A REGRESSION APPROACH FOR ZIRCALOY-2 IN-REACTOR CREEP CONSTITUTIVE EQUATIONS

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AUTHORS NOTES

This report contains two parts of the study on Zircaloy-2 in-reactor creep constitutive equations. Part I was completed earlier in May, 1976 in which the essentials and the preliminary results of and from the analysis are given. Part II which was completed later in November, 1976 is an addendum of Part I with additional results and discussions. Readers are advised to follow the sequence of presentation in order to see the entirety of the analysis.

A condensed version of Part I is presented at the SMiRT*-4th Conference August, 1977 and can be found in the conference proceedings under Division C, paper 3/3.

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* SMiRT - Structural Mechanics in Reactor Technology

ABSTRACT

Typical data analysis procedures used in developing current phenomenological in-reactor creep equations for Zircaloy cladding materials are examined. It is found that the data normalization assumptions and the curve fitting techniques generally adopted in these procedures can make the prediction of creep strain rate from the resulting equations highly questionable.

Multiple regression analysis performed on a set of carefully selected Zr-2 in-reactor creep data on the basis of comparable as fabricated metallurgical conditions indicates that models of the form $\dot{\varepsilon} = A\sigma^n\phi^m \exp(-Q/RT)$ can give significant account for the data. Both regression statistics and residual plots have provided strong evidences for the significance of the regression equations.

ABSTRACT OF THE ADDENDUM

The addendum of this report contains the results and discussions of the analysis we made on our revised Zircaloy-2 in-reactor creep data. Although fewer creep rate data were used, much of the same general conclusions can be made as we did previously. The differences between the final recommended regression Zircaloy-2 in-reactor creep equations in the report and the addendum are primarily those of the estimated coefficients. The starting model equations continue to provide excellent correlations for the creep strain rate data.

Our attempt to verify the additivity of thermal and irradiation creep components directly from the creep data set show that there is little merit in using a composite formula made up by the above two components for ranges covered by the test parameters. This statement should not be looked upon as a denial to such a treatment, however, especially in situations of combinations of high ϕ, σ and T where changes in dominating deformation mechanism are possible. At present, we do not have reliable data in those regimes.

Part I

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1. Introduction:

In this report results and discussions are given on the development of Zr-2 in-reactor creep constitutive equations. Although several theoretical irradiation enhanced creep models have been proposed[1,2,3], present fuel rod design and fuel clad deformation analysis involving in-reactor creep are still based largely on empirical equations. These empirical equations are often obtained directly from in-reactor creep data by certain kinds of procedures. Close examination of the current empirical creep models shows, however, that various normalization assumptions are often involved, and these assumptions are generally different among investigators. The final forms of these equations are arrived at by adjusting parameters until good agreement is reached between the equation predicted value and the actual creep data. While such procedure may be adequate in obtaining an equation which summarizes a given set of data in the test parameter ranges, the usage of the equation for prediction purpose at other parameter values is seriously questionable. Therefore, it is of no surprise to see rather large deviations in the predicted creep strain rates from these equations under equivalent stress, temperature and fast neutron flux conditions.

Statistical data analysis using multiple regression techniques, on the other hand, requires no normalization assumptions and the data can be explored in the original form as they are collected. The technique is particularly useful in establishing the functional relationship between the dependent variable (response) and the independent variables (factors)*.

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* In our case in-reactor creep strain rate is the dependent variable whereas stress, temperature and fast neutron flux are the independent variables.

All that is required is a tentatively selected model equation which relates the dependent variable to the independent variables with unknown coefficients. The problem then reduces to estimating these coefficients from data. Modern computer statistical programs are available which not only greatly shorten the lengthy computational effort but also provide means to check the adequacy of the underlying model. The process of model validation is perhaps the most important aspect of all good data analysis and should be exercised with caution. It is also important to point out at this time that although researchers are aided by various means for model selection, great savings can be achieved if one can start with a reasonably good model. Such models may be constructed from prior experience and/or from the understanding of the governing physical mechanisms. The latter may come directly from theory developments.

Starting from the next section, we shall first give a brief review on the data analysis procedure which had been used to derive the current empirical in-reactor creep equations. Much of the later efforts focus on the regression aspects of Zr-2 in-reactor creep data analysis. The principal areas discussed are:

(1) The selection of tentative model equations, their physical grounds and their use in conjunction with linear multiple regressions.

(2) The examination of Zr-2 in-reactor creep data. This includes the regrouping of the data according to test types, material conditions; the removal of improper data normalization assumptions, and the elimination of certain improper data points. The possible sources of errors in the data are also discussed.

(3) Regression results. Regression statistics, residual plots, estimated coefficients and confidence intervals are covered with major emphasis on model justifications.

2. Examination of current in-reactor creep models:

Table 1 contains five current empirical in-reactor creep models for Zr-2. The references of the data-base upon which these models were constructed are also indicated in Table 1. One notices immediately from the list of data references that a large portion of data used for obtaining these equations really come from the same in-reactor creep experiments. The five equations are arranged in chronological order as they were derived so that the latter of these equations actually use some of the more recent in-reactor creep experimental data.

Before we discuss these equations further, it would be interesting to compare the predicted in-reactor creep rates from these equations under the same σ, ϕ, and T values. Fig. 1 and Fig. 2 show the $\ln(\dot{\varepsilon})$ vs 1/T and $\ln(\dot{\varepsilon})$ vs $\ln(\sigma)$ plots respectively for these equations and one which is based on the irradiation creep model derived by Gittus[4]. In both cases the Gittus model predicts creep rates an order of magnitude lower than do the empirical models. Among the five empirical models, reasonably good agreements are attained only at low temperature and low stress regions. The deviations at high temperatures and high stresses are 2 to 3 orders of magnitude. An apparent inconsistency, therefore, exists among these models which raises serious doubts for their applicabilities especially at high stress and high temperature regions.

In spite of the difference in the various constants, the forms of the last four equations in Table 1 look rather similar. A flux* exponent of 0.85 originally obtained by Watkins and Wood for SGHWR pressure tubes in 1968 has been used rather consistenly in recent years and is the same exponent used in the latest model. It is, therefore, useful to review the Watkins and Wood's

*The word flux is referred to the fast neutron flux (E > 1 Mev) throughout this report.

TABLE 1 SUMMARY OF IN-REACTOR CREEP MODELS AND THEIR DATA BASES

Empirical models		Data References
(1) Ross-Ross[5] & Hunt	$\dot{\varepsilon}_h = 4\times10^{-24}\ \sigma_h\phi\ (T - 433)$	H-14
(2) Watkins[6] & Wood	$\dot{\varepsilon} = 1.02\times10^{-11}\ \exp\left(-\frac{14000}{RT}\right)\ \phi^{0.85}\ \sinh(1.15\times10^{-1}\sigma)$	I-14
(3) BUCKLE[7] (Pankaskie)	$\dot{\varepsilon} = (1+\alpha K\ \exp(-Kt))\ B\phi^{0.85}\ \exp\left(-\frac{Q}{RT}\right)\ \sinh\ (S\sigma)$ $\alpha = 900,\ B = 9.5\times10^{-13},\ S = 0.17,\ K = 6\times10^{-3}$ $Q = 16980$ for $T < T_{crit}$ $Q = 16980 - 76.2\ (T - T_{crit})$ for $T > T_{crit}$ $T_{crit} = 640 - \sigma$	H-1, K-6, I-11 I-14
(4) Vender A[8]	Proprietary Information	H-1, I-11, I-14 M-5, M-7
(5) Vender B[9]	Proprietary Information	H-1, E-1, I-11 I-14

**Units: σ(ksi), ϕ(E>1 Mev) in $n/cm^2 sec$, T(°K) for (1)-(4) and T(°R) for (5)

Figure-1

COMPARISONS OF CREEP LAWS AT STRESS=7.5 KSI,FLUX=1E+14

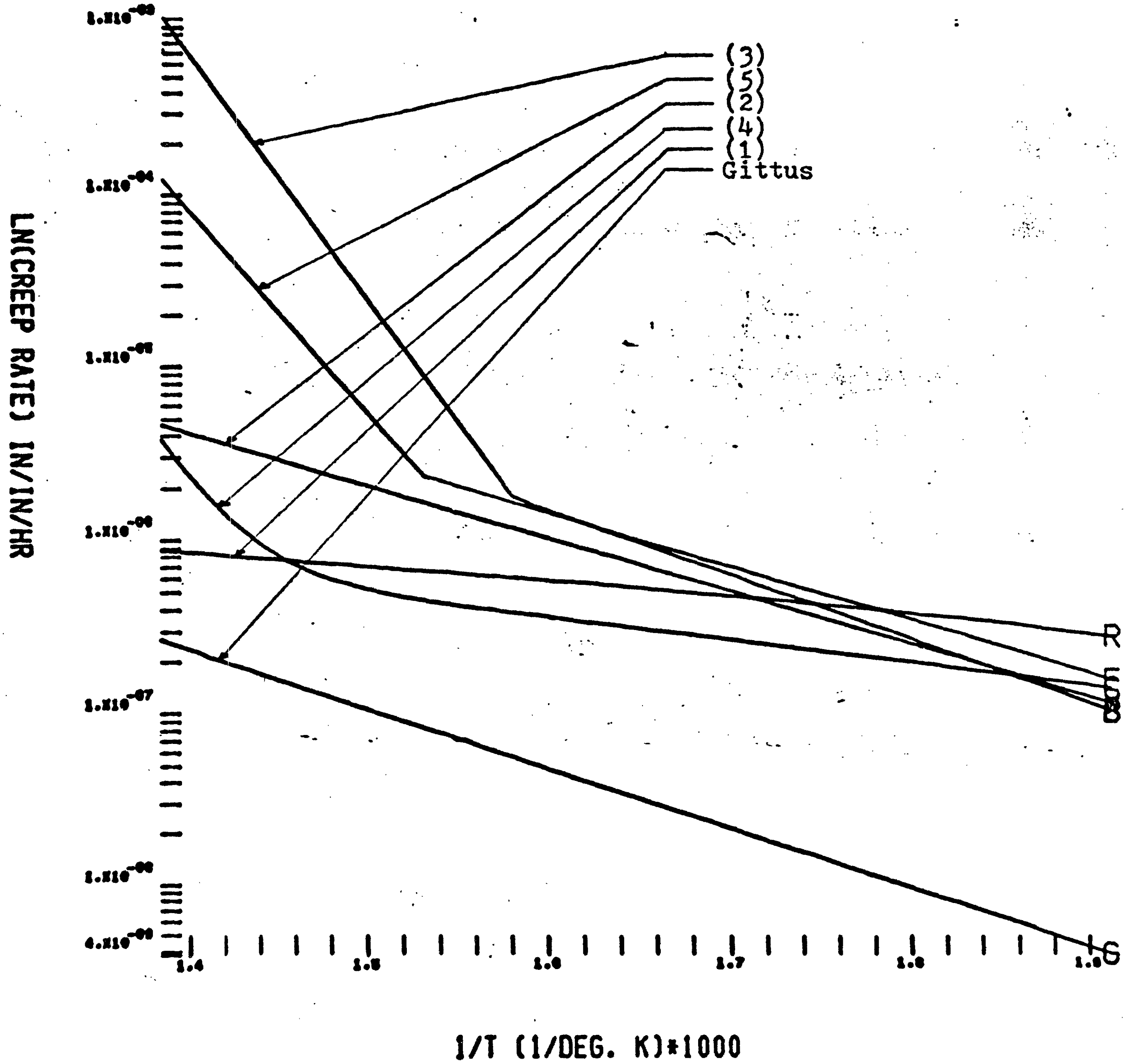
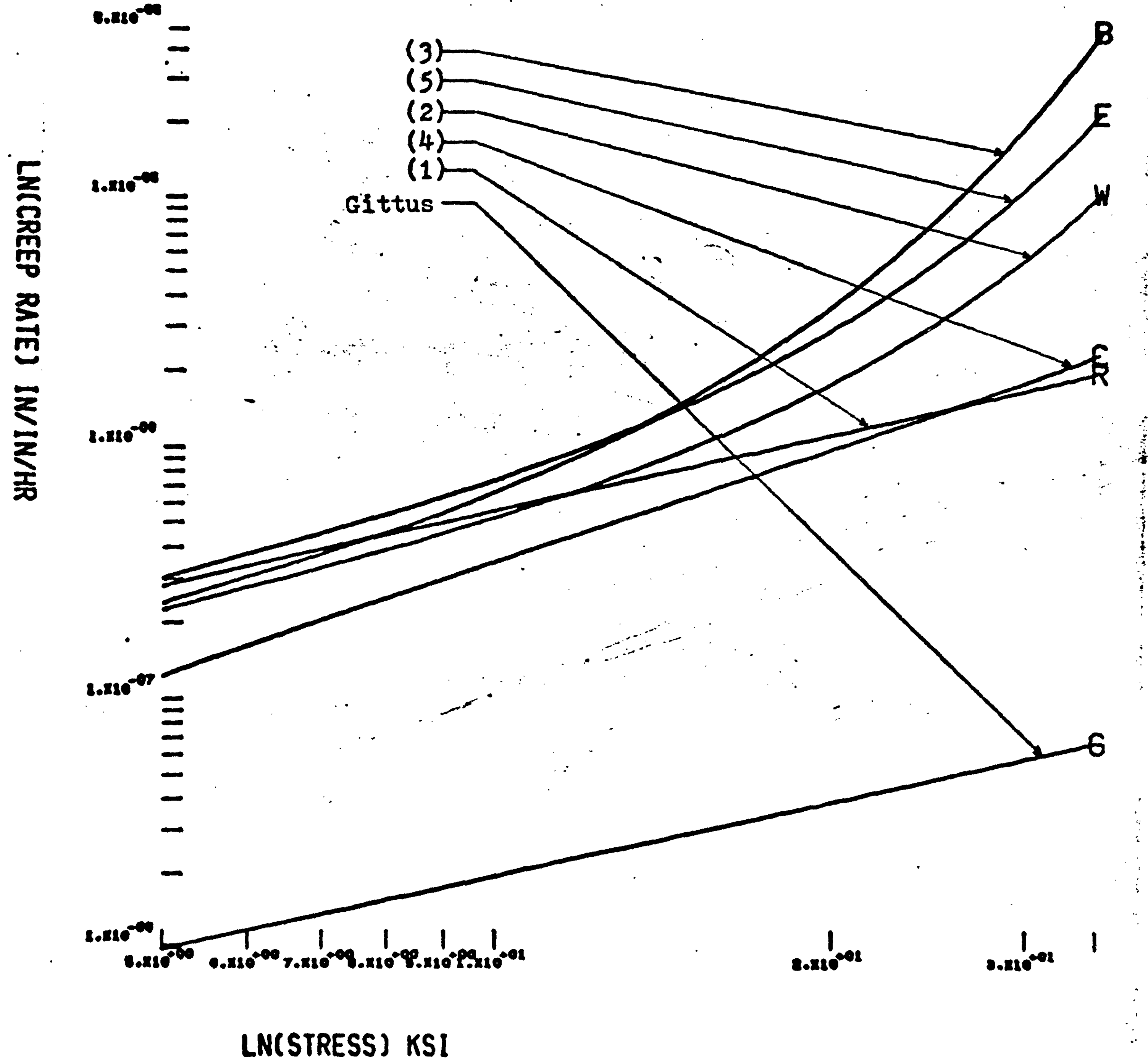


Figure-2

COMPARISONS OF CREEP LAWS AT T=300 C,FLUX=1E+14



method for deriving their creep equation. The conditions for the Ross-Ross and Hunt model will also be examined later because they are relevant to the data set on which the regression analysis is performed. Documented details for the rest of the models can be found in the references and will not be covered here. It suffices to mention that the analytical procedures behind these models are essentially no different than the one which is going to be discussed in the next section. There are certain features on the data base for these models which should be pointed out as follows:

(1) The constants in Pankaskie's equation are found by fitting to Fidleris' uniaxial in-reactor creep data.

(2) Data for Vender A and Vender B's model come from the same two major sources, i.e., work by Watkins and Wood and those by Ibrahim, Ross-Ross and Hunt. Although it is known that the pressure tubes tested by these investigators are different in the amount of cold work and were provided by different manufacturers, no recognition has been given to these aspects, and all of the data have been used to construct a single equation. This is unacceptable since creep depends strongly on the materials metallurgical conditions which are functions of the thermal-mechanical treatments.

2.1 Watkins and Wood's assumptions:

The basic assumption made by Watkins and Wood[6] in their data analysis procedure is that each variable (σ, T, and ϕ) affects the creep rate independently. The effect of each variable on creep rate is then considered in turn by the following assumptions:

(1) A power law relationship is assumed for fast neutron flux.

$$\dot{\varepsilon} \propto \phi^n$$

where n is a constant. The best fit to the data is obtained with n = 0.85, the uncertainty in this value being ± 0.15.

(2) An activation energy form of temperature dependency is assumed

$$\dot{\varepsilon} \propto \exp(- Q/RT)$$

where Q is the activation energy. The best fit to the data is obtained with a Q value of 14,000 cal/mole, the uncertainty in this value being ± 6000 cal/mole in the temperature range 250 to 300°C.

(3) Using the above expressions, the data have been normalized for flux, temperature, and biaxiality to SGHWR conditions and are plotted against the remaining variable σ. It was found that a sinh curve can fit the normalized creep rates acceptably with a stress coefficient of 1.15×10^{-1} /ksi and a pre-multiplier constant of 1.02×10^{-11}.

(4) The entire equation then follows by joining these three separate terms together as

$$\dot{\varepsilon} = 1.02\times10^{-11} \phi^{0.85} \exp(- \frac{14000}{R\ T}) \sinh (1.15\times10^{-1}\sigma)$$

The set of irradiation creep data used for the construction of the above model is shown in Table 2. It is interesting to

Table 2 SUMMARY OF IRRADIATION CREEP DATA USED IN ASSESSMENT OF WATKINS AND WOOD'S EQUATION*

Test No. and Ref.	Type	Temp., deg C	Stress, psi	Flux (>1 MeV), n/cm² sec	Duration, h	Creep Rate, in./in./h
829 [1]	uniax.	290	25 000	2.4×10^{13}	3 000	1.17×10^{-6}
829 [2]	uniax.	300	16 000	2.4	8 500	3×10^{-7}
829 [3]	uniax.	325	35 000	3.1	5 000	1.2×10^{-6}
629 [1]	tube	275	25 000	3.4	2 400	5.2×10^{-7}
U2-Mk. III [4]	tube	285	11 500	2.7	5 700	1.9×10^{-7}
U2-Mk. IV [4]	tube	281	11 000	2.7	11 000	1.8×10^{-7}
U2-Mk. IX [4]	tube	286	13 400	3.1	3 300	2.9×10^{-7}
	tube	286	17 300	3.1	3 300	3.6×10^{-7}
NPD [4]	tube	268	10 600	1.15	29 000	5.5×10^{-8}
U3-Mk. V [4]	tube	327	4 900	3.1	13 000	9.1×10^{-8}
R4 [3]	uniax.	300	30 000	0.59	1 300	8×10^{-7}
R6 [3]	uniax.	300	20 000	0.54	3 600	3.5×10^{-7}
R9 [3]	uniax.	300	18 000	0.58	1 500	3×10^{-7}
R × 14 [3]	uniax.	300	20 000	0.64	1 100	3×10^{-7}
R × 15 [3]	uniax.	350	30 000	0.94	530	3.2×10^{-6}
R × 21 [3]	uniax.	300	45 000	0.84	800	1.2×10^{-5}
R × 15 [3]	uniax.	220	30 000	0.96	2 100	1.5×10^{-7}

* Reproduced from Ref. (6).

note that out of the seventeen creep rate data, ten of them actually came from Fidleris'uniaxial creep tests. A biaxiality correction has been applied to the uniaxial data so that they can be used together with the tubular data. This is done by multiplying the stress by a factor of 1.15 and dividing the creep rate by the same factor. Such a conversion method is valid only for isotropic material, which is not the case for Zr-2. Furthermore, uncertainty of using test results from two different sources of materials is retained.

Steps (1) to (4) above outline the general procedure followed in developing current in-reactor creep models. The assumption that each variable affects creep rate independently appears to be highly unsatisfactory. This is because the creep rates used to determine the constant for one variable, with an assumed variable dependence, contain the influences from the other variables too. A realistic model or data analysis procedure must, therefore, be able to take into account the influence from the stress, temperature, and flux simultaneously. One convenient way for doing this is by regression analysis.

3. Regression analysis:

Regression analysis can be classified into two broad categories, i.e., linear and non-linear regressions. By linear it is meant that the model equation is linear in its coefficients whereas non-linear implies that the coefficients may contain higher order terms. Sometimes by proper linearization, a non-linear model can be transformed into a linear one and in that case the model is said to be inherently linear. Since the solution of non-linear problems generally requires iteration and is much more involved than linear problems, the standard practice is to start with a linear model unless there are strong reasons to believe that the underlying model is non-linear in nature. The starting equation (being linear or non-linear) is not that crucial because through the examination of results from regression analysis such as regression statistics and residual plots, the appropriateness of the model will be revealed. If the evidence shows that a linear model is inadequate, then it can be modified by either changing the variable dependence relations or considering non-linear models.

3.1 Regression Models:

The general form of a linear model with three independent variables can be written as

$$Y = B_0 + B_1 f(X_1) + B_2 f(X_2) + B_3 f(X_3) + B_4 f(X_1 X_2) +$$

$$B_5 f(X_2 X_3) + B_6 f(X_3 X_1) + B_7 f(X_1 X_2 X_3) \qquad (1)$$

where Y is the dependent variable, $f(X_1),\ldots,f(X_1 X_2 X_3)$ are some functional dependences of individual and combinatorial effects of X_1, X_2, and X_3 on Y, and $B_0,\ldots, B_7$ are the coefficients to be estimated. If we let $Y = \dot{\varepsilon}$, $X_1 = \phi$, $X_2 = \sigma$ and $X_3 = T$, then (1) becomes our general linear creep model. The task then is to specify explicitly the functional forms of $f(\phi)$, $f(\sigma)$, $f(T),\ldots, f(\phi\sigma T)$.

As we mentioned earlier, it would be greatly helpful if one can choose a model which has some physical meaning. Studies on materials thermal creep behavior have shown that in an intermediate temperature range and moderate stress level, creep is best represented by a power law-type relationship(10). That is,

$$\dot{\varepsilon} = A\,\sigma^n \exp\left(-\frac{Q}{R\,T}\right) \qquad (2)$$

Eq. (2) is of the form which is generally used to describe thermally activated rate processes. The exponential term or the Boltzmann frequency factor is a measure of the probability of dislocation climbing over its barriers. The driving force for dislocation climb over obstacles on the gliding plane comes from both stress and lattice thermal fluctuations. The activation energy, Q, is a measure of the barrier strength which may be a complex function of both stress and temperature.

In irradiation creep where fast neutron flux is also present, we may use a phenomenological equation of the following kind:

$$\dot{\varepsilon} = A\, \phi^{m}\, \sigma^{n} \exp\left(- \frac{Q}{R\,T}\right) \tag{3}$$

Namely, an additional flux dependent term is included. This type of relation has also been suggested by Fidleris(11). Taking logarithms on both sides, (3) becomes

$$\ln\dot{\varepsilon} = \ln A + m \ln\phi + n \ln\sigma - \frac{Q}{R}\frac{1}{T} \tag{4}$$

(4) is essentially a linear model as in (1) with the following transformations:

$$
\begin{aligned}
Y &= \ln \dot{\varepsilon} && ;\ B_0 = \ln A \\
f(X_1) &= \ln \phi && ;\ B_1 = m \\
f(X_2) &= \ln \sigma && ;\ B_2 = n \\
f(X_3) &= 1/T && ;\ B_3 = - Q/R
\end{aligned}
$$

This means that if we transform the original dependent and independent variables into the forms given above, the multiple regression analysis would enable us to find estimates for the coefficients B_o to B_3 and hence the values of A, m, n, and Q.

Two alternative models were also considered in which the activation energy is a function of stress:

$$\dot{\varepsilon} = A\ \phi^m\ \sigma^n\ \exp\left(-\frac{Q_o(1 - \sigma/\hat{\tau})}{R\ T}\right) \tag{5}$$

and

$$\dot{\varepsilon} = A\ \phi^m\ \sigma^n\ \exp\left(-\frac{Q_o(1 - \sigma/\hat{\tau})^2}{R\ T}\right) \tag{6}$$

Again these models were obtained by superimposing a flux dependent term to the thermal creep equations. The mechanistic content of such stress dependent activation energies has been discussed by Ashby and Frost[12]. It does not require much effort to show that these equations can also be transformed into linear models which lend themselves readily to examination by data analysis. Again taking logarithms on both sides, we have

$$\ln\dot{\varepsilon} = \ln A + m \ln\phi + n \ln \sigma - \frac{Q_o}{R}\frac{1}{T} + \frac{Q_o}{R\hat{\tau}}\frac{\sigma}{T} \tag{7}$$

and

$$\ln\dot{\varepsilon} = \ln A + m \ln\phi + n \ln \sigma - \frac{Q_o}{R}\frac{1}{T} + \frac{2Q_o}{R\hat{\tau}}\ \frac{\sigma}{T} - \frac{Q_o}{R\hat{\tau}^2}\ \frac{\sigma^2}{T} \tag{8}$$

The last two terms in (7), (8) give the interaction effects of σ and T on the creep rate respectively.

So far we have presented three models based on only three independent variables. Other functional forms of these independent variables could also be examined. For example, we could use a parameter σ/u instead of σ where u is the shear modulus or $\dot{\varepsilon}/D$ instead of $\dot{\varepsilon}$ where D is the diffusion coefficient, or a combination of the two. Both temperature dependent u and D introduced in this manner will take some temperature dependence outside the exponential term, and in some cases, as in thermal creep analysis, have been shown to give better correlations. The temperature dependent shear modulus of Zr-2 is given by the following formula[13]:

$$u(\text{ksi}) = 4.77\text{x}10^3 - 1.906\text{x}T(^\circ\text{F}) \tag{9}$$

It should be noted that the use of properly non-dimensionalized parameters is a fundamentally appealing approach. This is because of the inconsistancies in parameter units in the previous creep equations. If the variables are expressed in their ordinary units, e.g., $\dot{\varepsilon}$ in hr^{-1}, ϕ in n/cm^2 sec, σ in ksi, and T in °K; the constant A must have unit of $\left(\frac{n}{cm^2\ sec}\right)^{-m} \cdot (ksi)^{-n} \cdot hr^{-1}$ so that units on both sides of the equation are agreeable. But such a unit for A can hardly have any physical interpretation. Since the exponential term is already dimensionless and we replace σ by $\sigma/\mu(T)$, the problem left is then with the flux term. To make this term dimensionless, one may divide ϕ by a reference fast neutron flux ϕ_0 and (3), (5), and (6) become

$$\dot{\varepsilon} = A \left(\frac{\phi}{\phi_o}\right)^m \left(\frac{\sigma}{u(T)}\right)^n \exp\left(-\frac{Q}{R\,T}\right) \tag{10}$$

$$\dot{\varepsilon} = A \left(\frac{\phi}{\phi_o}\right)^m \left(\frac{\sigma}{u(T)}\right)^n \exp\left(-\frac{Q_o(1-\sigma/\hat{\tau})}{R\,T}\right) \tag{11}$$

$$\dot{\varepsilon} = A \left(\frac{\phi}{\phi_o}\right)^m \left(\frac{\sigma}{u(T)}\right)^n \exp\left(-\frac{Q_o(1-\sigma/\hat{\tau})^2}{R\,T}\right) \tag{12}$$

ϕ_o is taken to be 0.05×10^{13} n/cm^2 sec. This is deduced from Ibrahim's result[14] and gives approximately the fast flux threshold below which there is no difference in irradiation and thermal creep behavior. That is, when $\phi = \phi_o$ the creep equations reduce to

$$\dot{\varepsilon} = A\,(\sigma)^n \exp\left(-\frac{Q}{RT}\right), \text{ etc..}$$

After ϕ and σ have been non-dimensionalized, constant A should have unit of hr^{-1} which is reasonable since we know the lattice vibrational frequency ν_G (or the Derbye frequency) is involved in the rate processes.[15] There are, therefore, six regression models, (3), (5), (6), (10), (11) and (12), considered in this analysis.

3.2 Regression Programs:

Details on the descriptions of linear multiple regression analysis can be found from standard texts,[16],[17] and will not be covered here. Several computer statistical regression programs are available with varying capabilities [18],[19],[20],[21]. One program[18] which does least-squares only without giving residual plots is rejected because the model cannot be accepted or denied based on the regression statistics alone such as the multiple regression coefficient, R^2. The program, SPSS (Statistical Packages for Social Sciences)[21] was selected to be our major analytical tool because of its versatility in discriminatory data anlaysis.

Since the residual plots play a very important function in regression analysis, a brief discussion of their interpretation is warranted. Now suppose a linear model is selected and the coefficients have been estimated, the residuals are defined as the n differences $e_i = y_i - \hat{y}_i$, $i = 1, 2, \ldots n$ where y_i is an observation and $\hat{y}_i$ is the corresponding fitted value obtained by use of the fitted equation. These residuals can be plotted in a number of ways. The most important consideration in examining the residual plots is to notice their overall patterns. Fig. 3 shows four residual plots. Except for the straight band pattern (a), the other three patterns of the figure are all indicative of abnormalities that require corrective actions.

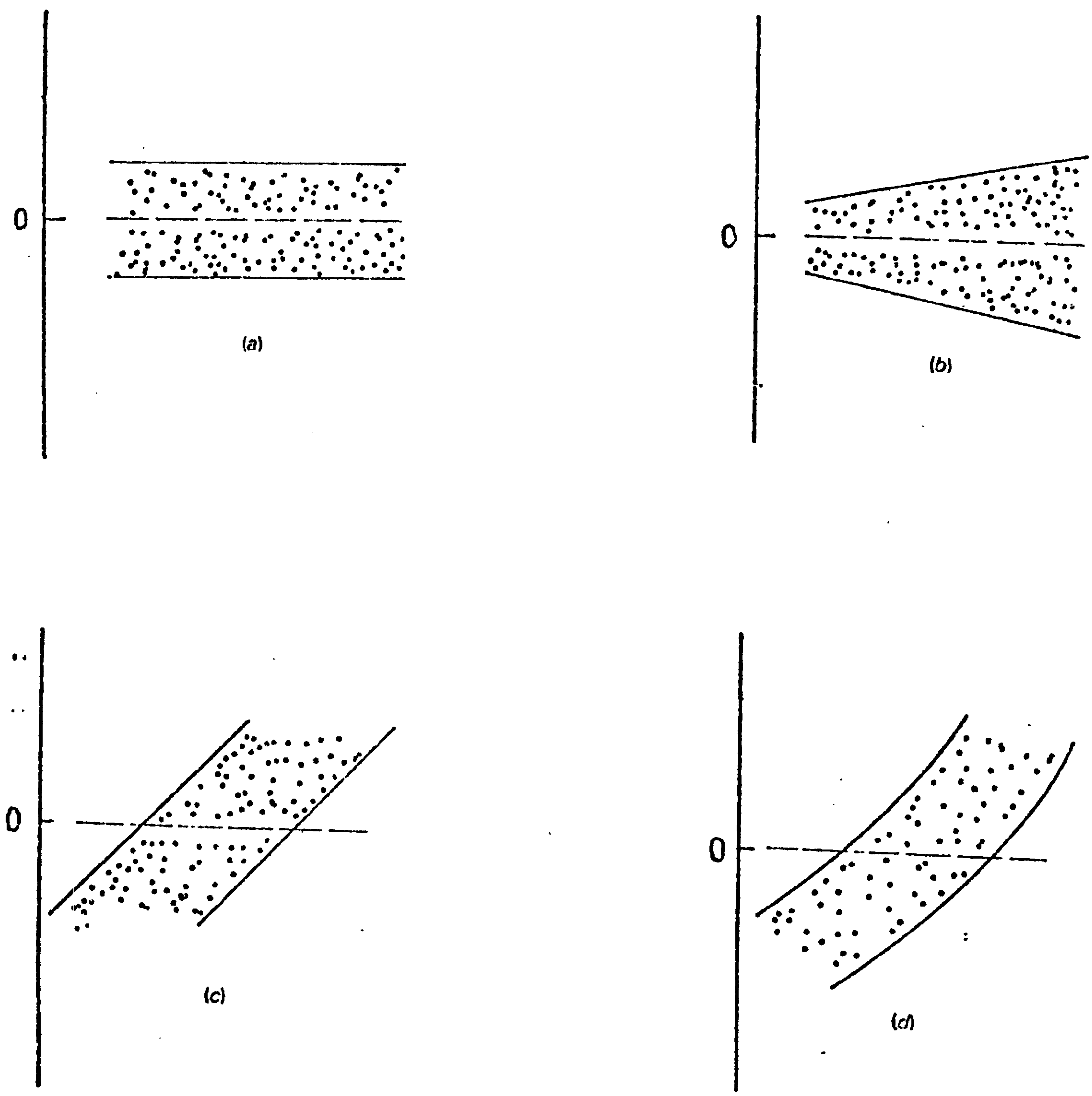


Figure 3. Schematic Residual Plots

For example, pattern (b) indicates that the variance of residuals is dependent on the value of the variable plotted in the horizontal axis. Pattern (c) indicates a linear relationship between residuals and the variable on the horizontal axis. Finally, the arched pattern of (d) indicates curvilinearity that may be removed by the addition of polynomial terms to the regression equation or, perhaps, by a transformation of the y_i values. The reason that a correct pattern is indicated by (a) is not only due to the Central Limit Theorem but also because of the Gaussian N(0,1) error model inherent in the least squares[16]. It is also intuitively expected since if the fitted equation is adequate in explaining the major portion of the data, the residuals should be distributed randomly and evenly across the zero residual line. Deviations from such a pattern then signals that the regression equation is probably inadequate.

Other than serving the purpose for visual examination of abnormalities, the residual plot has another important function which should not be overlooked; that is, to identify stray data points. As we know human errors or equipment malfunctions are sometimes inevitable even in well-ministered experiments. Accordingly, it is helpful to have a way for experimentors and/or data analysts to spot irregular points and to seek reasons for such behavior. If it can be ascertained that the irregularity is due to error, such data should be excluded to avoid the biasing of the result.

4. Examinations of Zr-2 in-reactor creep data:

We have recently compiled both uniaxial and tubular in-reactor creep data of Zirconium, Zr-2, and Zr, 2.5% Nb in the literature from 1962 to 1974[22]. There are in total 276 data observations and the breakdown of these observations into subsets is shown in Table 3.

TABLE 3. TOTAL NUMBER OF DATA OBSERVATIONS IN EACH SUBLET

	Zirconium	Zr-2	Zr-2.5%Nb
Uniaxial	9	89	65
Tubular	0	73	40

The subset of Zr-2 tubular in-reactor creep data was chosen for analysis and this portion of data is included in Appendix A. The term "Reference" on the second column of the data Table indicates where these data come from and can be compared with the reference list provided at the end of this report. One notices from the fourth column that there are about eight different cold-work and heat treatment material conditions. Since both cold-work and heat treatment affect the material condition and hence the creep behavior, the data set is further subdivided according to these material conditions.

As is shown, data taken from Reference I-11(Serial T14-T19), M-5 (Serial T39 - T56) and a portion of H-14, I-13 (Serial T1 - T13) with 20% C-W plus stress relief constitute the largest subdata set in this Table. This subset is, therefore, chosen for the regression analysis. It turns out that all these data observations were obtained by the same group of Canadian researchers on Zr-2 pressure tubes. The tube fabrication method and the alloy conditions are, therefore, reasonably similar. The only difference is the size of the test specimens. In early experiments full-size pressure tubes were creep tested whereas later for economical reasons and also for reasons of achieving higher stresses

Table 4. Summary of ~20% CW and Stress Relieved Zr-2 In-Reactor Creep Data

ZIRCALOY-2

Serial	Reference	Ident. No.	Material Condition***	0.2% Y.S. MN/m^2 (Temp °C)	Specimen Type	Test Type	Atmosphere	Temperature (°C)	Stress MN/m^2	Stress ksi	Neutron Flux (E > 1 MeV) 10^{13} $n/cm^2 \cdot s$ (Fluence, 10^{20} n/cm^2)	$10^{-6}h^{-1}$ Minimum In-reactor Creep Rate (h^{-1}) (Duration - h)	$10^{-6}h^{-1}$ Minimum Control Creep Rate (h^{-1}) (Duration - h)	Total Creep Strain (%)
1	H-14, I-5	U-3MK V	26%CW+SR	414B(300)	8.3-cm-i.d. pressure tube	Diametral creep	H_2O	327	33.8	4.9	3.1	0.091(13,000)		
2		NPD	15-19%CW+SR	"	"	"	"	264	72.5	10.5	1.15	0.054(29,000)		
3		U-2MK III	22%CW+SR	"	"	"	"	281	79.4	11.5	2.7	0.18(5700)		
4		U-2MK IX	20%CW+SR	"	10.3cm-i.d. pressure tube	"	"	281	92.4	13.4	3.1	0.23(3300)		
5		U-2MK IV	18%CW+SR	"	8.3cm-i.d. pressure tube	"	"	270	96.5	14	2.7	0.19(11,000)		
6		U-2MK IX	20%CW+SR	"	10.3cm-i.d. pressure tube	"	"	281	119	17.3	3.1	0.29(3300)		
7		U-2MK V	26%CW+SR	"	8.3cm-i.d. pressure tube	"	"	300-345	96.5+	14+	1+	0.063-0105++*	0.02-0.063++*	0.06-0.11++
8		NPD(F-7)	15-19%CW+SR	"	"	"	"	252-273	"	"	"	0.043-0.061++*	0.003-0.0085++*	0.11-0.15++
9		NPD(H-7)	"	"	"	"	"	"	"	"	"	0.063-0.08++*	"	"
10		U-2MK III	22%CW+SR	"	"	"	"	270-242	"	"	"	0.062-0.09++*	0.0085-0.014++*	0.16-0.2++
11		U-2MK IX	20%CW+SR	"	10.3cm-i.d. pressure tube	"	"	"	"	"	"	0.065-0.113++*	0.0085-0.013++*	0.18-0.24++
12		U-2MK IV(B1)	18%CW+SR	"	8.3cm-i.d. pressure tube	"	"	252-288	"	"	"	0.051-0.092++*	0.003-0.014++*	0.17-0.22++
13		U-2MK IV(B2)	"	"	"	"	"	240-257	"	"	"	0.045-0.08+*	"	"
14	I-11		20%CW+SR	376L(300)	23mm-dia pressure tube	Diametral creep	H_2O	258	108	15.7	2.56	0.13(9000)	($106MN/m^2$)0.01(9000)	
15			"	"	"	"	"	"	134	19.4	"	0.24(9000)	($129MN/m^2$)0.01(9000)	
16			"	"	"	"	"	"	165	23.9	"	0.27(9000)	($166MN/m^2$)0.048(9000)	
17			"	"	"	"	"	"	201	29.2	"	0.36(9000)	($198MN/m^2$)0.039(9000)	
18			"	"	"	"	"	"	234	34.0	"	0.61(9000)	($232MN/m^2$)0.056(9000)	
19			"	"	"	"	"	"	259	37.6	"	0.88(4700)	($266MN/m^2$)0.116(9000)	

*estimated from graph **not reported ***CW-cold work, SR-stress relieved 72h at 400°C, T-transverse, L-longitudinal, B-burst test 2:1

+normalized to 14ksi and $1x10^{13} n/cm^2 s$ ++ normalized to $10^{21} n/cm^2$

ZIRCALOY-2

Serial	Reference	Ident. No.	*** Material Condition	0.2% Y.S. MN/m^2 (Temp °C)	Specimen Type	Test Type	Atmosphere	Temperature (°C)	Stress MN/m^2	Stress ksi	Neutron Flux (E > 1 MeV) 10^{13} n/cm²·s (Fluence, 10^{20} n/cm²)	$10^{-6}h^{-1}$ Minimum In-reactor Creep Rate (h^{-1}) (Duration - h)	$10^{-6}h^{-1}$ Minimum Control Creep Rate (h^{-1}) (Duration - h)	Total Creep Strain (%)
39	M-5	NRU	20%CW+SR	374L(300)	23-mm dia. pressure tubes	diametral creep	H_2O	263	111	16.2	2.9	0.14 (5000)	(111MN/m²) <0.01(5000)	
40		"	"	"	"	"	"	"	"	"	"	0.062(20,000)		
41		"	"	"	"	"	"	"	136	19.7	"	0.2(5000)	(135MN/m²) <0.01(5000)	
42		"	"	"	"	"	"	"	"	"	"	0.1(20,000)		
43		"	"	"	"	"	"	"	171	24.8	"	0.22(5000)	(169MN/m²) 0.027(5000)	
44		"	"	"	"	"	"	"	"	"	"	0.11(20,000)		
45		"	"	"	"	"	"	"	204	29.6	"	0.3(5000)	(201MN/m²) 0.041(5000)	
46		"	"	"	"	"	"	"	"	"	"	0.14(20,000)		
47	M-5	NRU	20%CW+SR	374L(300)	23mm dia. pressure tube	diametral creep	H_2O	263	239	34.6	2.9	0.5 (5000)	(237MN/m²) 0.058 (5000)	
48		"	"	"	"	"	"	"	"	"	"	0.25 (20,000)		
49		"	"	"	"	"	"	"	261	37.8	"	0.7 (5000)	(270MN/m²) 0.095 (5000)	
50		"	"	"	"	"	"	"	"	"	"	0.37 (20,000)		
51		"	"	"	"	"	"	"	111	16.2	0.01-0.1	<0.01 (5000)	<0.01 (5000)	
52		"	"	"	"	"	"	"	135	19.6	"	0.017 (5000)	0.01 (5000)	
53		"	"	"	"	"	"	"	169	24.5	"	0.033 (5000)	0.027 (5000)	
54		"	"	"	"	"	"	"	201	29.2	"	0.039 (5000)	0.041 (5000)	
55		"	"	"	"	"	"	"	237	34.4	"	0.071 (5000)	0.058 (5000)	
56		"	"	"	"	"	"	"	270	39.2	"	0.092 (5000)	0.095 (5000)	

*estimated from graph **not reported ***CW-cold work L-longitudinal
SR-stress relieved 72h at 400°C
T-transverse B-burst test 2:1

+ without failure

during creep testing, small-sized specimens (23 mm diameter) were used. The small-sized specimens are probably stronger and of finer grain size than full-sized pressure tubes because of quicker cooling rates after extruding (due to the smaller size), giving greater residual hot work before cold drawing[14].

Since extensive cross references are made when using this subset of data, it is worthwhile to designate them into a new table given by Table 4. Our discussions of this Table will follow three general areas: (1) The accuracy of data, (2) normalization assumptions, and (3) time effects. But before we proceed, it is helpful to quickly review some of the key features of the tubular in-reactor creep experiments from which these data were obtained.

These experiments were conducted in NPD (Nuclear Power Demonstration) and NRU (National Research Universal) reactors with full-size pressure tubes and small-size specimens. A schematic diagram of the small-tube, in-reactor creep test assembly is shown in Fig. 4. Since the small-size specimens were enclosed in a secondary containment, there is no danger in damaging the reactor when tube rupture occurs, and, therefore, higher applied stresses giving much higher creep strains are permitted. Also, since the hot-pressurized water is maintained at rather constant pressure, the stress variable is altered by machining the outside of specimens to give different wall thicknesses. Depending on their relative positions in the reactor, three types of creep results were actually obtained for the fast-flux specimens, thermal-flux specimens, and out-of-flux specimens. This is also evident from Fig. 4.

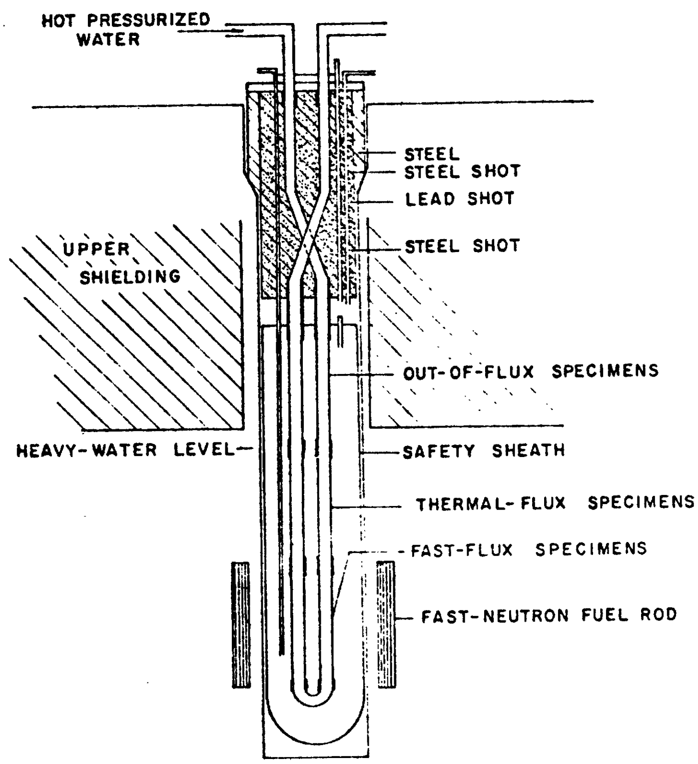


Figure 4. A schematic diagram of the small tube in-reactor creep specimen assembly (reproduced from ref. [I-11])

Typical reactor operating histories are shown in Fig. 5 for Ross-Ross and Hunt's full-size pressure tube experiments and in Table 5 for Ibrahim's small-sized specimen, U-49 tubular creep insert.

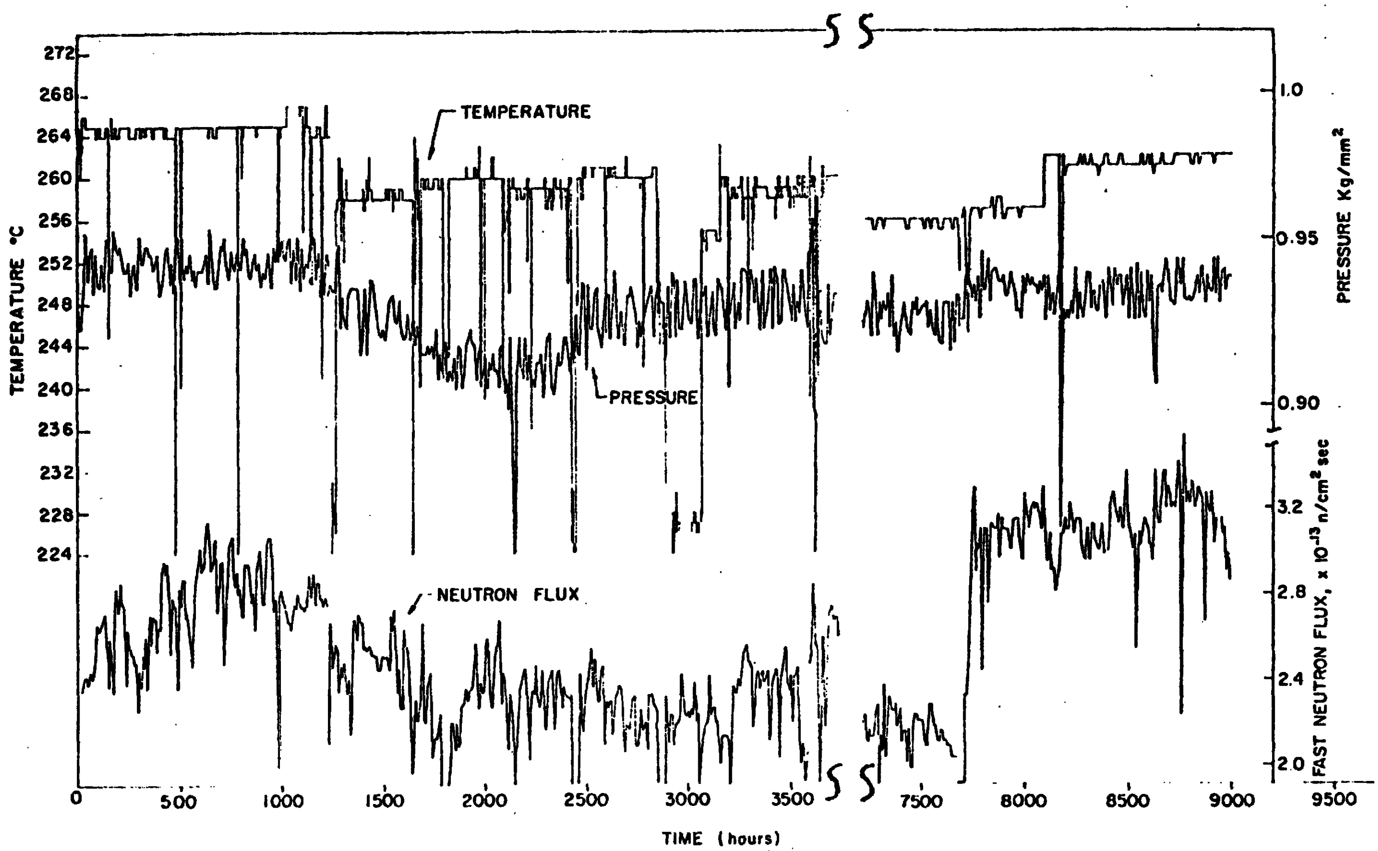


Fig. 5. The operating conditions for the Zircaloy-2 tubular creep experiment. (The complete 18 by 40 in. chart covering the operating conditions up to 9000 hours may be obtained from ASTM Headquarters, $3.) Reproduced from ref. (I-11).

TABLE 5 Operating conditions of U-49 tubular creep insert. (Reproduced from ref. (14))

Time period (h)	Average temperature (°C)	Average pressure (MN/m^2)	Fast neutron flux > 1 MeV ($\times 10^{-17}$)
0 to 1232	264.4	9.24	2.55
1232 to 2419	256.7	8.96	2.51
2419 to 3516	253.4	9.09	2.34
3516 to 4987	260.7	9.05	2.52
4987 to 6053	256.7	9.08	2.52
6053 to 7597	257.1	9.09	2.36
7597 to 8910	259.2	9.14	3.12
8910 to 9712	260.3	9.57	2.82
9712 to 10747	260.4	9.17	3.39
10747 to 13626	265.6	9.54	3.40
13626 to 14793	270.4	9.40	3.05
14793 to 19859	263.2	9.33	3.18
19859 to 20896	279.1	9.39	3.25
Average	262	9.3	2.9

The purpose of this reviewing is to emphasize that during the entire period of creep testing (which may run up to 20,000 hrs.), variables ϕ, σ, and T will have their own histories and are not constant values throughout the test. This is because the reactors are run according to their fuel management shcemes and these schemes are generally not dictated by the creep tests. Therefore, each time a fuel shuffling operation takes place, it will cause changes in all local conditions. A good example of such local changes is illustrated in Fig. 5. Data of ϕ, σ and T contained in Table 4 are then only average values obtained from the entire operating history of each variable respectively. As will be shown later, one or more normalization assumptions were used in some cases to reduce the data to the present values. While normalization is a viable procedure in data reduction, the assumptions must be carefully examined first. Otherwise the original information may be lost or distorted.

4.1 Accuracies of data:

There are at least three major sources of error which may be introduced into the values of the dependent as well as the independent variables: (1) errors due to the use of average values (ignoring the history effects), (2) errors of measurement and calculation, and (3) erros due to improper normalization assumptions. We cannot do much about the first type of error except to say that the deviations from average conditions are sufficiently small such that there are no significant history effects. Therefore, in this section only measurement and calculational errors are discussed, and normalization errors are discussed in the next section.

4.1.1. Errorsdue to measurement: ($\dot{\varepsilon}$, T, P)

Diametral creep strains were measured both at intermediate shutdowns and at the end of testing by linear variable differential transformer

(LVDT)[5], air gauges[14], and micrometers. The accuracies of these strain gauges have been discussed elsewhere[14],[5] and are generally considered satisfactory. Pressure and temperature measurements were taken at inlet and outlet only with standard instruments, and the measurement errors should be rather small. The errors of measurement are, in general, believed to be small when compared with the errors due to calculation.

4.1.2 Errors due to calculation:

Two types of errors are introduced into the calculations of tangential stresses in the reference data set H-14. One is caused by the assumption of a linear pressure gradient along the tube made by Ross-Ross and Hunt[5] and the other is the use of a thin shell approximation formula, $\sigma_t = p\ d/2t$, to convert the pressure into tangential stress where d is chosen to be the tube inside diameter and t is the wall thickness. Calculations using Lame's exact formula for internally pressurized tubes[23] show that the thin shell approximation underestimates stresses by about 1 to 5% depending upon the wall thickness. The pressure drop and hence the localized pressure can be calculated from the Darcy formula[24] but requires rather detailed knowledge of the flow conditions, entrance effects, etc.. Since this information is not available, we merely point it out that the pressure and hence the stress in H-14 are based on the linear pressure gradient assumption.

Coolant temperatures at inlet and outlet to the tube were measured, and the temperature gradient along the tube is calculated using fuel power information. Fast neutron flux (E>1 Mev) is calculated from reactor physics using fuel bundle powers and geometry factors.[5] The accuracies of these calculations must be determined from the actual conditions and the assumptions in the reactor physics model.

In any case, errors due to measurement and calculation are probably not major factors in these creep experiments. This is because of the averaging procedures used to normalize the history effects would likely to overshadow the magnitudes of the combined errors due to measurement and calculation.

4.2 Normalization assumptions:

The empirical equation obtained by Ross-Ross and Hunt in correlating their in-reactor creep data is reproduced as follows:

$$\dot{\varepsilon}_t = 4\times10^{-24}\,\sigma_t\phi(T - 433) \qquad (13)$$

where

$\dot{\varepsilon}_t$: hr^{-1}

σ_t: ksi (up to 20 ksi)

ϕ ; $n/cm^2 sec$ (0.5 to 3.5×10^{13} n/cm^2 sec)

T ; $^{\circ}K$ (523 to $573^{\circ}K$)

The equation is obtained in a similar manner as that of Watkins and Wood discussed previously. The stress and flux exponents were determined first by using $\dot{\varepsilon}_t$ sequentially with $\dot{\varepsilon} = \beta\sigma_t^n$ and $\dot{\varepsilon} = \beta'\phi^m$. After n, m are found (both close to 1), the temperature dependence is determined by assuming the creep rate is proportional to flux and stress, and $\dot{\varepsilon}$ is normalized to the reference conditions of 14 ksi and 10^{13} $n/cm^2 sec$ by the following formula:

$$\dot{\varepsilon}_N = \dot{\varepsilon}_{Act} \times \frac{14 \text{ ksi}}{\text{actual stress}} \times \frac{10^{13} \text{ n/cm}^2\text{sec}}{\text{actual flux}} \qquad (14)$$

This normalized creep rate is plotted against temperature in Fig. 6, and (13) is derived from the best fit.

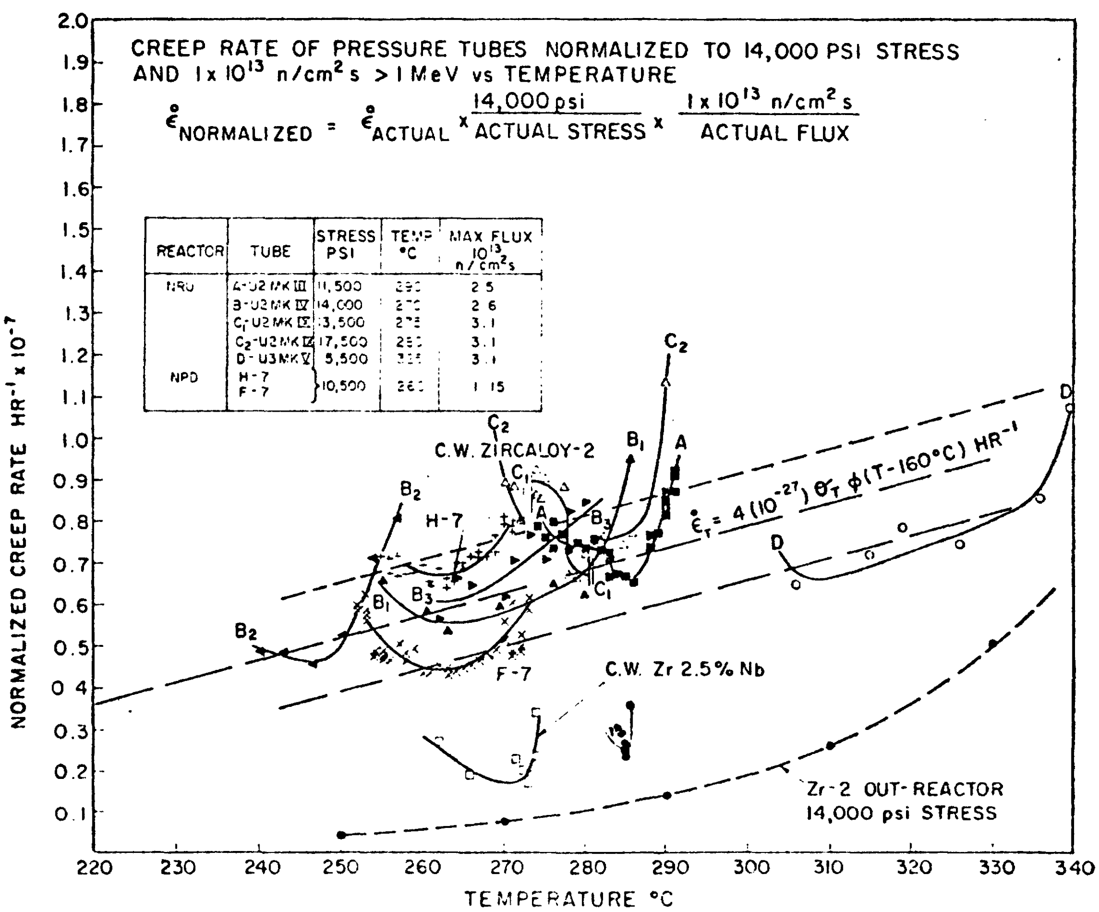


Figure 6. Creep rate of pressure tube normalized to 14 ksi and 10^{13} n/cm^{2}sec vs temperature. (Reproduced from ref. (5)).

Again the overall procedure is questionable. The following Table illustrates that if the correct creep model is given by (3) with m=0.85, n=1.2, and Q/R =4,000 cal/mole; the difference in the normalized creep rates from two normalization procedures can be quite large at the average reactor operating conditions.

TABLE 6 Comparison of normalized creep rates under two different normalization assumptions

Time period (hr)	Temperature (C°)	Pressure (MN/m^2)	Flux (n/cm^2s)	$\dot{\varepsilon}_1/\dot{\varepsilon}_2^*$
0-1232	264.4	9.24	2.55	1.169
1232-2419	256.7	8.96	2.51	0.740
2419-3516	253.4	9.09	2.34	0.612
3516-4987	260.7	9.05	2.52	0.941
4987-6053	256.7	9.08	2.52	0.742
6053-7597	257.1	9.09	2.36	0.767
7597-8910	259.2	9.14	3.12	0.836
8910-9712	260.3	9.57	2.82	0.914
9712-10747	260.4	9.17	3.39	0.887
10747-13626	265.6	9.54	3.40	1.200
13626-14793	270.4	9.40	3.05	1.598
14793-19859	263.2	9.33	3.18	1.058
19859-20896	279.1	9.39	3.25	2.509
Average or reference value	262.0	9.30	2.90	

*$\dot{\varepsilon}_1$: Normalized strain rate using linear dependence in ϕ, σ, and (T-160).

$\dot{\varepsilon}_2$: Normalized strain rate using $\dot{\varepsilon} \propto \phi^m \sigma^n \exp(-Q/RT)$ relation with m=0.85, n=1.2, and Q/R=4,000 cal/mole

$$\dot{\varepsilon}_1/\dot{\varepsilon}_2 = (\phi_r/\phi)^{1-m}(\sigma_r/\sigma)^{1-n}\left(\frac{T_r-160}{T-160}\right) \exp\left(\frac{Q}{R}\left(\frac{1}{T_r}-\frac{1}{T}\right)\right)$$

where ϕ_r, σ_r, and T_r are the reference values.

Creep strain rate data from Serial T7 to T13 in Table 4 normalized with Ross-Ross and Hunt's assumption should, therefore, be transformed back to the values according to the actual stress and flux, and this is done by both (14) and the Table insert of Fig. 6. The back transformations are necessary to remove any bias in the data which might have occurred from improper normalization assumptions.

4.3 Time effects:

All previous creep equations of the form $\dot{\varepsilon}=f(\sigma,\phi, T)$ apply only when materials are at a stage of constant or steady state creep. In thermal creep analysis, the creep rate is often found to be constantly diminishing with time and the creep strain can be represented by $\varepsilon = \beta t^m$. Differentiating ε with respect to time gives

$$\dot{\varepsilon} = m\, \beta t^{m-1}$$

Clearly steady state creep is possible only when m=1; for $m < 1$ the creep rate is decreasing with time which is indicative of strain hardening.

In irradiation creep, although some of the early in-reactor creep experiments[6],[5] did not show this kind of relationship after several hundred hours, results obtained by Ibrahim[14] over long test periods did. The rate of decrease in creep rate is somewhat slower for in-reactor creep than out-of-reactor creep (wiehgted mean m=0.468 for fast flux specimen and weighted mean m=0.270 for out-of-flux specimens)[14].

The problem caused by this time dependence of creep rate is as follows: since creep strain rates must be obtained from dividing the measure diametral creep strains by a small time interval, the time at which such creep strain measurement is taken will apparently matter. For example creep rate data serial T39 and T40 are at the same σ, ϕ, T values but estimated at 5,000 and 20,000 hours correspondingly, they differ by a factor of 2.4.

When the form of time dependence cannot be incorporated readily, we must select a convenient reference time for creep rate calculation such that the creep rate data can be compared and analyzed on an equal basis. A number of data observations in M-5 should thus be excluded. Since the major portion of creep rate data were estimated at 5,000 hours, we have chosen it to be the reference time and hence the even numbers of data observations (at 20,000 hrs.) from T40 to T50 inclusive should be excluded. The actual set of creep data used in regression analysis can be found in Apprndix B.

5. Regression results:

Results from regression analyses using the six regression models (3), (5), (6), (10), (11), (12) and one which is of a similar form to (13) are presented in this section. The last one is included for the purpose of demonstrating that if such a model of regression analysis is given by $\dot{\varepsilon} = A\ \phi^m\ \sigma^n$ $(T-433)^p$, the estimates for the exponents n, m, and p will not be close to 1 at all as obtained by Ross-Ross and Hunt's procedures. Instead, the equation should be written as

$$\dot{\varepsilon} = 3.41\text{x}10^{-26}\ \ \phi^{0.61}\ \sigma^{1.52}\ (T - 433)^{2.047} \qquad (16)$$

Computer printouts on the details of regression statistics such as R^2, F ratio, standard error of estimate (SEE), etc. are given in Appendix C. It is useful to summarize and assemble the information into the following Table:

TABLE 7 Multiple regression coefficients and F statistics

Equation No.	R^2(%)	F
3	96.969	178.498
5	97.109	136.525
6	97.702	134.482
10	96.969	178.516
11	97.106	136.359
12	97.708	134.865
16	96.902	174.466

R^2 stands for the goodness of fit or the fraction of data that has been explained by the regression equation. A high F value means that the null hypothesis H_0: R=0 must be rejected or the alternative hypothesis $H_1 : B_i \neq 0$ for one or more i is true. Several points are worth noting from Table 7. First of all, based on values of R^2 and F, all regression equations can be considered significant. We shall further substantiate this conclusion when we examine the residual plots. Second, R^2 increases as we use more elaborate forms of stress dependent activation energies, i.e., in ascending order in groups of (3), (5), (6) and (10), (11), (12), but the increase is marginal. Third, equations of non-dimensionalized parameters with a temperature-dependent shear modulus give higher R^2 than their counterparts in the original units of σ, ϕ, and T, but the difference is slight.

In order to assess whether one should include product terms such as σ/T, and σ^2/T to account for their interaction effects on $\dot{\varepsilon}$, stepwise (forward inclusion) regressions were also performed in which the independent variables are entered into the equation one by one on the basis of a preselected statistical criterion. In short, this step-by-step procedure helps to screen out the independent variables (be it single or product) whose partial F's are less than the pre-selected value. These variables are considered as having only minor contributions to the representation of the data. In all stepwise cases we have studied based on an F value of 3.2, no independent variables (single or product) have been eliminated. A more stringent criterion is therefore required if one intends to use a model with less than a maximum of five independent variables (σ, ϕ, T, σ/T, σ^2/T). Results from stepwise regressions are included in Appendix D.

5.1 Residual plots:

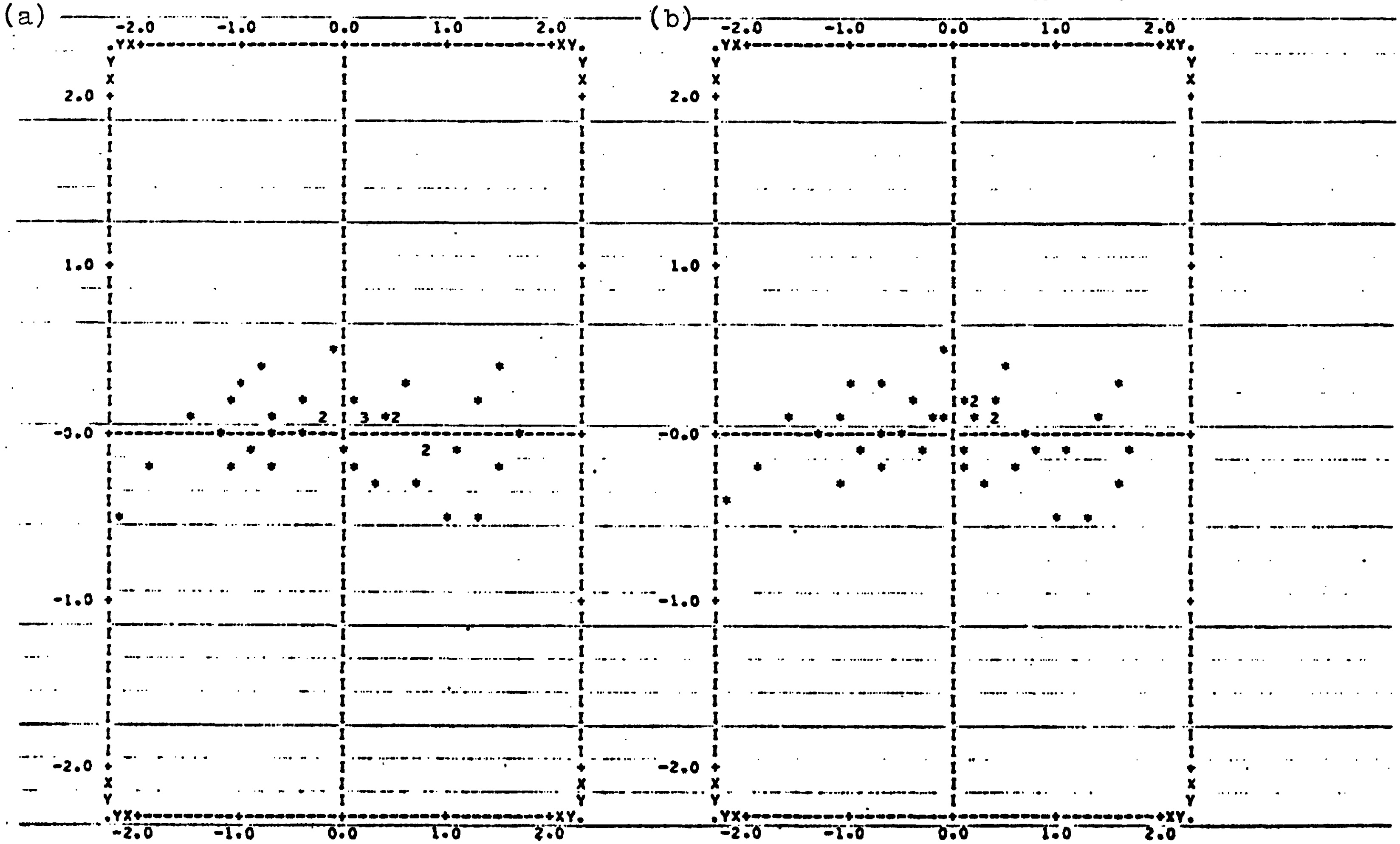
Fig. 7 to Fig. 10 give the standardized residual versus standardized fit plots for the previous regression models. They are identified by equation numbers. First we notice that the overall patterns of these residual plots look quite satisfactory. All residuals fall more or less into rather straight error bands. There are no indications of "abnormalities" as discussed earlier in Section 3.2. Fig. 10 which is based on the revised Ross-Ross and Hunt's model (16) shows that it is only slightly inferior to Fig. 7(a) which is based on (3) in terms of residual structures. Fig. 7(a), 7(b), 8(a), 8(b), 9(a), and 9(b) show that the error band gets narrower when more elaborate forms of stress-dependent activation energies were used. The corresponding residual plots in either original parameter units or in dimensionless form show little difference in their structures.

CREEP LAWS WITH STRESS DEPENDENCE OF ACTIVATION ENERGY 05/03/76 PAGE 22

FILE NONAME (CREATION DATE = 05/03/76)

* * * * * * * PLOT: STANDARDIZED RESIDUAL (DOWN) -- PREDICTED STANDARDIZED DEPENDENT VARIABLE (ACROSS) * * * * * * *

DEPENDENT VARIABLE: CRL2 VARIABLE LIST 1 REGRESSION LIST 1 DEPENDENT VARIABLE: CRL2 VARIABLE LIST 1 REGRESSION LIST 2



ROWS,COLUMNS Y: VALUES OUTSIDE (-3.0,3.0) ROWS,COLUMNS X: VALUES IN (-3.0,-2.05) OR (2.05,3.0)

Figure 7 Residual plots (a), (b) for regression models (3) and ~~(5)~~

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FILE NONAME (CREATION DATE = 05/03/76)

* * * * * * * PLOT: STANDARDIZED RESIDUAL (DOWN) -- PREDICTED STANDARDIZED DEPENDENT VARIABLE (ACROSS) * * * * * * *

DEPENDENT VARIABLE: CRL2 VARIABLE LIST 1 REGRESSION LIST 3 DEPENDENT VARIABLE: CRL2 VARIABLE LIST 1 REGRESSION LIST 4

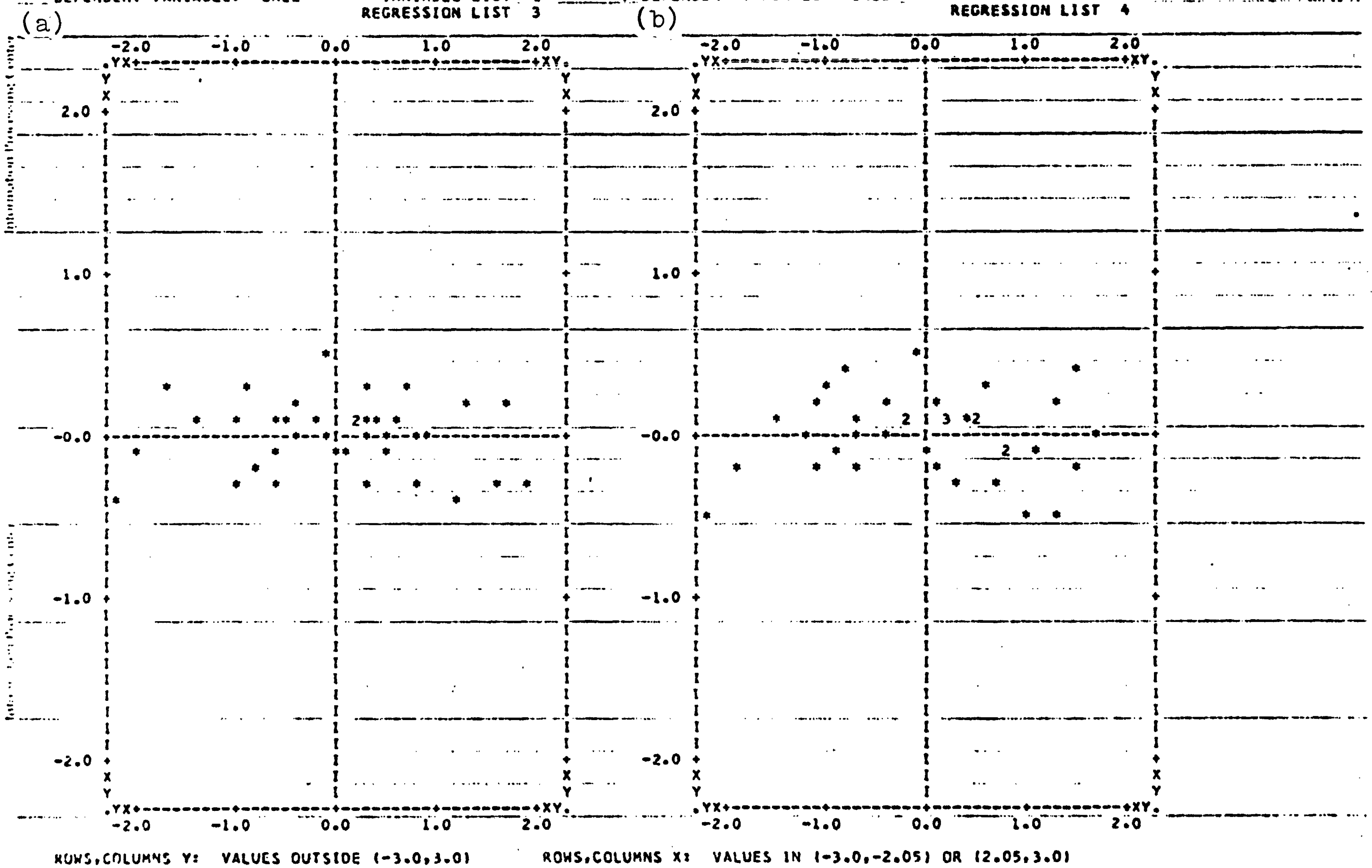

Figure 8 Residual plots (a), (b) for regression models (6) and (10)

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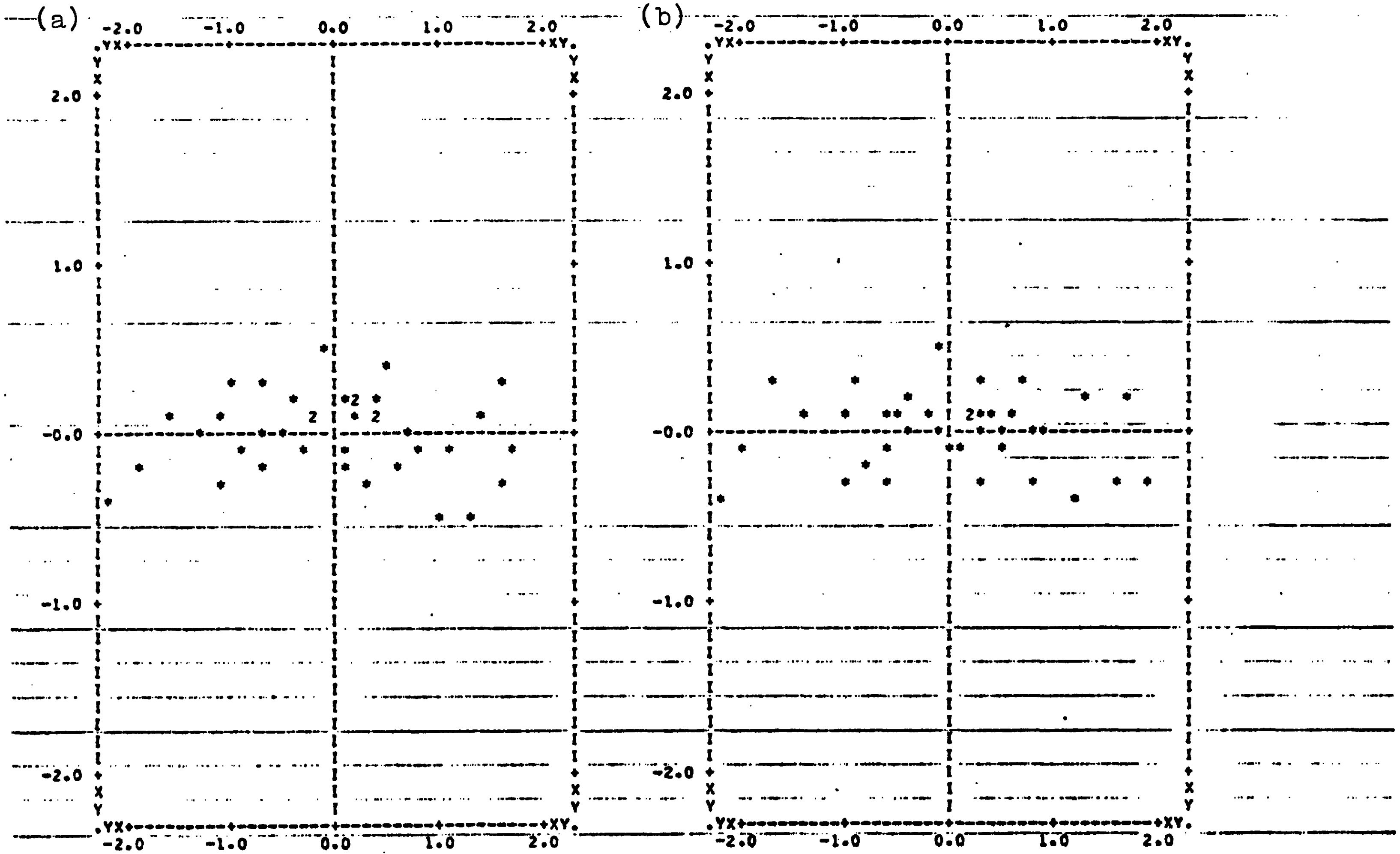
FILE NONAME (CREATION DATE = 05/03/76)

* * * * * * * PLOT: STANDARDIZED RESIDUAL (DOWN) -- PREDICTED STANDARDIZED DEPENDENT VARIABLE (ACROSS) * * * * * * *

DEPENDENT VARIABLE: CRL2 VARIABLE LIST 1 REGRESSION LIST 5

DEPENDENT VARIABLE: CRL2 VARIABLE LIST 1 REGRESSION LIST 6



ROWS,COLUMNS Y: VALUES OUTSIDE (-3.0,3.0) ROWS,COLUMNS X: VALUES IN (-3.0,-2.05) OR (2.05,3.0)

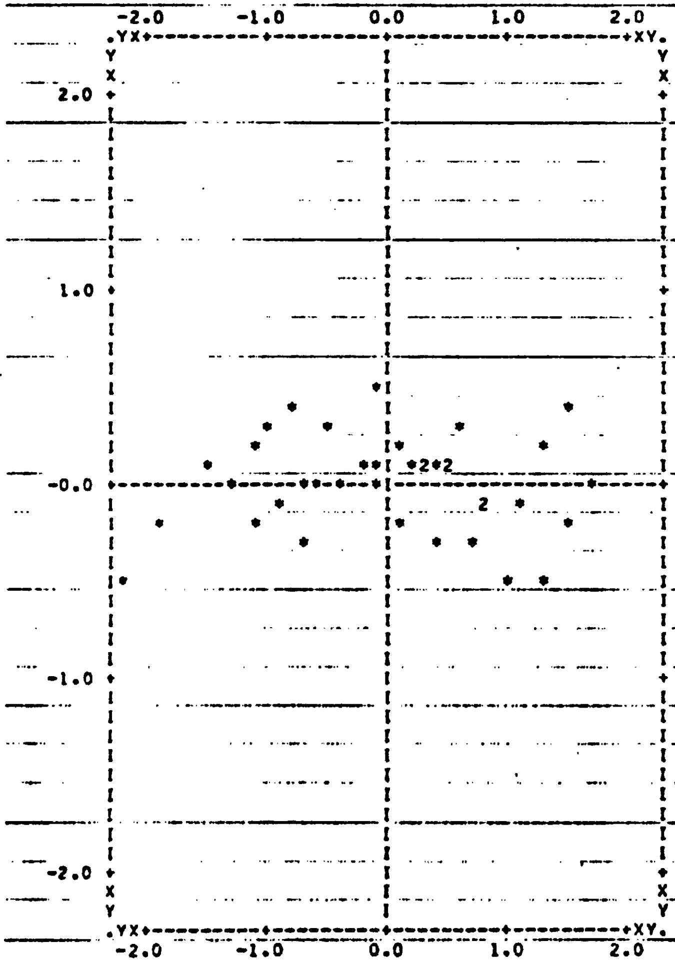
Figure 9 Residual plots (a), (b) for regression models (11) and (12)

CREEP LAWS WITH STRESS DEPENDENCE OF ACTIVATION ENERGY 05/03/76 PAGE 25

FILE NONAME (CREATION DATE = 05/03/76)

* * * * * * * PLOT: STANDARDIZED RESIDUAL (DOWN) -- PREDICTED STANDARDIZED DEPENDENT VARIABLE (ACROSS) * * * * * * *

DEPENDENT VARIABLE: CRL2 VARIABLE LIST 1
REGRESSION LIST 7



ROWS,COLUMNS Y: VALUES OUTSIDE (-3.0,3.0) ROWS,COLUMNS X: VALUES IN (-3.0,-2.05) OR (2.05,3.0)

Figure 10 Residual plot for the revised Ross-Ross and Hunt's regression model (14)

Based on our results from regression statistics, residual plots, and stepwise regressions, we conclude the followings:

(1) The ranking of regression models in terms of goodness of fit (in descending order) is as follows:

Group 1 (equations in original units): (6), (5), (3), (16)

Group 2 (equations with dimensionless parameters):(12), (11), (10).

(2) Although the corresponding regression models in Group 1 and Group 2 do not differ very much, Group 2 models are recommended because they offer better physical interpretations.

5.2 Estimated regression coefficients and 95% confidence invervals:

A summary of the estimated regression coefficients and their standard error of estimates (SEE) is given for each model in Table 8. From these coefficients one can construct in-reactor constitutive equations by sub-

TABLE 8 Regression coefficients and their SEE's

Equation No.	lnA	m	n	Q/R	$Q_0/R\hat{\tau}$	$Q_0/R\hat{\tau}^2$
(3)	-28.799	0.611	1.540	5298.06	---	---
SEE	--	0.030	0.100	816.00	---	---
(5)	-29.112	0.613	1.126	4746.49	11.406	---
SEE	--	0.030	0.345	920.96	9.093	---
(6)	-31.640	0.609	2.759	4276.19	-108.915*	1.676
SEE	--	0.027	0.652	851.15	42.969	0.587
(10)	- 0.470	0.611	1.541	4855.29	---	---
SEE	--	0.030	0.100	799.55	---	---
(11)	- 3.900	0.613	1.130	4425.72	11.310	---
SEE	--	0.030	0.347	866.03	9.142	---
(12)	6.323	0.609	2.800	3484.49	-111.175*	1.701
SEE	--	0.027	0.659	849.12	43.323	0.591

*In equation (6) and (12), the coefficients for σ/T are in the form of $2Q_0/R\hat{\tau}$.

stituting them back into the corresponding models. The 95% confidence intervals for each coefficient are found by using the following formula:

$$\hat{B}_i \text{ (estimated } i^{th} \text{ coefficient)} \pm t \text{ (SEE)}_i \qquad (17)$$

where t is obtained from a 95% point "Student-t" distribution with n-k degrees of freedom; n is the total number of observations and k is the number of coefficients to be estimated.

It is often more useful to know the overall 95% confidence interval for the entire regression equation, and this can be found from[25]

$$\hat{y}_i \text{ (fitted value)} \pm \sqrt{M \cdot f} \text{ (SEE)}_{\hat{y}} \qquad (18)$$

where M is the number of coefficients to be estimated, f is obtained from a 95% point F-distribution with M, and n-M degrees of freedom. The following Table contains the information which can be used to construct the over 95% confidence intervals.

TABLE 9 Overall 95% confidence intervals

Equation No.	M	f	$\sqrt{Mf}$	$(SEE)_{\hat{y}}$	$\pm\sqrt{Mf}\ (SEE)_{\hat{y}}$
(3)	3	2.88	2.939	0.2514	0.739
(5)	4	2.65	3.256	0.2493	0.812
(6)	5	2.49	3.528	0.2261	0.798
(10)	3	2.88	2.939	0.2514	0.739
(11)	4	2.65	3.256	0.2495	0.812
(12)	5	2.49	3.528	0.2258	0.797

5.3 Comparisons of current empirical and regression creep equations:

It is instructive to plot on a single set of axes creep rates from current in-reactor creep models, regression equations, and the actual creep data. Six such plots, Fig. 11 to Fig. 16, were made at a constant fast flux $\phi=5\times10^{13}$ n/cm^2sec to show the $\ln\dot{\varepsilon}$ vs 1/T and $\ln\dot{\varepsilon}$ vs $\ln\sigma$ relationships. Since creep rates in these figures are plotted against only one variable while keeping the remaining two constant, it is necessary to transform the original creep rate data to the reference values of these two remaining variables. This can be done by using one of the regression equations to provide the scaling factors. To avoid obscuring the diagram with too many curves, we merely used regression model (3) and its associated overall 95% confidence interval to demonstrate the difference. Those lines representing the current in-reactor creep models are identified by the corresponding equation numbers in Table 1. Both temperature and stress ranges taken in these plots are considered to be realistic values which can be achieved under LWR fuel clad operating conditions.

From these figures, one sees that while the Gittus' theoretical model always underestimates creep rates in both types of plots, good agreements among other models are achieved only at low stress and low temperature regions. Fig. 11 and Fig. 12 which are applicable to CANDU reactor pressure tube operating condition, except for the slightly higher fast neutron flux, show that all creep models give acceptably good predictions below about 20 ksi, since most of the curves fall within the 95% confidence interval. This is not the case, however, in Fig. 13 and Fig. 14 when temperatures are raised to 350 and 400°C respectively. Greater departures are seen among these curves as the temprature is increased. As one might have expected from an Arrhenius type relation, temperature should have a very strong effect on creep rate. This is again evidenced in Fig. 15 and Fig. 16 where the highest predicted creep rate is about three orders of magnitude larger than the one from the regression equation.

Fig. 13, 14 and Fig. 16 warrant special attention because the extraordinarily high creep rates predicted by some of the models at combined high stress and high temperature would make it almost impossible to maintain clad geometries even within a short period of reactor operating time. We are not necessarily stating that the regression model is better than the rest of the models at high temperature. There is no doubt about the danger in extrapolating beyond the available range of data. However, in situations where one has to extrapolate, it is better if one proceeds on a sound statistical basis. Equations obtained from parameter adjustment or curve fitting clearly fall short in that regard.

Figure 11

COMPARISON OF CREEP LAWS AT T=250 C, FLUX=5E+13

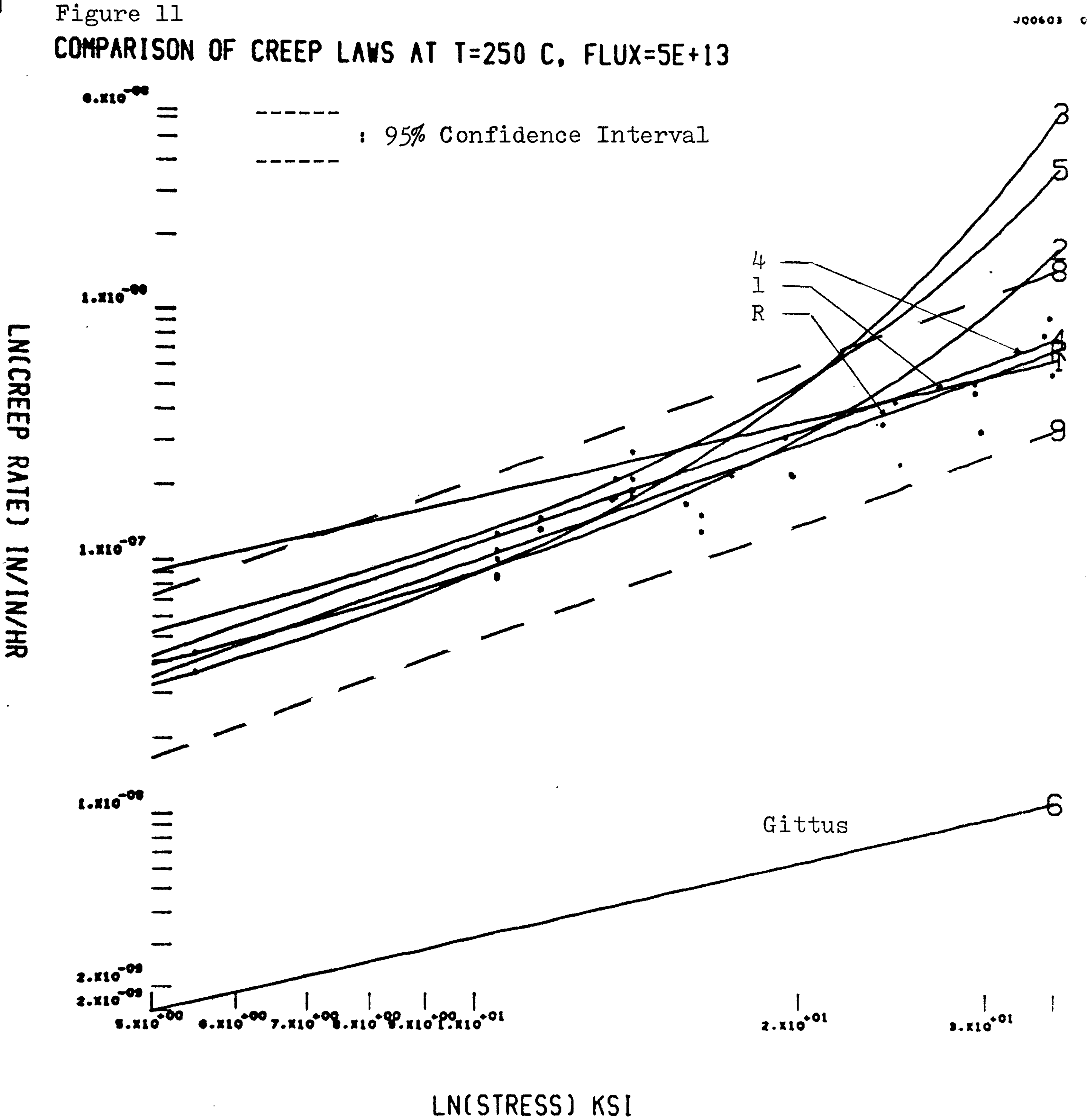


Figure 12

COMPARISON OF CREEP LAWS AT T=300 C, FLUX=5E+13

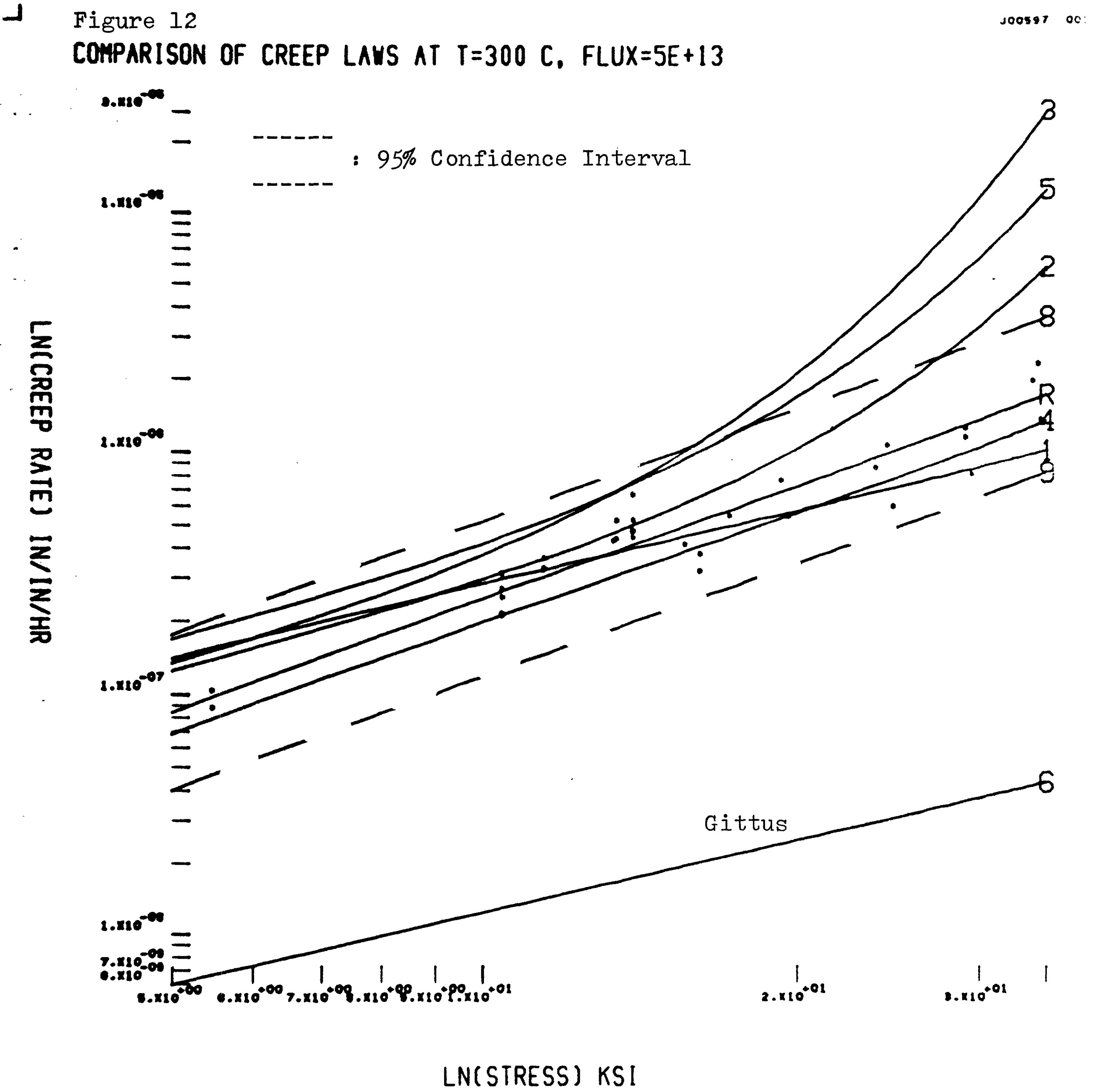


Figure 13

COMPARISON OF CREEP LAWS AT T=350 C, FLUX=5E+13

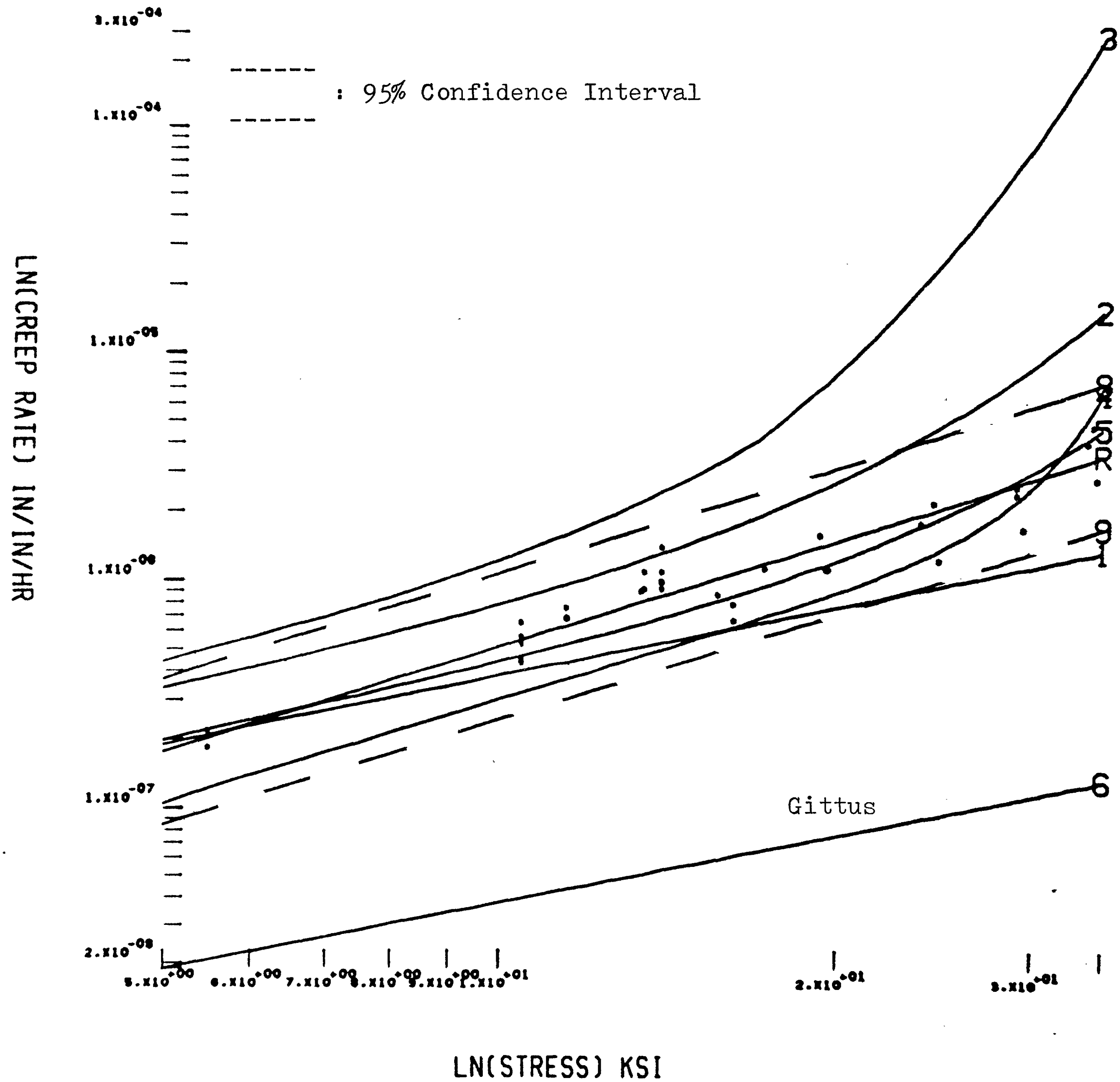


Figure 14

COMPARISON OF CREEP LAWS AT T=400 C, FLUX=5E+13

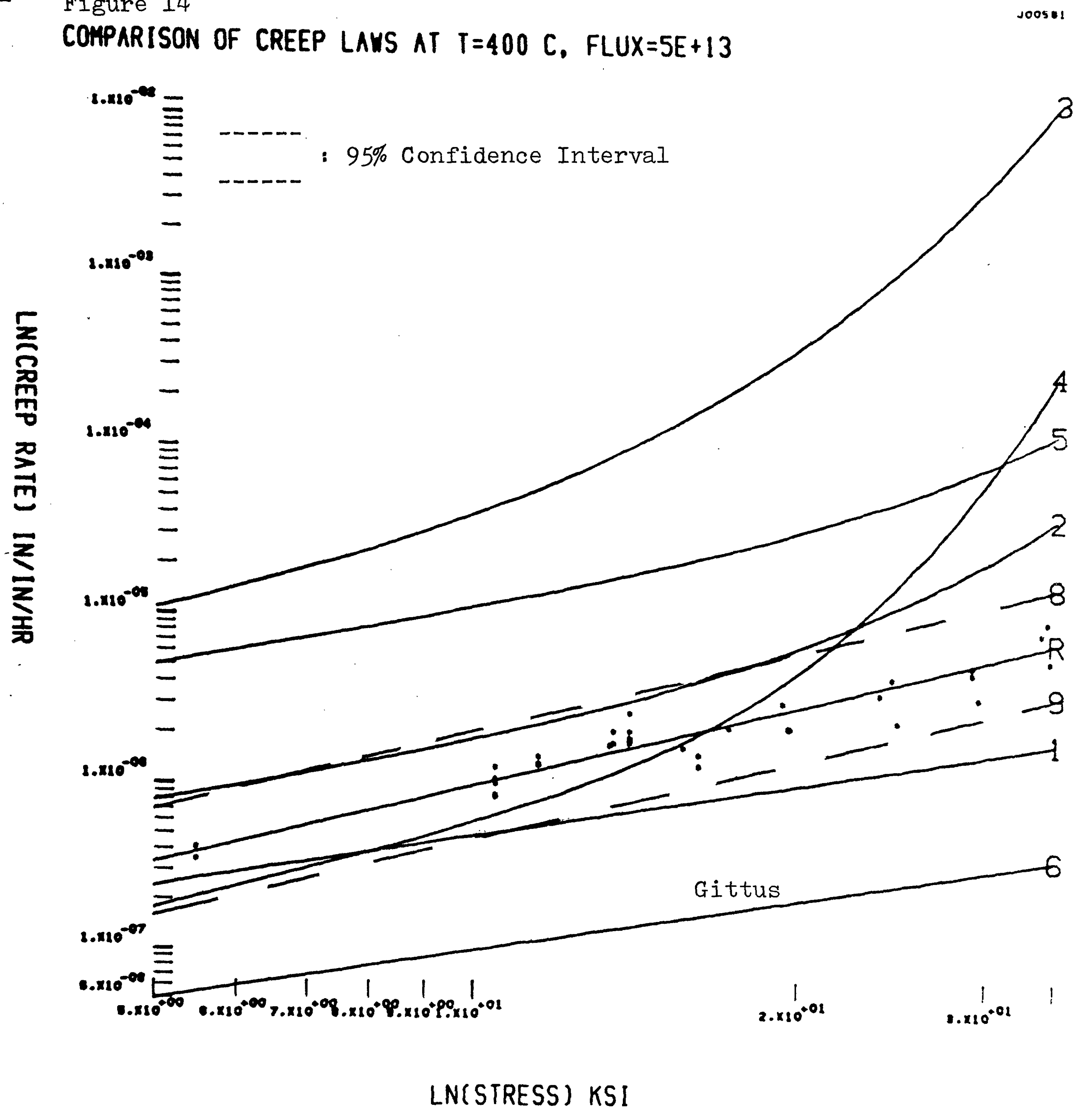


Figure 15

COMPARISON OF CREEP LAWS AT STRESS=7.5 KSI,FLUX=5E+13

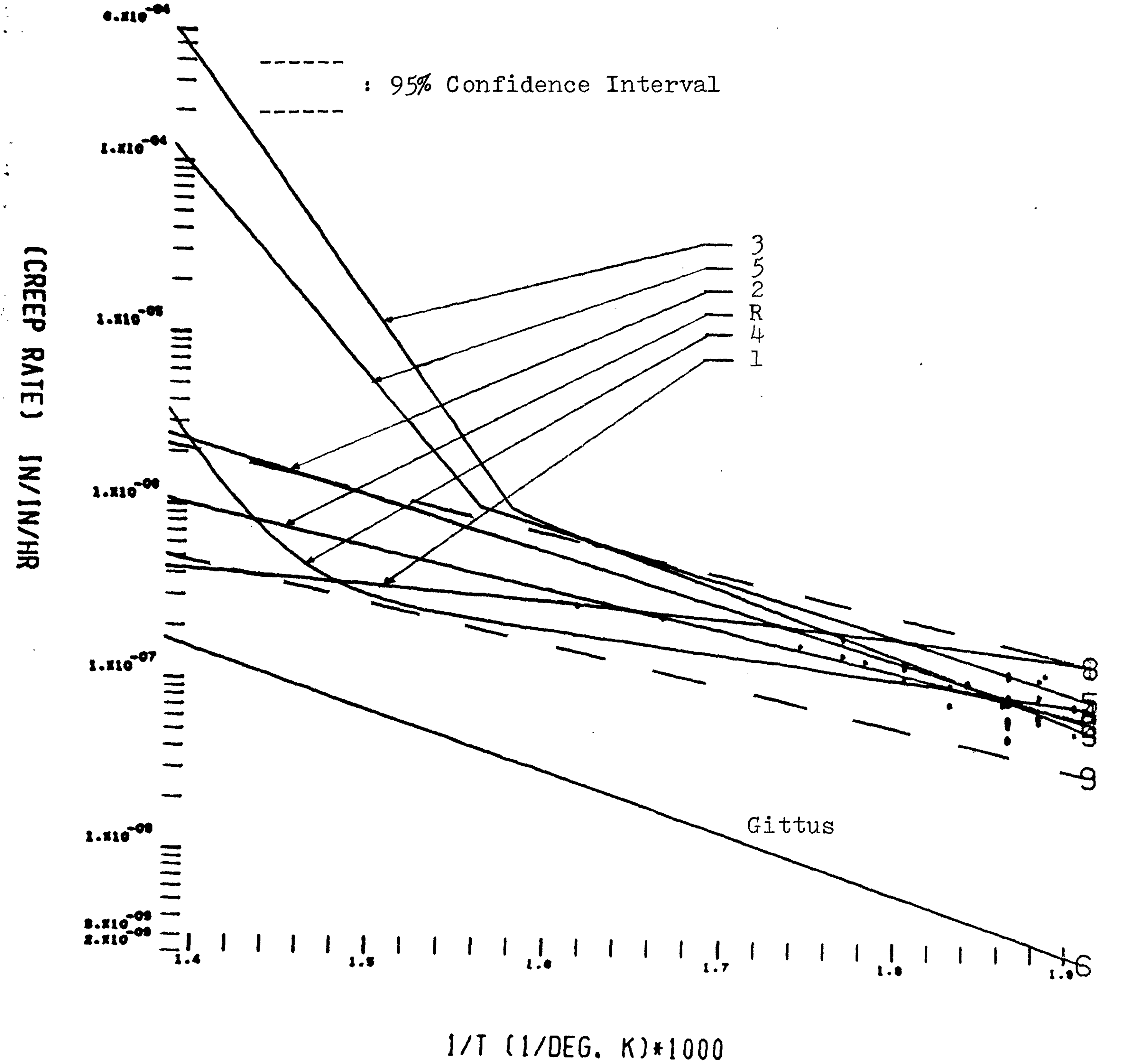
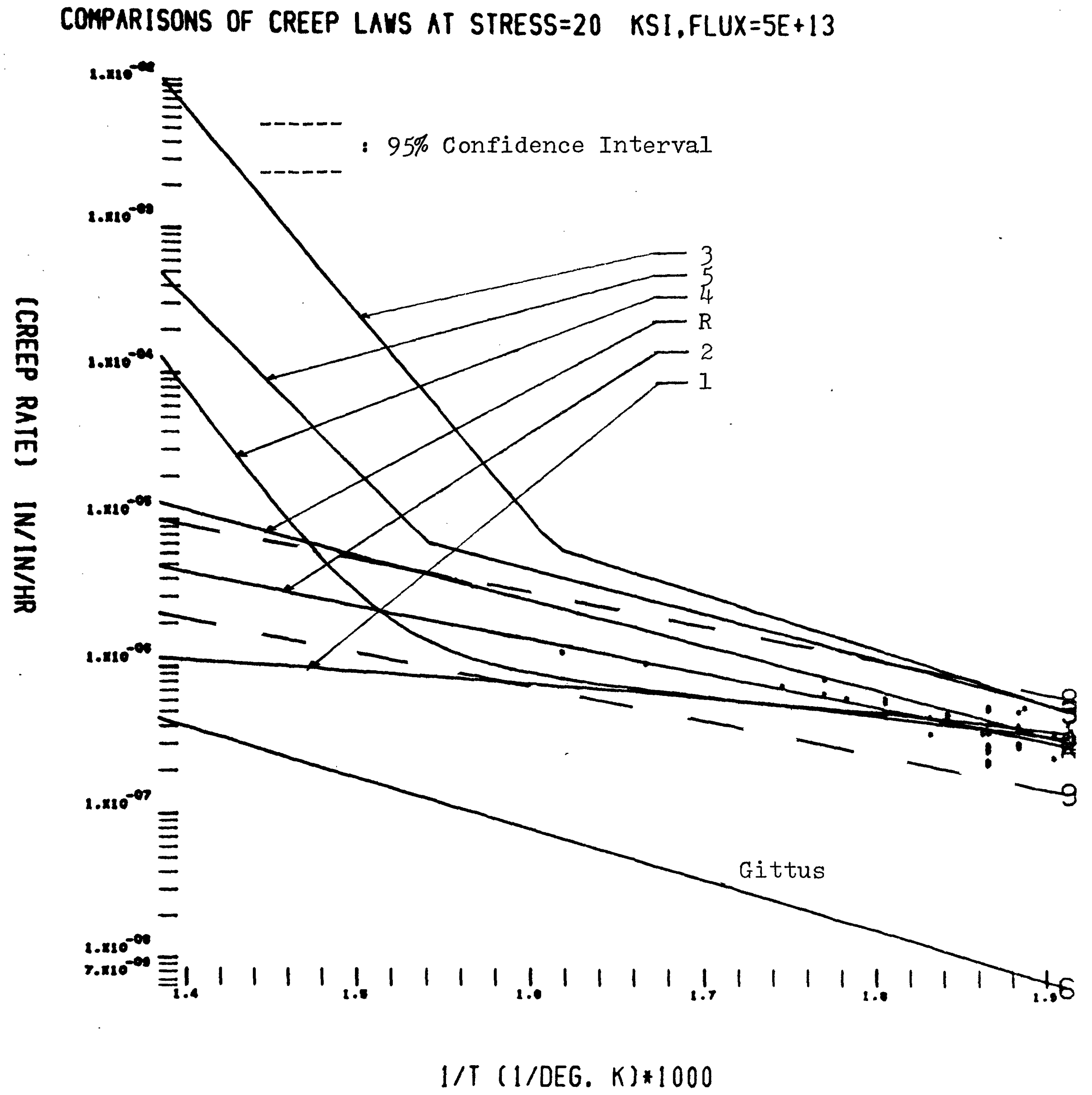


Figure 16


COMPARISONS OF CREEP LAWS AT STRESS=20 KSI,FLUX=5E+13
: 95% Confidence Interval
3
5
4
R
2
1
Gittus
6
9
(CREEP RATE) IN/IN/HR
1/T (1/DEG. K)*1000

5.4 Concluding remarks:

In this report we have discussed the analysis of Zr-2 in-reactor creep data. Current empirical in-reactor creep models obtained from parameter adjustments have been shown to be unsatisfactory both in terms of their underlying normalization assumptions and also from their high predicted creep strain rates. Regression models, on the other hand, give significant account for the stress, fast neutron flux, and temperature on the creep rate while allowing data analysis to be done in a well established statistical manner.

The relative success achieved by the regression models in representing the data not only suggests their values but also reveals the importance of examining the raw data. During the process of such an examination in this study we have both eliminated certain improper data points and removed the bias which may be introduced due to improper normalization assumptions. Furthermore, the limitations and the inherent inaccuracies of the data revealed in the data examination are helpful in understanding the full weight of the data such that they can be used in the proper framework.

In-reactor creep tests at LWR operating temperature and flux conditions are needed to extend the data range for verifying the adequacy of the regression models.

At present, we recommend the following regression model to be used as the in-reactor creep constitutve equation for 20% cold-worked and stress relieved Zircaloy 2:

$$\dot{\varepsilon} = A\left(\frac{\phi}{\phi_0}\right)^m \left(\frac{\sigma}{\mu(T)}\right)^n \exp\left(-\frac{Q_0(1-\sigma/\hat{\tau})}{R\,T}\right)$$

where the units are

$$\dot{\varepsilon} = \text{hr}^{-1},\ \phi\text{: n/cm}^2\text{s},\ \sigma\text{: ksi},\ T\text{: °K}$$

and

$$A = 0.020$$

$$m = 0.613$$

$$n = 1.130$$

$$\phi_o = 0.05\text{x}10^{13}\ \text{n/cm}^2\text{s (E> 1Mev)}$$

$$Q_o = 8851.5\ \text{cal/mole}$$

$$\hat{\tau} = 391.3\ \text{ksi}$$

$$u\ (\text{ksi}) = 4.77\text{x}10^3 - 1.906\text{x}T(°F)$$

The overall 95% confidence interval for $\dot{\varepsilon}$ can be constructed by using $\pm$ $\sqrt{Mf}$ $(SEE)_{\hat{y}}$ = 0.812 and is given by

$$\exp\ (\ln \dot{\varepsilon} \pm 0.812)$$

The above equation allows the dependence of activation energy on stress. There is evidence that the activation energy is also a function of temperature[11]. At sufficiently high temperature when irradiation creep is no longer significant as compared to thermal creep, there is a shift in dominating mechanism in the creep deformation process. The in-reactor creep equation over the entire temperature range can be constructed as a composite of multi-stage creep mechanisms acting over each of its dominating regimes. Temperature threshold (or thresholds) at which the shifting of mechanism occurs could be themselves a function of stress and fast neutron flux. Our present set of data does not permit us to extend the analysis to verify these points mainly because of the shortage of in-reactor creep data at higher temperatures.

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Appendix A

Zircaloy-2 Tubular In-Reactor Creep Data

TABLE B. TUBULAR IN-REACTOR CREEP DATA

9B

9A

ZIRCALOY-2

Trial	Reference	Ident. No.	Material Condition***	0.2% Y.S. MN/m² (Temp °C) Orientation	Specimen Type	Test Type	Atmosphere	Temperature (°C)	Stress MN/m²	Stress ksi	Neutron Flux (E > 1 MeV) 10^{13} n/cm²·s (Fluence, 10^{20} n/cm²)	$10^{-6}h^{-1}$ Minimum In-reactor Creep Rate (h^{-1}) (Duration - h)	$10^{-6}h^{-1}$ Minimum Control Creep Rate (h^{-1}) (Duration - h)	Total Creep Strain (%)
1	H-14, I-6	U-3MK V	26%CW+SR	414B(300)	8.3-cm-i.d. pressure tube	Diametral creep	H_2O	327	33.8	4.9	3.1	0.091(13,000)		
2		NPD	15-19%CW+SR	"	"	"	"	264	72.5	10.5	1.15	0.054(29,000)		
3		U-2MK III	22%CW+SR	"	"	"	"	281	79.4	11.5	2.7	0.18(5700)		
4		U-2MK IX	20%CW+SR	"	10.3cm-i.d. pressure tube	"	"	281	92.4	13.4	3.1	0.23(3300)		
5		U-2MK IV	18%CW+SR	"	8.3cm-i.d. pressure tube	"	"	270	96.5	14	2.7	0.19(11,000)		
6		U-2MK IX	20%CW+SR	"	10.3cm-i.d. pressure tube	"	"	281	119	17.3	3.1	0.29(3300)		
7		U-2MK V	26%CW+SR	"	8.3cm-i.d. pressure tube	"	"	300-345	96.5+	14+	1+	0.063-0105++	0.02-0.063++	0.06-0.11++
8		NPD(F-7)	15-19%CW+SR	"	"	"	"	252-273	"	"	"	0.043-0.061++	0.003-0.0085++	0.11-0.15++
9		NPD(H-7)	"	"	"	"	"	"	"	"	"	0.063-0.08++	"	"
10		U-2MK III	22%CW+SR	"	"	"	"	270-292	"	"	"	0.062-0.09++	0.0085-0.014++	0.16-0.2++
11		U-2MK IX	20%CW+SR	"	10.3cm-i.d. pressure tube	"	"	"	"	"	"	0.065-0.113++	0.0085-0.013++	0.18-0.24++
12		U-2MK IV(B1)	18%CW+SR	"	8.3cm-i.d. pressure tube	"	"	252-288	"	"	"	0.051-0.092++	0.003-0.014++	0.17-0.22++
13		U-2MK IV(B2)	"	"	"	"	"	240-257	"	"	"	0.045-0.08++	"	"
14	I-11		20%CW+SR	376L(300)	23mm-dia pressure tube	Diametral creep	H_2O	258	108	15.7	2.56	0.13(9000)	(106MN/m²)0.01(9000)	
15			"	"	"	"	"	"	134	19.4	"	0.24(9000)	(129MN/m²)0.01(9000)	
16			"	"	"	"	"	"	165	23.9	"	0.27(9000)	(166MN/m²)0.048(9000)	
17			"	"	"	"	"	"	201	29.2	"	0.36(9000)	(198MN/m²)0.039(9000)	
18			"	"	"	"	"	"	234	34.0	"	0.61(9000)	(232MN/m²)0.056(9000)	
19			"	"	"	"	"	"	259	37.6	"	0.88(4700)	(266MN/m²)0.116(9000)	
20	K-6	SGHWR	CW	**	13-cm dia. pressure tube	Diametral creep	H_2O	275	81.3*	11.8*	3	0.11-0.13*		
21			"	"	1.5,2.5cm-dia. pressure tubes	"	"	"	167*	24.2*	"	0.3*		
22			"	"	"	"	"	"	264*	38.4*	"	1.0*		
23			"	"	"	"	"	"	284*	41.2*	"	1.2*		

+normalized to 14ksi and 1×10^{13} n/cm²s ++ normalized to 10^{21} n/cm²

*estimated from graph **not reported ***CW-cold work, SR-stress relieved 72h at 400°C, T-transverse, L-longitudinal, B-burst test 2:1

TABLE B. TUBULAR, IN-REACTOR CREEP DATA (CONT'D)

10A

ZIRCALOY-2

Serial	Reference	Ident. No.	Material Condition***	0.2% Y.S. MN/m^2 (Temp °C) Orientation	Specimen Type	Test Type	Atmosphere	Temperature (°C)	Stress MN/m^2	Stress ksi	Neutron Flux (E > 1 MeV) 10^{13} $n/cm^2 \cdot s$ (Fluence, 10^{20} n/cm^2)	$10^{-6}h^{-1}$ Minimum In-reactor Creep Rate (h^{-1}) (Duration - h)	$10^{-6}h^{-1}$ Minimum Control Creep Rate (h^{-1}) (Duration - h)	Total Creep Strain (%)
24	K-6		CW+SR	**	1.5,2.5 cm dia. pressure tubes	diametral creep	H_2O	275	299*	43.4*	3	2.3*		
25		DMTR	CW+SR(20ppmH)	"	1.5 cm dia. pressure tubes	diametral creep	H_2O	300	276	40	4.4	(2910)		0.74+
26		"	"	"	"	"	"	"	294	42.7	4.3	"		0.81+
27		"	"	"	"	"	"	"	311	45	3.2	"		1.50+
28		DFR	CW+SR(20ppmH)	"	"	"	"	~ 275	352	51	10.7	(1720)		1.03+
29		"	"	"	"	"	"	"	311	45	16.3	"		1.7+
30		"	"	"	"	"	"	"	352	51	12.1	(2060)		1.3+
31		"	"	"	"	"	"	"	311	45	18.7	"		1.4+
32		"	"	"	"	"	"	"	207	30	12.8	(4000)		0.9+
33		"	CW+SR(300ppmH)	"	"	"	"	"	303	44	4.5	(2240)		2.6+
34		"	"	"	"	"	"	"	303	44	18.4	"		1.5+
35		"	"	"	"	"	"	"	311	45	19.4	"		3.1+
36		"	"	"	"	"	"	"	316	46	11.5	"		3.3+
37		"	CW+SR(20ppmH)	"	"	"	"	"	303	44	15.5	(3940)		2.7+
38	L-6		CW+SR	**	pressure tube	diametral creep	H_2O	275	90	13	12	1.8 (3500)		
39	H-5	NRU	20%CW+SR	374L(300)	23-mm dia. pressure tubes	diametral creep	H_2O	263	111	16.2	2.9	0.14 (5000)	($111 MN/m^2$) <0.01(5000)	
40		"	"	"	"	"	"	"	"	"	"	0.062(20,000)		
41		"	"	"	"	"	"	"	136	19.7	"	0.2(5000)	($135 MN/m^2$) <0.01(5000)	
42		"	"	"	"	"	"	"	"	"	"	0.1(20,000)		
43		"	"	"	"	"	"	"	171	24.8	"	0.22(5000)	($169 MN/m^2$) 0.027(5000)	
43		"	"	"	"	"	"	"	"	"	"	0.11(20,000)		
44		"	"	"	"	"	"	"	204	29.6	"	0.3(5000)	($201 MN/m^2$) 0.041(5000)	
45		"	"	"	"	"	"	"	"	"	"	0.14(20,000)		
46		"	"	"	"	"	"	"						

*estimated from graph **not reported ***CW-cold work, SR-stress relieved 72h at 400°C, T-transverse, L-longitudinal, B-burst test 2:1

+ without failure

TABLE B. TUBULAR, IN-REACTOR CREEP DATA (CONT'D)

Zircaloy-2

Serial	Reference	Ident. No.	Material Condition	0.2%Y.S. MN/m² *** (Temp°C) Orientation	Specimen Type	Test Type	Atmosphere	Temperature (°C)	Stress MN/m²	Stress ksi	Neutron Flux (E > 1 MeV) 10^{13} n/cm²·s (Fluence, 10^{20} n/cm²)	$10^{-6}h^{-1}$ Minimum In-reactor Creep Rate (h^{-1}) (Duration - h)	$10^{-6}h^{-1}$ Minimum Control Creep Rate (h^{-1}) (Duration - h)	Total Creep Strain (%)
T 47	M-5	NRU	20%CW+SR	374L(300)	23mm dia. pressure tube	diametral creep	H_2O	263	239	34.6	2.9	0.5 (5000)	(237MN/m²) 0.058 (5000)	
48		"	"	"	"	"	"	"	"	"	"	0.25 (20,000)		
49		"	"	"	"	"	"	"	261	37.8	"	0.7 (5000)	(270MN/m²) 0.095 (5000)	
50		"	"	"	"	"	"	"	"	"	"	0.37 (20,000)		
51		"	"	"	"	"	"	"	111	16.2	0.01-0.1	<0.01 (5000)	<0.01 (5000)	
52		"	"	"	"	"	"	"	135	19.6	"	0.017 (5000)	0.01 (5000)	
53		"	"	"	"	"	"	"	169	24.5	"	0.033 (5000)	0.027 (5000)	
54		"	"	"	"	"	"	"	201	29.2	"	0.039 (5000)	0.041 (5000)	
55		"	"	"	"	"	"	"	237	34.4	"	0.071 (5000)	0.058 (5000)	
56		"	"	"	"	"	"	"	270	39.2	"	0.092 (5000)	0.095 (5000)	
57		"	70%CW+6h at 495°	384L(300)	"	"	"	297	162	23.4	3.0	0.38 (5000)	(105MN/m²) 0.049 (5000)	
58		"	"	"	"	"	"	"	302	43.8	3.0	1.4 (5000)	(222MN/m²) 0.18 (5000)	
59		"	"	"	"	"	"	"	"	"	0	**	(282MN/m²) 0.32 (5000)	
60		"	70%CW+6h at 495°C		"	"	"	"	138	20	3.0	0.08 (5000)	(106MN/m²) 0.03 (5000)	
61		"	+1h at 750°C		"	"	"	"	209	30.3	3.0	0.13 (5000)	(173MN/m²) 0.088 (5000)	
62	M-7	DFR	75%CW+6h at 515°C	516L(20)	1.5 cm-dia pressure tubes	diametral creep	Na	284	352	51	(26)	(6450)	**	7.0+
63		"	" (200-400 ppm H)	"	"	"	"	276	310	45	(17)	(3520)	"	4.8+
64		"	75%CW+5h at 475°C	"	"	"	"	266	352	51	(6)	(1280)	"	3.6+
65		A11/1	75%CW+6h at 515°C	"	"	"	H_2O	300	276	40	4.4 (4.6)	(2910)	"	0.74+
66		A11/3	"	"	"	"	"	"	293	42.5	4.2 (4.4)	"	"	0.81+
67		A11/6	"	"	"	"	"	"	310	45	3.2 (3.4)	"	"	1.50+
68		A26/8	75%CW+5h at 475°C	"	"	"	"	275	406	59	4 (16)	0.82* (11,150)	"	9.2+
69		A26/9	"	"	"	"	"	"	396	56	4 (16)	0.67* (9,000)	"	5.7+
70		A26/10	"	"	"	"	"	"	421	61	3 (12)	(1020)	"	2.4+

+ without failure

*estimated from graph **not reported ***CW-cold work
SR-stress relieved 72h at 400°C
T-transverse L-longitudinal B-burst test 2:1

TABLE B TUBULAR, IN-REACTOR CREEP DATA (cont'd)

erial	Reference	Ident. No.	Material Condition	0.2%Y.S. MN/m² *** (Temp°C)	Specimen Type	Test Type	Atmosphere	Temperature (°C)	Stress MN/m²	Stress ksi	Neutron Flux (E > 1 MeV) 10^{13} n/cm²·s (Fluence, 10^{20} n/cm²)	10^{-6} h⁻¹ Minimum In-reactor Creep Rate (h⁻¹) (Duration - h)	10^{-6} h⁻¹ Minimum Control Creep Rate (h⁻¹) (Duration - h)	Total Creep Strain (%)
	Zircaloy-2													
T71	M-7	A26/11	75%cw+5h at475°C	516L(20)	1.5cm-dia pressure tube	diametral creep	H_2O	275	400	58	4 (8)	(0)	**	0
72		A26/12	"	"	"	"	"	"	"	"	4 (8)	0.52* (5600)	"	4.0†
73		A26/13	"	"	"	"	"	"	"	"	3 (6)	0.52* (5600)	"	3.7†
	Zr-2.5 Nb													
74	H-14,I-B	U-1 MkV	22%cw+SR	518B(300)	8.3cm.i.d. pressure tube	diametral creep	H_2O	285	114	16.5	2.9	0.65	**	
75		"	"	"	"	"	"	"	152	22.0	2.9	1.04	"	
76		U-1 Mk VIII	"	"	10.3 cm-i.d. pressure tube	"	"	270	107	15.5	3.1	0.67	"	
77		"	"	"	"	"	"	"	145	21.0	2.0	0.78	"	
'8		U-1 Mk VIII	"	"	"	"	"	"	96.5††	14††	1.0††	0.018-0.033††	"	
'9		U-1 Mk V	"	"	8.3 cm-i.d. pressure tube	"	"	285	"	"	"	0.024-0.035††	"	
:0	L-6		cw+SR	**	pressure tube	diametral creep	H_2O	300	138	20	3	0.5 (4000)		
1			"		"	"	"	275	"	20	"	0.3 (+6000)		
2	M-10		Q[870]+2%CW+A	592L(300)	23mm i.d. pressure tube	diametral creep	H_2O	295	103	14.9	2.3	0.11 (10,000)	(104 MN/m²) 0.012 (10,000)	
3			"	"	"	"	"	"	170	24.6	"	0.18 (10,000)	(171 MN/m²) 0.041 (10,000)	
			"	"	"	"	"	"	236	34.2	"	0.31 (10,000)	(237 MN/m²) 0.06 (10,000)	
			"	"	"	"	"	"	297	43	"	0.46 (10,000)	(246 MN/m²) 0.15 (10,000)	
			Q[870]+12%CW+A	543L(300)	"	"	"	"	103	14.9	"	0.16 (10,000)	(103 MN/m²) 0.023 (10,000)	
			"	"	"	"	"	"	171	24.8	"	0.24 (10,000)		
			"	"	"	"	"	"	237	34.4	"	0.43 (10,000)	(236 MN/m²) 0.12 (10,000)	
			"	"	"	"	"	"	301	43.6	"	0.87 (10,000)		

*** Q-quenched (Temp °C)
A-aged 24h at 500°C
CW- Cold Work
SR-Stress relieved 72h at 400°C
T-transverse, L-longitudinal B-burst test 2:1

*estimated from graph **not reported

†without failure ††normalized to 14 ksi and $1x10^{13}$ n/cm²·S

Appendix B

The Actual Set of In-Reactor Creep Data Used in Regression Analysis

ID*	$T(^oK)$	σ(ksi)	$\phi(10^{13}$ $n/cm^2s)$	$\dot{\varepsilon}(10^{-6}$ $hr^{-1})$
39	536.000	16.200	2.900	0.140
41	536.000	19.700	2.900	0.200
43	536.000	24.800	2.900	0.220
45	536.000	29.600	2.900	0.300
47	536.000	34.600	2.900	0.500
49	536.000	37.800	2.900	0.700
51	536.000	16.200	0.050	0.010
52	536.000	19.600	0.050	0.017
53	536.000	24.500	0.050	0.033
54	536.000	29.200	0.050	0.039
55	536.000	34.400	0.050	0.071
56	536.000	39.200	0.050	0.092
14	531.000	15.700	2.560	0.130
15	531.000	19.400	2.560	0.240
16	531.000	23.900	2.560	0.270
17	531.000	29.200	2.560	0.360
18	531.000	34.000	2.560	0.610
19	531.000	37.600	2.560	0.880
4	554.000	13.400	3.100	0.230
6	554.000	17.300	3.100	0.290
1	600.000	4.900	3.100	0.091
3	554.000	11.500	2.700	0.180
5	543.000	14.000	2.700	0.190
2	537.000	10.500	1.150	0.054
77	573.000	5.500	3.100	0.077
78	618.000	5.500	3.100	0.128
87	525.000	10.500	1.150	0.037
88	546.000	10.500	1.150	0.053
97	525.000	10.500	1.150	0.054
98	546.000	10.500	1.150	0.069
107	543.000	11.500	2.500	0.127
108	565.000	11.500	2.500	0.185
117	543.000	13.500	3.100	0.194
118	565.000	13.500	3.100	0.338
127	525.000	14.000	2.600	0.133
128	561.000	14.000	2.600	0.239
137	513.000	14.000	2.600	0.117
138	530.000	14.000	2.600	0.208

*ID refers to the serial numbers in Table 4, ID-77 to ID-138 are obtained by transforming the normalized Ross-Ross and Hunt's data serial T7-T13 to the original values.

Appendix C

Regression Statistics

The symbol meanings in Appendix C and Appendix D are:

CRL2	: $\ln \dot{\varepsilon}$
SNLOG	: $\ln(\sigma/u(T))$, normalized stress
FLUX4	: $\ln(\phi/0.05)$, normalized flux
TI	: $1/T$
STI	: σ/T
STIA	: σ^2/T
S3	: $\ln\sigma$
FLUX2	: $\ln\phi$

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FILE NONAME (CREATION DATE = 05/03/76)

CORRELATION COEFFICIENTS

A VALUE OF 99.00000 IS PRINTED
IF A COEFFICIENT CANNOT BE COMPUTED.

	SNLOG	FLUX4	TI	STI	STIA	S3	FLUX2	S2	T3	CRL2
SNLOG	1.00000	-0.31989	0.58740	0.96457	0.89614	0.99962	-0.31989	0.99962	-0.57075	0.35261
FLUX4	-0.31989	1.00000	-0.20837	-0.31773	-0.29733	-0.32047	1.00000	-0.32047	0.20093	0.70840
TI	0.58740	-0.20837	1.00000	0.48129	0.36194	0.60942	-0.20836	0.60942	-0.99758	-0.01745
STI	0.96457	-0.31773	0.48129	1.00000	0.97947	0.96105	-0.31773	0.96105	-0.47177	0.37104
STIA	0.89614	-0.29733	0.36194	0.97947	1.00000	0.88987	-0.29733	0.88987	-0.35547	0.38609
S3	0.99962	-0.32047	0.60942	0.96105	0.88987	1.00000	-0.32047	1.00000	-0.59286	0.34483
FLUX2	-0.31989	1.00000	-0.20836	-0.31773	-0.29733	-0.32047	1.00000	-0.32047	0.20093	0.70840
S2	0.99962	-0.32047	0.60942	0.96105	0.88987	1.00000	-0.32047	1.00000	-0.59286	0.34483
T3	-0.57075	0.20093	-0.99758	-0.47177	-0.35547	-0.59286	0.20093	-0.59286	1.00000	0.02269
CRL2	0.35261	0.70840	-0.01745	0.37104	0.38609	0.34483	0.70840	0.34483	0.02269	1.00000

FILE NONAME (CREATION DATE = 05/03/76)

* M U L T I P L E R E G R E S S I O N * * * * * * * * * * * * * * VARIABLE LIST 1
REGRESSION LIST 1

DEPENDENT VARIABLE.. CRL2

VARIABLE(S) ENTERED ON STEP NUMBER 1.. SNLOG
FLUX4
TI

MULTIPLE R	0.96969	
R SQUARE	0.94030	
ADJUSTED R SQUARE	0.93504	
STANDARD ERROR	0.25140	

ANALYSIS OF VARIANCE	DF	SUM OF SQUARES	MEAN SQUARE	F
REGRESSION	3.	33.84897	11.28299	178.51634
RESIDUAL	34.	2.14894	0.06320	

------------------ VARIABLES IN THE EQUATION ------------------

VARIABLE	B	BETA	STD ERROR B	F
SNLOG	1.54126	0.82770	0.09956	239.647
FLUX4	0.61070	0.90763	0.02977	420.880
TI	-4855.29223	-0.31452	799.54567	36.876
(CONSTANT)	-0.46957			

------------------ VARIABLES NOT IN THE EQUATION ------------------

VARIABLE	BETA IN	PARTIAL	TOLERANCE	F

ALL VARIABLES ARE IN THE EQUATION

CREEP LAWS WITH STRESS DEPENDENCE OF ACTIVATION ENERGY 05/03/76 PAGE 7

FILE NONAME (CREATION DATE = 05/03/76)

* M U L T I P L E R E G R E S S I O N * * * * * * * * * * * * * * VARIABLE LIST 1
REGRESSION LIST 2

DEPENDENT VARIABLE.. CRL2

VARIABLE(S) ENTERED ON STEP NUMBER 1.. SNLOG
FLUX4
TI
STI

MULTIPLE R	0.97106
R SQUARE	0.94295
ADJUSTED R SQUARE	0.93603
STANDARD ERROR	0.24947

ANALYSIS OF VARIANCE	DF	SUM OF SQUARES	MEAN SQUARE	F
REGRESSION	4.	33.94422	8.48605	136.35928
RESIDUAL	33.	2.05369	0.06223	

------------------ VARIABLES IN THE EQUATION ------------------

VARIABLE	B	BETA	STD ERROR B	F
SNLOG	1.12996	0.60682	0.34682	10.615
FLUX4	0.61259	0.91044	0.02958	428.951
TI	-4425.71989	-0.28670	866.03326	26.116
STI	11.30989	0.21298	9.14175	1.531
(CONSTANT)	-3.90013			

------------- VARIABLES NOT IN THE EQUATION -------------

VARIABLE	BETA IN	PARTIAL	TOLERANCE	F

ALL VARIABLES ARE IN THE EQUATION

CREEP LAWS WITH STRESS DEPENDENCE OF ACTIVATION ENERGY 05/03/76 PAGE 9

FILE NONAME (CREATION DATE = 05/03/76)

* M U L T I P L E   R E G R E S S I O N * * * * * * * * * * * * * *   VARIABLE LIST 1
REGRESSION LIST 3

DEPENDENT VARIABLE.. CRL2

VARIABLE(S) ENTERED ON STEP NUMBER 1.. SNLOG
FLUX4
TI
STI
STIA

MULTIPLE R	0.97708
R SQUARE	0.95469
ADJUSTED R SQUARE	0.94762
STANDARD ERROR	0.22575

ANALYSIS OF VARIANCE	DF	SUM OF SQUARES	MEAN SQUARE	F
REGRESSION	5.	34.36702	6.87340	134.86460
RESIDUAL	32.	1.63089	0.05097	

------------------ VARIABLES IN THE EQUATION ------------------

VARIABLE	B	BETA	STD ERROR B	F
SNLOG	2.80030	1.50384	0.65941	18.034
FLUX4	0.60917	0.90535	0.02679	516.923
TI	-3484.49447	-0.22572	849.12022	16.840
STI	-111.17463	-2.09354	43.32266	6.585
STIA	1.70137	1.43988	0.59070	8.296
(CONSTANT)	6.32307			

-------------- VARIABLES NOT IN THE EQUATION --------------

VARIABLE	BETA IN	PARTIAL	TOLERANCE	F

ALL VARIABLES ARE IN THE EQUATION

FILE NONAME (CREATION DATE = 05/03/76)

* M U L T I P L E R E G R E S S I O N * * * * * * * * * * * * * * VARIABLE LIST 1
REGRESSION LIST 4

DEPENDENT VARIABLE.. CRL2

VARIABLE(S) ENTERED ON STEP NUMBER 1.. TI
S3
FLUX2

MULTIPLE R	0.96969	ANALYSIS OF VARIANCE	DF	SUM OF SQUARES	MEAN SQUARE	F
R SQUARE	0.94030	REGRESSION	3.	33.84876	11.28292	178.49836
ADJUSTED R SQUARE	0.93503	RESIDUAL	34.	2.14915	0.06321	
STANDARD ERROR	0.25142					

------------------ VARIABLES IN THE EQUATION ------------------

VARIABLE	B	BETA	STD ERROR B	F
TI	-5298.06490	-0.34321	816.00206	42.155
S3	1.54035	0.84486	0.09951	239.622
FLUX2	0.61071	0.90764	0.02977	420.846
(CONSTANT)	-28.79870			

------------- VARIABLES NOT IN THE EQUATION --------------

VARIABLE	BETA IN	PARTIAL	TOLERANCE	F

ALL VARIABLES ARE IN THE EQUATION

FILE NONAME (CREATION DATE = 05/03/76)

* M U L T I P L E   R E G R E S S I O N * * * * * * * * * * * * * * * * VARIABLE LIST 1
REGRESSION LIST 5

DEPENDENT VARIABLE.. CRL2

VARIABLE(S) ENTERED ON STEP NUMBER 1.. TI
STI
S3
FLUX2

MULTIPLE R	0.97109	ANALYSIS OF VARIANCE	DF	SUM OF SQUARES	MEAN SQUARE	F
R SQUARE	0.94301	REGRESSION	4.	33.94657	8.48664	136.52487
ADJUSTED R SQUARE	0.93611	RESIDUAL	33.	2.05134	0.06216	
STANDARD ERROR	0.24932					

------------------ VARIABLES IN THE EQUATION ------------------ ------------- VARIABLES NOT IN THE EQUATION -------------

VARIABLE	B	BETA	STD ERROR B	F	VARIABLE	BETA IN	PARTIAL	TOLERANCE	F
TI	-4746.49083	-0.30748	920.96502	26.562					
STI	11.40631	0.21479	9.09338	1.573					
S3	1.12596	0.61758	0.34478	10.665					
FLUX2	0.61263	0.91049	0.02956	429.484					
(CONSTANT)	-29.11245								

ALL VARIABLES ARE IN THE EQUATION

FILE NONAME (CREATION DATE = 05/03/76)

* M U L T I P L E   R E G R E S S I O N * * * * * * * * * * * * * *   VARIABLE LIST 1
REGRESSION LIST 6

DEPENDENT VARIABLE.. CRL2

VARIABLE(S) ENTERED ON STEP NUMBER 1.. TI
STI
STIA
S3
FLUX2

MULTIPLE R	0.97702
R SQUARE	0.95457
ADJUSTED R SQUARE	0.94747
STANDARD ERROR	0.22606

ANALYSIS OF VARIANCE	DF	SUM OF SQUARES	MEAN SQUARE	F
REGRESSION	5.	34.36259	6.87252	134.48170
RESIDUAL	32.	1.63532	0.05110	

------------------ VARIABLES IN THE EQUATION ------------------

VARIABLE	B	BETA	STD ERROR B	F
TI	-4276.19254	-0.27701	851.15326	25.241
STI	-108.91474	-2.05099	42.96905	6.425
STIA	1.67551	1.41800	0.58724	8.141
S3	2.75870	1.51312	0.65207	17.899
FLUX2	0.60929	0.90553	0.02683	515.761
(CONSTANT)	-31.64044			

------------- VARIABLES NOT IN THE EQUATION -------------

VARIABLE	BETA IN	PARTIAL	TOLERANCE	F

ALL VARIABLES ARE IN THE EQUATION

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CREEP LAWS WITH STRESS DEPENDENCE OF ACTIVATION ENERGY                    05/03/76        PAGE   17
FILE   NONAME   (CREATION DATE = 05/03/76)

* * * * * * * * * * * * * * * * * * * * * * * * M U L T I P L E   R E G R E S S I O N * * * * * * * * * * * * *   VARIABLE LIST  1
                                                                                                                REGRESSION LIST  7
DEPENDENT VARIABLE..    CRL2

VARIABLE(S) ENTERED ON STEP NUMBER  1..    FLUX2
                                           S2
                                           T3

MULTIPLE R            0.96902                    ANALYSIS OF VARIANCE    DF      SUM OF SQUARES      MEAN SQUARE          F
R SQUARE              0.93900                    REGRESSION               3.         33.80204          11.26735      174.45918
ADJUSTED R SQUARE     0.93362                    RESIDUAL                34.          2.19587           0.06458
STANDARD ERROR        0.25413

---------------- VARIABLES IN THE EQUATION -----------------           ------------- VARIABLES NOT IN THE EQUATION -------------

VARIABLE              B          BETA      STD ERROR B        F              VARIABLE       BETA IN      PARTIAL   TOLERANCE        F

FLUX2              0.61132     0.90856      0.03009       412.763
S2                 1.52155     0.83456      0.09918       235.355
T3                 2.04780     0.33491      0.32164        40.535
(CONSTANT)       -58.64206

ALL VARIABLES ARE IN THE EQUATION
```

Appendix D

Stepwise Regressions of Zr-2 In-reactor Creep Data

FILE NONAME (CREATION DATE = 05/03/76)

* M U L T I P L E   R E G R E S S I O N * * * * * * * * * * * * * * * VARIABLE LIST 1
REGRESSION LIST 9

DEPENDENT VARIABLE.. CRL2

VARIABLE(S) ENTERED ON STEP NUMBER 1.. FLUX2

MULTIPLE R	0.70840	ANALYSIS OF VARIANCE	DF	SUM OF SQUARES	MEAN SQUARE	F
R SQUARE	0.50183	REGRESSION	1.	18.06474	18.06474	36.26412
ADJUSTED R SQUARE	0.48799	RESIDUAL	36.	17.93317	0.49814	
STANDARD ERROR	0.70579					

------------------ VARIABLES IN THE EQUATION ------------------

VARIABLE	B	BETA	STD ERROR B	F
FLUX2	0.47665	0.70840	0.07915	36.264
(CONSTANT)	-30.20251			

------------- VARIABLES NOT IN THE EQUATION -------------

VARIABLE	BETA IN	PARTIAL	TOLERANCE	F
S3	0.63731	0.85532	0.89730	95.388
TI	0.13606	0.18854	0.95658	1.290
STI	0.66306	0.89074	0.89905	134.425
STIA	0.65459	0.88548	0.91160	127.090

* *

VARIABLE(S) ENTERED ON STEP NUMBER 2.. STI

MULTIPLE R	0.94715	ANALYSIS OF VARIANCE	DF	SUM OF SQUARES	MEAN SQUARE	F
R SQUARE	0.89709	REGRESSION	2.	32.29326	16.14663	152.54679
ADJUSTED R SQUARE	0.89121	RESIDUAL	35.	3.70465	0.10585	
STANDARD ERROR	0.32534					

------------------ VARIABLES IN THE EQUATION ------------------

VARIABLE	B	BETA	STD ERROR B	F
FLUX2	0.61840	0.91907	0.03848	258.273
STI	35.21066	0.66306	3.03692	134.425
(CONSTANT)	-35.71747			

------------- VARIABLES NOT IN THE EQUATION -------------

VARIABLE	BETA IN	PARTIAL	TOLERANCE	F
S3	0.02813	0.02420	0.07613	0.020
TI	-0.18965	-0.51704	0.76494	12.406
STIA	0.24524	0.15371	0.04043	0.823

FILE NONAME (CREATION DATE = 05/03/76)

* M U L T I P L E   R E G R E S S I O N * * * * * * * * * * * * * *   VARIABLE LIST 1
REGRESSION LIST 9

DEPENDENT VARIABLE.. CRL2

VARIABLE(S) ENTERED ON STEP NUMBER 3.. TI

MULTIPLE R	0.96156
R SQUARE	0.92460
ADJUSTED R SQUARE	0.91795
STANDARD ERROR	0.28255

ANALYSIS OF VARIANCE	DF	SUM OF SQUARES	MEAN SQUARE	F
REGRESSION	3.	33.28363	11.09454	138.97377
RESIDUAL	34.	2.71429	0.07983	

VARIABLES IN THE EQUATION

VARIABLE	B	BETA	STD ERROR B	F
FLUX2	0.61053	0.90738	0.03349	332.293
STI	39.86030	0.75061	2.94937	182.651
TI	-2927.54851	-0.18965	831.18032	12.406
(CONSTANT)	-30.24551			

VARIABLES NOT IN THE EQUATION

VARIABLE	BETA IN	PARTIAL	TOLERANCE	F
S3	0.61758	0.49421	0.04829	10.665
STIA	-0.42720	-0.24602	0.02501	2.126

* *

VARIABLE(S) ENTERED ON STEP NUMBER 4.. S3

MULTIPLE R	0.97109
R SQUARE	0.94301
ADJUSTED R SQUARE	0.93611
STANDARD ERROR	0.24932

ANALYSIS OF VARIANCE	DF	SUM OF SQUARES	MEAN SQUARE	F
REGRESSION	4.	33.94657	8.48664	136.52487
RESIDUAL	33.	2.05134	0.06216	

VARIABLES IN THE EQUATION

VARIABLE	B	BETA	STD ERROR B	F
FLUX2	0.61263	0.91049	0.02956	429.484
STI	11.40631	0.21479	9.09338	1.573
TI	-4746.49083	-0.30748	920.96502	26.562
S3	1.12596	0.61758	0.34478	10.665
(CONSTANT)	-29.11245			

VARIABLES NOT IN THE EQUATION

VARIABLE	BETA IN	PARTIAL	TOLERANCE	F
STIA	1.41800	0.45034	0.00575	8.141

FILE NONAME (CREATION DATE = 05/03/76)

* M U L T I P L E R E G R E S S I O N * * * * * * * * * * * * * * VARIABLE LIST 1
REGRESSION LIST 9

DEPENDENT VARIABLE.. CRL2

VARIABLE(S) ENTERED ON STEP NUMBER 5.. STIA

			ANALYSIS OF VARIANCE	DF	SUM OF SQUARES	MEAN SQUARE	F
MULTIPLE R	0.97702						
R SQUARE	0.95457		REGRESSION	5.	34.36259	6.87252	134.48170
ADJUSTED R SQUARE	0.94747		RESIDUAL	32.	1.63532	0.05110	
STANDARD ERROR	0.22606						

------------------ VARIABLES IN THE EQUATION ------------------

VARIABLE	B	BETA	STD ERROR B	F
FLUX2	0.60929	0.90553	0.02683	515.761
STI	-108.91474	-2.05099	42.96905	6.425
TI	-4276.19254	-0.27701	851.15326	25.241
S3	2.75870	1.51312	0.65207	17.899
STIA	1.67551	1.41800	0.58724	8.141
(CONSTANT)	-31.64044			

------------- VARIABLES NOT IN THE EQUATION -------------

VARIABLE	BETA IN	PARTIAL	TOLERANCE	F

ALL VARIABLES ARE IN THE EQUATION

FILE NONAME (CREATION DATE = 05/03/76)

* M U L T I P L E   R E G R E S S I O N * * * * * * * * * * * * * * VARIABLE LIST 1
REGRESSION LIST 9

DEPENDENT VARIABLE.. CRL2

VARIABLE(S) ENTERED ON STEP NUMBER 1.. FLUX4

MULTIPLE R	0.70840	ANALYSIS OF VARIANCE	DF	SUM OF SQUARES	MEAN SQUARE	F
R SQUARE	0.50183	REGRESSION	1.	18.06475	18.06475	36.26415
ADJUSTED R SQUARE	0.48799	RESIDUAL	36.	17.93316	0.49814	
STANDARD ERROR	0.70579					

------------------ VARIABLES IN THE EQUATION ------------------ / ------------- VARIABLES NOT IN THE EQUATION -------------

VARIABLE	B	BETA	STD ERROR B	F	VARIABLE	BETA IN	PARTIAL	TOLERANCE	F
FLUX4	0.47665	0.70840	0.07915	36.264	SNLOG	0.64524	0.86614	0.89767	105.113
(CONSTANT)	-17.36266				TI	0.13606	0.18854	0.95658	1.290
					STI	0.66306	0.89074	0.89905	134.425
					STIA	0.65458	0.88548	0.91160	127.090

* *

VARIABLE(S) ENTERED ON STEP NUMBER 2.. STI

MULTIPLE R	0.94715	ANALYSIS OF VARIANCE	DF	SUM OF SQUARES	MEAN SQUARE	F
R SQUARE	0.89709	REGRESSION	2.	32.29327	16.14663	152.54690
ADJUSTED R SQUARE	0.89121	RESIDUAL	35.	3.70465	0.10585	
STANDARD ERROR	0.32534					

------------------ VARIABLES IN THE EQUATION ------------------ / ------------- VARIABLES NOT IN THE EQUATION -------------

VARIABLE	B	BETA	STD ERROR B	F	VARIABLE	BETA IN	PARTIAL	TOLERANCE	F
FLUX4	0.61840	0.91907	0.03848	258.273	SNLOG	0.10143	0.08330	0.06940	0.238
STI	35.21065	0.66306	3.03692	134.425	TI	-0.18965	-0.51704	0.76494	12.405
(CONSTANT)	-19.05911				STIA	0.24524	0.15371	0.04043	0.823

CREEP LAWS WITH STRESS DEPENDENCE OF ACTIVATION ENERGY 05/03/76 PAGE 28

FILE NONAME (CREATION DATE = 05/03/76)

* M U L T I P L E R E G R E S S I O N * * * * * * * * * * * * * * VARIABLE LIST 1 REGRESSION LIST 9

DEPENDENT VARIABLE.. CRL2

VARIABLE(S) ENTERED ON STEP NUMBER 3.. TI

MULTIPLE R	0.96156	ANALYSIS OF VARIANCE	DF	SUM OF SQUARES	MEAN SQUARE	F
R SQUARE	0.92460	REGRESSION	3.	33.28362	11.09454	138.97348
ADJUSTED R SQUARE	0.91795	RESIDUAL	34.	2.71429	0.07983	
STANDARD ERROR	0.28255					

------------------ VARIABLES IN THE EQUATION ------------------ / ------------- VARIABLES NOT IN THE EQUATION -------------

VARIABLE	B	BETA	STD ERROR B	F	VARIABLE	BETA IN	PARTIAL	TOLERANCE	F
FLUX4	0.61053	0.90738	0.03349	332.292	SNLOG	0.60682	0.49333	0.04984	10.615
STI	39.86027	0.75061	2.94937	182.651	STIA	-0.42719	-0.24602	0.02501	2.126
TI	-2927.53747	-0.18965	831.18114	12.405					
(CONSTANT)	-13.79916								

* *

VARIABLE(S) ENTERED ON STEP NUMBER 4.. SNLOG

MULTIPLE R	0.97106	ANALYSIS OF VARIANCE	DF	SUM OF SQUARES	MEAN SQUARE	F
R SQUARE	0.94295	REGRESSION	4.	33.94422	8.48605	136.35928
ADJUSTED R SQUARE	0.93603	RESIDUAL	33.	2.05369	0.06223	
STANDARD ERROR	0.24947					

------------------ VARIABLES IN THE EQUATION ------------------ / ------------- VARIABLES NOT IN THE EQUATION -------------

VARIABLE	B	BETA	STD ERROR B	F	VARIABLE	BETA IN	PARTIAL	TOLERANCE	F
FLUX4	0.61259	0.91044	0.02958	428.951	STIA	1.43988	0.45373	0.00567	8.296
STI	11.30989	0.21298	9.14175	1.531					
TI	-4425.71989	-0.28670	866.03326	26.116					
SNLOG	1.12996	0.60682	0.34682	10.615					
(CONSTANT)	-3.90013								

FILE NONAME (CREATION DATE = 05/03/76)

* M U L T I P L E R E G R E S S I O N * * * * * * * * * * * * * * VARIABLE LIST 1
REGRESSION LIST 9

DEPENDENT VARIABLE.. CRL2

VARIABLE(S) ENTERED ON STEP NUMBER 5.. STIA

MULTIPLE R	0.97708
R SQUARE	0.95469
ADJUSTED R SQUARE	0.94762
STANDARD ERROR	0.22575

ANALYSIS OF VARIANCE	DF	SUM OF SQUARES	MEAN SQUARE	F
REGRESSION	5.	34.36702	6.87340	134.86460
RESIDUAL	32.	1.63089	0.05097	

------------------ VARIABLES IN THE EQUATION ------------------

VARIABLE	B	BETA	STD ERROR B	F
FLUX4	0.60917	0.90535	0.02679	516.923
STI	-111.17463	-2.09354	43.32266	6.585
TI	-3484.49447	-0.22572	849.12022	16.840
SNLOG	2.80030	1.50384	0.65941	18.034
STIA	1.70137	1.43988	0.59070	8.296
(CONSTANT)	6.32307			

------------- VARIABLES NOT IN THE EQUATION -------------

VARIABLE	BETA IN	PARTIAL	TOLERANCE	F

ALL VARIABLES ARE IN THE EQUATION

Part II

ADDENDUM

TO

A REGRESSION APPROACH

FOR

ZIRCALOY-2 IN-REACTOR CREEP

CONSTITUTIVE EQUATIONS

by

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and

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(September, 1976)

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1.1 Introduction:

Since our last report released in May, 1976[1], we have made additional studies on the subject of Zr-2 in-reactor creep constitutuve equation. This is the first addendum in which further results are presented.

The overall structure and the methods of analysis in this addendum are essentially the same as in our previous report. Reanalysis and modifications were made, however, because (1) the deletion of some questionable data from the earlier creep data set and (2)the inclusion of two additional creep models. Finally, attempts have also been made to verify whether the total creep strain rate can be divided into two separate and additive thermal and irradiation creep components.

1.2 Deletion of some questionable data:

Although great care has been taken in examining the raw in-reactor creep data in the previous analysis, it was recognized later that some of the data may have been repetitively used. The following table summarizes which data have been deleted and why we deleted them. The revised creep data set is contained in Appendix 1.

ID No*	Reason for deletion
4,6	repetitive, they can be obtained as average of 117 and 118
3	repetitive, can be obtained as average of 107,108
1,77,78	repetitive, can be obtained as average of 77,78
2,87,88	incompatible creep test duration, 13,000 hrs repetitive, 2 can be obtained as average of 87,88
5,127, 128	incompatible creep test duration, 11,000 hrs repetitive, 5 can be obtained as average of 127,128
97,98	incompatible creep test duration, 29,000 hrs
137,138	incompatible creep test duration, 11,000 hrs

* The ID numbers are referring to Appendix B[1]

Creep test durations for the majority of creep data contained in the revised data set are of 5,000 hours. We deleted those data with incompatible test durations because the Zr-2 in-reactor creep rate may decrease with time[2].

1.3 Inclusion of additional creep models:

In the comparison of current Zr-2 in-reactor creep models, two additional ones are included. One is taken from MATPRO[3] and the other from the Preliminary Standardized Material Property Data Set used in the EPRI program for LWR fuel rod code evaluations[4]. This latter model is worth mentioning because of the likelihood it has of being incorporated into one or more of the six leading LWR fuel performance codes which are now under extensive evaluations.

The Zircaloy in-reactor creep constitutive equation in MATPRO is abbreviated as CCRPR(Clad CReeP Rate Model) and a formula by

$$\dot{\varepsilon}_t = K\, \phi\, (\sigma + B\, e^{C\sigma})\, \exp(-\,10{,}000/R\,T)\; t^{-0.5} \qquad \text{(A-1)}$$

where the corresponding units are

T: ^{o}K, t: sec, ϕ: fast neutron flux, n/m^{2}s (E> 1 Mev)

σ: tangential stress, N/m^2, $\dot{\varepsilon}_t$: tangential creep rate, m/m/sec

and

$K = 5.129 \cdot 10^{-29}$

$B = 7.252 \cdot 10^{2}$

$C = 4.967 \cdot 10^{-8}$

$R = 1.987$ cal/mole ^{o}K

The creep equation used in the EPRI program is given by

$$\dot{\varepsilon}_e = \{k_1 + 1.01\cdot 10^{-19} \exp(-\ 0.004\ t)\}\ \phi\ \sigma_e \exp(-\ 8{,}000/RT) + \{k_2\ \sigma_e^{(25.6\ -\ 0.026\ T)} \exp(-\ 138{,}000/RT)\} \quad \text{(A-2)}$$

where

$\dot{\varepsilon}_e$: effective strain rate, hr^{-1}

σ_e: effective stress, ksi (<40 ksi)

t: hours

ϕ: fast neutron flux, n/cm^2s (E>1 Mev)

R: 1.987 cal/mole ^oK

T: ^oK (<773 ^oK)

k_1: $0.667\cdot(1.36\cdot 10^{-18})$ } Zircaloy is assumed to be isotropic

k_2: $0.667\cdot(7.0\cdot 10^{-28})$

In order to change (A-2) into circumferential strain rate and tangential stress, simplifying assumptions of isotropic material and thin shell approximation were introduced with the following transformations.

Isotropic material

$$\sigma_e = \frac{1}{\sqrt{2}}\{ (\sigma_z - \sigma_\theta)^2 + (\sigma_\theta - \sigma_r)^2 + (\sigma_r - \sigma_z)^2 \}^{1/2} \quad \text{(A-3a)}$$

Thin shell approximation

$$\sigma_r \text{ negligible; } \sigma_z = 0.5\sigma_\theta \quad \text{(A-3b)}$$

(A-3a) then reduces to

$$\sigma_e = 0.866\ \sigma_\theta \quad \text{(A-4)}$$

The circumferential and effective strain rates relationship

$$\dot{\varepsilon}_\theta = \frac{\dot{\varepsilon}_e}{\sigma_e}\{ \sigma_\theta - \frac{1}{2}(\sigma_r + \sigma_z)\} \qquad \text{(A-5)}$$

with σ_e, σ_r and σ_z substituted from (A-3a), (A-3b), and (A-4), Eq. (A-5) becomes

$$\dot{\varepsilon}_\theta = 0.866\ \dot{\varepsilon}_e \qquad \text{(A-6)}$$

We have written a FORTRAN program to obtain σ_e from (A-4) and substituting that into (A-2) to get $\dot{\varepsilon}_e$. $\dot{\varepsilon}_e$ is then multiplied by a factor of 0.866 to get the circumferential creep strain rate.

It should be noted that both these two models have a time dependent parameter, t. By inspection one can see that the predicted creep rates are decreasing as irradiation time increases. We have discussed this time dependence before in our previous report and have raised the question of whether there is a steady state creep regime for Zircaloy in reactor. This issue is difficult to resolve at the moment primarily because of the effect of long term in-reactor creep tests during which the creep rate sensitivity on time can easily be masked due to the fluctuations in the controlled parameters ϕ, σ, and T.

The time dependency in these two models is believed to be coming from modeling of the long term effect rather than for the primary creep regime. For purpose of comparison with other creep models, the time parameter in (A-1) and (A-2) is taken equal to 5,000 hours.

1.4 Verification of whether thermal and irradiation creep components are additive :

Several current Zircaloy in-reactor creep models have had similar forms in which the total creep strain rate is expressed as the sum of thermal and irradiation creep components. We have made our attempt to verify this directly from our data set based on the presumption that the two components are indeed additive. The verification is made possible because of the unique creep test specimen arrangement in Ibrihim's in-reactor tests[2].

From Fig.4 in the previous report, one can see that actually there are three portions in Ibrihim's specimens and these are designated by fast flux, thermal flux and out-of-flux specimens respectively. Each portion according to its relative axial location with respect to the test reactor core receives neutron flux of different energy spectrum ranging from ~0 to E>1 Mev.

The second column to the right of Table-4 in our previous report gives the minimum control creep rates which are obtained from creep strain measurements for out-of-flux specimens. Since the temperature and pressure of the coolant in this portion are basically the same as in the other two portions; the tube outward dimensional change is due mainly to thermal creep and the fast neutron or irradiation creep contribution is negligible. This makes a very good case for the attempted verification since the total creep rate obtained at the fast flux portion, if it were made up by thermal and irradiation components and the two are independent and additive, the difference between the total creep strain rate and that of the control(or thermal) creep strain rate should be a strong function although not necessarily an exclusive function of fast neutron flux.

Regression analyses were performed progressively on ($\dot{\varepsilon}_T - \dot{\varepsilon}_{th}$) starting with using ϕ only and then with different combinations of ϕ, σ and T.

Regressions were also carried out on the control creep strain rate data by using a family of formula of the following kind

$$\dot{\varepsilon}_{th} = A' \sigma^{n'} \exp(-Q'/R\,T)$$

Creep strain rates from both irradiation and thermal creep regression equations are plotted against σ and 1/T and so are their sums.

2. Results and Discussions :

2.1 Creep model comparisons :

The comparisons of current Zircaloy in-reactor creep models are contained in Fig. A-1 to Fig. A-6. The same reference fast neutron flux value was used for these figures as well as for all the latter figures in this addendum.

2.1.1 Stress dependence:

Fig. A-1 to Fig. A-4 show the stress dependnece of the predicted creep rates from various in-reactor creep models. The fast neutron flux is fixed at $5 \cdot 10^{13}$ n/cm^{2}s and temperatures are systematically increased from 250 $^{\circ}$C to 300 $^{\circ}$C, 350 $^{\circ}$C and 400°C. The broad darkened lines in these figures represent our in-reactor creep model obtained from regression analysis. Both 95% confidence interval and the transformed actual creep data are plotted for comparisons. Transformation of the actual creep data to the fast flux and temperature values of interest is done by using the same scheme as depicted in the earlier analysis. That is, we use our regression model as the basis for transforming the actual data on σ, T, ϕ and $\dot{\varepsilon}$ to the corresponding values of interest and the regression model provides the necessary scaling factor.

Much of the same trend on stress dependence is observed for the two added creep models and the regression model obtained from using the revised data set. Good agreement in these models is found only when temperature is relatively low and stress is low to moderate. As temperature increases, its effect begins to override the stress effect and the greatest descrepancies among models are seen in Fig. A-4 when temperature is raised to 400 $^{\circ}$C. Again, BUCKLE gives the highest predicted in-reactor creep rate which is clearly unacceptable if clad hoop stress should exceed 20 ksi.

Both model (A-1) and model (A-2) agree reasonably well with other models at lower temperatures, 250 $^{\circ}$C-300 $^{\circ}$C, although they predict slightly higher creep rates at low stress regime. At higher temperatures, 350°C-400°C, these two models underpredict creep rates at high stress regime as compared to most

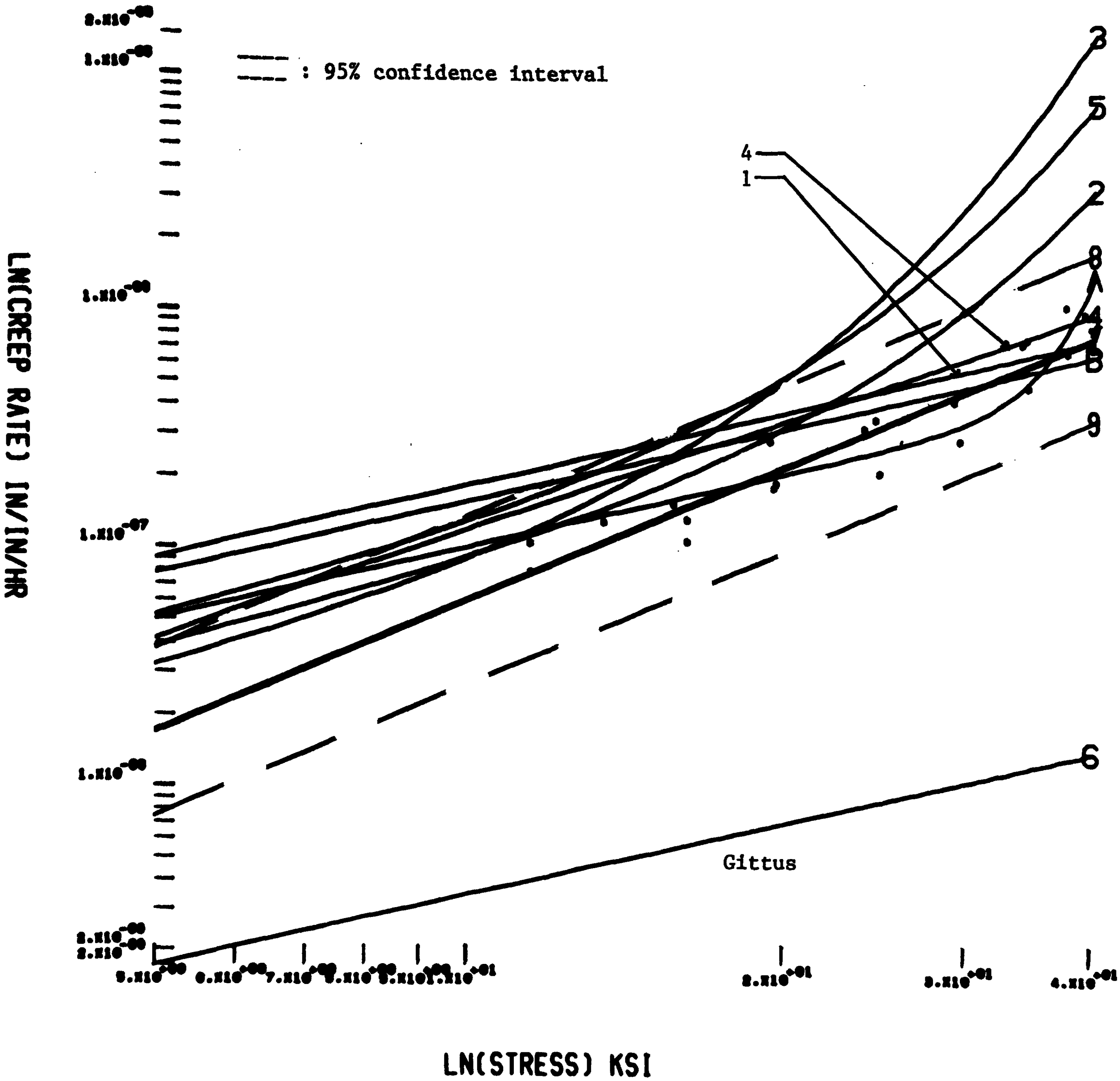

Figure A-1 Comparison of Creep Laws at T=250°C, ϕ= $5 \cdot 10^{13}$ n/cm^2s (E>1 Mev) (Numbers associated with the curves are equation numbers given in reference 1. They can also be found in Appendix 2)

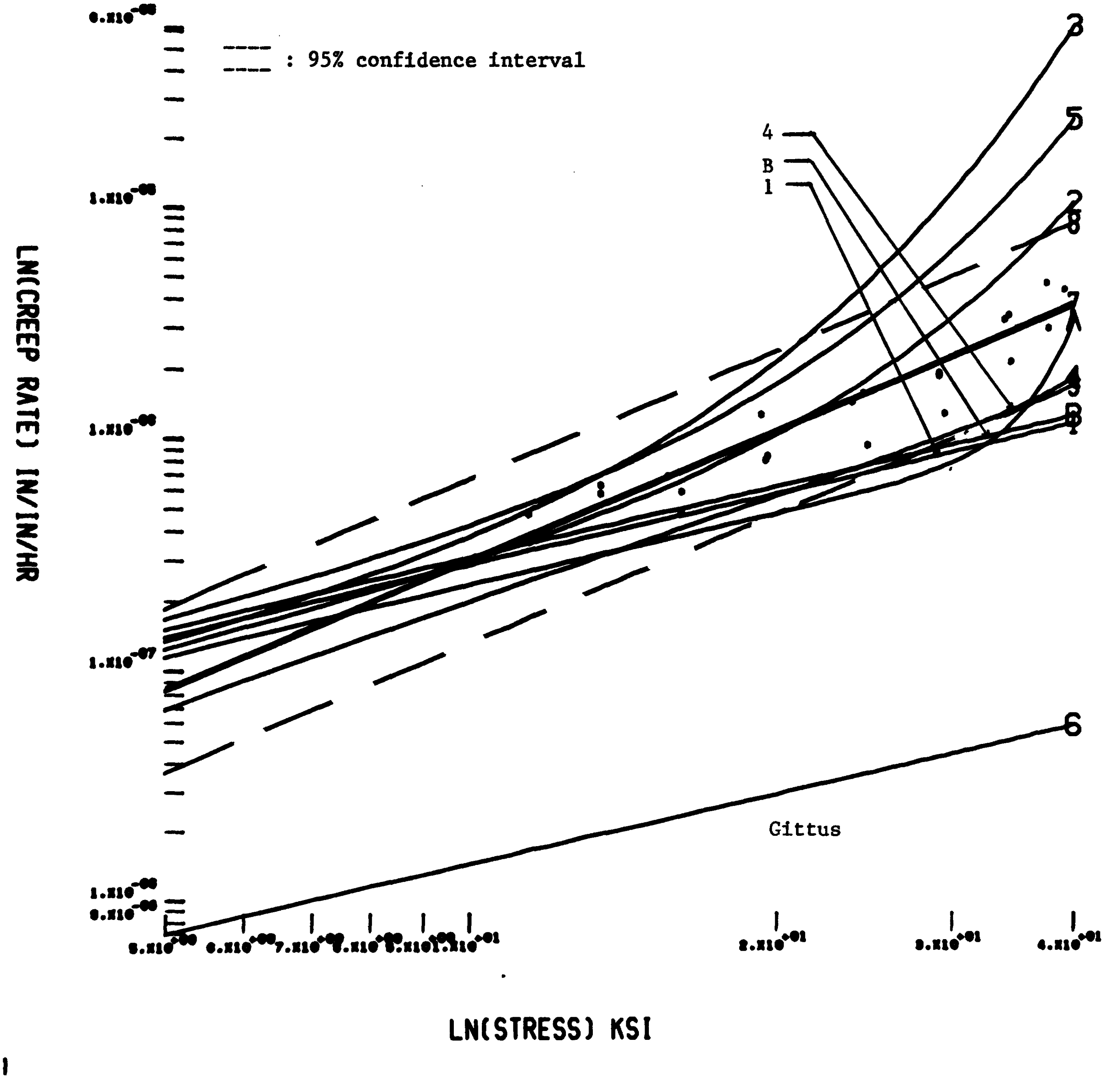

Figure A-2 Comparison of Creep Laws at T=300°C, $\phi = 5\cdot10^{13} n/cm^2 s$ (E>1 Mev)

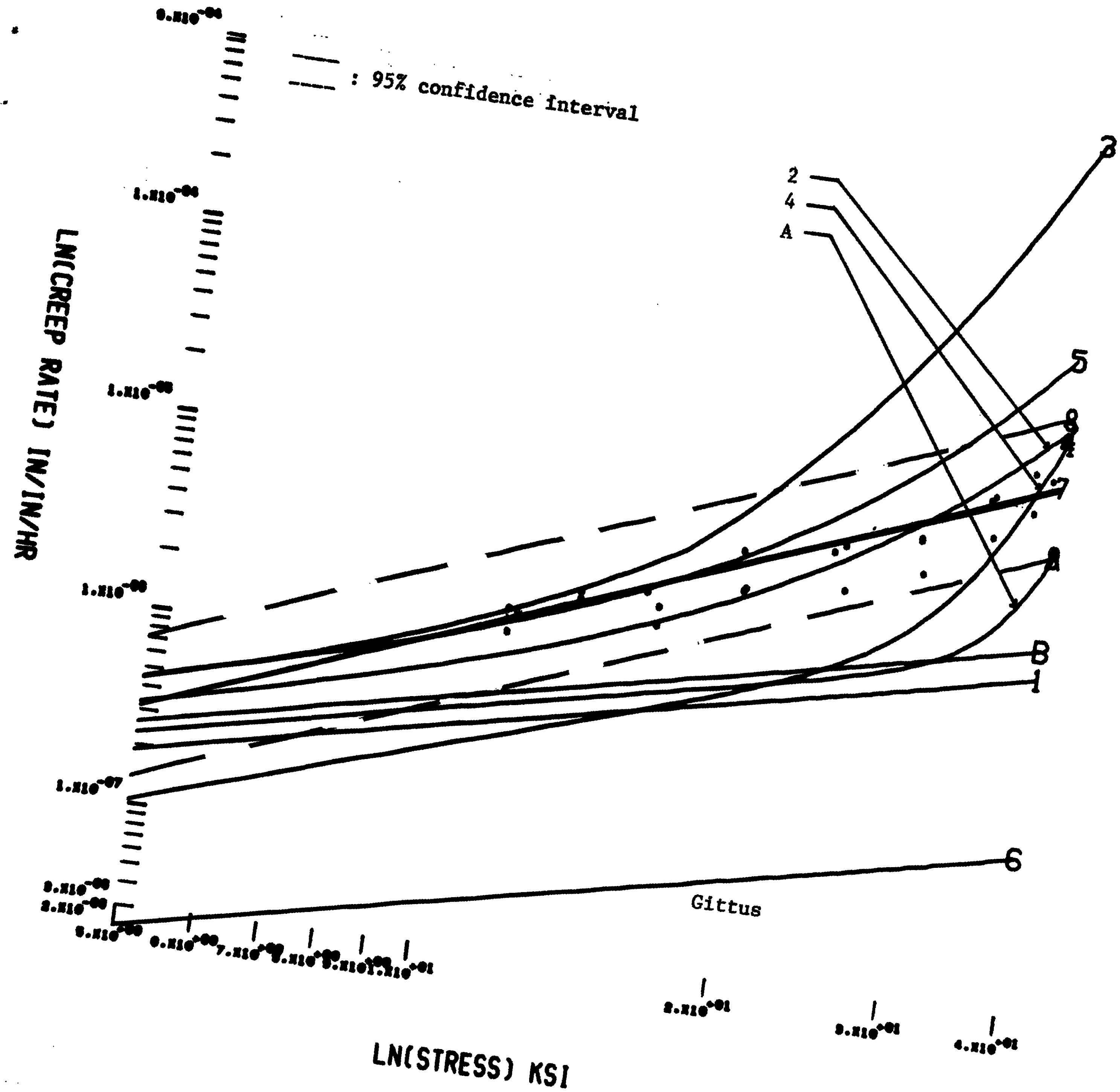

Figure A-3 Comparison of Creep Laws at T=350^{o}C, ϕ= $5\cdot 10^{13}$n/cm^{2}s (E>1 Mev)

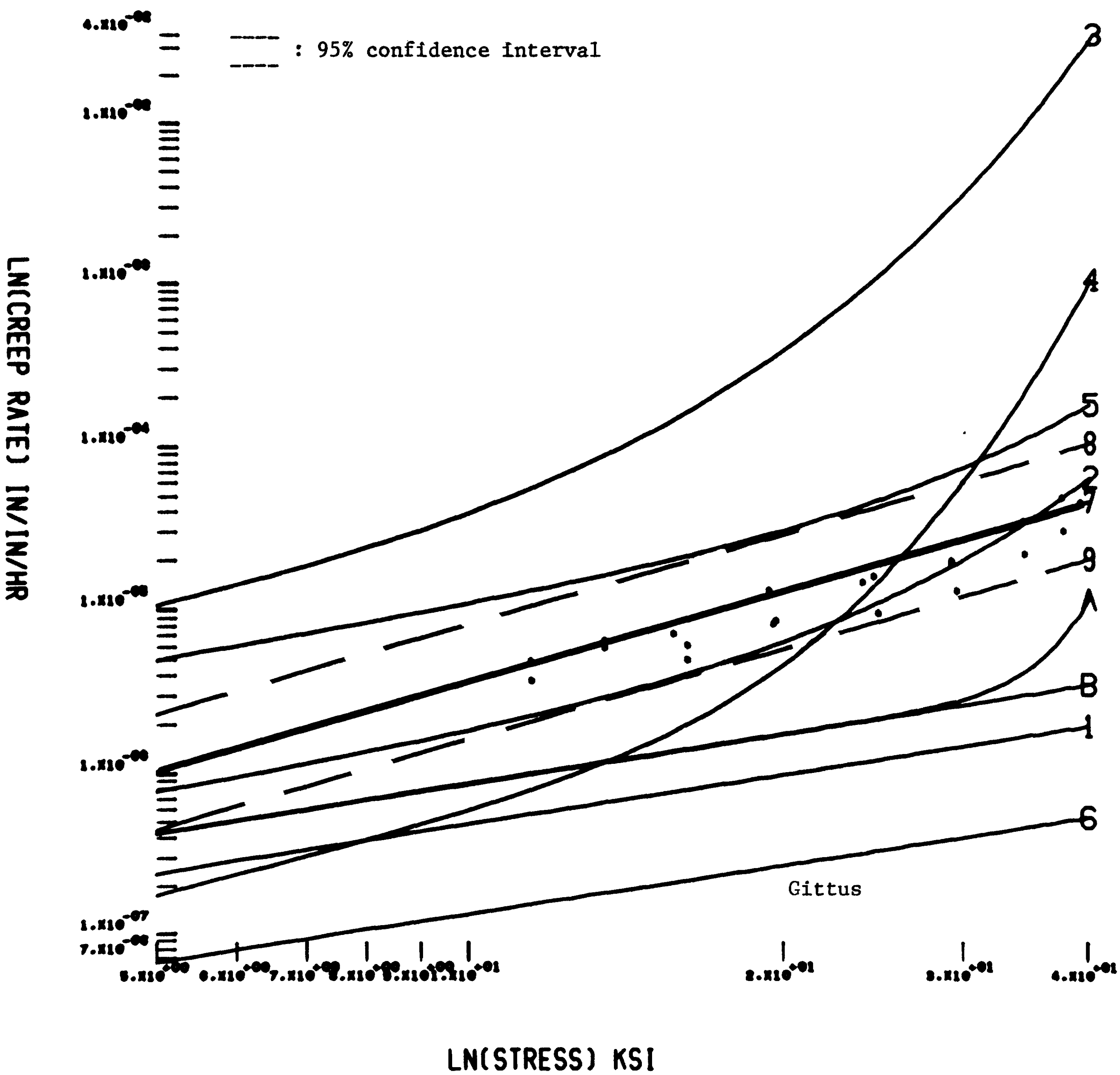

Figure A-4 Comparison of Creep Laws at T=400^{o}C, ϕ= $5 \cdot 10^{13}$n/cm^{2}s (E>1 Mev) of the other models.

2.1.2 Temperature dependence:

Fig. A-5 and Fig. A-6 give the 1/T dependence of the in-reactor creep rates at fixed fast neutron flux and two levels of stresses. Again one can observe similar trends on T dependence for the various curves. Model descrepancies become more evident when temperature is raised to a higher level. (A-1) and (A-2) also underpredict creep rates at high temperatures as compared to other models.

2.2 Regression analysis with revised creep data set:

As a result from the deletion of questionable creep data, sixteen out of thirty-eight previous data were eliminated. Using the remaining twenty-two data, we have rerun the analysis with the same six starting model equations[1]. Table A-1 and Table A-2 show the regression statistics, estimated coefficients and the standard error of estimates for these models. We shall first look at the regression statistics given in Table A-1.

Table A-1 Multiple Regression Coefficients,F Statistics Using the Revised Data Set

Equation No*	R^2(%)	F
3	97.712	126.638
5	98.381	128.086
6	98.381	96.443
10	97.713	126.716
11	98.380	128.014
12	98.380	96.394

* : All equation numbers without prefix refer to equations in reference (1)

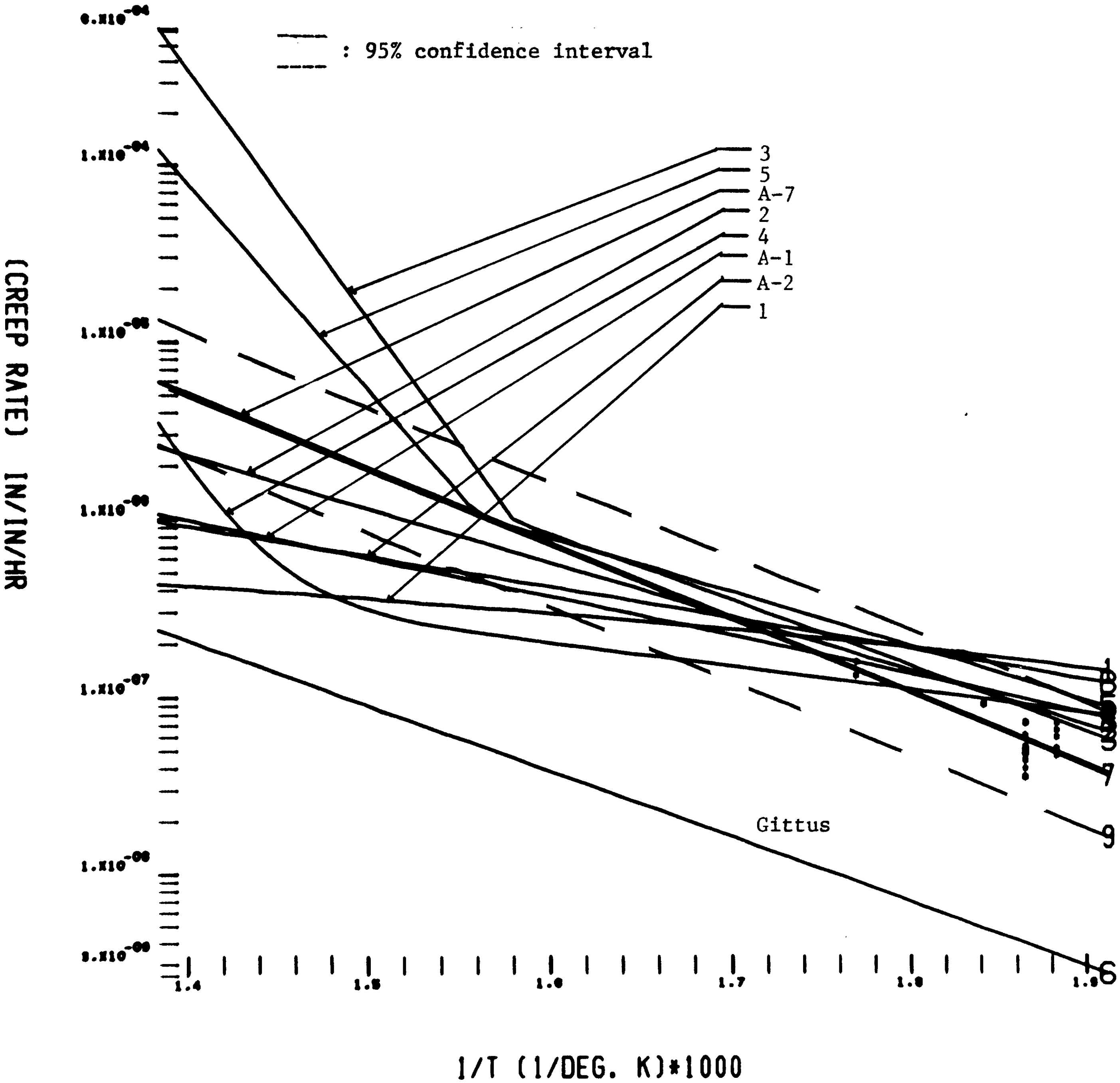

Figure A-5 Comparison of Creep Laws at σ=7.5 ksi, ϕ= $5 \cdot 10^{13}$ n/cm^{2}s (E>1 Mev)

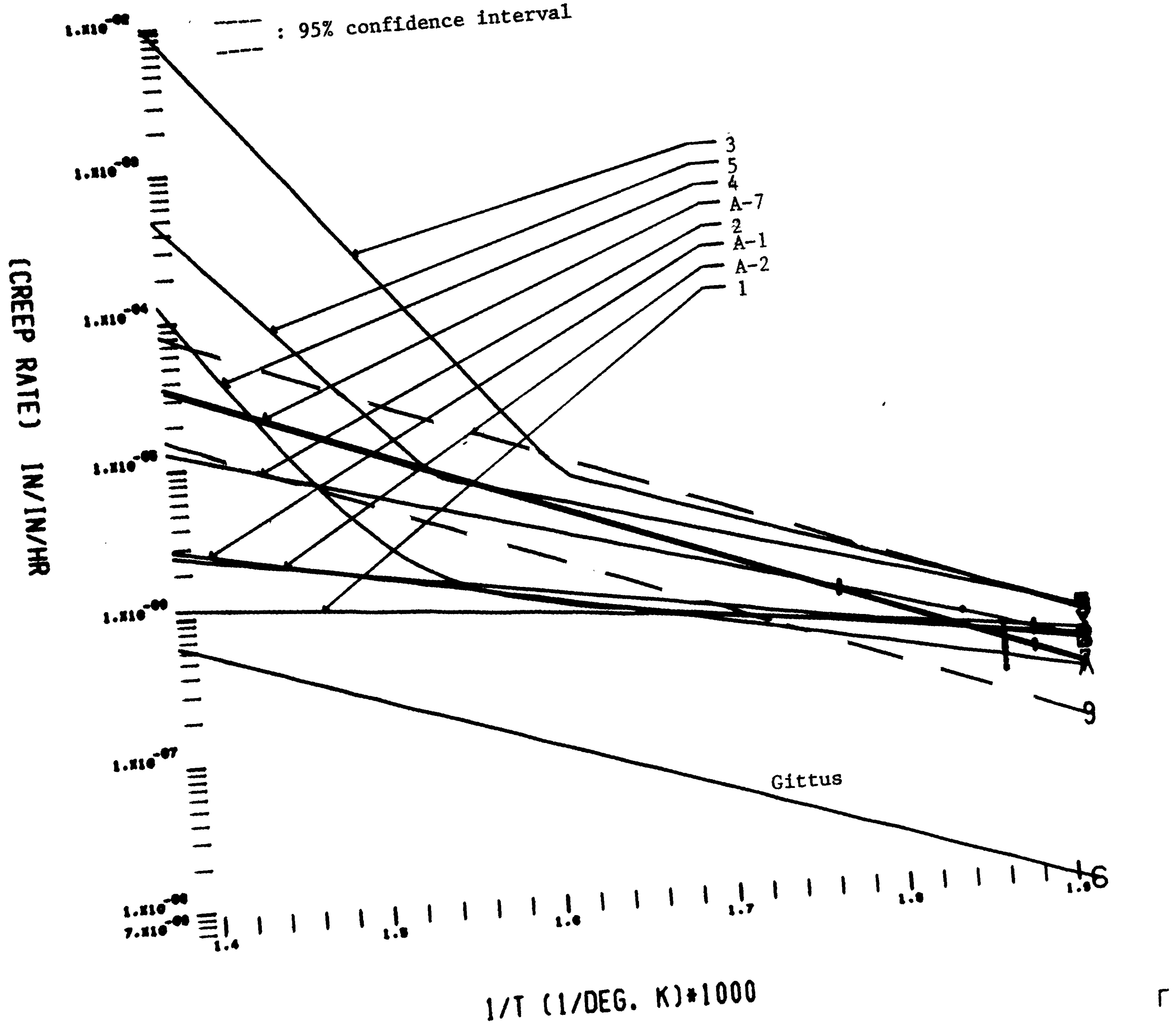

Figure A-6 Comparison of Creep Laws at σ=20 ksi, $\phi=5\cdot10^{13} n/cm^2 s$ (E>1 Mev)

The meanings of R^2 and F are explained before. We are thus able to make the following general conclusions : (1) Based on R^2 and F, all regressions can be considered significant; (2) R^2 increases as more complicated model equations are used.

The fact that the respective R^2 values for Eq.(5), (6) and Eq.(11), (12) are the same tells that there is probably little or no gain at all to use a second power in Eq.(6) and (12) for the stress dependent activation energies. Although Eq.(10) has a slightly higher R^2 than Eq.(3) by normalizing stress with respect to temperature dependent shear modulus, the reverse is true for pairs of equations (5), (11) and (6), (12). As we shall discuss later that the more complicated models may not be adequate under certain situation. We shall next examine another important piece of evidence, the residual plots.

Fig. A-7 to Fig. A-9 contain two residual plots in each figure for the six creep regression model equations. Although the error bands are narrower for the more complicated equations, all their residual patterns look quite satisfactory and there are no signs of model abnormalties.

Table A-2 Estimated Coefficients, SEE's Using the Revised Data Set

Eq. No.	lnA	m	n	Q/R	$Q_o/R\hat{T}$	$Q_o/R\hat{T}^2$
3	-21.484	0.597	1.827	9519.05	---	---
SEE	---	0.033	0.181	2310.16	---	---
5	-20.382	0.5847	-0.795	6937.05	58.290	---
SEE	---	0.029	1.007	2229.72	22.118	---
6	-20.502	0.5848	-0.744	6917.09	55.794*	0.026
SEE	---	0.031	3.934	2717.10	185.01	1.927
10	8.735	0.597	1.827	9019.03	---	---
SEE	---	0.033	0.181	2281.32	---	---
11	-10.731	0.5847	-0.789	7160.30	58.152	---
SEE	---	0.029	1.007	2101.44	22.109	---
12	-10.028	0.585	-0.660	7074.85	51.903*	0.066
SEE	---	0.031	3.933	3316.06	185.047	1.928

* In Eq.(6) and (12), the coefficients for σ/T are in form of $2Q_o/R\hat{T}$

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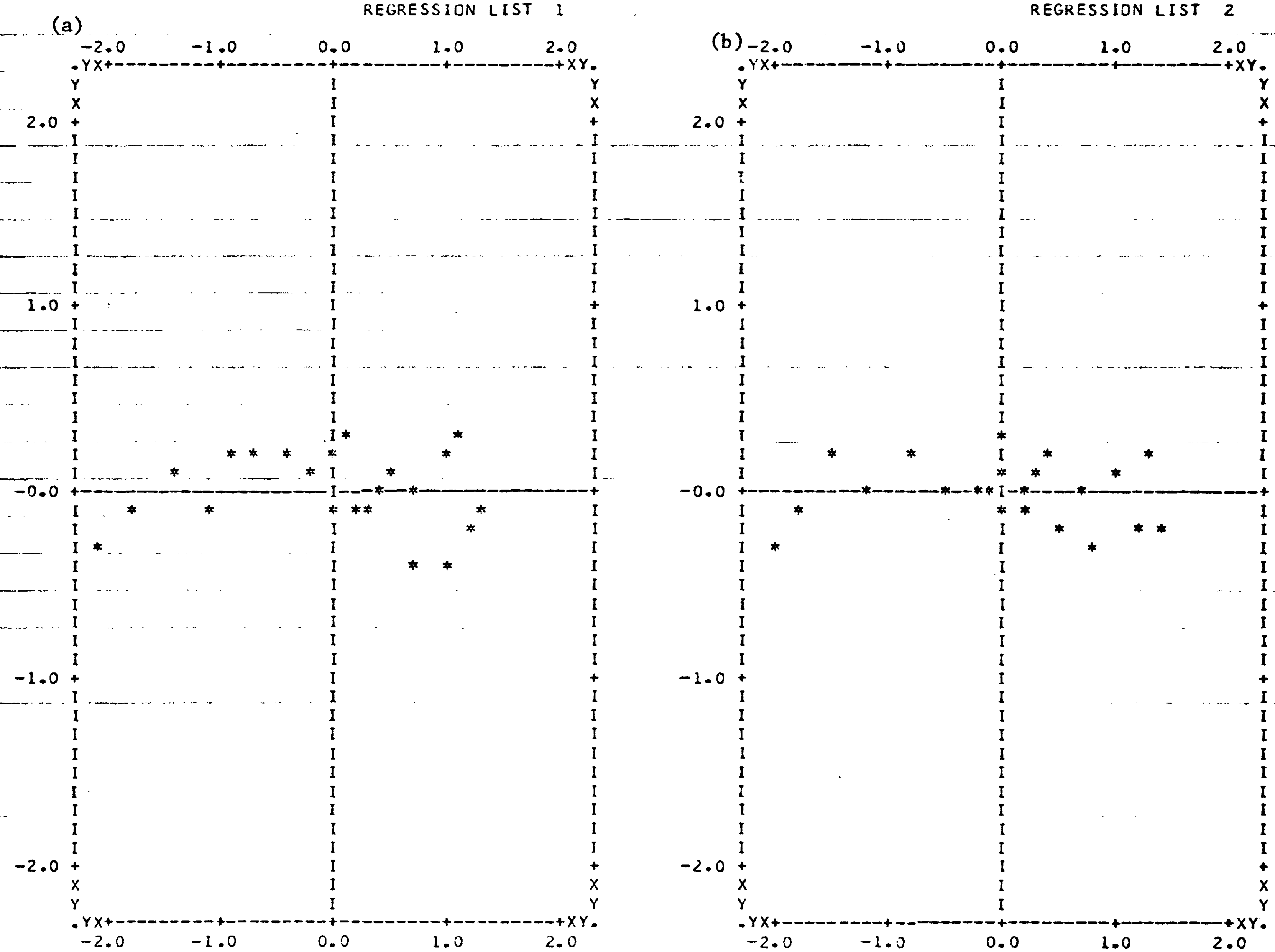
FILE NONAME (CREATION DATE = 07/28/76)

* * * * * * * PLOT: STANDARDIZED RESIDUAL (DOWN) -- PREDICTED STANDARDIZED DEPENDENT VARIABLE (ACROSS) * * * * * * *

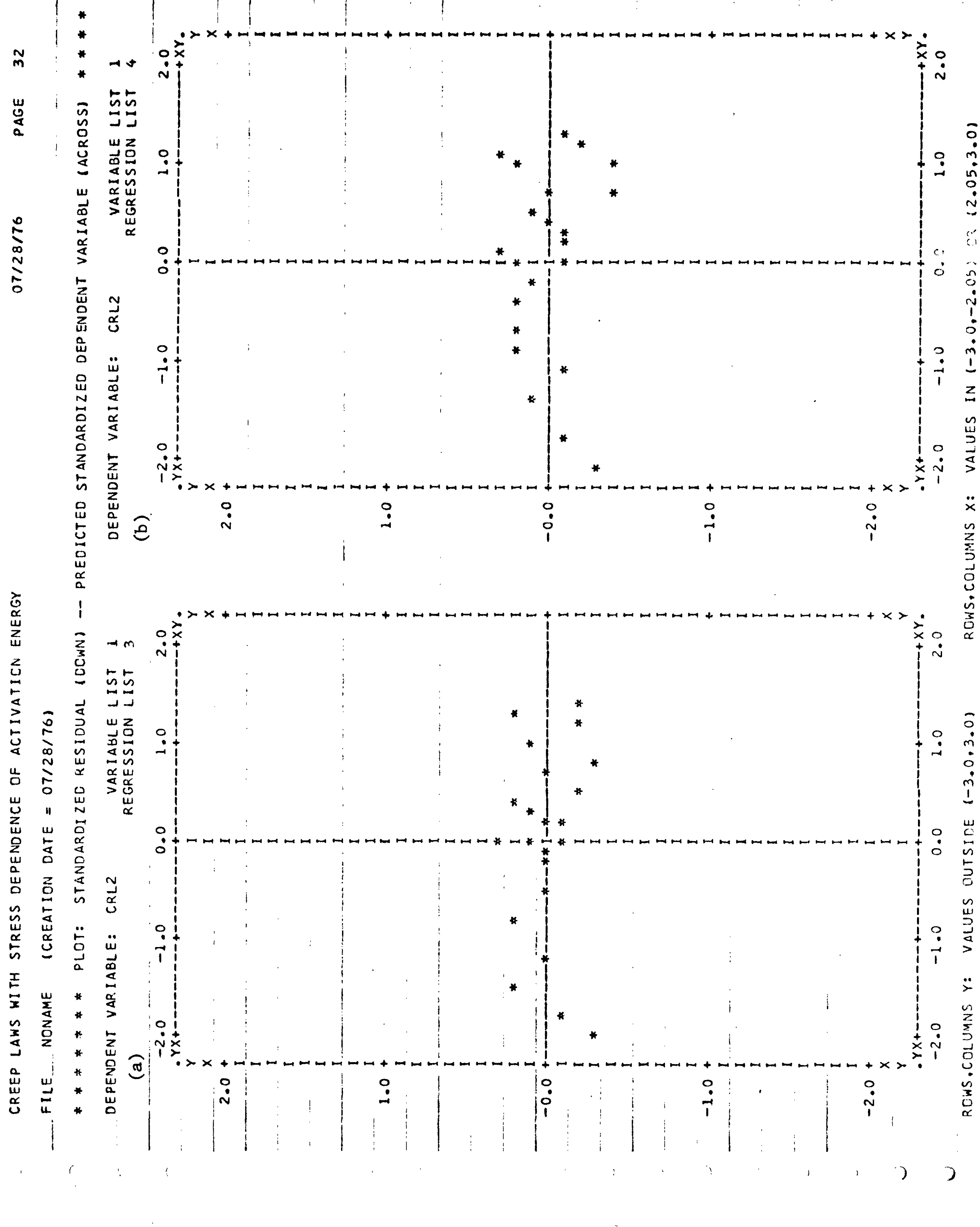
DEPENDENT VARIABLE: CRL2 VARIABLE LIST 1 REGRESSION LIST 1 DEPENDENT VARIABLE: CRL2 VARIABLE LIST 1 REGRESSION LIST 2



ROWS.COLUMNS Y: VALUES OUTSIDE (-3.0,3.0) ROWS,COLUMNS X: VALUES IN (-3.0,-2.05) OR (2.05,3.0)

Figure A-7 Residual Plots (a), (b) for Regression Models (3) and (5) respectively

Figure A-8 Residual Plots (a), (b) for Regression Models (6) and (10) respectively



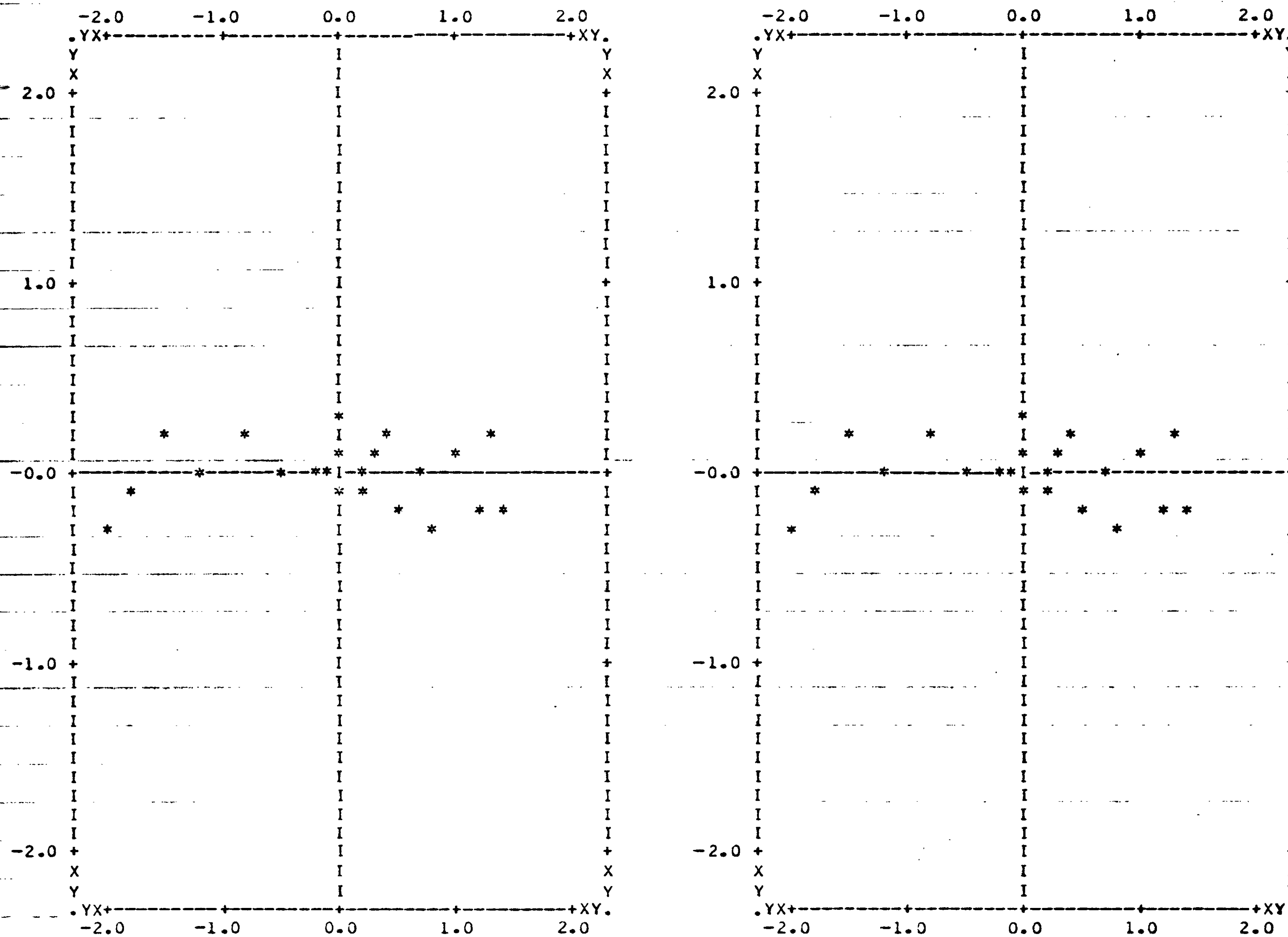
CREEP LAWS WITH STRESS DEPENDENCE OF ACTIVATICN ENERGY 07/28/76 PAGE 33

FILE NONAME (CREATION DATE = 07/28/76)

* * * * * * * PLOT: STANDARDIZED RESIDUAL (DOWN) -- PREDICTED STANDARDIZED DEPENDENT VARIABLE (ACROSS) * * * * * * *

DEPENDENT VARIABLE: CRL2 VARIABLE LIST 1 REGRESSION LIST 5 (a)

DEPENDENT VARIABLE: CRL2 VARIABLE LIST 1 REGRESSION LIST 6 (b)



ROWS,COLUMNS Y: VALUES OUTSIDE (-3.0,3.0) ROWS,COLUMNS X: VALUES IN (-3.0,-2.05) OR (2.05,3.0)

Figure A-9 Residual Plots (a), (b) for Regression Models (11) and (12) respectively

It is apparent from Table A-2 that except for creep models (3) and (10), the estimated coefficients for n which is the stress exponent are all negative. We tentatively rejected those models having negative stress exponent because they contradict to what is believed to be the stress exponent in power law creep. It should be pointed out, however, that the resultant creep rate is still increasing in these models as stress increases despite of the negative stress exponent. This is because of the overriding effect of the stress-temperature interaction factor included in the exponential term of these models.

Eq.(10) is finally selected as our regression creep model for the slightly better regression statistics it has over (3) and more importantly its more logical and consistent physical interpretations. The explicit formula for (10) will be given at the end of this addendum.

2.3 Verification:

In section 1.4, we have already discussed the assumptions and data characteristics for the attempted verification of whether thermal and irradiation creep components are additive. We shall proceed first in the following with the thermal creep analysis.

2.3.1 Thermal creep analysis:

The family of regression model equations for thermal creep analysis on the minimum control creep rate data are the followings:

$$\dot{\varepsilon}_{th} = A' \sigma^{n'} \exp(- Q'/RT) \qquad \text{(A-7)}$$

$$\dot{\varepsilon}_{th} = A' \sigma^{n'} \exp\{- Q_o'(1- \sigma/\hat{\tau})/RT\} \qquad \text{(A-8)}$$

$$\dot{\varepsilon}_{th} = A' \sigma^{n'} \exp\{- Q_o'(1- \sigma/\hat{\tau})^2/RT\} \qquad \text{(A-9)}$$

$$\dot{\varepsilon}_{th} = A' (\sigma/\mu(T))^{n'} \exp(- Q'/RT) \qquad \text{(A-10)}$$

$$\dot{\varepsilon}_{th} = A' \ (\sigma/\mu(T))^{n'} \ \exp\{- Q_o'(1- \sigma/\hat{\tau})/RT\} \qquad \text{(A-11)}$$

$$\dot{\varepsilon}_{th} = A' \ (\sigma/\mu(T))^{n'} \ \exp\{- Q_o'(1- \sigma/\hat{\tau})^2/RT\} \qquad \text{(A-12)}$$

Table A-3 shows the R^2,F values for the six thermal creep models above and Table A-4 gives the estimated coefficients and standard error of estimates.

Table A-3 Multiple regression coeffcients, F statistics for thermal creep analysis

Equation No	R^2(%)	F
A-7	94.654	81.798
A-8	96.169	73.833
A-9	96.790	63.038
A-10	94.658	81.858
A-11	96.168	73.812
A-12	96.778	62.777

We shall postpone the examinations of residual plots from these models until later but using the same arguements as we did in the previous section that based on information contained in Table A-3 and Table A-4, (A-10) was selected as our regression thermal creep equation. This equation is given by the following formula:

$$\dot{\varepsilon}_{th} = A' \ (\sigma/\mu(T))^{n'} \ \exp(- Q'/RT) \qquad \text{(A-10)}$$

where the units are

$\dot{\varepsilon}_{th}$: hr^{-1}, σ: ksi, T: ^oK, R=1.987 cal/mole ^oK

and

A'= 13200.37 $\mu(ksi)=4.77\cdot10^3 - 1.906\cdot T(^oF)$

n'= 2.441

Q'= 15476.28 cal/mole

Table A-4 Estimated Coefficients, SEE's From Thermal Creep Analysis

Eq. No.	lnA'	n'	Q'/R	$Q_o'/R\hat{T}$	$Q_o'/R\hat{T}^2$
A-7	- 9.390	2.441	8456.90	---	---
SEE	---	0.205	2649.68	---	---
A-8	- 8.618	-0.528	5513.53	66.291	---
SEE	---	1.143	2569.92	25.198	---
A-9	7.282	-7.445	8291.71	403.547*	-3.557
SEE	---	3.998	2875.32	189.194	1.979
A-10	9.488	2.441	7788.77	---	---
SEE	---	0.205	2616.40	---	---
A-11	-12.651	-0.521	5663.45	66.158	---
SEE	---	1.142	2424.62	25.189	---
A-12	-49.917	-7.379	10300.87	400.600*	-3.528
SEE	---	4.008	3473.53	189.77	1.986

* In (A-9) and (A-12), the coefficients for σ/T are in the form of $2Q_o'/R\hat{T}$

2,3,3 Irradiation creep analysis:

In this part of analysis as we mentioned earlier, the differences between minimum in-reactor creep rate and minimum control creep rate were taken from our revised creep data set and regressions were performed on these differences in the following progressive steps.

$$\dot{\varepsilon}_T - \dot{\varepsilon}_{th} = A'' \phi^{m''} \qquad \text{(A-13)}$$

$$\dot{\varepsilon}_T - \dot{\varepsilon}_{th} = A'' (\phi/\phi_o)^{m''} \qquad \text{(A-14)}$$

$$\dot{\varepsilon}_T - \dot{\varepsilon}_{th} = A'' \phi^{m''} \sigma^{n''} \qquad \text{(A-15)}$$

$$\dot{\varepsilon}_T - \dot{\varepsilon}_{th} = A'' (\phi/\phi_o)^{m''} (\sigma/\mu(T))^{n''} \qquad \text{(A-16)}$$

$$\dot{\varepsilon}_T - \dot{\varepsilon}_{th} = A'' \phi^{m''} \sigma^{n''} \exp(- Q''/RT) \qquad \text{(A-17)}$$

$$\dot{\varepsilon}_T - \dot{\varepsilon}_{th} = A'' (\phi/\phi_o)^{m''} (\sigma/\mu(T))^{n''} \exp(- Q''/RT) \qquad \text{(A-18)}$$

$$\dot{\varepsilon}_T - \dot{\varepsilon}_{th} = A'' \phi^{m''} \sigma^{n''} \exp\{- Q''_o(1-\sigma/\hat{\tau})/RT\} \qquad \text{(A-19)}$$

$$\dot{\varepsilon}_T - \dot{\varepsilon}_{th} = A'' (\phi/\phi_o)^{m''} (\sigma/\mu(T))^{n''} \exp\{-Q''_o(1-\sigma/\hat{\tau})/RT\} \qquad \text{(A-20)}$$

$$\dot{\varepsilon}_T - \dot{\varepsilon}_{th} = A'' \phi^{m''} \sigma^{n''} \exp\{- Q''_o(1-\sigma/\hat{\tau})^2/RT\} \qquad \text{(A-21)}$$

$$\dot{\varepsilon}_T - \dot{\varepsilon}_{th} = A'' (\phi/\phi_o)^{m''} (\sigma/\mu(T))^{n''} \exp\{-Q''_o(1-\sigma/\hat{\tau})^2/RT\} \qquad \text{(A-22)}$$

Table A-5 and Table A-6 give the regression statistics,estimated coefficients, SEE's for (A-13) to (A-22). The residual plots are contained in Fig.A-10 to Fig.A-14 for irradiation creep analysis and Fig.A-15 to Fig.A-17 for thermal creep analysis.

The information can be summarized as follows. In short, we have considered all possible combinations of ϕ,σ and T both in their original parameter units and in dimensionless forms. A number of observations can be made from Table A-5 and Table A-6 for the irradiation creep analysis. First of all, in using ϕalone, we are able to reproduce the fast neutron flux exponent m''=0.859 which has been so indiscriminatively used in other creep models since Watkins and Woods first proposed it in 1969[5]. However, as we turn to look at its R^2 value as compared to others, it is clearly inferior. But more importantly when we look at the

Table A-5 Multiple Regression Coefficients, F Statistics For Irradiation Creep Analysis

Equation No	R^2(%)	F
A-13	92.076	94.699
A-14	92.076	94.699
A-15	97.276	140.879
A-16	97.358	145.453
A-17	98.269	140.654
A-18	98.270	140.763
A-19	98.768	139.412
A-20	98.766	139.237
A-21	98.831	109.248
A-22	98.834	109.525

residual plots in Fig.A-10, there are distinct patterns of residual seggregations from which we know such models (A-13), (A-14) are not acceptable.

Secondly, although the residual structures improve considerably when more parameters are introduced, e.g., with more complicated models having stress dependent activation energies; we either obtain negative stress exponents as in (A-19), (A-20) or we have the associated standard error of estimates which are sometimes even larger than the estimated coefficients. What this means is that the uncertainties in the estimated coefficients are larger than the magnitudes of the estimated coefficients themselves and these models should also be regarded as unacceptable. We are, therefore, left with (A-15) to (A-18) to choose from. Using the same arguements as before, (A-18) has been selected as our model for the irradiation creep component and its explicit formula is given by

$$\dot{\varepsilon}_{irr} = \dot{\varepsilon}_T - \dot{\varepsilon}_{th} = A'' \left(\phi/\phi_o \right)^{m''} \left(\sigma/\mu(T)\right)^{n''} \exp(- Q''/RT) \qquad \text{(A-18)}$$

where the units are defined as before and

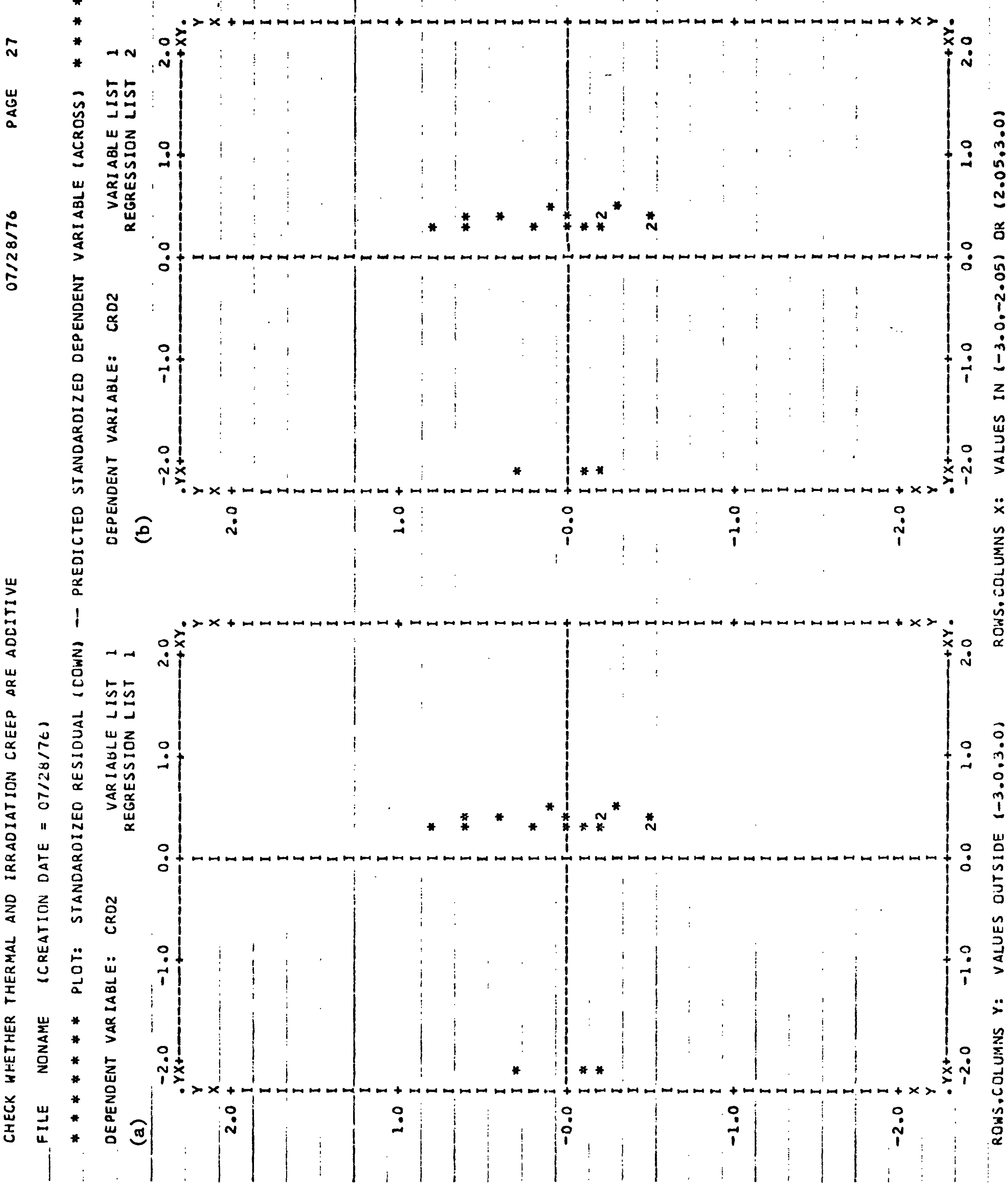
$$A'' = 6.234$$
$$m'' = 0.905$$
$$n'' = 1.482$$
$$Q'' = 13870.47 \text{ cal/mole}$$

Table A-6 Estimated Coefficients, SEE's From Irradiation Creep Analysis

Eq. No.	lnA"	m"	n"	Q"/R	$Q''_o/R\hat{T}$	$Q''_o/R\hat{T}$
A-13	-41.758	0.859	---	---	---	---
SEE	---	0.088	---	---	---	---
A-14	-18.618	0.859	---	---	---	---
SEE	---	0.088	---	---	---	---
A-15	-46.569	0.906	1.101	---	---	---
SEE	---	0.055	0.203	---	---	---
A-16	-12.982	0.9065	1.126	---	---	---
SEE	---	0.054	0.203	---	---	---
A-17	-34.012	0.905	1.482	7385.63	---	---
SEE	---	0.045	0.213	2536.23	---	---
A-18	1.830	0.905	1.482	6980.61	---	---
SEE	---	0.045	0.213	2499.91	---	---
A-19	-31.955	0.877	-1.280	4928.84	62.284	---
SEE	---	0.041	1.179	2447.49	26.265	---
A-20	-18.142	0.8776	-1.270	5287.48	62.061	---
SEE	---	0.041	1.179	2302.13	26.261	---
A-21	-40.693	0.878	2.384	3247.37	-121.330*	1.988
SEE	---	0.042	4.551	3191.34	221.670	2.383
A-22	2.157	0.878	2.522	2504.38	-128.000*	2.059
SEE	---	0.042	4.546	3970.95	221.520	2.383

* In (A-21), (A-22) the coefficients for σ/T are in the form of $2Q''_o/R\hat{T}$

Figure A-10 Residual Plots (a), (b) for Regression Models (A-13) and (A-14) respectively



CHECK WHETHER THERMAL AND IRRADIATION CREEP ARE ADDITIVE 07/28/76 PAGE 28

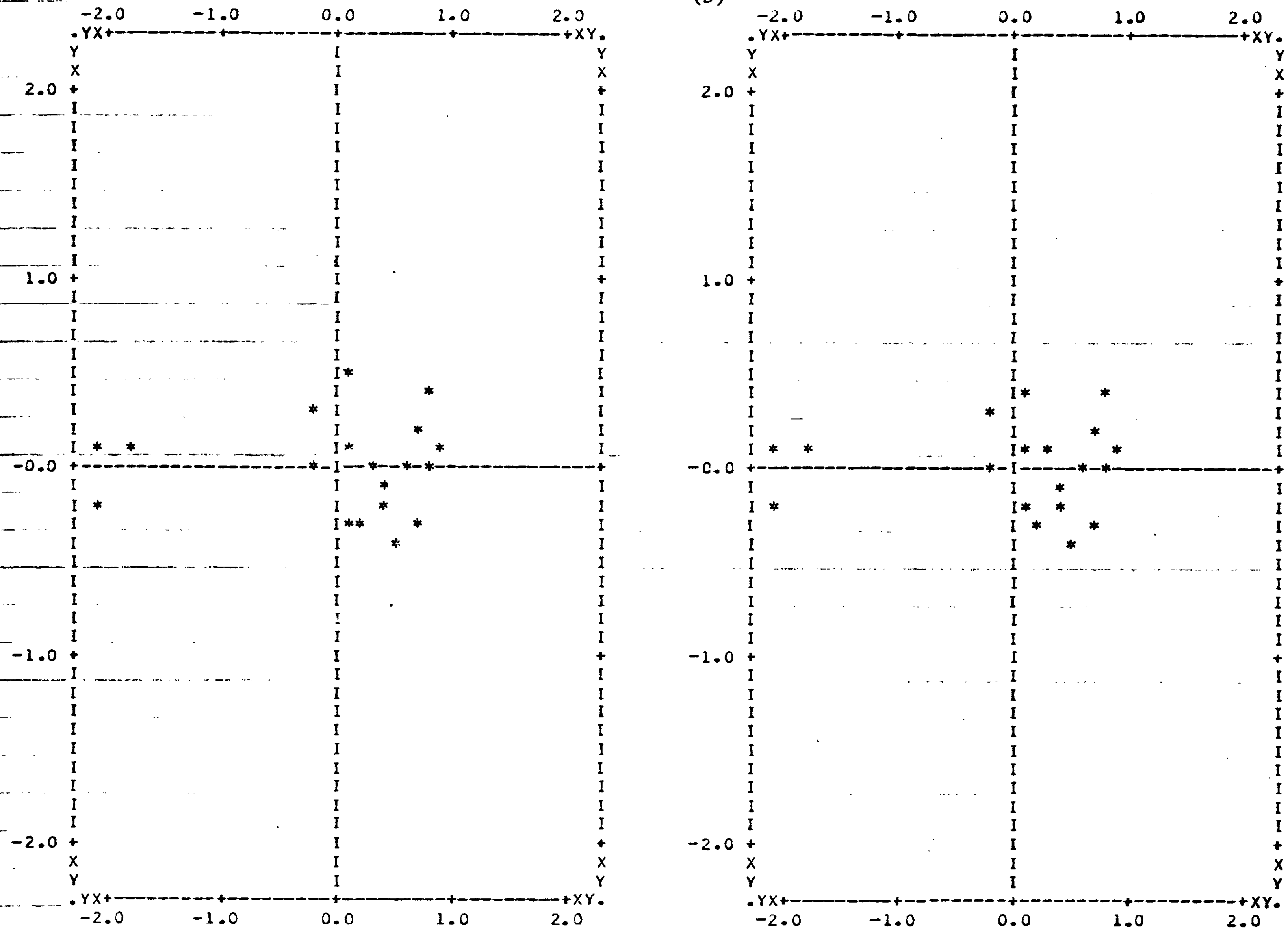
FILE NONAME (CREATION DATE = 07/28/76)

* * * * * * * PLOT: STANDARDIZED RESIDUAL (DOWN) — PREDICTED STANDARDIZED DEPENDENT VARIABLE (ACROSS) * * * * * * *

DEPENDENT VARIABLE: CRD2 VARIABLE LIST 1 REGRESSION LIST 3

DEPENDENT VARIABLE: CRD2 VARIABLE LIST 1 REGRESSION LIST 4

(a) (b)



ROWS,COLUMNS Y: VALUES OUTSIDE (-3.0,3.0) ROWS,COLUMNS X: VALUES IN (-3.0,-2.05) OR (2.05,3.0)

Figure A-11 Residual Plots (a), (b) for Regression Models (A-15) and (A-16) respectively

Figure A-12 Residual Plots (a), (b) for Regression Models (A-17) and (A-18) respectively

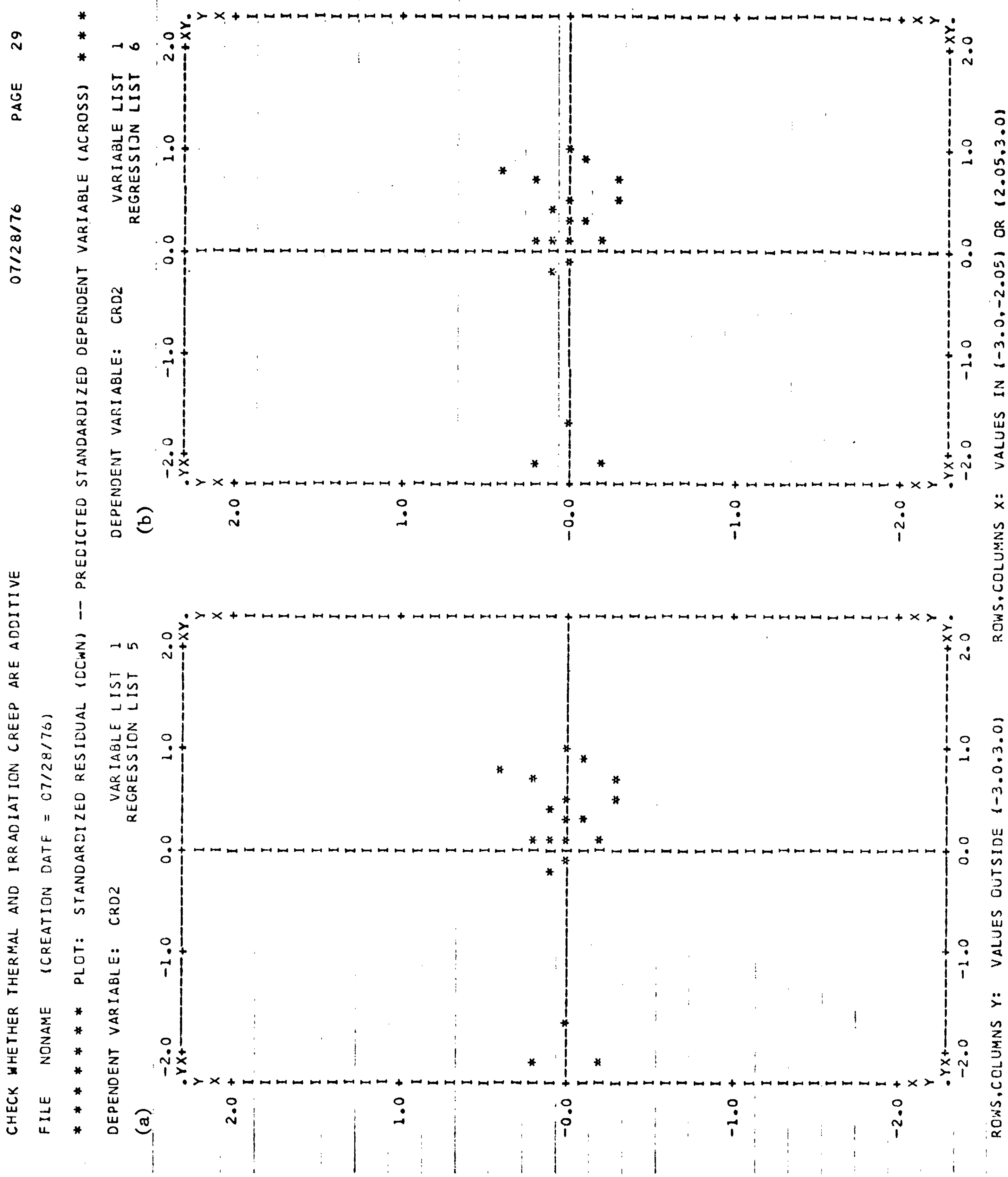
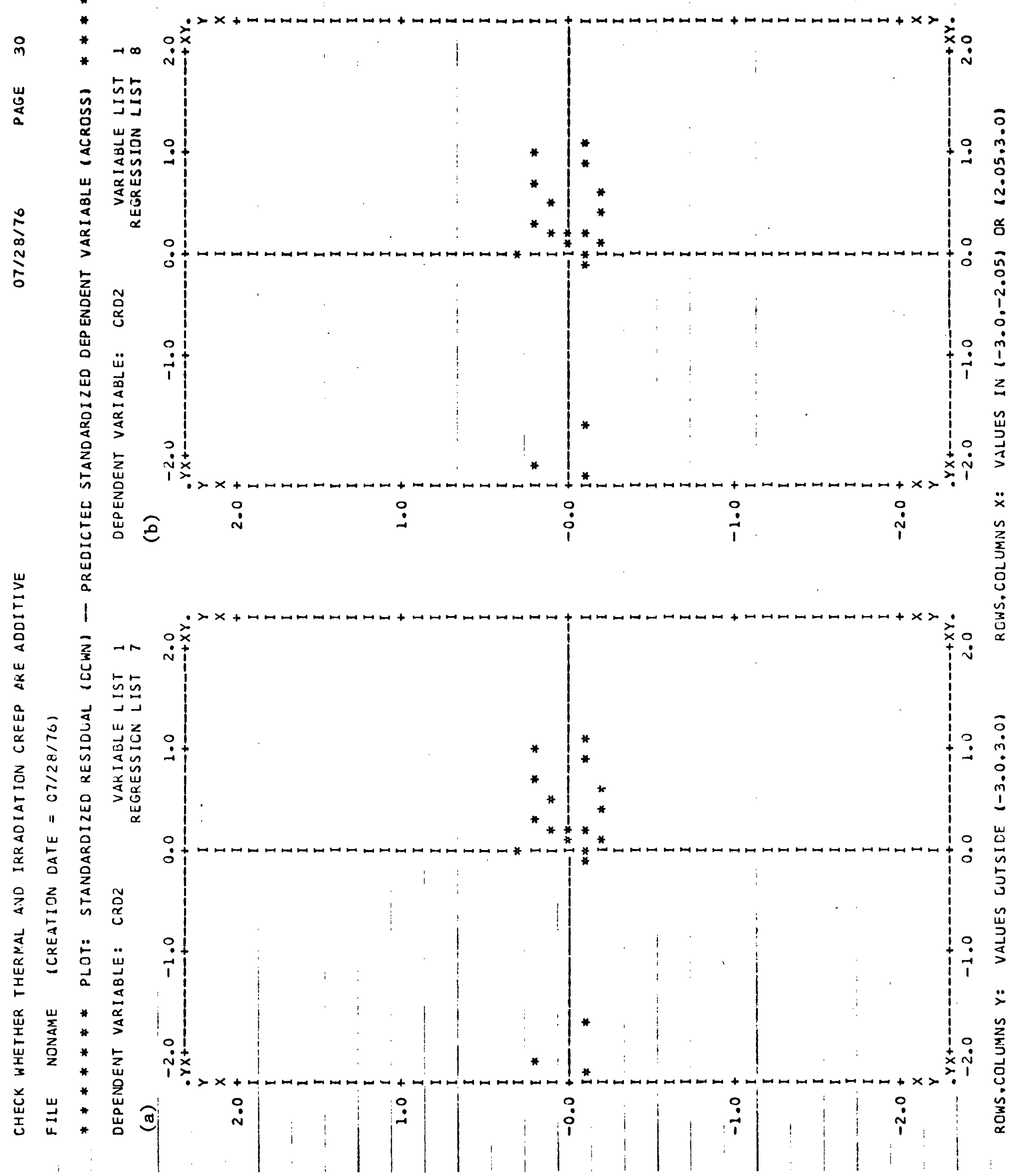


Figure A-13 Residual Plots (a), (b) for Regression Models (A-19) and (A-20) respectively



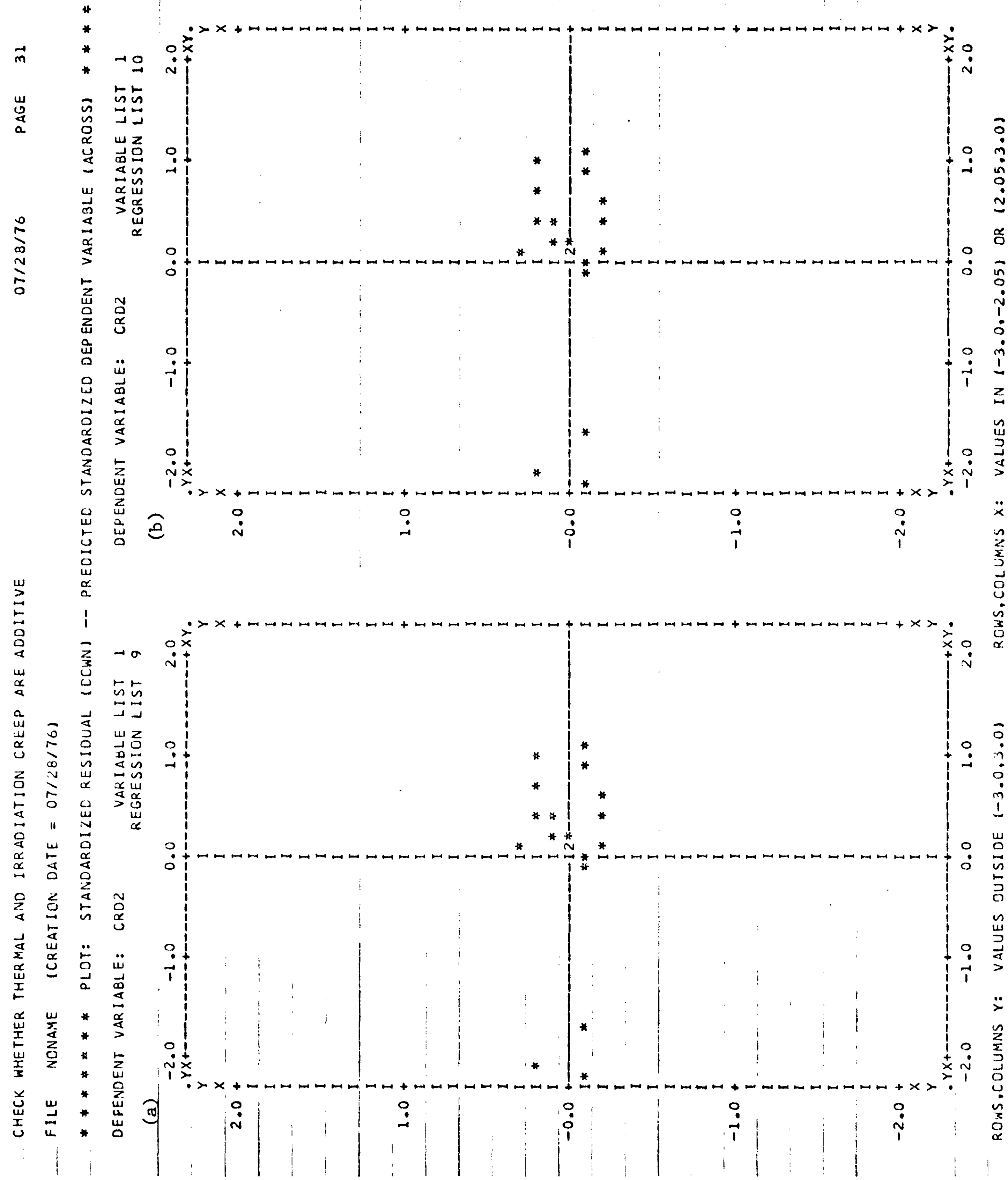


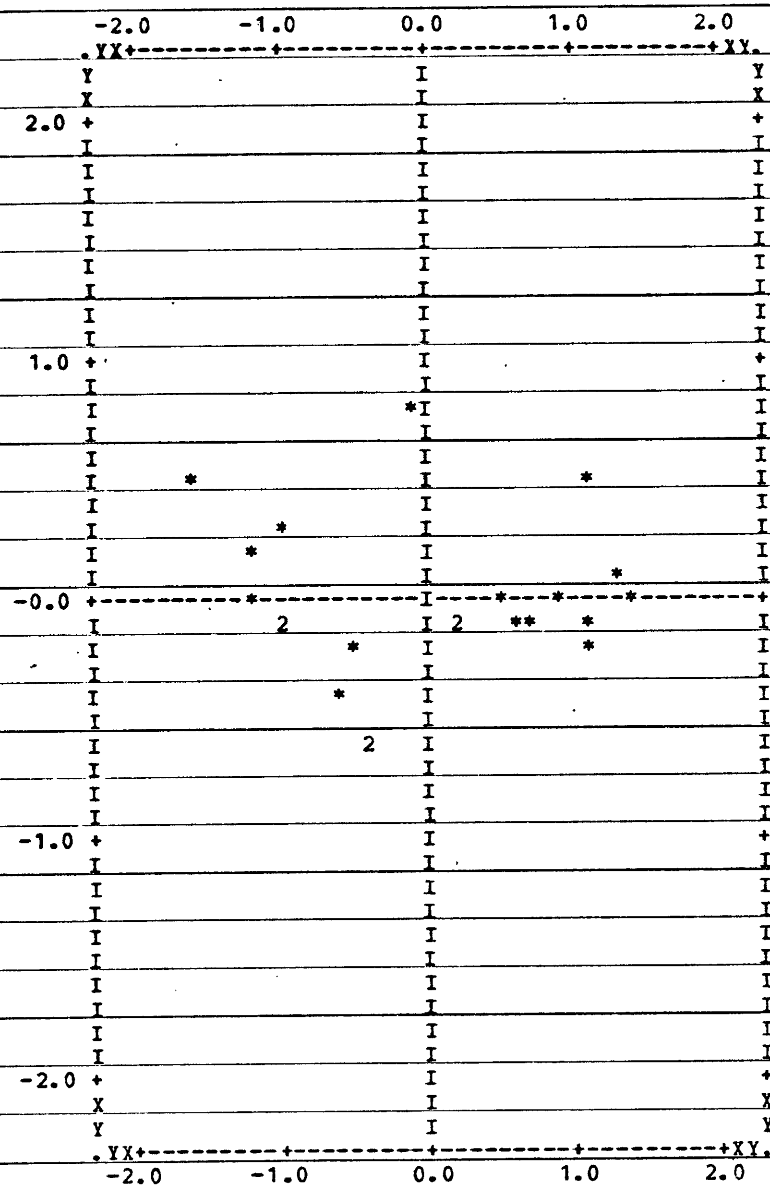
Figure A-14 Residual Plots (a), (b) for Regression Models (A-21) and (A-22) respectively

THERMAL CREEP ANALYSIS WITH CONTROL CREEP DATA 09/16/76 PAGE 19
ANALYSIS OF DATASET M5,I11,H14
FILE NONAME (CREATION DATE = 09/16/76)

* * * * * * * PLOT: STANDARDIZED RESIDUAL (DOWN) -- PREDICTED STANDARDIZED DEPENDENT VARIABLE (ACROSS) * * * * * * *

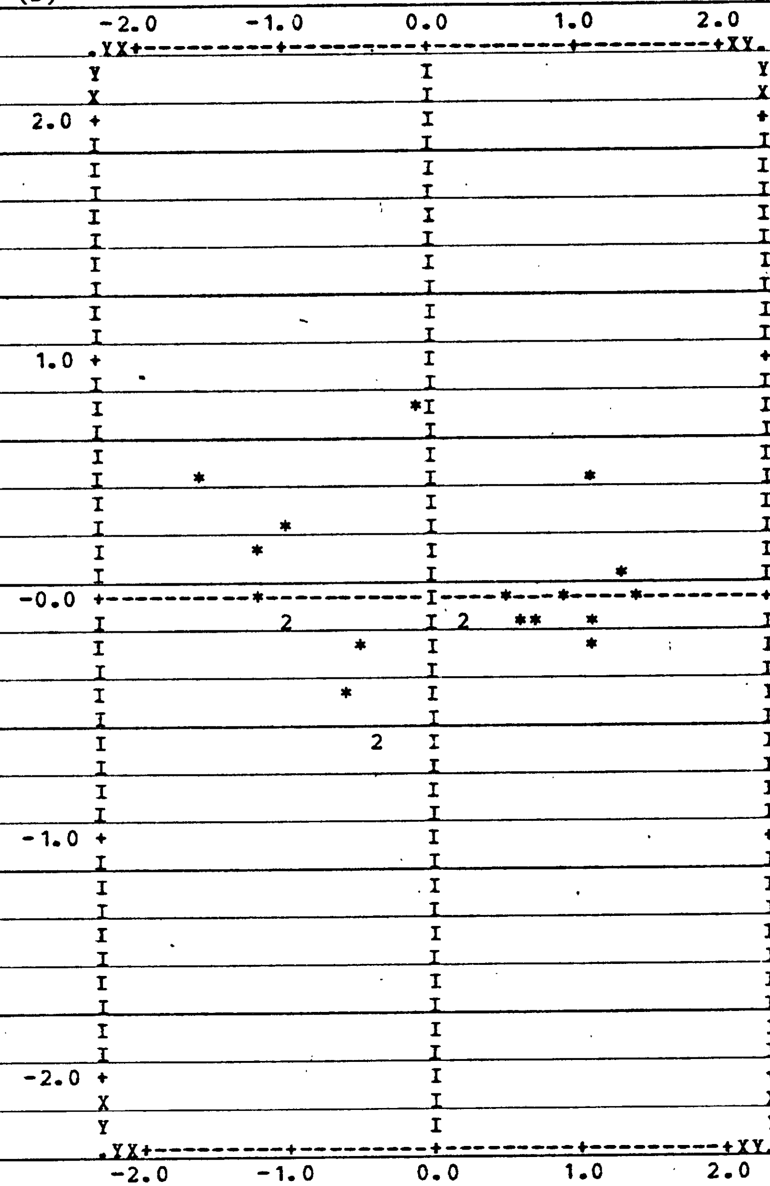
DEPENDENT VARIABLE: CCRL2 VARIABLE LIST 1
REGRESSION LIST 1

(a)



DEPENDENT VARIABLE: CCRL2 VARIABLE LIST 1
REGRESSION LIST 2

(b)



ROWS,COLUMNS Y: VALUES OUTSIDE (-3.0,3.0) ROWS,COLUMNS X: VALUES IN (-3.0,-2.05) OR (2.05,3.0)

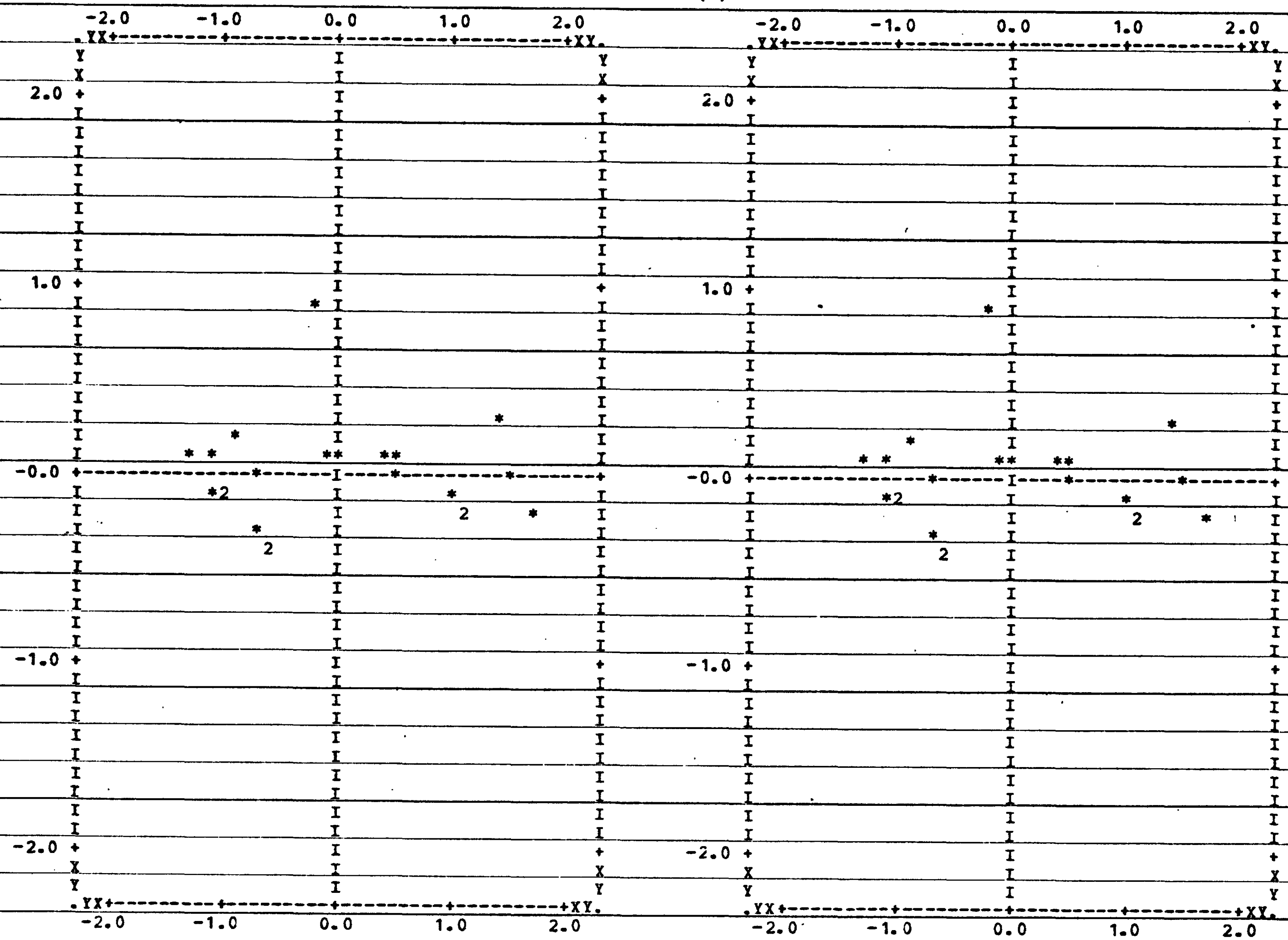
Figure A-15 Residual Plots (a), (b) for Regression Models (A-7) and (A-8) respectively

```
THERMAL CREEP ANALYSIS  WITH CONTROL CREEP DATA                              09/16/76        PAGE   20
ANALYSIS OF DATASET M5,I11,H14
FILE   NONAME   (CREATION DATE = 09/16/76)

* * * * * * *  PLOT:  STANDARDIZED RESIDUAL (DOWN) -- PREDICTED STANDARDIZED DEPENDENT VARIABLE (ACROSS)  * * * * * * *

DEPENDENT VARIABLE:  CCRL2        VARIABLE LIST  1          DEPENDENT VARIABLE:  CCRL2        VARIABLE LIST  1
                                  REGRESSION LIST  3                                          REGRESSION LIST  4
```

(a) (b)




```
ROWS,COLUMNS Y:  VALUES OUTSIDE (-3.0,3.0)        ROWS,COLUMNS X:  VALUES IN (-3.0,-2.05) OR (2.05,3.0)
```

Figure A-16 Residual Plots (a), (b) for Regression Models (A-9) and (A-10) respectively

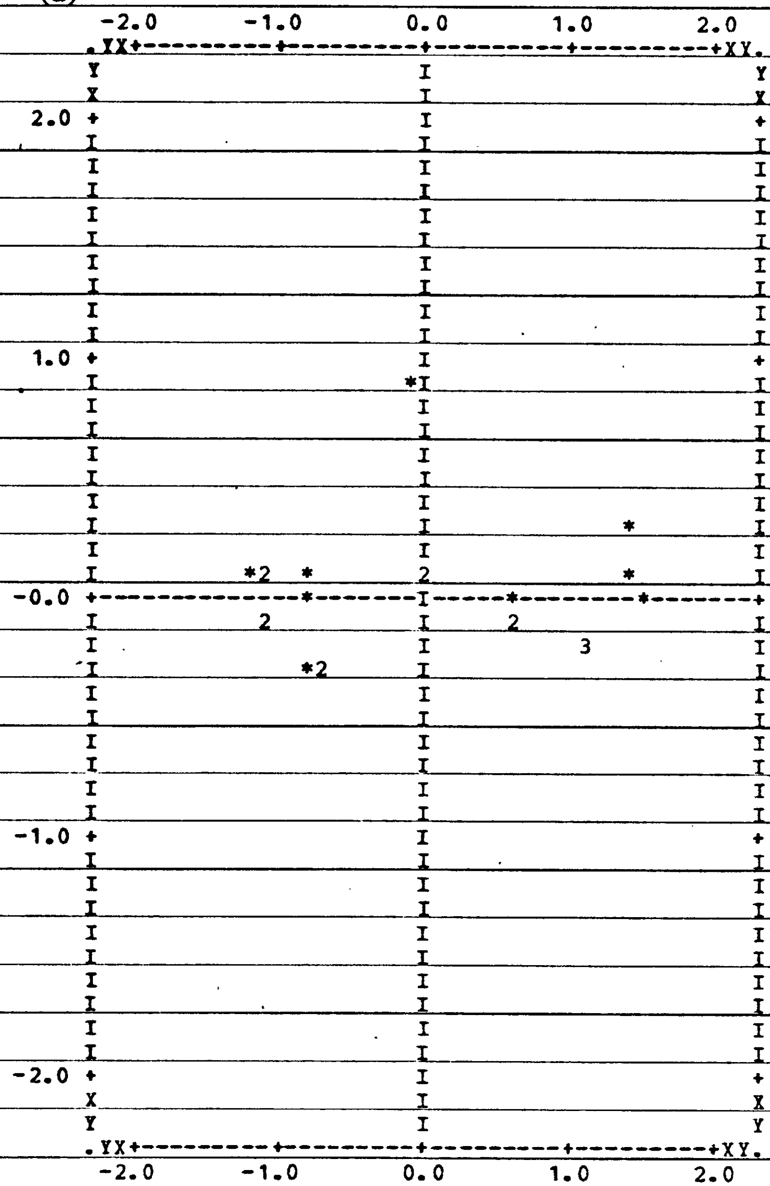
THERMAL CREEP ANALYSIS WITH CONTRCL CREEP LATA
ANALYSIS OF DATASET M5,I11,H14
FILE NONAME (CREATION DATE = 09/16/76)

09/16/76 PAGE 21

* * * * * * * PLOT: STANDARDIZED RESIDUAL (DOWN) -- PREDICTED STANDARDIZED DEPENDENT VARIABLE (ACROSS) * * * * * * *

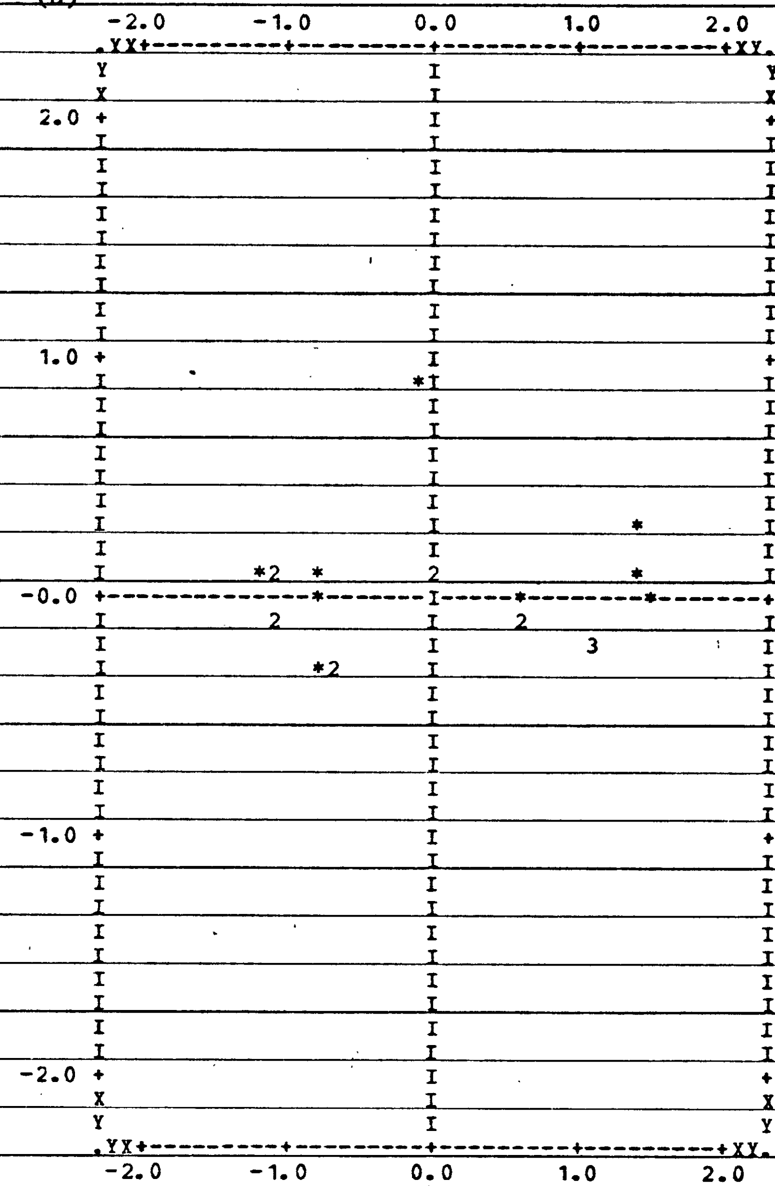
DEPENDENT VARIABLE: CCRL2 VARIABLE LIST 1
REGRESSION LIST 5

(a)



DEPENDENT VARIABLE: CCRL2 VARIABLE LIST 1
REGRESSION LIST 6

(b)



ROWS,COLUMNS Y: VALUES OUTSIDE (-3.0,3.0) ROWS,COLUMNS X: VALUES IN (-3.0,-2.05) OR (2.05,3.0)

Figure A-17 Residual Plots (a), (b) for Regression Models (A-11) and (A-12) respectively

2.4 Comparison of regression creep models:

Fig.A-18 to Fig.A-22 give the comparisons of creep models obtained from regressions. Five regression creep models are included. These are (10), (A-10), (A-18), the sum of (A-10), (A-18) and one based on the revised Ross-Ross and Hunt's model given in the previous report[1]. This last model has different estimated coeffcients because the revised creep data set was used in the analysis.

Notice that all except the thermal creep curves (A-10) are bounded by the 95% confidence interval derived from (10). The curves of total creep rate obtained as the sum of (A-10) and (A-18) to that of the irradiation creep rate (A-18) are often indistinguishable on these figures because the thermal creep contribution is negligible, i.e., at least two orders of magnitudes lower than the irradiation creep component based on the above studies. There are differences between the total creep rate and the one obtained from (10) in which no efforts have been made to divide the thermal and irradiation creep components and treat them separately, but the differences are slight.

It should be pointed out though that the numbers of data which we used in obtaining regression creep models for $\dot{\varepsilon}_{th}$ and $\dot{\varepsilon}_{irr}$ are different. Twenty-two data were used for $\dot{\varepsilon}_{th}$ whereas nineteen were used for $\dot{\varepsilon}_{irr}$. This inconsistency arises because in taking the difference between the minimum in-reactor creep rate and the minimum control creep rate, three of the differences come out to be negative which means that the control or thermal creep rates at those three points are larger than the corresponding in-reactor creep rates. The origins for such inconsistencies could either due to data recording mistakes, instrument errors, etc. but we have not been able to verify the exact causes. These three negative differences are removed because they cause problem in logarithmic operations. Such removals can be partially justified from the fact that in all figures, Fig.A-18 to Fig.A-22, there are only minor differences between the total creep rate and the one obtained directly from (10).

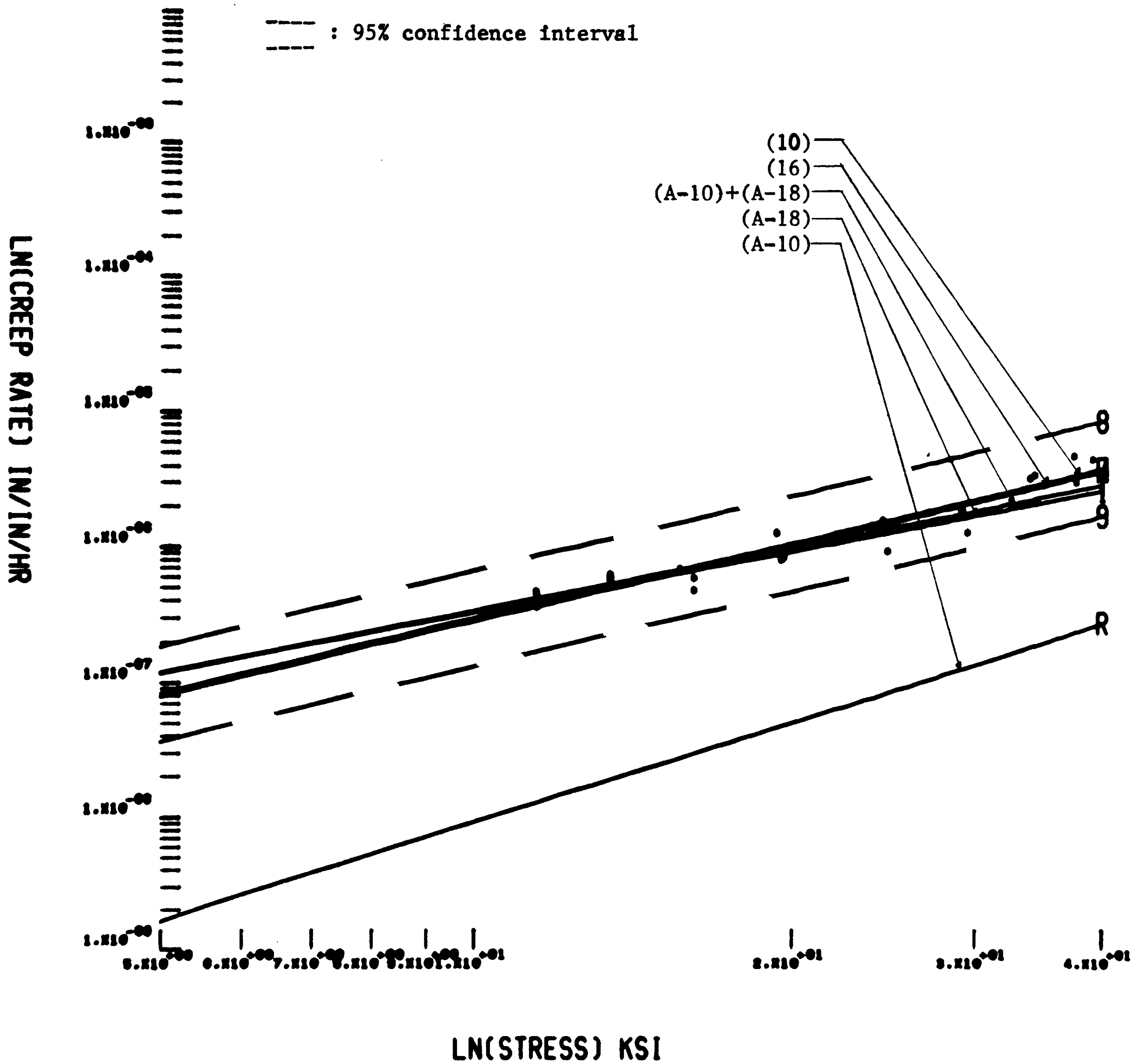
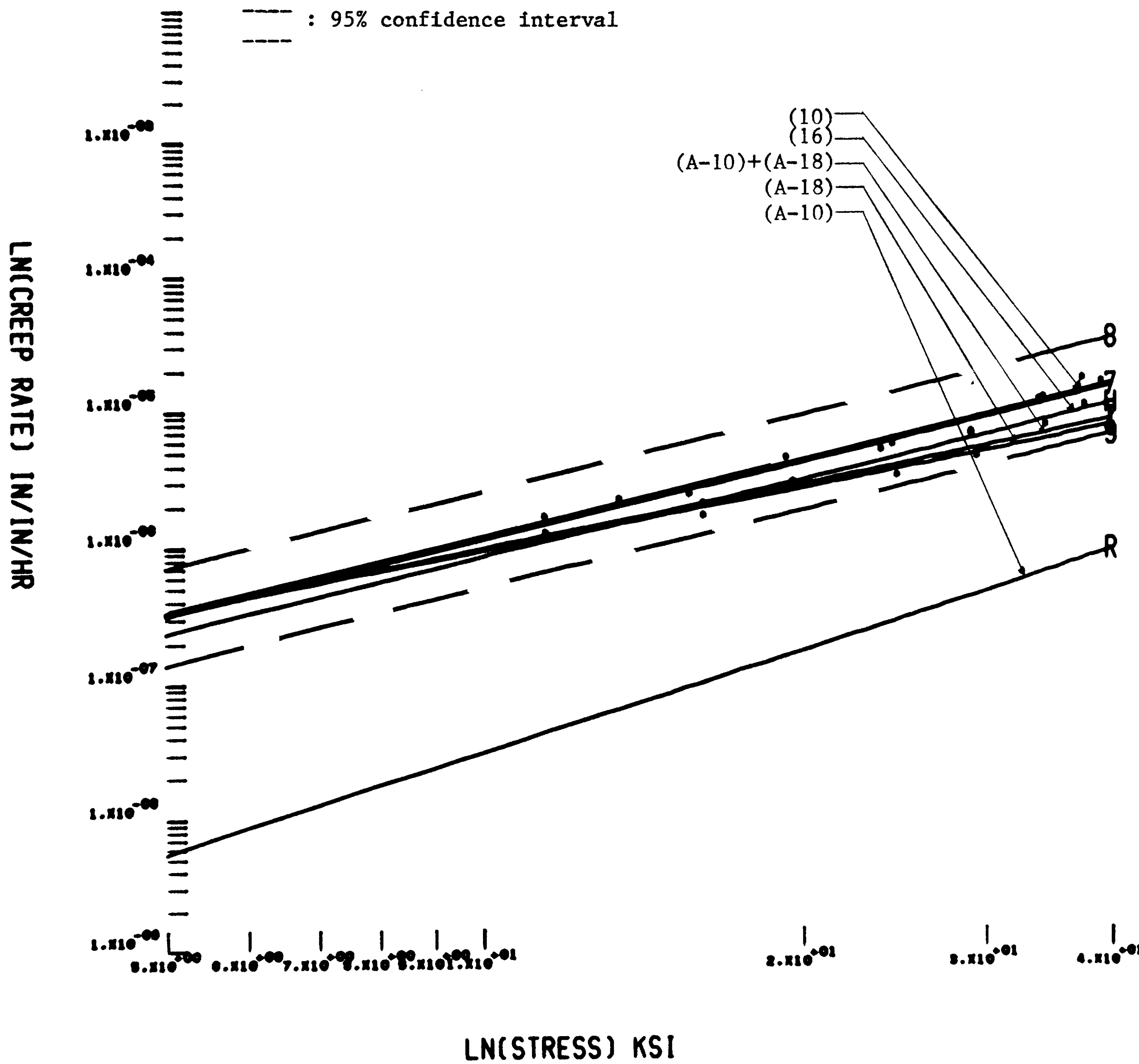


Figure A-18 Comparison of Regression Creep Laws at T=300°C, $\phi = 5\cdot10^{13} n/cm^2s$ (E>1 Mev), (Numbers associated with the curves are equation numbers and they can be found in Appendix 2)



1

Figure A-19 Comparison of Regression Creep Laws at T=350°C, $\phi = 5 \cdot 10^{13} n/cm^2 s$ (E>1 Mev)

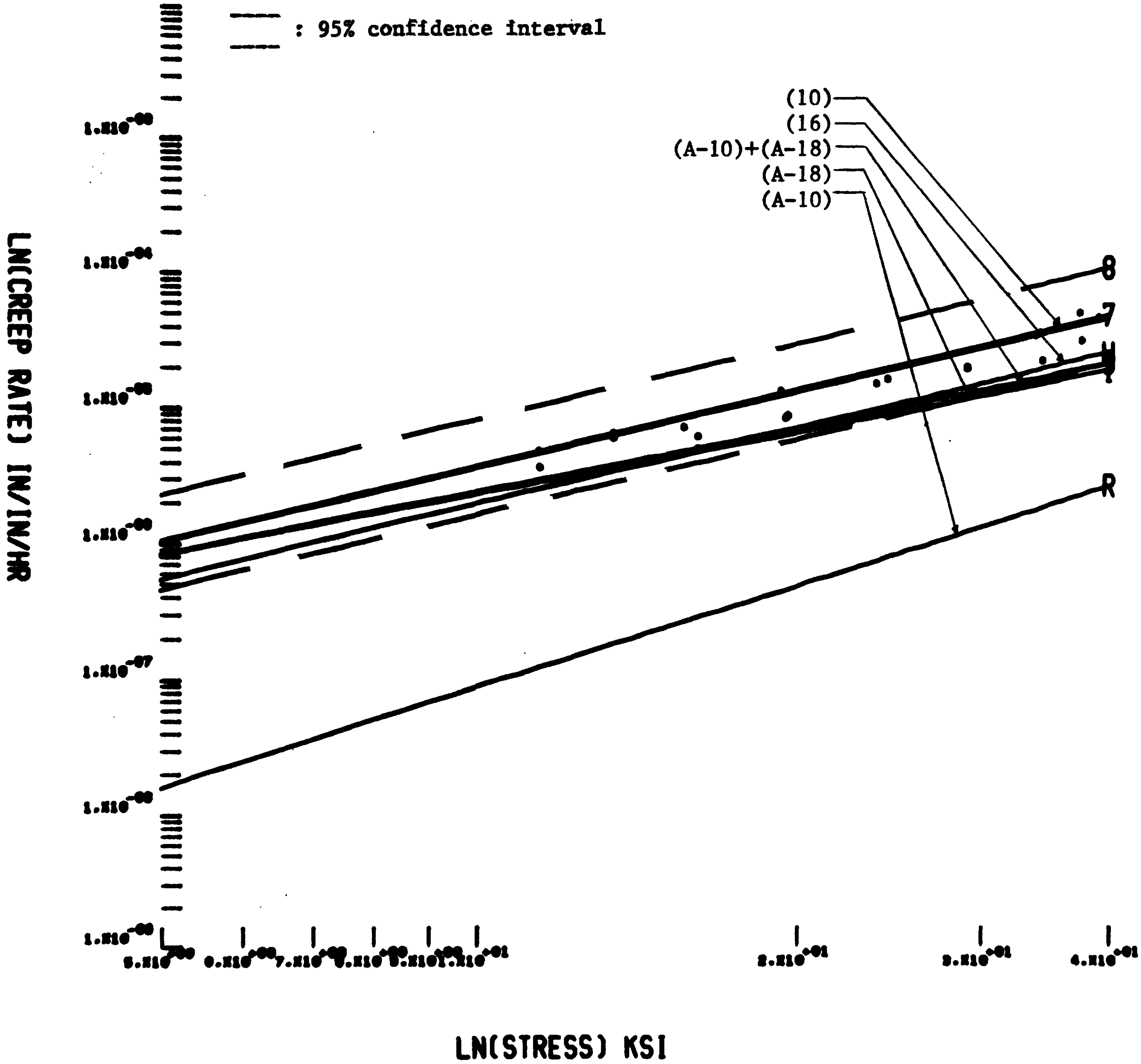


Figure A-20 Comparison of Regression Creep Laws at T=400°C, $\phi= 5\cdot 10^{13} n/cm^2 s$ (E>1 Mev)

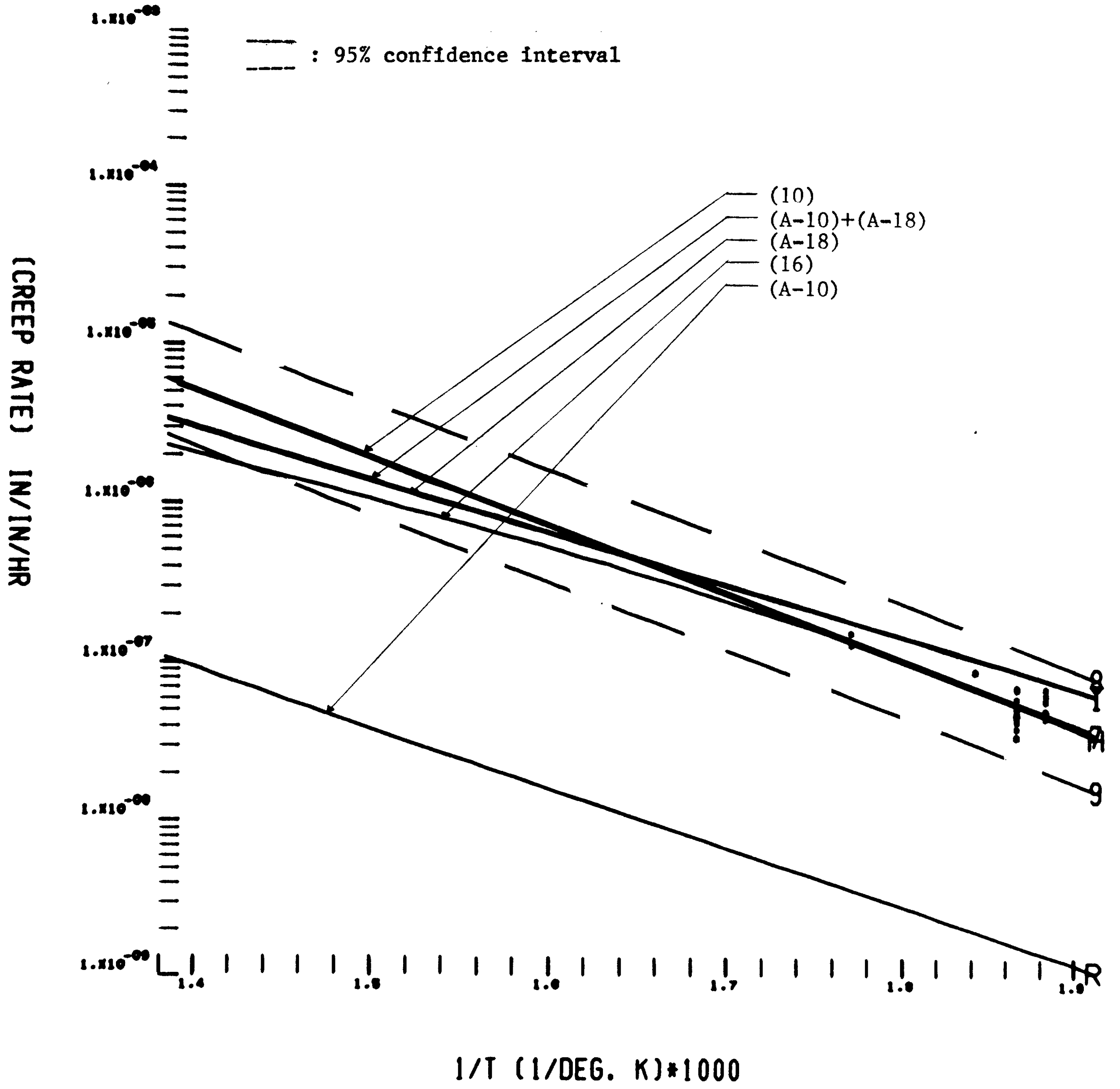


Figure A-21 Comparison of Regression Creep Laws at σ=7.5 ksi, ϕ= $5 \cdot 10^{13} n/cm^2 s$ (E>1 Mev)

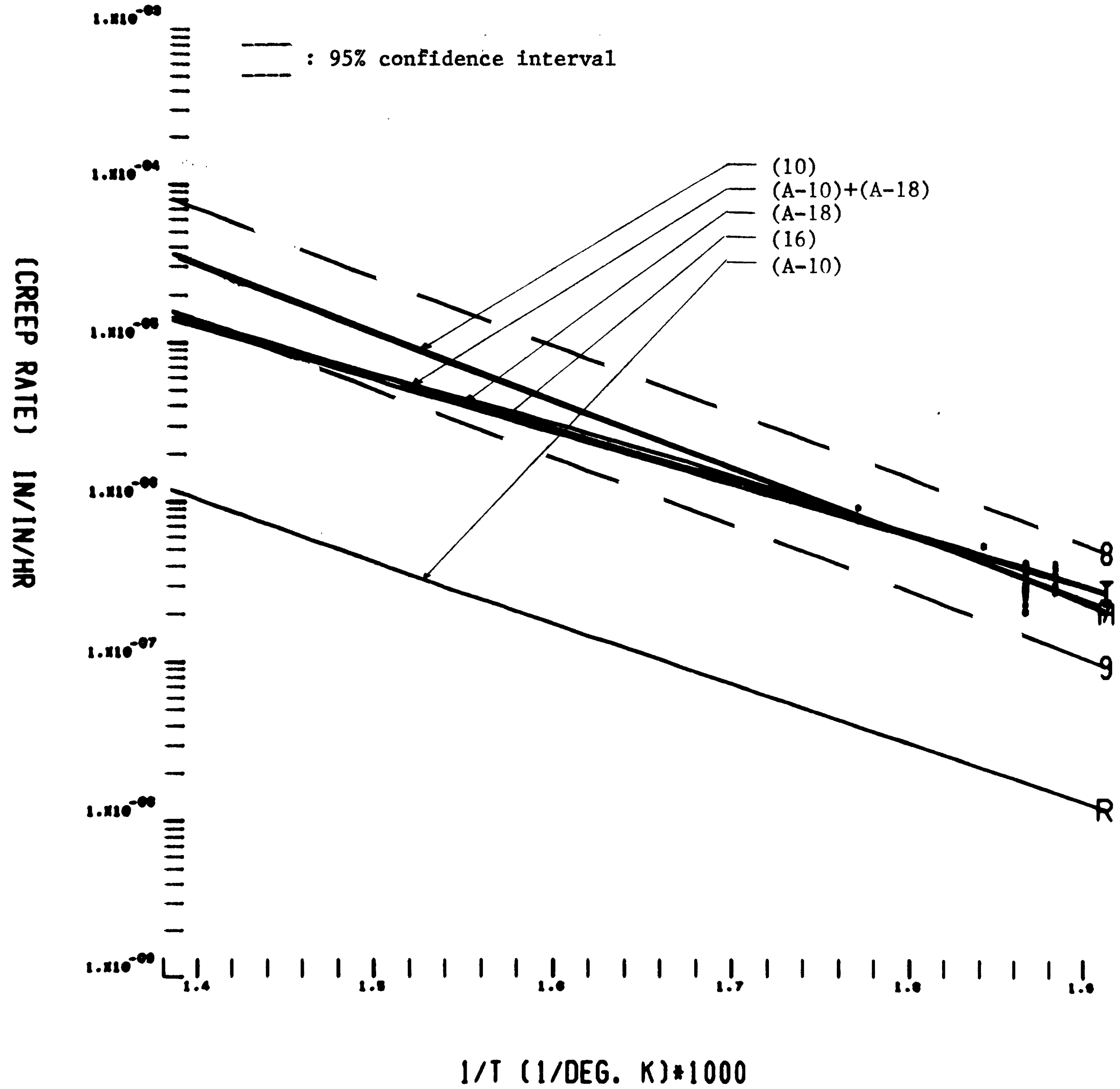


Figure A-22 Comparison of Regression Creep Laws at σ=20 ksi, $\phi = 5 \cdot 10^{13} n/cm^2 s$ (E>1 Mev)

Our tentative conclusion regarding to whether thermal and irradiation creep rates are additive is that at the particular test parameter ranges of σ, ϕ and T covered by the creep data set, they probably can be treated as additive provided the appropriate formula have been derived for each of the two separate components.

The above conclusion is based primarily on the regression statistics and the observations we have from Fig.A-18 to Fig.A-22. We should give our preference as to which final regression creep model we are going to recommend. Eq.(10) derived from the revised creep data set is our choice. The basis for such choice is made clearer when we examine the respective residual plots.

It is apparent from Fig.A-8(b), Fig.A-12(b) and Fig.A-16(b) that both the error band and residual structure are better for (10) than either (A-10) or (A-18). In the latter two cases, Fig.A-12(b) which is from irradiation creep analysis shows a clear residual clustering and Fig.A-16(b) which is from thermal creep analysis gives the largest residual scattering. Both of these features are of a less random nature than the residuals in Fig.A-8(b) which is obtained from (10).

2.5 Considerations in applying Zircaloy in-reactor creep constitutive equation:

At least two important considerations should be kept in mind in applying the Zircaloy in-reactor creep constitutive equations for LWR fuel clad:

(1) Caution must be taken in selecting the in-reactor creep models for LWR clad deformation evaluation. Comparatively speaking among the different creep models, underprediction of creep rate means that it is less conservative whereas overprediction means perhaps more conservative. For design purposes, it is probably safer to use a in-reactor creep equation that gives higher predicted creep rate. However, such equation should not be derived in the improper manner as we discussed in our last report and the cost of the likely over-conservatism is always at stake.

(2) It has been experimentally determined that Zircaloy exhibits a so called

"Strength Differential (SD)" effect in the yielding phenomenon[6,7,8]. For Zircaloy, the yield strength in compression is about ∿10% greater than the yield strength in tension. It is suspected that the SD effect may exist for creep as well. Currently, investigations are underway at MIT to study this possibility. We merely point it out because the SD effect certainly warrants attention in that during the early to mid-stage of a LWR fuel element life, the clad stresses are essentially compressive under the high external coolant pressure.

The creep equations that we have obtained are based on in-reactor creep tests in which Zircaloy-2 tubes are internally pressurized and therefore the hoop stress is tensile throughout the tests. This stress state does not correspond to the stress state of Zircaloy clad in service. However, if the same statement can be made that creep in compression is more difficult than creep in tension as is the SD effect for yielding, the use of creep equation derived from tensile creep data would be more conservative.

Lastly but by no means leastly, we would like to emphasize again that the users of these semi-empirical constitutive equations should always realize the inherent danger in extrapolations. While one can try his best to utilize the results from statistical data anlysis, there is no substitute for sound experiments.

2.6 Summary:

(1) Comparisons of current Zircaloy in-reactor creep models were made at several σ and T levels corresponding to the operating conditions of a in-service LWR Zircaloy clad. The results show that there are great departures among the model predicted creep rates especially at high stresses and high temperatures. The two additional creep models included in this addendum generally predict lower creep rates than most of the other models.

(2) Regression analyses were performed on the revised creep data set using the same six starting model equations as those in the previous report. Based on regression statistics, residual patterns and physical interpretation, Eq.(10) was selected as our recommended Zr-2 in-reactor creep constitutive equation.

(3) Both thermal and irradiation creep analyses were carried out on the minimum control and minimum in-reactor creep rates respectively from our revised creep data set. Although the two separate studies do satisfy the acceptance criteria for such treatments, we prefer Eq.(10) than the sum of (A-10) and (A-18) for reason of its better residual characteristics.

(4) The explicit formula for Eq.(10) is given as follows:

$$\dot{\varepsilon}_t = A\ (\phi/\phi_o)^m\ (\sigma/\mu(T))^n \exp(-Q/RT) \qquad (10)$$

where the units are

$\dot{\varepsilon}_t$: tangential creep strain rate, hr^{-1}

ϕ : fast neutron flux, n/cm^2s (E >1 Mev)

σ : ksi

T : ^oK

and

$$\phi_o = 0.05 \cdot 10^{13} \text{ n/cm}^2\text{s (E>1 Mev)}$$

$$A = 6218.47$$

$$m = 0.597$$

$$n = 1.827$$

$$Q = 17920.81 \text{ cal/mole}$$

$$\mu(\text{ksi}) = 4770 - 1.906 \cdot T(^oF)$$

The overall 95% confidence interval can be constructed by using $\pm \sqrt{M \cdot f}\ (SEE)_{\hat{y}} = \pm \sqrt{3 \cdot 3.05} \cdot 0.2685 = \pm 0.812$ and is given by

$$\exp(\ln \dot{\varepsilon}_t \pm 0.812)$$

References in the Addendum:

1. Yung Liu, Y., A.L. Bement, "A Regression Approach for Zircaloy-2 In-Reactor Creep Constitutive Equations", Part I of this Report.

2. Same as ref. (14) in Part I.

3. P.E. MacDonald (Ed.), MATPRO Materials Properties - Library Version 005, Aeroject Nuclear Company Report, RAM-93-75, June, 1975.

4. M.G. Andrews, et al., Light Water Reactor Fuel Rod Modeling Code Evaluation, Phase-II Topical Report, Appendix A: Standardized Properties and Models for Phase-II, April, 1976.

5. Same as ref. (6) in Part I.

6. G.E. Lucas, A.L. Bement, "Temperature Dependence of the Zircaloy-4 Strength Differential", J. of Nucl. Mtls., 58 (1975), No. 2, p. 163.

7. G.E. Lucas, The Strength Differential in Zirconium and Its Effect on Clad Creep Down Analysis, MS Thesis, Nucl. Eng. Dept., MIT, 1974.

8. G.E. Lucas, A.L. Bement, "The Effect of a Zirconium Strength Differential on Cladding Collapse Predictions", J. of Nucl. Mtls., 55 (1975), No. 3, p. 246.

Appendix 1

The Revised Zircaloy-2 In-Reactor Creep Data Set Used In Regression Analysis

ID*	T(^oK)	σ(ksi)	$\phi(10^{13})$ n/cm^{2}s (E>1 Mev)	$\dot{\varepsilon}(10^{-6})hr^{-1}$ min in-reactor creep rate	$\dot{\varepsilon}(10^{-6})hr^{-1}$ min control creep rate
39	536.000	16.200	2.900	0.140	0.010
41	536.000	19.700	2.900	0.200	0.010
43	536.000	24.800	2.900	0.220	0.027
45	536.000	29.600	2.900	0.300	0.041
47	536.000	34.600	2.900	0.500	0.058
49	536.000	37.800	2.900	0.700	0.095
51	536.000	16.200	0.050	0.010	0.010
52	536.000	19.600	0.050	0.017	0.010
53	536.000	24.500	0.050	0.033	0.027
54	536.000	29.200	0.050	0.039	0.041
55	536.000	34.400	0.050	0.071	0.058
56	536.000	39.200	0.050	0.092	0.095
14	531.000	15.700	2.560	0.130	0.010
15	531.000	19.400	2.560	0.240	0.010
16	531.000	23.900	2.560	0.270	0.048
17	531.000	29.200	2.560	0.360	0.039
18	531.000	34.000	2.560	0.610	0.056
19	531.000	37.600	2.560	0.880	0.116
107	543.000	11.500	2.500	0.127	0.0085
108	565.000	11.500	2.500	0.185	0.013
117	543.000	13.500	3.100	0.194	0.0085
118	565.000	13.500	3.100	0.338	0.013

* ID refers to the serial numbers in Table 4[(1)]. ID-107 to ID-118 are obtained by transforming the normalized Ross-Ross and Hunt's data serial T-10 and T-11 respectively to the original values.

Appendix 2

Summary of Current Zircaloy In-Reactor Creep Models And Their Data Bases

Eq. No*	Developer or Code Name	In-reactor Creep Model	Data References
(1)	Ross-Ross[5]** & Hunt	$\dot{\varepsilon}_h = 4\mathrm{x}10^{-24}\ \sigma_h\phi\ (T - 433)$	H-14
(2)	Watkins[6] & Wood	$\dot{\varepsilon} = 1.02\mathrm{x}10^{-11}\ \exp\ (-\frac{14000}{RT})\ \phi^{0.85}\ \sinh(1.15\mathrm{x}10^{-1}\sigma)$	I-14
(3)	BUCKLE[7] (Pankaskie)	$\dot{\varepsilon} = (1+\alpha K\ \exp(-Kt))\ B\phi^{0.85}\ \exp(-\frac{Q}{RT})\ \sinh\ (S\sigma)$ $\alpha = 900,\ B = 9.5\mathrm{x}10^{-13},\ S = 0.17,\ K = 6\mathrm{x}10^{-3}$ $Q = 16980$ for $T < T_{crit}$ $Q = 16980 - 76.2\ (T - T_{crit})$ for $T > T_{crit}$ $T_{crit} = 640 - \sigma$	H-1,K-6,I-11 I-14
(4)	Vender A[8]	Proprietary Information	H-1,I-11,I-14 M-5,M-7
(5)	Vender B[9]	Proprietary Information	H-1,E-1,I-11 I-14

* These equation numbers are the ones shown on all the figures of comparison of current creep laws.

** Superscripted numbers give the references for the respective creep models in the earlier report[1].

Units: σ(ksi), ϕ(E>1 Mev) in n/cm^2s, $T(^oK)$ for (1)-(4) and $T(^oR)$ for (5)

Eq. No.	Developer or Code Name	In-reactor Creep Model	Data References
A	MATPRO	$\dot{\varepsilon}_t = K\,\phi(\,\sigma + B\,e^{C\sigma}\,)\,\exp(-\,10{,}000/RT)\;t^{-0.5}$ T: ^oK, t: sec, ϕ : n/m^2s (E>1 Mev) σ: hoop stress, n/m^2; $\dot{\varepsilon}_t$: hoop creep strain rate, m/m/sec $K = 5.129\cdot10^{-29}$ $B = 7.252\cdot10^{2}$ $C = 4.967\cdot10^{-8}$	3
B	EPRI	$\dot{\varepsilon}_e = \{K_1 + 1.01\cdot10^{-19}\,\exp(-0.004\,t)\}\phi\,\sigma_e\,\exp(-8{,}000/RT)\,+$ $\{K_2\,\sigma_e^{(25.6-0.026\,T)}\,\exp(-\,138{,}000/RT)\}$ $\dot{\varepsilon}_e$: effective creep rate, hr^{-1} σ_e: effective stress, ksi(<40 ksi) t : hrs, ϕ: n/cm^2s (E>1 Mev), T: ^oK (<773^oK) For isotropic assumption : $K_1 = 2/3\,(1.36\cdot10^{-18})$ $K_2 = 2/3\,(7.0\cdot10^{-28})$	4