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Hastelloy X Fuel Element Creep Relaxation and Residual Effects

AUTHOR

R. A. Castle

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<table border="1"> <thead> <tr> <th>* NAME</th> <th>MAIL ADDR</th> </tr> </thead> <tbody> <tr><td>J. G. Asquith</td><td>LB02</td></tr> <tr><td>J. E. Brunings</td><td>LB41</td></tr> <tr><td>N. F. Davies</td><td>LB45</td></tr> <tr><td>R. L. Detterman</td><td>LB03</td></tr> <tr><td>L. M. Maki</td><td>LB02</td></tr> <tr><td>J. R. Miller</td><td>LB45</td></tr> <tr><td>K. E. Moore</td><td>LB45</td></tr> <tr><td>T. A. Moss</td><td>LB03</td></tr> <tr><td>T. G. Parker</td><td>LB45</td></tr> <tr><td>S. Siegel</td><td>LA05</td></tr> <tr><td>R. F. Wilson</td><td>LB01</td></tr> <tr><td>Reactor Program File</td><td>LB03</td></tr> <tr><td>Reactor Engineering Unit (12)</td><td>LB25</td></tr> </tbody> </table>		* NAME	MAIL ADDR	J. G. Asquith	LB02	J. E. Brunings	LB41	N. F. Davies	LB45	R. L. Detterman	LB03	L. M. Maki	LB02	J. R. Miller	LB45	K. E. Moore	LB45	T. A. Moss	LB03	T. G. Parker	LB45	S. Siegel	LA05	R. F. Wilson	LB01	Reactor Program File	LB03	Reactor Engineering Unit (12)	LB25	<p>A worst case, seven element, asymmetric fuel, thermal environment was assumed and a creep relaxation analysis generated. The fuel element clad is .020 inch Hastelloy X. The contact load decreased from 11.6 pounds to 5.87 pounds in 100,000 hours. The residual stresses were then computed for various shutdown times.</p>			
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INTRODUCTION

A Hastelloy X fuel element clad was analyzed for creep relaxation when loaded as a point load, 8 inches from the hot end, on a beam pinned at each end. The six theta stresses were also included in the relaxation analysis. These stresses were then allowed to relax using an incremental time, strain hardening rule, creep analysis. This relaxation reduced the stresses in addition to reducing the contact force which in turn reduced the beam bending moment and bending stresses.

The analysis is simple in concept and considers only uniaxial stresses and creep phenomenon. It is intended later to account for local biaxial effects which will reduce the creep rate and cause a different redistribution of stresses. The analysis was programmed on the GE Timeshare computer. The listing is presented in Reference 1 and the necessary changes shown in Appendix A.

DISCUSSION

Analysis Case - The condition chosen for analysis is the most severe case analyzed for temperatures with the GEXM2 heat transfer code. It assumed a seven element cluster across the zone boundary with asymmetric fuel oriented to give the worst transelement temperature gradients. A description of the temperatures is given in Figure 1 showing the hot line maximum and cold line minimum axial temperature profiles and the circumferential gradients at Z/L of 0.7. Element 17 (Figure 1) is the stress critical element with a maximum transelement clad temperature gradient of 55.5°F and a cross element coolant channel temperature of 32.2°. The structural equivalent transelement temperature gradient is 43°F.

The creep curves were obtained from Reference 2 and are reproduced in Figures 2 and 3 for reference. The Oak Ridge data (Reference 3) indicated approximately the same degree of first stage creep in Hastelloy X as existed in Incoloy 800. The first stage creep amplification used in the Incoloy analysis was also used in the Hastelloy X analysis.

The life fraction damage was computed by summing the time increment used in the analysis divided by the time to rupture for the stresses developed during that time increment.

FIGURE 1

70-D7-121-101

OPERATING STRESSES

- MOST SEVERE CONDITION
7 ELEMENT CLUSTER ASYMMETRIC FUEL
UPPER BOUND EQUIVALENT ΔT 43°
|
ELEMENT 17 CRITICAL

$$\text{Life Fraction} = \sum \frac{\text{time at stress } \sigma_2}{\text{time to rupture at stress } \sigma_2}$$

The room temperature residual stresses on cooldown were also calculated for the Incoloy analysis presented in Reference 1 and for the present analysis.

ANALYSIS

The initial stresses were derived from a .006 inch initial circular bow of the element due to manufacturing tolerances and a bow dictated by the thermal environment less the .001 inch clearance between elements. Then the six theta stresses were added.

The creep analysis is identical to that of Reference 3 except that the creep laws were changed from those for Incoloy 800 to those for Hastelloy X, and the life fraction creep damage was computed. Also residual effects were computed. The complete expanded analysis is presented .

The analysis method considers a beam made up of ten sections each 1.85 inches long with a circular cross section divided into 60 elements (Figures 4 & 5).

FIGURE 4 - Beam Stations

The beam (or fuel element contact) load is known from other analysis and is the result of a thermal gradient causing the element to bow and contact its neighbor. The contact load defines the bending moment and therefore the bending stress. The bending stress in each element J (Figure 5) of station I (Figure 4) is

$$\sigma(I, J) = \frac{M(I)}{\pi R^2 t} \cos \left(\left(\frac{\pi}{30} \right) (J - I) \right)$$

In addition the six theta stresses (computed from another program) are input and added to the bending stress for each element J at each station I. Having defined the basic stress levels above the logic of the program is as follows (see Figure 6):

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FIGURE 5. TYPICAL CROSS SECTION
CIRCUMFERENTIAL STATION J

PITCH : .670 INCH
 CLEARANCE : .002 INCH
 OD : .655 INCH

$$r(I) = R \cos\left(\frac{\pi}{30}(J-I)\right)$$

FIGURE 6
MOMENT DIAGRAMS

1. Compute the creep strain at each element J of each station I. The creep curves and equations are given in Figure 6.

2. Compute the fictitious load, at each element, defined by the creep strain at each element J times the modulus of elasticity times the distance from the neutral axis

$$M_F(I) = \sum_{J=1}^{J=60} \epsilon_c(I, J) \times E \times A \times R \cos \left(\frac{\pi}{30} (J - 1) \right)$$

3. Compute the change in deflection at the load point due to the fictitious moment distribution of step 2. The principal of vertical work is used by applying a unit moment at the load point.

$$\delta = \int_{I=1}^{I=11} \frac{M(I) m ds}{EI}$$

where

M is the Moment from step 2

m is the virtual moment

s is the beam length

E is modulus of elasticity

I = moment of inertia

4. The real load, or load relaxation, is computed which will cause the same deflection as in step 3.

$$\delta = \frac{Pab}{6EI} \left(2l - 2b^2 \right)$$

$$= 127.5 P/EI$$

5. A new moment diagram is drawn which is the sum of

- a. The moment for the previous step
- b. Less the moment relaxation computed in step 2
- c. Less the moment caused by the load relaxation computed in step 4
- d. Plus the moment of step 2 redistributed in a linear manner.

6. The stress at each element is then computed as described above

$$\sigma = \frac{M(I)}{\pi R_t^2} \cos \left(\frac{\pi}{30} (J - I) \right)$$

7. The creep relaxation is computed by assuming a time increment and computing the strain by the equations

$$\epsilon_c = 2.0596 \times 10^{-9} \sigma^{7.7248} e^{-109060/T_{oR}} \quad (\text{Ref. 2})$$

If the strain is below $.0528 \left(\frac{\epsilon_c}{\Delta T} \right)^{.22}$ then the strain rate is assumed to be 2.3 times the above equation.

8. The creep damage for this increment of time is computed by dividing the increment of time by the time to rupture at this particular stress level where time to rupture is defined as

$$t_R = 1 \times 10^{20} \sigma^{-9.96578} e^{104990/T_{oR}}$$

and the total damage is

$$D = \sum \frac{t_i}{t_R}$$

9. This completes one cycle and then the next cycle repeats from step 2.

The residual stresses listed in Table 1 were then computed as follows:

1. Find the room temperature contact load by:

- a. Subtract the bow caused by the existing operating contact load from the initial thermal bow. This defines the free bow in the opposite direction.
- b. Subtract out a .001 inch clearance.
- c. Compute the room temperature load necessary to deflect the element through the movement of steps a and b.

2. Compute the bending stresses defined by the load of step 1c.

3. Find the six theta and redistributed bending components of the residual stresses.
 - a. At temperature compute the bending stress relaxation by finding the moment and stresses due to the difference in load from time zero to the time in question.
 - b. Subtract this stress from the stress at time zero. The remainder is the initial ϵ_0 plus the remaining bending.
 - c. Subtract out the remaining stress in each element to obtain the "residual operating temperature" stress and divide this by E to find the strain.
 - d. Multiply the strains of step c by the room temperature modulus to find the six theta and redistributed bending residual stresses.
4. The total residual stress is found by combining steps 3d & 2.

RESULTS

The results are shown in Figure 7 and in Table 1. The load relaxation is seen to be from 11.60 pounds to 5.87 pounds in 100,000 hours while the corresponding stress relaxation is from -13260 psi to -3520 psi. Another aspect of the relaxation is when the reactor is shut down and the thermal environment neutralizes. Then if the stresses are completely relaxed out the room temperature strains will be equal and opposite to the initial operating strains. Since the stresses are not completely relaxed the residuals are not totally equal to the equal and opposite phenomena. The residual stresses introduced are 5510 psi compression and 11130 psi tension after 100,000 hours. Stresses at other time increments are shown in Table I.

A comparison of the total room temperature stresses, including the effects of the SCB coating induced stresses are shown in Table 2 for the Incoloy 800 and Hastelloy X elements. The Incoloy stresses are from Reference 1. These stresses are compared to the proportional limit at room temperature to determine the Margin of Safety against thermal ratcheting. It is seen that the .020 inch Hastelloy X clad maintains a positive margin of safety while the .032 clad Incoloy 800 margin of safety is negative after approximately 50 hours of operation in this "worst case" environment.

FIGURE 7
CREEP RELAXATION - HASTELLOY X

TABLE 1 CREEP ANALYSIS SUMMARY

TIME (HOURS)	LOAD (POUNDS)	COMPRESSIVE STRESS (psi)	RESIDUAL TENSILE STRESS (psi)	TENSILE STRESS (psi)	RESIDUAL COMPRESSIVE STRESS (psi)	MAX. CREEP STRAIN (%)	CREEP DAMAGE %
0	11.60	-13260	0	8995	0	0	0
1	11.57	-12791	640	8649	-465	-.002	.00009
10	11.38	-10873	3190	8589	-355	-.012	.00039
100	10.78	-8097	7050	7728	-1000	-.026	.00066
1000	9.54	-5946	8410	5920	-2350	-.038	.00078
10000	7.50	-4220	10220	4216	-4130	-.051	.00086
50000	6.37	-3771	10820	3459	-5160	-.056	.0009
100000	5.87	-3520	11130	3208	-5510	-.059	.0009

COMPARISON OF RESIDUAL STRESSES ~ INCOLOY & HASTELLOY

TABLE 2

TIME HOURS.	HASTELLOY X			INCOLOY 800		
	RESIDUAL TENSILE STRESS (psi.)	TOTAL ROOM TEMP STRESS (psi.)	MARGIN OF SAFETY (%)	RESIDUAL TENSILE STRESS (psi.)	TOTAL ROOM TEMP STRESS (psi.)	MARGIN OF SAFETY (%)
0	0	13400	169	0	10800	43
1	640	13400	169	5530	13050	19
10	3190	13250	172	6700	14000	11
100	7050	15600	130	9555	16250	-.05
1000	8410	17000	112	11340	17650	-.12
10000	10220	17710	103	12680	19000	-.19
50000	10820	19000	89	13290	19500	-.20
100000	11130	19300	86	13540	19700	-.21

- 7 ELEMENT CLUSTER
- ASYMMETRIC FUEL
- RESIDUAL STRESSES ARE RESULT OF CREEP ANALYSIS
- TOTAL STRESSES HAVE SCB COATING INDUCED STRESSES INCLUDED
- MARGIN OF SAFETY BASED ON PROPORTIONAL LIMIT
INCOLOY = 15500 psi
HASTELLOYX = 36000 psi

References

1. TI-759-200-003 "Fuel Element Creep Relaxation", R. A. Castle, 12/16/70.
2. Internal Letter "Design Data for Incoloy 800, Hastelloy N, and Hastelloy X", to T. G. Parker from K. E. Moore, August 17, 1970.
3. TI-759-200-005 "Tentative Creep Law for Incoloy 800", R. A. Castle, December 28, 1970.

APPENDIX A

CHANGES TO COMPUTER
CODE (REF: TI 759-200-003)

TYPE OLD OR NEW: OLD

PROBLEM NAME: CRP

READY

36

520 PRIM-NT T(7,2),D(7,2),U1

521 PRINT T(7,28),D(7,28),U2

522

523

876 PRINT P4

331 NEXT I

332 LET U1=T1/((1E20)*T(7,2)+(-9.96578)*EXP(104990/(G(7)+460)))+U1

335 LET U2=T1/((1E20)*T(7,28)+(-9.96578)*EXP(104990/(G(7)+460)))+U2

70 LET U1=0

71 LET U2=0

13 LET P=-11.6

121 LET T(I,J)=.895*T(I,J)

281 LET S(I,J)=(158/108.5)*S(I,J)

290 LET E(I,J)=2.05959E-9*B+7.7248*EXP(-109060.4/(G(I)+460))

730 LET A=-22.4E6*D(I,J)*.3175*COS((J-1)*3.1416/30)*.000665

735 LET H=-22.4*F(I,J)*.3175*COS((J-1)*3.1416/30)*665

874 LET P4=11.6-P1

RUN