Project #: E-18-642
Center #: R6381-0A0
Contract #: RP 2481-5
Prime #: RP 2481-5

Subprojects #: N
Main project #: 

Project unit: MAT ENGR
Project director(s):
SAXENA A MAT ENGR

Sponsor/division names: SOUTHWEST RESEARCH INSTITUTE
Sponsor/division codes: 500 / 054

Award period: 870715 to 900214 (performance) 900214 (reports)

Sponsor amount New this change Total to date
Contract value 0.00 87,291.00
Funded 0.00 22,017.00
Cost sharing amount 0.00

Does subcontracting plan apply #: N

Title: STEAM TURBINE ROTOR LIFE ASSESSMENT AND EXTENSION

PROJECT ADMINISTRATION DATA

OCA contact: Ina R. Lashley 894-4820

Sponsor technical contact Sponsor issuing office
DR G R LEVERANT V V KRAUSE, SR SUBCONT. ADMIN.
(512)684-5111 (512)684-5111
SOUTHWEST RESEARCH INSTITUTE SOUTHWEST RESEARCH INSTITUTE
P. O. DRAWER 28510/6220 CULEBRA RD.
SAN ANTONIO, TX 78284 P O DRAWER 28510/6220 CULEBRA RD.

Security class (U,C,S,TS): U ONR resident rep. is ACO (Y/N): N
Defense priority rating: NA NA supplemental sheet
Equipment title vests with: Sponsor X GIT
NONE PROPOSED. (REFERENCE EXHIBIT C, ARTICLE 11)

Administrative comments -
PROJECT INITIATION. CURRENT FUNDING THROUGH 12/31/87. FUNDS MAY BE CARRIED OVER (REFERENCE SUBCONTRACT, P.1, PARA. 3.B). SUPERSEDES ADVANCE PROJECT.
NOTICE OF PROJECT CLOSEOUT

Closeout Notice Date 06/21/91

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<td>School/Lab</td>
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Comments

Subproject Under Main Project No. _____________

Continues Project No. _____________

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NOTE: Final Patent Questionnaire sent to PDPI 06/30/91
November 3, 1987

Mr. S.J. Hudak, Jr.
Southwest Research Institute
P.O. Drawer 28510
6220 Culebra Road
San Antonio, Texas 72824

Subject: SWRI Project 06-1536
Ga Tech. Project E-18-642
"Evaluation of Retired Rotors"

PROGRESS REPORT FOR PERIOD OCTOBER 1-31, 1987

Dear Steve,

The papers on creep crack growth and creep-fatigue crack growth of turbine rotor steels which were identified in the computer literature search were obtained. Mr. Donald Brosche of NSP has not yet received permission from his company and from Westinghouse for release of data on the Black Dog rotor. Therefore, these data have not yet been received.

Results of 20 creep crack growth tests on Japanese 1Cr-1Mo-0.25v steel were obtained from Prof. T. Yokobori of the Japanese Society for Promotion of Science. These data are currently being processed using our computer program and methods. Combining these data with the other available creep crack growth data will provide a very extensive data base.

By comparison, creep-fatigue data are somewhat limited. The data from the Gallatin rotor and also from the previous work of Saxena and co-workers have been gathered and digitized. These data cover a limited range of loading waveforms and cyclic frequencies of 1 Hz to 1 cycle per day.

In the next reporting period, plots of these data will be generated and an outline of the report will be prepared.

Enclosed is also the cost performance report.

Sincerely yours,

Ashok Saxena

cc: K. Banerji
## EPRI CONTRACT NUMBER
RP 248105

## EPRI DIVISION NUMBER
For EPRI Use Only

## CONTRACTOR NAME, ADDRESS AND TELEPHONE NUMBER
Fracture and Fatigue Research Lab
Georgia Tech. Research Corp.
Centennial Research Building
Atlanta, Ga 30332

## EPRI PROJECT MANAGER
Name: R. Townsend

## PERIOD OF PERFORMANCE
From 10/1/87 to 10/31/87

### Note:
- Instructions for completing this form are on the reverse side.
- All figures are to be shown in U.S. dollars—whole thousands only.
- Show EPRI portion of the contract only. Do not include contractor cost sharing.

### Actual (booked) cost in the current year 1987

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### Unbooked liability

Please list dollar amount, description of cost, and month/year in which costs are expected to be booked

### Forecast to complete the future year(s)

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### Grand total of lines (1) + (2) + (3) + (4)

87.2

### Remarks:
Comments on significant items

## PREPARED BY
Print name: Ashok Saxena
Date: 11/3/87
Title: Professor of Materials Engineering
December 15, 1987

Mr. S.J. Hudak, Jr.
Southwest Research Institute
P.O. Drawer 28510
6220 Culebra Road
San Antonio, Texas 7824

Subject: SWRI Project 06 - 1536
"Evaluation of Retired Rotors"
Progress report for period ending 11-30-87

Dear Steve,

Creep crack growth analysis of all available rotor steels, both new and ex-service have been completed. Creep crack growth rate da/dt have been correlated with the parameter $C_t$ and the influence of variables such as material chemistry, test temperature, sidegrooves, etc. as well as inherent variabilities in the data have been studied.

Analysis of Creep-Fatigue Crack Growth in Cr-Mo-V rotor steels, both new and ex-service have been partially completed in that the crack growth rate per cycle, da/dn have been plotted against the nominal stress intensity range, $\Delta K$. The influence of various external variables such as test temperature, environment, etc have been examined. Software is being developed to compute the $C_t$/avg parameter for correlating the hold time effects during creep-fatigue crack growth. The results of the (da/dt)$_{avg}$ vs. $C_t$/avg are expected shortly.

Some example plots are attached with this report and the detailed discussions will be provided in the topical report covering the literature search.

Also enclosed is the cost performance report.

Sincerely yours,

Ashok Saxena

Enclosures
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**Notes:**
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- All figures are to be shown in U.S. dollars—whole thousands only.
- Show EPRI portion of the contract only. Do not include contractor cost sharing.

**Remarks:** Comments on significant items

**Prepared by:**
Ashok Saxena
Date: 11/3/87
Title: Professor of Materials Engineering
CREEP CRACK GROWTH ANALYSIS

Mustang 3 Rotor Material

Cr–Mo–V Steel
1000°F

= New Forging (1977)
= Mustang 3 Rotor

Scatter Band

= New Material
CREEP CRACK GROWTH ANALYSIS

Gakushin Rotor Material (Japan)

Cr-Mo-V Steel
1000°F

○ = New Material, CT
□ = Gakushin Rotor, SG-CT

Scatter Band

New Material
CREEP CRACK GROWTH ANALYSIS
Black Dog Rotor Material

Ni–Cr–Mo Steel

- \( o = 950^\circ F \)
- \( \square = 900^\circ F \)
CREEP CRACK GROWTH ANALYSIS
Effect of Side-Grooving (Japanese Program)

C_t, kJ/m^2·hr

Cr-Mo-V Steel
CT, 1100°F

Scatter Bands
--- Non Side-Grooved
- - - Side-Grooved
CREEP CRACK GROWTH ANALYSIS

Effect of Material Chemistry

Cr–Mo–V Steel
1000°F, CT Specimens

○ = Argon
□ = Air
△ = New Forging (1977)
◊ = ASTM Round Robin
▽ = JPS Round Robin
CREEP CRACK GROWTH ANALYSIS

Effect of Test Temperature (Air Env.)

Cr-Mo-V Steel
Air, CT (Non Side-Grooved)

Scatter Bands

900°F
1000°F
1100°F
CREEP—FATIGUE CRACK GROWTH ANALYSIS

Pure Fatigue Crack Growth Data

$\Delta K$, MPa–m$^{1/2}$

Cr—Mo—V Rotor Steels

- $1000^\circ$F, Virgin Material
- $800^\circ$F, Virgin Material
- $800^\circ$F, Gallatin Material

$da/dN$, in/cycle vs. $\Delta K$, ksi–in$^{1/2}$

$t_r (s)$, $t_d (s)$, $t_h (h)$

- $0.5$, $0.5$, $0.000$
- $0.5$, $0.5$, $0.000$
CREEP–FATIGUE CRACK GROWTH ANALYSIS

Effect of Wave–Shape on Virgin Material

ΔK, MPa–m$^{1/2}$

Cr–Mo–V Rotor Steels
1000°F, Air Environment

ΔK, ksi–in$^{1/2}$

da/dN, in/cycle

10$^{-3}$

10$^{-4}$

10$^{-5}$

10$^{-6}$

10$^{-7}$

10$^{-8}$

10$^{-9}$

ΔK, mm/cycle

10$^{-2}$

10$^{-3}$

10$^{-4}$

10$^{-5}$

10$^{-6}$

10$^{-7}$

10$^{-8}$

10$^{-9}$

$\circ$ 0.5 0.5 0.000

$\square$ 0.5 0.5 0.014

$\triangle$ 60.0 60.0 0.470

$\diamond$ 0.5 0.5 24.000

$t_r$ (s) $t_d$ (s) $t_h$ (h)
CREEP—FATIGUE CRACK GROWTH ANALYSIS
Effect of Wave—Shape on Virgin Material

Cr—Mo—V Rotor Steels
800°F, Air Environment
CREEP—FATIGUE CRACK GROWTH ANALYSIS

Effect of Wave—Shape on Ex—Service Material

ΔK, MPa—m^{1/2}

Cr—Mo—V Gallatin Rotor Steel
800°F, Air Environment

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CREEP–FATIGUE CRACK GROWTH ANALYSIS

Effect of Test Environment

Cr–Mo–V Rotor Steels
1000°F, Virgin Material

\( \Delta K, \text{ MPa} \cdot \text{m}^{1/2} \)

\( \frac{\text{da}}{\text{dN}}, \text{ in/cycle} \)

\( \text{da/dN, mm/cycle} \)

\( \Delta K, \text{ ksi-in}^{1/2} \)

- \( \bigcirc \) = Air
- \( \square \) = Air
- \( \bigtriangleup \) = Air
- \( \Diamond \) = Air
- \( \bigtriangledown \) = Argon

\( t_r (s) \quad t_d (s) \quad t_h (h) \)

- 0.5 0.5 0.000
- 0.5 0.5 0.014
- 60.0 60.0 0.470
- 0.5 0.5 24.000
- 0.5 0.5 0.500
January 12, 1988

Mr. S. J. Hudak, Jr.
Southwest Research Institute
P.O. Drawer 28510
6220 Culebra Road
San Antonio, Texas 72824

Subj: SWRI Project 06-1536
"Evaluation of Retired Rotors"
*Progress Report for the period ending 12-31-87*

Dear Steve,

As indicated in our last progress report, the final phase of analysis of creep-fatigue crack growth namely, (da/dt)avg vs (C_t)avg have been completed. The data are currently being plotted with respect to various test and environmental parameters. This is expected to be completed within the next reporting period.

Hence all the work related to the literature survey is now complete. A draft report is being prepared and should be available by mid February.

Also enclosed is the monthly cost performance report.

Sincerely yours

Ashok Saxena

\jm

enclosure
### EPRI CONTRACT NUMBER
RP 248105

### EPRI DIVISION NUMBER

### FOR EPRI USE ONLY

### CONTRACTOR NAME, ADDRESS AND TELEPHONE NUMBER
Fracture and Fatigue Research Lab
Georgia Tech. Research Corp.
Centennial Research Building
Atlanta, GA 30332

### FROM 12/1/87 TO 12/31/87

**Note:** Instructions for completing this form are on the reverse side.
- All figures are to be shown in U.S. dollars—whole thousands only.
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#### Unbooked liability

Please list dollar amount, description of cost, and month/year in which costs are expected to be booked.

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**Remarks:** Comments on significant items

**Prepared by**

Print name Ashok Saxena Date 1/12/88

Title Professor of Materials Engineering
February 19, 1988

Mr. S. J. Hudak, Jr.
Southwest Research Institute
P.O. Drawer 28510
6220 Culebra Road
San Antonio, Texas 72824

Subj: SWRI Project 06-1536
"Evaluation of Retired Rotors"

PROGRESS REPORT FOR THE PERIOD ENDING 1-31-88

Dear Steve,

A draft copy of the report promised in the last letter has been completed and is currently in typing. Hence, this work is complete. The report will be mailed to SWRI for comments shortly.

Also enclosed is the monthly cost performance report.

Sincerely yours,

Ashok Saxena
**EPRI Project Contract Report**

**EPRI Contract Number:** RP 24811 - 05

**EPRI Division Number:**

**For EPRI Use Only:**

**Contractor Name, Address and Telephone Number:**
Fracture and Fatigue Research Lab
Georgia Tech. Research Corp.
Centennial Research Building
Atlanta, GA 30332

**EPRI Project Manager:**
R. Townsend

**Period of Performance:**
From 1/1/88 to 1/31/88

**Note:**
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### Actual (booked) cost in the current year

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### Forecast to complete the current year

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### Forecast to complete the future year(s)

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**Grand total of lines (1) + (2) + (3) + (4)**

**Remarks:** Comments on significant items

**Prepared by:**
Ashok Saxena

**Print name:** Ashok Saxena
**Date:** 2/18/88
**Title:** Professor of Materials Engineering
May 9, 1988

Mr. S. J. Hudak, Jr.
Southwest Research Institute
P.O. Drawer 28510
6220 Culebra Road
San Antonio, TX 72824

Subject: SWRI Project 06-1536
"Evaluation of Retired Rotors"
PROGRESS REPORT FOR THE PERIOD ENDING 4-30-88

Dear Steve,

The corrected copy of the report on the literature survey was sent to G.R. Leverant for transmittal to EPRI. Additional work on the project is awaiting specimens from SWRI.

Also enclosed is the monthly cost performance report.

Sincerely yours,

Ashok Saxena
**EPRI CONTRACT NUMBER**
RP 248105

**EPRI DIVISION NUMBER**

**For EPRI Use Only**

**CONTRACTOR NAME, ADDRESS AND TELEPHONE NUMBER**
Fracture and Fatigue Research Lab
Georgia Tech. Research Corp.
Centennial Research Building
Atlanta, GA 30332

**EPRI PROJECT MANAGER**
Name: R. Townsend

**PERIOD OF PERFORMANCE**
From 4/1/88 to 4/30/88

---

**Note:**
- Instructions for completing this form are on the reverse side.
- All figures are to be shown in U.S. dollars—whole thousands only.
- Show EPRI portion of the contract only. Do not include contractor cost sharing.

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**Unbooked liability**
Please list dollar amount, description of cost, and month/year in which costs are expected to be booked.

**Forecast to complete the future year(s)**

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**Grand total of lines (1) + (2) + (3) + (4)**

**Remarks:**
Comments on significant items
Cost figures for the current month are estimates. Final figures will be included in the next month's report.

**PREPARED BY**

Print name: Ashok Saxena Date:  

---
September 29, 1989

Dr. S.J. Hudak, Jr.,
Southwest Research Institute
6220 Culebra Road
Post Office Drawer 28510
San Antonio, Texas 78228-0510

Re: Progress report for the duration August-September, 1989
(Georgia Institute of Technology)

Dear Steve:

This letter constitutes the progress report on our subproject from EPRI RP-2481-5.

To date we have completed four elevated temperature fatigue crack growth tests on the Moss landing Rotor Material from the bore and rim regions. These include three tests at a loading frequency of 1Hz (one each from the bore and rim regions) and one test with a hold time of 100 sec from the bore region sample. The results from these tests are plotted in Figs. 1 and 2, with $\Delta K$ and $(C_t)_\text{avg}$, respectively.

We have one additional test in progress at a 100 sec hold time from a sample taken from the rim region of the rotor. After completion of the 100 sec hold time test, we will be starting a test with 15 minutes hold time using a sample from the bore region of the Moss landing rotor.

Sincerely yours,

Ashok Saxena
Professor of Materials Engineering

AS/gef

Enclosures
Fig. 1 - Fatigue crack growth behavior of specimens from the Moss landing rotor material tested at 1000°F - air environment.
Fig. 2 - Creep-fatigue crack growth behavior of the Moss landing rotor material with similar data from new material (1000°F).
**EPRI CONTRACT NUMBER**

[2841-05]

**EPRI PROJECT MANAGER**

Name: S. J. Hudak, Jr.

**PERIOD OF PERFORMANCE**

From 08/01/89 to 09/30/89

Note: *Instructions for completing this form are on the reverse side.*

- All figures are to be shown in U.S. dollars—whole thousands only.
- Show EPRI portion of the contract only. Do not include contractor cost sharing.

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**Unbooked liability**

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Grand total of lines (1) + (2) + (3) + (4) 88.9

**Remarks:** Comments on significant items

**PREPARED BY**

Print name: Ashok Saxena

Date: 09/28/89

Title: Professor of Materials Engineering
November 3, 1989

Mr. M. L. Bartlett  
Southwest Research Institute  
P.O. Drawer 28510  
6220 Culebra Road  
San Antonio, Texas 78284

Re: Monthly Progress Letter EPRI Project  
2481-5, GTRI Project E-18-642

Dear Marty:

Enclosed is a graph of da/dN versus ΔK summarizing data from 100 second hold time tests available to date. As you can see the data for the rim specimens appear to agree with the data from the bore region specimens both in a 1 Hz continuous cycling test as well as in a 100 second hold time test. The 100 second hold time test is still running after two months test time.

We have also initiated tests with 6 second rise and decay times to simulate the loading/unloading rates observed during the 100 second hold time tests. These results will be presented in the next report.

The estimated expenditure for the month of October was $2.2K.

Sincerely yours,

Ashok Saxena  
Professor of Materials Engineering

AS/gef  
Enclosure
Representation of Crack Growth Behaviour for Moss Landing Specimen

\[ \frac{da}{dN} \text{ [in/cycle]} \]

- ▼ Bore material (MLCT10 & 12) 1 Hz
- ○ Rim material (MLRCT9) 1 Hz
- ■ Bore material (MLCT11) th=100sec
- ★ Rim material (MLRCT10) th=100sec

\[ \Delta K \text{ [ksi/in]} \]
Dr. Steve Hudak  
Southwest Research Institute  
Post Office Drawer 28510  
6220 Culebra Road  
San Antonio, Texas 78284  

Re: Monthly Progress Report EPRI Project 2481-5,  
Subcontract No: 06-1536, November 1989

Dear Steve,

In the past month, we have completed two additional tests. The first test was conducted on a rim specimen from the Moss Landing rotor with a 100 second hold time. Figs. 1 and 2 compare the crack growth data on $\Delta K$ and $C_\alpha$ basis, respectively, from this specimen to the data obtained from a bore region specimen tested under identical conditions. No significant differences were observed between the data for the two regions on either plots.

On the basis of the above results and the creep crack growth results generated at Southwest Research Institute, the two locations will be considered equal in terms of the crack growth response.

The second test completed during this reporting period was conducted using 6 seconds loading and unloading time with no hold time. The crack growth rates were significantly higher compared to the 1Hz test data obtained previously (see Fig. 3). A crossover is observed between the data obtained under conditions of continuous cycling with 6 sec loading/unloading time and the data from a test which also had a hold time of 100 sec in addition to the 6 sec loading/unloading. At this time no rational explanation can be provided for such behavior. Additional testing and analysis is underway to help the understanding of this phenomenon.

The writer attended an ASTM meeting in Orlando between 6-8 November for which travel expenses were partially charged to this project. The approximate expenses for the month of November were $2,000.

Sincerely yours,

Ashok Saxena  
Professor of Materials  
Engineering

AS/gef  
Enclosures
Figure 1 - Representation of Crack Growth Behaviour for Moss Landing Specimen

- $\Delta K$ vs $\frac{da}{dN}$ [in/cycle]

- $\Delta K$ in [ksi/in]

- Bore material (MLCT10 & 12) 1 Hz
- Rim material (MLRCT9) 1 Hz
- Bore material (MLCT11) $\tau_h=100$ sec
- Rim material (MLRCT10) $\tau_h=100$ sec
Fig. 2. Representation of Crack Growth Behaviour for Moss Landing (100s hold time).

![Graph showing crack growth behaviour with corresponding data points labeled as *= MLRCT10 (rim) and * = MLCT11 (bore).]
Crack Growth Behaviour for Moss Landing bore specimen

\[ \frac{da}{dN} \text{ [in/cycle]} \]

\[ \Delta K \text{ [ksi/sqrt/in]} \]

- \( \triangledown \) = MLCT10 \( t_r=0.5s \ t_d=0.5s \ t_h=0s \)
- \( \square \) = MLCT11 \( t_r=6s \ t_d=6s \ t_h=100s \)
- \( + \) = MLCT13 \( t_r=6s \ t_d=6s \ t_h=0s \)
January 29, 1990

Dr. S.J. Hudak, Jr.
Southwest Research Institute
6220 Culebra Rd.
Post Office Drawer 28510
San Antonio, Texas 78228-0510

Subject: Monthly Progress Report E-18-642,
EPRI Project 2481-5
Period of Performance: 12/1/89 to 1/25/90

Dear Steve:

During the captioned period, we have completed another 100 second hold time fatigue crack growth test. This test (MLRCT8) was conducted in air, but the important distinction from the previous tests is that we were able to successfully measure the load-line deflection change during the hold period. This allowed us to have a measured estimate of $(C_t)_{avg}$, which was previously not possible. Figure 1 shows the load-line deflection as a function of elapsed hold time during the various stages of the test. A comparison of the $da/dt$ versus $(C_t)_{avg}$ plot using the measured and analytical values of $(C_t)_{avg}$ from specimen MLRCT-8 is shown in Fig. 2. The measured $(C_t)_{avg}$ values are based on the total deflection rate $(V)$ instead of the deflection rate due to creep $(V_c)$ only. We are currently incorporating the capability to calculate $V_c$ in our code. It is estimated that this will cause the measured $(C_t)_{avg}$ values to decrease by about 5 percent. This correction will be made during the next reporting period. There appears to be an excellent agreement between the measured and analytical values of $(C_t)_{avg}$.

Figure 3 shows all the creep-fatigue crack growth data from three specimens tested with 100 second hold time. Figure 4 shows a comparison between the creep crack growth rate data obtained at Southwest Research Institute and the creep-fatigue crack growth rate data obtained at Georgia Tech. Only the measured $(C_t)_{avg}$ data are included for comparison.

Sincerely yours,

Ashok Saxena
Professor of Materials Engineering

AS/bc
cc: Pat Ledon
Fig. 1. Load line deflection for MLRCT08
Fig. 2. Comparison of measured and analytical values of $C_t$ for Moss Landing Specimen (@ 100 sec hold time).
Fig. 3  Representation of Crack Growth Behaviour
for Moss Landing Specimen (@100 sec hold time)
Fig. 4. Representation of Crack Growth Behaviour
for Moss Landing Specimens (measured Ct values).

\[
\frac{da}{dt} [\text{in./hr}] \\
Ct (avg) [\text{in.kips/sq.in.hr}]
\]
Dr. S.J. Hudak, Jr.
Southwest Research Institute
8220 Culebra Road
Post Office Drawer 28510
San Antonio, Texas 78288-0510

Subject: Monthly Progress Report E-18-642
Period of Performance: 01/26/90 - 3/26/90

Dear Steve:

During the captioned period, we completed a creep-fatigue test in ultra high purity \( N_2 \) with a hold time of 100 sec. and rise and decay times of 6 sec. each. The crack growth data from this test are shown in Fig.1 as a function of \( \Delta K \). The results from previous tests are also included in the plot.

Compared to the previous tests under similar loading conditions but tested in air, the crack growth rates at lower \( \Delta K \) levels are considerably higher. At the higher \( \Delta K \) levels, the crack growth rates are comparable to the rates in air. This implies that oxide induced crack closure is a significant factor in determining the crack growth rates in air. We are recommending that future tests be performed in \( N_2 \) and in air to characterize this effect further.

Figure 2 shows the \( da/dt \) versus \( C_t \) data from all tests conducted with a hold time of 100 sec. The data from the tests conducted in \( N_2 \) does not show a bend in the crack growth rate behavior at lower \( C_t \) values as do the data from tests conducted in air. Instead, the crack growth rates follow the trend obtained by extrapolating the higher crack growth rate data in air at lower values. This reinforces the earlier conclusions about the role of oxide induced crack closure in these tests.

If you have any further questions, please call me.

Sincerely yours,

Ashok Saxena
Professor of Materials Engineering

AS/gef

Enclosures

cc: OCA
Pat Ledon
Representation of Crack Growth Behaviour for Moss Landing Specimen

Fig. 1 -

\( \frac{da}{dN} \text{ [in/cycle]} \)

\( \Delta K \text{ [ksi\sqrt{in}]} \)

- \( \nabla = \text{MLCT10,12 & R9 (AIR - 1 Hz)} \)
  \( (\text{AIR} - t_r = t_d = 0.5\text{sec, } t_h = 0\text{sec}) \)
- \( = \text{MLCT11,R8 & R10} \)
  \( (\text{AIR} - t_r = t_d = 6\text{sec, } t_h = 100\text{sec}) \)
- \( = \text{MLCT14} \) (\( N_2 - t_r = t = 6\text{sec, } t_h = 100\text{sec} \))
- \( = \text{MLCT13} \) (\( \text{AIR} - t_r = t_d = 6\text{sec, } t_h = 0 \))
**Fig. 2**

**Representation of Crack Growth Behaviour**

for Moss Landing Specimen (@100 sec hold time)

- ■ = MLCT11 analytical (air)
- ★ = MLRCT12 analytical (air)
- ○ = MLRCT8 analytical (air)
- ● = MLRCT8 measured (air)
- ● = MLCT14 analytical (N₂)
May 4, 1990

Dr. S.J. Hudak, Jr.
Southwest Research Institute
6220 Culebra Road
Post Office Drawer 28510
San Antonio, Texas 78228-0510

Subject: Monthly Progress Report E-18-642
EPRI Project 2481-5
Period of Performance 4-1-90 to 4-30-90

Dear Steve:

During the captioned period, we have started and continued a fifteen minute hold time creep-fatigue crack growth test. It is anticipated that this test will take approximately ten weeks to complete. The results to date from the test are summarized in the accompanying figure.

It appears that the trend of $\frac{da}{dN}$ versus $\Delta K$ is very similar to the earlier 100 sec. hold time tests. The growth rate is initially high and decreases progressively to a minimum level. We feel that this is also due to oxide induced crack closure. To verify this, we intend to conduct a test under similar loading conditions in high purity $N_2$.

Sincerely yours,

Ashok Saxena
Professor of Materials Eng.

AS:gef
Enclosure
Representation of Crack Growth Behaviour
for Moss Landing Specimen

\[ \frac{da}{dN} \text{ [in/cycle]} \]

\[ \Delta K \text{ [ksi\sqrt{in}]} \]

- \( \nabla = \text{MLCT10,12 & R9 (AIR—1 Hz)} \)
- \( \square = \text{MLCT11,R8 & R10} \)
- \( \blacksquare = \text{MLCT14} \)
- \( \bullet = \text{MLCT13} \)
- \( \times = \text{MLCT15} \)
CREEP CRACK GROWTH ANALYSIS
ASTM Round Robin Program

$K_{eff}$, MPa–m$^{1/2}$

$\frac{da}{dt}$ vs. $K_{eff}$

- ○ = SG–CT–11
- □ = SG–CT–12
- △ = Ct–19
- ◊ = Ct–20
- ▽ = Ct–21
- + = Ct–22
CREEP CRACK GROWTH ANALYSIS
ASTM Round Robin Program

![Graph showing da/dt vs. C_t]

- $C_t$, kJ/m$^2$-hr
- da/dt vs. C_t
- $C_t$, in-kips/in$^2$-hr
- da/dt, in/hr
- da/dt, mm/hr
June 11, 1990

Dr. S.J. Hudak, Jr.
Southwest Research Institute
6220 Culebra Road
Post Office Drawer 28510
San Antonio, Texas 78228-0510

Subject: Monthly Progress Report E-18-642
        EPRI Project 2481-5
        Period of Performance: 5/1/90 - 5/31/90

Dear Steve:

During the captioned period, we have completed the 15 minute hold time test in air. The da/dN versus ∆K and da/dt versus C_t data from this test are shown in Figs. 1 and 2, respectively. The data from this test are compared with other previous data obtained for 100 second hold time.

The decreasing crack growth rate as a function of ∆K during the initial portion of the test is consistent with the trends observed for the 100 second hold time tests in air. At this time, we feel that this is caused by oxide induced crack closure. In the future, we will be conducting tests in N₂ to resolve this issue.

We are now starting a creep-fatigue crack growth test in air with an eight hour hold time as per our discussion. We will follow it with a 15 minute hold time test in N₂.

It is also observed in Figs 1 and 2 that the crack growth rates (da/dN) for 15 minutes of hold time are not significantly different from the crack growth rates for 100 second hold time. This indicates that the crack tip stresses relax significantly during the first 100 seconds such that the crack growth rates decrease rapidly beyond that period. The results from the 8 hour hold time tests will provide further clarification on this issue.
As of May 31, 1990, $68.0K had been spent on the project. The presently committed amount from SWRI is $65.0K. Hence, the remainder of the allocation should be committed at this time to avoid interruptions in the project. If you have any questions, please contact me at (404) 894-2888.

Sincerely yours,

Ashok Saxena, Professor
School of Materials Engineering

AS:gef
Enclosure
July 5, 1990

Dr. S.J. Hudak, Jr.
Southwest Research Institute
6220 Culebra Road
Post Office Drawer 28510
San Antonio, Texas 78228-0510

Subject: Monthly Progress Report E-18-642
        EPRL Project 2481-5

        Period of Performance: 6/1/90 - 6/30/90

Dear Steve:

During the reporting period, we started a creep-fatigue crack
growth test with eight hours of hold time as per discussions with
you and Gerry Leverant. This is a long term test and we do not
have any data to report from this test at this time.

We also conducted a calibration test in which we measured the value
of $(C_t)_{avg}$ for several different hold times and crack sizes. These
results will be used to experimentally verify the analytical
estimates of $(C_t)_{avg}$.

The next month's report will include data from the above tests

Sincerely yours,

Ashok Saxena
Professor, School of
Materials Engineering

AS:gef
September 7, 1990

Dr. S.J. Hudak, Jr.
Southwest Research Institute
6220 Culebra Road
P.O. Box 28510
San Antonio, TX 78228-0510

Subject: Monthly Progress Report, EPRI Project 2481-5 Georgia Tech
Project E-18-642

Dear Steve:

This letter constitutes the monthly progress report for August 1990.

The eight hour hold time creep-fatigue crack growth test was completed and the data are presented as a function of ΔK and Ct in the attached figures. On the da/dt versus Ct basis, these crack growth rates from this test appear to agree with the creep crack growth rates.

Further evaluation of the methods for estimating Ct analytically (in other words, without access to the measured load-line deflection rates) was conducted. It was concluded that more creep data are needed before an accurate equation can be developed for estimating Ct. An attached figure shows a plot of the steady-state creep rate as a function of applied stress. The literature data and the SWRI data from the Mosslanding Rotor are both included in the plot. The literature data and the Mosslanding data appear to agree at the higher stress levels. However, the creep rates from the Mosslanding rotor appear to be somewhat lower than the previous data at the lower stress levels. Further, the data also appear to show a bi-linear relationship between logs of strain rate and logs of stress. More data from the Mosslanding rotor are needed at the lower stress levels to complete the description of the creep rates in that material. The strain-time data from the Mosslanding tests also exhibited a prominent primary creep region suggesting that primary creep should be included in the creep rate description of this material. Additional creep deformation tests are planned to fill these gaps in the data. The issue of analytically estimating Ct will be revisited when the additional data become available.

Sincerely yours,

Ashok Saxena
Professor
Representation of Crack Growth Behaviour for Moss Landing Specimen

\[
\frac{da}{dN} \text{ [in/cycle]} \quad \Delta K \text{ [ksi} \sqrt{\text{in}}]
\]

\[v = \text{MLCT10,12} \& \text{R9 (AIR—1 Hz)}\]
\[\text{v = } (\text{AIR—}t_r = t_d = 0.5\text{sec, } t_h = 0\text{sec})\]
\[\Box = \text{MLCT11,R8} \& \text{R10} \]
\[\Box = (\text{AIR—}t_r = t_d = 6\text{sec, } t_h = 100\text{sec})\]
\[\blacksquare = \text{MLCT14 (N_a—}t_r = t = 6\text{sec, } t_h = 100\text{sec)}\]
\[\bullet = \text{MLCT13 (AIR—}t_r = t_d = 6\text{sec, } t_h = 0)\]
\[\times = \text{MLCT15 (AIR—}t_r = t_d = 6\text{sec, } t_h = 900\text{sec)}\]
\[\triangle = \text{MLCTM1 (AIR—}t_r = t_d = 6\text{sec, } t_h = 8\text{hrs)}\]
Representation of Crack Growth Behaviour for Moss Landing Specimen

- $x = \text{Air, CCG}$
- $\square = \text{Air, } t_h = 8 \text{ hrs}$
- $\circ = \text{Air, } t_h = 900s$
- $\blacktriangle = \text{N}_2, \ t_h = 100s$
- $\triangle = \text{Air, } t_h = 100s$
Steady State Creep Strain Rate

- **Lit. Data**
- **Moss Landing**
- **Fitted Curve**

![Graph showing steady state creep strain rate with data points and a fitted curve.](image_url)
October 3, 1990

Dr. S.J. Hudak, Jr.
Southwest Research Institute
6220 Culebra Road
Post Office Drawer 28510
San Antonio, Texas 78228-0510

Period of Performance: 9/1/90 to 9/30/90

Dear Steve:

In this month's letter, I am summarizing the progress on the experimental portion of our work which will assist you in your presentation to EPRI on October 9.

We have completed creep-fatigue crack growth tests with hold times of 0, 0.278 hrs (100 sec), 0.25 hrs and 8 hrs. The data are plotted as the average crack growth rate, da/dt, during the hold time versus the average value of $C_t$ during the hold time, Fig-1. For comparison, the creep crack growth rate data obtained by SWRI on side-grooved specimens are also plotted. The crack growth rate per cycle, da/dN, from the creep-fatigue tests are also plotted as a function of $\Delta K$, Fig 2. The following observations are made from these results.

On a da/dN versus $\Delta K$ basis, the crack growth rates generally increase with increasing hold time. For tests conducted in air with 100 sec hold time, the da/dN at the low $\Delta K$ values exhibit lower crack growth rates than the tests conducted at 1 Hz ($t_r = t_d = 0.5$ sec) and also the tests conducted at 0.08Hz ($t_r = t_d = 6$ sec) with no hold time. The loading and unloading times ($t_r$ and $t_d$, respectively) for all tests with hold times were 6 sec. The above result was surprising but very reproducible. Thus, in order to better understand this behavior, we conducted another test with a 100 sec hold time but in high purity $N_2$ environment to prevent oxidation of the fracture surface. The crack growth rates in this test were either comparable to or higher than the tests without hold time. This led us to conclude that the lower crack growth rates in the 100 sec hold time tests in comparison to the no hold time tests were most likely caused by oxide induced crack closure at the low $\Delta K$ values.
On the da/dt versus C_t basis, it was found that the crack growth rates for hold times of 0.25 hrs and less appear to follow a single trend in which the crack growth rates were considerably lower than the creep crack growth rates for the same C_t value. The crack growth rates for the 8 hour hold time tests appear to merge with the creep crack growth results of SWRI. However, the last data point from the 8 hour hold time test appears to have a higher crack growth rate when compared to the creep crack growth trend. This needs further explanation.

Creep-fatigue crack growth tests are conducted under load-controlled conditions. If small-scale creep conditions dominate during the test, the creep deformation at the crack tip during hold time is expected to be approximately reversed by plastic deformation during unloading. This occurs due to the elastic constraint exerted by the regions outside of the creep zone in the test specimen. Thus, no substantial creep deformation accumulates on the specimen from cycle to cycle. However, as the crack size increases, the transition time for extensive creep conditions to develop from small scale creep conditions decreases rapidly. The transition time, t_T, is given by:

$$t_T = \frac{K^2(1-v^2)}{E(n+1)C^*}$$

where, K = applied stress intensity parameter, v = Poisson’s ratio, E = elastic modulus, n = creep exponent and C^* is the magnitude of the C^* - integral. Figure 3 shows a plot of the transition time as a function of the crack size for the specimen tested with 8 hours of hold time. It can be seen that the transition time decreases rapidly toward the end of the test indicating that creep deformation could be accumulating during each fatigue cycle at a more rapid rate. The rapid decrease in transition time appears to coincide with the rapid increase in crack growth rates. Thus, the crack growth behavior toward the end of the test may be explained by the presence of accumulated creep deformation. This hypothesis will be further confirmed by another test to be performed with 8 hours of hold time at a ΔK level higher than the previous test. Until the results of this test are available, this explanation should be considered tentative.
Another objective of the test program is to validate the analytical expressions for estimating $C_t$ in Cr-Mo-V steel under the conditions of hold time during cyclic loading. Figure 4 shows the secondary creep rate as a function of applied stress. The data include the Moss Landing data from SWRI tests and previous data on Cr-Mo-V steel from the literature compiled for an ASTM program. It appears that a bi-linear relationship on a log-log plot between creep rate and stress is more appropriate than a single power-law fit. Further, the SWRI creep deformation tests also showed evidence of primary creep deformation. The expressions for estimating $C_t$ were modified for a bilinear steady-state creep rate versus stress relationship and for primary creep deformation. The calculated values with steady-state creep only and with steady-state plus primary creep were compared with experimental estimates of $C_t$ in Figs. 5 and 6. Figure 5 is for hold times of 100 sec and Fig. 6 is for hold times of 900 sec. It appears that at least for short hold times of 100 seconds, primary creep is very significant, with its contribution being reduced for hold times of 900 sec. There are no measured $C_t$ data for eight hours of hold time.

There are few areas in the above results which need further attention. As we have talked on the phone before, I would like to have a $20,000 and one year extension on the project to address these areas. The primary focus of the experimental work will be to obtain additional creep-fatigue crack growth rate data with eight hours of hold time starting at different $\Delta K$ levels, crack sizes and hold times. A criterion for assuring that the crack growth rates are in the $C_t$ controlled regime will be developed from these results.

The available data on primary creep is extremely limited at the present time. Also, the creep deformation rates have not been characterized at lower stress levels in the range of 25-30 ksi. These data are important for developing accurate expressions and methods for estimating $C_t$. Additionally, we would also perform nonlinear, time-dependent finite element analyses of compact specimens with cyclic loading and varying loading rates. The loading conditions will be identical to the loading conditions in laboratory specimens. This analysis will help considerably in understanding the crack growth trends observed in Figs. 1 and 2 and also help in developing models for creep-fatigue crack growth.

If you have any further questions about the work completed or proposed work, please feel free to call me.

Yours sincerely,

Ashok Saxena
Professor

/lmw
Figure 1

Representation of Crack Growth Behaviour for Moss Landing Specimen

+ = Creep Crack Growth
\( \square = t_h = 0.0278 \text{ hrs} \)
\( \triangle = t_h = 0.25 \text{ hrs} \)
\( \bullet = t_h = 8 \text{ hrs} \)

linear EL–SC
Representation of Crack Growth Behaviour for Moss Landing Specimen

\( \frac{d}{dN} \) [in/cycle] vs. \( \Delta K \) [ksi\(\sqrt{\text{in}}\)]

- \( \triangledown \) = MLCT10,12 & R9 (AIR—1 Hz)
  \( t_r = t_d = 0.5 \text{sec}, t_h = 0 \text{sec} \)
- \( \square \) = MLCT11,R8 & R10
  \( t_r = t_d = 6 \text{sec}, t_h = 100 \text{sec} \)
- \( \blacksquare \) = MLCT14 \( N \)2—\( t_r = t_d = 6 \text{sec}, t_h = 100 \text{sec} \)
- \( \bullet \) = MLCT13 (AIR—\( t_r = t_d = 6 \text{sec}, t_h = 0 \))
- \( \times \) = MLCT15 (AIR—\( t_r = t_d = 6 \text{sec}, t_h = 900 \text{sec} \))
- \( \triangle \) = MLCTM1 (AIR—\( t_r = t_d = 6 \text{sec}, t_h = 8 \text{hrs} \))
Steady State Creep Strain Rate

\[ \varepsilon_{ss} = A' \sigma^{n'} + A'' \sigma^{n''} \]

- \( n' = 7 \quad A' = 1.49 \times 10^{-16} \)
- \( n'' = 18 \quad A'' = 9.68 \times 10^{-38} \)
MOSS LANDING SPECIMEN (8 hr hold time)
Comparison of Measured and calculated $C_t$

![Graph showing comparison of measured and calculated $C_t$. The graph plots $C_t$ (in kips/in² hr) on the y-axis and $t/t_m$ on the x-axis. The graph includes two curves labeled as static (EL-SC) and static (EL-SC-PC). There are data points indicating a 6s rise / 100s hold.](image-url)
Comparison of Measured and calculated $C_t$

- static (EL-SC)
- static (EL-SC-PC)
- $6s$ rise / $900s$ hold

![Graph showing comparison of measured and calculated $C_t$](image)
October 2, 1987

Mr. S. J. Hudak, Jr.
Southwest Research Institute
6220 Culebra Rd.
San Antonio, Texas 78284

Re: Subcontract-19329 from EPRI
project RP2481-5

Dear Steve:

Enclosed are two copies of our technical progress report and
the monthly cost (EPRI form 177). If you have any questions,
please call me at (404) 894-2888.

Sincerely,

Ashok Saxena
Professor of Materials Eng.

AS/ptl
Monthly Technical Progress Report

submitted to:

Southwest Research Institute
6220 Culebra Rd.
San Antonio, Texas 78284
Attn.: S.J. Hudak, Jr.

STEAM TURBINE ROTOR LIFE ASSESSMENT AND EXTENSION

EPRI-RP-2481-5
Subcontract - 19329

Contractor: Fracture and Fatigue Research Lab
Georgia Tech Research Corp.
Atlanta, GA 30332

Principal Investigator: Dr. A. Saxena

Period of Performance: 8-1-87 to 9-30-87
Technical Progress

Dr. A. Saxena participated in a one-day meeting at Palo Alto on the overall RP-2481 project.

Literature Search

Data from creep and creep-fatigue crack growth in turbine rotor steels available from tests conducted at Westinghouse R&D Center were consolidated. The data include eleven tests each of creep and creep-fatigue crack growth under various conditions. The creep tests were conducted at 900°F and 1000°F in air and argon environments. Most of the data are for CT specimens although a few tests were conducted for CCT specimens also. Creep fatigue crack growth data include tests at 800°F and 1000°F on virgin rotor forgings as well as used Gallatin material. Various combinations of waveform variables (rise, hold and decay times) were utilized with cycle times ranging from 1 second (pure fatigue) to 24 hours.

In an effort to compile all available data on creep and creep-fatigue crack growth of turbine rotor steels, a computerized literature search was conducted through the Georgia Tech Library. The search operates on the principle of occurrence of a preselected "set" of keyword definitions in the title and abstract of the document.

Two specific literature data bases were scanned with a key extraction set comprised of the materials used for turbine rotors together with creep. Note that this set will include creep-fatigue because the word 'creep' exists in the extraction set. The databases scanned are COMPENDEX - which is an engineering type information bank (maintained by Engineering Info., Inc.) and METADEX - a materials science (metallurgy) type source operated by ASM International.

COMPENDEX was searched from 1970 to July 1987 and resulted in 84 citations while METADEX yielded 21 items between 1966 to September 1987. On cursory examinations of the outputs (in form of the abstracts), it was found that a majority of the papers deal with creep and creep fatigue deformation and rupture rather than crack growth. The percentage of relevant articles dealing with creep or creep-fatigue crack growth is about 15 and 25 from the COMPENDEX and METADEX, respectively.

The next task will be to obtain copies of the relevant articles from the library and conduct a manual search of more current periodicals whose contents may not have been included in the data bases investigated. In addition, we are soliciting a few utility companies for unpublished or 'internal' data on creep or creep-fatigue crack growth of rotor materials. Results of the ASTM round robin are also being restructured for inclusion in the report in a consistent format.
**EPRI CONTRACT NUMBER**
RP 2481-05

**EPRI DIVISION NUMBER**

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**CONTRACTOR NAME, ADDRESS AND TELEPHONE NUMBER**
Centennial Research Building
Atlanta, GA 30332
(404) 894-2888

**EPRI PROJECT MANAGER**
Name

**PERIOD OF PERFORMANCE**
From 8/1/87 to 9/30/87

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- Show EPRI portion of the contract only. Do not include contractor cost sharing.

**Actual (booked) cost in the current year**

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**Remarks:** Comments on significant items

**PREPARED BY**

Print name Ashok Saxena Date 10-2-87
Title Professor
September 20, 1988

Mr. S. J. Hudak, Jr.
Southwest Research Institute
P. O. Box 28510
6220 Culebra Road
San Antonio, Texas 78284

Dear Steve:

Enclosed are three copies of the revised report on "Creep and Creep-fatigue Crack Growth Behavior in Steam Turbine Rotor Steels." We have revised the report in accordance with EPRI's and your comments. We have also arranged the report in the EPRI format.

Please review the report and let us know if we can proceed to print the report on EPRI mats and send the report to them for publishing.

Sincerely yours,

Ashok Saxena
Professor of Materials Engineering

AS/1lg/264AS.LTR

Enclosure
CREEP AND CREEP-FATIGUE CRACK GROWTH IN STEAM TURBINE ROTOR STEELS

K. Banerji and A. Saxena
Fracture and Fatigue Research Laboratory
School of Materials Engineering
Georgia Institute of Technology
Atlanta, GA 30332-0245

Interim Project Report submitted to Southwest Research Institute
Subcontract No: 06-1536
EPRI Project: RP 2481-5

SwRI Project Managers: S. J. Hudak, Jr.
G. Leverant
LIBRARY DOES NOT HAVE

Revised Report
June 11, 1991

Dr. S.J. Hudak, Jr.
Southwest Research Institute
6220 Culebra Road
Post Office Drawer 28510
San Antonio, Texas 78228-0510

Dear Steve:

Enclosed is a copy of our final contact report on SWRI subcontract 06-1536 (Georgia Tech Project E-18-642). Please review this report and send us your comments.

Since I will be away during the summer, June 15 - September 15, I would appreciate it if you can direct your comments to Mr. Negussi Adefris who will make the necessary changes and supply you with a revised copy of the report. Negussi can be reached at (404) 894-2847. I can be reached in Germany at 49-04152-87-2500. The FAX number is 49-04152-87-2534. Please do not hesitate to contact Negussi or me if you have questions.

Sincerely yours,

Ashok Saxena
Professor

cc: Dr. R. Viswanathan, EPRI
Creep-Fatigue Crack Growth Behavior in an Ex-service Cr-Mo-V Rotor Steel

N.B. Adefris and A. Saxena
School of Materials Engineering
Georgia Institute of Technology
Atlanta, GA 30332-0245

Subcontract No. 06-1536
EPRI Research Project 2481-5

SwRI Project Managers:
S.J. Hudak, Jr.
G. Leverant
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Prepared by Mechanical Properties Research Laboratory, Georgia Institute of Technology, Atlanta, GA 30332-1245, under contract with Southwest Research Institute.
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Section 1

Summary and Conclusions

Creep-fatigue crack growth behavior of an ex-service Cr-Mo-V steel was investigated under hold times of 0, 0.0278, 0.25, and 8 hours for a trapezoidal loading waveform at a temperature of 538°C (1000°F). These data are compared with the creep crack growth behavior obtained on the same material by Southwest Research Institute. Non-linear finite element (FEM) analyses with various creep deformation laws as well as experiments with various hold times were performed on compact type specimens with stationary cracks. The work was aimed at developing accurate expressions for estimating $(C_t)_{avg}$ for 1Cr-1Mo-0.25V Steel at 538°C. These expressions were then used for estimating $(C_t)_{avg}$ in crack growth specimens tested under the various hold times.

When elastic-plastic-primary creep-secondary creep deformation model was used in the FEM analyses, the calculated values of $C_t$ compared well with the measured values. The FEM results also showed that the accumulated creep during the hold time was not significantly reversed during the unloading portion of the creep-fatigue cycle. A new method of calculating $(C_t)_{avg}$, which is most suitable for this material is proposed on the basis of these numerical and experimental results.

The correlation of the crack growth rate with $(C_t)_{avg}$ was significantly improved when the new estimation scheme was used to estimate $(C_t)_{avg}$. Recommendations for additional work are also provided.
Section 2
Introduction and Background

Recently, there has been an increased interest in assessing the remaining life of highly stressed components operating at high temperatures in power plants. Dominant cracks have a tendency to develop in these components in highly stressed regions and grow under the condition of fatigue and creep in the small scale creep (SSC) regime. Therefore, characterizing creep-fatigue crack growth (CFCG) rates is an important step in predicting the design life time and the remaining life time of such components. Several CFCG models have been proposed in the past. In an early study, Saxena and co-workers [1] proposed that creep-fatigue crack growth rates in the small-scale creep regime can be correlated by a parameter related to the amplitude of the crack tip stress fields. In a later study, Saxena and Gieseke [2] proposed the use of the average value of the $C_t$ parameter for characterizing creep-fatigue crack growth rates. $C_t$ characterizes the Hutchinson [3], Rice and Rosengren [4] (HRR) crack tip stress field in the extensive creep regime, and is also uniquely related to the rate of expansion of the creep zone size in the small-scale creep regime. In a more recent study [5], it was shown that for some materials the effect of instantaneous plasticity on creep is considerable and it is necessary to include this effect in estimating the average value of the $C_t$ parameter. However, plasticity-creep interactions is a material dependent phenomenon and its extent can vary from one material to another.

The objective of this report is to characterize creep-fatigue crack growth rate behavior in an ex-service rotor steel and to develop a method for estimating the magnitude of the most appropriate crack tip parameter. CFCG data were obtained by testing compact type specimens subjected to trapezoidal loading waveforms. Considerable use of nonlinear finite element analyses was made to develop accurate methods of estimating the average values of $C_t$. 
2.1 Background

2.1.1 Constitutive Relations

A material deforming under a given state of stress, \( \tilde{\sigma} \), and temperature, \( T \), will generally obey a constitutive relation given by:

\[
\dot{e} = f(\tilde{\sigma}, T, t)
\]

...(1)

where \( t \) is the time and \( \dot{e} \) is the strain rate. Generally \( \dot{e} \) can be partitioned into an elastic part, \( \dot{e}^e \), and a non-elastic, \( \dot{e}^{\alpha} \), part as:

\[
\dot{e} = \dot{e}^e + \dot{e}^{\alpha}
\]

...(2)

The elastic strain is related to the applied stress by Hooke's law, which for a multi-axial state of stress is given by:

\[
\tilde{e}^e = \frac{1}{E} \tilde{\sigma} - \frac{V}{E} (tr(\tilde{\sigma})) \tilde{I}
\]

...(3)

where \( V \) and \( E \) are Poisson's ratio and Modulus of Elasticity respectively. The trace of the stress, \( tr(\tilde{\sigma}) \), is given by \( \sigma_{11} + \sigma_{22} + \sigma_{33} \). For a uniaxial stress condition:

\[
\tilde{e}^e = \frac{\tilde{\sigma}}{E}
\]

...(4)

The non-elastic component, \( \dot{e}^{\alpha} \), represents the strain rate associated with permanent (dissipative) deformation. The time-independent isotropic hardening plastic strain rate, \( \dot{e}^{pl} \), is given by:

\[
\dot{e}^{pl} = \frac{3}{2} D \tilde{\sigma}' \left( \sqrt{\frac{3}{2} \tilde{\sigma}' \cdot \tilde{\sigma}'} \right)^{(m-1)}
\]

...(5)

Throughout these equations the dots, (.), represent rates, the tildes, (\(~\)), tensor quantities and the colon (:) double contraction of a tensor. \( D \) and \( m \) are material constants and \( \tilde{\sigma}' \) is the deviatoric stress. For the uniaxial state of stress this relation reduces to:
\[ \dot{\varepsilon}^p = D \dot{\sigma}^n \quad \text{...(6)} \]

Under steady-state creep conditions, the secondary creep strain rate, \( \dot{\varepsilon}_{(ss)} \), for multi-axial state of stress is given by:

\[ \dot{\varepsilon}_{(ss)} = \frac{3}{2} A \dot{\sigma} \left( \sqrt{\frac{3}{2} \tilde{\sigma}' \cdot \tilde{\sigma}'} \right)^{(n-1)} \quad \text{...(7)} \]

where \( A \) and \( n \) are material constants that depend on the temperature. For the case of uniaxial loading, Equation (7) reduces to the simple power law form:

\[ \dot{\varepsilon}_{(ss)} = A \sigma^n \quad \text{...(8)} \]

For a material that shows appreciable hardening during the beginning of loading due to dislocation tangles and/or due to dislocation substructure, the non-elastic strain rate, \( \dot{\varepsilon}_{(pc)} \), becomes a function of time as well as stress, temperature and material properties:

\[ \dot{\varepsilon}_{(pc)} = \frac{3}{2} A_1 \dot{\sigma} \left( \sqrt{\frac{3}{2} \tilde{\sigma}' \cdot \tilde{\sigma}'} \right)^{-p} \left( \sqrt{\frac{3}{2} \tilde{\sigma}' \cdot \tilde{\sigma}'} \right)^{n_1 (1+p)-1} \quad \text{...(9)} \]

where \( A_1, p \) and \( n \) are temperature dependent material constants and \( \tilde{\varepsilon}' \) is the deviatoric strain. For the uniaxial case, Equation (9) becomes:

\[ \dot{\varepsilon}_{(pc)} = A_1 \varepsilon^{-p} \sigma^{n_1 (1+p)} \quad \text{...(9a)} \]

Thus, for a material that deforms in an 'elastic-primary creep-secondary creep', the uniaxial strain rate is given by

\[ \dot{\varepsilon} = \frac{\dot{\sigma}}{E} + A \sigma^n + A_1 \varepsilon^{-p} \sigma^{n_1 (1+p)} \quad \text{...(10)} \]
2.1.2 Crack Tip Parameters

a) Extensive Creep Conditions

For a cracked body under extensive steady-state creep conditions, Landes and Begley [6] proposed a path independent crack tip parameter, $C^*$, given by:

\[
C^* = \int_{\Gamma} W_s^* dy - \overline{T} \cdot \left( \frac{\partial \dot{u}}{\partial x} \right) ds
\]

...(11)

where $W_s^*$ is the stress working power, $\dot{u}$ is the displacement rate vector, $\Gamma$ is the contour taken from the lower crack surface to the upper crack surface in the clockwise direction, $ds$ is a differential length along $\Gamma$, and $\overline{T}$ is the traction vector, a unit normal vector along $\Gamma$. $C^*$ was defined by analogy to the J-integral and represents the stress-power difference between two identical bodies under the same loading conditions with an infinitesimally differing crack lengths. For a cracked body with a thickness, $B$, and a crack length, $a$, $C^*$ is given by:

\[
C^* = -\frac{1}{B} \frac{dU^*}{da}
\]

...(12)

where $U^*$ is the power input into the cracked body. $C^*$ also represents the amplitude of the stress singularity at the crack tip under the condition of extensive secondary creep.

Under the condition of extensive primary creep, when the primary creep term in Equation (10) is said to dominate the secondary creep term, Riedel [7] has defined the $C_h^*$ parameter to describe the amplitude of the stress singularity. $C_h^*$ is also a path independent integral, and differs from $C^*$ by factor which depends on time. It can be shown that $C^*$ at any instant, $t$, is also path-independent for dominant primary creep conditions.
b) **Small-Scale Creep Conditions**

Under small-scale creep conditions, the strain rate is a function of time as well as stress, as described by Equation (1). The C*-integral under such circumstances will not be path independent. However, in the vicinity of the crack tip, creep strain rates dominate over elastic strain rates. If an integration path is selected in the creep dominated region, the integral given by Equation (11) will be path independent and will describe the amplitude of the crack tip stress singularity [8]. This integral, C(t), is given by:

\[
C(t) = \int_{r=0}^{\infty} \left[ W^* \mathbf{d}v - T \cdot \left( \frac{\partial \mathbf{u}}{\partial x} \right) \right] ds
\]

...(13)

Under the extensive creep conditions C(t) approaches C*.

Riedel and Rice [9] have derived an approximate expression for C(t) in the small scale creep (SSC) regime for a material deforming by elastic and secondary creep:

\[
(C(t))_{ssc} = \frac{(1 - v^2)K^2}{E(n+1)t}
\]

...(14)

Ehlers and Riedel [10] have given an approximate interpolation scheme for calculating C(t) in between the SSC and the extensive creep regimes:

\[
C(t) = (C(t))_{ssc} + C^*
\]

...(15)

The transition time from the SSC to extensive creep condition, t, is defined by the condition (C(t))_{ssc} = C* as:

\[
t_t = \frac{(1 - v^2)K^2}{E(n+1)C^*}
\]

...(16)

For a material which exhibits elastic and primary creep behavior, the transition time, t1, from small scale primary creep to extensive primary creep has
been defined by the condition:

\[ t_i = \frac{1}{n_i + 1} \left[ J \right]^{n_i+1} \quad \text{(17)} \]

where J is the path-independent integral for a non-linear elastic material.

For a material that exhibits both primary and secondary creep behavior, initially the primary creep dominates the behavior, and the appropriate parameter is \( C^*_h \). With time, a secondary creep zone evolves within the region of primary creep which eventually grows out of the primary creep zone and engulfs the entire ligament after a time, \( t_2 \), given by:

\[ t_2 = \left[ \frac{n + p + 1}{(1 + p)(n + 1)} \right]^{\frac{1+p}{p}} \quad \text{(18)} \]

The C(t)-integral that characterizes the amplitude of the HRR field under such conditions has been given by Riedel and Detampel [11] as:

\[ C(t) = (C(t)_{ssc}) + C^* \left[ \left( \frac{t}{t_2} \right)^{\frac{p}{1+p}} + 1 \right] \quad \text{(19)} \]

One major limitation of the C(t) parameter is that it cannot be measured in the small-scale creep regime, and it lacks the experimental evidence to sufficiently support its use for characterizing the crack growth behavior in this regime.

\( C_t \) Parameter

\( C_t \) is an alternate crack tip parameter to describe small scale creep conditions. For a given cracked body with a thickness, B, and a crack of length, \( a \), the crack tip parameter \( C_t \) was proposed by Saxena [12] as the instantaneous stress power \( (U^*_t) \) dissipation rate given by the expression:

\[ C_t = \lim_{\Delta a \to 0} \left[ -\frac{1}{B} \frac{\Delta U^*_t}{\Delta a} \right] = -\frac{1}{B} \frac{\partial U^*_t}{\partial a} \quad \text{(20)} \]
Under the steady-state conditions of extensive secondary creep, \( C_t \) is identical to the \( C^* \)-integral:

\[
C_t \equiv C^* = \frac{1}{B} \frac{dU^*}{da}
\]

...(21)

The above expression is valid for any creep law of the form in which the creep rate \( \dot{\epsilon} \) is a unique function of the stress, \( \sigma \). This occurs in the steady-state region in which the steady-state creep rate can be represented, for example, by the power law relation as given by Equation (8).

Under the conditions of extensive primary creep, \( C_t \) is equal to the instantaneous value of the path independent \( C^* \)-integral:

\[
C_t = C^*(t) = C^*_h \frac{1}{(1 + p)t^{p(1+p)}}
\]

...(22)

An expression for \( C_t \) for the small scale creep (SSC) regime is defined by applying the concept of Irwin’s effective crack length:

\[
a_{\text{eff}} = a + \beta r_c
\]

...(23)

where \( \beta \) is Irwin’s correction factor and \( a_{\text{eff}}, a \) and \( r_c \) are the effective crack length, the actual crack length and the creep zone size, respectively [12]:

\[
(C_t)_{\text{ssc}} = \frac{P(V_c)_{\text{ssc}} F'}{BW F}
\]

...(24)

where \( P, W \) and \( (V_c)_{\text{ssc}} \) are applied load, specimen width, and the load line deflection rate under small-scale creep respectively. This expression allows one to conveniently measure \( C_t \) at the loading pins. \( F(a/W) = (KB\sqrt{W})/P \) and \( F' \) is defined by \( dF/d(a/W) \). \( (V_c)_{\text{ssc}} \) is given by:

\[
(V_c)_{\text{ssc}} = \frac{2B(1 - v^2)}{EP} K^2 \beta \tilde{r}_c(\theta, n)
\]

...(25)
For components, a suitable expression for $C_t$ in the SSC [12,13] is given by:

$$(C_t)_{ssc} = 2(1 - \nu^2)\beta \frac{F'K^2\dot{r}_c(\theta,t)}{EW} \quad ...(26)$$

With the relationships, $r_c(\theta,t) = \alpha K^2 (EAt)^{2(n-1)} \tilde{r}(\theta,n)$ for secondary creep and $r_c(\theta,t) \propto \alpha(n_i)K^2 (E(A_i,t))^{2(n_i-1)} \tilde{r}(\theta,n_i)$ for primary creep, useful expressions have been derived by substituting the creep zone expansion rates in Equation (25).

Analogous to the definition of $C(t)$, $C_t$ has been defined over the entire creep range as:

$$C_t = (C_t)_{ssc} + C^* \quad ...(27)$$

If the expression for $(C_t)_{ssc}$ from Equation (24) is substituted in the above Equation, a useful expression to measure $C_t$ experimentally over the entire creep regime can be obtained.

$$C_t = \frac{P(\dot{V}_c - \dot{V}_{ss})}{BW} \frac{F'}{F} + C^* \quad ...(28)$$

A wide range of expression for $C_t$ in the presence of primary and secondary creep can be obtained by analogy to Equation (19) as:

$$C_t = (C_t)_{ssc} + C^* \left[ \left( \frac{L_i}{t} \right)^{1+p} + 1 \right] \quad ...(29)$$

The average value of $C_t$ for creep-fatigue crack growth (CFCG) under trapezoidal loading condition is determined by averaging $C_t$ over the hold time. This is done by integrating $C_t$ over the hold time and dividing the integral by the hold time as given by:

$$(C_t)_{avg} = \frac{1}{t_h} \int_{t}^{t_h} C_t dt \quad ...(30)$$
which for a material deforming by elastic and secondary creep will be:

\[
(C_t)_{avg} = \frac{2\alpha\beta_F(\theta,n)}{EW}(1 - v^2)K^4 \frac{F'}{F}(EA)^{2/(n-1)}(t_h)\frac{n-1}{n-3} + C^* \quad ...(31)
\]

In a recent study [5], creep retardation due to cyclic plasticity was considered in the calculation of \((C_t)_{avg}\) by introducing a time constant, \(t_{pl}\). It was assumed that the stress field of a material that deforms in elastic-plastic-secondary creep at time \(t\) can be represented by the stress fields of a material that deforms by elastic and secondary creep at time \(t + t_{pl}\). The expression for \(C_t\) was then modified as follows:

\[
C_t = \frac{4\alpha\beta_F(\theta,n)}{(n-1)EW}(1 - v^2)K^4 \frac{F'}{F}(EA)^{2/(n-1)}(t + t_{pl})\frac{n-1}{n-3} + C^* \quad ...(32)
\]

The effect of plasticity can then be included in the calculations of \((C_t)_{avg}\) by averaging the values of \(C_t\) given by Equation (32) between the time limits of 0 and \(t_h\). Thus, \(t_{pl}\) is a factor that accounts for creep retardation due to cyclic plasticity.

For a material deforming by elastic, plastic and secondary creep, Equation (30) then becomes:

\[
(C_t)_{avg} = \frac{2\alpha\beta_F(\theta,n)}{EW}(1 - v^2)K^4 \frac{F'}{F}(EA)^{2/(n-1)} \left(\frac{(t_h + t_{pl})^{n-1} - t_{pl}^{n-1}}{t_h^{n-1}}\right)\frac{2}{n-3} + C^* \quad ...(33)
\]
Section 3
Experimental Techniques and Finite Elements Analyses

3.1 Test Material and Specimen Description

The test material used in this study was from the retired Moss Landing steam turbine rotor made from 1Cr-1Mo-0.25V steel. The material had been in service for 163,000 hours at 538°C (1000°F). The chemical composition of this material is given in Table 1. The creep-fatigue crack growth tests were conducted using the standard 1T Compact Type (CT) specimens shown in Figure 1. Some specimens tested were 0.5 inch thick but had the same in-plane dimensions as a standard 1T specimen. A schematic of these specimens is also shown in Figure 1. The CT specimens were taken from the bore as well as the rim regions of the rotor. The locations of the various specimens tested are shown in Table 2.

3.2 Creep Deformation testing

The creep deformation data for this material were obtained from Southwest Research Institute (SwRI) [14]. However, these data were at high stress values in the range of 172-207 MPa (25-30 ksi). To supplement these data, a creep deformation test at a stress of 207 MPa (30 ksi) was performed according to ASTM E139-79 [15].

3.3 Creep-Fatigue Testing

3.3.1 Stationary Crack Calibration Tests

Two tests, one with a 0.0278 hour hold time and another with a 0.25 hour hold time were specially performed in order to measure the load-line deflection as a function of time during the hold period. The measured values of $C_t$ were obtained
from these experiments. The load-line deflection was measured using a high
temperature capacitance clip gage. The specimens were precracked under fast fatigue
loading to a specific crack length and then the desired hold time was applied at a
predetermined load. The load-line deflection during the hold time was measured
for several fatigue cycles which was subsequently used to estimate \((C_t)_{avg}\). These
values of \((C_t)_{avg}\) were then compared to analytically estimated values of \((C_t)_{avg}\) and
those obtained from finite element analyses. Thus, a suitable expression for
estimating \((C_t)_{avg}\) was developed for reducing the data obtained from the creep-
fatigue crack growth tests.

3.3.2 Creep-Fatigue Crack Growth Tests

Creep fatigue crack growth tests were conducted on four specimens without
side grooves. The remaining specimens were side grooved ten percent on each side
to assure a straight crack front. The initial values of \(\Delta K\), ranged from 22 MPa\(\sqrt{m}\) to
40 MPa\(\sqrt{m}\). The complete matrix of tests that were performed is given in Table 2.

The experiments with hold times of 100 seconds or more were conducted
using a dead weight, lever arm type creep frame with a provision to cycle the
applied load using a pneumatic ram controlled by an OMEGA 2260 controller. Load
on the specimen was directly monitored using a load cell in the load-train. The
creep machines were equipped with a resistance furnace to heat the specimen.
Some tests were performed in a high purity nitrogen environment in a specially
designed chamber. Crack growth rates were monitored using the DC electric
potential method [16]. In some tests the load line deflection was monitored using a
high temperature capacitance clip gage. All the creep-fatigue specimens were fatigue
precracked in accordance with ASTM E399 using a servo-hydraulic test system under
load control condition at room temperature. After fatigue precracking, the
specimens were subjected to trapezoidal load cycle with hold times of 0.0278 hour,
0.25 hour and 8 hours, respectively at 538\(^\circ\)C (1000\(^\circ\)F). The loading and unloading
durations were six seconds each. Experiments with a triangular loading waveform
at frequencies of 0.5 Hz and 0.083 Hz were also performed without hold time to
assess the contributions of the loading and unloading portions of a cycle to the overall creep-fatigue crack propagation rate.

3.4 Finite Element Analyses

Finite element analyses was carried out using the code originally developed by Hinton and Owen [17] and modified by McDowell and Leung [18,19] to include a kinematic hardening plasticity model.

3.4.1 Description of the Model

Detailed description of the model regarding the computational procedures and the code structure as well as program listing can be found in the literature [17]. At this point, only brief discussion of the analyses is appropriate. McDowell and Leung [18,19] have modified the original program which included Elastic, Isotropic hardening plasticity, Classical strain hardening primary creep and Power law creep. The modification that was applied to the original code was the inclusion of rate independent state variable plasticity model instead of an isotropic hardening plasticity. This will apply for the non-linear kinematic hardening associated with cyclic loading. Like the original version, the total strain increment was also partitioned into elastic, plastic and creep component in this model. Evaluation of the creep increment, \( \dot{\varepsilon}_p \), was given by:

\[
\dot{\varepsilon}_p = \frac{1}{h} \left\langle \dot{\sigma}': \hat{n} \right\rangle \quad ... (34)
\]

where \( \dot{\sigma}' \) is the deviatoric stress rate and the unit normal, \( \hat{n} \), is given by:

\[
\hat{n} = \frac{\hat{\sigma} - \hat{\alpha}}{\| \hat{\sigma} - \hat{\alpha} \|} \quad ... (35)
\]

The Macauley bracket, \( \langle \rangle \), in Equation (9) is defined as the argument if the argument within the bracket is positive and it becomes zero when the argument is
negative (or zero). The sign \( \| \tilde{\sigma} - \tilde{\alpha} \| = (\langle \tilde{\sigma} - \tilde{\alpha} \rangle : (\tilde{\sigma} - \tilde{\alpha}))^{\frac{1}{2}} \). The hardening modulus, \( h \), is given by:

\[
h = H^*(b^* \hat{n} - \hat{\alpha}^*): \hat{n} + C(\delta)(b \hat{n} - \hat{\alpha}^*): \hat{n} \quad \text{(36)}
\]

\[
\delta = \| b \hat{n} - \hat{\alpha}^* \| \quad \text{(37)}
\]

\[
\dot{\alpha} = \dot{\alpha}^* + \hat{\alpha}^* \quad \text{(38)}
\]

where \( \hat{\alpha} \) is the deviatoric back stress and \( \hat{\alpha}^* \) and \( \hat{\alpha}^t \) are the long range and the short range deviatoric back stresses, respectively. \( b^* \) and \( b \) are the amplitude of the long range and short range internal stresses respectively.

The yield and bounding surfaces are given by the von-Misses form as:

\[
f = (\gamma_2)^{\frac{1}{2}} \| \tilde{\sigma}' - \tilde{\alpha} \| - R^2 \quad \text{(39)}
\]

\[
f^* = (\gamma_2)^{\frac{1}{2}} \| \tilde{\sigma}' - \tilde{\alpha}^* \| - R^* \quad \text{(40)}
\]

where \( R \) and \( R^* \) are the yield and bounding surface radii respectively.

\[
C(\delta) = k_1 + k_2 \left[ \sinh \left( k_3 \frac{\delta}{2} b \right) \right]^{k_4} \quad \text{(41)}
\]

\( k_1, k_2, k_3, k_4, H^*, \) and \( C(\delta) \) are hardening related constants. Through out these equations the dots, (.), represented rates and the tildes, (\~{}), tensor quantities. Since cyclically stable stress and strain conditions are examined, the present formulation employs only kinematic hardening. Thus:

\[
\dot{R} = \dot{b} = 0
\]

During each time increment, the field and state variables were updated by using central difference approximation. Convergence was determined by calculating the residual forces and adding them to the applied force increment in the next time step.
In order to gain numerical stability, the implicit trapezoidal marching scheme was employed. The maximum effective creep strain increment did not exceed 15% of the total load increment in order to increase the accuracy. The current time step increments were not more than 150% of the previous time step increment to avoid oscillatory solution. Further details of the finite element code is found in references [17,18,19].

3.4.2 Cases Analyzed by FEM

Data on the monotonic stress-strain behavior in this material was obtained from SwRI [14]. The material was assumed to be cyclically stable and the cyclic stress-strain behavior was approximated by the monotonic stress-strain curve. Since this material has been shown to exhibit some cyclic softening [20,21,22], this assumption is approximate. The necessary plasticity constants for the FEM were obtained by fitting the monotonic stress-strain curve. The list of the constants used is presented in Table 3.

Plane strain analyses of a specimen with a thickness of 25.4 mm (1 in) and a width of 50.8 mm (2 in) was performed using a finite element mesh of 202 isoparametric elements with straight edges. At the crack tip, degenerated elements were created by collapsing 3 nodes along one side into one initial point, at the same time allowing them to deform independently. These degenerated elements produced a 1/r type singularity in displacement derivatives leading to the achievement of an acceptable approximation of \( r^{-n/(1-n)} \) HRR singularity. A crack length, \( a \), of 20.38 mm (0.8 in) giving a crack ratio \( (a/W) \) of 0.4 was investigated. The applied load was distributed over the upper portion of the pin hole over a span of 450°.
Section 4
Results and Discussion

4.1 Creep deformation

Steady-state creep strain rate as a function of the applied stress is shown in Figure 2. The data on this figure include previous data on Cr-Mo-V steel from the literature [23] as well as the data from SwRI tests conducted on the Moss Landing rotor material. The results obtained in this study at a stress level of 207 MPa (30 ksi) are also included. The previous data exhibited better fit when the strain rate is related to the applied stress by using a power-law relationship containing two terms:

\[ \dot{\epsilon}_{(ss)} = A'\sigma^n + A''\sigma^{n''} \] ...(42)

The values of \( A', A'', n' \) and \( n'' \) were found to be \( 1.49 \times 10^{-16} \text{(ksi)}^{-7}/\text{hr}, 9.65 \times 10^{-35} \text{(ksi)}^{-13}/\text{hr}, 7 \) and \( 13 \), respectively. Another approach for representing the creep data is to use the hyperbolic sine function as proposed by Bassani [24]. The advantage of using a power-law relation is that the analytical expressions for estimating crack tip parameters are readily available for such constitutive relations and are not available for the hyperbolic sine model. In this study, a single value of \( 8 \) for the exponent, \( n \), and \( 1.24 \times 10^{-24} \text{(MPa)}^{-8}/\text{hr} \) for \( A \) were used. The fit obtained by employing these values of \( A \) and \( n \) is also shown in Figure 2. This material also showed evidence of primary creep deformation. Primary creep data were obtained from SwRI tests as well as from the literature data and primary creep constants were derived by fitting Equation (9a) to the data. All the creep deformation constants are presented in Table 4.

4.2 Verification of the Methods for Estimating \( C_t \) and \( (C_t)_{avg} \)

In order to select a proper constitutive model for the creep deformation in the FEM, measured values of \( C_t \) were obtained during a hold time of 0.0278 hour and 0.25 hour. \( C_t \) values were determined from Equation (24) using the values of
measured load-line deflection rates. These values are presented in Figure 3 as a function of time normalized with respect to the transition time of a 1T CT specimen with a crack to width ratio, $a/W$, of 0.4 and loaded to a stress intensity factor, $\Delta K$, of 22 MPa$\sqrt{m}$ (20 ksi$\sqrt{in}$). Figure 3 also shows the results the first cycle of a 0.0278 hour hold time FEM results predicted from elastic-secondary creep model. Since the results from the static FEM analyses agree entirely with the results from the analytical estimation for an elastic-secondary creep model, the accuracy of the finite element code is verified. Due to the considerable discrepancy between the analytical (or FEM) results and the measured values of $C_t$, it is concluded that the elastic-secondary creep model is not adequate for representing the creep behavior of the Moss Landing material. Figure 4 shows the FEM results for a similar situation predicted for a material deforming by elastic, plastic and secondary creep. During the hold time for a material that obeys such a constitutive relation, $C_t$ appears to be relatively independent of time. The values of $C_t$ obtained using this model are considerably lower than the ones that were experimentally measured during the hold time. Also shown in Figure 4 are analytically predicted values of $C_t$ for the first cycle for an elastic-plastic secondary creep material. In order to fit the FEM results, a $t_{pi}$ value of 0.3 hour was used in equation (33). The prediction from this model deviates from the experimental data even more than the prediction from an elastic, secondary-creep model. Hence, this representation is also inadequate.

Figure 5a shows FEM prediction for elastic-plastic-primary and secondary creep model. In this figure three cycles of 20 minutes hold time are presented and the time at the beginning of each cycle was set to zero. The values of $C_t$ appear to be slightly lower than the experimentally observed values during the first 100 seconds of the first cycle. At higher times these differences disappeared. The introduction of primary creep also appears to reduce the $t_{pi}$ value significantly. $t_{pi}$ reduces to 0.004 hrs for primary creep from a value of 0.3 hrs without primary creep.

Another method of representing the data in Figure 5a is to let the time at the end of the previous cycle be the time at the beginning of the current cycle as shown in Figure 5b. It appears from these figure that the $C_t$ values obtained from the FEM
for the three cycles are not significantly affected by the unloading and reloading. In other words, the magnitude of $C_t$ at the beginning of the hold period during any cycle is approximately equal to the $C_t$ value at the end of the previous cycle. It appears that the creep deformation is not significantly reversed by plastic deformation during unloading. The experimental values of $C_t$ during the 15 minutes hold time also appear to agree with the FEM values of $C_t$ for the three cycles when time is considered cumulatively. This is further evidence that the $C_t$ values for 0.0278 hrs hold time are not significantly affected by the unloading-reloading. Thus, when the specimen is loaded again the creep deformation process resumes with no significant influence from the load cycling. There was also a significant difference in the values of $C_t$ between the second and the third cycle in the FEM analyses. These observations are significantly different from the observations of Yoon et al. [5] from a similar analyses on 1.25Cr-0.5Mo steels.

Figure 6 shows the relative sizes of the monotonic plastic zone, cyclic plastic zone and creep zone at the end of the third cycle for a hold time of 20 minutes. The monotonic plastic zone boundary is defined by the locus of points where $\bar{\varepsilon}_p/\bar{\varepsilon}_e = 1$, the creep zone boundary by the locus of points where $\bar{\varepsilon}_c/\bar{\varepsilon}_e = 1$, and the cyclic plastic zone boundary is defined by the locus of points where $\Delta\bar{\varepsilon}_p/\Delta\bar{\varepsilon}_e = 1$ where $\bar{\varepsilon}_e, \bar{\varepsilon}_p$ and $\bar{\varepsilon}_c$ are effective elastic, plastic and creep strains respectively. $\Delta$ represents the differences in strains between the end of a hold time and the beginning of the next cycle. The cyclic plastic zone was found to be inside the creep zone in Figure 6 suggesting the domination of creep over fatigue in this material. Similar plots for 1.25Cr-0.5Mo Steels [5] have shown that the cyclic plastic zone entirely engulfed the creep zone at the end of the third cycle of a 600 sec. hold time FEM simulation. It should be pointed out that the plastic and the creep zones constructed in the above figures are derived from very few gauss points. The mesh sizes of 0.127 mm (0.005 in) were comparable to the creep and plastic zone sizes, which may explain the distorted plastic and creep zone shapes in Figure 6.
4.3 **Suggested Modifications for the method of Estimating** \((C_t)_{avg}\) **in Cr-Mo-V Steel**

In the previous section, it was shown that the effect of loading and unloading during creep-fatigue crack growth on the stress-strain behavior in this material is not considerable. It was also shown that the values of \(C_t\) beyond the first cycle did not deviate appreciably from the monotonic values of \(C_t\). This leads to the conclusion that for subsequent cycles, resetting the value of \(C_t\) to its value at the beginning of the initial hold time as given by Equation (30) may not be proper in this material. In this section a new approximation method for estimating \((C_t)_{avg}\) for this material is presented.

It is proposed that reversal of the accumulated creep deformation during the hold time by a single fatigue cycle (unloading and reloading) may not be possible in 1Cr-1Mo-0.25V steels. This is due to the high cyclic yield strength of this material as compared to 1.25Cr-0.5Mo steels [5]. The high cyclic yield strength leads to a small cyclic plastic zone which is surpassed in size by the creep zone for relatively small hold times. In order to reverse the creep accumulated during the hold time, it may be necessary to provide a hold time at the minimum load.

If it is assumed that the creep deformation which is reversed by cyclic plasticity is negligible, a modification to the approach for estimating \((C_t)_{avg}\) is necessary. The analytical expression for \(C_t\) in small scale creep (SSC) regime has been given as [13]:

\[
(C_t)_{ssc} = \frac{4\alpha\beta\bar{r}(\theta,n)}{EW(n-1)}(1 - \nu^2)K^4\frac{F'}{F}(EA)^{2(n-1)}\left[\frac{\pi}{\alpha-3}\right]^{\frac{\alpha-1}{\alpha-3}} \ldots(43)
\]

\[
\alpha = \frac{1}{2\pi}\left[\frac{(n + 1)I_n}{2\pi(1 - \nu^2)}\right]^{\frac{2}{\alpha-1}}
\]

where \(I_n\) is a dimensionless parameter related to the HRR stress field [25].
The average value of $C_t$ for creep-fatigue crack growth (CFCG) is determined by averaging $C_t$ over the hold time, as given by equations (30) and (31).

For an arbitrary Nth cycle the value of $(C_t)_{avg}$ can be given as follows:

$$\frac{(C_t)_{avg}}{t_h(N-1)} = \int_0^{N_h} C_t dt \quad ...(44)$$

which, upon integration will give:

$$\frac{(C_t)_{avg}}{t_h(N-1)} = \frac{2\alpha \beta \bar{r}(\theta, n)}{E \omega} \left(1 - v^2\right) K^4 \frac{F'}{F} (EA)^{2(n-1)} \left[N^{2/n} - (N-1)^{2/n-1}\right] \left[t_h\right]^{n-1} + C^* \quad ...(45)$$

This expression makes $(C_t)_{avg}$ not only a function of crack length and applied stress but also of time because of the term related to the number of cycles, $N$. This equation can further be simplified as follows if the value $(N-1)^{2/n-1}$ could be approximated using binomial expansion:

$$\frac{(C_t)_{avg}}{t_h(N-1)} = \frac{4\alpha \beta \bar{r}(\theta, n)}{(n-1)E \omega} \left(1 - v^2\right) K^4 \frac{F'}{F} (EA)^{2(n-1)} (Nt_h)^{\frac{n-1}{n-3} + C^*} \quad ...(46)$$

This representation is identical to the analytical $C_t$ expression proposed by Bassani et al [13], with the value $Nt_h$ replacing time.

Using a similar method for elastic-primary creep-secondary creep material the following approximate expression for $(C_t)_{avg}$ can be derived from Equation (29):

$$(C_t)_{avg} = ((C_t)_{SSC})^{\frac{n_t}{n_t}} + C^* \left[\left(\frac{I_n}{Nt_h}\right)^{\frac{p}{1+p}} + 1\right] \quad ...(47)$$

$(C_t)_{SSC}$ for elastic-primary creep-secondary creep material is given by:

$$(C_t)_{SSC} = \frac{2\beta \bar{r}(\theta, n)}{\pi E \omega} \frac{(1 - v^2)K^4}{(1 + p)(n_t - 1) F} \frac{F'}{F} (n_t + 1)(1 + p)A_n^{2(1+p)(n_t-1)} \left[I_n \frac{E}{n_t + 1}\right]^{2} \left[\frac{2}{2\pi(1 - v^2)}\right]^{n_t - 1} \left[I_{n_t+1}^{(1+p)}\right]^{\frac{1}{1+p}} \quad ...(48)$$

where $I_n$ is a dimensionless factor related to the HRR field.[25]
4.4 Creep-Fatigue Crack Growth Test Results

Creep-fatigue crack growth (CFCG) data for Cr-Mo-V turbine rotor steel have been reported previously [26,27]. Plots of stress intensity factor, $\Delta K$, versus cyclic crack growth rates, $da/dN$, have been used in the past to represent CFCG behavior. Recently, CFCG data has been correlated with the $(C_t)_{avg}$ parameter [2,5,28] in which the average value of $da/dt$ during hold time is correlated with the average value of $C_t$ during the hold time. Both types of data representations are given in this report.

4.4.1 $da/dN$ versus $\Delta K$ Behavior

Figure 7 shows the cyclic crack growth rate, $da/dN$, as a function of the stress intensity factor, $\Delta K$, for hold times of 0.0278 hour, 0.25 hour and 8 hours respectively. The results from the 1 Hz and 0.083 Hz tests with no hold times are also included on this Figure. The crack growth rates generally increase with increasing hold times. For the tests conducted with 0.0278 hour hold time the crack growth rate at the low $\Delta K$ values exhibited lower crack growth rates than the tests conducted at 1 Hz with no hold times. The same effect was also observed when comparing the 0.0278 hour hold time with the 0.083 Hz data with no hold time. A possible explanation could be due to crack tip blunting which occurs during the hold time and possibly reduces the stresses around the crack tip as compared to a sharp fatigue crack.

Figure 8 shows the effect of specimen location within the rotor (Bore versus Rim) on the cyclic crack growth rate. The rim material appears to have a slightly higher crack growth rate at a given $\Delta K$ in comparison to the bore material at a cyclic frequency of 1 Hz without hold time. The effect is even less significant when the hold time is 0.0278 hours. Therefore, for the purposes of creep-fatigue crack growth behavior, no distinction will be made between the properties of the bore and the rim regions of the rotor material.
4.4.2 \( da/dt \) versus \( (C_t)_{avg} \) Behavior

The total crack growth rate was partitioned into a cycle dependent part and a
time-dependent part (as in [1,2,5,28]):

\[
\frac{da}{dN} = \left( \frac{da}{dN} \right)_{cycle} + \left( \frac{da}{dN} \right)_{time}
\]  

...(49)

And the crack growth rate during the hold time is given by:

\[
\left( \frac{da}{dt} \right)_{avg} = \frac{1}{t_h} \left[ \frac{da}{dN} - \left( \frac{da}{dN} \right)_{cycle} \right]
\]  

...(50)

Paris' fatigue crack propagation law was used to represent the cyclic-part of the crack
growth rate. Paris-law coefficient and exponents were determined from the 0.083 Hz
data shown in Figure (7) as 2.28x10\(^{-18}\) in(ksi\(\sqrt{\text{in}}\))\(^{-2.2}\) and 2.2 respectively. In this study \( da/dt \) refers to the average value of crack growth rate during the hold time as
defined Equation (50).

Figure 9 shows the representation of the creep-fatigue crack growth rate data
as a function of \( (C_t)_{avg} \) as defined by Equations (46) for a material deforming by elastic
and secondary creep. For a given \( (C_t)_{avg} \), the values of crack growth rate seem to be
much higher in CFCG than in CCG. This may be partly due to the under-estimation
of \( (C_t)_{avg} \) when only secondary creep deformation is considered as was also observed
in the finite element analyses results. Crack growth rate data as a function of \( (C_t)_{avg} \)
as defined by Equations (44) for a material deforming by elastic, primary creep and
secondary creep is shown in Figure 10. This representation collapses all the creep
fatigue crack growth data as well as the creep crack growth data from SwRI into a
single trend with a significantly less scatter. The CFCG data are presented again in
Figure 11 along with the scatter band for the creep crack growth data for the same
material as well as the scatter band for a new Cr-Mo-V steel data obtained from the
literature [23]. Creep fatigue crack growth in this ex-service material is significantly
higher than in the new Cr-Mo-V material.
4.4.3 Effect of the Environment

CFCG tests in high purity Nitrogen environment were conducted with a 0.0278 hour hold time. The results are presented in Figures 12 as correlations of da/dN versus ΔK. The crack growth rates in this environment seem to be comparable to the tests in air. However, upon correlating the same data with \((C_t)_{avg}\) values obtained by Equation (47) the crack growth rates for a given \((C_t)_{avg}\) were found to be higher in air than in nitrogen environment as shown in Figure 13. This could be due to oxide induced cracking as reported in Cr-Mo-V steels during high cycle fatigue in the past [29]. A CFCG test in vacuum environment should be done to further understand the effect of environment.
Section 5
Recommendations for Future Work

The scheme for estimating \((C_t)_{av}\) represented by Equation (44) is an extreme case where little creep deformation is reversed by cyclic plasticity. An experiment should be performed on the same material with a balanced loading waveform (with hold times both at the maximum and minimum loads). This will provide additional insight into the extent to which creep can be reversed under these conditions. Other areas that need more work are:

i. The influence of cyclic hardening and softening on the reversal of the accumulated creep deformation during hold time by cyclic plasticity should be analytically explored. This will lead to expressions for estimating \((C_t)_{av}\) for conditions ranging from complete reversal of creep, which appears to be the case for 1.25Cr-0.5Mo steel, to the case of very little creep reversal as demonstrated by 1Cr-1Mo-0.25V steel.

ii. The effect of the environment is still not well understood in this material. More work is needed in inert and vacuum environments to determine the effects of oxide induced cracking and oxide induced crack closure.

iii. The effect of loading rate and waveform is still not well understood in this material and more work needs to be done to study creep-fatigue crack growth during slow loading and unloading. Such an effect can be seen in Figure [7] where due to some contribution of creep the crack growth rates in the 0.083 Hz test are higher than the crack growth rates in the 0.5 Hz test.
References


<table>
<thead>
<tr>
<th>Data Source</th>
<th>ASTM</th>
<th>Moss Landing</th>
</tr>
</thead>
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<tr>
<td>C</td>
<td>0.31</td>
<td>0.35</td>
</tr>
<tr>
<td>Cr</td>
<td>1.13</td>
<td>1.05</td>
</tr>
<tr>
<td>Mo</td>
<td>1.15</td>
<td>1.29</td>
</tr>
<tr>
<td>Mn</td>
<td>0.78</td>
<td>0.80</td>
</tr>
<tr>
<td>V</td>
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<td>0.27</td>
</tr>
<tr>
<td>Ni</td>
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<td>0.16</td>
</tr>
<tr>
<td>Si</td>
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<td>0.27</td>
</tr>
<tr>
<td>P</td>
<td>0.007</td>
<td>0.035</td>
</tr>
<tr>
<td>S</td>
<td>&lt;0.001</td>
<td>0.03</td>
</tr>
<tr>
<td>Al</td>
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<td>&lt;0.01</td>
</tr>
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<td>Cu</td>
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Table 1: Elemental Composition (%wt) of New and Moss Landing Rotor Steel
<table>
<thead>
<tr>
<th>Specimen</th>
<th>Hold Time</th>
<th>Loading Time</th>
<th>Nominal Thickness</th>
<th>Net Thickness</th>
<th>Initial Crack Length</th>
<th>Final Crack Length</th>
<th>Maximum Load</th>
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<tbody>
<tr>
<td>MLCT10/Bore</td>
<td>0</td>
<td>1</td>
<td>25.4(1)</td>
<td>25.4(1)</td>
<td>22.9(0.901)</td>
<td>34.8(1.370)</td>
<td>16.67(3.74)</td>
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<tr>
<td>MLCT12/Bore</td>
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<td>25.4(1)</td>
<td>25.4(1)</td>
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<td>35.7(1.407)</td>
<td>15.50(3.7)</td>
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<tr>
<td>MLRCT09/Rim</td>
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<td>1</td>
<td>25.4(1)</td>
<td>25.4(1)</td>
<td>23.0(0.907)</td>
<td>36.8(1.448)</td>
<td>14.72(3.3)</td>
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<tr>
<td>MLCT13/Bore</td>
<td>0</td>
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<td>25.4(1)</td>
<td>25.4(1)</td>
<td>23.1(0.909)</td>
<td>34.0(1.339)</td>
<td>16.50(3.7)</td>
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<tr>
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<td>0.0278</td>
<td>6</td>
<td>25.4(1)</td>
<td>25.4(1)</td>
<td>25.8(1.018)</td>
<td>37.3(1.467)</td>
<td>18.28(4.1)</td>
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<td>25.4(1)</td>
<td>25.4(1)</td>
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<td>0.0278</td>
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<td>29.5(1.171)</td>
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<td>25.4(1)</td>
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<td>10.2(0.4)</td>
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<td>10.2(0.4)</td>
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<td>27.6(1.087)</td>
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<td>17.5(0.690)</td>
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* Test conducted in Nitrogen environment  § Tests for measuring Load line Deflection

Table 2: Description of the Tests Conducted in the Study of CFCG
Table 3: Rate Independent State Variable Plasticity Constants at 538 C (1000 F)

<table>
<thead>
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<th>Variable</th>
<th>Units</th>
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<tbody>
<tr>
<td>b</td>
<td>$208.3(30.21)$ MPa(ksi)</td>
</tr>
<tr>
<td>$b^*$</td>
<td>$2758(400)$ MPa(ksi)</td>
</tr>
<tr>
<td>$k_1$</td>
<td>800</td>
</tr>
<tr>
<td>$k_2$</td>
<td>12000</td>
</tr>
<tr>
<td>$k_3$</td>
<td>1.5</td>
</tr>
<tr>
<td>$k_4$</td>
<td>2.5</td>
</tr>
<tr>
<td>$H^*$</td>
<td>$3.45(0.5)$</td>
</tr>
<tr>
<td>R</td>
<td>$240(35)$ MPa(ksi)</td>
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</table>
Elastic Properties at 538 C (1000 F)

<p>| | |</p>
<table>
<thead>
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<tbody>
<tr>
<td>E</td>
<td>162 GPa (23500ksi)</td>
</tr>
<tr>
<td>n</td>
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Yield Stress 473 MPa (68.44ksi)

Plasticity Constants (Ramberg-Osgood) at 538 C(1000 F)

<p>| | |</p>
<table>
<thead>
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<tbody>
<tr>
<td>D</td>
<td>9.5E-61 1.23E-42</td>
</tr>
<tr>
<td>m</td>
<td>21.6    21.6</td>
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Secondary Creep Constants

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<table>
<thead>
<tr>
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<tbody>
<tr>
<td>A</td>
<td>1.14E-24 5.95E-18</td>
</tr>
<tr>
<td>n</td>
<td>8       8</td>
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Primary Creep Constants

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<thead>
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<tbody>
<tr>
<td>Al</td>
<td>6.17E-25 4.516E-20</td>
</tr>
<tr>
<td>p</td>
<td>1.99    1.99</td>
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<tr>
<td>nl</td>
<td>1.94    1.94</td>
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</table>

Table 4: Elastic, Plastic, Primary Creep and Secondary Creep Constants for Cr-Mo-V rotor Steel
Figure 1: Compact type (CT) creep-fatigue crack growth specimen geometry and the finite element mesh used in the computational studies. (all dimensions in inches, 1 inch = 25.4 mm)
Figure 2: Steady-state creep strain rate as a function of the applied stress.
Figure 3: Measured $C_t$ values from the first cycle of a 0.0278 hour hold time test compared with FEM and analytical prediction for an elastic-secondary creep model.
Figure 4: Measured $C_t$ values from the first cycle of a 0.0278 hour hold time test compared with FEM and analytical prediction for an elastic-plastic-secondary creep model.
Figure 5a: $C_t$ as a function of normalized time for three cycles from the FEM analyses with 20 minutes hold time including primary creep. The measured $C_t$ values for the first cycle are also included.
Figure 5b: The same data as in Fig. 5a, except, the time for the second and the third cycles is taken cumulatively instead of referencing it to the start of the hold period during each cycle.
Figure 6: Relative sizes of the cyclic and monotonic plastic and creep zones at the end of the third cycle.
Figure 7: Cyclic crack growth rate, $da/dN$, as a function of the stress intensity factor, $\Delta K$, for different hold times.
Figure 8: The influence of specimen location (Bore and Rim) on the cyclic crack growth rate.
Figure 9: Representation of the creep-fatigue crack growth rate data as a function of \((C_t)_{avg}\) for various hold times. The \((C_t)_{avg}\) in this plot is estimated using only the elastic-secondary creep deformation model (i.e. primary creep is not included).
Figure 10: The same data as in Fig. 9 after inclusion of primary creep.
Figure 11: Comparison of ex-service creep-fatigue crack growth rate data with CCG rate from New Material.
Figure 12: CFCG tests in high purity Nitrogen environment correlations of $da/dN$ versus $\Delta K$. 

\[ da/dN \text{ [in/cycle]} \]

\[ \Delta K \text{ [ksi$/\text{in}$.] \]
Figure 13: CFCG tests in high purity Nitrogen environment correlation of $da/dt$ versus $(C_t)_{avg}$. 