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A. E. Carden,† D. G. Harman, and E. A. Franco-Ferreira
Metals and Ceramics Division
Oak Ridge National Laboratory
Oak Ridge, Tennessee

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THERMAL FATIGUE ANALYSIS OF A CRYOGENICALLY COOLED ROCKET NOZZLE*

A. E. Carden,† D. G. Harman, and E. A. Franco-Ferreira
Metals and Ceramics Division
Oak Ridge National Laboratory
Oak Ridge, Tennessee

INTRODUCTION

Most interplanetary mission profiles require a source of primary thrust which can be throttled and cycled on and off a large number of times during a given journey. One attractive propulsion scheme for a mission of this type is the nuclear rocket presently under development in the Rover Program.

In essence, a nuclear rocket is a cryogenically cooled exhaust nozzle coupled to a reactor which acts as a heat source for the propellant. The configuration of the exhaust nozzle is typical of most regeneratively cooled nozzles. That is, the interior surface of the nozzle, which is in contact with the hot propellant gas, is made up of a multiplicity of suitably shaped, thin-walled tubes which are bonded to each other. The cryogenic coolant passes through the insides of these tubes, thereby preventing them from melting. In many cases it is necessary, in order to provide greater strength to resist high chamber pressures, to bond a relatively heavy reinforcement jacket to those portions of the tubes which make up the outer surface of the nozzle. A schematic diagram of a typical cross section of such a configuration is shown in Fig. 1.

It is apparent that, in a nozzle of the type described above, there will be a very large ΔT between the tube crowns on the hot gas side and those portions of the tubes bonded to each other and to the jacket. The ΔT 's experienced in normal modes of operation are capable of producing calculated thermal strains

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of as much as 2%. Due to the restraint provided by the jacket, it is likely that a significant portion of the longitudinal thermal strain will be converted into mechanical deformation of the tube crowns. Thus, under conditions of cyclic nozzle operation, it may be possible to induce low-cycle thermal fatigue failures in the tubes.

It is not economically feasible to use full-scale nozzle hardware to analyze experimentally the behavior described above. Consequently, there is an incentive to devise a scale-model type of test which is capable of evaluating the effects of all the important parameters which are operative in an actual nozzle. In the case of thermal cycling stresses, as discussed here, the important considerations include (a) the temperature distribution, (b) the physical and mechanical properties of the nozzle material, (c) the operating environment, (d) the geometry of the nozzle elements, and (e) the loading conditions.

This paper describes the thermal cycle testing of specimens which were designed to simulate and evaluate the conditions existing in a nozzle of the general configuration shown in Fig. 1. The test results are related to important fabrication and operating parameters. An effort is also made to relate the results to a range of nozzle operating conditions.

SPECIMEN PREPARATION

Each test specimen consisted of a planar array of six thin-walled Hastelloy X tubes brazed to each other and to a thick Hastelloy X base plate. The tubes were 1/2-in. diam with a 0.012-in. wall and the base plate was 4 in. wide, 10 in. long, and 7/8 in. thick. A schematic diagram of the specimen is shown in Fig. 2. Both ends of each tube were plugged. Entry and exit ports for the coolant were drilled through the base plate and into the tubes near opposite ends of each specimen.

Each specimen was instrumented with numerous thermocouples to provide temperature distribution data. These thermocouples were Chromel-P-Alumel with a wire diameter of 0.010 in. They were resistance welded to the tube crowns and to the base plate at various locations. For each thermocouple, the individual wires were welded to the specimen a short distance apart so that a portion of the specimen itself would be included in the junction. The thermocouple locations and attachment procedure were carefully controlled and reproduced for each test.

The heat source used in these experiments was a quartz lamp radiant furnace. It was positioned parallel to, and approximately 1/2 in. above, the tube crowns. The furnace had a lamp area of 8 in. by 2 1/2 in. and an electrical power input to the lamps of 13.2 kw. This produced a measured heat flux at the specimen surface of approximately 700 w/in.². An overall view of the test setup, with the furnace tilted up to expose the lamps, is shown in Fig. 3.

The specimen base plate was kept at or near the coolant temperature by bolting it to a massive copper heat sink. As evident in Fig. 3, this heat sink was contained in a pan which enabled it to remain completely submerged in coolant during the test.

Coolant flow was introduced into the insides of the tubes through a copper manifold, shown at the left end of the specimen in Fig. 3. This manifold was positioned beneath the surface of the coolant in the pan to maintain a constant temperature for the flow of tube coolant.

TESTING PROCEDURE

In all tests, LN_2 was used as the coolant. The pan shown in Fig. 3 was maintained full of LN_2 for the duration of each test. A separate source of LN_2 was connected to the tube coolant inlet manifold. The LN_2 flow which cooled the tubes was allowed to exhaust directly into the pan at atmospheric pressure. Provisions were made to maintain an argon atmosphere over the tube surfaces to protect them from excessive oxidation.

A test run for a given specimen was characterized by thermally cycling the tube crowns from LN_2 temperature to an elevated temperature and back to LN_2 temperature. A number of identical cycles were reproduced until tube failure occurred.

A complete thermal cycle proceeded as follows:

1. The heat sink and base plate were held at or near LN_2 temperature.
2. The tubes were cooled to LN_2 temperature by their internal coolant flow.
3. The quartz lamp furnace was turned on and the tube crowns brought to the specified peak temperature and held for a predetermined length of time (hold times of 15 sec and 5 min were studied). Coolant flow through the tubes was maintained during this step.
4. The furnace was turned off and the entire specimen was cooled to LN_2 temperature.

A typical test thermal cycle, as traced by a strip-chart recorder connected to the specimen thermocouples, is shown in Fig. 4. This particular cycle was for the 5-min hold time.

During test equipment checkout runs using mockup specimens, it was noticed that small dents in the tubes of the mockup specimens acted as geometric instabilities and led to premature failure. Since the existence of small tube dents as fabrication defects cannot be ignored, it was decided to include a study of their effects in this program. Controlled dents were therefore made in some of the

specimen tube crowns. This was done using a 1/4-in.-diam cylindrical indenter with its longitudinal axis parallel to the plane of the specimen base plate, but at a 90° angle to the longitudinal axes of the tubes. Dents were made to depths of 0.005, 0.010, and 0.020 in.

A closeup view of the tube crown surfaces of one of the specimens prior to testing is shown in Fig. 5. Both smooth and predented (with two controlled dents, 0.020 in. deep) tubes, as well as the attachment points of six monitor thermocouples, are shown. The various parameters studied in the entire series of tests are listed in Table 1.

Table 1. Thermal Cycle Data^a

Specimen Number	Temperature, °F		Hold Time at Temperature Maximum	Tube Condition	Number of Thermal Cycles to Failure		
					First Visible Wrinkling	First Visible Crack	Crack Through Wall
X-1	1800	-200	5 min	Smooth	14	41	50
X-2	1800	-200	15 sec	Smooth	30	70	80
X-3	1900	-200	5 min	Smooth	11	32	42
				20-mil dent ^b		18	22
				20-mil dent ^b		21	26
X-4	1800	-200	5 min	Smooth	14	49	57
				Small sharp dent ^c		25	33
				Medium deep dent ^c		39	49
				Large shallow dent ^c		56	d
				20-mil dent ^b		19	28
				20-mil dent ^b		22	30
				20-mil dent ^b		25	33
				10-mil dent ^b		25	35
				5-mil dent ^b		d	d
X-5	1600	-200	5 min	Smooth	15	75	79
				20-mil dent ^b		23	35
				20-mil dent ^h		25	38

^aTube crown heating time from -200°F to temperature maximum was approximately 5 sec/cycle.

^bDepth of controlled dent made in top of tube crown with a 1/4-in.-diam indenter.

^cDescription of dents in as-received specimen.

^dNo failure.

TEST RESULTS

The results of all the tests are detailed in Table 1. For undented tubes, local creep buckling in the form of ripples occurred in the tube crowns in approximately 15 to 30 cycles, depending on hold time. The ripples stabilized in location but increased in amplitude as the cycling progressed. Failure was always associated with a ripple and normally occurred in a valley rather than on a peak. Failure was defined as a crack through the tube wall capable of passing LN₂.

In the case of dented tubes, the dent locations can be considered to be "pre-rippled" sites. During cycling, the dents deepened while the adjacent smooth tubing develops ripples. The deepening dents invariably were responsible for premature failure. The presence of these deleterious dents appears to reduce tube life, as compared with that for a smooth tube, by a factor of $1/3$ to $1/2$. However, there does seem to be a threshold value of dent severity below which damage does not occur. For example, the 0.005-in.-deep controlled dent and the so-called "large shallow" as-received dent had no effect on tube life.

The appearance of the specimen pictured in Fig. 5 at the 22-cycle point in its test is shown in Fig. 6. Failure has occurred at both of the 0.020-in.-deep controlled dents and the ripples are well established in the originally smooth tube surfaces. Figure 7 shows the specimen at the test termination point of 42 cycles. Both the cracked dents and the ripples have continued to deepen. The tube shown at the top, which was originally smooth, has also failed at a ripple location which suddenly became unstable and grew considerably deeper than its neighbors. This general behavior was typical of all the specimens tested.

ANALYSIS OF RESULTS

An effort was made to relate the data obtained in these tests to existing fatigue data. A survey of the literature revealed only a small amount of such data¹ for Hastelloy X, and it was for isothermal strain fatigue. It was not possible to obtain a good correlation between this and our thermal fatigue data. However, appropriate information,² obtained by thermal cycle testing of tubular specimens, was available for a similar alloy, Hastelloy N. This was used for correlations with our test results.

¹M. B. Reynolds, Strain-Cycle Phenomena in Thin-Wall Tubing, GEAP-4462, (Jan. 30, 1964).

²A. E. Carden, "Thermal Fatigue of a Nickel-Base Alloy," J. Basic Eng. Trans. ASME, Ser. D 87, 237 244 (1965).

The Hastelloy N thermal fatigue data is plotted as ΔT (thermal cycle test temperature range) versus N_f (number of cycles to failure) in Fig. 8. The curve is for a constraint factor F of unity. This constraint factor is defined as the ratio of actual mechanical deformation in the specimen to the total available thermal strain ($\alpha\Delta T$) calculated from the thermal cycle. Figure 9 shows a family of thermal fatigue curves for Hastelloy N, plotted for three different constraint factors. The curve for $F = 1$ is a repetition of the curve shown in Fig. 8, while the curves for $F = 1.2$ and $F = 1.5$ are derived by calculation from the $F = 1$ curve.

An analysis of the geometry of the specimens used in these tests indicated that the tube crowns were under very effective constraint. In fact, it appeared reasonable to consider the constraint factor for a smooth-tubed specimen to be on the order of unity. Variables such as longer hold times and dented tubes were expected to increase the constraint factor.

The data generated by these tests have been superimposed on the family of curves of Fig. 9. This is shown in Fig. 10. The data for the 15-sec hold time and the $F = 1$ curve correlate quite well. The data for the longer hold time of 5 min indicate that the effective constraint factor has been increased to the order of $F = 1.2$. It is felt that this is due primarily to stress relaxation of the tube crowns which can occur under the conditions of time and temperature studied. The results for the dented tubes show constraint factors in the vicinity of $F = 1.5$ due to the strain concentrating effects of the dents.

It appears from this correlation that the techniques used for the determination of the Hastelloy N data are appropriate to the thermal fatigue problems in regeneratively cooled rocket nozzles. Therefore, work is presently under way to obtain similar data for Hastelloy X. This data will be associated with the points plotted in Fig. 10. It should then be possible to extrapolate accurately the data obtained in the tests reported here to a wide range of nozzle operating conditions. Additional tests will be performed to investigate the effects of internal pressure on the fatigue life of the tubes.

CONCLUSIONS

1. Thermal fatigue can be a serious problem for the coolant tubes of regeneratively cooled rocket nozzles.
2. A laboratory test has been devised which provides thermal conditions similar to those seen in service. This test has been capable of producing tube failure in substantially less than 100 thermal cycles. Thus, the principles of similitude and modeling appear to be appropriate for the examination or determination of low-cycle fatigue characteristics of large complex structures.

3. Increasing high-temperature hold times, up to 5 min, and dents in the tubes appreciably curtail the fatigue life.

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Fig. 1 Schematic Diagram of a Transverse Cross Section of a Typical Regeneratively Cooled Nozzle.

Fig. 2 Schematic Diagram of Thermal Cycle Specimen.

Fig. 3 Overall view of Thermal Cycle
Test Setup

Fig. 5 Pretest Specimen. Note thermocouple locations and two 0.020" deep controlled dents made with $\frac{1}{4}$ -in diameter indenter.

Fig. 6 Appearance of specimen after 22 cycles. Note failures at both dent locations and wrinkling in the remainder of the tubing.

Fig. 7 Appearance of specimen after 42 cycles. Note failure of an originally smooth tube at a wrinkle location.

Fig. 8 Thermal Cycle Fatigue Curve For Hastelloy N.
For a Constraint Factor of Unity.

Fig. 9 Thermal Cycle Fatigue Curves for Hastelloy N. For Constraint Factors (F) of 1.0, 1.2, & 1.5.

Fig. 10 A correlation of Hastelloy X thin-wall tubing thermal fatigue data points with Hastelloy N thermal cycle fatigue curves for various constraint factors.