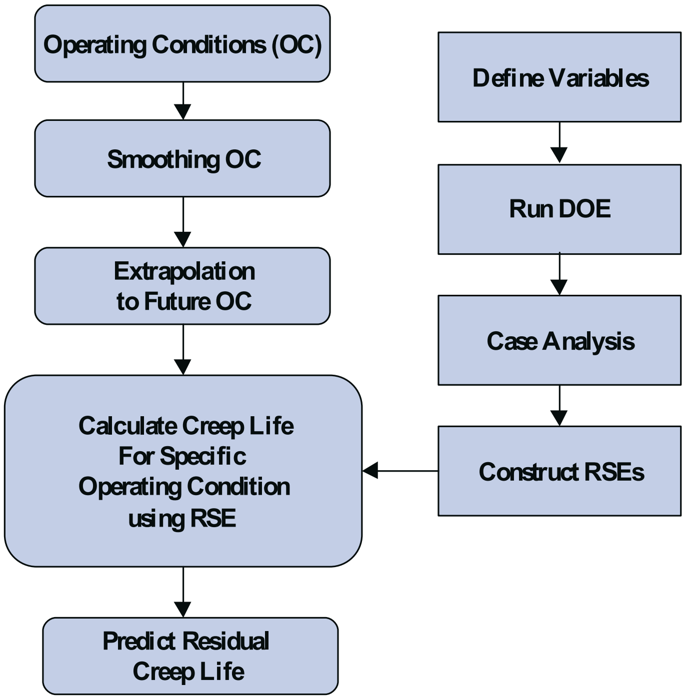

Figure 1. General Methodology

PROPOSED APPROACH

The calculations to obtain the creep life corresponding to a certain operating condition is computationally very expensive. The proposed approach, as shown in Figure 1, uses a Response Surface model to approximate the relationship between the creep life and operating conditions. As a result, a computationally efficient creep life prediction model was constructed to take variations in operating conditions into account.

This proposed approach could be viewed as an environment, which can easily accommodate future modifications and better models. The methodology will be illustrated by predicting the creep life for a simplified bucket under time varying high temperatures and rotating speeds.

Response Surface Method (RSM)

RSM is based on a statistical approach to building and rapidly assessing empirical models. By careful design and analysis of empirical data, or the results from simulations, the methodology seeks to relate and identify the relative contributions of the various input variables to the system response (Mavris and Bandte, 1995). As described below, a component creep life is predicted along with its variations due to operating conditions. The exact relationship between creep life (response) and operating conditions (input) is very complex, so a simplified approach such as RSM is used to approximate such a relationship. A quadratic regression is applied, yielding the Response Surface Equation (RSE). This RSE is given as a second order polynomial as follows:

$$R = b_0 + \sum_{i=1}^{k} b_i x_i + \sum_{i=1}^{k} b_{ii} x_i^2 + \sum_{i=1}^{k} \sum_{j=i+1}^{k} b_{ij} x_i x_j \qquad (2)$$

Where R is the response and x_i, x_j are the design variables. Once RSEs are obtained, no further runs of FE analyses are necessary. This permits studies of the dependence of the response on the parameters that are of interst in an expedient manner. The resulting response surface model provides a computationally efficient tool for studying how variations in the operating conditions influence the response (creep life).

MODEL DESCRIPTION

The model used in this paper is a simplified second stage gas cooling turbine bucket, shown in figure Figure 2. Material properties of a uniaxial nickel super alloy are employed in the considered example. The length of the bucket is 17” (0.43m), and it is mounted on a 70” (1.77m) diameter rotor. The bucket has eight cooling holes.

Monitoring Operating Conditions

The primary operating conditions associated with the bucket are its rotational speed and the temperature and velocity distributions of both external hot flow and internal cooling flows. In this example, only the temperature of the external hot flow and the rotational speed are selected to illustrate the methodology. The external hot flow field is very complex, and its prediction is a formidable task, even when the most sophisticated computational fluid dynamics (CFD) analysis tools are employed. By putting sensors at selected locations, one can obtain historical data for operating conditions for a given part.

Smoothing the Data

Although the major operating conditions can be continuously monitored, this data should be smoothed in order to reduce computational efforts. Such averaging can be considered as a necessary trade off between accuracy and computational cost/time and it will depend on the available computational resources, variations of the monitored data and the desired fidelity.

Extrapolating Future Operating Conditions

Operating conditions in the future will be extrapolated based on the monitored data from the past. In addition, manual input for running schedule should be allowed, and adjusted based on the user preferences.

Strictly speaking, it is impossible to predict the future operating conditions exactly. But, unlike the stock market’s value,

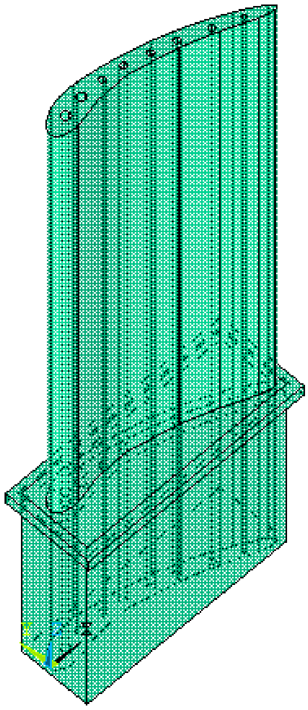

Figure 2. Geometry of a simplifed bucket

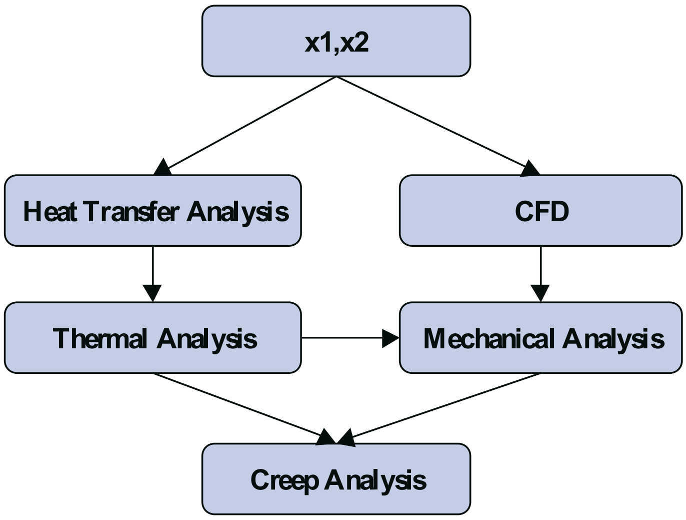

Figure 3. Analysis tools

it might be reasonable to assume that the past provides decent estimates of the future operating conditions.

At the very beginning, when the unit just put in service, some "zero hypotheses" might be employed (which would be equivalent to traditional life estimates), since there are no significant data accumulated for the precise prediction of future operating conditions. On the other end of the spectrum, when predicted residual life is close to an end, the accuracy of the prediction will highly depend on how the unit will be operating in the near future. Based on the accumulated data for this specific unit, as well as expected schedule in the near future, a reasonable profile of the operating conditions can be predicted.

Design Variables

For simplicity, variations in two of the operating conditions are considered and other conditions remain fixed. Here x_1 is the temperature of hot flow (C°) and x_2 is rotational speed (rpm).

Design of Experiments (DOE)

A widely used type of DoE, two-level full factorial Central Composite design is selected. For two design variables, nine cases with different combinations of variable code values (-1, 0, +1) are analyzed. -1 stands for the lower limit of the range of the variable, 0 for middle and +1 for the upper limit. Figure 3 shows the analysis tools involved in the procedure for each case.

Thermal Analysis

Figure 4 shows the mesh for ANSYS thermal and mechanical analyses. The meshed model has 21596 elements and 100874 nodes. The finite element type is SOLID90. By applying boundary conditions, through thermal analysis, one can get the temperature distribution over the bucket body, or more precisely, the nodal temperatures. Figure 5 shows typical results from a thermal analysis. It takes about 15 minutes to run one thermal case on a 933MHz/1G RAM PC.

Mechanical Analysis

The element used for mechanical analysis is SOLID 95. The thermal analysis result is input to obtain thermal stresses and pressures that were estimated using CFD analysis are added as surface loads. In this paper, only the airfoil section was considered for CFD analysis. All 4 side-surfaces of the lower cube are fixed (all degrees of freedom). The results are nodal stresses. Figure 6 shows typical results from a mechanical analysis. It takes about one our to run one mechanical case on a 933MHz/1G RAM PC.

Construction of RSEs

After calculation of creep life for each node from the nine DoE cases, an RSE for each node can be constructed. The RSE relates nodal creep life to the operating conditions. With the help of JMP, a statistical analysis package, the construction of such

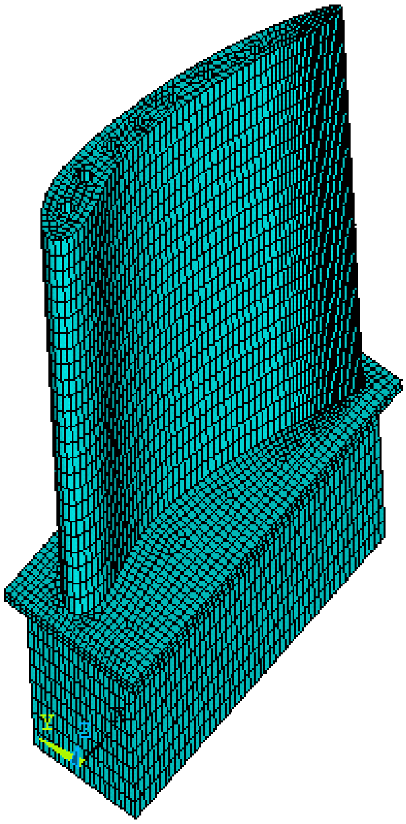

Figure 4. Meshed Bucket

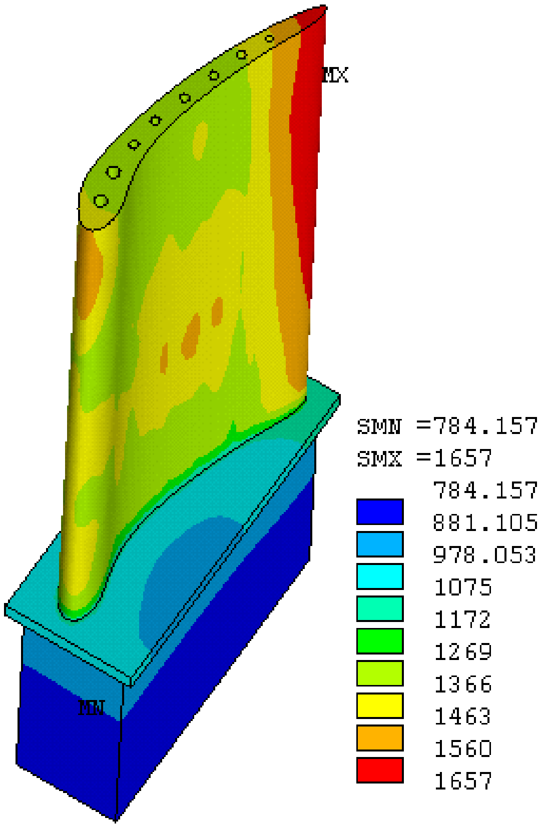

Figure 5. Typical Results of thermal analysis

RSE is straightforward.

In order to avoid constructing RSEs for thousands of unnecessary nodes, engineering judgment can be used to screen for the "hot spots" – the nodes with an critical combinations of stresses and temperatures. This is required for each of the nine DoE cases, (since the "hot spots" can move with changes in input parameters. After RSEs are constructed, a higher level screening can be performed to discard the "benign" nodes (*i.e.*, is the nodes that have a longer creep life). The remaining RSEs will be programmed into the life assessment tool. A typical nodal RSE is shown as following:

$$\log(life) = 5.3106714 - 0.592347x_1 - \\ -0.171625x_2 + 0.0001133x_1x_2 + \\ +0.26269190x_1^2 + 0.0090881x_2^2 \quad (3)$$

x_1 and x_2 are converted to fit the range (-1, +1) from their original values. The RSEs fit the analyzed results quite well. Figure 7 demonstrates the ability of RSE to approximate the analysis tool in life prediction. The dotted lines indicate the confidence interval for the model, showing a small range with no points falling outside the range. The R-square (RSq) value, which varys from 0 to 1, is the square of correlation between the analyzed response and response predicted by RSE. An R-square value of 1 means a perfect fit (Montgomery, 1997). In the considered example RSEs fit well with very high RSq values.

Creep Modeling

Taking into account the high sensitivity of the creep life to operating conditions, it seems reasonable to sacrifice certain precision and use a "statically determinate" hypothesis that assumes that at each point, the component stress redistribution is neglected. Then, creep life at a node can be estimated based on the stresses and temperature at this node.

As an illustration, Graham-Walles theory has been used: it is assumed that total creep strain is the sum of a finite number of independent terms in a power series (Harrison and Homewood, 1994):

$$\varepsilon_c = \sum C\sigma^{\beta} t^{\kappa} (T' - T)^{(-20\kappa)} \quad (4)$$

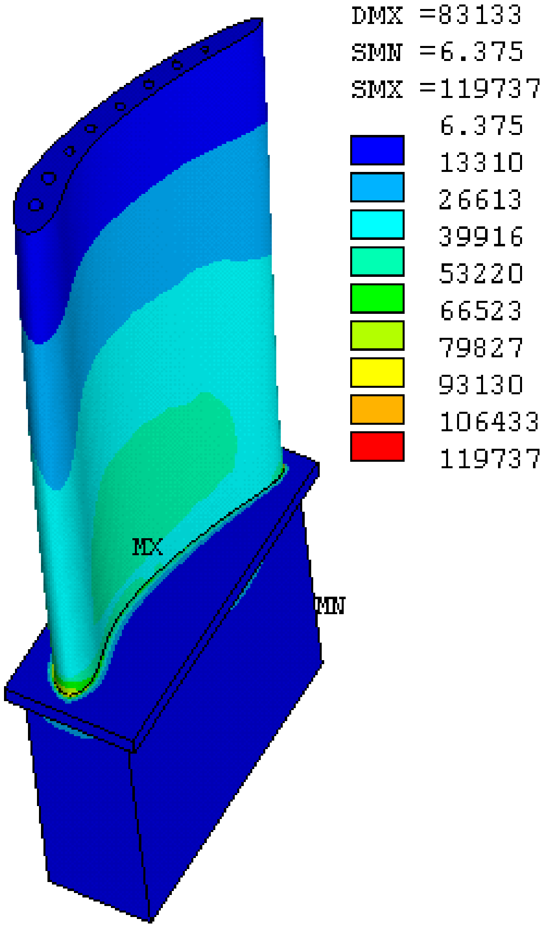

Figure 6. Typical Results of Mechanical Static analysis

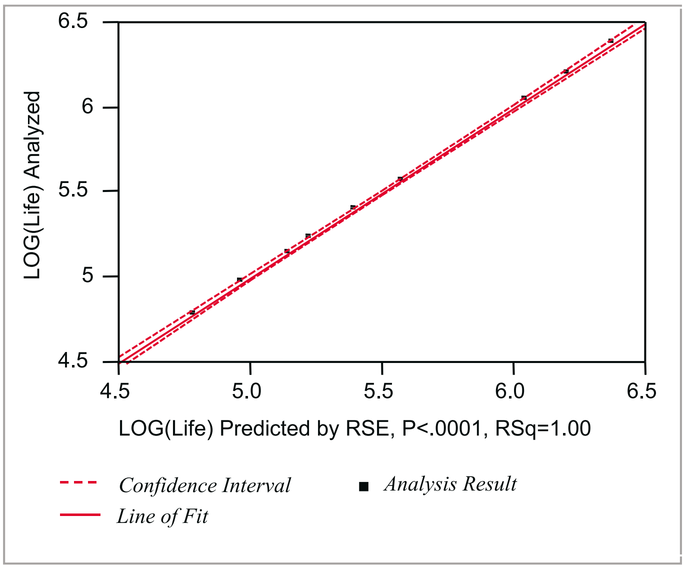

Figure 7. RSE's fit

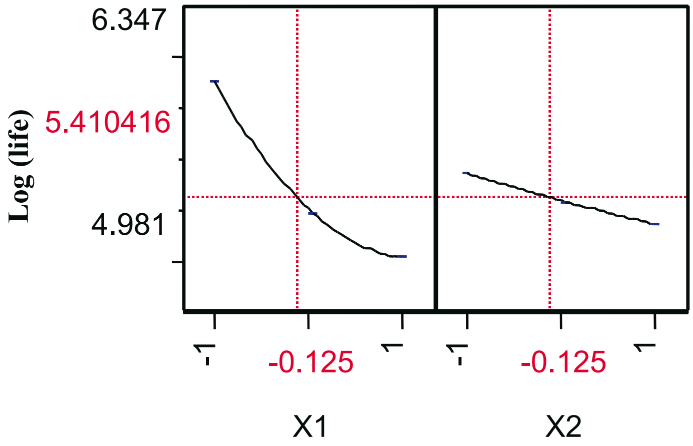

Figure 8. Sensitivity of creep life to the operatiing conditions

Here C, β, κ and T' are constants, σ is stress, T operating temperature, and t time-on-the-load.

Creep life for a certain part depends on various factors like operating conditions, material properties, geometry, sealing and installation, etc. Symbolically, one can represent

$$\text{Creep life} = F(d_1, d_2, d_2 \ldots, m_1, m_2 \ldots) \tag{5}$$

where $d_1, d_2, d_2 \ldots$ are parameters describing operating conditions and $m_1, m_2 \ldots$ are variations due to manufacturing, etc. some of the parameters $d_1, d_2, d_2 \ldots$ can vary in time. The proposed procedure provides a efficient way to account for such variations

RSE Analysis

It is instructive to employ an RSE in order to monitor how the design variables affect the response at a specified node. These relationships can be represented by prediction profiles as shown in Figure 8. It can be seen that the *log*(life) is very sensitive to the flow temperature, and also is quite sensitive to the rotational speed. Figure 9 shows a representative Pareto plot, which shows the contribution of variables to the variability of the response. For this RSE, the x_1 term is the primary contributor and the x_2^2 term has almost no impact on the creep life.

DISCUSSION OF THE RESULTS

First, for comparison, the creep life is predicted under the most adverse combination of operating conditions. In this case, under the highest hot flow temperature ($900°C$) and rotating

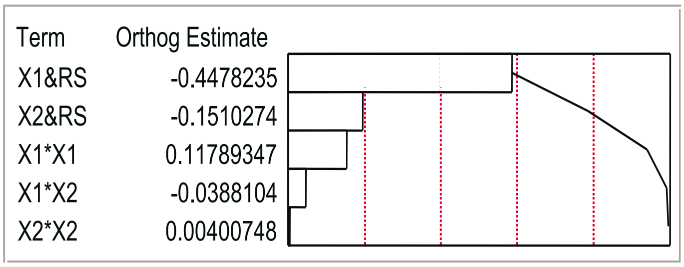

Figure 9. Paretto chart

speed (3600rpm), the creep life predicted is 57563 hours. Next, a simplified typical one-day operating condition profile,a combination of temperature of hot flow (C) and rotational speed (rpm), as shown in Figure 10, is evaluated. The predicted creep life increases to 130450 hours. Thus, the model predicts an increase in creep life of 72887 hours for the less severe operating conditions. This clearly demonstrates that how the model relates the change in creep life to the variation in operating conditions.

Once the procedure is verified and correlated, taking into account variations of operating conditions in creep life prediction can lead to significant savings.

CONCLUSIONS

This paper emphasizes the importance of taking specific varing operating conditions into account in creep life prediction. A methodology is described, where a real-time life prediction model for a component can be constructed. The procedure described here was applied in a deterministic fashion, although it will be subsequently extended to a stochastic model. The following steps are envisioned:

1. Probabilistic methods are used to model variations in material properties in manufacturing as well as various sources of noise in operating conditions
2. RSEs are constructed to link all relevant variables with the creep life
3. Probabilistic distributions that are varying in time are assigned to those variables
4. Monte Carlo Simulations or other probabilistic methods based on RSEs are conducted

Such a procedure will provide a distribution for the residual life, which can be used to predict the residual creep life of a part with a desired level of confidence.

The final product of this methodology will be a software that is compact and efficient enough to be placed on a regular PC. It will help the customers to better estimate the residual lives of components in service, thus providing assistance in making decision about a timely replacement of the part.

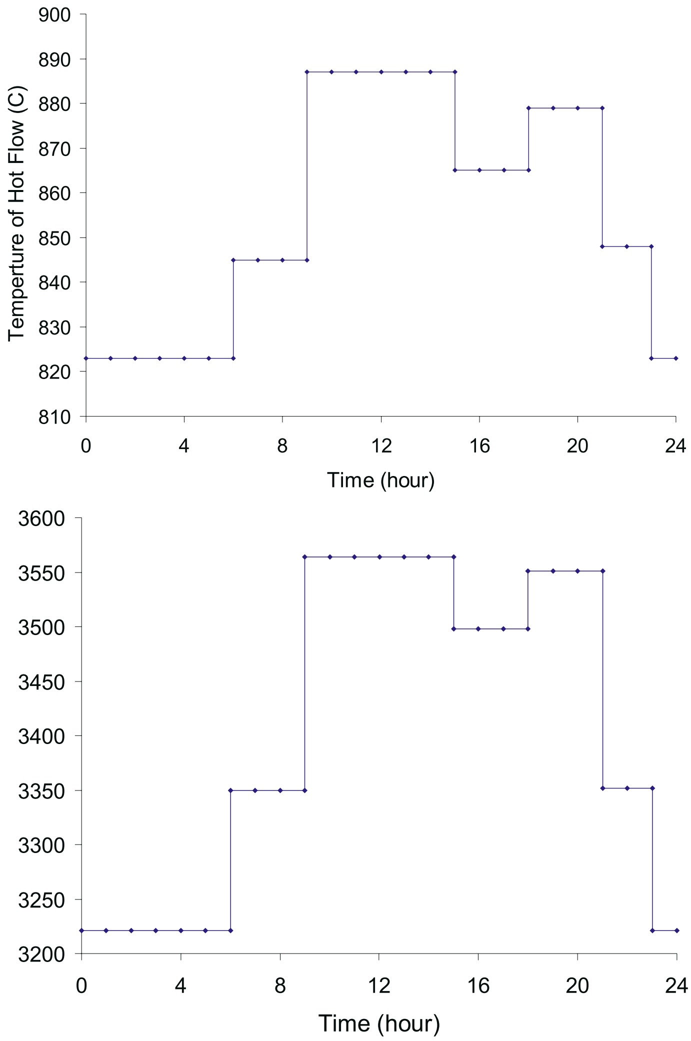

Figure 10. an example of the operational profile

REFERENCES

Becker et al., 1994. Becker, A. A., Hyde, T., and Xia, L. 1994. Numerical Analysis of Creep Components. *Jounral of Strain Analysis*, 29(3):27–34.

Danzer, 1992. Danzer, R. 1992. The Influence of Creep on the Fatigue Life of Nickel Base Superalloys. In *Proceedings of the Fifth International Conference on Creep of Materials*, pp. 350–368, Lake Buena Vista, Florida, USA.

Harrison and Homewood, 1994. Harrison, G. F. and Homewood, T. 1994. The Application of the Graham and Welles Creep Equation to Aeroengine Superalloys. *Journal of Strain Analysis*, 29(3):19–26.

Hurst, 1984. Hurst, R. C., editor 1984. *Design of High Temperature Metallic Components*. Elsevier Applied Science Publishers, London.

Mavris and Bandte, 1995. Mavris, D. N. and Bandte, O. 1995.

Economic Uncertainty Assessment Using a Combined Design of experiments/Monte Carlo Simulation Approach with Application to an HSCT. In *17th Annual Conference of the International Society of Parametric Analysts*, San Diego, CA.
Montgomery, 1997. Montgomery, D. C. 1997. *Design and Analysis of Experiments*. John W Ley and Sons, NY.
Pawlik and Saff, 1999. Pawlik, M. E. and Saff, C. R. 1999. Creep Failure Assessment of a Turbine Disc Using Non-Linear Finite Element Method. In *14th International Symposium on Air Breathing Engines*, Florence, Italy. International Society for Air Breathing Engines.
Penny and Marriott, 1971. Penny, R. K. and Marriott, D. L. 1971. *Design for Creep*. McGraw Hill, London.