HEDL-SA-1461
CONF-780722--4
1461

EFFECTS OF IRRADIATION TEMPERATURE, FLUENCE, AND HEATING RATE ON FLOW PROPERTIES OF CLADDING UNDER SIMULATED TEMPERATURE TRANSIENT HEATING AND DEFORMATION CONDITIONS

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MASTER

January 1978

For presentation at the 9th International Symposium on Effects of Radiation on Structural Materials to be held in Richland, WA, July 10, 1978.

HANFORD ENGINEERING DEVELOPMENT LABORATORY
Richland, Washington
operated by
WESTINGHOUSE HANFORD COMPANY
a subsidiary of Westinghouse Electric Corporation
for the
DEPARTMENT OF ENERGY
UNDER CONTRACT EY-76-C-14-2170

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EFFECTS OF IRRADIATION TEMPERATURE, FLUENCE, AND HEATING RATE ON FLOW PROPERTIES OF CLADDING UNDER SIMULATED TEMPERATURE TRANSIENT HEATING AND DEFORMATION CONDITIONS

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ABSTRACT

Irradiation temperature, fluence, and heating rate effects on plastic flow and failure properties of fast reactor cladding were investigated by heating internally pressurized specimens until failure occurred. Specimens tested were from 20% cold-worked Type 316 stainless steel cladding, irradiated in the Experimental Breeder Reactor-II at temperatures to 720^{o} C and fluences to 10^{23} n/cm^2 (E > 0.1 Mev).

A monotonic decrease of transient failure temperature with increasing irradiation temperature was observed at the "standard" heating rate of 5.6 C^{o}/s. This effect became more pronounced for irradiation temperatures above 600^{o} C. Transient failure temperatures generally decreased with increasing fluence for tests performed at the standard heating rate. Irradiated and unirradiated specimens were tested at several heating rates. For equal stress, fluence, and irradiation temperature, decreasing the heating rate decreased failure temperatures by as much as 170^{o} C for irradiated specimens and 150^{o} C for unirradiated specimens. The data reported herein fall well within FFTF design limits for transient conditions and serve to confirm the material properties currently used in the design analyses.

Key Words: radiation, irradiation, mechanical properties, nuclear fuel cladding, stainless steels, ductility, strain rate, safety analysis, transient.

1. Introduction

During an overpower transient above the steady state irradiation temperature, alteration of the mechanical properties (strength, ductility, et cetera) of the irradiated cladding can be expected. Knowledge of cladding behavior with stress under transient heating conditions is important. Since in-reactor measurement of these properties during an actual transient is currently impossible, this data must be obtained from simulated transients under laboratory conditions.

The Fuel Cladding Transient Tester (FCTT) was developed at the Hanford Engineering Development Laboratory (HEDL) to perform tests under transient heating conditions.(1) With this system, pressurization is accomplished using argon gas, and controlled specimen heating is provided by an induction heater.

2. Experimental Procedure

Specimens tested for this work were from 20% cold-worked Type 316 stainless steel of Fast-Flux Test Facility (FFTF) cladding geometry (5.84 mm O.D., 5.08 mm I.D.). These specimens were irradiated in the Experimental Breeder Reactor-II (EBR-II) subassemblies X-195, X-221, and X-222. Specimens obtained from X-195 were 63.5 mm in length and were irradiated to a fluence of 9-10 x 10^{22} n/cm^2 (E > 0.1 MeV) at temperatures of 400 and 650^o C. Specimens from X-221 were 44.5 mm in length and were irradiated to a fluence of 2.1 - 3.1 x 10^{22} n/cm^2 (E > 0.1 MeV) at temperatures between 425 and 720^o C. Irradiated samples exposed in the X-222 subassembly were 44.5 mm long and were irradiated to fluences between 4.4 to 5.2×10^{22} n/cm^2 (E>0.1 MeV) at temperatures between 510 to 670°C. Some tests performed on unirradiated specimen (length of 44.5 mm) are also reported.

Specimens were fabricated by inserting a quartz filler plug inside the cladding to minimize the gas volume and welding stainless steel caps on each end. A capillary tube used for pressurization is an integral part of one end cap. After pressurization to the desired hoop stress, the samples were heated at the desired rate until failure occurred. Test apparatus and procedure are discussed in greater detail by Hunter, et al.[1] Pre-test and post-test diametral measurements were performed on each specimen at 2.54 mm intervals and at rotational intervals of 45°.

3. Results

Irradiation temperature dependence of cladding failure has been examined using transient test data from X-221 specimens irradiated to a relatively constant fluence ($2.1\text{-}3.1 \times 10^{22}$ n/cm^2). These data are presented in Fig. 1 and range in irradiation temperature between 400 and 720°C. (Data from additional transient specimens, irradiated at 650°C to a fluence of 10^{23} n/cm^2, are also included in Fig. 1).

The fluence dependence of cladding failure temperature under transient conditions is shown in Fig. 2. The specimens used to produce these data were irradiated at temperatures of either 400-425°C or 650°C at varying fluences.

Heating rate dependence of cladding failure has been examined from transient test data presented in Fig. 3 (unirradiated specimens) and Fig. 4 (specimens irradiated at 510°C or 670°C).

4. Discussion

4.1 Irradiation Temperature Dependence. The dependence of cladding failure temperature and failure strain on irradiation temperature has been examined for specimen heating rates of 5.6 C°/s. It is apparent from Fig. 1 that failure temperature essentially decreases with increasing irradiation temperature. In Figs. 5 and 6, failure temperature and failure strain are plotted as a function of irradiation temperature. Failure strain measurements for these tests exhibit significant scatter. However, with the exception of the lowest irradiation temperature, there is a general trend of increasing failure strain with increasing irradiation temperature. In Fig. 5 the decrease in transient failure temperature with increasing irradiation temperature becomes dramatic for irradiation temperatures greater than 625°C.

It is shown in Fig. 7 that the degradation of failure temperature for the highest irradiation temperature examined is large, approaching that of fueled cladding irradiated at low temperatures.(2) It is noted, incidentally, that at low stress, the failure temperature of specimens irradiated at 675^{o} C and 720^{o} C lies slightly below the calculated transient curve (based on HEDL burst test data(3))for failure temperature of annealed AISI 316 stainless steel, and on the order of 60 MPa below the failure temperatures of thermally aged 20% CW AISI 316 stainless steel (21.6 Ms at 760°C).

4.2 Fluence Dependence. The data reported in Fig. 2 are from specimens irradiated in the temperature range of either 390-425°C or 650°C, at varying fluences, and tested at a heating rate of 5.6 C°/s. Failure temperature increases slightly with fluence when cladding irradiated at low temperature (390-425°C) was tested at high stress (496 MPa). For all other conditions shown, failure temperature decreases with increasing fluence; the greatest decrease corresponding to low stress (124 MPa) and high irradiation temperature (650°C).

4.3 Heating Rate Dependence. It can be seen from Fig. 3 that the failure temperature for unirradiated specimens varies with the heating rate; i.e., the faster the heating rate, the higher the failure temperature for a given hoop stress. The separation between failure temperatures for the various heating rates is fairly constant at 500 MPa hoop stress and below. Above 500 MPa, the separation decreases. The differing heating rate results are attributed to "time-at-temperature" effects which will be considered in the following.

The concept of "life fraction" has been used with some success to predict cladding failure. For instance, defining life fraction (LF) as

$$LF = \int_0^t \frac{dt}{t_r(\sigma, T)} \qquad (1)$$

is an example[4] of a life fraction rule where t_r is a function dependent upon the engineering stress σ at temperature T. When t equals the time to failure, the life fraction equals unity. It should be noted that reaching the failure limit is a cumulative, history dependent process. A similar rule

$$LF = \int_0^t \frac{\dot{\varepsilon}(\sigma^*,\sigma,T)\ dt}{\varepsilon_L} \qquad (2)$$

has been used[5] to predict transient failure temperatures. The function $\dot{\varepsilon}(\sigma^*,\sigma,T)$ is related to the specimen's plastic strain rate and is determined from σ^* (a parameter dependent upon the specimen history), σ, and T. ε_L is a constant cutoff strain; when t equals the failure time, the life fraction is one. At lower heating rates, the specimen spends more time in a given temperature range than at higher heating rates. The functions in Eqs. (1) and (2) are independent of heating rate. Thus, the life fraction for a specimen would increase more in a given temperature range at a lower heating rate then it would at a higher heating rate. This results in a life fraction of one (and thus failure) occurring at a lower temperature for a lower heating rate. Recovery during a transient test also further separates the different heating rate failure curves at high failure temperatures; an effect which also can be understood from time-at-temperature considerations.

The postirradiation data at 0.56 and 111 C°/s show the same trend of higher failure temperatures at the fast heating rate. This observation is made from Fig. 4. Also apparent in Fig. 4, is a degradation of failure temperature resulting from irradiation exposure. A general slight decrease in failure temperature is observed with increasing irradiation temperature at the slower rate, while opposite behavior is seen at the faster rate at stresses of $\sim$130 and 300 MPa. No attempt is made to explain the apparent increase in failure temperature with increasing irradiation temperature at the 111 C°/s rate, which may be an artifact of data scatter or a reflection of the competing effects of strain rate, temperature, and helium embrittlement on cladding strength.

Postirradiation ductility results in Figs. 8 and 9 show similar trends at each heating rate. Little difference exists in the postirradiation ductility data for the 0.56, 05.6, and 111 C°/s heating rates. Cases for which the specimen ductility increased after irradiation are attributed to substructure recovery during reactor exposure. Decreases in ductility after specimen irradiation are thought to be due to helium embrittlement.

5. Conclusions

It has been shown that the failure temperature of a transient test specimen is reduced with increasing irradiation temperature when the specimen is tested at 5.6 C°/s. This reduction is most pronounced for irradiation temperatures above 625°C. Specimens from fuel pin cladding have shown the greatest deterioration of failure temperature thus far produced;[2] however, the 720°C irradiation temperature transient tests presented herein show degradation of as much as 200°C. Generally, failure strain was observed to increase with increasing irradiation temperature.

Data taken from specimens irradiated to fluences of 10^{23} n/cm^2 are reported. At the constant irradiation temperatures of 390-425°C and 650°C, failure temperatures were observed to decrease with increasing fluence (with the exception of the lowest stress and irradiation temperature combination). A saturation trend for the failure temperature with increasing fluence was not apparent from the data. Postirradiation results show relative heating rate effects similar to unirradiated specimen results. Increasing the heating rate increases the failure temperature for a given test stress.

The data reported herein fall well within FFTF design limits for transient conditions and serve to confirm the material properties currently used in the design analyses.

REFERENCES

1. Hunter, C. W., Fish, R. L., and Holmes, J. J., Nuclear Technology, Vol. 27, November 1975, pp. 376-388.

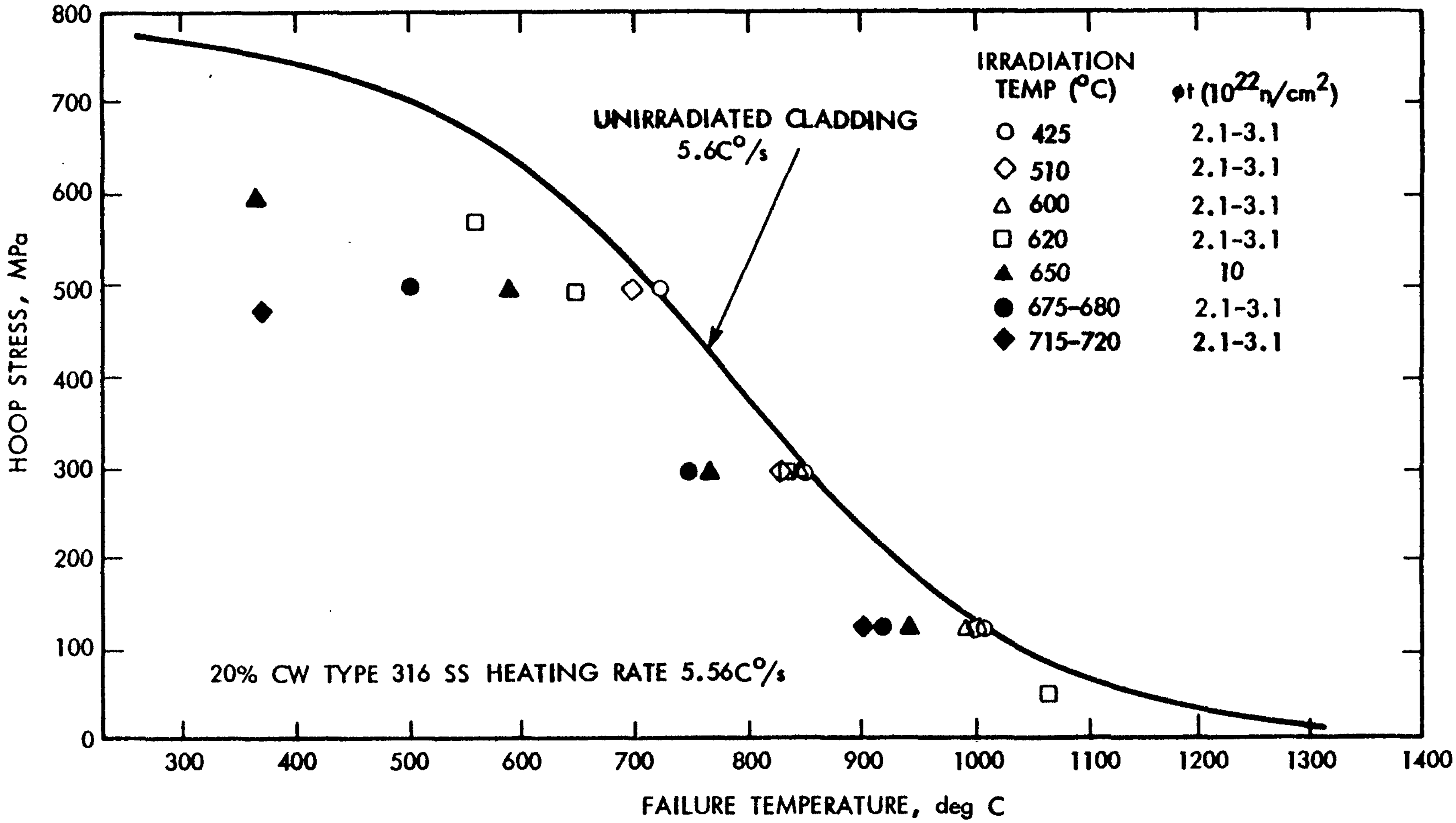
2. Hunter, C. W., and Johnson, G. D., ASTM-STP 611, American Society for Testing and Materials, 1976, pp. 101-118.

3. Paxton, M. M., "Mechanical Properties of Annealed and Cold Worked Type 316 Stainless Steel Fast Reactor Seamless Tubing", HEDL TME 74-11, Hanford Engineering Development Laboratory, Richland, WA., February 1974.

4. Straalsund, J. L., Fish, R. L., and Johnson, G. D., Nuclear Technology, Vol. 25, March 1975, pp. 531-540.

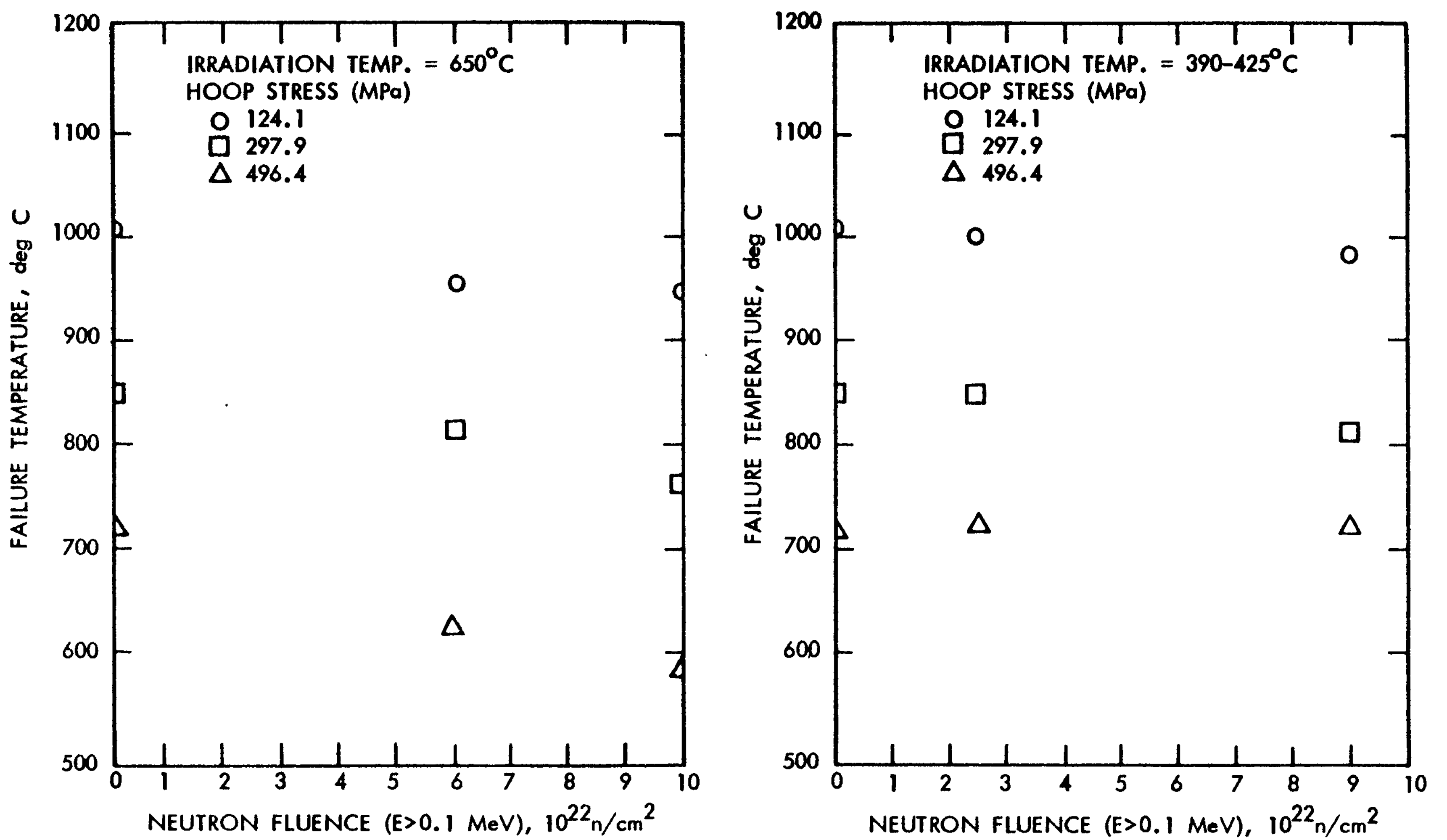
5. Johnson, G. D., Cannon, N. S., and Wire, G. L., "Prediction of Transient Mechanical Response of 316 SS Cladding Using an Equation of State Approach", to be published.

FIGURES



HEDL 7805-55.4

FIG 2



HEDL 7805-55.1

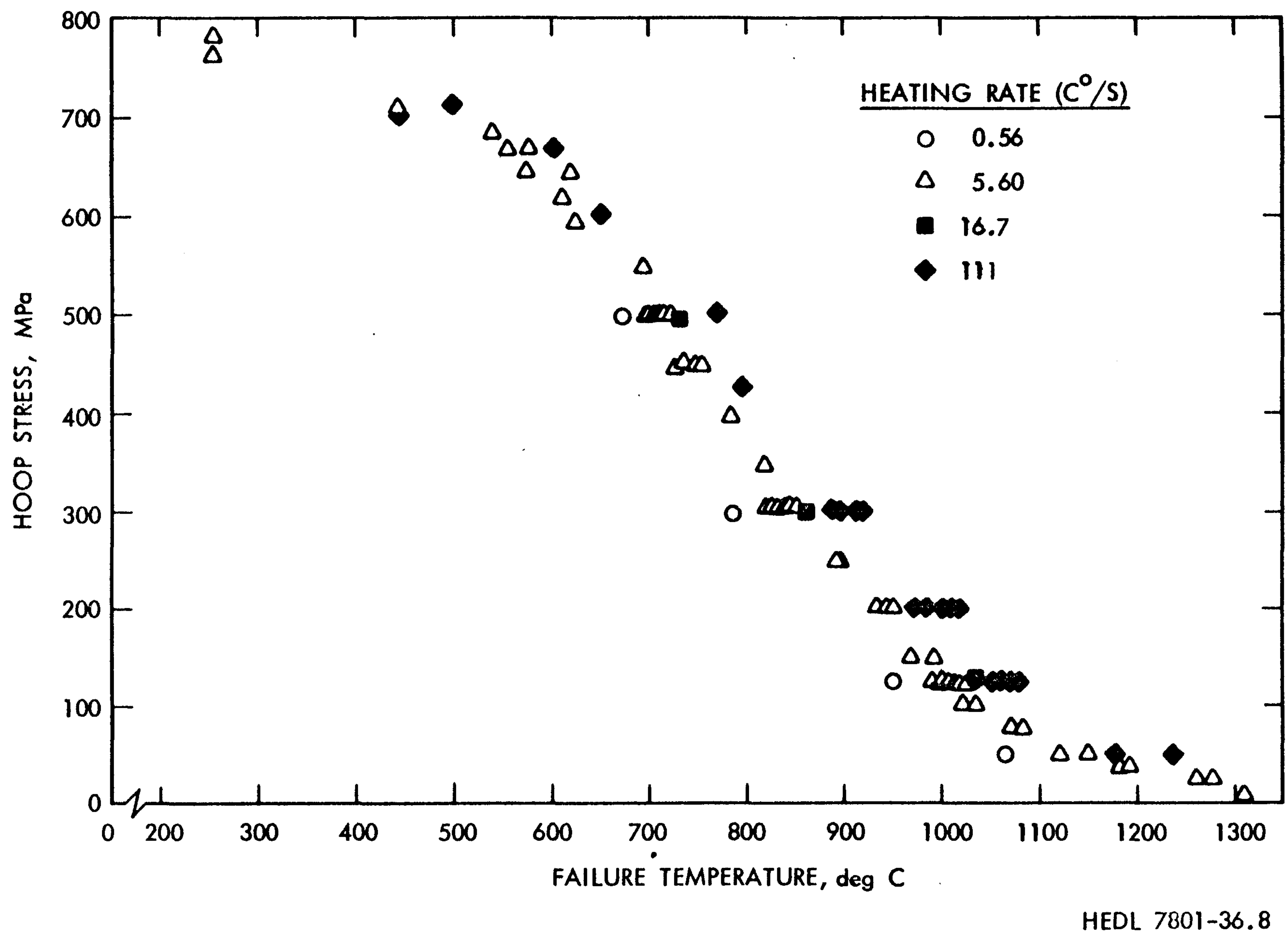

800
700
600
500
400
300
200
100
0
HOOP STRESS, MPa
0
200
300
400
500
600
700
800
900
1000
1100
1200
1300
FAILURE TEMPERATURE, deg C
HEATING RATE (C°/S)
0.56
5.60
16.7
111
HEDL 7801-36.8

FIG 3

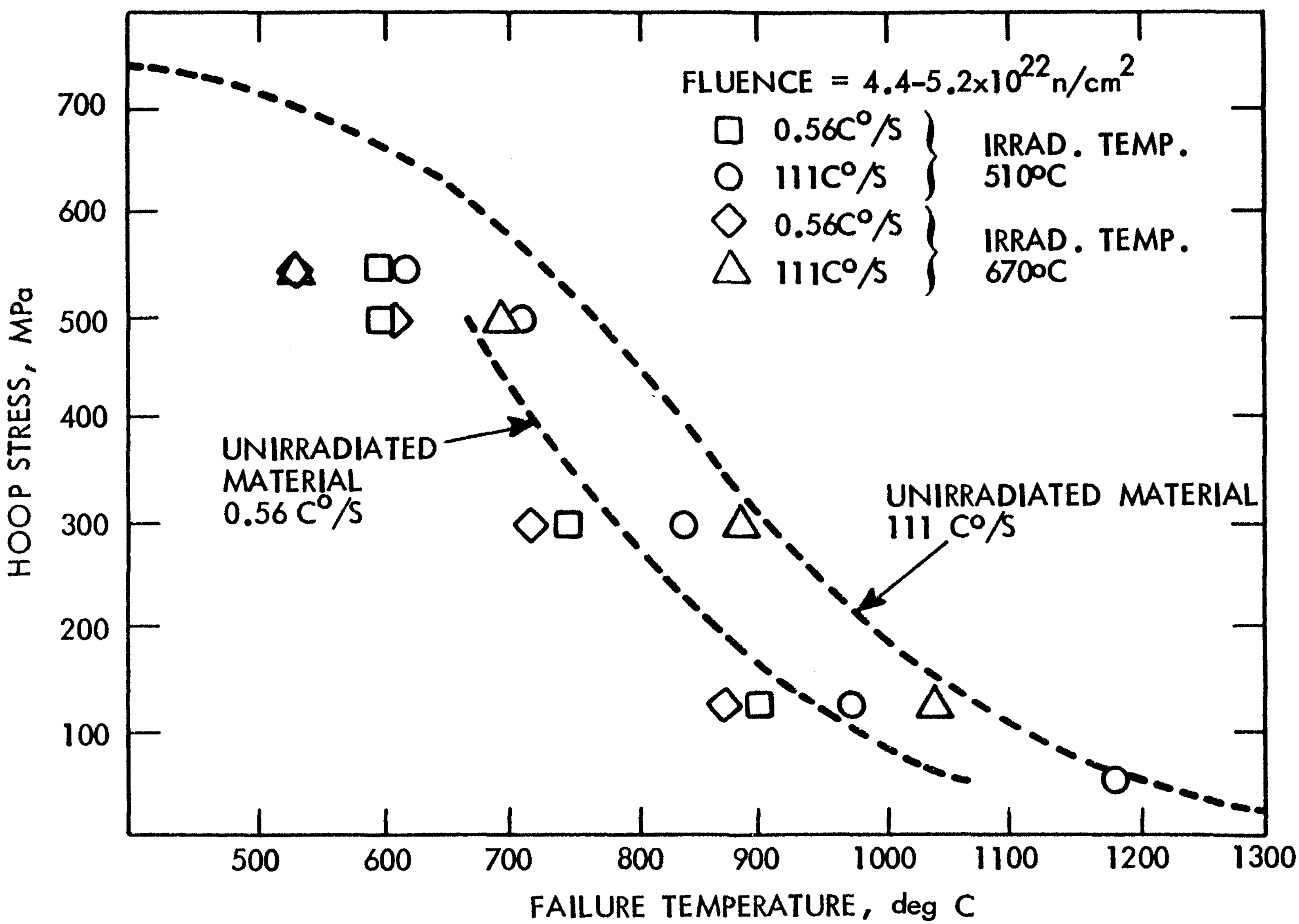


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FIG 4

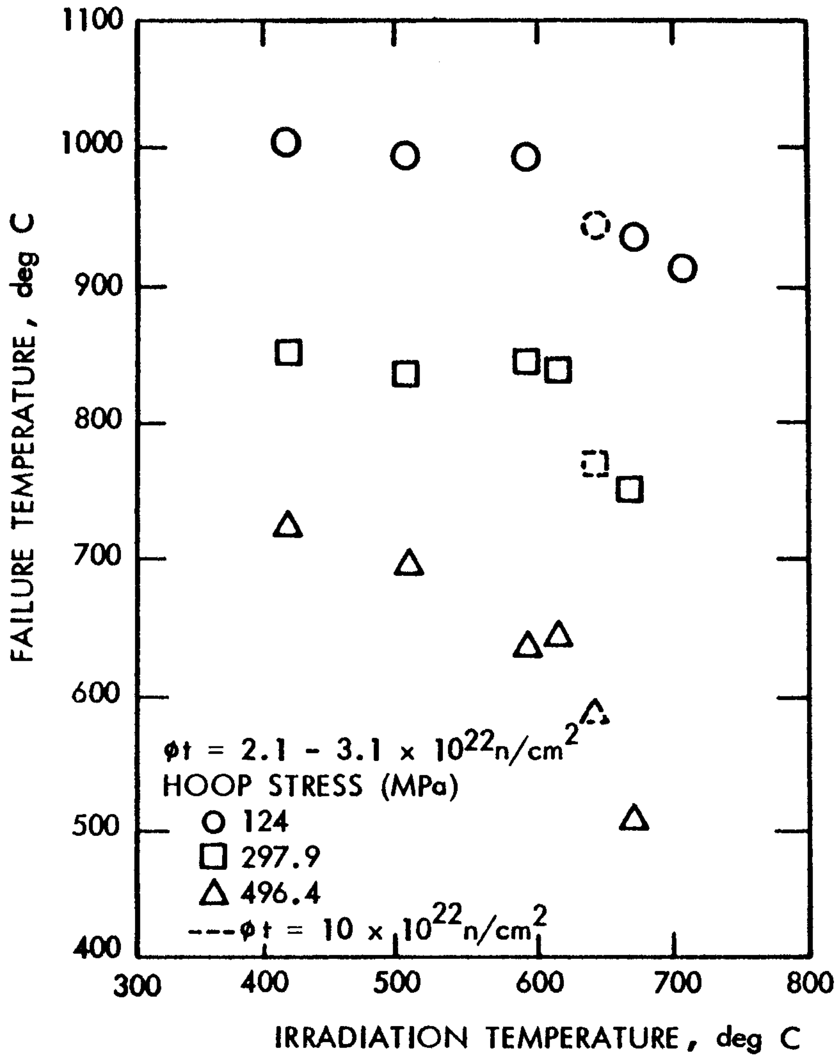


FIG 5

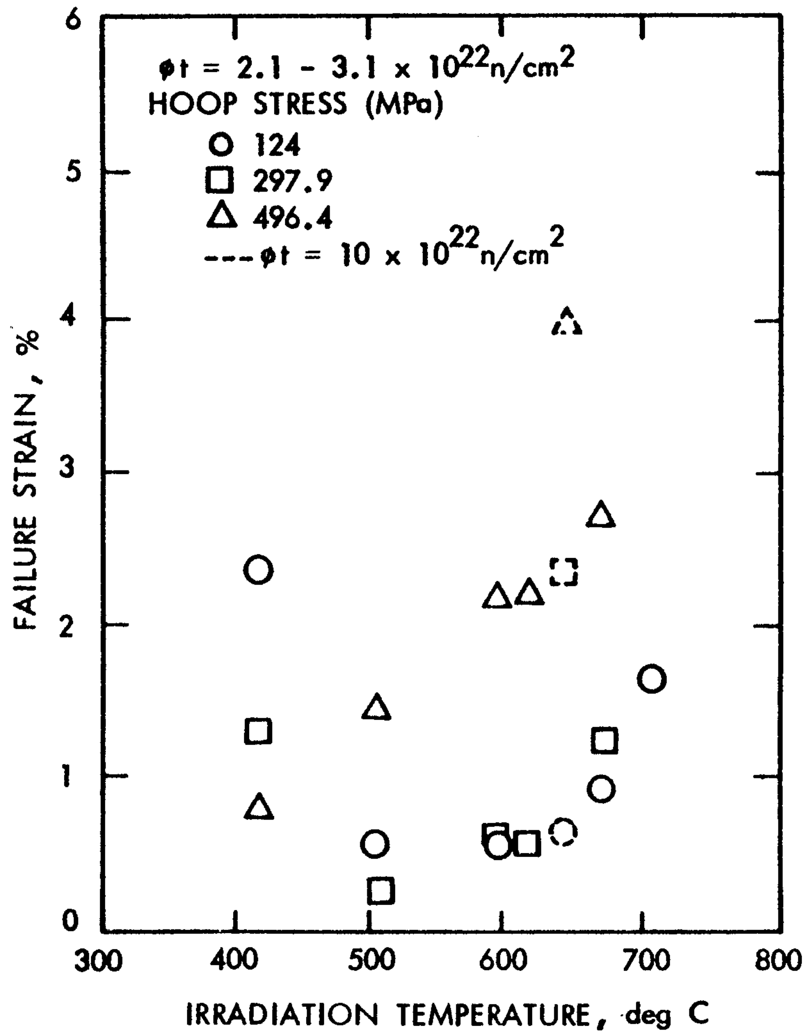
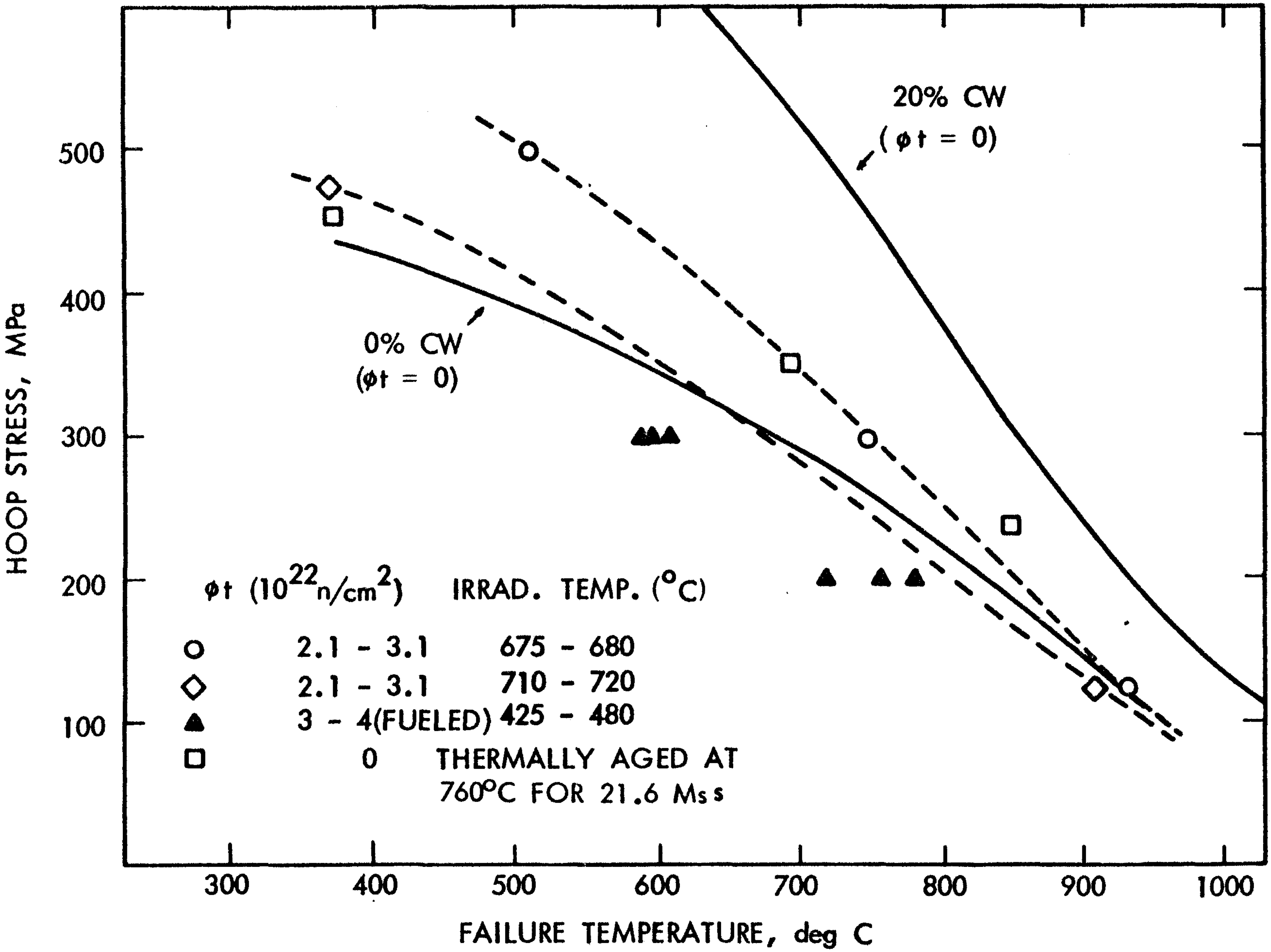


FIG 6

HEDL 7805-55.5



HEDL 7805-55.3

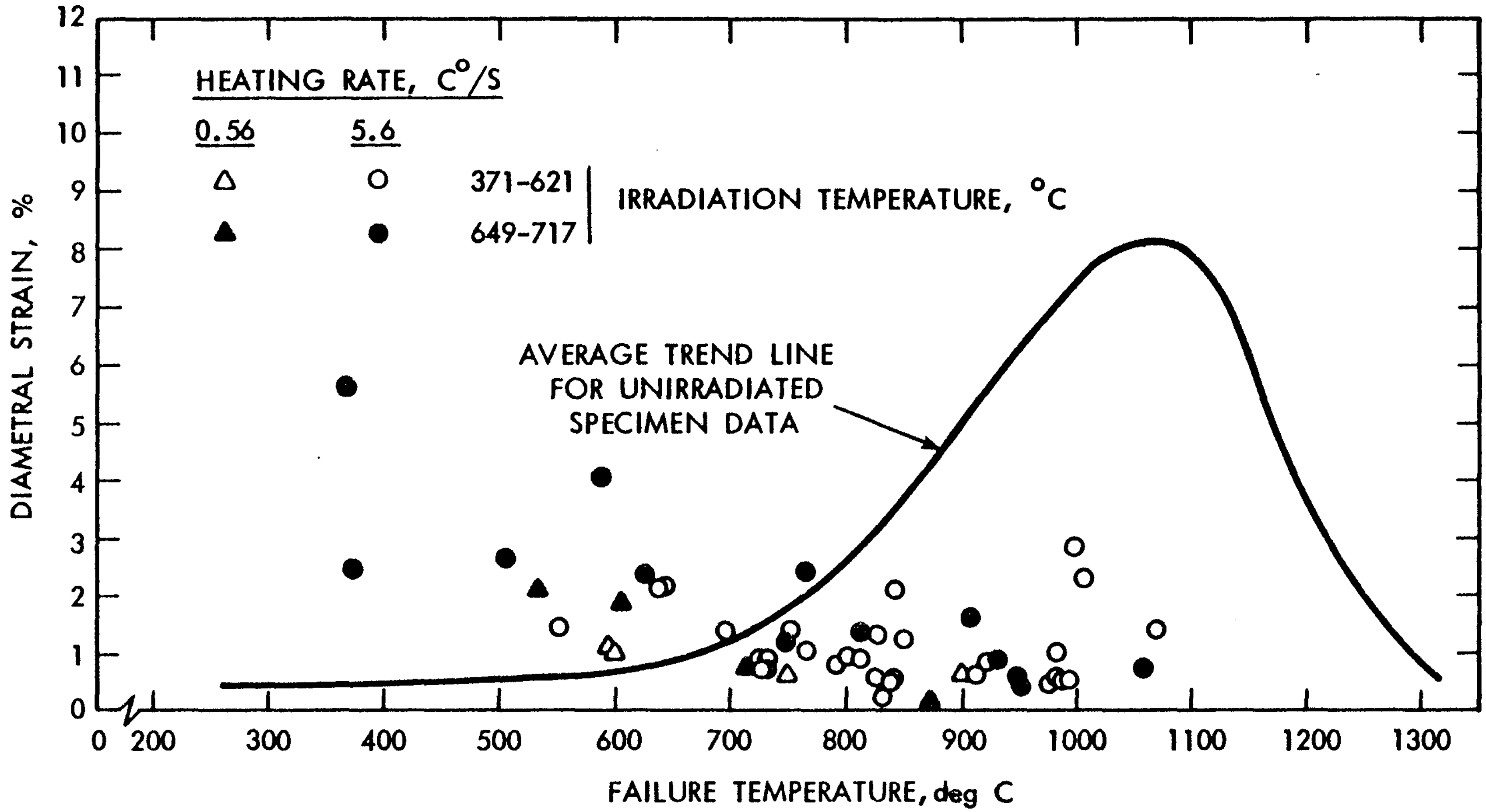


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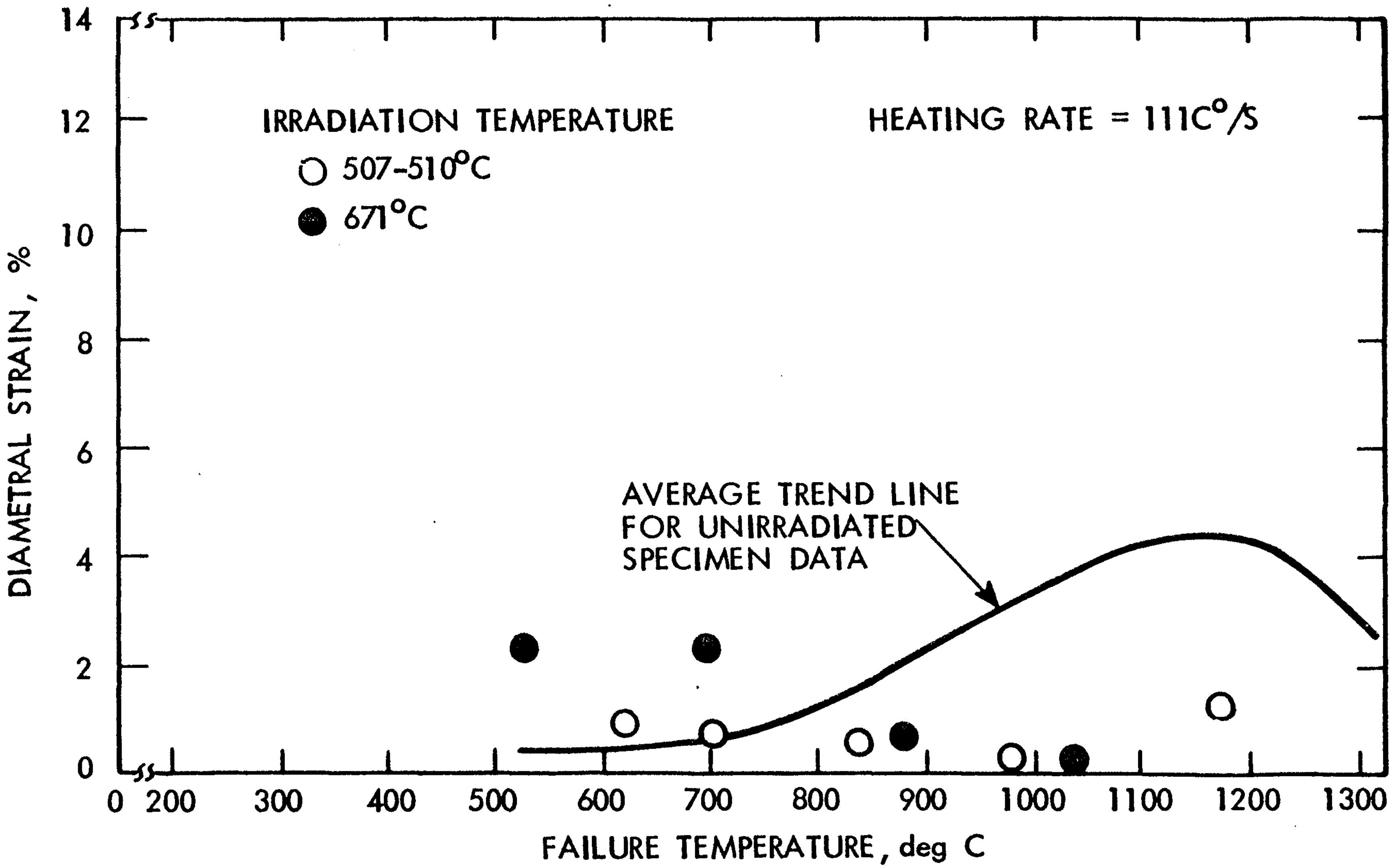
FIG 8



HEDL 7805-074.1

FIG 9