High Temperature, Slow Strain Rate Forging of Advanced Disk Alloy ME3

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Acknowledgments

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Introduction

The advanced disk alloy ME3 was designed in the HSR/EPM disk program to have extended durability at 1150-1250F in large disks. This was achieved by designing a disk alloy and process producing balanced monotonic, cyclic, and time-dependent mechanical properties, combined with robust processing and manufacturing characteristics. The resulting baseline alloy, processing, and supersolvus heat treatment produces a uniform, relatively fine mean grain size of about ASTM 7, with as-large-as (ALA) grain size of about ASTM 3 (ref. 1).

There is a long term need for disks with higher rim temperature capabilities than 1250F. This would allow higher compressor exit (T3) temperatures and allow the full utilization of advanced combustor and airfoil concepts under development. Several approaches are being studied that modify the processing and chemistry of ME3, to possibly improve high temperature properties. Promising approaches would be applied to subscale material, for screening the resulting mechanical properties at these high temperatures. An obvious path traditionally employed to improve the high temperature and time-dependent capabilities of disk alloys is to coarsen the grain size (ref. 2, 3). A coarser grain size than ASTM 7 could potentially be achieved by varying the forging conditions and supersolvus heat treatment (ref. 4).

The objective of this study was to perform forging and heat treatment experiments ("thermomechanical processing experiments") on small compression test specimens of the baseline ME3 composition, to identify a viable forging process allowing significantly coarser grain size targeted at ASTM 3-5, than that of the baseline, ASTM 7.

Material and Procedure

Specimen machining, testing, and heat treatments were performed by Wyman-Gordon Forgings, Houston, Texas. A 1.1" thick cross-section of extrusion SMK05398 was removed using an abrasive disk saw. Specimen blanks were then electrodisharge machined along a 4.5" diameter circle centered in the cross section. Twenty right circular cylinder (RCC) specimens having a diameter of 0.50" and length of 0.75" were then machined. Six double cone (DC) specimens were also machined according to Fig. 1 (ref. 5). The matrix of test conditions for the RCC and DC specimens is shown in Table 1. RCC specimens were tested at 3 temperatures 2025, 2050, and 2075F using 3 strain rates of 0.0001, 0.0003, and 0.001 sec⁻¹, after being pre-soaked at the test temperature for times of either 1 or 10 h. This represented a 3x3x2 full factorial statistical test matrix. Additional RCC tests were performed at the mid temperature 2050F and strain rate 0.003 sec⁻¹: after a pre-soak of 5h to represent the centerpoint of the test matrix, and after
an extended pre-soak of 24h. All RCC tests were continued to an upset of at least 50%, and true strain of 0.70. DC specimens were tested at the 2 extreme temperatures of 2025 and 2075F and 2 extreme strain rates of 0.0001 and 0.001 sec\(^{-1}\) after a 10h presoak, giving a 2x2 test matrix. Additional DC tests were performed at the mid temperature 2050F and strain rate 0.003 sec\(^{-1}\) after a pre-soak of 5h as for the RCC matrix centerpoint, and after an extended pre-soak of 24h. All DC tests were continued to an upset of 50%.

After the tests, all specimens were sliced into four quarters. Single quarters of each specimen were heat treated together on a tray in a resistance heated furnace using a “direct heatup” (DH) supersolvus heat treatment of 2140F/1h and then air cooled. Other quarters were given a “pre-annealed” (PA) supersolvus heat treatment consisting of a subsolvus pre-anneal of 2075F/1h, followed by an extended supersolvus treatment of 2140F/3h. Heat treated and as-forged quarters were then sectioned, metallographically prepared, and swab etched for 3 minutes using Kallings reagent. Five fields near the center of the forging specimen were measured to determine mean grain size in each case, using a circular overlay grid according to ASTM E112. The largest grain observed on each metallographic section was measured for as-large-as (ALA) grain size according to ASTM E930. Statistical evaluations of flow stress and grain sizes were then performed. The test datum of 2050F/0.0003s\(^{-1}\)/24h presoak was not used in the statistical evaluations, as it would unbalance the statistical matrix designed around presoak times of 1 and 10h. Controlled variables were orthogonally scaled to standardized form in all cases using the relationship \(v'_i = (v_i - v_{mean})/(0.5*(v_{max} - v_{min}))\). This produced a range for each standardized variable of -1 to +1. This gave standardized variables for temperature (T'), pre-soak time (P'), and log strain rate (\(\log(R)\)') of:

\[
T'=(T-2050)/25\quad P'=(P-5.5)/4.5\quad \log(R)'=(\log(R)+3.5)/0.5
\]

After regression model equations were selected, major effects, residuals, and predicted confidence intervals were examined for each response.

**Results and Discussion**

**Forging Stress-Strain Response**

Typical engineering stress-strain curves are shown for RCC tests, and load-displacement curves for DC tests are shown in Fig. 2. Flow stress at a true strain of 0.5 for each RCC test was employed in detailed analyses. Scatter plots of this flow stress (S) vs. temperature (T), pre-soak time (P) and strain rate (R) are shown in Fig. 3. Strong dependencies of flow stress on temperature and strain rate are obvious. Reverse stepwise selection linear regression of \(\log(stress)\) on \(\log(strain\ rate)\), temperature, pre-soak time, and their interactive products were performed, using an F-to-enter=4. The resulting linear regression equation was:

\[
\log(stress)=-.240553+0.041239T'+0.018252P'+0.554102\log(R)'
\]  

(1)

with a correlation coefficient \(R^2_{\text{adj}}=.984\) and rms error=0.03434. The complete statistical output is included in Appendix A-1. Plots of the resulting predicted and observed \(\log(stress)\) vs. pre-soak time and vs. \(\log(strain\ rate)\) showed only random error. A plot

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of predicted and observed log(stress) vs. temperature is also shown in A-1. A systematic
divergence at intermediate temperature is obvious, suggesting a non-linear dependence
of log(stress) on temperature. Therefore, reverse stepwise selection regressions were
performed including the squares of each variable. The resulting nonlinear regression
equation was:

\[
\log(\text{stress}) = 381.044539 - 0.371578T' + 0.000091T'^2 + 0.019031P' + 0.563907\log(R')
\] (2)

with a higher correlation coefficient R^2_{adj} = 0.995 and lower rms error = 0.0194. The plot of
predicted and observed log(stress) vs. temperature showed improved agreement (A-2).
This equation indicated flow stress generally increased with presoak time and strain rate,
but the dependence varied with temperature. In the temperature range of 2025 to 2050F,
flow stress only slightly increased with temperature. Such a temperature response would
be preferable in a production process. But at higher temperatures, flow stress increased
more sharply with temperature.

It is highly preferable that the alloy exhibit superplastic flow during a forging
process. This allows complete flow of the material into all forging die cavities with
uniform strain and strain rates in the disk alloy, and minimizes the buildup of stresses in
the dies. Superplastic flow is present when a material exhibits high strain rate sensitivity
(m), as usually defined by the relationship \( \sigma = K(\dot{e}/\dot{t})^m \). A material is considered
superplastic in deformation conditions where a strain rate sensitivity m of at least 0.3 is
observed. The strain rate sensitivity m was determined by fitting a second order
polynomial to the log(stress) data as a function of log(strain rate) for each temperature
and pre-soaks of 1 and 10h. The first derivative was then taken and evaluated at each
tested strain rate. It should be cautioned that only three strain rates were tested for each
temperature and pre-soak. Therefore, the second order polynomial fit used three data
points to estimate 3 constants, resulting in 0 degrees of freedom and a perfect fit through
the data. This did not allow an estimate of the remaining rms standard deviation between
the experimental data and the curve fit. The resulting equation constants are in Table 2,
and strain rate sensitivities are included in Table 1. The material exhibited superplastic
flow for all conditions evaluated.

**Grain Size Response**

1. As-Forced

Images of the typical microstructures observed in all specimens in the as-forged
state are compared in Fig. 4-9. Macrostructures appeared uniform in all cases. Scatter
plots of as-forged mean grain size (AFG) versus temperature (T), pre-soak time (P), and
log(strain rate) (R) are shown in Fig. 3. Dependencies of grain size on temperature and
strain rate are obvious. Reverse stepwise linear regression of mean ASTM grain size
number on temperature, pre-soak time, log(strain rate), and their interactive products
were performed, using an F-to-enter=4. The resulting linear regression equation was:

\[
\text{AFG} = 11.294737 - 0.416667T'
\]

with a correlation coefficient R^2_{adj} = 0.6598 and rms error = 0.2408. The complete
statistical output is given in Appendix B. Plots of the resulting predicted and observed
mean grain size vs. pre-soak time and vs. log(strain rate) showed only random error (A-3). The accompanying plot of predicted and observed mean grain size vs. temperature showed a systematic divergence at intermediate temperature, suggesting a non-linear dependence of mean grain size on temperature as observed for flow stress. Therefore, additional reverse stepwise regressions were performed including the squares of each variable. The resulting nonlinear regression equation was:

$$\text{AFG} = 11.486292 - 0.415313T' - 0.0772181T'' + 0.091960R' - 0.100000T'P' + 0.088773T'R' - 0.301556(T')^2$$

with a higher correlation coefficient $R^2_{adj} = 0.9072$ and lower rms error=0.1258. The plot of predicted and observed grain size vs. temperature showed improved agreement with random remaining error. These results mirrored the flow stress analysis in the respect that within a temperature range of 2025-2050F, as-forged grain size did not strongly increase with temperature. This would be a favorable temperature response range for production considerations.

2. Direct Heatup (DH) vs. Pre-Annealed (PA) Heat Treatment Response

Images of the typical macrostructures and microstructures observed in all specimens after DH and PA heat treatments are compared in Fig. 10-29. During forging, disks could have significant localized variations in strain rate, based on forging shape and material flow characteristics. During solution heat treatment, disks could have significant localized variations in solution time at temperature and subsequent cooling rate based on forging section thickness and mass, along with production practices. The microstructures are therefore compared at constant forging temperature and pre-soak time, to inspect the variations in grain size due to forging strain rate and solutioning time. Macroscopic variations of grain size with location are obvious for long presoaks, slow strain rates, and higher temperatures, especially at 2075F. Some of the variations in grain size were localized near the surface and might be machined away from a disk forging. However, the grain size variations for higher temperatures extended nearly across the entire specimen cross section. The RCC and DC specimens tested at 2075F often had over 100% larger grains in the center of the specimen, than near the sides. This excessive grain growth, while not classifiable as true critical grain growth at high strain rates (ref. 5), was definitely not conducive to a uniform supersolvus heat treatment grain size response desired in this study.

Grain sizes were consistently measured near the center of the cross section of each specimen. Scatter plots of averaged DH and PA mean grain size and ALA grain size are shown versus temperature (T), pre-soak time (P), and log(strain rate) (R) are shown in Fig. 30. Dependencies of grain size on temperature and strain rate are obvious. Regression analyses were therefore employed.

Two approaches were used to analyze this data. The first approach C evaluated the stability of grain size response with the Constraint that the two solution heat treat types DH and PA could be used to simulate expected random cause heat treatment process variations. The average and standard deviation between DH and PA mean grain sizes and the average between DH and PA ALA grain sizes were first analyzed in
approach C. The C analyses therefore had 19 data points for each of averaged grain size, standard deviation of grain size, and averaged ALA grain size.

The second approach U used solution time as a fourth Unconstrained process variable. From a practical standpoint, solution time variations could be due to furnace run-to-run dwell time variations, material location in a disk, and location of a disk on a tray of multiple disks within a furnace. Note that approach U ignored the contribution of the pre-anneal step of the PA heat treatment on resulting grain size. Approach U assumed that the grain size differences between DH and PA heat treatments were primarily due to only solution time, which for a disk can be measured with embedded thermocouples and modeled as a function of location for any disk shape. The U analyses therefore had 38 data points for each of mean grain size, standard deviation of grain size, and ALA grain size. The evaluations below indicated solution time did not significantly affect mean grain size, ALA grain size, and standard deviation of grain size.

Reverse stepwise selection linear regression of mean grain size (G) on the standardized variables and their interactive products were performed, using an F-to-remove=3.9. The resulting linear regression equations (A-4C and A-4U) were:

\[
G = 3.577042 - 1.008333T' - 0.325844P' \\
G = 3.550790 - 1.000000T' - 0.314903P'
\]

\[R^2_{adj} = 0.8251, \ \text{rms error}=0.403 \quad (4C)\]
\[R^2_{adj} = 0.7394, \ \text{rms error}=0.5077 \quad (4U)\]

These equations both indicated ASTM grain size number decreased (grain size increased) with increasing temperature and presoak time.

Linear regression of ALA grain size on the standardized variables and their interactive products were also performed, using an F-to-remove=3.9. The resulting linear regression equations were:

\[
\text{ALA} = -0.499171 - 1.066667T' - 0.428152P' + 0.197674R' \\
\text{ALA} = -0.496379 - 1.062500T' - 0.425361P' + 0.206261R' - 0.179167 T'P'
\]

\[R^2_{adj} = 0.8700, \ \text{rms error}=0.3756 \quad (5C)\]
\[R^2_{adj} = 0.8467, \ \text{rms error}=0.4122 \quad (5U)\]

The complete statistical output is given in Appendix A-5C and A-5U. Plots of the resulting predicted and observed mean and ALA grain size vs. temperature, pre-soak time and vs. log(strain rate) showed only random error. The equations both indicated that ALA grain size coarsened with increasing temperature, presoak time, and decreasing strain rate. Equation 5U indicated an additional interactive contribution of combining high temperature and long presoak times gave coarser ALA grain sizes.

The regressions of standard deviation of supersolvus grain size (SDG) gave mixed results:

\[
\text{SDG} = -0.357895 \\
\log(\text{SDG}) = -1.172359 + 0.394899T' - 0.192353R' - 0.259390T'R'
\]

\[R^2_{adj} = 0.0000, \ \text{rms error}=0.2969 \quad (6C)\]
\[R^2_{adj} = 0.4186, \ \text{rms error}=0.4417 \quad (6U)\]
The complete statistical output is given in Appendix A-6C and A-6U. Plots of the
resulting predicted and observed standard deviation of grain size vs. temperature, pre-
soak time and vs. log(strain rate) showed only random error. While the rms error was
larger using approach 6U, this equation did provide guidance in what variables controlled
SDG. The standard deviation of grain size increased with temperature and decreased
with strain rate, with their additional interactive contribution decreasing standard
deviation.

**Selection of Modified Forging Conditions**

The equations generated to describe flow stress, mean as-forged grain size, as
well as supersolvus heat treated mean, standard deviation, and ALA grain sizes could
now be used to allow selection of modified forging conditions. It was clear that the target
grain size of ASTM 3-5 could easily be attained using various combinations of
temperature, presoak, and strain rate. The flow stresses were all acceptably low, and the
material remained superplastic in all conditions evaluated. However, the uniformity goal
was a key discriminator. The variation in grain size observed across the TMP specimens
and across specimens with varied strain rates and presoaks clearly increased with
temperature. Further, the ALA grain size coarsened unacceptably at high temperatures.
These trends all pointed to the lower temperature of near 2025F as preferable. Flow
stress and as-forged grain size was relatively stable between 2025 and 2050F. Heat
treated grain size and ALA grain size only moderately increased with increasing presoak
time at 2025F, as opposed to the larger changes at 2050 and 2075F. ALA grain size
became finer with increasing strain rate.

The statistical software was used to determine optimal conditions for minimized
ALA grain size in equ. 5C and 5U, and for minimized standard deviation of heat treated
grain size in equ. 6U. The optimal conditions were 2025F/1h presoak/0.001 s\(^{-1}\) strain
rate. However, a constant presoak time of 1h would not be possible in a section greater
than 1" thick, due to variations in heat up time in a furnace. Heat up times can vary by
1 hour between a surface and midsection. So a longer presoak time would be necessary
to allow for such heat up effects. An intermediate presoak of 5h was selected for several
reasons. This time should minimize the effects of the above heat up time variations
according to the regressions, and therefore be practical to use as an aim in a variety of
forging shapes. A 5 h presoak time would also fit best into the statistical test matrix
design, giving a tightened full factorial of two temperatures 2025 and 2050F by 3 presoak
times of 1, 5, and 10h. The conditions of 2025F/5h presoak/0.001s\(^{-1}\) were therefore
entered into the above equations.

The resulting regression equation predictions of flow stress, as-forged grain size,
mean supersolvus grain size, standard deviation of supersolvus grain size, and ALA
supersolvus grain size are listed for the selected conditions of 2025F/5h presoak/0.001s\(^{-1}\)
with 95% confidence intervals in Table 3. The predictions and confidence intervals were
all judged acceptable and will be compared to experimental results when these conditions
are employed to forge and heat treat 20 pound subscale pancakes.
Summary and Conclusions

A series of forging experiments were performed with subsequent supersolvus heat treatments, in search of suitable forging conditions producing ASTM 3-5 supersolvus grain size. High forging temperatures of 2025F to 2075F and slow strain rates of 0.0001 to 0.001s⁻¹ were used, after presoaks of 1h to 24h. Two supersolvus heat treatments were then used having solution times of 1h or 3h. The findings can be summarized as follows:

1) The material displayed superplastic response under all tested conditions.
2) Forging flow stress increased with strain rate, but did not significantly increase with temperature from 2025-2050F.
3) As-forged grain size coarsened with decreasing strain rate and increasing presoak time, but did not significantly vary with temperature from 2025 to 2050F.
4) Heat treated mean and ALA grain size coarsened with increasing temperature, presoak time, and decreasing strain rate.
5) The forging temperature of 2075F gave very nonuniform supersolvus grain sizes.
6) The forging conditions of 2025F/5h presoak/0.001s⁻¹ strain rate were selected, based on grain size uniformity, standard deviation, ALA, and processing window, for evaluations on subscale pancakes.

It can be concluded from this work that:
1) Forging at high temperatures of 2025-2050F at moderately slow strain rates can produce consistent supersolvus grain sizes of ASTM 4-5 in ME3 disk alloy.
2) The supersolvus grain sizes do not significantly vary with solution times of 1 to 3h or with the introduction of a subsolvus pre-anneal before solutioning.
3) The forging temperature of 2075F should be avoided for this alloy if uniform grain size is desired.

References

Table 1. Test conditions and results.

| Temp | Presoak | StrainRate | log  | Stress | log  | m   | As-forged GS | PA heat treat GS | PA heat treat GS | PA heat treat GS | DH heat treat GS | DH heat treat GS | DH heat treat GS | PA+ DH heat treat GS | PA+ DH heat treat GS | PA+ DH heat treat GS |
|------|---------|------------|------|--------|------|-----|--------------|-----------------|-----------------|-----------------|----------------|----------------|----------------|----------------|---------------------|---------------------|---------------------|
| 2025 | 1       | 0.0001     | -4   | 0.73   | -0.14| 0.44| 11.5         | 4.5             | 0.2             | 0.5             | 5.0            | 0.1            | 1.0            | 4.8              | 0.8                 | 0.4                 |
| 2025 | 1       | 0.0003     | -3.5229 | 1.25 | 0.097 | 0.54| 11.5         | 5.7             | 0.3             | 0.5             | 4.8            | 0.2            | 0.0            | 5.3              | 0.3                 | 0.6                 |
| 2025 | 1       | 0.001      | -3   | 2.56   | 0.408 | 0.65| 11.6         | 4.8             | 0.2             | 1.0             | 4.9            | 0.4            | 1.3            | 4.9              | 1.1                 | 0.1                 |
| 2025 | 10      | 0.0001     | -4   | 1.04   | 0.017 | 0.6 | 11.7         | 3.9             | 0.2             | 0.0             | 3.6            | 0.2            | 0.0            | 3.8              | 0.0                 | 0.2                 |
| 2025 | 10      | 0.0003     | -3.5229 | 1.99 | 0.299 | 0.58| 11.7         | 3.7             | 0.4             | 0.0             | 4.7            | 0.2            | 0.0            | 4.2              | 0.0                 | 0.7                 |
| 2025 | 10      | 0.001      | -3   | 3.97   | 0.599 | 0.56| 11.6         | 4.3             | 0.1             | 0.5             | 4.3            | 0.2            | 0.5            | 4.3              | 0.5                 | 0.0                 |
| 2050 | 1       | 0.0001     | -4   | 0.69   | -0.16 | 0.55| 11.6         | 3.8             | 0.3             | -0.5            | 4.6            | 0.4            | 0.3            | 4.2              | -0.1                | 0.6                 |
| 2050 | 1       | 0.0003     | -3.5229 | 1.28 | 0.107 | 0.58| 11.7         | 4.1             | 0.3             | 0.5             | 4.2            | 0.3            | 0.5            | 4.2              | 0.5                 | 0.1                 |
| 2050 | 1       | 0.001      | -3   | 2.61   | 0.417 | 0.61| 11.7         | 3.9             | 0.1             | -0.5            | 3.2            | 0.3            | 0.3            | 3.6              | -0.1                | 0.5                 |
| 2050 | 5       | 0.0003     | -3.5229 | 1.65 | 0.217 | 0.16| 11.4         | 3.7             | 0.3             | -0.5            | 2.9            | 0.2            | -0.3           | 3.3              | -0.4                | 0.6                 |
| 2050 | 10      | 0.0001     | -4   | 0.97   | -0.01 | 0.65| 11.1         | 3.3             | 0.6             | -0.5            | 2.3            | 0.3            | -1.0           | 2.8              | -0.8                | 0.7                 |
| 2050 | 10      | 0.0003     | -3.5229 | 1.91 | 0.281 | 0.58| 11.5         | 3.7             | 0.3             | -0.5            | 4.2            | 0.5            | 0.0            | 4.0              | -0.3                | 0.4                 |
| 2050 | 10      | 0.001      | -3   | 3.66   | 0.563 | 0.5 | 11.4         | 3.4             | 0.2             | -1.3            | 3.3            | 0.3            | -0.5           | 3.4              | -0.9                | 0.1                 |
| 2050 | 24      | 0.0003     | -3.5229 | 2.51 | 0.4   | 10.7| 3.0           | 0.4             | 0.0             | 2.0             | 0.2            | -1.5           | 2.5             | -0.8             | 0.7                 |
| 2075 | 1       | 0.0001     | -4   | 0.89   | -0.05 | 0.53| 10.8         | 2.4             | 0.2             | -1.5            | 2.4            | 0.7            | -1.5           | 2.4              | -1.5                | 0.0                 |
| 2075 | 1       | 0.0003     | -3.5229 | 1.61 | 0.207 | 0.55| 10.8         | 3.1             | 0.7             | -1.0            | 3.4            | 0.4            | -0.8           | 3.3              | -0.9                | 0.2                 |
| 2075 | 1       | 0.001      | -3   | 3.17   | 0.501 | 0.57| 11.1         | 3.1             | 0.5             | -0.5            | 2.0            | 0.3            | -1.0           | 2.6              | -0.8                | 0.8                 |
| 2075 | 10      | 0.0001     | -4   | 1.32   | 0.121 | 0.62| 10.5         | 2.7             | 0.7             | -2.8            | 2.7            | 0.5            | -3.0           | 2.7              | -2.9                | 0.0                 |
| 2075 | 10      | 0.0003     | -3.5229 | 2.44 | 0.387 | 0.5 | 10.5         | 2.3             | 1.0             | -2.0            | 1.1            | 0.6            | -2.3           | 1.7              | -2.1                | 0.8                 |
| 2075 | 10      | 0.001      | -3   | 4.1    | 0.613 | 0.36| 10.9         | 2.5             | 0.2             | -2.0            | 2.5            | 0.2            | -1.8           | 2.5              | -1.9                | 0.0                 |
Table 2. Constants for the polynomial equations fit for flow stress versus strain rate:
\[ \log_{10}(\text{flow stress}) = C_1 + C_2 \log_{10}(\text{strain rate}) + C_3 \log_{10}(\text{strain rate})^2 \]

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<th>Temp(F)</th>
<th>Presoak(h)</th>
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<th>C2</th>
<th>C3</th>
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<td>10</td>
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Table 3. Equation predictions and confidence intervals for the selected forging conditions of 2025F/5h presoak/0.001s\(^{-1}\) strain rate.

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<td>5.0</td>
<td>1.4</td>
<td>1.3</td>
<td>0.4</td>
</tr>
</tbody>
</table>
Fig. 1. Schematic drawing of double cone (DC) compression specimen.

Fig. 2. Comparison of a) stress-strain curves during compression testing of RCC specimens, b) load-displacement curves during compression testing of DC specimens.
Fig. 3. Scatter plots of flow stress and as-forged average grain size vs. temperature, presoak time, and strain rate.
Fig. 4. Comparison of as-forged microstructures observed in RCC specimens after forging at 2025F.
Fig. 5. Comparison of as-forged microstructures observed in RCC specimens after forging at 2050F.
Fig. 6. Comparison of as-forged microstructures observed in RCC specimens after forging at 2050F/0.0003s⁻¹.
Fig. 7. Comparison of as-forged microstructures observed in RCC specimens after forging at 2075°F.
Fig. 8. Comparison of as-forged microstructures observed in DC specimens 10hr presoak.
Fig. 9. Comparison of as-forged microstructures observed in DC specimens after forging at 2050F/0.0003 s\(^{-1}\) approximate strain rate.
Fig. 10. Comparison of macrostructures observed in RCC specimens after forging at 2025°F/1h presoak.
Fig. 11. Comparison of macrostructures observed in RCC specimens after forging at 2025F/10h presoak.

PA

DH

0.0001 s⁻¹

0.0003 s⁻¹

1 mm
Fig. 12. Comparison of macrostructures observed in RCC specimens after forging at 2050°F/1h presoak.
Fig. 13. Comparison of macrostructures observed in RCC specimens after forging at 2050F/10h presoak.
Fig. 14. Comparison of macrostructures observed in RCC specimens after forging at 2050F/0.0003 s\(^{-1}\) strain rate.
Fig. 15. Comparison of macrostructures observed in RCC specimens after forging at 2075°F/1 h presoak.
Fig. 16. Comparison of macrostructures observed in RCC specimens after forging at 2075F/10h presoak.
Fig. 17. Comparison of macrostructures observed in DC specimens after forging at 2025°F/10h presoak.

0.001 s⁻¹

0.0001 s⁻¹

PA

DH
Fig. 18. Comparison of macrostructures observed in DC specimens after forging at 2050F/0.0003 s\(^{-1}\) approximate strain rate.
Fig. 19. Comparison of macrostructures observed in DC specimens after forging at 2075°F/10h presoak.
Fig. 20. Comparison of microstructures observed in RCC specimens after forging at 2025F/1h presoak.
Fig. 21. Comparison of microstructures observed in RCC specimens after forging at 2025F/10h presoak.
Fig. 22. Comparison of microstructures observed in RCC specimens after forging at 2050F/1h presoak.
Fig. 23. Comparison of microstructures observed in RCC specimens after forging at 2050°F/10h presoak.
Fig. 24. Comparison of microstructures observed in RCC specimens after forging at 2050°F/0.003 s\(^{-1}\) strain rate.
Fig. 25. Comparison of microstructures observed in RCC specimens after forging at 2075F/1h presoak.
Fig. 26. Comparison of microstructures observed in RCC specimens after forging at 2075°F/10h presoak.
Fig. 27. Comparison of microstructures observed in DC specimens after forging at 2025F/10h presoak.
Fig. 28. Comparison of microstructures observed in DC specimens after forging at 2050F/0.0003 s\(^{-1}\) approximate strain rate.
Fig. 29. Comparison of microstructures observed in DC specimens after forging at 2075F/10h presoak.
Fig. 30 Scatter plots of average and ALA grain size versus temperature, presoak time, and strain rate.
Appendix A-1

Least Squares Coefficients, Response LS, Model DESIGN__AUTO__LS

<table>
<thead>
<tr>
<th>Term</th>
<th>Coeff.</th>
<th>Std. Error</th>
<th>T-value</th>
<th>Signif.</th>
<th>Transformed Term</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.240553</td>
<td>0.007880</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2 ~T</td>
<td>0.041239</td>
<td>0.009913</td>
<td>4.16</td>
<td>0.0008</td>
<td>((T-2.05e+03)/2.5e+01)</td>
</tr>
<tr>
<td>3 ~P</td>
<td>0.082134</td>
<td>0.008091</td>
<td>10.15</td>
<td>0.0001</td>
<td>((P-5.5)/4.5)</td>
</tr>
<tr>
<td>4 ~LSR</td>
<td>0.277051</td>
<td>0.009909</td>
<td>27.96</td>
<td>0.0001</td>
<td>((LSR+3.5)/5e-01)</td>
</tr>
</tbody>
</table>

No. cases = 19   R-sq. = 0.9836   RMS Error = 0.03434
Resid. df = 15   R-sq-adj. = 0.9804   Cond. No. = 1.022
~ indicates factors are transformed.

Least Squares Summary ANOVA, Response LS Model DESIGN__AUTO__LS

<table>
<thead>
<tr>
<th>Source</th>
<th>df</th>
<th>Sum Sq.</th>
<th>Mean Sq.</th>
<th>F-Ratio</th>
<th>Signif.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total (Corr.)</td>
<td>18</td>
<td>1.081545</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Regression</td>
<td>3</td>
<td>1.063857</td>
<td>0.354619</td>
<td>300.70</td>
<td>0.0000</td>
</tr>
<tr>
<td>Residuals</td>
<td>15</td>
<td>0.017689</td>
<td>0.001179</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

R-sq. = 0.9836
R-sq-adj. = 0.9804
Model obeys hierarchy. The sum of squares for each term is computed assuming higher order terms are first removed.

Least Squares Components ANOVA, Response LS Model DESIGN__AUTO__LS

<table>
<thead>
<tr>
<th>Source</th>
<th>df</th>
<th>Sum Sq.</th>
<th>Mean Sq.</th>
<th>F-Ratio</th>
<th>Signif.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant</td>
<td>1</td>
<td>1.052870</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>~T</td>
<td>1</td>
<td>0.020408</td>
<td>0.020408</td>
<td>17.31</td>
<td>0.0008</td>
</tr>
<tr>
<td>~P</td>
<td>1</td>
<td>0.121505</td>
<td>0.121505</td>
<td>103.00</td>
<td>0.0000</td>
</tr>
<tr>
<td>~LSR</td>
<td>1</td>
<td>0.921797</td>
<td>0.921797</td>
<td>781.70</td>
<td>0.0000</td>
</tr>
<tr>
<td>Residuals</td>
<td>15</td>
<td>0.017689</td>
<td>0.001179</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

~ indicates factors are transformed. R-sq. = 0.9836
R-sq-adj. = 0.9804
Default sum of squares.
Model obeys hierarchy. The sum of squares for each term is computed assuming higher order terms are first removed.
Appendix A-1 (cont.)

Mulreg EXTPMPXNULREG, Model DESIGN_AUTO_LS
Main Effects on Response LOGSTRESS
(with 95% Confidence Intervals)

T: 2025 to 2075
P: 1 to 10
LSR: -4 to -3

Increase in LS

LOGSTRESS vs TEMP, Adjusted for Remaining Predictors
Using Mulreg EXTPMPXNULREG, Model DESIGN_AUTO_LS

LOGSTRESS vs PRESOAK, Adjusted for Remaining Predictors
Using Mulreg EXTPMPXNULREG, Model DESIGN_AUTO_LS
Appendix A-1 (cont.)

LOGSTRESS vs LOGSTRART, Adjusted for Remaining Predictors
Using Mulreg @EXPTMP@MULREG, Model DESIGN_AUTO_LSM

Case Order Graph of Residuals of LS
Using Studentized Residuals in Model DESIGN_AUTO_LSM

Residuals of LS vs Fitted Values
Using Studentized Residuals in Model DESIGN_AUTO_LSM
Appendix A-1 (cont.)

Normal Probability Plot of Residuals of LS
Using Studentized Residuals in Model DESIGN_AUTO_LS
(Sample size = 19)

Histogram of Residuals of LS
Using Studentized Residuals in Model DESIGN_AUTO_LS
(Sample size = 19)

<table>
<thead>
<tr>
<th>0 Factor, Response</th>
<th>1 Range</th>
<th>2 Initial Setting</th>
<th>3 Optimal Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Factors</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2 TEMP</td>
<td>2025 to 2075</td>
<td>2050</td>
<td>2025</td>
</tr>
<tr>
<td>3 PRESOAK</td>
<td>1 to 10</td>
<td>5.5</td>
<td>1.0004</td>
</tr>
<tr>
<td>4 LOGSTRART</td>
<td>-4 to -3</td>
<td>-3.5</td>
<td>-3.9974</td>
</tr>
<tr>
<td>5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6 Responses</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7 LOGSTRESS</td>
<td>MIN</td>
<td></td>
<td>-0.15841</td>
</tr>
</tbody>
</table>

Converged to a tolerance of 0.000077 after 109 steps.
Appendix A-1 (cont.)

Normal Probability Plot of Residuals of LS Using Studentized Residuals in Model DESIGN_AUTO_LS (Sample size = 19)

Histogram of Residuals of LS Using Studentized Residuals in Model DESIGN_AUTO_LS (Sample size = 19)

<table>
<thead>
<tr>
<th>0 Factor, Response</th>
<th>1 Range</th>
<th>2 Initial Setting</th>
<th>3 Optimal Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Factors</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TEMP</td>
<td>2025 to 2075</td>
<td>2050</td>
<td>2025</td>
</tr>
<tr>
<td>PRESOAK</td>
<td>1 to 10</td>
<td>5.5</td>
<td>1.0004</td>
</tr>
<tr>
<td>LOGSTART</td>
<td>-4 to -3</td>
<td>-3.5</td>
<td>-3.9974</td>
</tr>
<tr>
<td>Responses</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LOGSTRESS</td>
<td>MIN</td>
<td></td>
<td>-0.15841</td>
</tr>
</tbody>
</table>

Converged to a tolerance of 0.000077 after 109 steps.
### Bisquare Coefficients, Response LS, Model DESIGNAUTO_LS

<table>
<thead>
<tr>
<th>Term</th>
<th>Coef.</th>
<th>Std. Error</th>
<th>T-value</th>
<th>Signif.</th>
<th>Transformed Term</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.207982</td>
<td>0.007335</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2~T</td>
<td>0.046337</td>
<td>0.005602</td>
<td>18.73</td>
<td>0.0001</td>
<td>((T-2.05e+03)/2.5e+01))</td>
</tr>
<tr>
<td>3~P</td>
<td>0.083639</td>
<td>0.004572</td>
<td>18.73</td>
<td>0.0001</td>
<td>((P-5.5)/4.5))</td>
</tr>
<tr>
<td>4~LSR</td>
<td>0.281954</td>
<td>0.005600</td>
<td>50.35</td>
<td>0.0001</td>
<td>((LSR+3.5)/5e-01))</td>
</tr>
<tr>
<td>5~T**2</td>
<td>0.056926</td>
<td>0.009229</td>
<td>6.17</td>
<td>0.0001</td>
<td>((T-2.05e+03)/2.5e+01))**</td>
</tr>
</tbody>
</table>

No. cases = 19  
R-sq, = 0.9953  
Resid. df = 14  
R-sq-adj, = 0.9940  
Cond. No. = 2.958  
~ indicates factors are transformed.

### Bisquare Summary ANOVA, Response LS Model DESIGNAUTO_LS

<table>
<thead>
<tr>
<th>Source</th>
<th>1 df</th>
<th>2 Sum Sq.</th>
<th>3 Mean Sq.</th>
<th>4 F-Ratio</th>
<th>5 Signif.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total(Corr.)</td>
<td>18</td>
<td>1.133631</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Regression</td>
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<td>1.128359</td>
<td>0.282090</td>
<td>749.20</td>
<td>0.0000</td>
</tr>
<tr>
<td>Linear</td>
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<td>1.114033</td>
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<td>986.20</td>
<td>0.0000</td>
</tr>
<tr>
<td>Non-linear</td>
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<td>0.014326</td>
<td>0.014326</td>
<td>38.04</td>
<td>0.0000</td>
</tr>
<tr>
<td>Residual</td>
<td>14</td>
<td>0.005272</td>
<td>0.000377</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

R-sq, = 0.9953  
R-sq-adj, = 0.9940  
Model obeys hierarchy. The sum of squares for each term is computed assuming higher order terms are first removed.

### Bisquare Components ANOVA, Response LS Model DESIGNAUTO_LS

<table>
<thead>
<tr>
<th>Source</th>
<th>1 df</th>
<th>2 Sum Sq.</th>
<th>3 Mean Sq.</th>
<th>4 F-Ratio</th>
<th>5 Signif.</th>
<th>6 Transformed Term</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant</td>
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<td>1.082406</td>
<td>0.025765</td>
<td>68.43</td>
<td>0.0000</td>
<td>((T-2.05e+03)/2.5e+01))</td>
</tr>
<tr>
<td>~T</td>
<td>1</td>
<td>0.025765</td>
<td>0.025765</td>
<td>68.43</td>
<td>0.0000</td>
<td>((T-2.05e+03)/2.5e+01))</td>
</tr>
<tr>
<td>~P</td>
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<td>0.132090</td>
<td>0.132090</td>
<td>350.80</td>
<td>0.0000</td>
<td>((P-5.5)/4.5))</td>
</tr>
<tr>
<td>~LSR</td>
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<td>0.954705</td>
<td>0.954705</td>
<td>2535.00</td>
<td>0.0000</td>
<td>((LSR+3.5)/5e-01))</td>
</tr>
<tr>
<td>~T**2</td>
<td>1</td>
<td>0.014326</td>
<td>0.014326</td>
<td>38.04</td>
<td>0.0000</td>
<td>((T-2.05e+03)/2.5e+01))**</td>
</tr>
<tr>
<td>Residual</td>
<td>14</td>
<td>0.005272</td>
<td>0.000377</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

~ indicates factors are transformed.  
R-sq, = 0.9953  
R-sq-adj, = 0.9940  
Default sum of squares.  
Model obeys hierarchy. The sum of squares for each term is computed assuming higher order terms are first removed.
Appendix A-2 (cont.)

Main Effects on Response LOGSTRESS
(with 95% Confidence Intervals)

- T: 2040 to 2075
- P: 1 to 10
- LSR: -4 to -3

LOGSTRESS vs TEMP, Adjusted for Remaining Predictors
Using Mulreg @EXPTMP@MULREG, Model DESIGN_AUTO_LS

LOGSTRESS vs PRESOAK, Adjusted for Remaining Predictors
Using Mulreg @EXPTMP@MULREG, Model DESIGN_AUTO_LS
Appendix A-2 (cont.)

LOGSTRESS VS LOGSTRART, Adjusted for Remaining Predictors
Using Mulreg @EXPTMP@MULREG, Model DESIGN__AUTO__LS

Case Order Graph of Residuals of LS
Using Studentized Residuals in Model DESIGN__AUTO__LS

Residuals of LS vs Fitted Values
Using Studentized Residuals in Model DESIGN__AUTO__LS
Appendix A-2 (cont.)

Normal Probability Plot of Residuals of LS
Using Studentized Residuals in Model DESIGN_AUTO_LS
(Sample size = 19)

Histogram of Residuals of LS
Using Studentized Residuals in Model DESIGN_AUTO_LS
(Sample size = 19)

0 Factor, Response 1 Range 2 Initial 3 Optimal
or Formula Setting Value

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Factors</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>TEMP 2025 to 2075 2050 2039.3</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>PRESOA K 1 to 10 5.5 1.0512</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>LOGSTRA R T -4 to -3 -3.5 -3.9999</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Responses</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>LOGSTRESS MIN -0.16798</td>
<td></td>
</tr>
</tbody>
</table>

Converged to a tolerance of 0.000077 after 71 steps.
Appendix A-2 (cont.)

Predictions and 95% simultaneous confidence intervals for mean responses of LOGSTRESS using model DESIGN__AUTO__LS
\( P = 1.0512, \quad LSR = -3.9999 \)

![Graph 1: Predictions and 95% simultaneous confidence intervals for mean responses of LOGSTRESS using model DESIGN__AUTO__LS (Temp vs. LOGSTRESS).](image1)

Predictions and 95% simultaneous confidence intervals for mean responses of LOGSTRESS using model DESIGN__AUTO__LS
\( LSR = -3.9999, \quad T = 2039.3 \)

![Graph 2: Predictions and 95% simultaneous confidence intervals for mean responses of LOGSTRESS using model DESIGN__AUTO__LS (Presoak vs. LOGSTRESS).](image2)

Predictions and 95% simultaneous confidence intervals for mean responses of LOGSTRESS using model DESIGN__AUTO__LS
\( T = 2039.3, \quad P = 1.0512 \)

![Graph 3: Predictions and 95% simultaneous confidence intervals for mean responses of LOGSTRESS using model DESIGN__AUTO__LS (Logstart vs. LOGSTRESS).](image3)
Appendix A-2 (cont.)

LOGSTRESS
LOGSTRESS _START = -3.9999

P  R  E  S  O  A  K

TEMP

LOGSTRESS
PRESOAK = 1.0512

LOGSTRESS
TEMP = 2039.3

Predictions and 95% simultaneous confidence intervals
for mean responses of LOGSTRESS using model DESIGN__AUTO__LS
LSR = -3

P  T=2025
Lower 0.453458
Predicted 0.491009
Upper 0.528560

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Appendix A-3C

Least Squares Coefficients, Response AFGS, Model DESIGN__AUTO__AFGS

<table>
<thead>
<tr>
<th>Term</th>
<th>1 Coef.</th>
<th>2 Std. Error</th>
<th>3 T-value</th>
<th>4 Signif.</th>
<th>5 Transformed Term</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>11.294737</td>
<td>0.055255</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>-0.416667</td>
<td>0.069527</td>
<td>-5.99</td>
<td>0.0001</td>
<td>((T-2.05e+03)/2.5e+01)</td>
</tr>
</tbody>
</table>

No. cases = 19    R-sq. = 0.6787    RMS Error = 0.2408
Resid. df = 17    R-sq-adj. = 0.6598    Cond. No. = 1

~ indicates factors are transformed.

Least Squares Summary ANOVA, Response AFGS Model DESIGN__AUTO__AFGS

<table>
<thead>
<tr>
<th>Source</th>
<th>1 df</th>
<th>2 Sum Sq.</th>
<th>3 Mean Sq.</th>
<th>4 F-Ratio</th>
<th>5 Signif.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total(Corr.)</td>
<td>18</td>
<td>3.069474</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Regression</td>
<td>1</td>
<td>2.083333</td>
<td>2.083333</td>
<td>35.91</td>
<td>0.0000</td>
</tr>
<tr>
<td>Residual</td>
<td>17</td>
<td>0.986140</td>
<td>0.058008</td>
<td>0.0000</td>
<td></td>
</tr>
</tbody>
</table>

R-sq. = 0.6787    R-sq-adj. = 0.6598
Model obeys hierarchy. The sum of squares for each term is computed assuming higher order terms are first removed.

Least Squares Components ANOVA, Response AFGS Model DESIGN__AUTO__AFGS

<table>
<thead>
<tr>
<th>Source</th>
<th>1 df</th>
<th>2 Sum Sq.</th>
<th>3 Mean Sq.</th>
<th>4 F-Ratio</th>
<th>5 Signif.</th>
<th>6 Transformed Term</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant</td>
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<td>2424</td>
<td></td>
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<tr>
<td>~T</td>
<td>1</td>
<td>2.083333</td>
<td>2.083333</td>
<td>35.91</td>
<td>0.0000</td>
<td>((T-2.05e+03)/2.5e+01)</td>
</tr>
<tr>
<td>Residual</td>
<td>17</td>
<td>0.986140</td>
<td>0.058008</td>
<td>0.0000</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

~ indicates factors are transformed. R-sq. = 0.6787    R-sq-adj. = 0.6598
Default sum of squares.
Model obeys hierarchy. The sum of squares for each term is computed assuming higher order terms are first removed.
Appendix A-3C (cont.)

Main Effects on Response ASFORGEDGS
(with 95% confidence intervals)

T: 2025 to 2075

Increase in AFGS

ASFORGEDGS vs TEMP, Adjusted for Remaining Predictors
using Multireg @EXPT@MULREG, Model DESIGN_AUTO_AFGS

Case Order Graph of Residuals of AFGS
using Studentized Residuals in Model DESIGN_AUTO_AFGS
Appendix A-3C (cont.)

Residuals of AFGS vs Fitted Values
Using Studentized Residuals in Model DESIGN_AUTO_AFGS

Normal Probability Plot of Residuals of AFGS
Using Studentized Residuals in Model DESIGN_AUTO_AFGS
(Sample size = 19)

Histogram of Residuals of AFGS
Using Studentized Residuals in Model DESIGN_AUTO_AFGS
(Sample size = 19)
Appendix A-3C (cont.)

<table>
<thead>
<tr>
<th>Factor, Response</th>
<th>1 Range</th>
<th>2 Initial Setting</th>
<th>3 Optimal Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Factors</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2 TEMP</td>
<td>2025 TO 2075</td>
<td>2050</td>
<td>2025</td>
</tr>
<tr>
<td>3 PRESOAK</td>
<td>1 TO 10</td>
<td>5.5</td>
<td>7.75</td>
</tr>
<tr>
<td>Responses</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6 ASFORGEDGS</td>
<td>MAX</td>
<td></td>
<td>11.711</td>
</tr>
<tr>
<td>7 AVGs_ALA</td>
<td></td>
<td></td>
<td>3.9699</td>
</tr>
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Converged to a tolerance of 0.00012 after 46 steps.

Predictions and 95% simultaneous confidence intervals for mean responses of ASFORGEDGS using model DESIGN_AUTO_AFGS

![Graph showing predictions and confidence intervals](image-url)
Appendix A-3U

Least Squares Coefficients, Response AFGS, Model DESIGN_AUTO_AFGS

<table>
<thead>
<tr>
<th>Term</th>
<th>Coeff.</th>
<th>Std. Error</th>
<th>T-value</th>
<th>Signif.</th>
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<td>-0.415313</td>
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<td>-0.077218</td>
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<td>4</td>
<td>0.091960</td>
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<td>0.0003</td>
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<tr>
<td>5</td>
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<td>0.059832</td>
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<td></td>
</tr>
</tbody>
</table>

NO. cases = 19  R-sq. = 0.9381  RMS Error = 0.1258
Resid. df = 12  R-sq-adj. = 0.9072  Cond. No. = 2.958
~ indicates factors are transformed.

Least Squares Summary ANOVA, Response AFGS Model DESIGN_AUTO_AFGS

<table>
<thead>
<tr>
<th>Source</th>
<th>df</th>
<th>Sum Sq.</th>
<th>Mean Sq.</th>
<th>F-Ratio</th>
<th>Signif.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total(Corr.)</td>
<td>18</td>
<td>3.069474</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Regression</td>
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<td>2.879564</td>
<td>0.479927</td>
<td>30.33</td>
<td>0.0000</td>
</tr>
<tr>
<td>Linear</td>
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<td>2.294470</td>
<td>0.764823</td>
<td>48.33</td>
<td>0.0000</td>
</tr>
<tr>
<td>Non-Linear</td>
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<td>0.585094</td>
<td>0.195031</td>
<td>12.32</td>
<td>0.0006</td>
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<tr>
<td>Residual</td>
<td>12</td>
<td>0.189909</td>
<td>0.015826</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

R-sq. = 0.9381  R-sq-adj. = 0.9072
Model obeys hierarchy. The sum of squares for each term is computed assuming higher order terms are first removed.

Least Squares Components ANOVA, Response AFGS Model DESIGN_AUTO_AFGS

<table>
<thead>
<tr>
<th>Source</th>
<th>df</th>
<th>Sum Sq.</th>
<th>Mean Sq.</th>
<th>F-Ratio</th>
<th>Signif.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant</td>
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<td></td>
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<tr>
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<td>2.083333</td>
<td>2.083333</td>
<td>131.60</td>
<td>0.0000 (T-2.05e+03)/2.5e+01</td>
</tr>
<tr>
<td>P</td>
<td>1</td>
<td>0.107391</td>
<td>0.107391</td>
<td>6.79</td>
<td>0.0230 (P-55)/4.5</td>
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<tr>
<td>~LSR</td>
<td>1</td>
<td>0.120000</td>
<td>0.120000</td>
<td>7.58</td>
<td>0.0175 (LSR+3.5)/5e-01</td>
</tr>
<tr>
<td>~TP</td>
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<td>0.063089</td>
<td>3.99</td>
<td>0.0691 (T-2.05e+03)/2.5e+01</td>
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<tr>
<td>~T**2</td>
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<td>0.402005</td>
<td>25.40</td>
<td>0.0003 (T-2.05e+03)/2.5e+01</td>
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<tr>
<td>Residual</td>
<td>12</td>
<td>0.189909</td>
<td>0.015826</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

~ indicates factors are transformed.  R-sq. = 0.9381  R-sq-adj. = 0.9072
Default sum of squares.  Model obeys hierarchy. The sum of squares for each term is computed assuming higher order terms are first removed.
Appendix A-3U (cont.)

Main Effects on Response \( AFGS \) (with 95% Confidence Intervals)

- \( T: \) 2033 to 2075
- \( P: \) 1 to 20
- \( \text{LSR}: \) -4 to -3

\( AFGS \):

\( 0.2 \quad 0.4 \quad -0.2 \quad 0.0 \quad -0.4 \quad -0.6 \quad -0.8 \quad -1.0 \quad -1.2 \)

Interaction Effects of \( TEMP \) with \( \log \) \( \text{START} \) on Response \( AFGS \)

- \( T: \) 2033 to 2075
- \( \text{LSR} = -4 \)
- \( \text{LSR} = -3 \)
- \( \text{LSR}: \) -4 to -3

95% Confidence Intervals

For Increase in \( AFGS \)

Interaction Effects of \( TEMP \) with \( \text{PRESOAK} \) on Response \( AFGS \)

- \( T: \) 2033 to 2075
- \( P = 1 \)
- \( P = 10 \)
- \( P: \) 1 to 10

95% Confidence Intervals

For Increase in \( AFGS \)
Appendix A-3U (cont.)

**ASFORGEDGS vs TEMP,** Adjusted for Remaining Predictors
Using Mulreg @EXPT@MULREG, Model DESIGN_AUTO_AFGS

![Graph showing Adjusted Data Values and Adjusted Fitted Curve for ASFORGEDGS vs TEMP.]

**ASFORGEDGS vs PRESOAK,** Adjusted for Remaining Predictors
Using Mulreg @EXPT@MULREG, Model DESIGN_AUTO_AFGS

![Graph showing Adjusted Data Values and Adjusted Fitted Curve for ASFORGEDGS vs PRESOAK.]

**ASFORGEDGS vs LOGSTRART,** Adjusted for Remaining Predictors
Using Mulreg @EXPT@MULREG, Model DESIGN_AUTO_AFGS

![Graph showing Adjusted Data Values and Adjusted Fitted Curve for ASFORGEDGS vs LOGSTRART.]

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Appendix A-3U (cont.)

Case Order Graph of Residuals of AFGS
Using Studentized Residuals in Model DESIGN_AUTO_AFGS

Residuals of AFGS vs Fitted Values
Using Studentized Residuals in Model DESIGN_AUTO_AFGS

Normal Probability Plot of Residuals of AFGS
Using Studentized Residuals in Model DESIGN_AUTO_AFGS
(Sample size = 19)
Appendix A-3U (cont.)

Histogram of Residuals of AFGS
Using Studentized Residuals in Model DESIGN_AUTO_AFGS
(Sample size = 19)

0 Factor, Response 1 Range 2 Initial 3 Optimal
or Formula Setting Value

1 Factors
2 TEMP 2025 to 2075 2050 2040.3
3 PRESOAK 1 to 10 5.5 1.002
4 LOGSTRAT -4 to -3 -3.5 -3.001

5 Responses
6 ASFORGEDGS MAX 11.698
7 LOGSTRESS 0.39439

Converged to a tolerance of 0.00012 after 45 steps.

Predictions and 95% simultaneous confidence intervals
for mean responses of ASFORGEDGS using model DESIGN_AUTO_AFGS
P = 1.002, LSR = -3.001
Appendix A-3U (cont.)

Predictions and 95% simultaneous confidence intervals for mean responses of \text{ASFORGEDGS} using model \text{DESIGN\_AUTO\_AFGS}

\[
\text{LSR} = -3.001, \ T = 2040.3
\]

\begin{figure}
\centering
\includegraphics[width=\textwidth]{chart1}
\caption{Curve 1}
\end{figure}

Predictions and 95% simultaneous confidence intervals for mean responses of \text{ASFORGEDGS} using model \text{DESIGN\_AUTO\_AFGS}

\[
\ T = 2040.3, \ P = 1.002
\]

\begin{figure}
\centering
\includegraphics[width=\textwidth]{chart2}
\caption{Curve 1}
\end{figure}

\text{ASFORGEDGS}

\[
\text{LOGSTRART} = -3.001
\]

\begin{figure}
\centering
\includegraphics[width=\textwidth]{chart3}
\caption{AFGS}
\end{figure}
Predictions and 95% simultaneous confidence intervals for mean responses of ASFORGEDGS using model DESIGN_Auto_AFGS

\[ \text{LSR} = -3 \]

\[ \begin{align*}
\text{P} & = 2025 \\
\text{Lower} & = 11.249138 \\
\text{S Predicted} & = 11.600705 \\
\text{Upper} & = 11.952272
\end{align*} \]
Appendix A-4C

Least Squares Coefficients, Response AVG, Model DESIGN_AUTO_AVG

0 Term 1 Coef. 2 Std. Error 3 T-value 4 Signif. 5 Transformed Term

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th></th>
<th></th>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3.577042</td>
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</tr>
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<td>2</td>
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<td>0.0034</td>
<td>((P-5.5)/4.5)</td>
</tr>
</tbody>
</table>

No. cases = 19  R-sq. = 0.8445  RMS Error = 0.403
Resid. df = 16  R-sq-adj. = 0.8251  Cond. No. = 1.006
- indicates factors are transformed.

TABLE:49296 3R x 5C

Least Squares Summary ANOVA, Response AVG Model DESIGN_AUTO_AVG

0 Source 1 df 2 Sum Sq. 3 Mean Sq. 4 F-Ratio 5 Signif.

<p>| | | | | | |</p>
<table>
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<td>2.59836</td>
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<td></td>
</tr>
</tbody>
</table>

R-sq. = 0.8445  R-sq-adj. = 0.8251
Model obeys hierarchy. The sum of squares for each term is computed assuming higher order terms are first removed.

Least Squares Components ANOVA, Response AVG Model DESIGN_AUTO_AVG

0 Source 1 df 2 Sum Sq. 3 Mean Sq. 4 F-Ratio 5 Signif. 6 Transformed Term

<p>| | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
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<th></th>
<th></th>
</tr>
</thead>
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<tr>
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<td>1.91238</td>
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<tr>
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<td>16</td>
<td>2.59836</td>
<td>0.16240</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- indicates factors are transformed. R-sq. = 0.8445  R-sq-adj. = 0.8251
Default sum of squares. Model obeys hierarchy. The sum of squares for each term is computed assuming higher order terms are first removed.
Main Effects on Response AVGS (with 95% confidence intervals)

T: 2025 to 2075
P: 1 to 10

Increase in AVG

AVGS vs TEMP, Adjusted for Remaining Predictors
Using Mulreg @EXPT_MULREG, Model DESIGN__AUTO__AVG

AVGS vs PRESOAK, Adjusted for Remaining Predictors
Using Mulreg @EXPT_MULREG, Model DESIGN__AUTO__AVG

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Appendix A-4C (cont.)

Case Order Graph of Residuals of AVG
Using Studentized Residuals in Model DESIGN_AUTO_AVG

Residuals of AVG vs Fitted Values
Using Studentized Residuals in Model DESIGN_AUTO_AVG

Normal Probability Plot of Residuals of AVG
Using Studentized Residuals in Model DESIGN_AUTO_AVG
(Sample size = 19)
Appendix A-4C (cont.)

Histogram of Residuals of AVG
Using Studentized Residuals in Model DESIGN__AUTO__AVG
(Sample size = 19)

<table>
<thead>
<tr>
<th>0 Factor, Response</th>
<th>1 Range</th>
<th>2 Initial Setting</th>
<th>3 Optimal Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Factors</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2 TEMP</td>
<td>2025 to 2075</td>
<td>2050</td>
<td>2025</td>
</tr>
<tr>
<td>3 PRESOAK</td>
<td>1 to 10</td>
<td>5.5</td>
<td>1.0065</td>
</tr>
<tr>
<td>4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5 Responses</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>6 AVGS</td>
<td>MAX</td>
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<td>4.9106</td>
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</table>

Converged to a tolerance of 0.00036 after 39 steps.

Predictions and 95% simultaneous confidence intervals
for mean responses of AVGS using model DESIGN__AUTO__AVG
P = 1.0065
Appendix A-4C (cont.)

Predictions and 95% simultaneous confidence intervals for mean responses of AVGS using model DESIGN.AUTO.AVG

\[ T = 2025 \]

Predictions and 95% simultaneous confidence intervals for mean responses of AVGS using model DESIGN.AUTO.AVG

\[ T = 2025 \]

- Lower: 4.157342
- Predicted: 4.621580
- Upper: 5.085819

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Appendix A-4U

Least Squares Coefficients, Response AVG, Model DESIGN__AUTO__AVG

<table>
<thead>
<tr>
<th>0 Term</th>
<th>1 Coeff.</th>
<th>2 Std. Error</th>
<th>3 T-value</th>
<th>4 Signif.</th>
<th>5 Transformed Term</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3.550790</td>
<td>0.082366</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>2 ~T</td>
<td>-1.000000</td>
<td>0.103639</td>
<td>-9.65</td>
<td>0.0001</td>
<td>(((T-2.05e+03)/2.5e+01)</td>
</tr>
<tr>
<td>3 ~P</td>
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<td>-3.72</td>
<td>0.0007</td>
<td>(((P-5.5)/4.5)</td>
</tr>
</tbody>
</table>

No. cases = 38  R-sq. = 0.7534  RMS Error = 0.5077
Resid. df = 35  R-sq-adj. = 0.7394  Cond. No. = 1.006
~ indicates factors are transformed.

Least Squares Summary ANOVA, Response AVG Model DESIGN__AUTO__AVG

<table>
<thead>
<tr>
<th>0 Source</th>
<th>1 df</th>
<th>2 Sum Sq.</th>
<th>3 Mean Sq.</th>
<th>4 F-Ratio</th>
<th>5 Signif.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Total(Corr.)</td>
<td>37</td>
<td>36.59474</td>
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<tr>
<td>2 Regression</td>
<td>2</td>
<td>27.57221</td>
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<td>53.48</td>
<td>0.0000</td>
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<tr>
<td>3 Residual</td>
<td>35</td>
<td>9.02253</td>
<td>0.25779</td>
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<td></td>
</tr>
</tbody>
</table>

R-sq. = 0.7534  R-sq-adj. = 0.7394
Model obeys hierarchy. The sum of squares for each term is computed assuming higher order terms are first removed.

Least Squares Components ANOVA, Response AVG Model DESIGN__AUTO__AVG

<table>
<thead>
<tr>
<th>0 Source</th>
<th>1 df</th>
<th>2 Sum Sq.</th>
<th>3 Mean Sq.</th>
<th>4 F-Ratio</th>
<th>5 Signif.</th>
<th>6 Transformed Term</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Constant</td>
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<td>479.60526</td>
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<tr>
<td>2 ~T</td>
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<td>0.0000</td>
<td>(((T-2.05e+03)/2.5e+01)</td>
</tr>
<tr>
<td>3 ~P</td>
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<td>3.57221</td>
<td>3.57221</td>
<td>13.86</td>
<td>0.0007</td>
<td>((P-5.5)/4.5)</td>
</tr>
<tr>
<td>4 Residual</td>
<td>35</td>
<td>9.02253</td>
<td>0.25779</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

~ indicates factors are transformed.  R-sq. = 0.7534  R-sq-adj. = 0.7394
Default sum of squares.
Model obeys hierarchy. The sum of squares for each term is computed assuming higher order terms are first removed.
Appendix A-4U (cont.)

Main Effects on Response AVGs
(with 95% confidence intervals)

T: 2025 to 2075
P: 1 to 10

Increase in AVG

AVGS vs TEMP, Adjusted for Remaining Predictors
using Mulreg @EXPT_MULREG, Model DESIGN_AUTO_AVG

AVGS vs PRESOAK, Adjusted for Remaining Predictors
using Mulreg @EXPT_MULREG, Model DESIGN_AUTO_AVG

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Appendix A-4U (cont.)

Case Order Graph of Residuals of AVG
Using Studentized Residuals in Model DESIGN__AUTO__AVG

Residuals of AVG vs Fitted Values
Using Studentized Residuals in Model DESIGN__AUTO__AVG

Normal Probability Plot of Residuals of AVG
Using Studentized Residuals in Model DESIGN__AUTO__AVG
(Sample size = 38)

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Appendix A-4U (cont.)

Histogram of Residuals of AVG
Using Studentized Residuals in Model DESIGN__AUTO__AVG
(Sample size = 38)

0 Factor, Response 1 Range or Formula 2 Initial 3 Optimal Setting Value

<table>
<thead>
<tr>
<th>1 Factors</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 TEMP</td>
</tr>
<tr>
<td>3 PRESOAK</td>
</tr>
</tbody>
</table>

5 Responses
6 AVGS MAX 4.8616

Converged to a tolerance of 0.00046 after 29 steps.

Predictions and 95% simultaneous confidence intervals
for mean responses of AVGS using model DESIGN__AUTO__AVG
P = 1.0088
Appendix A-4U (cont.)

Predictions and 95% simultaneous confidence intervals for mean responses of AVGS using model DESIGN__AUTO__AVG

$T = 2025.1$

---

**Graph 1:** AVGS vs. PRESOAK

**Graph 2:** AVGS vs. TEMP

---

NASA/TM—2001-210901
Appendix A-5C

Least Squares Coefficients, Response AVA, Model DESIGN__AUTO__AVA

<table>
<thead>
<tr>
<th>Term</th>
<th>Coeff.</th>
<th>Std. Error</th>
<th>T-value</th>
<th>Signif.</th>
<th>Transformed Term</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-0.499171</td>
<td>0.086190</td>
<td>-9.84</td>
<td>0.0001</td>
<td>(T-2.05e+03)/2.5e+01</td>
</tr>
<tr>
<td>2</td>
<td>-1.066667</td>
<td>0.108427</td>
<td>-9.84</td>
<td>0.0002</td>
<td>(P-5.5)/4.5</td>
</tr>
<tr>
<td>3</td>
<td>-0.428152</td>
<td>0.088501</td>
<td>-4.84</td>
<td>0.0001</td>
<td>(T-2.05e+03)/2.5e+01</td>
</tr>
<tr>
<td>4</td>
<td>0.197674</td>
<td>0.108385</td>
<td>1.82</td>
<td>0.0882</td>
<td>(LSR+3.5)/5e-01</td>
</tr>
</tbody>
</table>

No. cases = 19  R-sq. = 0.8917  RMS Error = 0.3756
Resid. df = 15  R-sq-adj. = 0.8700  Cond. No. = 1.022

~ indicates factors are transformed.

Least Squares Summary ANOVA, Response AVA Model DESIGN__AUTO__AVA

<table>
<thead>
<tr>
<th>Source</th>
<th>df</th>
<th>Sum Sq.</th>
<th>Mean Sq.</th>
<th>F-Ratio</th>
<th>Signif.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total(Corr.)</td>
<td>18</td>
<td>19.5400</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Regression</td>
<td>3</td>
<td>17.4238</td>
<td>5.80795</td>
<td>41.17</td>
<td>0.0000</td>
</tr>
<tr>
<td>Residual</td>
<td>15</td>
<td>2.11815</td>
<td>0.14108</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

R-sq. = 0.8917
R-sq-adj. = 0.8700
Model obeys hierarchy. The sum of squares for each term is computed assuming higher order terms are first removed.

Least Squares Components ANOVA, Response AVA Model DESIGN__AUTO__AVA

<table>
<thead>
<tr>
<th>Source</th>
<th>df</th>
<th>Sum Sq.</th>
<th>Mean Sq.</th>
<th>F-Ratio</th>
<th>Signif.</th>
<th>Transformed Term</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant</td>
<td>1</td>
<td>4.7500</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>~T</td>
<td>1</td>
<td>13.6533</td>
<td>13.6533</td>
<td>96.78</td>
<td>0.0000</td>
<td>(T-2.05e+03)/2.5e+01</td>
</tr>
<tr>
<td>~P</td>
<td>1</td>
<td>3.30180</td>
<td>3.30180</td>
<td>23.40</td>
<td>0.0002</td>
<td>(P-5.5)/4.5</td>
</tr>
<tr>
<td>~LSR</td>
<td>1</td>
<td>0.46926</td>
<td>0.46926</td>
<td>3.33</td>
<td>0.0882</td>
<td>(LSR+3.5)/5e-01</td>
</tr>
<tr>
<td>Residual</td>
<td>15</td>
<td>2.11615</td>
<td>0.14108</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

~ indicates factors are transformed. R-sq. = 0.8917
R-sq-adj. = 0.8700
Default sum of squares.
Model obeys hierarchy. The sum of squares for each term is computed assuming higher order terms are first removed.
Appendix A-5C (cont.)

Main Effects on Response AVALA
(with 95% confidence intervals)

T: 2025 to 2075
P: 1 to 10
LSR: -4 to -3

Increase in AVALA

AVALA vs LOGSTRART, Adjusted for Remaining Predictors
Using Mulreg @EXPT@MULREG, Model DESIGN__AUTO__AVA

AVALA vs TEMP, Adjusted for Remaining Predictors
Using Mulreg @EXPT@MULREG, Model DESIGN__AUTO__AVA
Appendix A-5C (cont.)

AVALA vs PRESOAK, Adjusted for Remaining Predictors
Using Mulreg @EXPT@MULREG, Model DESIGN_AUTO_AVA

![Graph Image]

- Adjusted Data Values
- Adjusted Fitted Curve

Case Order Graph of Residuals of AVALA
Using Studentized Residuals in Model DESIGN_AUTO_AVA

![Graph Image]

Residuals of AVALA vs Fitted Values
Using Studentized Residuals in Model DESIGN_AUTO_AVA

![Graph Image]
Appendix A-5C (cont.)

Normal Probability Plot of Residuals of AVA
Using Studentized Residuals in Model DESIGN.AUTO.AVA
(Sample size = 19)

Histogram of Residuals of AVA
Using Studentized Residuals in Model DESIGN.AUTO.AVA
(Sample size = 19)

<table>
<thead>
<tr>
<th>0 Factor, Response or Formula</th>
<th>1 Range</th>
<th>2 Initial Setting</th>
<th>3 Optimal Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Factors</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2 TEMP</td>
<td>2025 TO 2075</td>
<td>2050</td>
<td>2025</td>
</tr>
<tr>
<td>3 PRESOAK</td>
<td>2 TO 10</td>
<td>5.5</td>
<td>1.0001</td>
</tr>
<tr>
<td>4 LOGSTRART</td>
<td>-4 TO -3</td>
<td>-3.5</td>
<td>-3.0015</td>
</tr>
<tr>
<td>5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6 Responses</td>
<td>MAX</td>
<td></td>
<td>1.1916</td>
</tr>
</tbody>
</table>

Converged to a tolerance of 0.0004 after 65 steps.
Appendix A-5C (cont.)

Predictions and 95% simultaneous confidence intervals for mean responses of AVALA using model DESIGN.AUTO.AVA
P = 1.0001, LSR = -3.0015

Predictions and 95% simultaneous confidence intervals for mean responses of AVALA using model DESIGN.AUTO.AVA
LSR = -3.0015, T = 2025

Predictions and 95% simultaneous confidence intervals for mean responses of AVALA using model DESIGN.AUTO.AVA
T = 2025, P = 1.0001

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Appendix A-5C (cont.)

AVALA
LOGSTART = -3.0015

TEMP
--- AVALA

AVALA
PRESOAK = 1.0001

TEMP
--- AVALA

AVALA
TEMP = 2025

Predictions and 95% simultaneous confidence intervals
for mean responses of AVALA using model DESIGN自动AVA
LSR = -3

P = 2025
-------------------------------
Lower 0.293091
S Predicted 0.812742
Upper 1.432393
Appendix A-5U

Least Squares Coefficients, Response AVA, Model DESIGN__AUTO__AVA

<table>
<thead>
<tr>
<th>Term</th>
<th>Coeff.</th>
<th>Std. Error</th>
<th>T-value</th>
<th>Signif.</th>
<th>Transformed Term</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-0.496379</td>
<td>0.066884</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>-1.062500</td>
<td>0.084141</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>-0.425361</td>
<td>0.08678</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>0.206261</td>
<td>0.084108</td>
<td>2.45</td>
<td>0.0197</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>-0.179167</td>
<td>0.084141</td>
<td>-2.13</td>
<td>0.0408</td>
<td></td>
</tr>
</tbody>
</table>

No. cases = 38  R-sq. = 0.8633  RMS Error = 0.4122
Resid. df = 33  R-sq-adj. = 0.8467  Cond. No. = 1.022
~ indicates factors are transformed.

Least Squares Summary ANOVA, Response AVA Model DESIGN__AUTO__AVA

<table>
<thead>
<tr>
<th>Source</th>
<th>df</th>
<th>Sum Sq.</th>
<th>Mean Sq.</th>
<th>F-Ratio</th>
<th>Signif.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total(Corr.)</td>
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<td>41.00974</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Regression</td>
<td>4</td>
<td>35.40267</td>
<td>8.85067</td>
<td>52.09</td>
<td>0.0000</td>
</tr>
<tr>
<td>Linear</td>
<td>3</td>
<td>34.63225</td>
<td>11.54408</td>
<td>67.94</td>
<td>0.0000</td>
</tr>
<tr>
<td>Non-linear</td>
<td>1</td>
<td>0.77042</td>
<td>0.77042</td>
<td>4.53</td>
<td>0.0408</td>
</tr>
<tr>
<td>Residual</td>
<td>33</td>
<td>5.60707</td>
<td>0.16991</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

R-sq. = 0.8633  R-sq-adj. = 0.8467
Model obeys hierarchy. The sum of squares for each term is computed assuming higher order terms are first removed.

Least Squares Components ANOVA, Response AVA Model DESIGN__AUTO__AVA

<table>
<thead>
<tr>
<th>Source</th>
<th>df</th>
<th>Sum Sq.</th>
<th>Mean Sq.</th>
<th>F-Ratio</th>
<th>Signif.</th>
<th>Transformed Term</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant</td>
<td>1</td>
<td>9.40026</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>~T</td>
<td>1</td>
<td>27.09375</td>
<td>27.09375</td>
<td>159.50</td>
<td>0.0000</td>
<td>((T-2.05e+03)/2.5e+01)</td>
</tr>
<tr>
<td>~P</td>
<td>1</td>
<td>6.51780</td>
<td>6.51780</td>
<td>38.36</td>
<td>0.0000</td>
<td>((P-5.5)/4.5)</td>
</tr>
<tr>
<td>~LSR</td>
<td>1</td>
<td>1.02183</td>
<td>1.02183</td>
<td>6.01</td>
<td>0.0197</td>
<td>((LSR+3.5)/5e-01)</td>
</tr>
</tbody>
</table>
| ~T*P   | 1 | 0.77042  | 0.77042  | 4.53   | 0.0408 | ((T-2.05e+03)/2.5e+01)*(
| Residual | 33 | 5.60707  | 0.16991  |        |         |                  |

~ indicates factors are transformed. R-sq. = 0.8633  R-sq-adj. = 0.8467
Default sum of squares.
Model obeys hierarchy. The sum of squares for each term is computed assuming higher order terms are first removed.
Main Effects on Response AVALA
(with 95% Confidence Intervals)

T: 2025 to 2075
P: 1 to 10
LSR: -4 to -3

Interaction Effects of TEMP with PRESOAK
on Response AVALA

95% Confidence Intervals
for Increase in AVALA

AVALA vs TEMP, Adjusted for Remaining Predictors
Using Mulreg @EXPT@MULREG, Model DESIGN__AUTO__AVA
Appendix A-5U (cont.)

AVALA vs PRESOAK, Adjusted for Remaining Predictors
Using Mulreg @EXPT@MULREG, Model DESIGN__AUTO__AVA

AVALA vs LOGSTRART, Adjusted for Remaining Predictors
Using Mulreg @EXPT@MULREG, Model DESIGN__AUTO__AVA

Case Order Graph of Residuals of AVA
Using Studentized Residuals in Model DESIGN__AUTO__AVA

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Appendix A-5U (cont.)

Residuals of AVA vs Fitted Values
Using Studentized Residuals in Model DESIGN__AUTO__AVA

Normal Probability Plot of Residuals of AVA
Using Studentized Residuals in Model DESIGN__AUTO__AVA
(Sample size = 38)

Histogram of Residuals of AVA
Using Studentized Residuals in Model DESIGN__AUTO__AVA
(Sample size = 38)
Appendix A-5U (cont.)

<table>
<thead>
<tr>
<th>0 Factor, Response</th>
<th>1 Range</th>
<th>2 Initial Setting</th>
<th>3 Optimal or Formula Setting Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Factors</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 TEMP</td>
<td>2025 to 2075</td>
<td>2050</td>
<td>2025</td>
</tr>
<tr>
<td>2 PRESOAK</td>
<td>1 to 10</td>
<td>5.5</td>
<td>1.0016</td>
</tr>
<tr>
<td>3 LOGSTRT</td>
<td>-4 to -3</td>
<td>-3.5</td>
<td>-3.0003</td>
</tr>
<tr>
<td>4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6 Responses</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7 AVALA</td>
<td>MAX</td>
<td></td>
<td>1.0176</td>
</tr>
</tbody>
</table>

Converged to a tolerance of 0.00043 after 69 steps.

Predictions and 95% simultaneous confidence intervals for mean responses of AVALA using model DESIGN_AUTO_AVA

\[ P = 1.0016, \text{LSR} = -3.0003 \]

![Graph showing predictions and confidence intervals for AVALA vs. TEMP]

Predictions and 95% simultaneous confidence intervals for mean responses of AVALA using model DESIGN_AUTO_AVA

\[ \text{LSR} = -3.0003, T = 2025 \]

![Graph showing predictions and confidence intervals for AVALA vs. PRESOAK]
Appendix A-5U (cont.)

Predictions and 95% simultaneous confidence intervals for mean responses of AVALA using model DESIGN_AUTO_AVA

\[ T = 2025, \quad P = 1.0016 \]

\[
\begin{array}{cccccccccccc}
-4.0 & -3.9 & -3.8 & -3.7 & -3.6 & -3.5 & -3.4 & -3.3 & -3.2 & -3.1 & -3.0 \\
\hline
0.0 & 0.5 & 1.0 & 1.5 & 2.0 & \\
\hline
\end{array}
\]

\[ \text{LOGSTART} \]

\[
\begin{array}{cccccccccccc}
2025 & 2030 & 2035 & 2040 & 2045 & 2050 & 2055 & 2060 & 2065 & 2070 & 2075 \\
\hline
0.0 & 0.2 & 0.4 & 0.6 & 0.8 & \\
\hline
\end{array}
\]

\[ \text{AVALA} \]

\[ \text{PRESOAK} = 1.0016 \]

\[
\begin{array}{cccccccccccc}
-4.0 & -3.5 & -3.0 & -2.5 & -2.0 & -1.5 & -1.0 & -0.5 & 0.0 & 0.5 & 1.0 \\
\hline
0.0 & 0.2 & 0.4 & 0.6 & 0.8 & 1.0 & \\
\hline
\end{array}
\]

\[ \text{LOGSTART} = -3.0003 \]

\[
\begin{array}{cccccccccccc}
2025 & 2030 & 2035 & 2040 & 2045 & 2050 & 2055 & 2060 & 2065 & 2070 & 2075 \\
\hline
0.0 & 0.2 & 0.4 & 0.6 & 0.8 & 1.0 & 1.2 & 1.4 & 1.6 & 1.8 & \\
\hline
\end{array}
\]

\[ \text{AVALA} \]

\[ \text{AVA} \]
Appendix A-5U (cont.)

AVALA
TEMPE = 2025

Predictions and 95% simultaneous confidence intervals
for mean responses of AVALA using model DESIGN.AUTO.AVA
LSR = -3

P = T = 2025

<table>
<thead>
<tr>
<th>Lower</th>
<th>Predicted</th>
<th>Upper</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.312069</td>
<td>0.799737</td>
<td>1.287406</td>
</tr>
</tbody>
</table>
Appendix A-6C

Least Squares Coefficients, Response SDG, Model DESIGN__AUTO__SDG

<table>
<thead>
<tr>
<th>Term</th>
<th>Coeff.</th>
<th>Std. Error</th>
<th>T-value</th>
<th>Signif.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.357895</td>
<td>0.068105</td>
<td>5.26</td>
<td>0.0001</td>
</tr>
</tbody>
</table>

No. cases = 19  R-sq. = 0.0000  RMS Error = 0.2969
Resid. df = 18  R-sq-adj. = 0.0000  Cond. No. = 1

Least Squares Summary ANOVA, Response SDG Model DESIGN__AUTO__SDG

<table>
<thead>
<tr>
<th>Source</th>
<th>df</th>
<th>Sum Sq.</th>
<th>Mean Sq.</th>
<th>F-Ratio</th>
<th>Signif.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total(Corr.)</td>
<td>18</td>
<td>1.586316</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Regression</td>
<td>0</td>
<td>0.000000</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Residual</td>
<td>18</td>
<td>1.586316</td>
<td>0.088129</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

R-sq. = 0.0000  R-sq-adj. = 0.0000
Model obeys hierarchy. The sum of squares for each term is computed assuming higher order terms are first removed.

Least Squares Coefficients, Response SDA, Model DESIGN__AUTO__SDA

<table>
<thead>
<tr>
<th>Term</th>
<th>Coeff.</th>
<th>Std. Error</th>
<th>T-value</th>
<th>Signif.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.247368</td>
<td>0.042830</td>
<td>5.78</td>
<td>0.0001</td>
</tr>
</tbody>
</table>

No. cases = 19  R-sq. = 0.0000  RMS Error = 0.1867
Resid. df = 18  R-sq-adj. = 0.0000  Cond. No. = 1

Least Squares Summary ANOVA, Response SDA Model DESIGN__AUTO__SDA

<table>
<thead>
<tr>
<th>Source</th>
<th>df</th>
<th>Sum Sq.</th>
<th>Mean Sq.</th>
<th>F-Ratio</th>
<th>Signif.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total(Corr.)</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Regression</td>
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<td>0.0000000</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Residual</td>
<td>18</td>
<td>0.6273684</td>
<td>0.0348538</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

R-sq. = 0.0000  R-sq-adj. = 0.0000
Model obeys hierarchy. The sum of squares for each term is computed assuming higher order terms are first removed.
Appendix A-6U

Bisquare Coefficients, Response $\log_{10}SDG$, Model DESIGN_AUTO_SDG

<table>
<thead>
<tr>
<th>Term</th>
<th>Coeff.</th>
<th>Std. Error</th>
<th>T-value</th>
<th>Signif.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$-T$</td>
<td>0.394899</td>
<td>0.090187</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$-LSR$</td>
<td>-0.192353</td>
<td>0.090137</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$-T*LSR$</td>
<td>-0.259390</td>
<td>0.110399</td>
<td>-2.35</td>
<td>0.0247</td>
</tr>
</tbody>
</table>

No. cases = 38  R-sq. = 0.4657  RMS Error = 0.4417
Resid. df = 34  R-sq-adj. = 0.4186  Cond. No. = 1.021
~ indicates factors are transformed.

Bisquare Summary ANOVA, Response $\log_{10}SDG$ Model DESIGN_AUTO_SDG

<table>
<thead>
<tr>
<th>Source</th>
<th>df</th>
<th>Sum Sq.</th>
<th>Mean Sq.</th>
<th>F-Ratio</th>
<th>Signif.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total(Corr.)</td>
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<td>12.41884</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Regression</td>
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<td>9.88</td>
<td>0.0001</td>
</tr>
<tr>
<td>Linear</td>
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<td>4.70673</td>
<td>2.35337</td>
<td>12.06</td>
<td>0.0001</td>
</tr>
<tr>
<td>Non-linear</td>
<td>1</td>
<td>1.07729</td>
<td>1.07729</td>
<td>5.52</td>
<td>0.0247</td>
</tr>
<tr>
<td>Residual</td>
<td>34</td>
<td>6.63482</td>
<td>0.19514</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

R-sq. = 0.4657  R-sq-adj. = 0.4186
Model obeys hierarchy. The sum of squares for each term is computed assuming higher order terms are first removed.

Bisquare Components ANOVA, Response $\log_{10}SDG$ Model DESIGN_AUTO_SDG

<table>
<thead>
<tr>
<th>Source</th>
<th>df</th>
<th>Sum Sq.</th>
<th>Mean Sq.</th>
<th>F-Ratio</th>
<th>Signif.</th>
</tr>
</thead>
<tbody>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
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<td>3.81805</td>
<td>19.57</td>
<td>0.0001</td>
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<td>0.88868</td>
<td>0.88868</td>
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<td>0.0401</td>
</tr>
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<td>$-T*LSR$</td>
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<td>1.07729</td>
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<td>0.0247</td>
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<tr>
<td>Residual</td>
<td>34</td>
<td>6.63482</td>
<td>0.19514</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

~ indicates factors are transformed. R-sq. = 0.4657  R-sq-adj. = 0.4186
Default sum of squares.
Model obeys hierarchy. The sum of squares for each term is computed assuming higher order terms are first removed.

NASA/TM—2001-210901  86
Appendix A-6U (cont.)

**Mulreg @EXPT*MULREG, Model DESIGN_AUTO_SDG**

Main Effects on Transformed Response SDGS
(with 95% Confidence Intervals)

- **T:** 2025 to 2075
- **LSR:** -4 to -3

Increase in Transformed SDG

---

**Mulreg @EXPT*MULREG, Model DESIGN_AUTO_SDG**

Interaction Effects of TEMP with LOGSTART
On Transformed Response SDGS

- **T:** 2025 to 2075
- **LSR:** -4 to -3
- **T:** 2025
- **T:** 2075

95% Confidence Intervals
For Increase in Transformed SDGS

---

**SDGS vs TEMP, Adjusted for Remaining Predictors**
Using Mulreg @EXPT*MULREG, Model DESIGN_AUTO_SDG

- **TRANSDG**
- **TEMP**

Adjusted Data Values
- Adjusted Fitted Curve
Appendix A-6U (cont.)

**SDGS vs LOGSTRART, Adjusted for Remaining Predictors**
Using Muleg EXPTMULREG, Model DESIGN_AUTO_SDG

---

**Case Order Graph of Residuals of Transformed SDG**
Using Studentized Residuals in Model DESIGN_AUTO_SDG

---

**Residuals of Transformed SDG vs Fitted Values**
Using Studentized Residuals in Model DESIGN_AUTO_SDG
Appendix A-6U (cont.)

Normal Probability Plot of Residuals of Transformed SDG
Using Studentized Residuals in Model DESIGN__AUTO__SDG
(Sample size = 38)

Histogram of Residuals of Transformed SDG
Using Studentized Residuals in Model DESIGN__AUTO__SDG
(Sample size = 38)

<table>
<thead>
<tr>
<th>0 Factor, Response 1 Range or Formula</th>
<th>2 Initial Setting</th>
<th>3 Optimal Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Factors</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2 TEMP</td>
<td>2025 to 2075</td>
<td>2050</td>
</tr>
<tr>
<td>3 LOGSTRART</td>
<td>-4 to -3</td>
<td>-3.5</td>
</tr>
<tr>
<td>4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5 Responses</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6 SDGS</td>
<td>MIN</td>
<td>0.19518</td>
</tr>
</tbody>
</table>

converged to a tolerance of 0.00009 after 43 steps.
Appendix A-6U (cont.)

Predictions and 95% simultaneous confidence intervals for mean responses of SDGS using model DESIGN_AUTO_SDG

LSR = -3.9999

Predictions and 95% simultaneous confidence intervals for mean responses of SDGS using model DESIGN_AUTO_SDG

T = 2025

Predictions and 95% simultaneous confidence intervals for mean responses of SDGS using model DESIGN_AUTO_SDG

LSR T=2025

-3 Predicted 0.223081
Upper 0.407435
High Temperature, Slow Strain Rate Forging of Advanced Disk Alloy ME3

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Forging: Superalloy; Disk; Grain size; Thermomechanical processing

The advanced disk alloy ME3 was designed in the HSR/EPM disk program to have extended durability at 1150 to 1250 °F in large disks. This was achieved by designing a disk alloy and process producing balanced monotonic, cyclic, and time-dependent mechanical properties, combined with robust processing and manufacturing characteristics. The resulting baseline alloy, processing, and supersolvus heat treatment produces a uniform, relatively fine mean grain size of about ASTM 7, with as-large-as (ALA) grain size of about ASTM 3. There is a long term need for disks with higher rim temperature capabilities than 1250 °F. This would allow higher compressor exit (T3) temperatures and allow the full utilization of advanced combustor and airfoil concepts under development. Several approaches are being studied to improve the high temperature and time-dependent capabilities of disk alloys to coarsen the grain size. A coarser grain size than ASTM 7 could potentially be achieved by varying the forging conditions and supersolvus heat treatment. The objective of this study was to perform forging and heat treatment experiments ("thermomechanical processing experiments") on small compression test specimens of the baseline ME3 composition, to identify a viable forging process allowing significantly coarser grain size targeted at ASTM 3–5, than that of the baseline. ASTM 7.