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EXPERIMENTAL DETERMINATION OF CRITICAL PHYSICAL PARAMETERS AFFECTING JA2 PROPELLANT GRAIN RESPONSE, PHASE I: SCREENING DESIGN

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Uniaxial compression tests are performed on single grain, seven-perforation JA2 propellant specimens using a statistically-based, 2^4 (factorial) design strategy. A total of sixteen tests are performed and a mechanical response surface is generated over the range of continuous variables, strain rate (10^{-4} and 500 sec^{-1}), temperature (0 and 60 degrees Celsius), and specimen aspect ratio (0.8 and 1.3), and discrete variable, specimen end lubrication ("yes" or "no"). It is found that specimen end lubrication reduces the variability of the mechanical response of JA2 but does not affect the magnitude of the mechanical response as characterized by the yield stress, yield strain, compressive modulus, and strain energy absorbed at yield. The specimen aspect ratio did not affect the mechanical response of JA2 because of the limited aspect ratio range investigated. The mechanical response of JA2 is well represented by a second degree polynomial model, since the RMS errors between data and model are only slightly greater than standard deviations in the mechanical response derived from prior replicate testing of JA2.

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1. INTRODUCTION

Constitutive models for deformable media are developed by performing material tests, preferably under environmental conditions which are identical to those in the service environment. The environmental conditions are implicitly assumed to be measurable and controllable independent variables such as temperature, pressure, and relative humidity. Complications arise in the development of constitutive models if the service environment conditions are harsh, unknown or impossible to exactly reproduce in laboratory testing.

The "classical" one-factor-at-a-time[1] material test program proceeds by testing the material over the operating range of a particular variable, while the other variables are held constant at a value within their respective ranges. The test program can become time consuming and costly if the effects of a number of variables are to be investigated. Furthermore, if nonlinear effects (interaction, curvature) are present among the variables, one-factor-at-a-time experimentation will not detect them. As an alternative, a statistically valid experimental design strategy can be used to minimize the total number of tests performed and to maximize the amount and quality of information that is obtained.

This report describes the implementation of a statistically based experimental design strategy for evaluating the relative importance of three independent continuous variables, i.e., temperature, strain rate, and specimen aspect ratio (L/D), and one independent discrete variable, specimen end lubrication, in predicting the uniaxial compressive mechanical response of JA2 gun propellant. The design strategy lends itself to the development of a mechanical response model whose prediction error is comparable to the standard deviation obtained in replicate testing. Since a hierarchy of importance in the independent variables will be established, the experiments will essentially form a screening design. JA2 gun propellant has been shown to be a rate-sensitive and temperature-sensitive material[2,3], and in a variety of materials, the specimen aspect ratio and degree of end lubrication affects the mechanical response by perturbing the homogeneous stress state in the specimen during uniaxial compression[4]. Although other variables, such as relative humidity and hydrostatic pressure, may affect the mechanical response of the propellant, these variables are not investigated since they are not directly controllable with the experimental apparatus.

2. EXPERIMENTAL METHOD

2.1 Apparatus, Data Acquisition and Data Reduction. The High Rate 810 MTS Material Test System (Figure 1) consists of a conventional two-pole press with a servohydraulically actuated ram that operates from quasistatic velocities to a maximum velocity of about 12 m/sec; the maximum velocity imparts a maximum strain rate of 1200 sec^{-1} on a 10 mm long specimen. A Thermotron oven/refrigerator

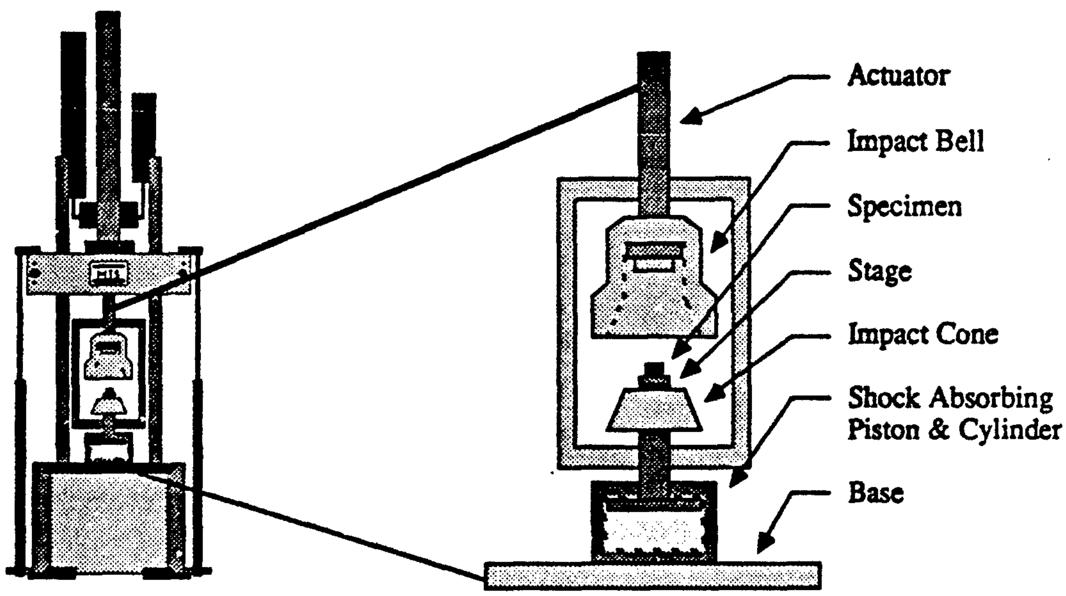

Figure 1. Servohydraulic Test Apparatus with Upper Bell and Impact Cone Piston Assembly.

environmental chamber surrounds the upper and lower piston which helps to maintain a constant test temperature. Gun propellant specimens are thermally conditioned within the chamber for at least one hour prior to testing at a given temperature. A more complete description of the servohydraulic test apparatus can be found in the initial report by Gazonas[2]. Uniaxial compression tests are performed at constant strain rate by computer control of the piston velocity via feedback from an externally-mounted displacement transducer (LVDT). Force measurements are made with a 60 kN quartz force gage that is mounted on the upper moving piston. The raw force and displacement data are acquired, stored, and then analyzed with a Norland 3001 data acquisition system. The raw force and displacement data are reduced to engineering stress versus strain plots by normalizing to initial specimen area and length respectively, and correcting for apparatus distortion as previously reported[2]. The uniaxial compression test results for this material are highly reproducible and are illustrated by plotting the results for five replicate tests at strain rates of 10^{-2} and 200 sec^{-1} (Figure 2).

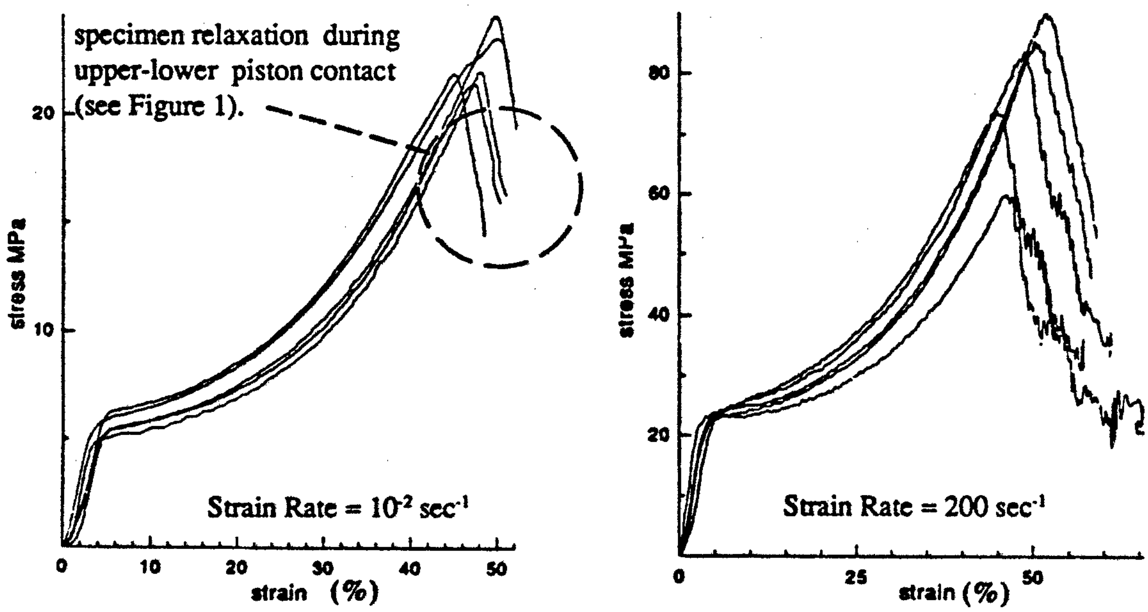

Figure 2. Experimental Reproducibility of the Mechanical Response of JA2 in Uniaxial Compression at Strain Rates of 10^{-2} and 200 sec^{-1}.

2.2 Specimen Preparation. Right circular cylinders of JA2 (lot # 81E001S110) propellant are cut from seven-perforation granular stock using an Isomet double-bladed diamond saw. A double-bladed saw is used to cut specimen ends parallel to each other and to help maintain coaxial deformation with the cylinder axis. Specimens with aspect ratios, length-to-diameter (L/D), of 0.8 and 1.3 are tested, with a limit on the upper L/D set by the initial length of the granular stock. The specimen diameters averaged 8.72 mm and the perforation diameters averaged 0.483 mm. Molybdenum disulfide , MoS_2, is applied sparingly to the specimen ends in those tests that require end lubrication.

2.3 Experimental Design. A 2^4 (factorial) experimental design is utilized[1]; the name of the design arises from having four independent, controllable, variables. We test these variables at two levels (low and high). The total possible number of low/high combinations is thus 2^4, yielding sixteen experiments.

Recall that three of our independent variables (strain rate, aspect ratio, and temperature) are continuous throughout their respective ranges. The fourth variable is discrete, "yes" or "no", corresponding to whether lubrication is present or not present. A desirable feature of the family of factorial designs is the ability to accommodate both continuous and discrete variables.

The present design is orthogonal since there is no correlation (linear association) between the independent variables. The orthogonal design assumes that any estimate of a factor effect (e.g. specimen aspect ratio) is independent of the effects of all others, whether they are linear or nonlinear. In some cases, variables which were initially assumed to be independent, may in fact be dependent upon one another. For example, the coupling of thermodynamic and mechanical fields becomes important in media subjected to inertial loading[5]. Thermomechanical coupling is assumed to be negligible in our tests.

An experimenter often encounters a situation where one or more environmental factors are present which cannot be directly controlled in the experiment. An example might be a drifting ambient relative humidity in the laboratory. The tests are conducted in random order to minimize the confounding effects of environmental variables. In our case the sixteen experiments are performed in a statistically random order. Table 1. shows the experimental conditions (A=strain rate, B=temperature, C=aspect ratio, D=lubrication), the experimental responses (R1=yield stress, R2=yield strain, R3=absorbed energy, R4=compressive modulus), and the random order in which our sixteen experiments are executed. The standard order represents how the variables are permuted beginning at settings (low,low,low,low) and ending at settings (high,high,high,high). One can visualize the design endpoints in our 2^4 experimental design using a cube plot. Each vertex in the cube represents a "low" or "high" test condition for a particular experiment (Figure 3). Two cubes are needed to represent the sixteen experiments in our 2^4 design; one cube represents all lubricated experiments, and the second cube represents all unlubricated experiments.

In contrast, the experimenter would perform 80 tests using a "classical" test approach (Figure 4) to obtain mechanical responses at all sixteen experimental conditions addressed in this research; in this calculation, it is assumed that five tests are sufficient to ensure reproducibility at each experimental condition. However, this example (Figure 4) respresents a five-fold replication of the factorial design (Figure 3). The hidden replication present in factorial designs removes the necessity of performing multiple tests at each test condition. The actual number of tests required at each experimental condition,

Table 1. Experimental Protocol with Random Run Number and Experimental Responses. (DESIGN - EASE is a Trademark Name of a Product of STAT - EASE, Inc.)

DESIGN-EASE ANALYSIS TM

	Run Order	1	2	3	4
	Block	1	1	1	1
	Standard Order	2	14	12	9
A - STRAINRTE	LOG	2.7	2.7	2.7	-4
B - TEMPERATU	DEGREES C	0	0	60	0
C - ASPECTRAT	L/D	.8	1.3	.8	.8
D - LUBRICATE	DISCRETE	NONE	MOLYCOAT	MOLYCOAT	MOLYCOAT
R1 - STRESS	MPa	44.3000	34.9000	7.9700	4.3000
R2 - STRAIN	M/M	5.1000	3.3400	1.4800	3.9400
R3 - ENERGY	MPa	0.7880	0.5490	0.0570	0.1030
R4 - EMODULUS	MPa	1738.0000	1448.0000	667.0000	221.0000

DESIGN-EASE ANALYSIS

	Run Order	5	6	7	8
	Block	1	1	1	1
	Standard Order	15	8	3	5
A - STRAINRTE	LOG	-4	2.7	-4	-4
B - TEMPERATU	DEGREES C	60	60	60	0
C - ASPECTRAT	L/D	1.3	1.3	.8	1.3
D - LUBRICATE	DISCRETE	MOLYCOAT	NONE	NONE	NONE
R1 - STRESS	MPa	1.2600	6.1900	0.9600	5.3300
R2 - STRAIN	M/M	4.9600	1.8000	3.7900	2.4900
R3 - ENERGY	MPa	0.0370	0.0400	0.0170	0.0490
R4 - EMODULUS	MPa	36.6000	544.0000	27.7000	314.0000

DESIGN-EASE ANALYSIS

	Run Order	9	10	11	12
	Block	2	2	2	2
	Standard Order	7	16	6	4
A - STRAINRTE	LOG	-4	2.7	2.7	2.7
B - TEMPERATU	DEGREES C	60	60	0	60
C - ASPECTRAT	L/D	1.3	1.3	1.3	.8
D - LUBRICATE	DISCRETE	NONE	MOLYCOAT	NONE	NONE
R1 - STRESS	MPa	0.8340	5.7500	38.1000	6.0000
R2 - STRAIN	M/M	2.5400	1.8300	3.1400	0.8500
R3 - ENERGY	MPa	0.0090	0.0420	0.3780	0.0200
R4 - EMODULUS	MPa	37.2000	428.0000	3046.0000	977.0000

DESIGN-EASE ANALYSIS

	Run Order	13	14	15	16
	Block	2	2	2	2
	Standard Order	1	10	13	11
A - STRAINRTE	LOG	-4	2.7	-4	-4
B - TEMPERATU	DEGREES C	0	0	0	60
C - ASPECTRAT	L/D	.8	.8	1.3	.8
D - LUBRICATE	DISCRETE	NONE	MOLYCOAT	MOLYCOAT	MOLYCOAT
R1 - STRESS	MPa	4.0000	42.0000	6.2900	1.0900
R2 - STRAIN	M/M	1.7800	3.5200	2.8400	4.5600
R3 - ENERGY	MPa	0.0330	0.8140	0.0760	0.0180
R4 - EMODULUS	MPa	224.0000	1127.0000	273.0000	41.0000

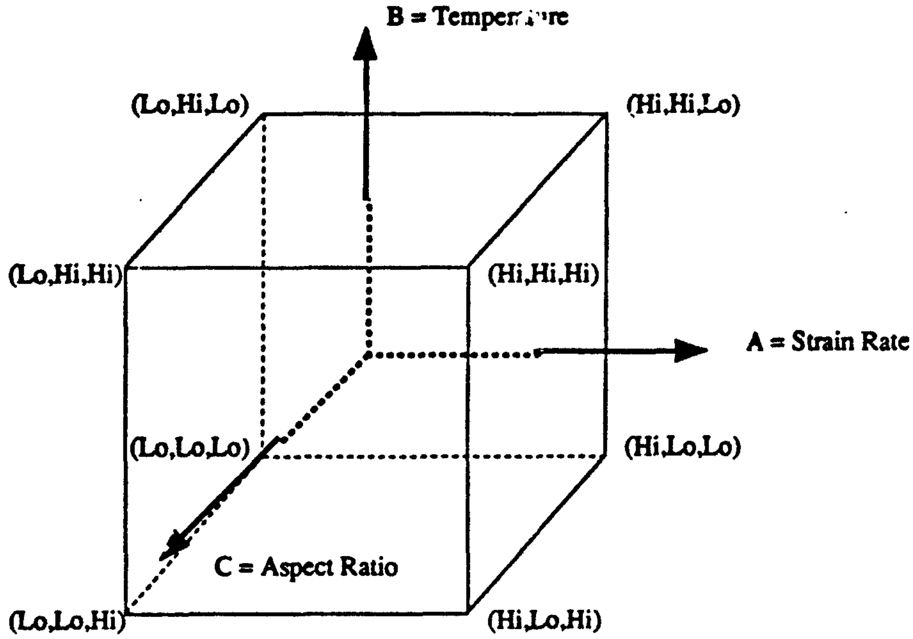

Figure 3. Cube Plot with 2^3 Design Points.

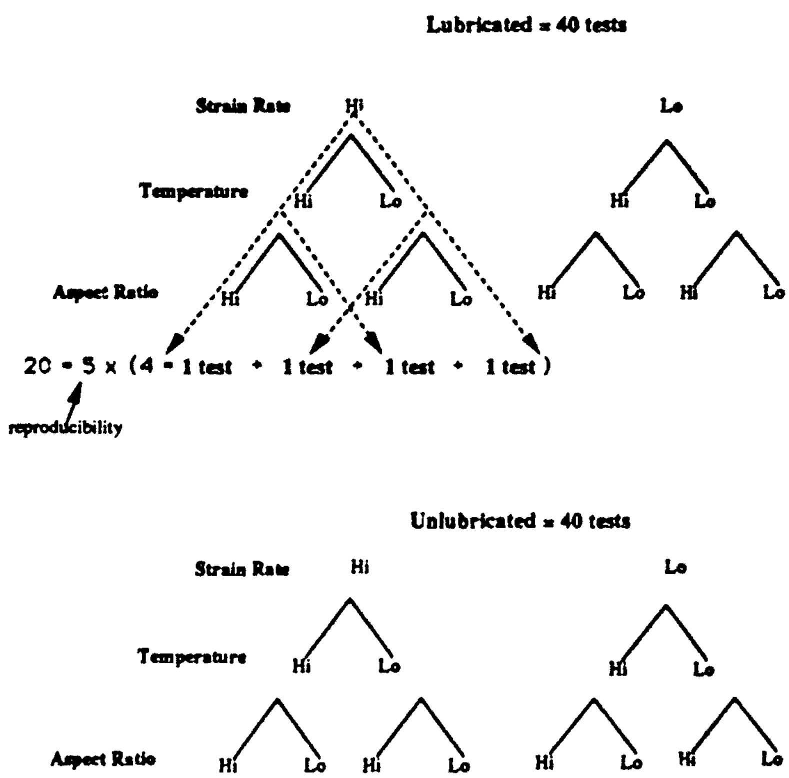

Figure 4. "Classical" Material Test Program for Strain Rate, Temperature, Aspect Ratio, and Specimen End Lubrication.

using the "classical" test approach, is directly proportional to the variance of the measured quantity and inversely proportional to the required tolerance[6].

The sixteen experiments in this phase of investigation serve as a screening function, rather than a basis for a predictive mathematical model. Specifically, we seek to determine which of the four independent, controllable variables have significant effects on the measured mechanical responses. In addition, we wish to determine the effect of the discrete variable, lubrication, on the mechanical response of the JA2 gun propellant.

3. EXPERIMENTAL RESULTS

The mechanical response of the JA2 propellant is characterized by the compressive modulus, stress and strain at yield, and absorbed strain energy density at yield (Figure 5). These particular measures of the mechanical response are chosen so that a comparison can be made with previous one-factor-at-a-time experiments[2,3].

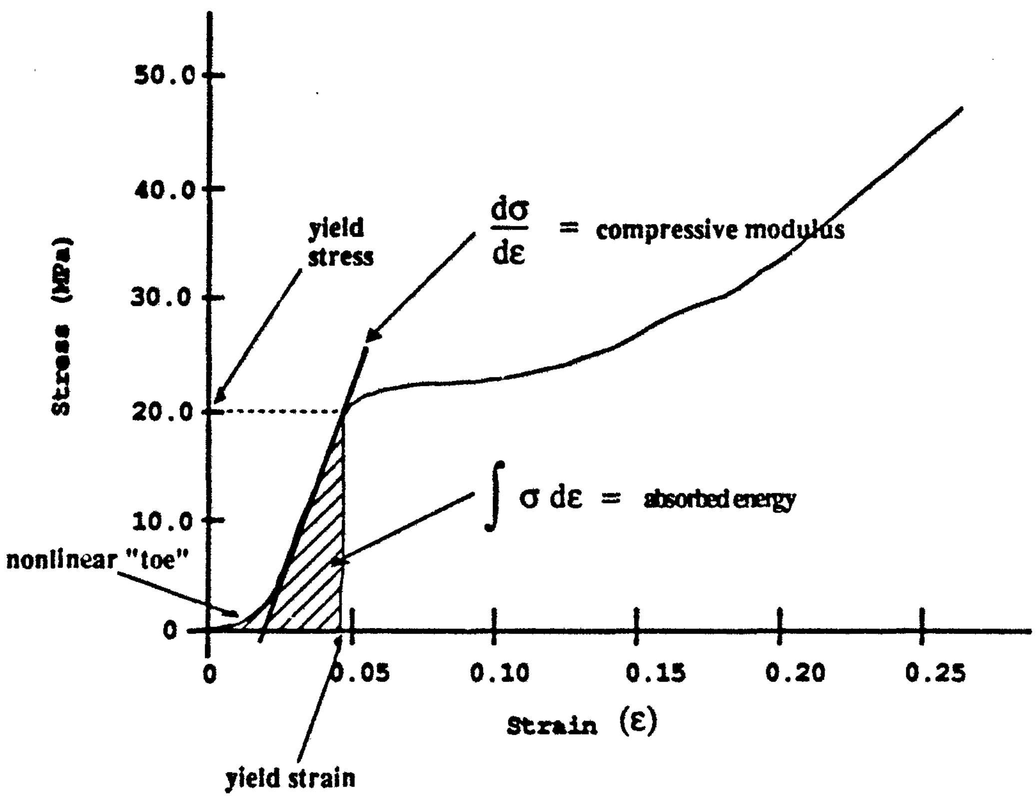

Figure 5. Measured Mechanical Responses.

The yield stress is defined as the stress level where the material most rapidly loses its ability to sustain load. The stress level is determined by finding the minimum in the second derivative of stress with respect to time[2]. The mechanical response is measured at the following independent variable endpoints: strain rate (10^{-4} and 500 sec^{-1}.), temperature (0 and 60 degrees Celsius), aspect ratio (0.8 and 1.3), and end lubrication (yes and no) (see Table 1). Cube plots which illustrate the stress at yield response of the JA2 propellant appear in Figure 6. The encircled numbers at the cube vertices include the yield stresses (in MPa) determined at the various experimental conditions (Table 1), and the random run numbers. The plots indicate that the yield stress increases as the strain rate increases, and decreases as the temperature is increased in both lubricated and unlubricated tests. In addition, there does not appear to be, by mere visual inspection of the plots, a yield stress dependence on specimen aspect ratio.

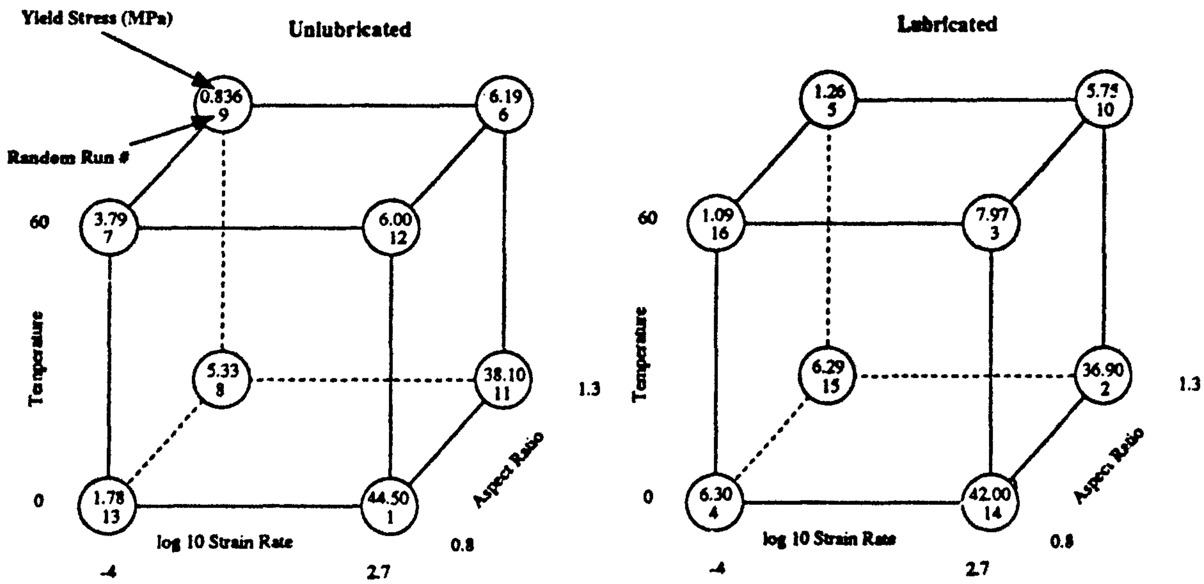

Figure 6. Cube Plots of Stress at Yield Response With and Without Specimen End Lubrication.

An inspection of the remaining cube plots (Appendix A, Figures A4, A7, and A10), indicates that in addition to the yield stress, the absorbed strain energy at the yield stress and the compressive modulus increase with an increase in strain rate, yet decrease with an increase in temperature. The strain at yield is independent of strain rate, temperature, and aspect ratio, yet increases if the specimen ends are lubricated.

4. DISCUSSION OF RESULTS

A mechanical response surface is generated to determine the relative linear and nonlinear contributions of the independent variables. In this research, the empirical response surface, Y, is written as a second degree polynomial expansion of the four independent variables, (X_1, X_2, X_3, and X_4) as:

$$Y = b_0 + b_1X_1 + b_2X_2 + b_3X_3 + b_4X_4 + b_{12}X_1X_2 + b_{13}X_1X_3 + b_{14}X_1X_4 + b_{23}X_2X_3 + b_{24}X_2X_4 + b_{34}X_3X_4$$

or, more generally as:

$$Y = b_0 + \sum_{i=1}^{q} b_iX_i + \sum_{i=1}^{q}\sum_{j\geq i}^{q} b_{ij}X_iX_j$$

where, $b_0 = \sum_{i=1}^{n} Y_i/n$ and q = the number of factors, n = total no. of experiments.

The b_i terms quantify the main effects of the independent, controllable variables. The b_{ij} terms describe the pairwise interaction effects of the independent variables. The intercept term, b_0, is simply the arithmetic mean of all the recorded responses. The second degree polynomial model is the fit to the data using standard least squares regression techniques. First, however, the actual numerical values of the independent variables, X_i, are standardized (nondimensionalized) to range from +1 for "high" experimental conditions, and -1 for "low" experimental conditions. By nondimensionalizing the variables, and ranking the magnitudes of the coefficients determined by regression analysis, one can determine the relative contribution of each variable to the measured mechanical response.

The coefficients, (b_0, b_i, and b_{ij}), of the linear and nonlinear terms in the second degree polynomial expansion with an alpha significance level of .05 or more are included in Table 2. A complete list of response coefficients appears in Appendix A (Figures A2, A5, A8, and A11). A positive coefficient for a particular variable, e.g., strain rate, indicates that the response, e.g., yield stress, increases if the controlled variable increases. A negative coefficient for a particular variable indicates that the response decreases if the controlled variable increases. In addition, the yield stress, absorbed strain energy, and the natural log of the compressive modulus is predicted to a high degree of precision since the adjusted R-square values are all greater than 0.91. Recall, the R-square statistic is one of several goodness-of-fit measures[1]. However, it is more difficult to predict the yield strain and compressive modulus as evidenced by the relatively low adjusted R-square values of 0.75, and 0.79 respectively (Table 2). An adjusted R-square of of 0.91 implies 91% of the total variation in our system is explained by the second degree polynomial model that was fit to the data. The R-square value is adjusted by normalizing the R-square statistic by the number of coefficients to be estimated. In addition, the adjusted R-square value represents contributions from all eleven terms, some of which are not significant at the alpha=.05 confidence level.

Table 2. Least Squares Regression Coefficients (alpha = .05).

RESPONSE	Const	$\dot{\varepsilon}$	T	A	L	$\dot{\varepsilon}$ T	$\dot{\varepsilon}$ A	$\dot{\varepsilon}$ L	TA	TL	AL	R^2_{adj} *	RMS **	s ***
Stress @ Yield	13.34	10.1	-9.58			-7.36						0.990	1.625	1.418
Strain @ Yield	3.12				.436	-.996						0.752	0.707	0.656
Energy @ Yield	.189	.146	-.159			-.137						0.916	0.082	0.046
Modulus	698.2	551.2	-350.9			-239.5						0.799	367.2	112.78
Ln (Mod)	5.75	1.20	-.746			.245		.128	-.14			0.985	n/a	n/a

$\dot{\varepsilon}$ = strain rate
T = temperature
A = aspect ratio
L = lubrication

* Adjusted R-square statistic.
** Root-Mean-Square error of data and model in this report.
*** Standard Deviation from Gazonas[2]

$$0 \le R^2_{adj} = 1 - \frac{\sum_i (Y_i - \hat{Y}_i)^2 / (n-p-1)}{\sum_i (Y_i - \bar{Y})^2 / (n-1)} \le 1$$

where n = no. of tests, p = no. of coefficients

$\bar{Y}$ = mean response, $\hat{Y}_i$ = estimated response

$$RMS = \sqrt{\sum_i (Y_i - \hat{Y}_i)^2 / (n-p-1)}$$

The variability in our estimates of the mechanical response is also quantified using the root-mean-square, RMS, error which agrees well with the error estimated from replicate tests[2] on JA2 gun propellant (Table 2). The RMS error includes contributions from both data-model mismatch and test variability.

The results of this sixteen-test study are corroborated by previous one-factor-at-a-time experiments[2,3] insofar as the JA2 compressive modulus, yield stress, and absorbed strain energy are found to increase with an increase in strain rate and decrease with an increase in temperature. The previous work[2] also corroborates the observation (Table 2.) that the yield strain is insensitive to strain rate. Some of the dominant nonlinear effects include a decrease in the yield stress, yield strain, and absorbed strain energy, and an increase in the compressive modulus, as both strain rate and temperature are simultaneously increased. Tests where the specimen ends are lubricated have less variability than tests where specimen ends are not lubricated. A comparison of the degree of variability between lubricated and unlubricated test results is illustrated by plotting the difference (residual) between the model prediction and the observed data for each measure of mechanical response as a function of whether or not lubrication is used (Appendix B). A higher degree of variability in the mechanical response is present in the unlubricated specimens even though they are relatively insensitive (all except strain at yield) to lubrication (Table 2). Some of the interesting coupled nonlinear effects include a decrease in the stress and strain at yield, and absorbed energy at yield, as both strain rate and temperature are simultaneously increased. The interaction of strain rate and temperature can be visualized with interaction surface plots (Appendix A, Figures A3, A6, A9, and A12). Additional linear and nonlinear responses are present (Table 2) but they are not significant at the alpha=.05 confidence level. The effects of aspect ratio and lubrication are discussed in more detail in the remainder of this section.

4.1 <u>Specimen Aspect Ratio.</u> The screening design indicates that the specimen aspect ratio does not significantly affect the mechanical response of JA2. However, we expect that aspect ratio should affect the mechanical response of materials deformed in uniaxial compression. Specimens with large aspect ratios become unstable due to bending under uniaxial compression and therefore have lower strengths than specimens with small aspect ratios which have higher strengths[4]. A series of constant strain rate (100 sec^{-1}), uniaxial compression tests performed on JA2 and M30 gun propellants at -30 degrees Celsius reveal that, for specimens that deform by macroscopic fracture, the absorbed strain energy density per unit volume at maximum stress decreases as the specimen aspect ratio is increased from 1.5

to 3 (Figure 7). The observation that aspect ratio did not affect the mechanical response of JA2 in this study is a result of the limited range in the aspect ratios of the tested specimens (0.8 to 1.3); the upper bound on the aspect ratio is limited due to the length of the initial granular JA2 propellant stock.

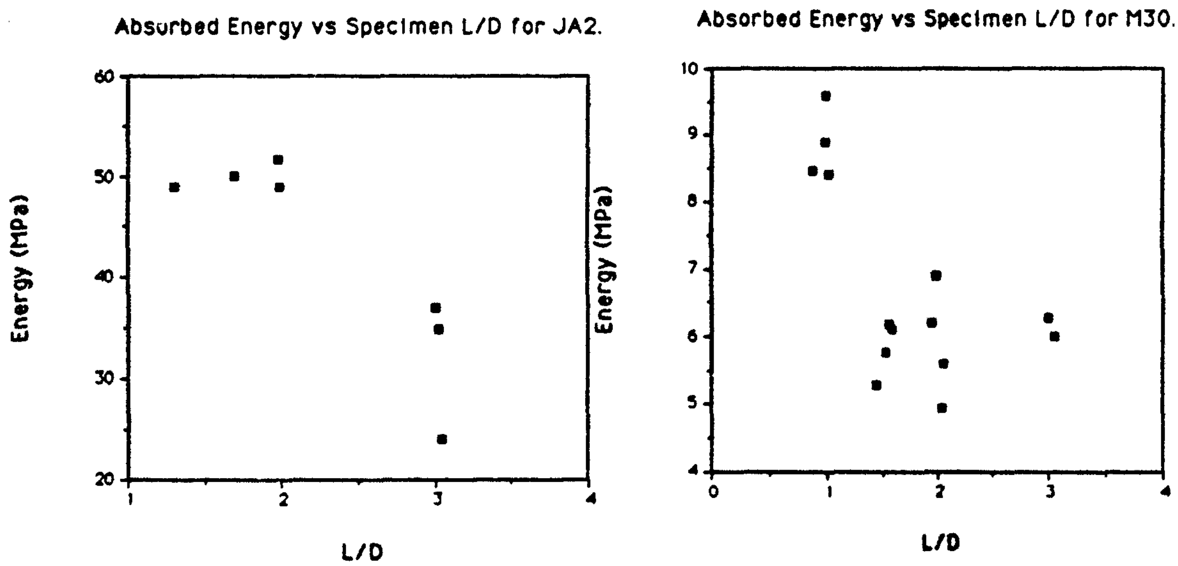

Figure 7. Absorbed Strain Energy Density at Maximum Stress and -30 degrees Celsius for JA2 and M30 Deformed at 100 sec^{-1} in Uniaxial Compression versus Specimen Aspect Ratio.

One obtains a much better fit to the polynomial model if the natural log of the compressive modulus ($R^2_{adj} = 0.985$) rather than the compressive modulus ($R^2_{adj} = 0.799$) is used as a measure of the mechanical response (Table 2). The logarithmic transformation provides a superior fit to the polynomial model, yet it is difficult to explain or rationalize why specimen aspect ratio and end lubrication become significant (Table 2) when the compressive modulus is transformed. Furthermore, it is observed that the strain rate and aspect ratio interaction is not significant, yet the temperature and aspect ratio interaction is significant when the transformed compressive modulus is used to characterize the mechanical response.

4.2 End Lubrication. End lubrication did not significantly affect the mechanical response of the JA2 gun propellant in uniaxial compression. However, the degree of variability in the mechanical response was minimized by using lubrication (Appendix B). Since lubrication alters the boundary conditions at the specimen-piston interface, the increase in yield strain in lubricated specimens could be attributed to an increase in the size of the nonlinear "toe" (Figure 5), rather than an intrinsic material response.

5. CONCLUSIONS

1) The use of a well designed testing approach maximizes the information obtainable concerning the sensitivity of the mechanical response of JA2 gun propellant to the effects of strain rate, temperature, specimen aspect ratio, and lubrication, while simultaneously minimizing the number of tests required. The 2^4 statistical design used in the present research is particularly useful for determining a subset of important variables (screened variables) from a larger set of potentially important variables.

2) Experimental design methods provide an empirically derived material model for quantifying factor effects within the test range. The empirical model can then be used to validate micro- or macro-phenomenological constitutive models for JA2.

3) JA2 is sensitive to changes in strain rate and temperature. Therefore, JA2 constitutive models should incorporate rate and temperature dependent effects.

4) The effect of specimen lubrication is to increase the strain at yield and reduce the variability in the measured mechanical responses (i.e., stress and strain at yield, absorbed strain energy density at yield, and compressive modulus). The use of lubrication is recommended for future compression tests on JA2.

5) The effect of specimen aspect ratio in the limited test range is not detectable with the available experimental equipment. Replicate compression tests on JA2 and M30 gun propellant at strain rates of 100 sec^{-1}, and -30 degrees Celsius indicate that the absorbed energy decreases as specimen aspect ratio increases from 1.5 to 3.0. Additional testing is required to quantify the effects of aspect ratio on the mechanical response of the gun propellant.

6) The measured mechanical response of JA2 is well represented by a second degree polynomial model, since the RMS errors in the mechanical response are only slightly greater than the standard deviations in the mechanical response derived from prior one-factor-at-a-time replicate tests on JA2.

6. FUTURE WORK

This report describes a screening design performed on perforated JA2 gun propellant. The next phase of this research is to use the data collected from an expanded test matrix to determine if effects arising from the presence of perforations can be detected. This can be done using a face-centered cube (FCC) design with perforations being considered as a discrete variable. The other independent variables, (i.e. strain rate, temperature, and specimen aspect ratio), will be identical to those used in this report, with the exception that lubrication will be used in all tests. The FCC design will serve two purposes: 1) to provide the ability to measure the effects of perforations, and 2) to provide the ability to detect the presence of second-order nonlinear effects, curvature and quantification of these effects.

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APPENDIX A:

CUBE PLOTS, LEAST SQUARE COEFFICIENTS, AND INTERACTION PLOTS FOR THE RESPONSES

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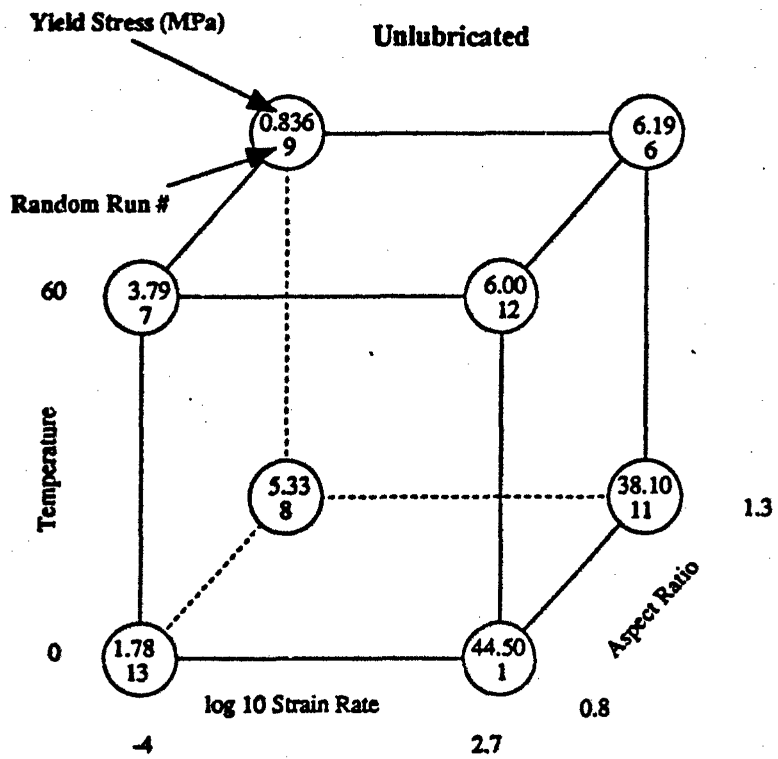


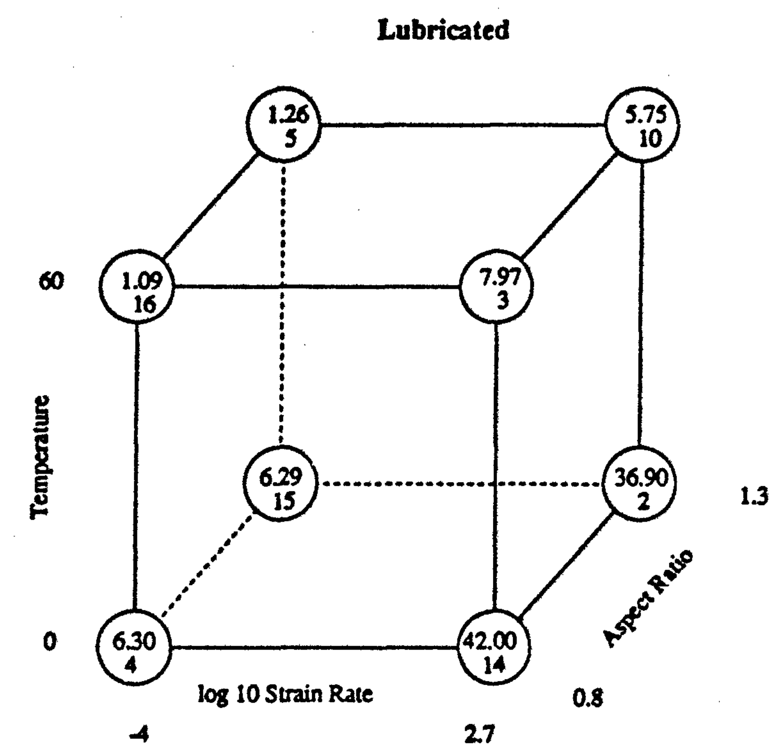


Figure A1. Cube Plots for Stress at Yield

STRESS_COEFF 19R x 5C

Least Squares Coefficients, Response ST, Mode

0 Term	1 Coeff.	2 Std. Error	3 T-value	4 Signif.
1 1	13.342250	0.406284	32.84	0.0001
2 -S	10.084000	0.406284	24.82	0.0001
3 -T	-9.585250	0.406284	-23.59	0.0001
4 -A	-0.760250	0.406284	-1.87	0.1202
5 L<1df>				0.8104
6 NO	-0.102750	0.406284	-0.25	0.8104
7 YES	0.102750	0.406284	0.25	0.8104
8 -S*T	-7.363500	0.406284	-18.12	0.0001
9 -S*A	-0.931000	0.406284	-2.29	0.0705
10 -S*L<1df>				0.3995
11 NO	0.374000	0.406284	0.92	0.3995
12 YES	-0.374000	0.406284	-0.92	0.3995
13 -T*A	0.512250	0.406284	1.26	0.2630
14 -T*L<1df>				0.7138
15 NO	-0.157750	0.406284	-0.39	0.7138
16 YES	0.157750	0.406284	0.39	0.7138
17 -A*L<1df>				0.7536
18 NO	0.134750	0.406284	0.33	0.7536
19 YES	-0.134750	0.406284	-0.33	0.7536

No. cases = 16   R-sq. = 0.9967   RMS Error = 1.625
Resid. df = 5   R-sq-adj. = 0.9901   Cond. No. = 1
- indicates factors are transformed.

Figure A2. Least Squares Coefficients for Stress at Yield.

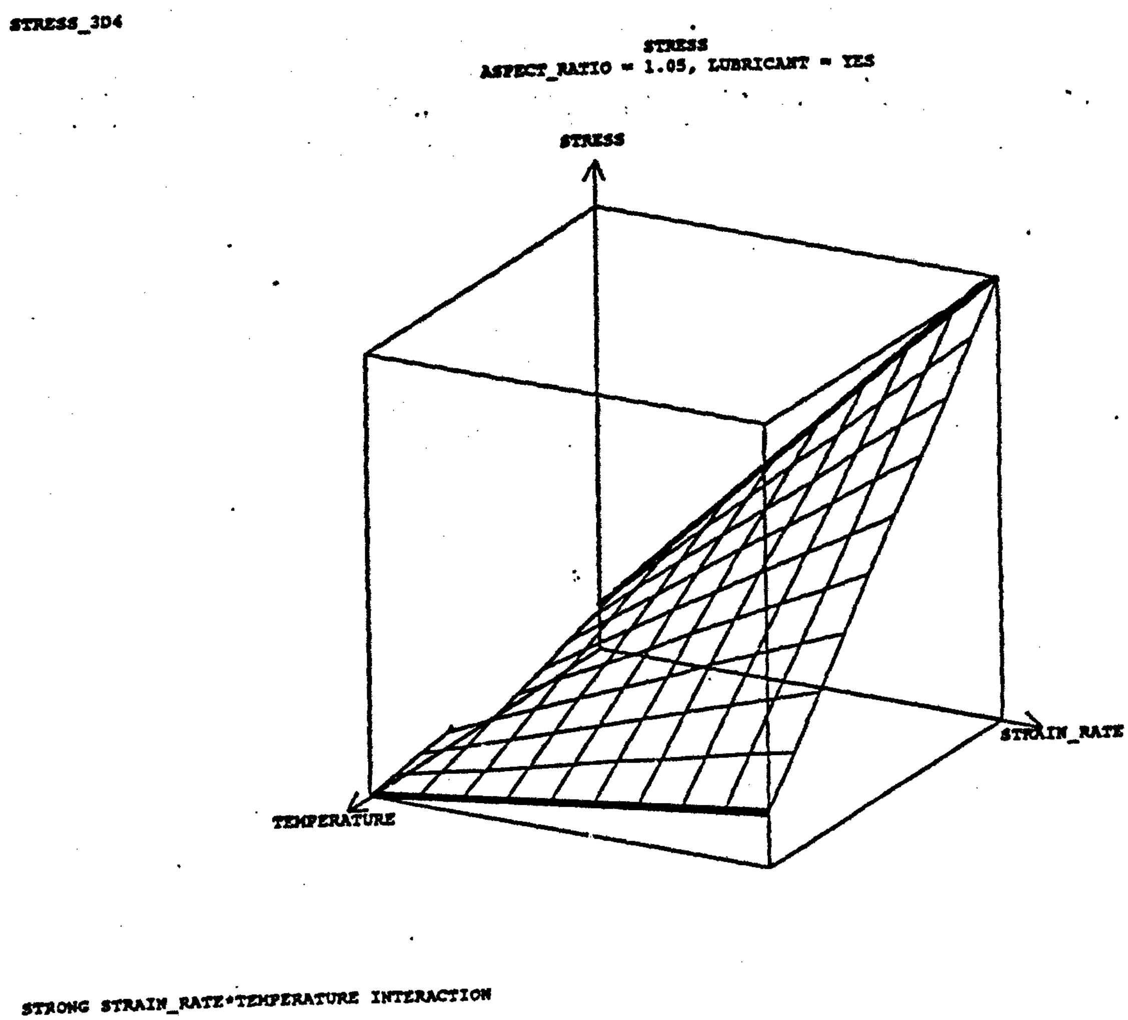


Figure A3. Strain Rate*Temperature Interaction Surface for Stress at Yield.

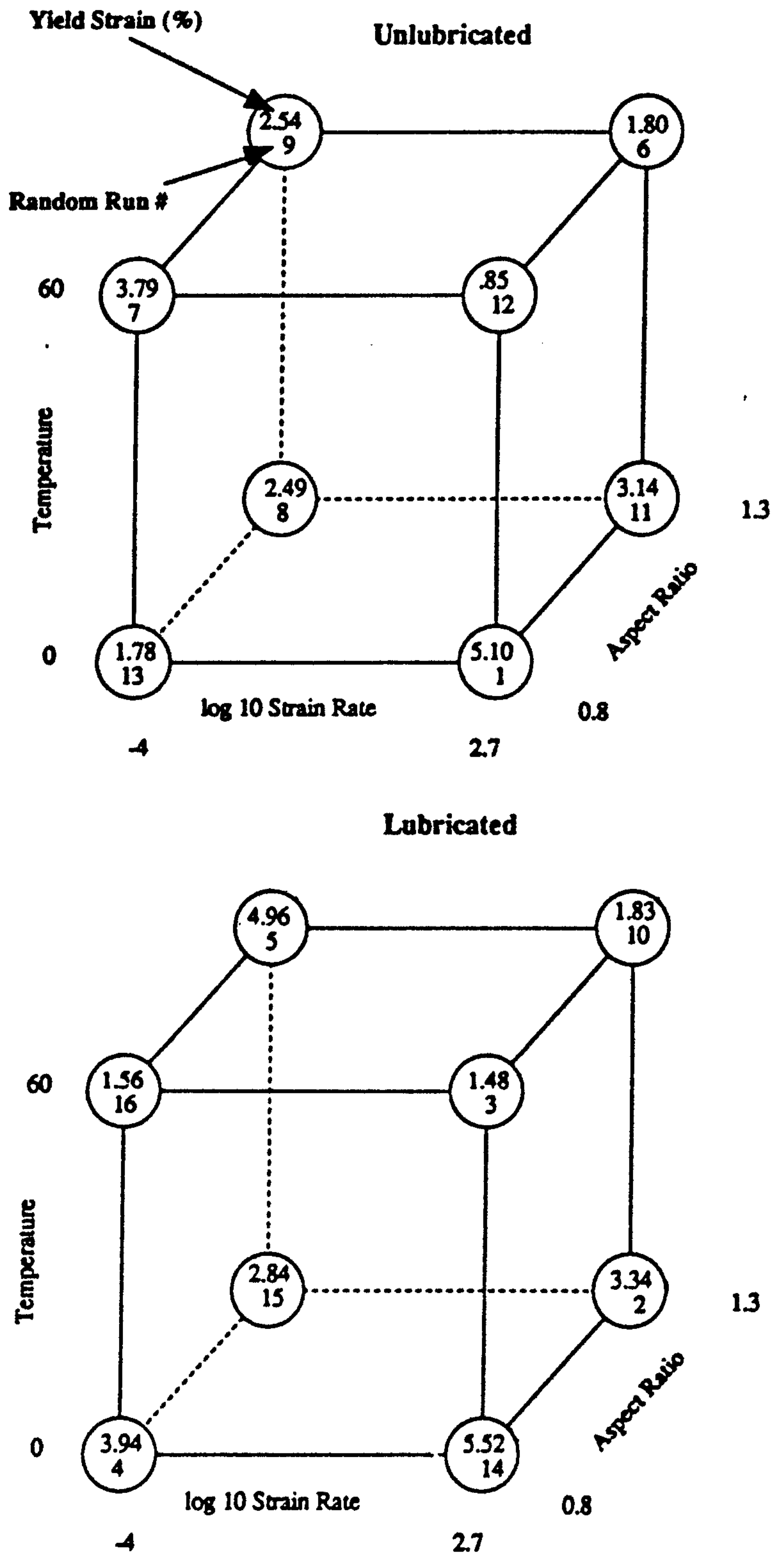


Figure A4. Cube Plots for Strain at Yield.

STRAIN_COEFF 12R x 5C

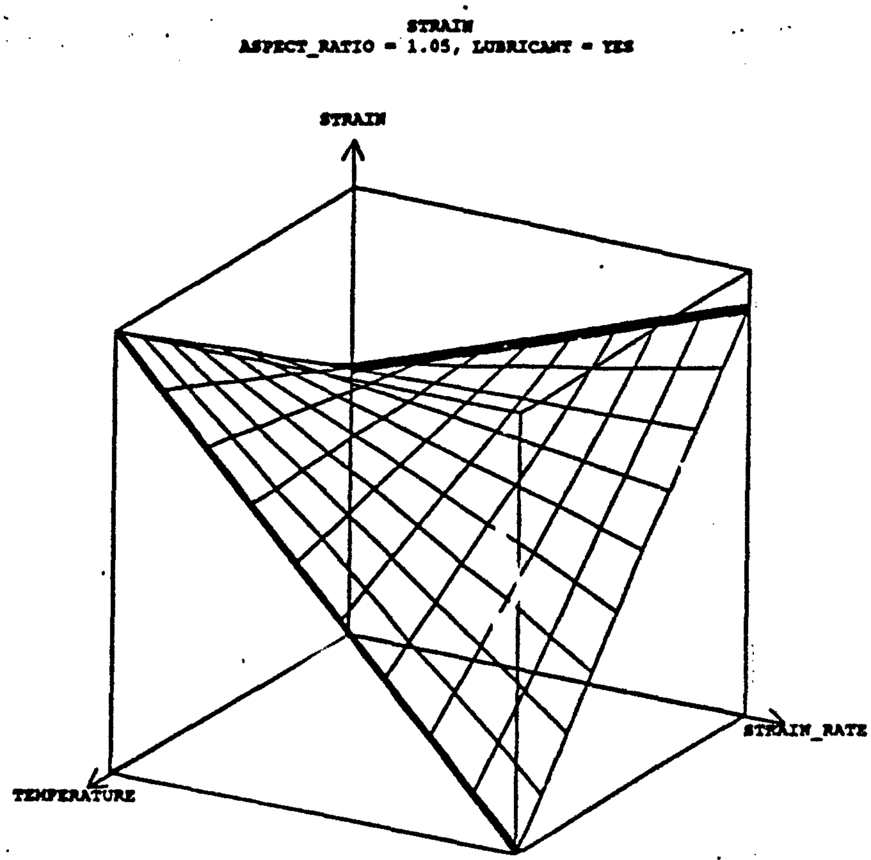
Least Squares Coefficients, Response STR, Mode

0 Term	1 Coeff.	2 Std. Error	3 T-value	4 Signif.
1 1	3.122500	0.176674	17.67	0.0001
2 ~S	-0.240000	0.176674	-1.36	0.2114
3 ~T	-0.396250	0.176674	-2.24	0.0552
4 ~A	-0.255000	0.176674	-1.44	0.1869
5 L<1df>				0.0388
6 NO	-0.436250	0.176674	-2.47	0.0388
7 YES	0.436250	0.176674	2.47	0.0388
8 ~S*T	-0.996250	0.176674	-5.64	0.0005
9 ~S*L<1df>				0.1565
10 NO	0.276250	0.176674	1.56	0.1565
11 YES	-0.276250	0.176674	-1.56	0.1565
12 ~T*A	0.311250	0.176674	1.76	0.1161

No. cases = 16 R-sq. = 0.8676 RMS Error = 0.7067
Resid. df = 8 R-sq-adj. = 0.7517 Cond. No. = 1
~ indicates factors are transformed.

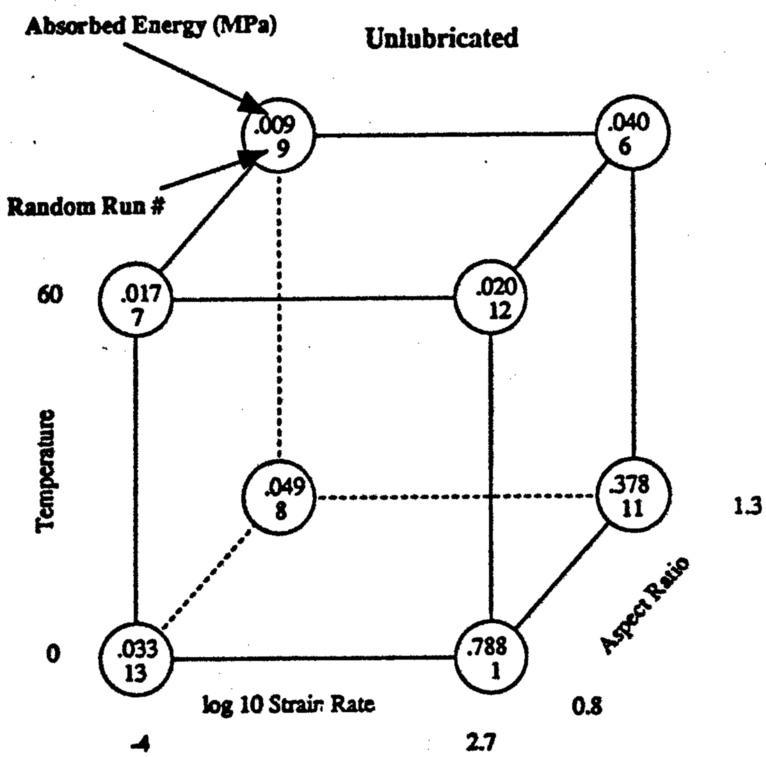
Figure A5. Least Squares Coefficients for Strain at Yield.

STRAIN_3D3



STRONG STRAIN_RATE*TEMPERATURE INTERACTION

Figure A6. Strain Rate*Temperature Interaction Surface for Strain at Yield.



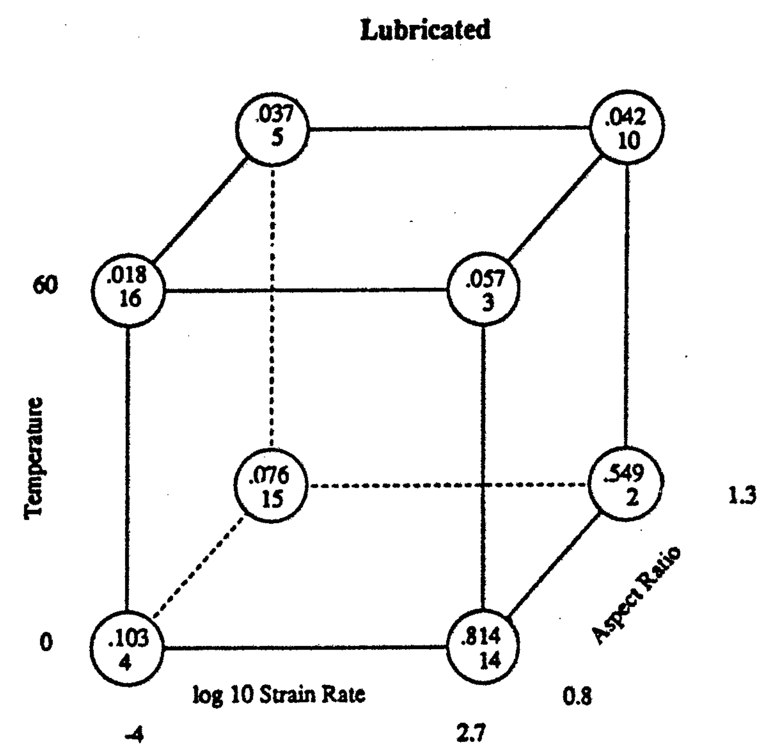


Figure A7. Cube Plots for Energy.

ENERGY_COEFF 19R x 5C

Least Squares Coefficients, Response E, Model

0 Term	1 Coeff.	2 Std. Error	3 T-value	4 Signif.
1 1	0.189375	0.020378	9.29	0.0002
2 ~S	0.146625	0.020378	7.20	0.0008
3 ~T	-0.159375	0.020378	-7.82	0.0005
4 ~A	-0.041875	0.020378	-2.05	0.0950
5 L<1df>				0.3174
6 NO	-0.022625	0.020378	-1.11	0.3174
7 YES	0.022625	0.020378	1.11	0.3174
8 ~S*T	-0.136875	0.020378	-6.72	0.0011
9 ~S*A	-0.041875	0.020378	-2.05	0.0950
10 ~S*L<1df>				0.7495
11 NO	-0.006875	0.020378	-0.34	0.7495
12 YES	0.006875	0.020378	0.34	0.7495
13 ~T*A	0.043875	0.020378	2.15	0.0839
14 ~T*L<1df>				0.5191
15 NO	0.014125	0.020378	0.69	0.5191
16 YES	-0.014125	0.020378	-0.69	0.5191
17 ~A*L<1df>				0.7847
18 NO	-0.005875	0.020378	-0.29	0.7847
19 YES	0.005875	0.020378	0.29	0.7847

No. cases = 16 R-sq. = 0.9719 RMS Error = 0.08151
Resid. df = 5 R-sq-adj. = 0.9158 Cond. No. = 1
~ indicates factors are transformed.

Figure A8. Least Squares Coefficients for Energy.

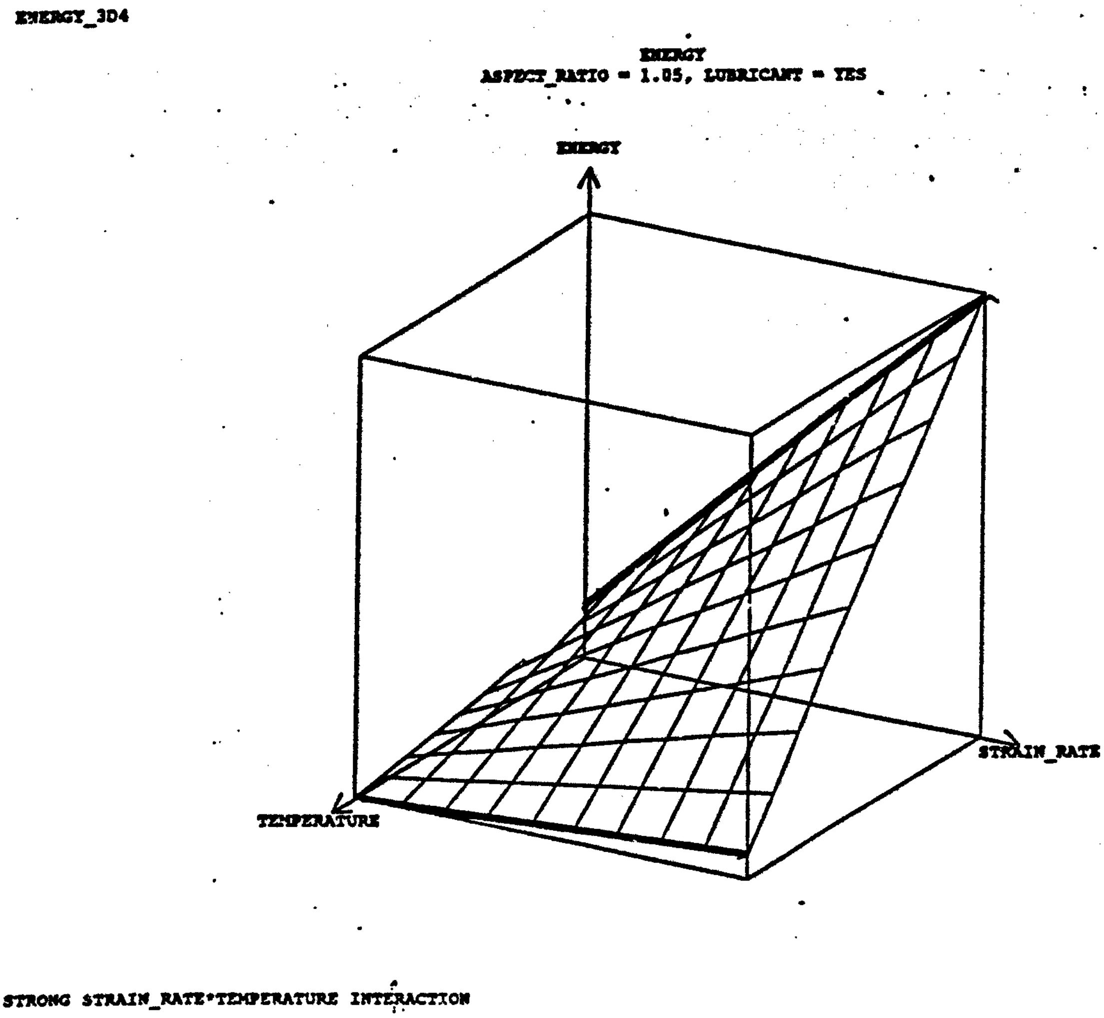
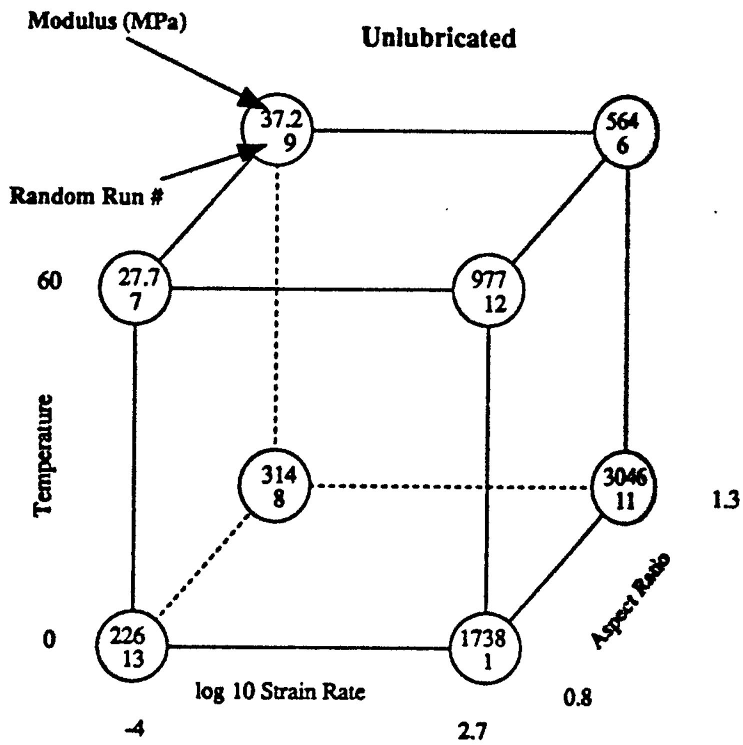


Figure A9. Strain Rate*Temperature Interaction Surface for Energy.



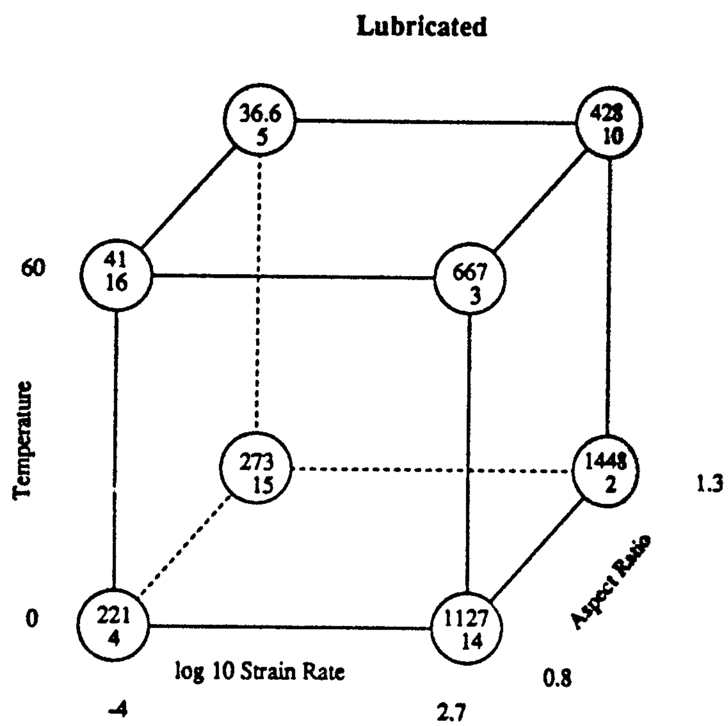


Figure A10. Cube Plots for Modulus.

EMODULUS_COEFF 19R x 5C

Least Squares Coefficients, Response EM, Model

0 Term	1 Coeff.	2 Std. Error	3 T-value	4 Signif.
1 1	698.218750	91.811305	7.60	0.0006
2 ~S	551.156250	91.811305	6.00	0.0018
3 ~T	-350.906250	91.811305	-3.82	0.0123
4 ~A	70.131250	91.811305	0.76	0.4794
5 L<1df>				0.1268
6 NO	168.018750	91.811305	1.83	0.1268
7 YES	-168.018750	91.811305	-1.83	0.1268
8 ~S*T	-239.468750	91.811305	-2.61	0.0478
9 ~S*A	51.993750	91.811305	0.57	0.5957
10 ~S*L<1df>				0.1344
11 NO	163.856250	91.811305	1.78	0.1344
12 YES	-163.856250	91.811305	-1.78	0.1344
13 ~T*A	-150.993750	91.811305	-1.64	0.1610
14 ~T*L<1df>				0.2700
15 NO	-113.856250	91.811305	-1.24	0.2700
16 YES	113.856250	91.811305	1.24	0.2700
17 ~A*L<1df>				0.5824
18 NO	53.931250	91.811305	0.59	0.5824
19 YES	-53.931250	91.811305	-0.59	0.5824

No. cases = 16 R-sq. = 0.9329 RMS Error = 367.2
Resid. df = 5 R-sq-adj. = 0.7986 Cond. No. = 1
~ indicates factors are transformed.

Figure A11. Least Squares Coefficients for Modulus.

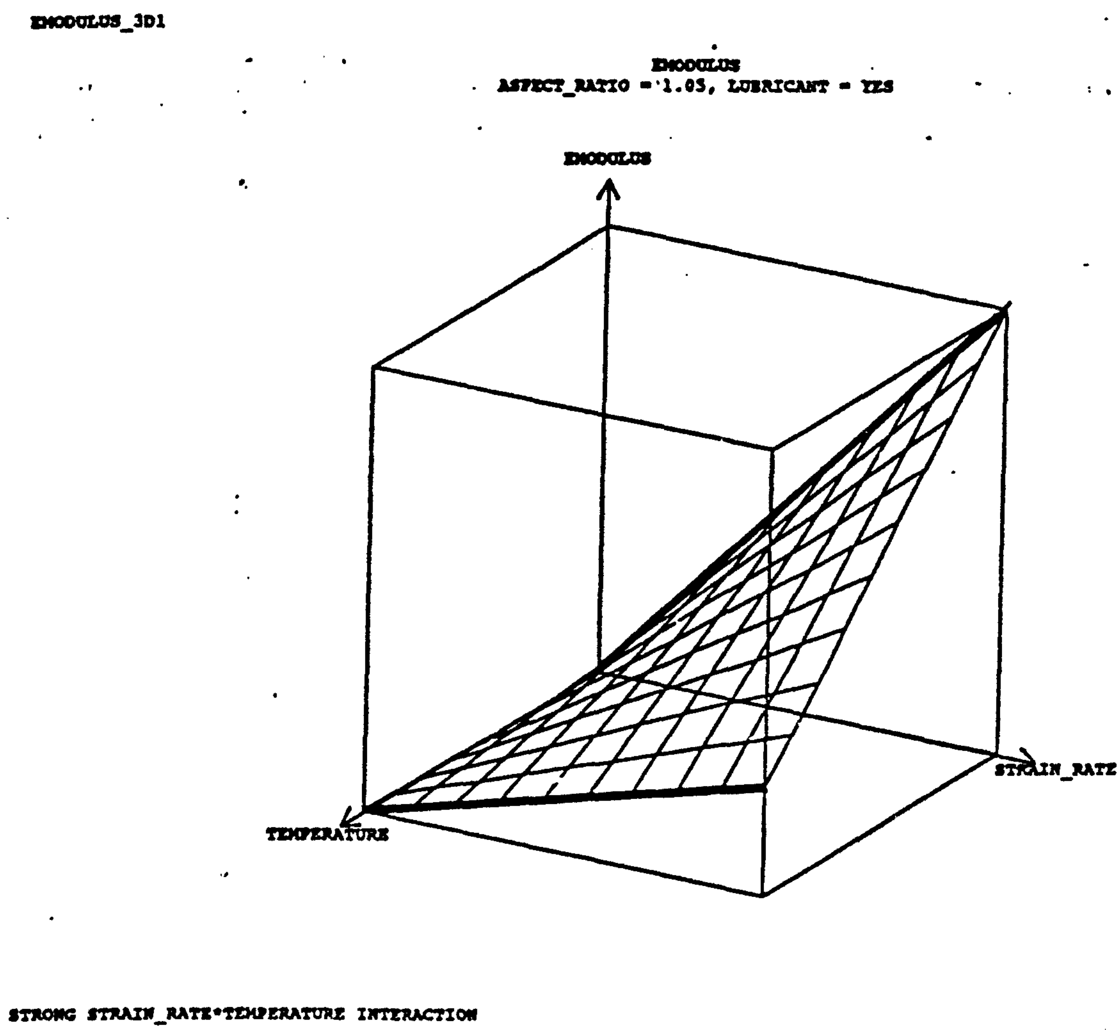


Figure A12. Strain Rate*Temperature Interaction Surface for Modulus.

APPENDIX B:

MODEL RESIDUALS FOR RESPONSES BY END LUBRICATION.

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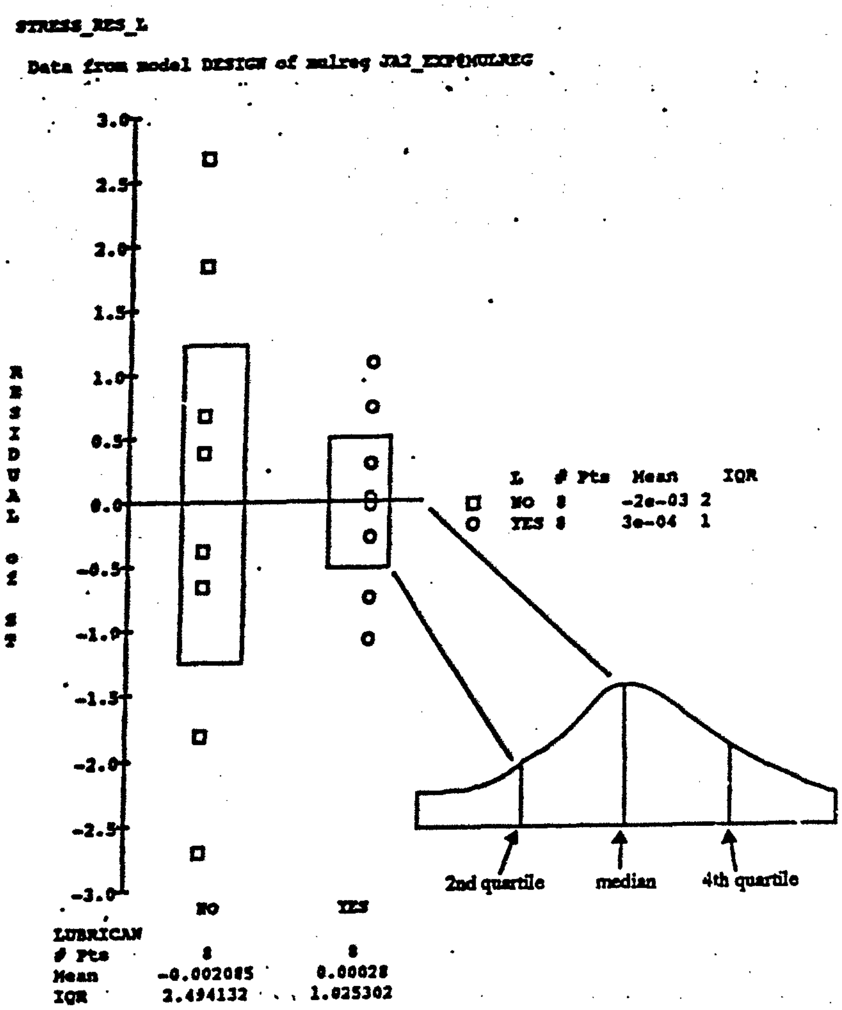

Figure B1. Model Residuals for Stress at Yield by End Lubrication.

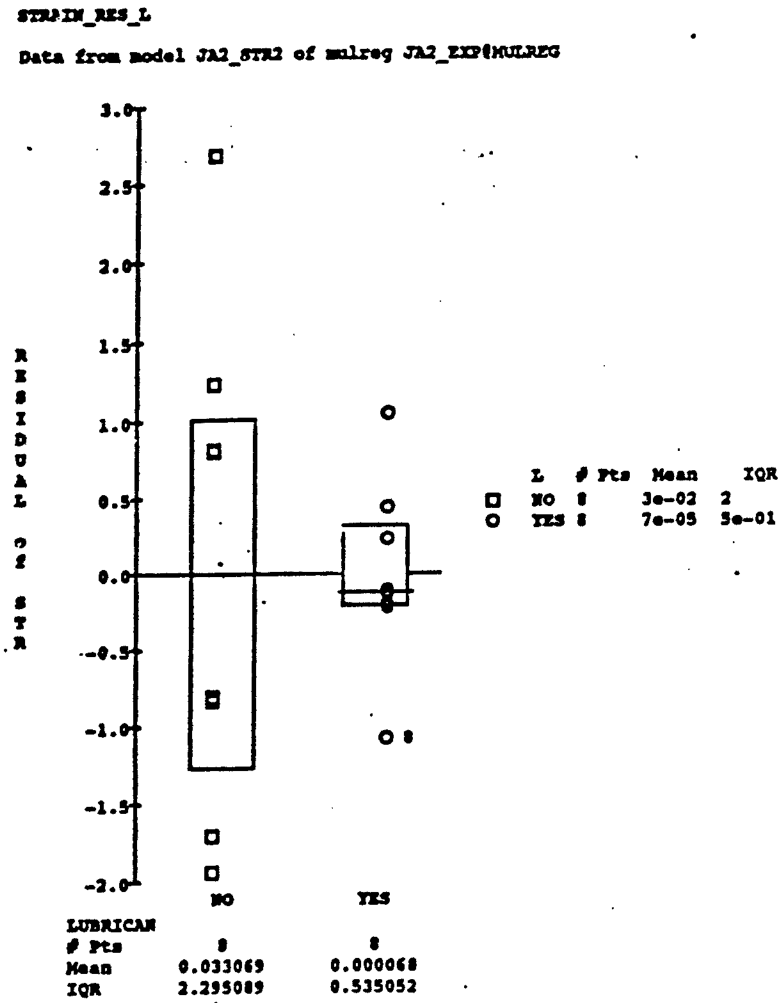

Figure B2. Model Residuals for Strain at Yield by End Lubrication.

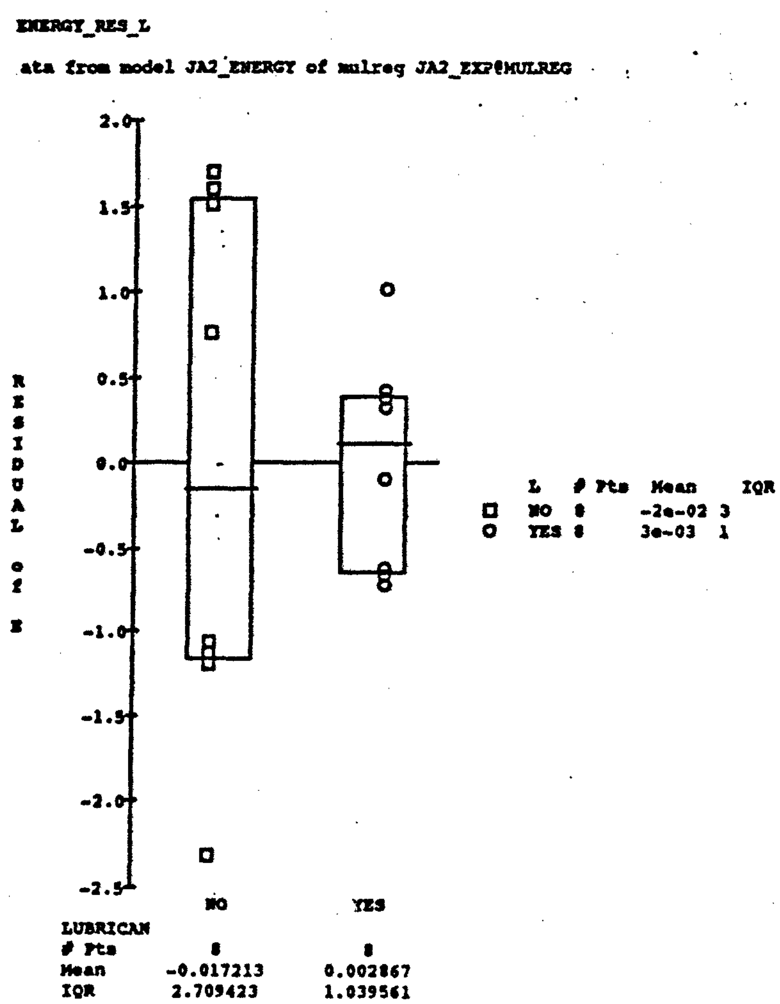

Figure B3. Model Residuals for Energy at Yield by End Lubrication.

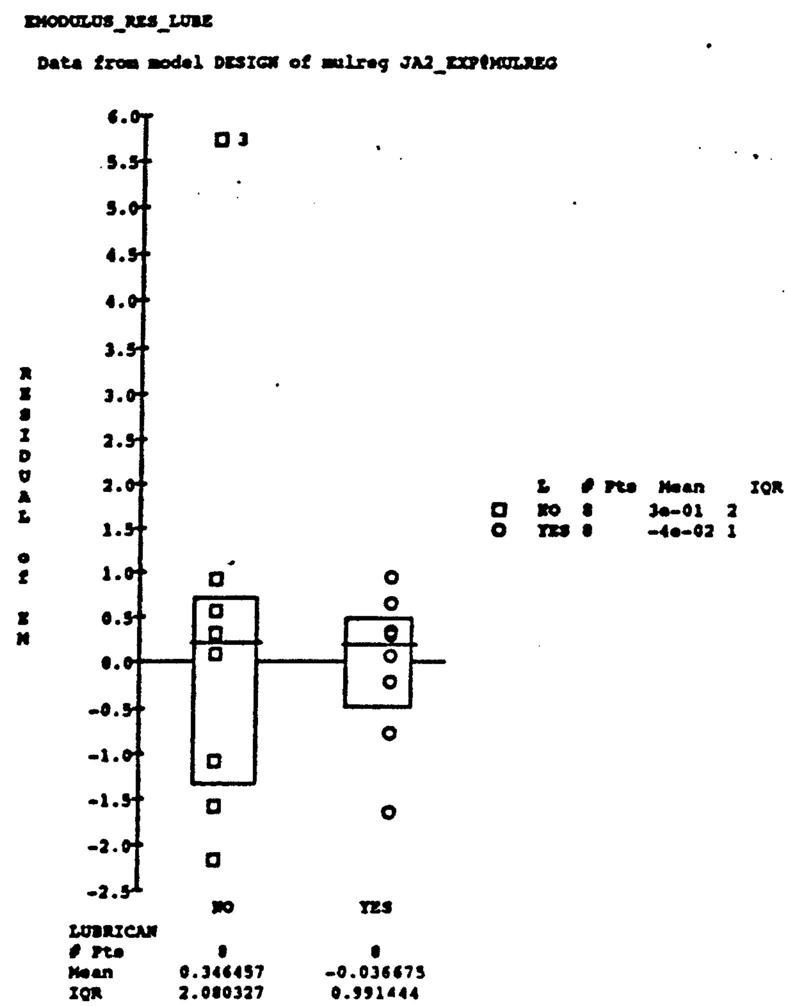

Figure B4. Model Residuals for Modulus by End Lubrication.

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