# Validation of Creep Testing Equipment and Methodology in Stress Engineering's Remaining Life Assessment Laboratory

Acting on Renewed Interest in Creep Testing

Beginning in the 1950s and running through the 1980s a great deal of the high temperature creep work for design and remaining life assessment was carried out. Much of the foundation work was done in the 1970s by a group of individuals whose impact on the field is unmatched. Unfortunately, time has taken its toll and many of this group have left the field. Institutions which once supported work of this nature, such as government agencies and major power and transportation industries, have reduced their direct involvement in high temperature testing in favor of contracting out to specialist test laboratories, or have abandoned the activity altogether due to changing priorities.

In the past two decades or so those same priorities have changed once more. Renewed interest in nuclear power, cycling of combined cycle power plants and life extension of refineries have led to a resurgence in interest in high temperature design and fitness-for-service assessment. Economic pressures have also brought new materials into the picture. In the conventional engineering alloy category, newer creep resistant steels, such as Grade 91 have emerged as candidates for new construction and repair of aging equipment.
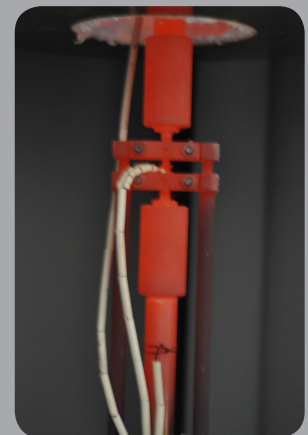

a

b

c

Figure 1b

d
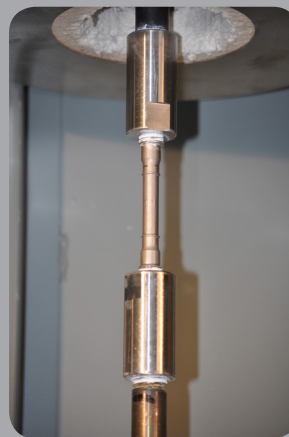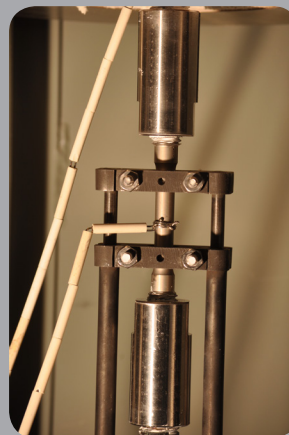
Figure 1a

Structural Non-Metallics Enter the Domain of Interest

Non-metallics, notably thermoplastics such as HDPE, conventionally viewed as a material for manufacture of relatively small components, are now being used in large volumes for pipelines and containment vessels. Fiber reinforced composites, previously viewed as "high-tech" or "aerospace" materials are now being used in heavy, ground based industrial applications, both for primary component construction and for repair of existing equipment. Both these categories of material can be classed as "high temperature" applications because they too experience creep deformation and time dependent damage in service, although the temperature is not "high" in the absolute sense.
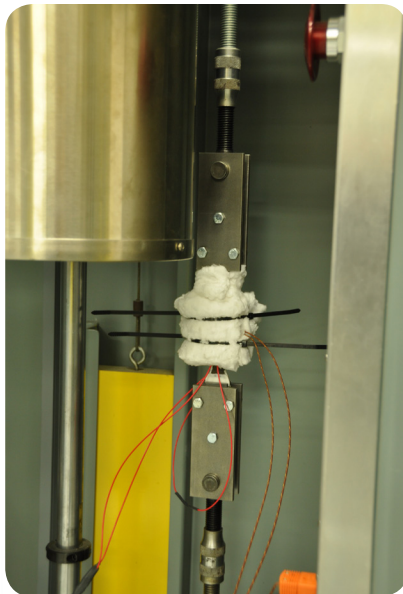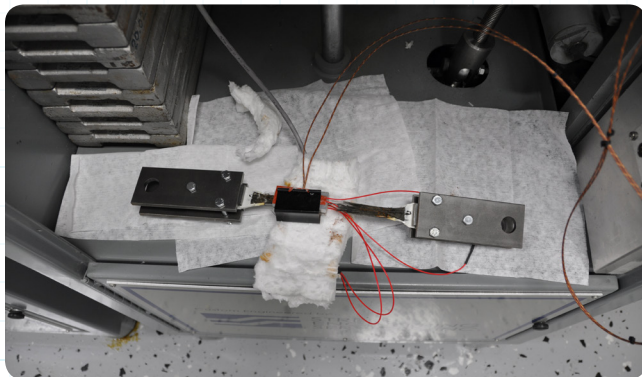

Figure 2a

Figure 2b

Figure 2c

New Assessment Methods Require Additional Creep Data

New methods of analysis may be needed to utilize these materials efficiently but even more important is the need to generate the appropriate material property data required to carry out reliable assessments. Modern assessment techniques, such as finite element analysis, alone have resulted in a need for additional material property characterizations which were not required to fuel the simplified assessment methods in use several decades ago. The break with tradition is clear to see with the use of non-metallic and fiber reinforced materials, whose time dependent properties differ in subtle but significant ways from the framework surrounding traditional metallic alloys, but even advances in conventional alloy development have resulted in unique characteristics which require testing that goes beyond the scope of established material databases.

There is currently a convergence in two trends – the established centers that at one time provided the data to fuel the engineering work have contracted in numbers and, in some cases, in their breadth of scope, while global construction and plant operations are calling for more and possibly more technically advanced testing resources.

On top of the ever present need for generic material properties to support design, material selection, fitness-for-service (FFS) or remaining life assessment is the need for data on specific materials, in specific plants, having experienced specific and possibly unique prior operating history. This is a situation where generic data, no matter how rigorously generated, has limited value. High temperature material properties of virtually any kind, are chronically prone to wide scatterbands. Some of this is found in the nature of high temperature deformation, which is fundamentally stochastic, but much of it derives from the considerable differences observed in performance of seemingly identical materials obtained from different sources. Design can cope with this uncertainty by operating on a conservative lower bound drawn under the cumulative data, but is not satisfactory for providing a plant operator with a decision to make regarding a specific condition of his particular plant. Finding the right answer for him may require more than basic material data. It will likely call for testing of sizeable subcomponents or models of portions of the plant, possibly under simulated operating conditions. This requires large test machines and advanced control and data acquisition.

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Stress Engineering Creep Testing Laboratory

For effective, plausible life assessment it is important, if not essential, to obtain case specific material properties and for this purpose, case specific testing is necessary. This does not simply mean conducting standard ASTM tests on samples cut from service-exposed components. It means carrying out experiments that capture the nature of the specific component's service conditions. For this reason SES concluded that a creep lab of its own is not merely a convenience, but a necessity if one hopes to perform meaningful remaining life assessments for its clients. To that end, SES completed the construction and start-up of a new creep lab in late 2010. The result has been the development of new, more accurate solutions to old creep testing problems, a 're-development' of creep testing technology, if you will.

SES has several types of creep testing frames with a range of capacities, as shown in Figures 3a through 3d. Load ranges are summarized in Table 1.

Figure 3a

Figure 3b

Figure 3c

Load Range of SES Creep Machines	
Frame	**Capacity**
SES Direct Hang	500 lb
M3 Lever	3000 lb
JE Lever	6000 lb
100 kip Lever	100,000 lb

Table 1

As part of the laboratory development process SES completed a detailed validation of the creep test systems and methods to be sure the data that was being collected was correct. To that end, validation testing was completed to quantify the measurement accuracy for:

- Load
- Temperature
- Strain

Figure 3d

The validation results presented here are for SES's 100 kip creep frames. However, the methods and test systems are applicable to all SES creep frames.

Validation of Stress Engineering Creep Testing Methods and Test Systems

The 100 kip frames are 2-column, vertical machines standing 12 ft high, with an available test volume 60" high and 36" between the columns (Figure 3d). Load is provided by dead weight via a two-stage 50:1 lever arm system, situated on top of the columns. To compensate for lever arm tilt, a screw jack, controlled by a tilt transducer on the major lever arm, maintains the lever inclination to less than 3° from the horizontal.

In their current configuration, these 100 kip machines are set up to test full size welds in heavy plate. In this set up, specimen heating is produced by split 48" long, 3-zone resistance heaters with the ability to accommodate a 6" diameter test section. Each zone is controlled separately by a thermocouple connected directly to the specimen surface (Figure 4).

Figure 4

Methods for Validating Strains and Deflections

Strains and deflections are the important measurable outputs of a creep test. For simple geometries, such as the welded plate tests, as carried out for this validation testing, a version of "clamped-on" extensometry is used. This consists of two sets of extension rods clamped onto the specimen on a defined gauge length with time and temperature stable optical encoders, in place of the more common LVDTs, measuring the displacements independently on two sides of the plate. This approach captures both tensile extension and section bending, if it occurs (Figure 5).

A detailed discussion of SES's smaller specimen designs is provided in SES Document #451, "SES Creep Laboratory for High Temperature Remaining Life Assessment."

Figure 5

Several other methods were used to provide a check on extensometer readings. The first, also used on the conventional creep machines, is correlation of strain in the gauge length with tilt measurements made with the tilt transducers attached to the lever arms. This is an innovation not available several decades ago, and is made possible by advances in transducer technology and the ability, via finite element analysis techniques, to calculate an accurate distribution of the mechanical and thermal conditions in the specimen.

A second, primitive but still effective method of checking creep strains, which is possible in large specimens but not practical in standard sized specimens, is direct measurement of movements between scribed marks using manual calipers.

Machine Control and Automated Data Acquisition

All the machine control and data acquisition systems attached to the creep machines have been purpose designed and built by SES.

Temperature on the creep sample is controlled by a three zone high temperature oven. Each zone is controlled independently by thermocouples attached either to the sample and/or pull rods. SES proprietary software controls each of the three different zones within +/- 1°F. Temperature set points, temperature ramp rates, oven power levels, PID parameters, etc, are programmable within the SES software.

Figure 6

Figure 6 shows the touch screen controller mounted to each creep machine. In addition to temperature control, the software developed also performs a wide range of error checking on each of the thermocouples during testing. All thermocouples are welded by SES personnel using controlled lots of special limits wire. Strain or deformation measurements are made using SES-designed mechanical extensometry using stable optical digital encoders with a resolution of 1µm, providing a minimum strain increment of 40µ on a 1" gauge length (Figure 7).

Figure 7

4

Specimen Heating and Temperature Control

Heating validation testing work was also completed. Heating is achieved through a split 3-zone furnace, the zones being controlled independently by special tolerance Type N thermocouples with a standard tolerance of +/- 4.5°F at the test temperature of interest. For purposes of the validation work being presented here-in, the test temperature was 1150°F. These control thermocouples were located in the central gauge section of the validation specimen which, in a test of a welded specimen, would cover the gauge length of approximately 6" spanning the weld and associated heated zones. A further six thermocouples of similar type were distributed over the remaining length of the specimen in order to obtain a temperature profile along the entire length.

Creep strains on the 100 kip validation test are monitored with an extensometer attached to the specimen with clamps, having concentric tube extension rods which extend outside the bottom of the furnace and whose relative motion is measured with optical decoders with a resolution of 1μm. This combined with a gauge length of 6 inches gives a strain resolution of 6μ strain.

The object of the test was to ensure that results obtained in the SES test are compatible with results obtained with other conventional, historical creep testing equipment.
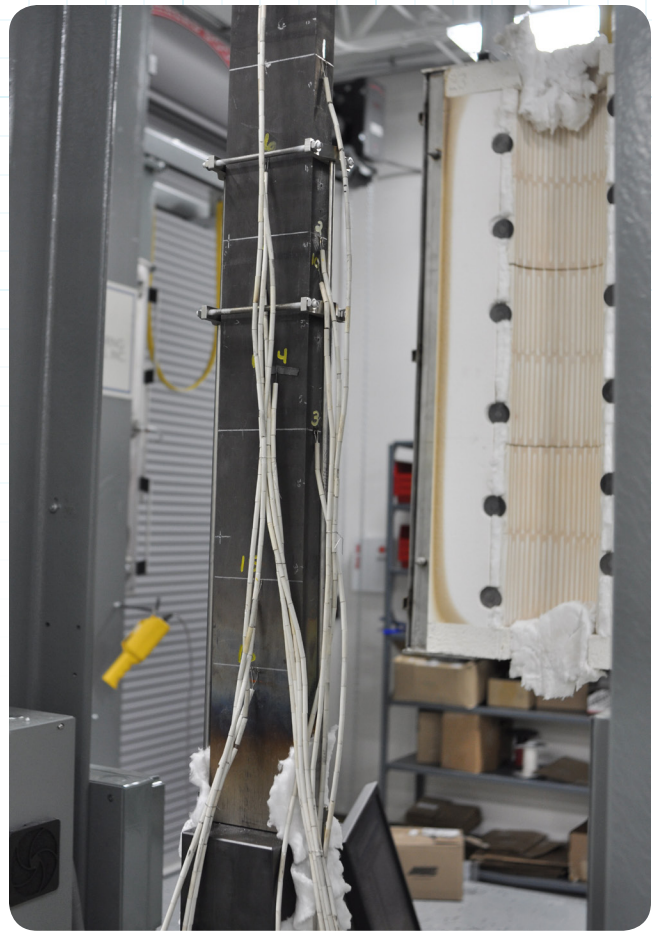
Testing the Accuracy of Stress Engineering Services Creep Machines

The validation testing focused on three measurements:

i.   Load
ii.   Temperature
iii. Strain

Each of these parameters has been checked separately by independent means using a wide plate specimen made out of 304L stainless steel. A general view of the specimen with extensometers and some thermocouples attached is shown in Figure 8.

Several ½" standard creep specimens were made out of the same bar stock, to be tested in parallel with the simulated wide plate test in standard, 6 kip capacity lever arm creep machines (Figure 9).

Testing of the three variables of interest was carried out as follows:
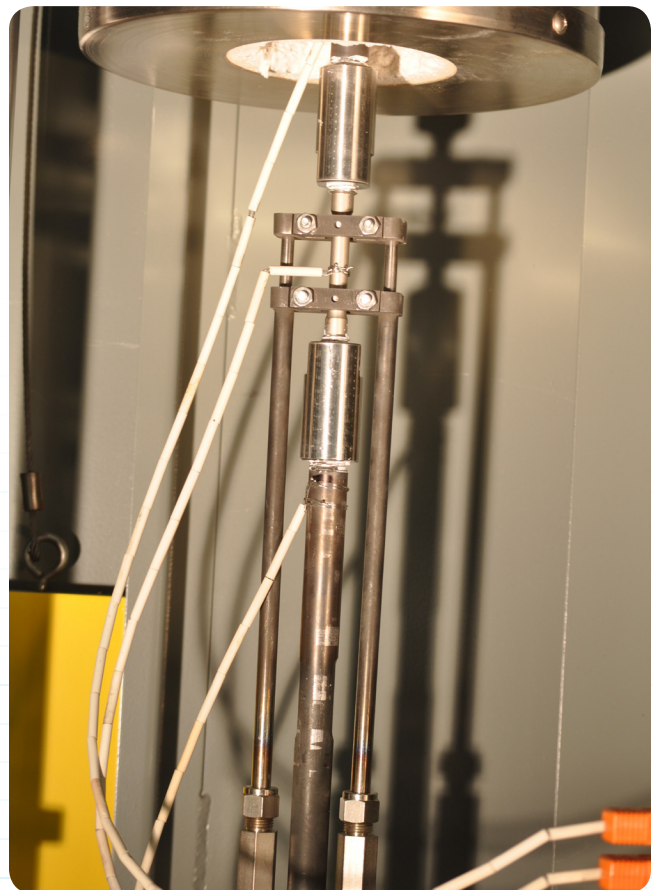

Figure 8

Figure 9

Load Evaluation

All dead load machines in the SES creep lab are calibrated annually against a standard load cell as an integral part of the company QA program. The accuracy of the lever system is within 0.1% at the load of 60,000 lb. which develops 10,000 psi in the wide plate sample on the 100 kip frames.

To ensure that the 10,000 psi stress was being applied to the specimen, the specimen itself was strain gauged and loaded at room temperature with the identical dead weight used in the test. Using a published value of 28×10^6 psi for the Young's Modulus of 304L SS, this check yielded a calculated stress of 9989 psi, or within 0.01%.

Temperature

All thermocouples used in the SES creep lab are taken from a single roll of special tolerance Type N thermocouple wire with a certified standard error for the grade of wire of approximately 4.5°F at 1150°F and 5.2°F at 1300°F, based on a calibration procedure traceable to an NIST standard. Accuracy is further monitored with an independent S-type Pt/Rh thermocouple, which indicates test accuracy to be conservatively within about 3°F. The position of the thermocouples on the wide plate validation specimen is shown in Figure 10.
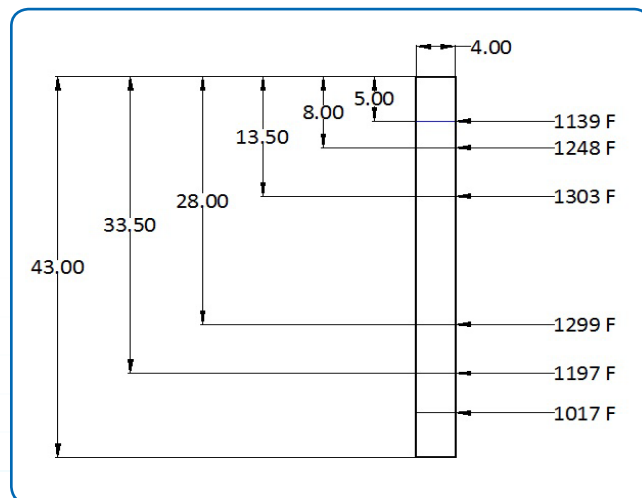

Figure 10

Discrete temperatures along the length of the creep specimen are also shown on the right side of Figure 10.

The graph in Figure 11 demonstrates the large zone of nearly constant temperature (within a degree or so) over the center section of the specimen. When this equivalent "constant temperature length" of 20 inches is used with lever arm tilt measurements, it is possible to estimate the creep strains from lever arm
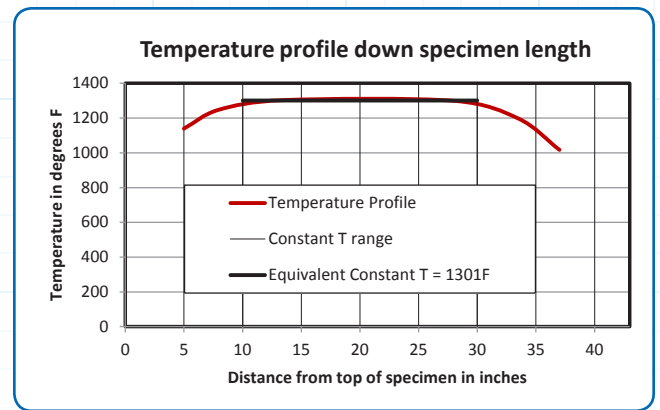

Figure 11

movements as a check on the direct extensometer measurements.

Since the calibration procedure also provides a measure of the systematic error of the specific roll of thermocouple wire, additional corrections can be made to bring the error down to between 1 and 2°F. Given the context of these measurements the effort required to minimize the error any further is probably not justified since, according to the API 579 Omega database, a 3°F deviation in temperature represents an error in the minimum creep rate of 12% and 9% in the rupture life. These differences are negligible compared with the variations typical of creep data.
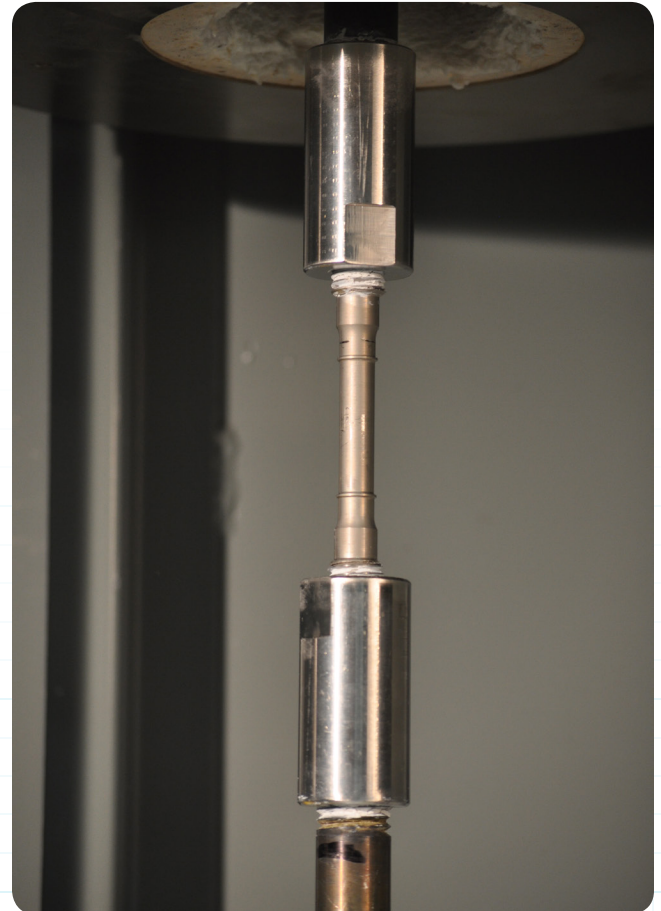

Figure 12

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There is good correspondence between the creep deformations measured in the standard specimen and the wide plate test bar, as well as good correlation with the minimum creep rate calculated from the API 579 database (Table 2). Unfortunately the Omega database does not contain any information on primary creep, for which it was necessary to go to other sources of information.

Strain Measurement

To check strain measurement, the wide plate validation test bar was tested in parallel with a standard 0.505" diameter specimen of a type that has been used extensively in the SES creep lab and for which there is a high confidence of accurate measurement from frequent use. Strain in the 0.505" specimen was measured with standard optical encoder extensometry attached to the specimen by machined ridges (Figure 12).

In addition, comparisons were made with two reference sources of generic creep data on this material. First of these references is a constitutive model developed at Oak Ridge National Laboratory by Booker [1], and the second is an estimate of the minimum creep rate obtained from the API 579 MPC Omega model [2] (Figure 13).
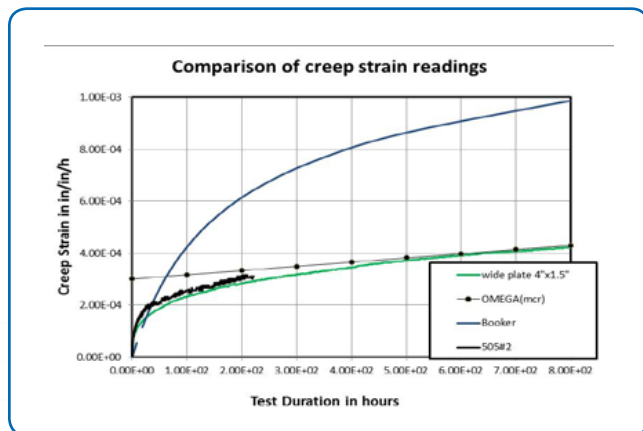

Figure 13

The ORNL model developed by Booker was the only source in the literature containing a clear estimate of primary creep. It can be seen from Figure 13 that this is significantly larger than the primary creep measured in either of the SES tests, although the minimum creep rate compares very closely with the API 579 data. Primary creep depends strongly on initial material condition, so this disparity is not unexpected. Comparisons of minimum creep rates are very close however, as shown in Table 2.

304SS 10 ksi and 1150°F

Data Source	Minimum Creep Rate (in/in/h)
SES Wide Test Plate	1.65×10^{-7}
Omega Model	1.62×10^{-7}
Booker (ORNL)	1.60×10^{-7}

Table 2

A final note on the effectiveness of the lever arm tilt procedure. Attachment of extensometers to large section specimens has been found to be a challenge. In standard sized specimens with fractional diameters, substantial ridges can be machined into the specimen to provide a secure mounting (Figure 12). In a specimen with transverse dimensions amounting to several inches, the lateral Poisson-type contraction can be up to ½ inch in the tertiary range where strains in excess of 5% are to be expected, with the result that extensometer attachments tend to fall off unless secured by methods like spot welding or screws, both methods with their own problems. This is where the tilt procedure provides significant value.
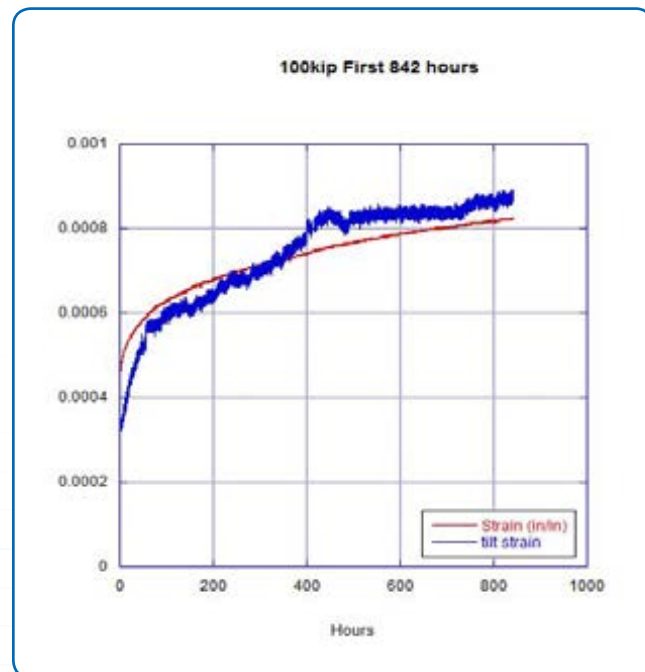

Figure 14

Figure 14 gives a comparison of strain measurements by both tilt and extensometer collected in parallel on the same specimen. Not precise in the small strain range limited by the capacity of the standard extensometer, but good enough to monitor the latter stages of deformation.

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CONCLUSION

Responding to the needs of the refining, chemical and power industries to conduct remaining life assessments on aging plants, SES set out to develop a state-of-the-art laboratory to generate the required high temperature creep data. Now calibrated against independent standards, the creep testing methods and machines have been demonstrated to deliver accurate data.

REFERENCES

1. Appendix 1 A Combined High-Temperature Database for 304SS, 308SS Filler and Their Weldment, Draft report to PVRC, Feb 6 2002.
2. Annex F, "Fitness-For-Service", API 579-1/ASME FFS-1, June 5, 2007, 2nd ed.

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