GENERAL ELECTRIC

FUEL SWELL AND RUPTURE MODEL

EXPERIMENTAL DATA REVIEW

AND

SENSITIVITY STUDIES

May 12, 1981

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1.0 INTRODUCTION

This report was prepared in response to the NRC request (Reference 1) to (a) provide supplemental calculations using the NUREG-0630 model and, (b) to revise the cladding models of both CHASTE-05 and CHASTE-06 to conform to recent experimental data. It provides 1) a discussion of the experimental data used to develop the General Electric and NUREG-0630 cladding swelling and rupture model, 2) the results of sensitivity studies performed using the General Electric heatup model (CHASTE) which show the impact of the NUREG-0630 model on calculated peak cladding temperatures.

It is shown that the NUREG-0630 perforation strain versus temperature curve is not applicable to the BWR due to non-prototypicality of the experimental conditions used to generate the curve. Even so, substitution of a bounding NUREG-0630 curve into the current GE ECCS analysis produces only a negligible effect on the peak clad temperature (PCT). Therefore, it is General Electric's position that the current strain model is valid for the BWR and should continue to be used for all ECCS analyses.

This report shows that the GE hoop stress vs. rupture temperature curve is more valid than the corresponding NUREG-0630 curve at temperatures above 1600°F and that the NUREG-0630 curve is more representative of existing data at temperatures below 1600°F. A sensitivity study presented using a combination of the two curves (adjusted curve) resulted in a PCT impact of $\leq$ 10°F. Even though this PCT impact is small, GE proposes to revise the current model to incorporate the adjusted curve and implement the change at the same time the complete LOCA model improvement package is implemented.

2.0 EXPERIEMENTAL DATA

2.1 Cladding Hoop Stress Versus Perforation Temperature

The NRC staff has expressed a concern (Reference 2) that the General Electric Hoop Stress Versus Perforation Temperature curve is non-conservative for temperatures above ~1000°C (1832°F). The staff is using as a basis for this concern the data and curves contained in NUREG-0630 (Reference 3) and are requesting that supplemental calculations be performed with the most conservative curve (0°F/sec) from NUREG-0630.

General Electric does not believe that this concern is justified and in this section provides the basis for the position that the GE curve should be used for any analysis of GE BWR fuel.

Figure 1 shows the General Electric perforation curve together with the corresponding experimental data base for cladding heatup rates of ≤10°F/sec. (10°F/sec is considered a conservative upper bound heatup rate for GE BWR's.) The figure shows that the GE curve is a good representation of the data. Figure 2 shows the NUREG-0630 correlation for 0°F/sec and the GE curve together with NUREG-0630 data for heatup rates of less than 10°F/sec.

The following points are apparent from Figures 1 and 2:

(a) The NUREG-0630 curve contains no data for hoop stresses below ~3500 psi and temperatures above ~ 1600°F.

(b) In the temperature range of concern to the staff (>1832°F), a considerable amount of data typical to the BWR exists to support the GE curve.

Furthermore, General Electric has examined <u>all</u> data in NUREG-0630 (irrespective of heatup rate) with perforation temperatures above 1832°F (1000°C). These data have been plotted in Figure 3. This figure indicates that the GE curve is conservative with respect to these data.

In addition, the recent data generated by KfK (Reference 5) have been examined with respect to the General Electric model. These data, which are shown in Figure 4 indicates that the GE model is conservative with respect to the data for temperatures above ~1600°F. Figures 2 and 4, however, indicate that the GE design curve may be non-conservative with respect to the data for temperatures below ~1600°F.

General Electric agrees with the NUREG-0630 data presented in this temperature range. However, the overall effect of revising the GE curve in this range is <10°F on the PCT. Figure 5 shows the data from Figures 2 and 4 for temperatures below ~1600°F together with the GE data base and adjusted curve.

Figure 6 shows the adjusted GE curve together with data generated by ANL (Reference 4) which is not included in NUREG-0630. These data were taken under conditions not prototypical of a BWR (direct heating, uniform temperature profile, etc.) which are known to produce larger values of circumferential strain, from a hoop stress versus temperature standpoint. The adjusted curve is an accurate representation of these data also.

To summarize, the NUREG-0630 0°F/sec curve is not applicable to the BWR above ~1600°F, whereas the General Electric curve is well qualified for temperatures in this range. The General Electric correlation is however, non-conservative with respect to the NUREG-0630 data below 1600°F.

General Electric believes that the adjusted GE hoop stress versus perforation temperature curve (Figure 5) is an accurate representation of BWR fuel behavior for LOCA analysis and that the replacement of this curve with the corresponding 0°F/sec NUREG-0630 is not appropriate.

2.2 Circumferential Strain Versus Temperature

The NRC staff is also requesting (Reference 2) that supplemental calculations be performed with a combination of the slow and fast heat-up rate circumferential strain versus temperature curves from NUREG-0630. This combination of the slow and fast ramps (shown in Figure 7) is biased to produce the maximum strain at any given temperature.

General Electric does not believe that the NUREG-0630 strain-temperature curves are sufficiently qualified to warrant application to GE BWR fuel. Furthermore, the combination of the slow and fast ramp curves represents a further departure from applicability to BWR fuel. The following paragraphs provide the technical basis for this position.

There is convincing evidence available (including the data contained in NUREG-0630) that heat-up rate has a pronounced effect on the value of cladding circumferential strain at perforation. Hence the development in NUREG-0630 of two separate correlations for strain versus perforation temperature, one for fast heat-up rates and one for slow heat-up rates, is considered appropriate although simplified. The application of data obtained under fast heat-up rates to the BWR (which has a maximum heatup rate of <10°F/sec) is therefore not considered technically justified.

Figure 8 shows the General Electric perforation strain-temperature model together with the founding data base for heatup rates of ≤ 10°F/second. This figure shows that the GE model conservatively bounds greater than 90% of the data. Figure 9 shows the GE model compared to the slow heatup correlation from NUREG-0630 together with the NUREG-0630 data for heatup rates of ≤10°F/sec. It is apparent from this figure that the NUREG-0630 correlation is unqualified for temperatures above ~1600°F. Furthermore, General Electric also questions the criteria used to select the data from which the curve has been derived. In NUREG-0630, it is stated that most of the data falling below this curve were discounted as they were from tests with features known to reduce perforation strain.

i.e., non-uniform temperature profiles, corrosion fission products and cold shrouds. However, all these features would be present in a BWR during a LOCA. For example, a large number of BWR rods can freely radiate to a cold surface (fuel channel or water rods) during a LOCA thus establishing significant temperature variations. Furthermore, significant axial temperature variations, also known to reduce cladding strain (Reference 7), occur due to the stochastic stacking and tilting of the fuel pellets within the fuel column. Therefore, as the majority of the data used must have been obtained under conditions (heated shroud, uniform temperature) which are not prototypical of the BWR, the applicability of any correlation derived from this data is questionable.

In addition to the NUREG-0630 data, the staff recently supplied GE with additional circumferential strain data (Reference 6). This data is shown in Figure 10. In this figure, the ORNL data with heated shroud displays considerably higher circumferential strain than the data taken with the cold shroud; i.e., the 5°C/sec hot shroud data at ~780°C lies between ~95 and 110% strain while the cold shroud data is less than ~30%. It is apparent therefore that to obtain meaningful results, which are applicable to the BWR, care must be taken to establish test conditions that ensure prototypicality. Note that the GE perforation strain temperature model is derived from simulated LOCA tests on full scale BWR fuel bundles, thereby imposing the prototypicality criteria. The GE strain temperature model is therefore considered more appropriate for the analysis of GE BWR fuel than the NUREG-0630 curves.

To summarize, the General Electric perforation strain curve conservatively bounds the circumferential strain data for slow heat-up rates at temperatures above 925°C (1700°F). In the alpha phase region, the strain data has been shown to be extremely sensitive to test conditions with the majority of the data contained in NUREG-0630 considered inapplicable to the BWR. General Electric believes that the GE perforation strain temperature curve is applicable to GE BWR fuel, due to the prototypicality of its founding data base and should be used in GE BWR LOCA analyses for the prediction of perforation strain.

3.0 SENSITIVITY STUDIES

A number of sensitivity studies have been performed to evaluate the effect of the NUREG-0630 cladding swelling and rupture model on CHASTE heatup calculations. They show that the peak cladding temperatures (PCTs) calculated with CHASTE have a small sensitivity to various parameters of the cladding swelling and rupture model.

The studies were performed for plants with 7x7 and prepressurized 8x8 - 2 water rod fuel at high exposures to maximize the number of perforations and hence any sensitivity of the calculated PCT. The plants selected had long reflooding times and short blowdown periods. This then results in a longer period over which the rods are calculated to be perforated and hence a greater sensitivity to changes in the swelling and rupture model. Calculations were also performed for plants with shorter reflooding times which are typical of most BWRs.

Overall model sensitivity studies were performed as follows:

a) Perforation stress curve for 0°C/second heatup rate below ~1600°F and GE curve above 1600°F (adjusted curve from Section 2.1);

b) Peak strain of 80% below a stress of 1500 psi, peak strain of 90% above 1500 psi;

c) Swelling initiation criteria and strain rate from GE model described in Section I.B.2.5 of Reference 8.

The bounding strain assumption (item b) was made because the CHASTE code does not accept a temperature dependent rupture strain curve. The GE perforation stress curve was used in the high temperature range (T > 1600°F) because it provides a better fit to the available perforation stress data than the NUREG-0630 curve in the high temperature region (see section 2.0 for a detailed discussion on experimental data).

Additional calculations were performed with the NUREG-0630 perforation stress curve for 0°C/second heatup rate over the entire temperature range. This curve bounds the 1 to 3°C/second heatup rate typical of BWR fuel during the time when perforations occur.

In addition to the overall model comparisons, sensitivity studies were also performed on individual components of the model. These studies are discussed in section 3.2 and include:

1. Variation of cladding strain at perforation;
2. Variation of perforation stress versus temperature curve;
3. Variation of swelling initiation criteria.

3.1 Overall Model Sensitivity

The purpose of this study was to determine the peak cladding tenperature sensitivity to the NUREG-0630 swelling and rupture model. The NUREG-0630 model was approximated in CHASTE using the adjusted stress curve and bounding strain values which were discussed earlier. The GE swelling initiation criteria (swelling begins 200°F before perforation temperature is reached) was used for all cases.

The PCT sensitivity for 7x7 fuel was found to be ±5°F for all cases in which perforations occurred. For 8x8 fuel the PCT sensitivity depends on how fast reflooding of the high power elevation occurs following a LOCA. If reflooding occurs in ~220 seconds or less no perforations are calculated to occur and the PCT impact is 0°F. For BWRs which take more than 220 seconds to reflood the PCT impact was found to be small (±5°F) for prepressurized 8x8 - 2 water rod fuel. For 8x8 fuel designs other then prepressurized 8x8 - 2 water rod fuel, no perforations are calculated to occur.

To determine the maximum possible impact, bounding calculations were performed using the NUREG-0630 0°C/second heatup rate stress curve for all temperatures. In most cases the results obtained were the same as described above. For prepressurized 8x8 - 2 water rod fuel at early exposures the NUREG-0630 model can result in a PCT increase of 10 to 50°F if it results in a large number of perforations at high temperatures. However, this result is not considered meaningful as it is due to the anomalously low perforation stress at high temperature predicted by the NUREG-0630 model that is not supported by the available experimental data.

3.2 Individual Model Component Sensitivity Studies

3.2.1 Variation of Cladding Strain at Perforation

The purpose of this study was to determine the effect of cladding strain at perforation on calculated PCTs. The GE and bounding NUREG-0630 rupture strain curves (Figure 11) were used for the comparison. The results show a small (0 to 5°F) PCT decrease with bounding NUREG-0630 strains. This is because even though individual rod temperatures are affected (by as much as 20°F just after a rod perforates during the transient), the temperature of all the rods in the bundle tends to equalize as a result of redistribution of energy by radiation heat transfer. Consequently, the overall effect on PCT is small. The studies show that as the strain is increased on an individual rod its temperature decreases, because for larger strains there is a larger area for heat transfer. For smaller strains the temperatures are higher as the area for heat transfer is smaller.

The conclusion from this study is that the cladding temperature of perforated rods is relatively insensitive (<10°F, 15 seconds after perforation) and the PCT is almost completely insensitive to the perforation strains. Hence, continued use of the General Electric strain values is considered appropriate.

3.2.2 Variation of Perforation Stress Versus Temperature Curve

The purpose of this study was to determine the effect of changing the perforation stress versus temperature curve only. Three different stress curves were used: 1) the GE curve (Figure 2), 2) the adjusted stress curve (Figure 5), and 3) the NUREG-0630 curve (Figure 2) for all temperatures.

Most cases analyzed had about the same number of perforations for each perforation stress curve and the calculated PCT change was ±10°F. For 7x7 fuel the PCT sensitivity was smaller (±5°F).

Calculations using the NUREG-0630 0°C/second heatup curve for all temperatures yielded a higher PCT by about 50°F when a large number of perforations were calculated to occur late in the transient. As discussed earlier, this sensitivity result is not considered meaningful as it results from the use of unsupported values of perforation stress. Cases like this were limited to the early exposure range for prepressurized 8x8 - 2 water rod fuel only.

One additional study was performed using the 10°C/second heatup rate curve from NUREG-0630. It resulted in a PCT decrease of up to 2°F over use of the 0°C/second curve.

3.2.3 Variation of Swelling Initiation Criteria

CHASTE calculates plastic swelling on rods for all temperatures above a certain temperature. This temperature is nominally set at 200°F below the perforation temperature. Calculations were done assuming that plastic swelling starts at 0°F, 200°F, and 400°F below the perforation temperature. The results show that for the case of 0°F, the PCT increased by up to 6°F, and for the 400°F case the PCT change was ±5°F relative to the 200°F nominal case. The effect on PCT was small (<10°F), and the effect on individual rod temperatures was also small (<[illegible]°F), and hence it can be concluded that the use of 200°F is still appropriate.

4.0 SUMMARY

This report has presented sensitivity studies and a review of the data used to support the GE and NUREG-0630 cladding swelling and rupture model. These models differ in two areas (perforation stress vs. temperature and perforation strain vs. temperature) which are discussed separately below.

A review of data to support the perforation stress versus temperature curves shows that both models agree well with experimental data in certain temperature ranges. The NUREG-0630 perforation stress curve more closely matches experiemental data at low temperatures (T <1600°F) while the GE curve agrees better with the data at higher temperatures (T >1800°F). In the intermediate temperature range both perforation stress curves are similar and provide a good fit to the experimental data. Sensitivity studies performed with the GE model and with the GE perforation stress curve adjusted in the low temperature range show a small peak cladding temperature sensitivity (±10°F).

A review of the cirumferential strain data shows that the General Electric design curve conservatively bounds the data for slow heatup rates above 925°C (1700°F). In the alpha phase region, the strain data has been shown to be extremely sensitive to test conditions with the majority of the data contained in NUREG-0630 considered inapplicable to the BWR. General Electric believes that the GE perforation strain temperature curve is applicable to GE BWR fuel due to the prototypicality of its founding data base. In addition, sensitivity studies performed using a strain curve which bounds the NUREG-0630 curve show a small (0 to 5°F) PCT decrease over the current GE model.

5.0 CONCLUSIONS

1) The GE hoop stress versus rupture temperature curve is more valid than the NUREG-0630 curve for the BWR at temperatures above 1600°F. However, the NUREG-0630 curve is more representative of existing data for temperatures less than 1600°F. Sensitivity studies performed using a combination of the two curves (adjusted curve) resulted in a PCT impact of $\leq$ 10°F. Even though this PCT impact is small, GE proposes to revise the current model to incorporate the adjusted hoop stress curve. Implementation of this curve into the ECCS analysis will be coincident with implementation of the complete LOCA model improvement package.

2) The NUREG-0630 perforation strain curves are not considered applicable to GE BWR fuel due to non-prototypicality of the experimental conditions. The small PCT sensitivity shown when a bounding NUREG-0630 burst strain vs. temperature correlation is substituted into the ECCS analysis justifies the continued use of the current GE strain curve.

3) This report satisfies regulatory position 4(a) of Reference 1 requiring supplemental calculations and should be made available for referencing on individual plant FSAR submittals.

4) Revisions to the cladding models of both CHASTE-05 and CHASTE-06 (regulatory position 4(b) of Reference 1) are not required, although a revision to the GE burst curve will be made as identified in (1) above.

REFERENCES

1. Letter, R. L. Tedesco (NRC) to G. G. Sherwood (GE), "Acceptance for Referencing of Topical Report NEDE-20566P, NEDO-20566-1 Revision 1 and NEDE-20566-4 Revision 4," dated February 4, 1981.

2. Telecon: D. K. Dennison, D. A. Hamon, A. S. Rao and R. J. Williams to R. O. Meyer (NRC) and D. A. Powers (NRC) on Fuel Swelling and Rupture Issues, 3/19/81.

3. "Cladding, Swelling and Rupture Models for LOCA Analysis," NUREG-0630.

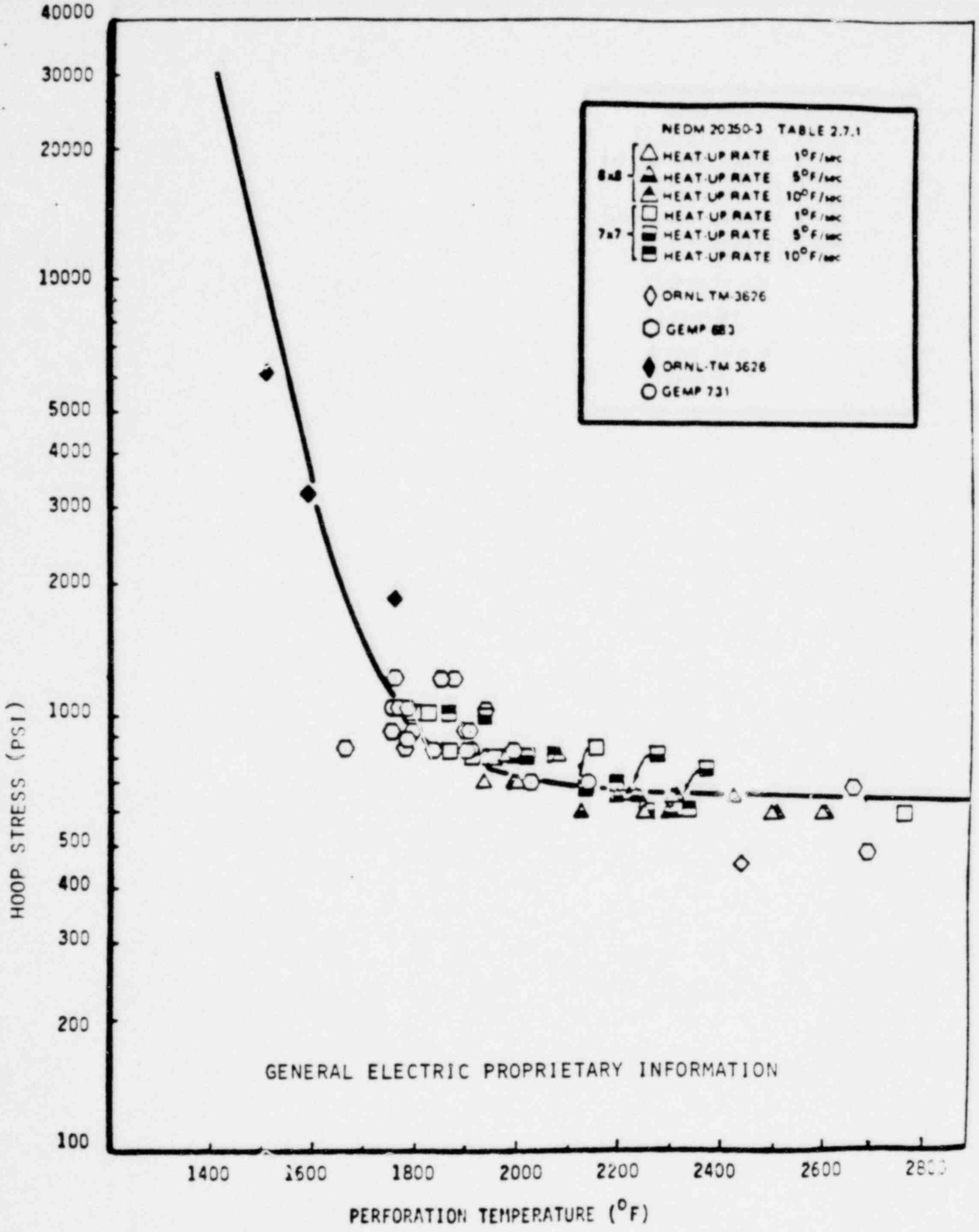
4. "Deformation Characteristics of Zircaloy Cladding in Vacuum and Steam Under Transient Heating Conditions," NUREG/CR-0344, July 1978.

5. "Burst Criteria of Zircaloy Fuel Claddings in a LOCA," by F. J. Erbacher, et.al. Fifth International Conference on Zirconium in the Nuclear Industry, Boston, August 1980.

6. Telecopy of LOCA data from D. Powers (NRC) to D. K. Dennison (GE), 2/10/81.

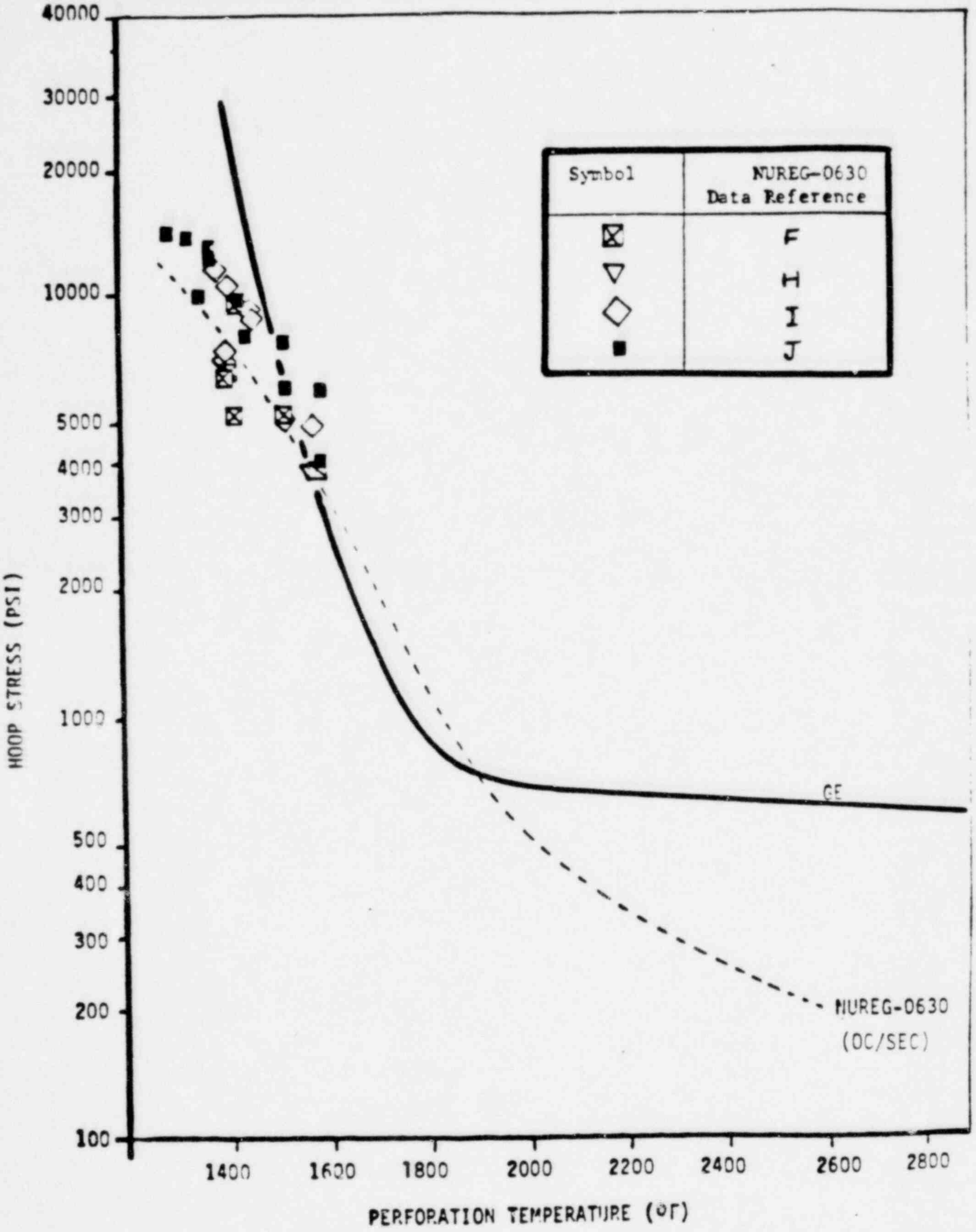
7. Letter, T. F. Kassner (ANL) to K. Kniel (NRC), "Review of CPB Report on ECCS Cladding Models," 1/3/80.

8. General Electric Company Analytical Model for Loss-of-Coolant Analysis in Accordance with 10CFR50 Appendix K, Volume 1, NEDE-20566P, November 1975.



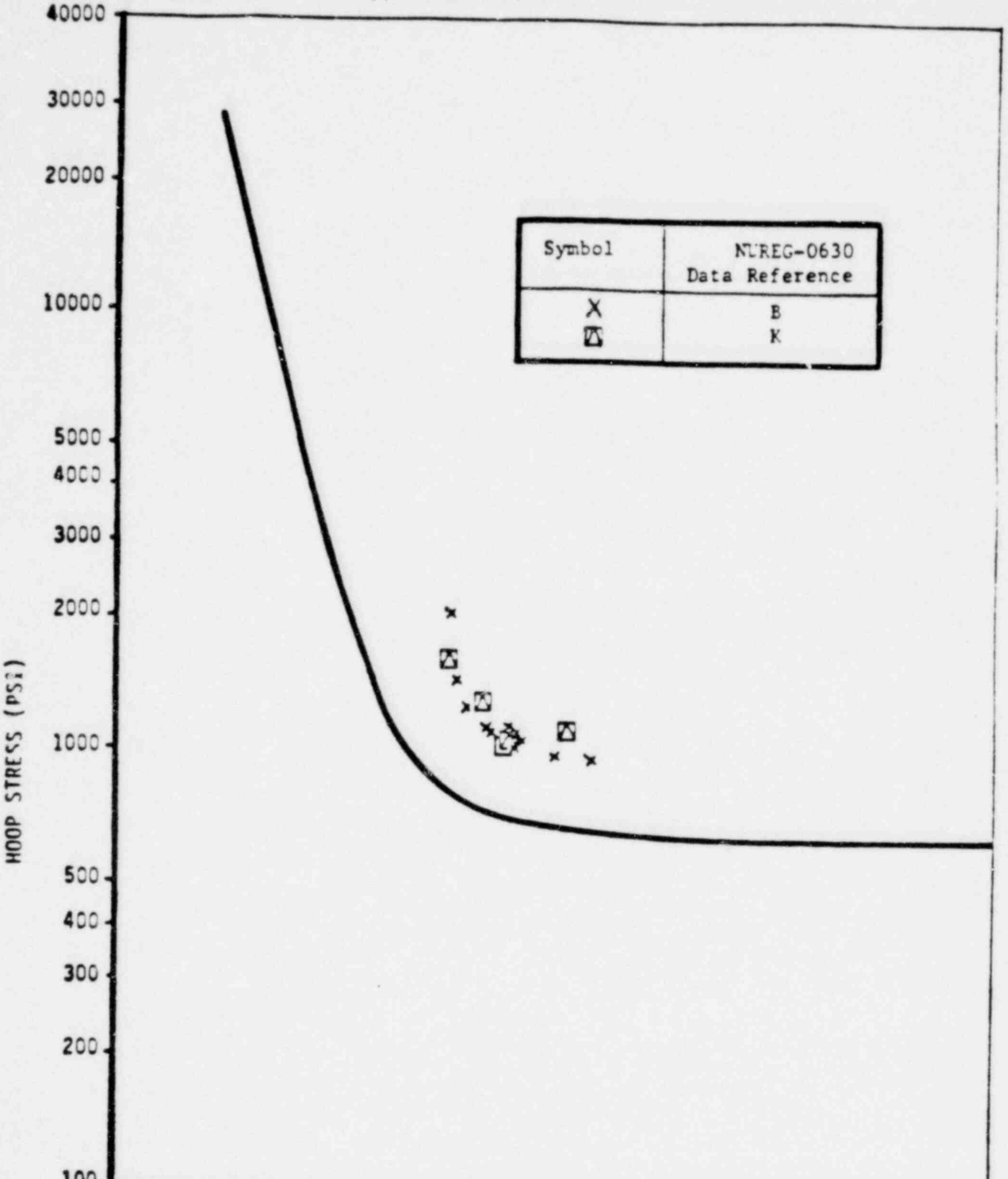
HOOP STRESS VERSUS PERFORATION TEMPERATURE
FOR HEAT-UP RATES LESS THAN 10°F/SEC

FIGURE 1



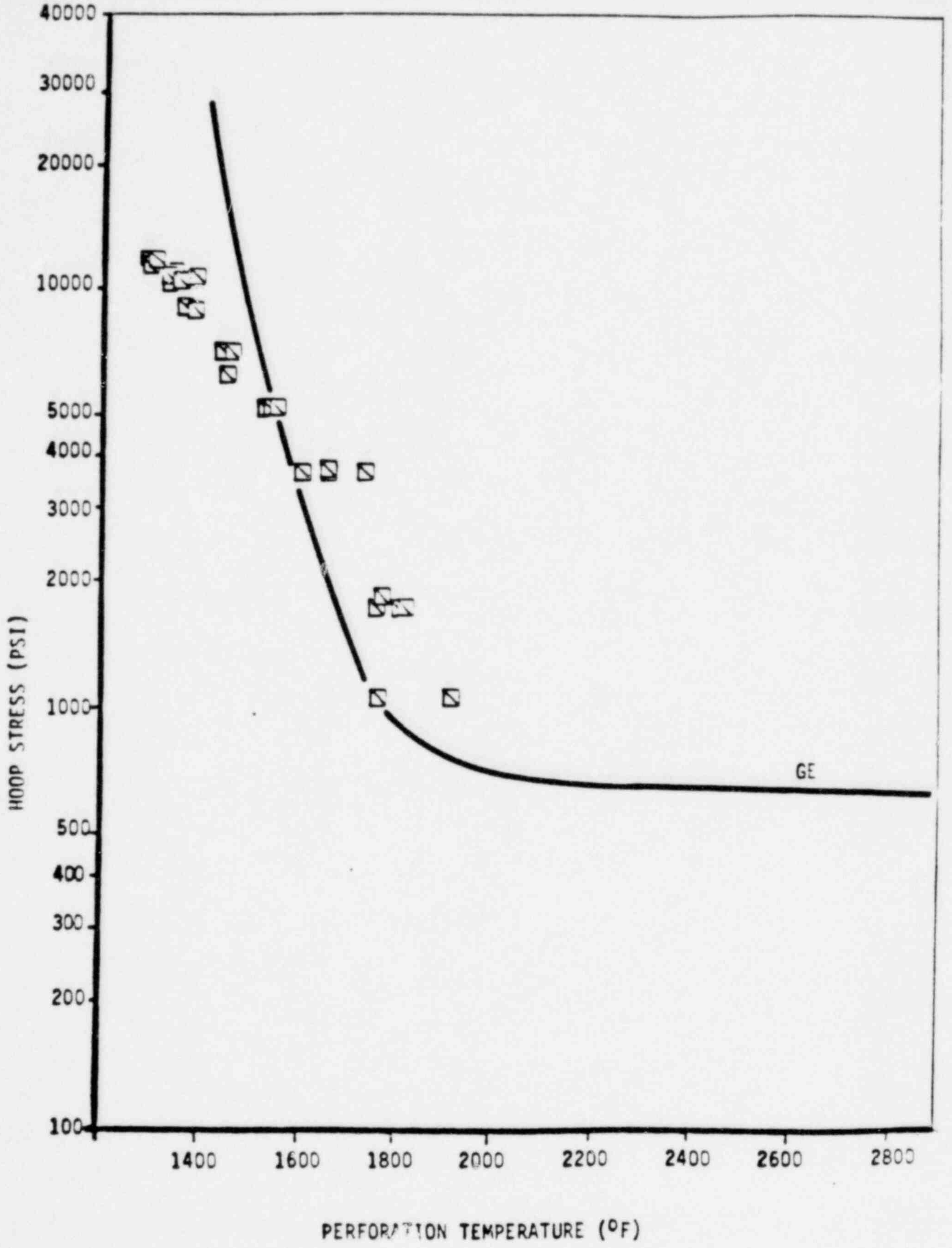
DATA FROM NUREG-0630 FOR HEAT-UP RATES LESS THAN 10°F/SEC

FIGURE 2



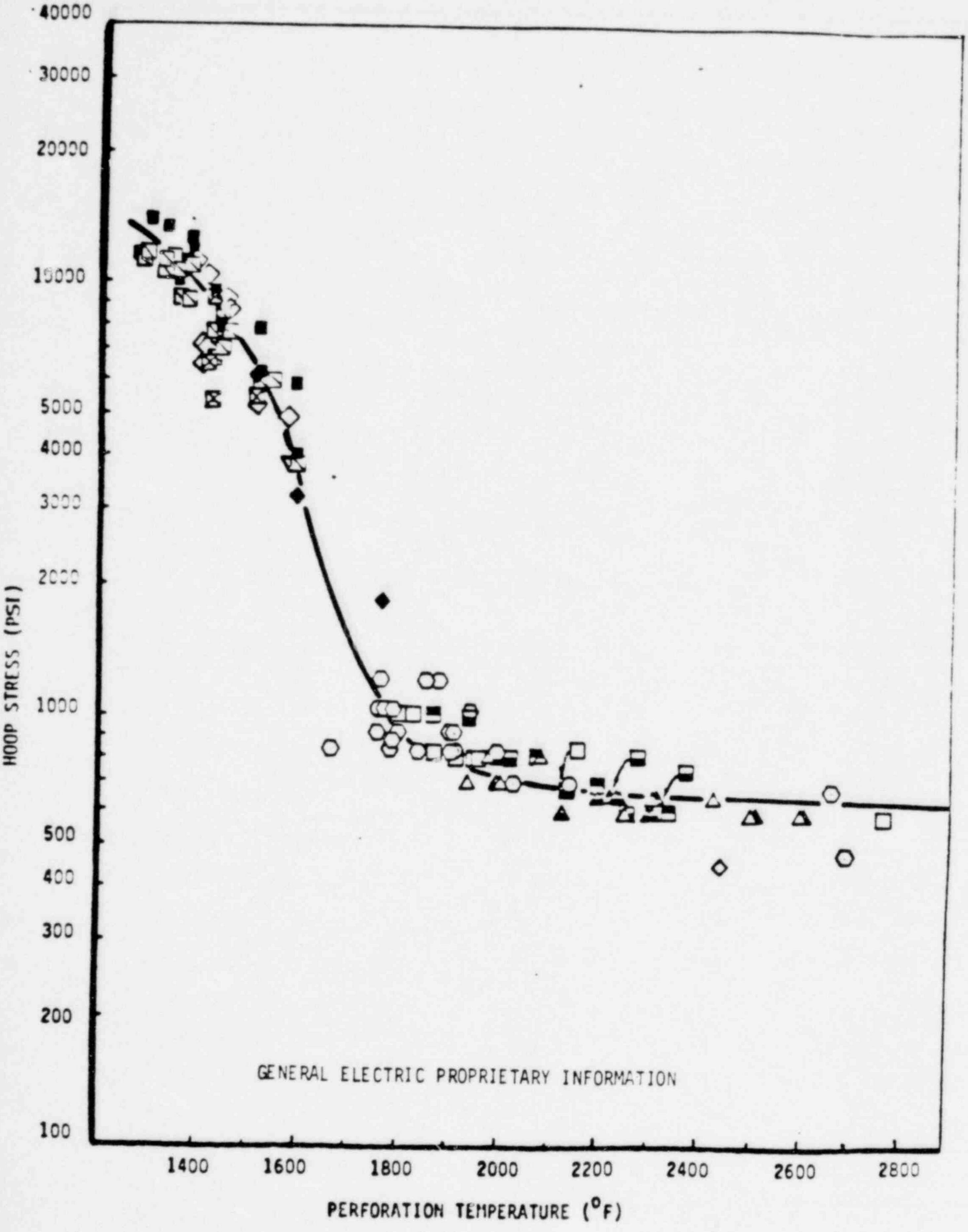
NUREG-0630 DATA ABOVE 1000°C

FIGURE 3

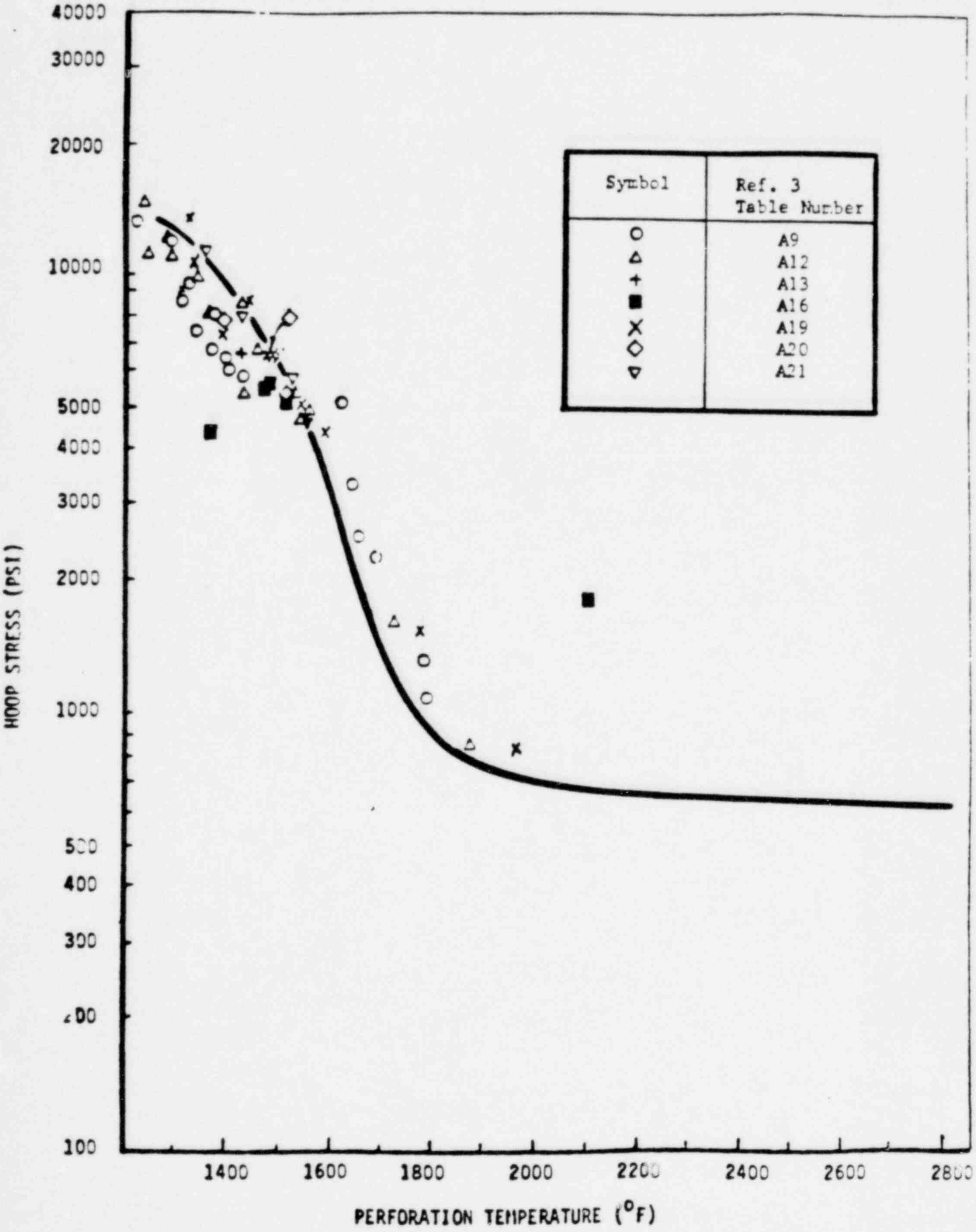


KfK DATA FOR RAMP RATES BETWEEN 0.8 and 1.6 K/SEC

FIGURE 4



- HOOP STRESS VERSUS PERFORATION TEMPERATURE FOR HEAT-UP RATES LESS THAN 10°F/SEC



ANL DATA FOR HEAT UP RATES LESS THAN 10°F/SEC

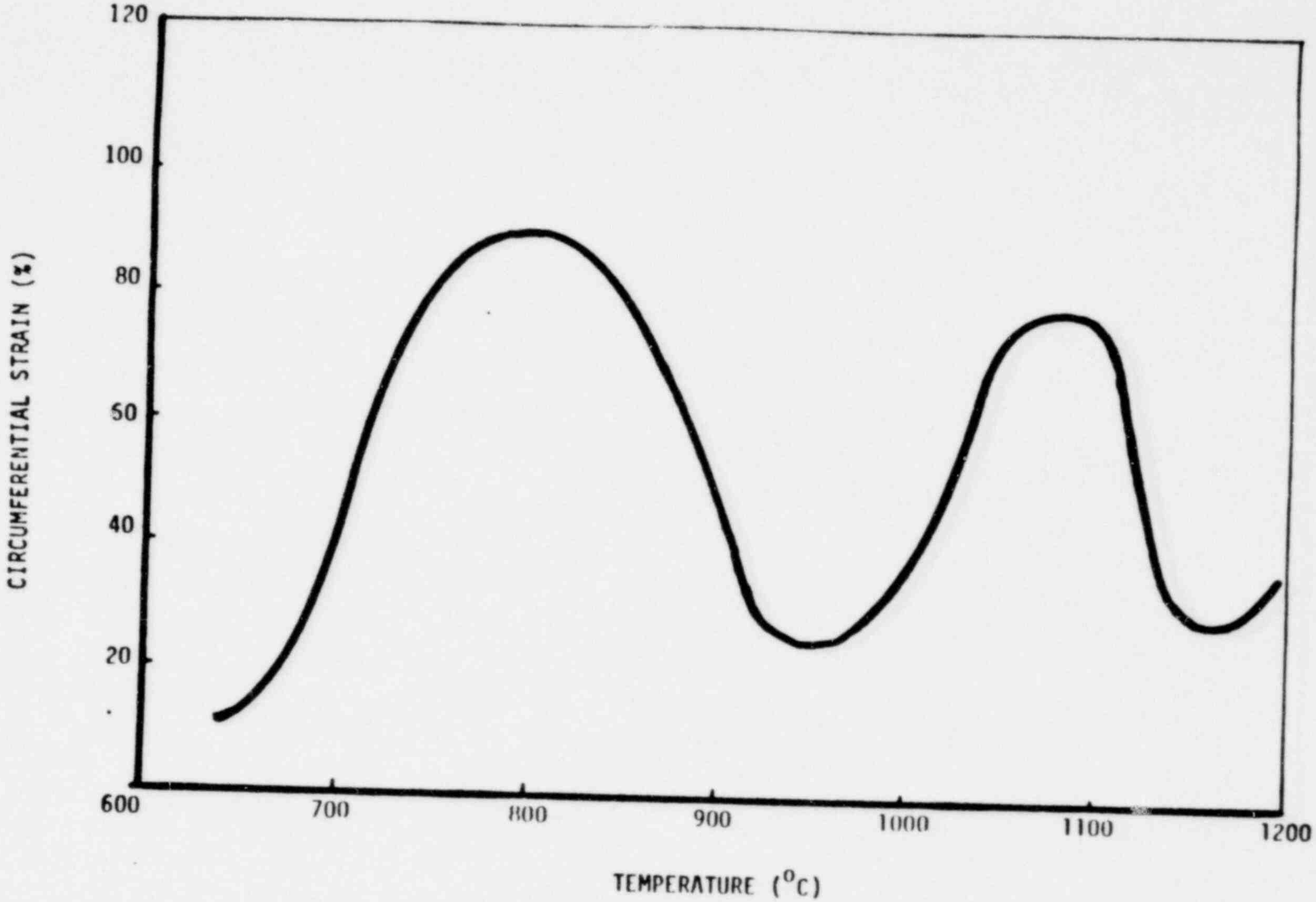
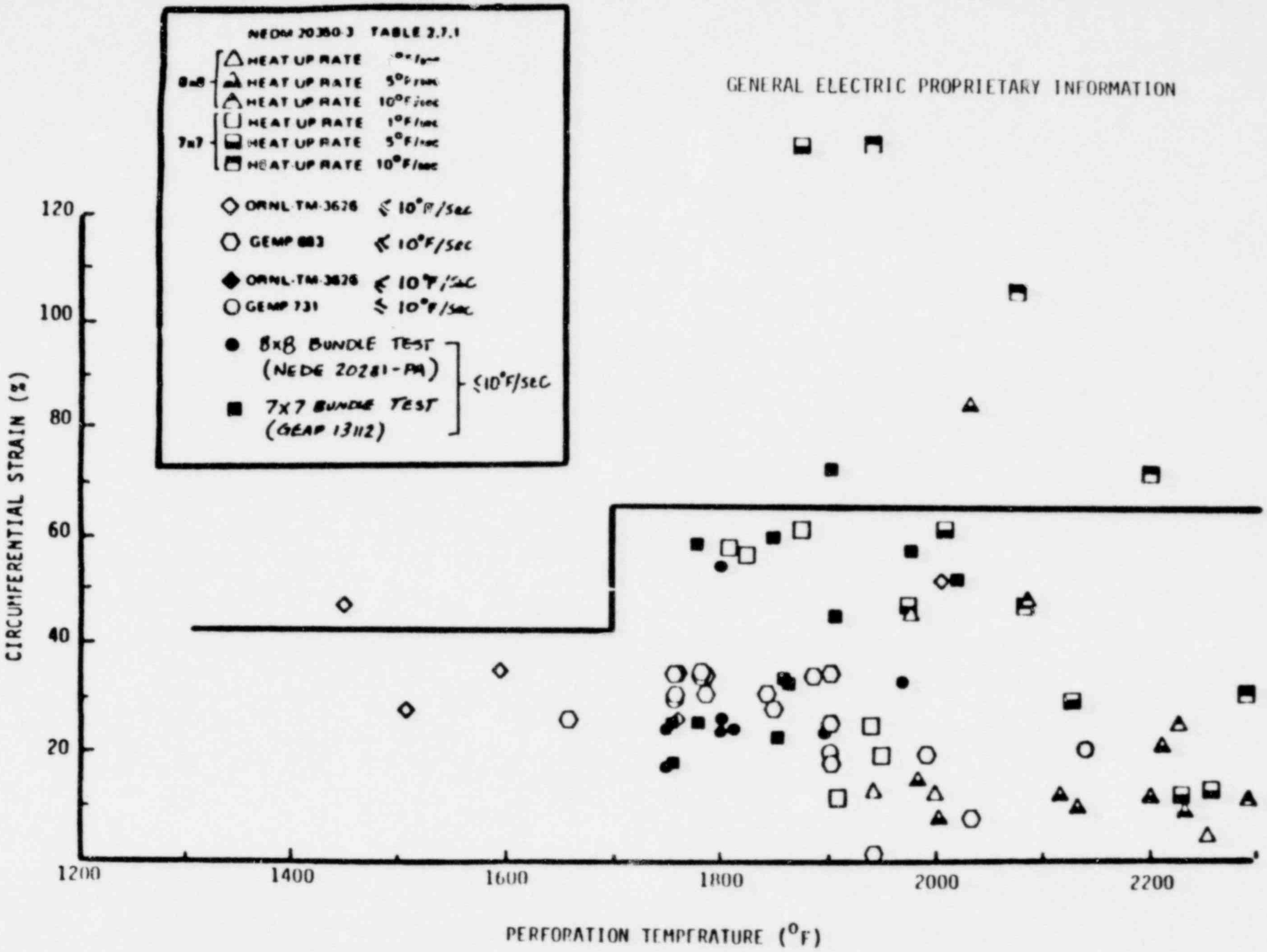


FIGURE 7: COMBINATION OF NUREG-0630 SLOW AND FAST HEAT-UP RATE CORRELATIONS

GENERAL ELECTRIC PROPRIETARY INFORMATION



CIRCUMFERENTIAL STRAIN VS. TEMPERATURE FOR HEAT-UP RATES ≤ 10°F/SEC

FIGURE 3

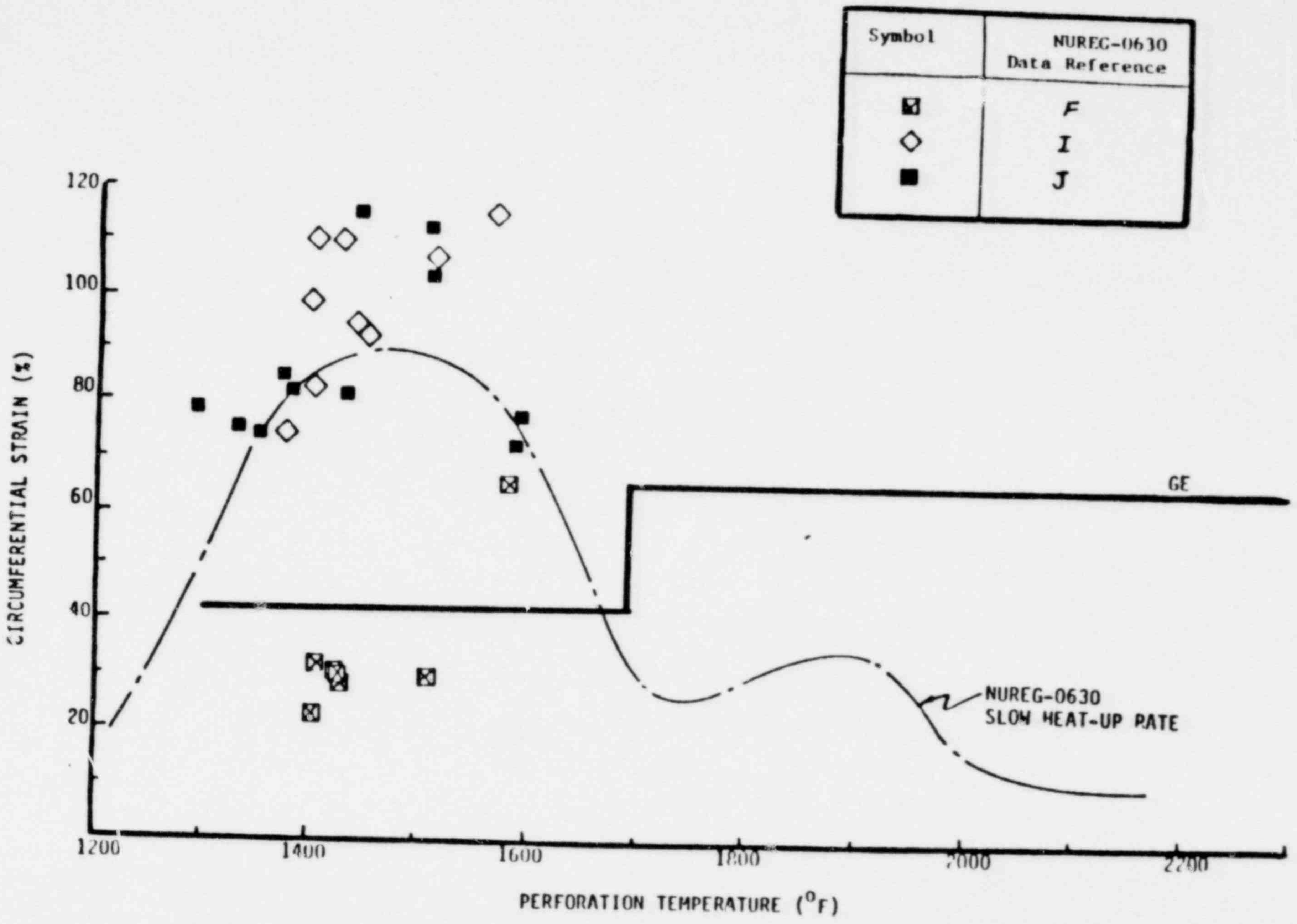
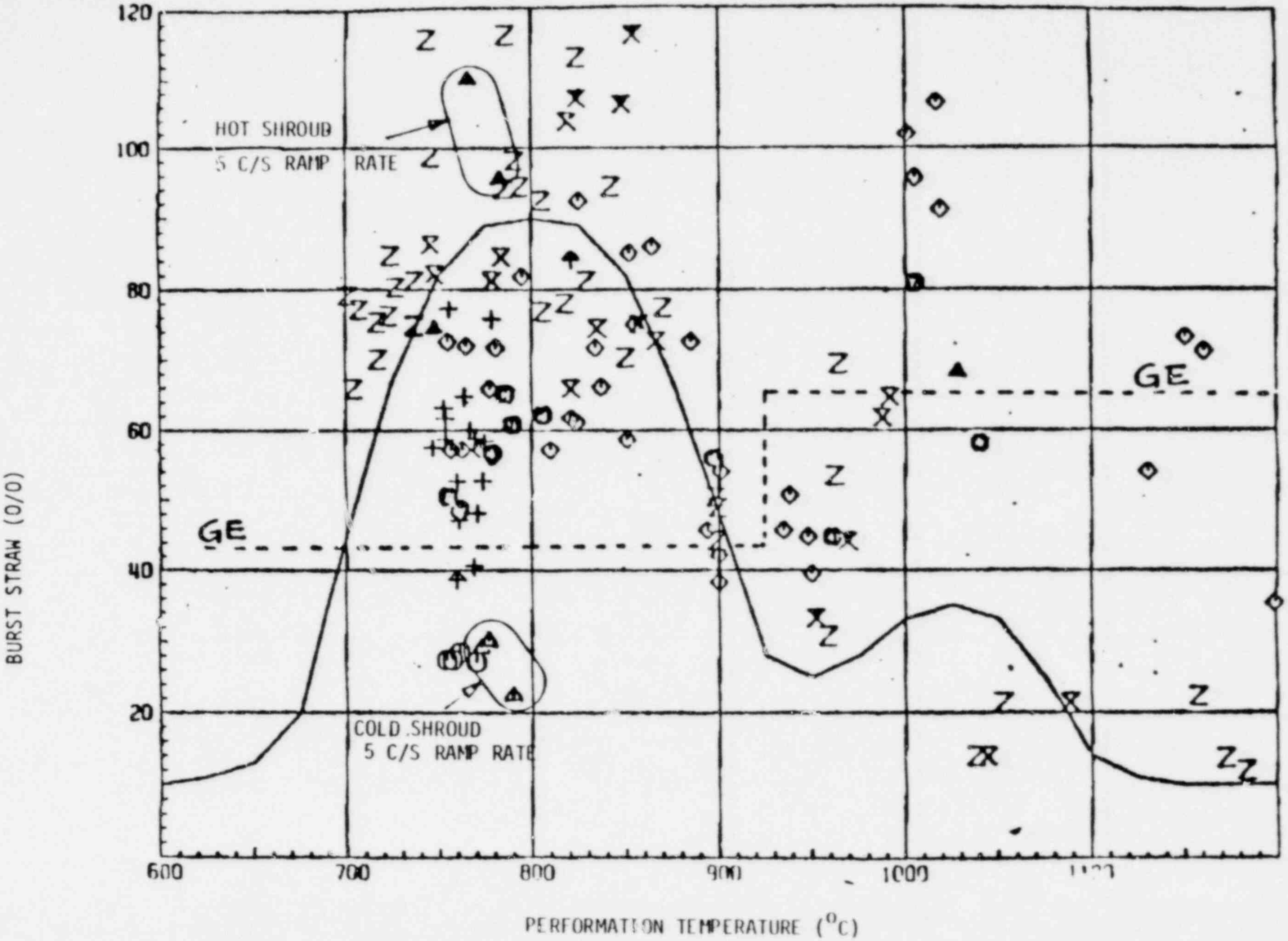


FIGURE 9: NUREG-0630 DATA FOR HEAT-UP RATES $\leq 10^{o}$F/SEC



COMPARISON OF RECENT MRBT AND KFK HEATED SHROUD
SLOW RAMP STRAIN DATA WITH NUREG-0630 MODEL

FIGURE 10

LEGEND FOR FIGURE 10

SYMBOL	LAB.	RAMP RATE (K/SEC.)	SHROUD
Z	K_fK	1	HEATED
X̄	K_fK	2	HEATED
◇	K_fK	10	HEATED
⏀	K_fK	5	HEATED
▲	ORNL	5	HEATED
X̄	ORNL	1	HEATED
C	ORNL	10	HEATED
⊖	ORNL	10	COLD
△	ORNL	5	COLD
+	ORNL	10	HEATED

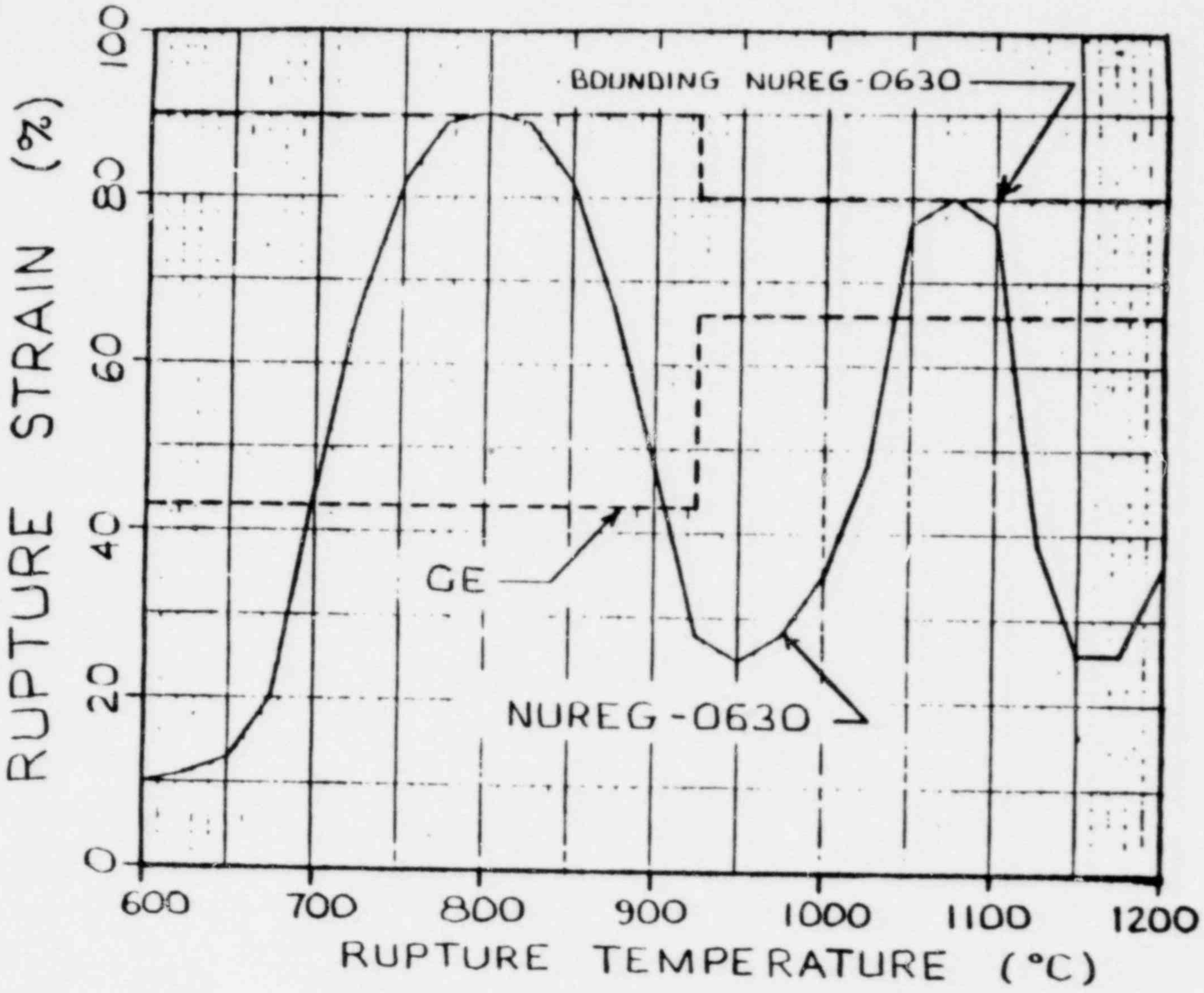


Figure 11. RUPTURE STRAIN vs. RUPTURE TEMPERATURE