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# SES Creep Laboratory for High Temperature Remaining Life Assessment

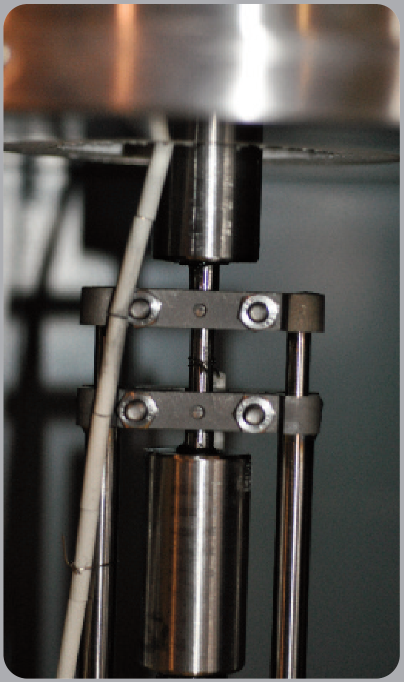
## Idea to Reality

In 2008 Stress Engineering Services (SES) began work on a new creep laboratory as part of the Mason, Ohio office. Today this facility has grown from an idea to a facility supporting 68 fully instrumented creep machines ranging in capacity from 3000 lbs. up to 100,000 lbs. Engineering alloys at test temperatures up to 2000˚F can be accommodated.

Capabilities include standard creep testing, special purpose creep tests using nonstandard specimens for collecting information on samples extracted from process equipment in service, and testing subcomponents such as weldments. Constant strain rate testing at 1 micron/hour is also possible using a purpose built electromechanical test machine, as well as programmed operation of the instrumented creep machines.

*Specimen at temperature*

**Figure 1** *View of creep lab*



*Extensometer located on specimen*

Much of the creep lab effort is in support of our Plant Fitness-for-Service (FFS) work, for which modern standards, such as ASME/API 579 [Ref 1], require a high level of precision in the control of test conditions and measurement of specimen deformations.

The lab performs testing in accordance with established standards, but it is also equipped to deal with unconventional testing, when information is required quickly to make decisions in the course of a scheduled shutdown or, more critically, when a failure has led to an unscheduled shutdown.

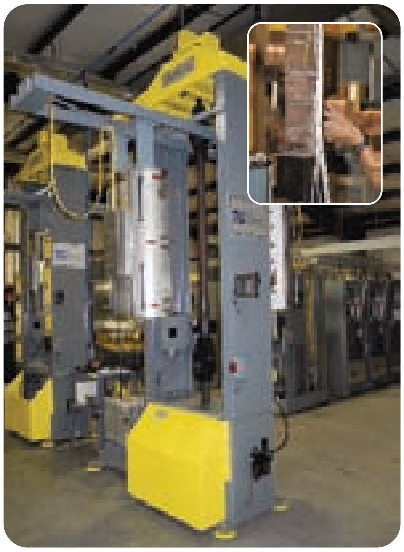


**Figure 2** *100 kip creep test specimen with thermocouples and AE sensor mounted*

## Creep in Perspective

SES has been involved in plant services work since the company's inception in 1972, and over the decades has developed a broad range of testing and component evaluation services, all under one roof. As a full service firm, SES now offers everything from the design and manufacture of creep test specimens, through testing, data collection, data reduction and full structural FFS/Remaining Life evaluation. As a matter of policy, all stages of data acquisition are transparent and available to the client as part of the project deliverable.

Over the past 10 years, SES involvement in high temperature applications has grown in response to a global revival of concern over remaining life assessment of aging plants operating in the creep range. This renewed interest has highlighted some industry-wide problems that extend beyond a simple shortage of working creep test frames. In general, there is a lack of capability in providing the quality of information called for in recently developed methods of structural evaluation offered in guidelines such as API 579, ASME/FFS-1, and British R5 [Ref 2].

With the new creep lab now fully operational performing standard creep testing, the lab has ventured into the more advanced aspects of the job, such as:

- Sub-miniature specimen testing and evaluation using minimal amounts of material extracted from components in service.
- Different specimen geometries to suit special needs, such as notched, notched-bend or C-shaped specimens, to explore parameters, such as stress state or multiaxiality on the evolution of creep rupture damage.
- Subcomponent testing, notably weldments or subassemblies of significant structural complexity, to test, for example, the effectiveness of predictive methods based on simple tensile test data in predicting the failure of realistic components.

**Figure 3A** *Custom creep test specimens*

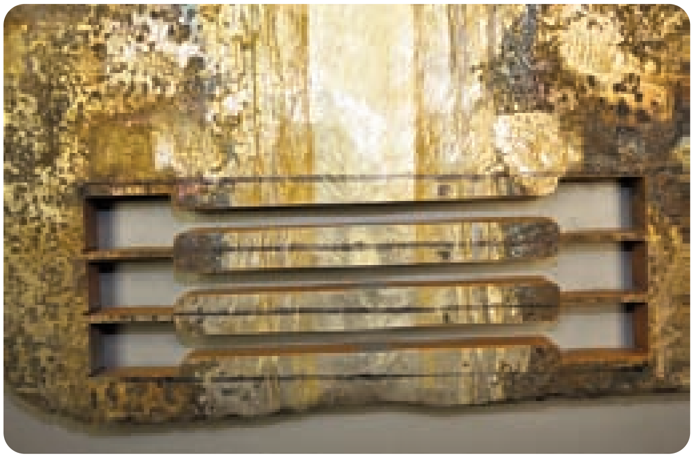


**Figure 3B** *Creep Specimens cut out of material extracted from process equipment*

## Creep Testing Methodology

**The Load Train** Mechanically, the heart of good creep testing is provision of an accurate stress. This is commonly attempted using a long load train, possibly 3 or more feet long, with the specimen located at approximately the midpoint. Universal joints are provided at the ends of the load train and, sometimes also as part of the specimen grip, as in the grips designed by Roy Penny in the 1960's [Ref 3] and still widely used today by many test facilities who came in contact with this design when it was first proposed (see Figure 4).

An alternative, also widely used but frowned upon by many, is the simple threaded end connection. This connection is widely believed to produce an unacceptable degree of bending and indeed, it can be shown, by analysis of a tensile specimen with a persistent load eccentricity, that sustained bending in a creep test can produce a false overestimate of apparent axial strain.

In fact this concern is groundless. A combined experimental and theoretical evaluation of this type of end connection was carried out by SES and, when the effect of nonlinear geometry changes are taken into account, the threaded connection actually turns out to be superior to other far more intricate and sophisticated grips, such as the pin-and-clevis design still commonly used today.

The reason is simple. An eccentrically loaded load train will certainly generate significant bending, and this may be quite large on initial loading. However, there is just so much bending possible before the load train straightens out and eliminates the bending. There is a kinematic limitation to the amount of bending deformation possible in a threaded end specimen. It can be shown that the worst bending strain possible, $\varepsilon_b$, is limited to:

Using the typical numerical values cited above, this means

$$\varepsilon_b = \frac{2de}{lL}$$

where,

d = specimen diameter (e.g. 0.505")

e = eccentricity of load line at the specimen (typically < 0.05")

l = gauge length (e.g. 2")

L = total length of load train (typically 30")(see figure 3)

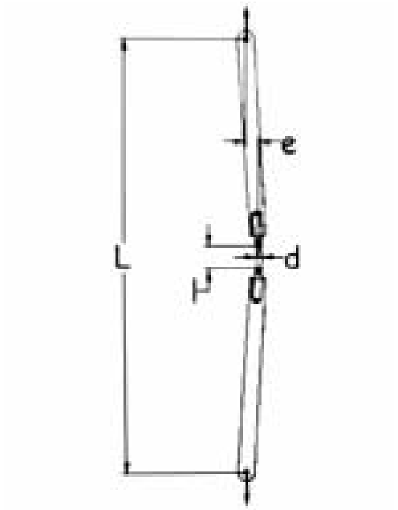


**Figure 4** *Eccentric load on threaded specimen*

that the bending strain can never be greater than about 0.08%. This is comparable with the initial elastic strain, which is why the attachment method has acquired such a bad reputation but, under creep conditions, the bending strain never gets bigger than this initial value and, in fact, more detailed finite element analysis studies have shown that bending stresses relax away very rapidly with a negligible influence on the mean axial strain. In practice, with even moderate attention to detail, the eccentricity on a threaded load train is usually much less than the 0.05 inch assumed here. Rationally speaking, load train eccentricity more like the 0.01 inch range is expected.

Ironically, due to friction, the universal joint design can actually be worse than the threaded connection on occasions and it does not get any better without a considerable amount of tinkering, which still does not always solve the problem.

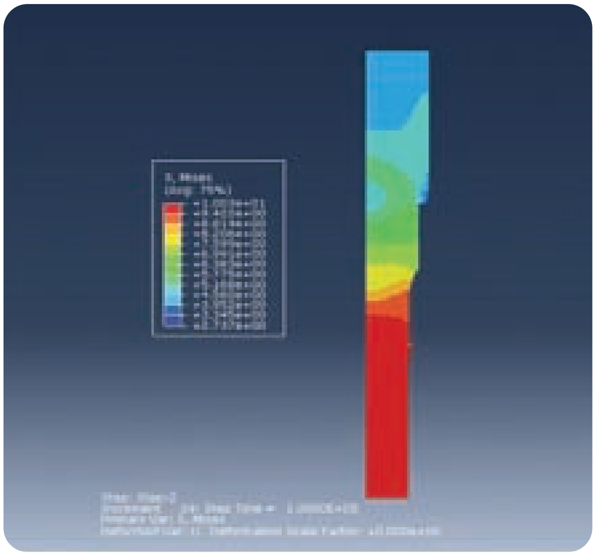


**Figure 5** *Finite Element Analysis of specimen geometry (0.505D) under creep conditions*

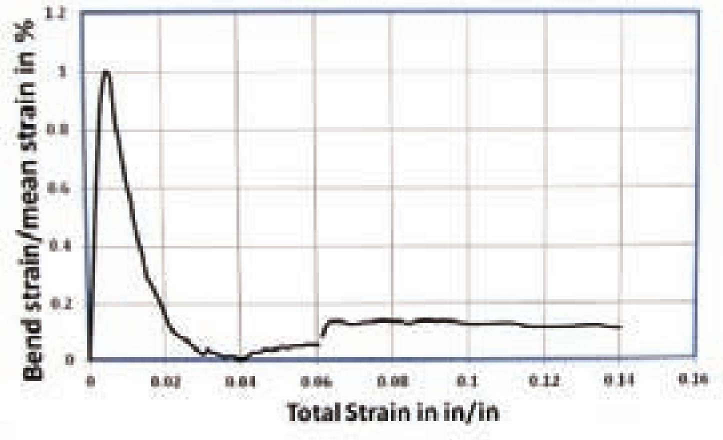


**Figure 6** *Bend/mean strain ratio in a percentage — a typical creep test*

SES has developed other features of the creep specimen, in addition to the end connections. All designs were examined in detail using finite element methods to study their behavior under creep conditions. Figure 5 illustrates the final configuration of a critical component of specimen geometry, the end taper, and the extensometer attachment detail.

**Extensometry** The challenge with creep testing is that affordable deformation measuring devices tend not to work at high temperature, so the deformation has to be transferred out of the heated zone with extension arms. Attaching the extensions to the specimens can be a problem. The method adopted by SES is to use raised ridges defining a clear gauge length. Ridges, unlike grooves, do not cause significant stress or strain concentrations, and placing them directly across the gauge length eliminates the uncertainty of additional deformation occurring in the tapered ends of the specimen.

Since extensometers cannot easily be mounted coaxially with the specimen (although it is possible), strain is measured by separate transducers mounted at 180° to one another. This is more expensive than using a single transducer and some form of averaging mechanism, but has the incidental advantage of providing information on specimen bending during the test. Figure 6 is a typical example of bending vs. mean strain achieved with the load train designed by SES. The initial bending is never more than a few percent, much less than worst case estimates, and decays to a low constant value which is within the accuracy of the measurement and is effectively zero.

## Data Evaluation

Since the publication of ASME/API 579 for the petrochemical and refining industries, it is common for test requests on specimens extracted from plants in-service to be accompanied by the requirement that the data be analyzed and presented in the form of the MPC/Omega model. Where possible every effort is made to comply with such requests. Sometimes, however, the Omega model is not a good fit to the real world creep test data.

Where it is possible to utilize the Omega model, data reduction is a standard procedure. What follows is not intended to be a detailed description of the method used to fit data using the Omega model, but merely to illustrate various techniques used by SES in remaining life evaluations.

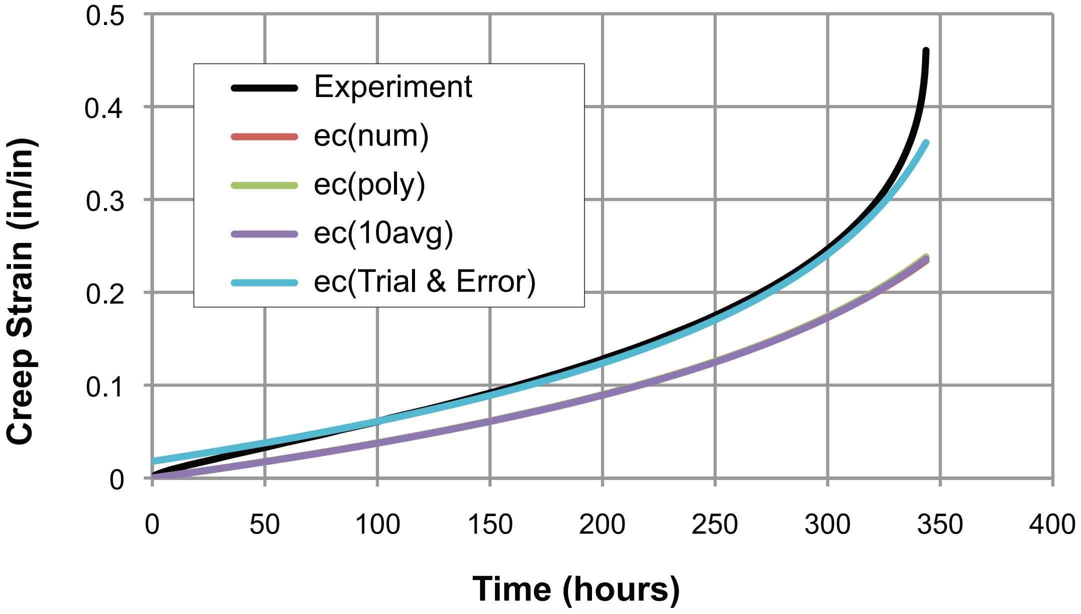


**Figure 7** *Creep curve for P9 at 1120°F, 11.4ksi*

Figure 7 shows a well behaved creep curve that conforms reasonably well with the Omega model.

The Omega model is a modification of the simple steady state creep law to account for strain induced softening in order to include the phenomenon of tertiary creep.

$$\dot{\varepsilon_c} = \dot{\varepsilon_0}\exp(\Omega\varepsilon_c)$$

where the integrated creep curve is given by,

$$\varepsilon_c = \frac{1}{\Omega}\ln(1-\Omega\varepsilon_0 t)$$

$\Omega$ and $\varepsilon_0$ are parameters obtained in several possible ways. These are illustrated in Figure 7 where they are compared with the experimental curve.

The two methods used here are "trial and error", guessing the parameter values and making a sight comparison with the data. This procedure allows primary creep, which is not accounted for in the Omega model, to be included as an offset at time zero. A more rigorous approach involves plotting the log of the creep against the creep strain. Taking the logs of each side of the creep rate equation,

$$\ln(\dot{\varepsilon_c}) = \ln(\dot{\varepsilon_0}) + \Omega\varepsilon_c$$

The slope of the resulting plot should be $\Omega$, and the intercept at zero strain is $\ln(\dot{\varepsilon_0})$ (Figure 8—following page)

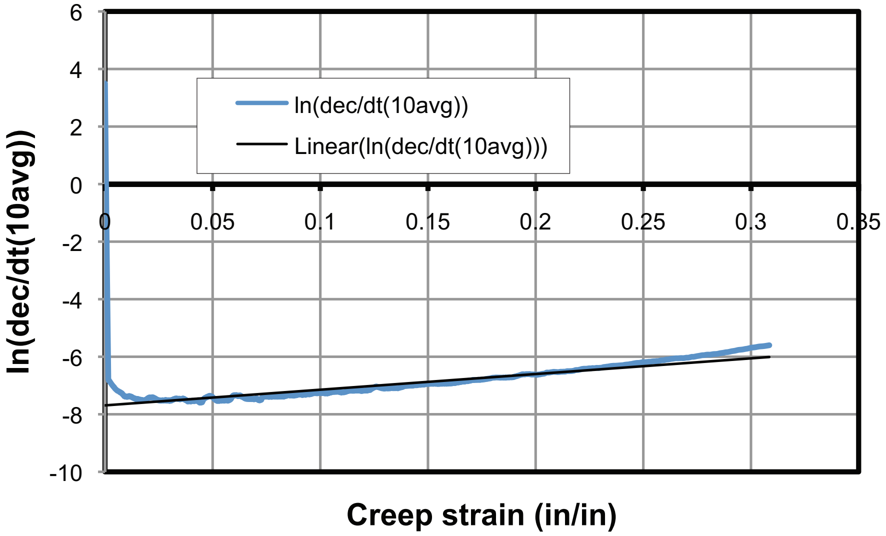


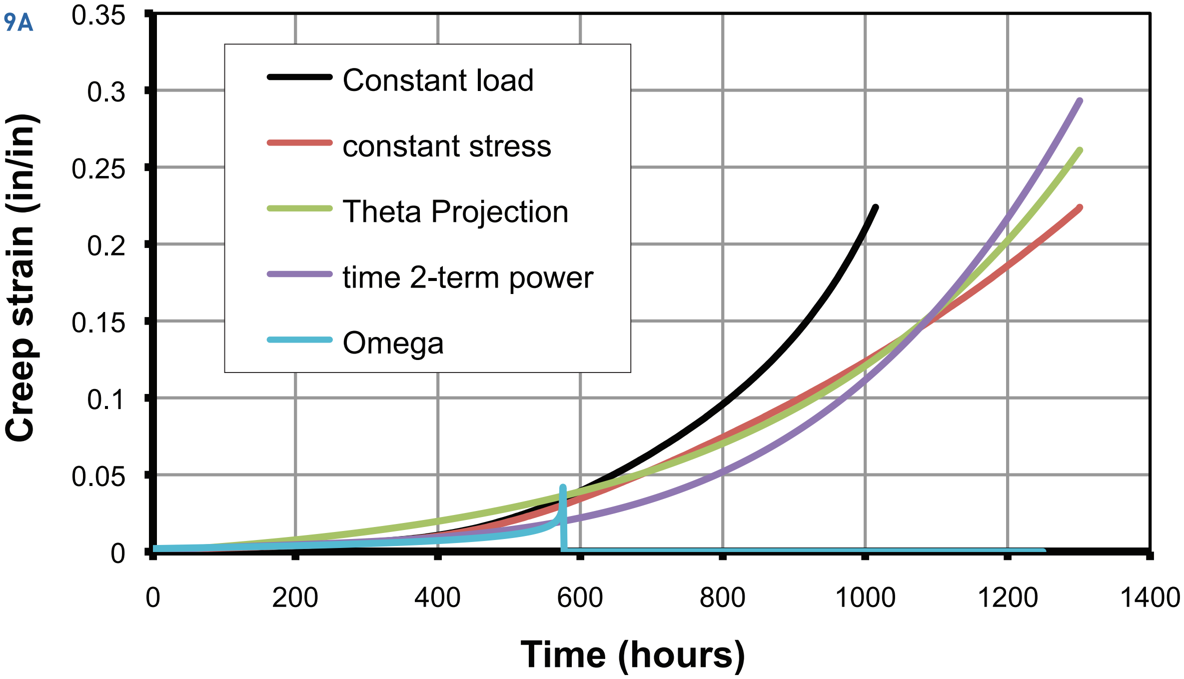
**Figure 8** *ln(dec/dt) vs. creep strain; P9 at 1120°F, 11.4ksi*

Calculating the log of the creep rate gives problems as it involves differentiating an experimental curve which contains scatter. The methods used here are, firstly, to make sure the data is as smooth as possible to start with, then either perform a numerical differentiation using some form of averaging technique, or fit the creep data with a polynomial and do the differentiation analytically. As can be seen, all methods have their problems.

It has been found that some materials refuse to conform with the Omega model. Figure 9 shows data for a 347 SS whose log (strain rate) vs. creep strain curve has either a double slope, or a continuously varying slope, depending on how one looks at it. In this case a prediction of the complete creep history is seriously in error. An alternative method, the Theta Projection Method, has slightly better luck but loses one of the claimed advantages of the Omega model, which is the ability to predict rupture life from the shape of the early portion of the creep curve. It may not be possible therefore, to always deliver on one of the promises of the Omega method, which is the ability to predict creep life reliably from very short term data.

**Figure 9A,B**
*Non-classical "Omega" behavior—creep model (A,left) and ln(dec/dt) vs. creep strain (B,right) of 347SS at 1400°F, 10.3ksi*

**9A**



This example is not isolated. The same behavior has been observed with several high temperature alloys as well as being repeatable in 347 SS. Figure 10 shows an interesting example of a nickel-based alloy used for reformer tube manufacture. This material has two clear tertiary regimes, both fit quite well by separate Omega models. Unfortunately, as in the case of the 347 SS, this also removes the ability to predict life from the early stages of the creep curve because the model seems to change in mid course. Given the variation in high temperature behavior, SES draws upon whatever approach is most suited for making the remaining life assessment.

**Stress Engineering Services** has a long-term strategic development plan in place that recognizes the significant challenges operators of high temperature process equipment face with respect to run/repair decisions of aging plants. The creep lab is evidence of Stress Engineering Services' commitment to serving the plants in these industries.

## References

1. API 579-1/ASME FFS-1, June 5, 2007.
2. "Assessment Procedure R5," Issue 3, *British Energy Generation Ltd*, 2003.
3. R. K. Penny and D. L. Marriott, *Design for Creep*.
4. R. W. Evans, J. D. Parker and R. Wilshaw, "The Θ Projection Concept—A Model-based Approach in Design and Life Extension of Engineering Plant," *J. Pres. Ves. & Piping*, Vol 50, 1992: 147–160.

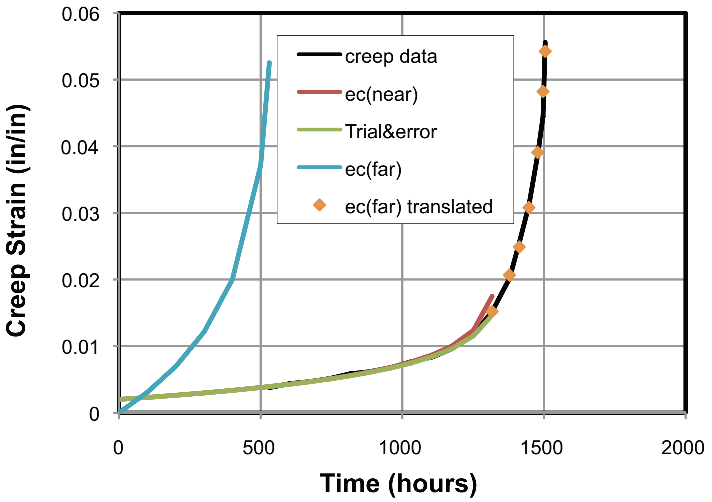
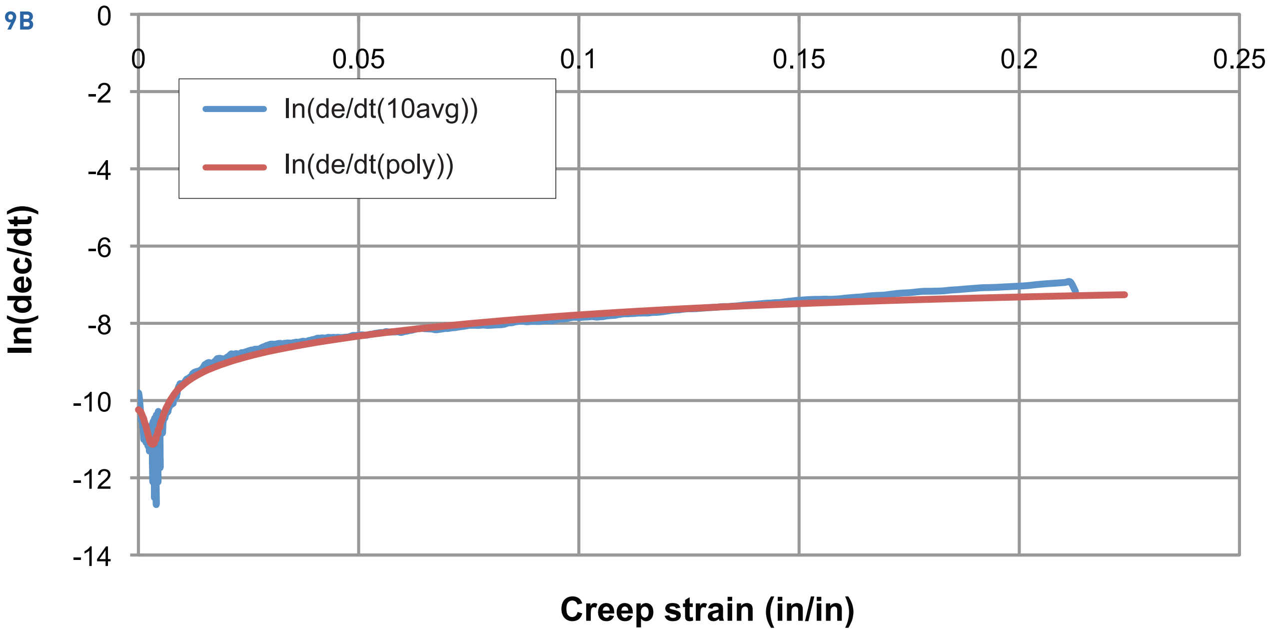


**Figure 10** *Reformer material at 1800°F showing "double" Omega behavior*

*100 kip creep frames*

**9B**



## About Stress Engineering Services

Established in 1972, SES is employee owned. Our staff covers a score of engineering disciplines including mechanical, civil, electrical, metallurgical, materials, water chemistry, theoretical and applied mechanics. Over 80% of SES engineers hold advanced degrees, most are licensed P.E.'s and the average engineer has more than 15 years experience.

## For More Information About

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