ENCLOSURE

SAFETY EVALUATION REPORT ON
XN-NF-82-07, REVISION 1

"EXXON NUCLEAR COMPANY ECCS CLADDING SWELLING AND RUPTURE MODEL"

1.0 Introduction

In demonstrating conformance to the cladding temperature and oxidation requirements of the ECCS Acceptance Criteria of 10 CFR 50.46, several fuel behavior models are employed. This review has focused on three of those models, which have recently been revised. One fuel model, the rupture temperature model, describes the thermomechanical conditions that will result in cladding perforation. A second model, the strain model, describes the extent of cladding plastic deformation before and after perforation has occurred. And the third model, the flow blockage model, describes the reduction in fuel assembly flow area subsequent to cladding rupture.

Regulatory requirements applicable to these three models are set forth in Appendix K to 10 CFR 50, which defines required and acceptable features of ECCS evaluation models. With regard to the provision for fuel swelling and rupture analyses, Appendix K states that to be acceptable the swelling and rupture calculations shall be based on applicable data in such a way that the degree of swelling and incidence of rupture are not underestimated.

Newly proposed Exxon Nuclear Company swelling and rupture models are contained in the ENC report XN-NF-82-07, Revision 1, "Exxon Nuclear Company ECCS Cladding Swelling and Rupture Model" (Ref. 1). The models described in XN-NF-82-07, Revision 1 have been incorporated into ENC codes, i.e., RELAP4 (PWR blowdown), RELAX (BWR blowdown), TOODEE2 (PWR heatup) and HUXY/BULGEX (BWR heatup). The new models are applicable to the analyses of both large and small breaks and constitute submodels of the overall ECCS evaluation model (e.g., Ref. 2).

2.0 Summary of Staff Evaluation

2.1 Data Base

The ENC swelling and rupture data base of the subject report is composed exclusively of the most prototypical data inasmuch as all of the data were obtained from test programs that employed (a) pressurized zirconium-clad fuel-rod simulators that were internally heated with UO_2 or cartridge heaters and (b) aqueous atmospheres. The data base incorporates that given in NUREG-0630 (Ref. 3), GEAP-13112 (Ref. 4), and that (Refs. 5, 6, 7, and 8) which has become available since the publication of NUREG-0630. However, the phenomenological basis for model development (i.e., curve fitting) was, as described in NUREG-0630, qualitatively assisted by results from simpler, but less prototypical, experiments (Ref. 9) that utilized direct, self-resistance heating of the cladding. The staff has found the data base to be appropriate.

2.2 Cladding Temperature Ramp Rate

For simplicity the effects of cladding heating rate and strain rate are empirically treated as a single combined parameter expressed as temperature ramp rate. The ramp rate will be continuously averaged over 10-second intervals (in HUXY the lesser of 10 seconds or the time required for 41 times steps). The use of a 10-second period (a) attenuates spurious numerical oscillations, (b) minimizes the effect of temperature fluctuations just prior to rupture, and (c) results in a conservatively lower heating rate when nearing the rupture temperature than would be obtained from the use of a longer period. The ramp rate will be set to the value of 0°C/s for (a) instances when the calculated ramp rate is less than 0°C/s, and (b) RELAP4 and RELAX analyses. Conversely, the ramp rate will be set to 28°C/s for instances when the calculated ramp rate is greater than 28°C/s.

The basis for the 0 and 28°C/s limits are given in the following Section 2.3. The ENC method of calculating ramp rates and application of the artificial adjustments to the ramp rate are conservative and hence, acceptable.

2.3 Cladding Rupture Temperature Model

The new ENC model for predicting the occurrence of LOCA-induced cladding rupture is shown in Figure 1. The two curves that are depicted in Figure 1 represent the boundary limits of the model, which are associated with cladding temperature ramp rates of 0 and 28°C/s. A family of intermediate curves (not shown but available from the use of an equation in Section 3.2 of the report) is used to predict failure at ramp rates between 0 and 28°C/s.

At rupture temperatures below 950°C, Exxon has adopted the rupture temperature correlation described in NUREG-0630. At rupture temperatures above 950°C, Exxon has used newly acquired data (Refs. 5, 6, 7, and 8) to develop a ramp-rate dependent extension to the low-temperature portion of the model. The high and low segments of the rupture temperature model merge smoothly at the transition temperature of 950°C. The high-temperature portion of the model is less conservative than the NUREG-0630 correlation; however, it more closely fits the available data base. (See Figure 3.2 in XN-NF-82-07, Revision 1 or Figure 2 of a recent SER given in Reference 10 for comparisons of the new high-temperature data to the new Exxon model and the similar General Electric model.)

The new ENC model is acceptable inasmuch as it does not underestimate the incidence of cladding failure.

2.4 Cladding Prerupture Strain Model

Exxon calculates prerupture plastic strain in a standard fashion similar to that described in WREM (Ref. 11). Based on experimental results by Hardy (Ref. 12), non-elastic swelling commences 111°C below the predicted rupture temperature at a given cladding wall hoop stress and exponentially increases with further increases in temperature. The model (a) does not account for the potential of creep rupture (i.e., failure at stresses less than the ultimate tensile stress) and (b) analytically limits prerupture plastic strains to a fraction of the affiliated burst strain. Figure 2 depicts the maximum degree of prerupture strain in the ENC analysis. As shown in Figure 2 (and the subsequent strain and blockage Figures 3-6), the dashed curve is applicable to ramp rates greater than or equal to 25°C/s whereas the solid curve is applicable to ramp rates less than or equal to 10°C/s. Linear interpolation is used for intermediate ramp rate applications.

The pre-exponential coefficient in the original ENC PWR model was modified in the ENC report XN-76-51 (Ref. 13) to obtain better agreement with experimental data from the Multirod Burst Test Program at ORNL. This modified model has not been further changed in XN-NF-82-07, Revision 1 and it thus remains acceptable.

In addition, ENC has incorporated the prerupture strain model into the HUXY code thus improving the realism of the BWR LOCA analysis. The inclusion of prerupture strain consideration into HUXY necessitated a reduction in the bulging probability constant, which is employed in the stochastic treatment of BWR cladding ballooning and failure. Specifically, the bulging probability is the ratio of the number of failed rods in the plane of maximum blockage to the total number of failed rods in the bundle. Inasmuch as the previous version of HUXY did not account for prerupture strain, the probability of rupture occurring in the plane of interest had been artifically set to a value of 83.8% - - a value which provided a psuedo-agreement with the Zircaloy-2 FLECHT experiment (Ref. 4). The revised bulging probability as directly calculated from Reference 4 is 61.5%.

The term bulging probability is somewhat of a misnomer now that prerupture strain is an integral part of the ballooning analysis, and the term rupture probability would be more appropriate. Notwithstanding, the prerupture strain modifications to HUXY are clear improvements and are acceptable.

2.5 Cladding Burst Strain Models

Exxon uses three models for cladding burst strain; they are depicted in Figures 3 through 5. The model in Figure 3 is used for all PWR and some BWR (RELAX and BULGEX) calculations. The models in Figures 4 and 5 are used for HUXY BWR calculations.

The first burst strain model, as shown in Figure 3, is actually a hybrid model. For rupture temperatures below 950°C, Exxon has adopted the burst strain correlation described in NUREG-0630. For rupture temperatures above 950°C, Exxon has used newly acquired data (Refs. 5, 6, 7, and 8) to develop a new high-temperature portion of the model. At temperatures below 950°C, the model is temperature ramp rate dependent. Figures 6 and 7 of NUREG-0630 and 4.2 of XN-NF-82-07, Revision 1 provide comparisons of these models to the available data base.

We conclude that the ENC burst strain model shown in Figure 3, is acceptable because it does not underestimate the degree of swelling.

As shown in Figure 4, the first ENC HUXY model for general BWR calculations (i.e., surface heat transfer area, radiation view factor, and gap conductance after rupture) is a truncated version of the model shown in Figure 3. The truncation is at a strain level where a swollen fuel rod's diameter would equal the design fuel rod pitch (i.e., about 30%). Limiting strain in this manner mathematically simplifies the radiation heat transfer calculations. Similar unnatural limitations are imposed in counterpart ECCS evaluation models (see, for instance, the General Electric model described in Reference 10 or the MOXY model described in Reference 14). In support of this model, Exxon has (a) stated that the average burst strain in the FLECHT tests was only 34.5% and (b) provided the results of LOCA sensitivity studies that exemplify the inconsequential effect of this strain artificiality.

Those sensitivity studies were performed on an 8x8 BWR assembly in which 4 center rods were allowed to rupture in the plane of interest. For one case, the strains were 20%; for another case, the strains were 32%. The new result of the calculations was that the case with the higher strains yielded 7°F lower peak cladding temperature (PCT) and 0.3% higher local cladding oxidation (LCO).

These results are understandable in light of the competing effects that are operative; that is, increases in strain create (a) increases in convective and radiation heat transfer, (b) decreases in gap conductance, and (c) increases in metal-water reaction heat. The latter variable will increase PCTs while the former two will decrease PCTs.

As discussed in Reference 10, a higher coplanar strain of 40% would perhaps be more appropriate to assess than strain to rod pitch, but nevertheless the impact of strain on PCT and LCO is clearly in the same direction and of the same magnitude as that calculated by General Electric (Ref. 10) and evidently of relatively little significance. Consequently, we approve the ENC strain model used for BWR general calculations not on the basis of its realism but because the PCT and LCO are sufficiently insensitive to variations in cladding strain.

The second ENC HUXY burst strain model is shown in Figure 5. This model is used for oxide thinning and metal-water heat generation calculations for ruptured rods in the plane of interest. The oxidation calculations elsewhere along the fuel rods are performed using the prerupture strain model described in Section 2.4 and shown on Figure 2. The new version of HUXY calculates oxide thinning and oxidation heat generation both prior to and after the occurrence of rupture. It is thus an improvement over the old version of HUXY, which did not model oxidation effects prior to rupture.

As with the other HUXY strain model shown in Figure 4, this model as shown in Figure 5 is also a modified version of the model shown in Figure 3. Specifically, this model is a 0.614 reduced-scale version of that given in Figure 3. Exxon states that the basis for this reduction in the degree of strain is derived from the FLECHT tests in which the linear strain averaged over 3 inches on ruptured rod burst lobes was 61.4% of the maximum strain. Exxon uses a span length of 3 inches because of the Appendix K requirement for evaluation models to calculate cladding inside oxidation over a 3-inch axial span that is centered at the burst location. Furthermore, Exxon assumes that the metal-water heat generated on fuel rod surface areas larger than that corresponding to the surface area equivalent to a condition of rod-to-rod contact is lost due to convective heat transfer. The basis for this assumption is derived from the empirical analysis of unreferenced ENC spray cooling tests. The relevancy of the Appendix K requirement to axial strain averaging and the appropriateness of the excess convective loss term are both questionable to us, but they do not require explanation in light of the results from additional LOCA sensitivity studies ENC has performed.

Those sensitivity studies were performed on an 8x8 BWR fuel assembly in which the 4 center rods were allowed to rupture in the plane of interest. For one case, the ratio of average to maximum strain was 0.462; and for the other case, the ratio was 0.614. (For this example, the absolute magnitude of the difference in coplanar strain was 11%.) The net result from the calculations was that the later case with the higher strain ratio yielded 11°F higher PCT and 0.1% higher LCO. Though the more greatly deformed bundle produced a more limiting result, the degree of the effect was small. And once again, this trend is similar to that calculated by General Electric (Ref. 10)

Consequently, we approve this ENC strain model used for BWR oxidation calculations on the basis of the reported small evaluation model sensitivity to strain rather than on the basis of its realism.

2.6 Fuel Assembly Flow Blockage Model

The Exxon methodology for calculating PWR fuel assembly flow blockage is the same as that described in NUREG-0630. The only differences in the ENC model are use of (a) a new modified burst strain model (discussed previously and shown in Figure 3), and (b) an NSSS-design-specific scaling factor to account for the beneficial presence of non-fuel elements (i.e., guide and instrument tubes) in the fuel assembly. With regard to the latter difference, the NUREG-0630 method employed an averaged scaling factor. Other aspects of the model, such as the empirical coefficient used in the determination of average coplanar strains are unchanged.

Exxon has provided an example calculation of the flow blockage that would be predicted for ENC 15x15 reload fuel in a PWR NSSS plant subjected to a design-basis large-break LOCA. That example is shown in Figure 6.

We conclude that the ENC flow blockage model does not underestimate the degree of blockage and is hence acceptable.

3.0 Regulatory Conclusions

For the reasons mentioned above, we conclude that the cladding swelling and rupture models described in Exxon's report XN-NF-82-07, Revision 1 are acceptable for use in licensing LOCA analyses and, as such, may be referenced without condition.

4.0 References

1. "Exxon Nuclear Company ECCS Swelling and Rupture Model," ENC report XN-NF-82-07, Revision 1, August 1982.
2. "Exxon Nuclear Company Evaluation Model EXEM/PWR ECCS Model Updates," ENC report XN-NF-82-20, March 1982.
3. D.A. Powers and R.O. Meyer, "Cladding Swelling and Rupture Models for LOCA Analysis," NRC report NUREG-0630, April 1980.
4. J.D. Duncan and J.E. Leonard, "Thermal Response and Cladding Performance of an Internally Pressurized, Zircaloy-Clad Simulated BWR Fuel Bundle Cooled By Spray Under Loss-of-Coolant Conditions," AEC report GEAP-13112, April 1971.
5. S.O. Peck and D.K. Kerwin (NRC) letter to R.R. Sherry (NRC), February 12, 1980.
6. F. Erbacher, et al., "Burst Criterion of Zircaloy Fuel Claddings in a LOCA," paper presented at the ASTM Fifth International Conference on Zirconium in the Nuclear Industry, Boston, Massachusetts, August 4-7, 1980.
7. R.H. Chapman (ORNL) telex to D.A. Powers (NRC), July 20, 1981.
8. T.R. Yackle and N.T. LeFebre, "PBF-LOCA Test Series: LOC-6 Quick Look Report," EG&G report EGG-TFBP-5329, February 1981.
9. H.M. Chung and T.F. Kassner, "Deformation Characteristics of Zircaloy Cladding in Vacuum and Steam under Transient-Heating Conditions: Summary Report," NRC report NUREG/CR-0344, July 1978.
10. H. Bernard (NRC) letter to G.G. Sherwood (GE), Subject: Supplementary Acceptance of Licensing Topical Report NEDE 20566A (P), May 11, 1982.
11. "WREM: Water Reactor Evaluation Model," NRC report NUREG-75/056, Revision 1, May 1975.
12. D.G. Hardy, "High Temperature Expansion and Rupture Behavior of Zircaloy Tubing," p. 254, Conference on Water-Reactor Safety, AEC report CONF-730304, Salt Lake City, Utah, March 26-28, 1973.
13. "Flow Blockage and Exposure Sensitivity Study for D.C. Cook Unit 1 Reload Fuel Using ENC WREM-II Model," ENC report XN-76-51, Supplement 1, January 1977.
14. D.R. Evans, "MOXY: A Digital Computer Code for Core Heat Transfer Analysis," Idaho Nuclear Report IN-1392, August 1970.

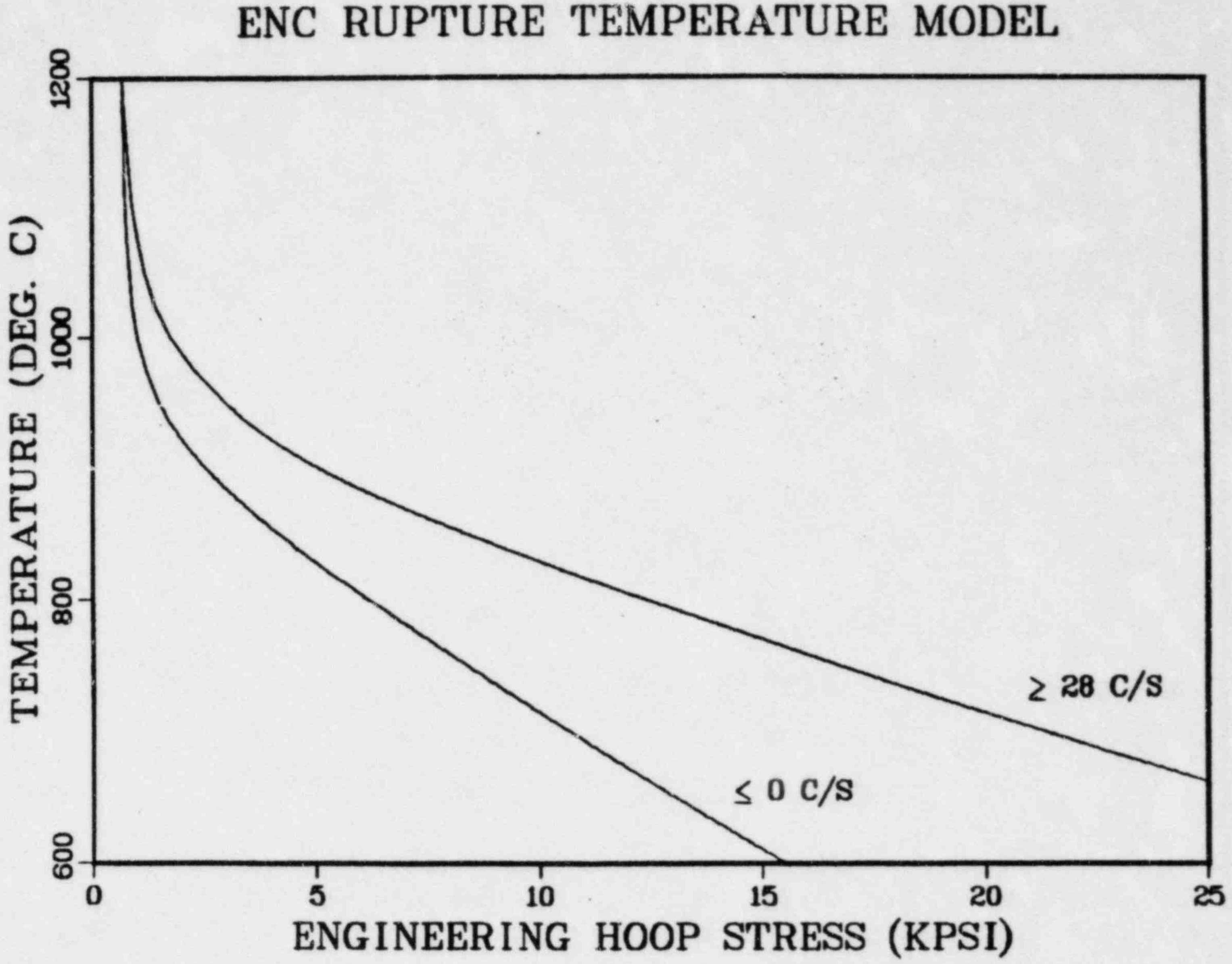

ENC RUPTURE TEMPERATURE MODEL
TEMPERATURE (DEG. C)
1200
1000
800
600
0
5
10
15
20
25
ENGINEERING HOOP STRESS (KPSI)
≥ 28 C/S
≤ 0 C/S

Figure 1

ENC PRERUPTURE BURST STRAIN MODEL

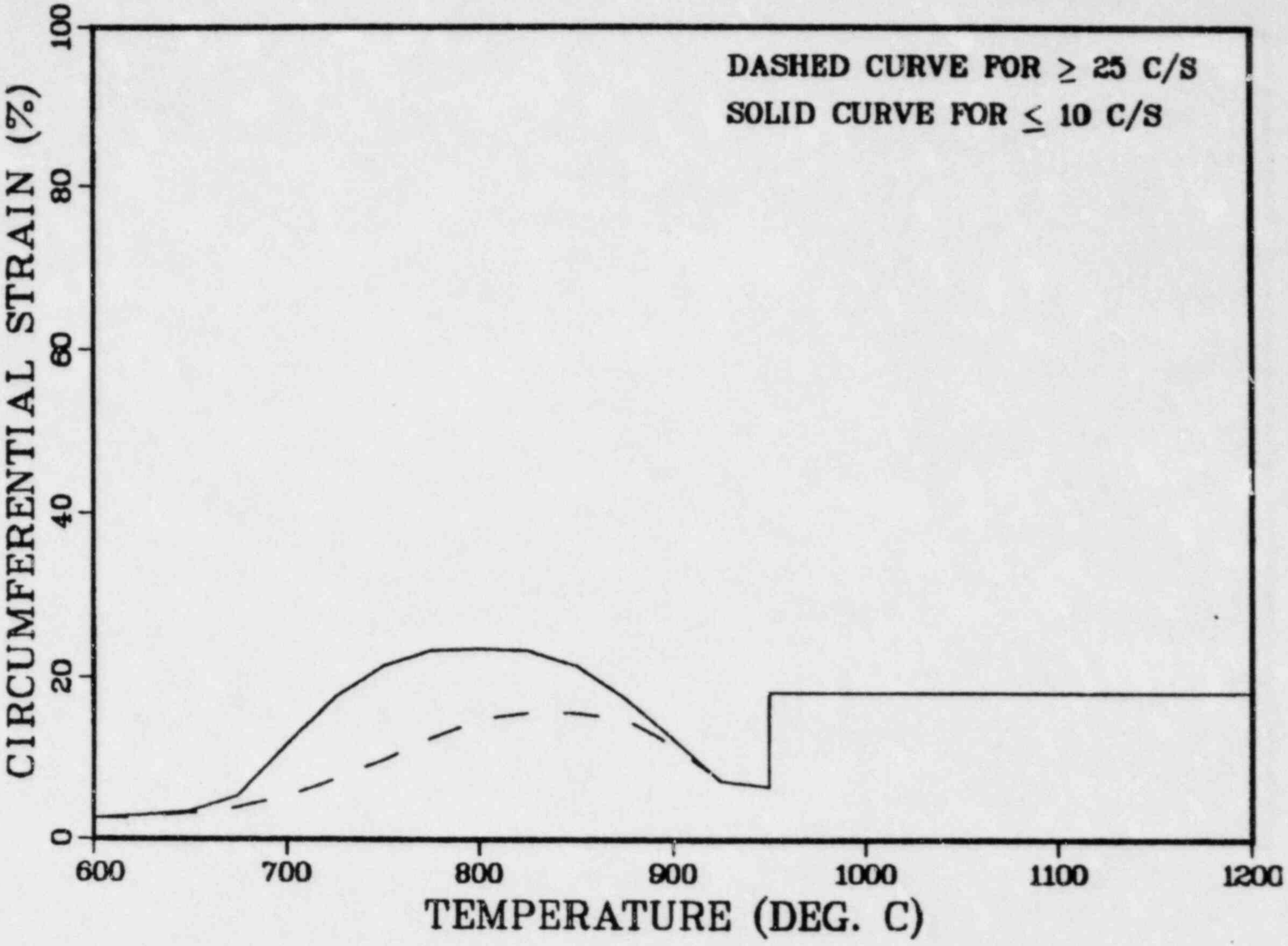


Figure 2

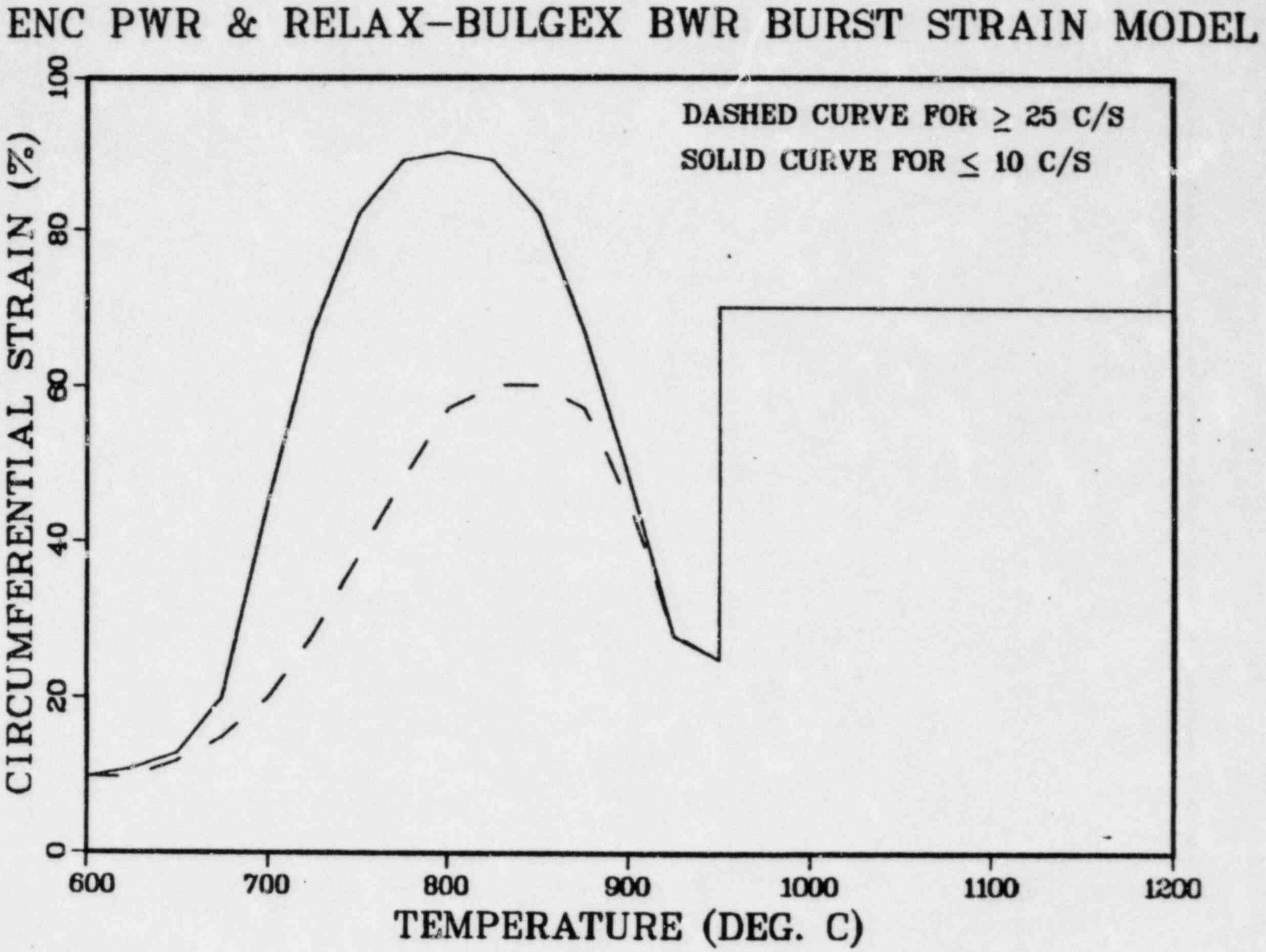

ENC PWR & RELAX-BULGEX BWR BURST STRAIN MODEL
DASHED CURVE FOR ≥ 25 C/S
SOLID CURVE FOR ≤ 10 C/S
CIRCUMFERENTIAL STRAIN (%)
0
20
40
60
80
100
600
700
800
900
1000
1100
1200
TEMPERATURE (DEG. C)

Figure 3

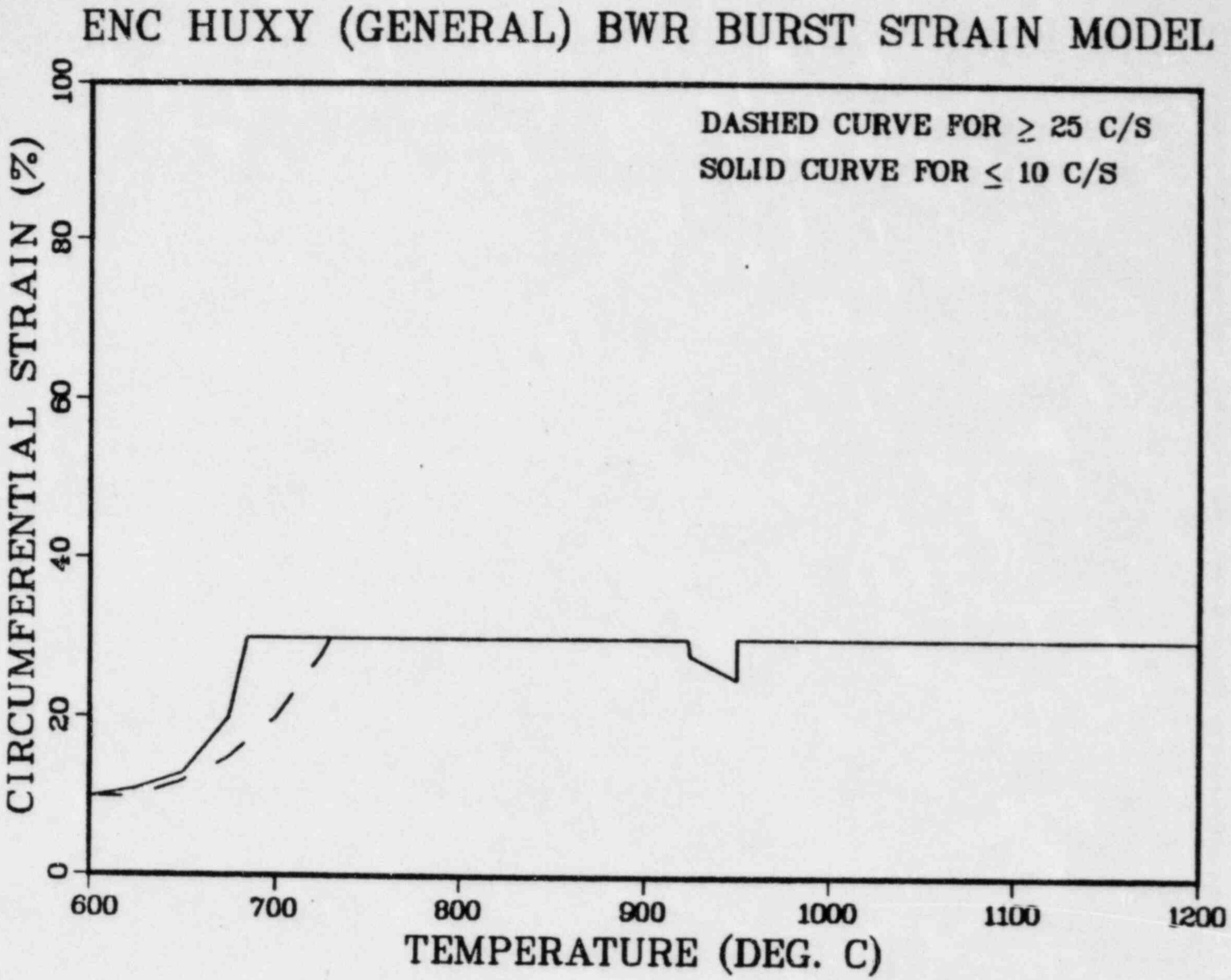

ENC HUXY (GENERAL) BWR BURST STRAIN MODEL
DASHED CURVE FOR ≥ 25 C/S
SOLID CURVE FOR ≤ 10 C/S
CIRCUMFERENTIAL STRAIN (%)
0
20
40
60
80
100
600
700
800
900
1000
1100
1200
TEMPERATURE (DEG. C)

Figure 4

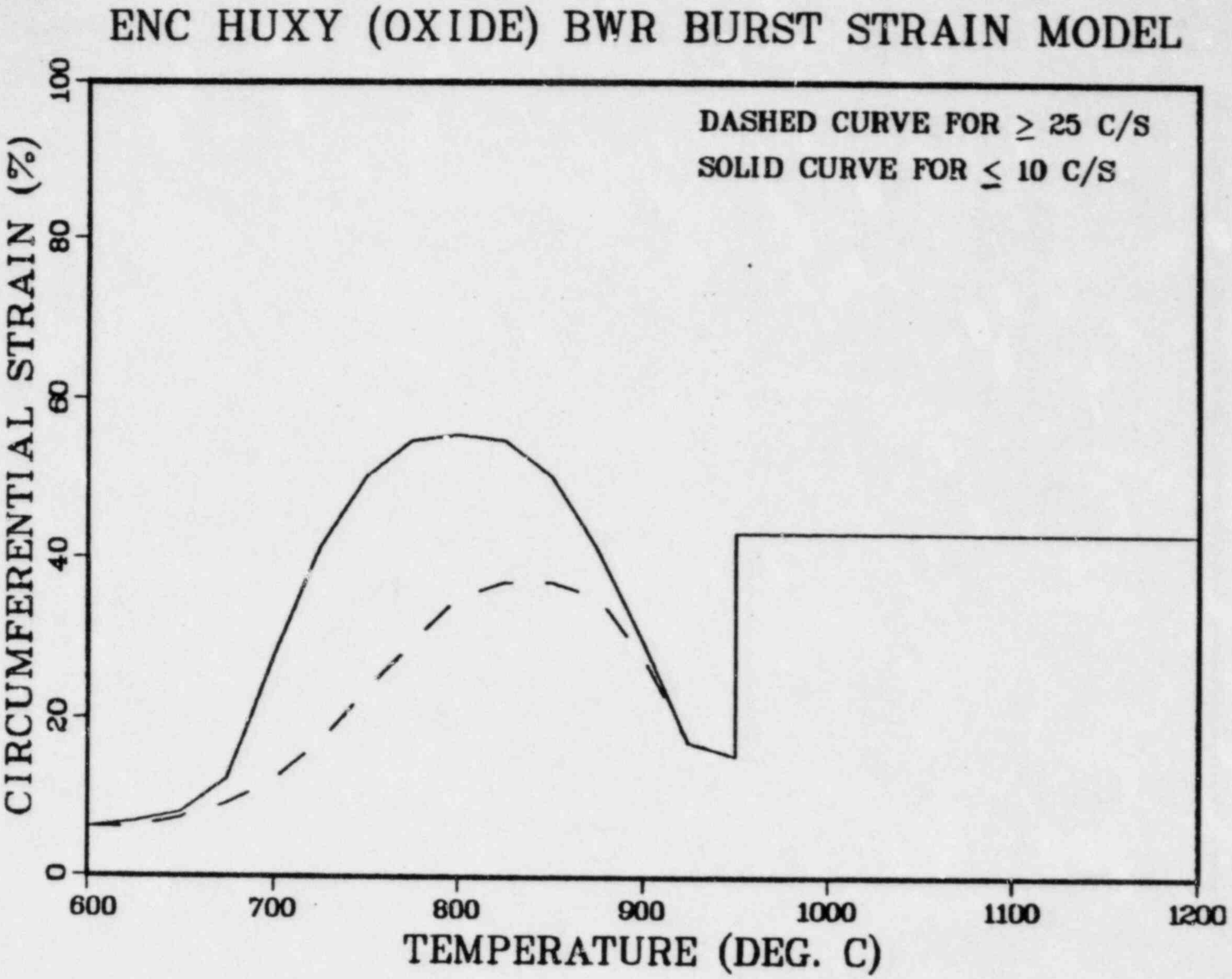
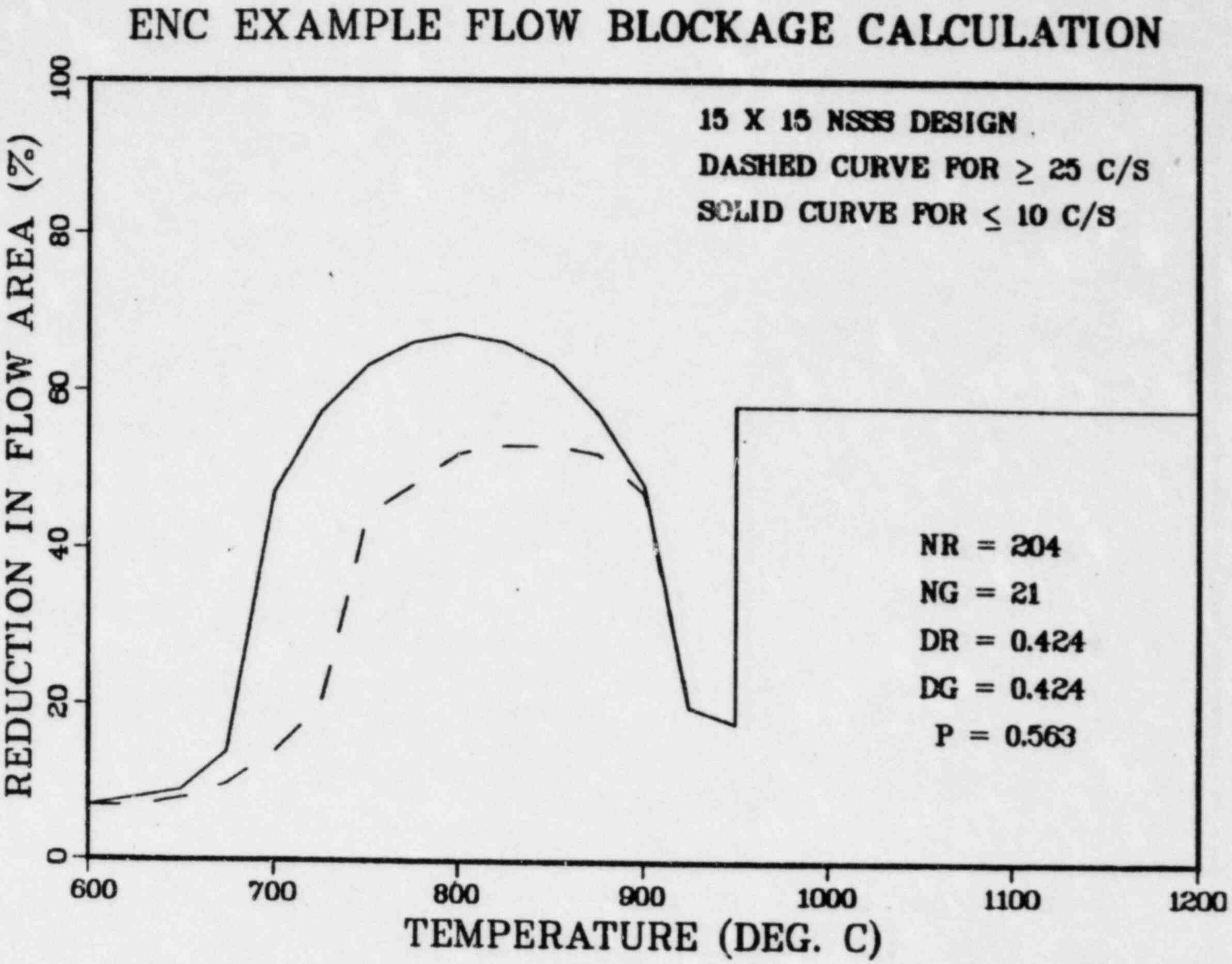

ENC HUXY (OXIDE) BWR BURST STRAIN MODEL

Figure 5



ENC EXAMPLE FLOW BLOCKAGE CALCULATION
15 X 15 NSSS DESIGN
DASHED CURVE FOR ≥ 25 C/S
SOLID CURVE FOR ≤ 10 C/S
NR = 204
NG = 21
DR = 0.424
DG = 0.424
P = 0.563
REDUCTION IN FLOW AREA (%)
0
20
40
60
80
100
TEMPERATURE (DEG. C)
600
700
800
900
1000
1100
1200

Figure 6