39. ✓Rover Rocket Nozzle Materials

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We are continuing¹ to provide materials and fabrication support to the AEC-NASA Space Nuclear Propulsion Office on the Rover Nuclear Rocket Program. In general, we provide technical liaison between NASA and its contractors, and, where necessary, perform appropriate experimental studies. This assistance has been directed mainly toward the fabrication of nozzles to be used in static reactor test firings at the Nevada test site.

Two types of nuclear rocket engines are involved: Phoebe II (a 5000-Mw, 250,000-lb-thrust system primarily for reactor development) and NERVA II (a 5000-Mw, 250,000-lb-thrust engine development system ultimately aimed at a flight mission).

The work may be divided into two broad categories: studies in direct support of NASA contractor operations and studies aimed at developing a generalized rocket materials technology. Some aspects of the general experimental program will be discussed below.

THERMAL FATIGUE TESTING OF NOZZLE TUBE CONFIGURATIONS

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The nozzles used with nuclear rockets are 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 to prevent 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 that make up the outer surface of the nozzle. A schematic diagram of a typical cross section of such a configuration is shown in Fig. 39.1.

It is apparent that, in a nozzle of the type described above, there will be a very large temperature difference between the tube crowns on the hot gas side and those portions of the tubes bonded to each other and to the jacket. The temperature differences experienced in normal modes of operation are capable of producing calculated thermal strains 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, low-cycle thermal fatigue failures may be induced in the tubes.

A scale-model test was devised³ to measure the effects of all the important parameters operative in an actual nozzle. In the case of thermal-cycling stresses, as discussed here, the important considerations include (1) the temperature distribution, (2) the physical and mechanical properties of the nozzle material, (3) the operating environment, (4) the geometry of the nozzle elements, and (5) the loading conditions.

A schematic diagram of the specimen is shown in Fig. 39.2. Each test specimen consisted of a planar array of six thin-walled Hastelloy X tubes brazed to

¹E. A. Franco-Ferreira, *Metals and Ceramics Div. Ann. Progr. Rept. June 30, 1966*, ORNL-3970, pp. 236-44.

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³A. E. Carden, D. G. Harman, and E. A. Franco-Ferreira, "Thermal Fatigue Analysis of a Cryogenically Cooled Rocket Nozzle," pp. 102-1-102-12 in *Proceedings of the Southeastern Symposium on Missiles and Aerospace Vehicles Sciences*, Dec. 5-7, 1966, American Astronautical Society, Huntsville, Alabama, American Astronautical Society, Southeast Section, Huntsville, Ala., 1966.

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each other and to a thick Hastelloy X baseplate. The tubes were $\frac{1}{2}$ in. in diameter with a 0.012-in. wall, and the baseplate was $4 \times 10 \times \frac{7}{8}$ in. Both ends of each tube were plugged. Entry and exit ports for the coolant were drilled through the baseplate and into the tubes near opposite ends of each specimen. Suitable thermocouple instrumentation was added to the tubes and baseplate.

The heat source used in these experiments was a quartz-lamp radiant furnace. It was positioned

Fig. 39.1. Typical Cross Section of a Cryogenically Cooled Rocket Nozzle.

Fig. 39.2. Thermal Cycle Test Specimen. Baseplate is about 4 in. wide, 10 in. long, and $\frac{7}{8}$ in. thick. Coolant tubes are $\frac{1}{2}$ -in. diam with 0.012-in. wall.

parallel to and approximately $\frac{1}{2}$ in. above the tube crowns. The furnace had a lamp area of $8 \times 2\frac{1}{2}$ 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. The specimen baseplate was kept at or near the liquid nitrogen coolant temperature by bolting it to a massive copper heat sink. Coolant flow was introduced into the tubes through a copper manifold.

A test run for a given specimen was characterized by thermally cycling the tube crowns from liquid-nitrogen temperature to an elevated temperature and back. A number of identical cycles were reproduced until the tube failed. A typical test thermal cycle, as traced by a strip-chart recorder connected to the specimen thermocouples, is shown in Fig. 39.3. This particular cycle was for the 5-min hold time.

The results of all the tests are detailed in Table 39.1. 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 liquid nitrogen.

A transverse section of a tube crown through a typical failure is shown in Fig. 39.4. This failure

Fig. 39.3. Typical Test Cycle Showing Tube-Crown and Baseplate Temperatures.

Table 39.1. Thermal Cycle Data^a

Specimen	Maximum Temperature (°F)	Hold Time at Temperature (min)	Tube Condition	Number of Thermal Cycles to Failure		
				First Visible Wrinkling	First Visible Crack	Crack Through Wall
X-1	1800	5	Smooth	14	41	50
X-2	1800	0 25	Smooth	30	70	80
X-3	1900	5	Smooth	11	32	42
			20-mil dent ^b		18	22
			20-mil dent ^b		21	26
X-4	1800	5	Smooth	14	49	57
			Small sharp dent ^c		25	33
			Medium deep dent ^c		39	49
			Large shallow dent ^c		56	<i>d</i>
			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		<i>d</i>	<i>d</i>
			Smooth	15	75	79
X-5	1600	5	20-mil dent ^b		23	35
			20-mil dent ^b		25	38

^aTube crown heating time from -200°F the common minimum temperature, to maximum temperature was approximately 5 sec each cycle

^bDepth of controlled dent made in top of tube crown with a $\frac{1}{4}$ -in -diam indenter

^cDescription of dent in as-received specimen

^dNo failure

Fig. 39.4. Cross Section of a 42-Cycle Failure Crack in a Smooth Tube from Specimen X-3. 100 $\times$. As polished.

Fig. 39.5. Thermal Cycle Data for Hastelloy X Thin-Wall Tube Bundles Cycled Between -200°F and 1600 , 1800 , and 1900°F . Hastelloy N constraint curves are shown for comparison. Failure is defined as a crack through a tube wall capable of passing liquid nitrogen.

occurred in 42 cycles in a smooth tube in specimen X-3. Note that this is an intergranular tension failure, indicating that it occurred while the tube was cooling down from peak temperature and in the temperature range 1200 to 1500°F .

We tried to relate the data obtained in these tests to existing fatigue data. Appropriate information,⁴ 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.

The data generated by these tests were superimposed on a family of thermal fatigue curves for Hastelloy N, plotted for three different constraint factors: $F = 1$, 1.2 , and 1.5 . This is shown in Fig. 39.5. 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 near $F = 1.2$. We feel 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.

⁴A. E. Carden, "Thermal Fatigue of a Nickel-Base Alloy," *J. Basic Eng.* 87, 237-44 (1965).

RADIATION DAMAGE TO BRAZING ALLOYS

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E. E. Bloom

The coolant tubes in a nuclear rocket are brazed in place with precious-metal-base brazing alloys. The braze joints must be able to withstand structural loads in the presence of a high neutron flux. Thus, there is an interest in the effects of radiation damage on these brazing alloys. A modest program was conducted to study this problem.

Miller-Peaslee specimens were made of Hastelloy-X base metal and brazed with three different brazing alloys. The specimen was designed to load the braze joint in shear, and shear-stress-strain data were generated. The three brazing alloys studied were Nicro 18 (Au-18% Ni), Palnicro 7 (Au-8% Pd-22% Ni), and Nicoro 80 (Au-16.5% Cu-2% Ni).

One specimen of each brazing alloy was tested in the unirradiated condition at liquid-nitrogen, room, and 400°C testing temperatures. The irradiated specimens were all irradiated at a temperature of 50°C to a dose of 9×10^{19} neutrons/cm² thermal and 5×10^{18} neutrons/cm² fast (> 2.9 Mev). The irradiated specimens of each brazing alloy were then tested at the same three temperatures.

The data were analyzed by comparing the stress-strain curves generated during the tests. The areas under those curves are proportional to the total energy absorbed to fracture the specimens.

The stress-strain curves for the specimens brazed with Nicro 18 are shown in Fig. 39.6. Curves are shown for both irradiated and unirradiated specimens at all three testing temperatures. Radiation damage can be seen at all test temperatures, as evidenced by the greatly reduced areas under the three curves for the irradiated specimens.

Similar behavior is shown in Fig. 39.7 for Palnicro 7. The strengths and ductilities of the unirradiated specimens are comparable to those for the Nicro 18, although there may be a slight bias toward less strength and greater ductility for the Palnicro 7. There is no question that damage is evident in the 400°C and room-temperature tests. However, in the liquid-nitrogen test, only a slight strengthening and slight loss in ductility were shown.

The curves for Nicoro 80 are shown in Fig. 39.8. The 400°C tests show a relatively large amount of damage, while the room- and liquid-nitrogen-temperature tests show little if any damage. Although this may appear to be the most radiation resistant of the three brazing alloys tested, the mechanical properties of this alloy are inferior to those of the

Fig. 39.6. Stress-Strain Curves for Joints Brazed with Nicro. Curves are identified by specimen serial number, testing temperature, and whether irradiated (I) or unirradiated (U).

Fig. 39.8. Stress-Strain Curves for Joints Brazed with Nicoro 80. Curves are identified by specimen serial number, testing temperature, and whether irradiated (I) or unirradiated (U).

Fig. 39.7. Stress-Strain Curves for Joints Brazed with Palnro 7. Curves are identified by specimen serial number, testing temperature, and whether irradiated (I) or unirradiated (U).

other two throughout the entire range of test variables.

No data are available regarding the boron contents of the three brazing alloys, as all specimens were supplied in the brazed form by Aerojet General Corporation. It is likely, though, that the damage is a result of the transmutation of ^{10}B to helium by a thermal-neutron (n, α) reaction rather than by the transmutation of the gold in the brazing alloys into mercury. This statement is based primarily on the great similarity of the behavior seen here to that reported by Martin and Slaughter.⁵

ELEVATED-TEMPERATURE TESTING OF TUBING MATERIAL

D. G. Harman

As the performance of the nuclear rocket is upgraded, the nozzle coolant tubes will have to oper-

⁵W R. Martin and G. M Slaughter, "Irradiation Embrittlement of Welds and Brazes at Elevated Temperatures," *Welding J. (N. Y.)* 45(9), 385-s-391-s (September 1966).

Table 39.2. Short-Time Tensile Properties of 0.012-in.-Thick Allvac 625 Sheet
(Heat 5940) and Hastelloy X Sheet (Heat 261-5-4002)

Property	Value of Property at					
	Room Temperature	1200°F	1400°F	1600°F	1800°F	2000°F
Allvac 625						
As received, at 0.05 min ⁻¹						
0.2% yield strength, psi	53,530	34,280	35,790			
Upper yield strength, psi				33,080	20,750	8,330
Lower yield strength, psi				30,370	17,830	7,520
Ultimate tensile strength, psi	117,290	66,160	59,250	33,080	20,750	8,330
Uniform elongation, %	58.8	22.3	21.7	5.6	1.5	7.1
Total elongation, %	58.8	25.9	53.3	58.2	19.0	22.9
Braze cycle treated, at 0.05 min ⁻¹						
0.2% yield strength, psi	53,530	35,190	33,980			
Upper yield strength, psi				29,770	22,650	8,720
Lower yield strength, psi				27,070	18,650	8,270
Ultimate tensile strength, psi	118,190	90,220	55,340	30,070	22,650	8,720
Uniform elongation, %	63.9	59.8	21.0	5.3	2.0	2.3
Total elongation, %	64.1	59.8	45.9	35.7	23.0	30.0
Braze cycle treated, at 0.005 min ⁻¹						
0.2% yield strength, psi		33,980	31,880		11,730	
Upper yield strength, psi				20,450		5,050
Lower yield strength, psi				16,840		4,540
Ultimate tensile strength, psi		71,580	39,100	20,450	12,330	5,170
Uniform elongation, %		35.5	4.6	2.2	2.0	4.2
Total elongation, %		41.5	40.7	33.4	25.3	22.0
Hastelloy X						
As received, at 0.05 min ⁻¹						
0.2% yield strength, psi	78,200	49,620	43,000	30,980	18,650	9,380
Ultimate tensile strength, psi	115,790	78,190	52,330	31,580	19,850	10,070
Uniform elongation, %	35.3	36.5	11.0	4.6	4.0	3.5
Total elongation, %	38.2	38.6	46.5	39.3	42.3	40.0
Braze cycle treated, at 0.05 min ⁻¹						
0.2% yield strength, psi	51,430	39,400	38,500	27,370	17,380	9,770
Ultimate tensile strength, psi	112,780	80,300	52,930	29,320	18,590	10,380
Uniform elongation, %	38.1	35.7	11.0	3.2	3.0	4.2
Total elongation, %	35.3	43.0	55.8	65.0	41.0	47.9
Braze cycle treated, at 0.005 min ⁻¹						
0.2% yield strength, psi		40,900	34,590	18,050	10,830	5,260
Ultimate tensile strength, psi		70,070	40,000	19,550	11,940	6,230
Uniform elongation, %		23.9	4.9	2.8	5.8	4.2
Total elongation, %		53.8	60.5	46.5	31.5	27.4

ate at ever-increasing tube-crown temperatures. Thus, there is an interest in the ability of candidate tubing materials to retain useful mechanical properties to a temperature as high as 2000°F. Elevated-temperature tensile tests were conducted on two promising candidate materials, Hastelloy X and Allvac 625, in the temperature range from 1200 to 2000°F.

Testing was done in an Instron testing machine using constant cross-head speeds corresponding to strain rates of 0.05 and 0.005 min⁻¹ at room temperature, 1200, 1400, 1600, 1800, and 2000°F. The specimen axis was parallel to the rolling direction of the 0.012-in.-thick sheet. Each specimen was given the standard three-stage braze cycle. In addition, as-received sheet was tested at the same temperatures at a strain rate of 0.05 min⁻¹.

The tensile strength data are listed in Table 39.2. For Allvac 625, an upper and a lower yield stress are reported at the higher temperatures because of the unusual shape of the stress-strain curve for this alloy. The ultimate tensile strength is taken as the maximum in the curve and quite often coincides with the upper yield stress. The uniform elongation is taken as the plastic strain beyond which no increase in load occurs.

The data show that the two alloys are very similar in tensile properties over the temperature range investigated. Allvac 625 has some advantage in yield strength up to about 1800°F but has a lower yield strength at 2000°F than does Hastelloy X. The ultimate tensile strengths are about the same for these two alloys in the 1400 to 1800°F region: Below this range Allvac 625 has an advantage in ultimate tensile strength, and above it Hastelloy X is stronger. Hastelloy X has slightly better ductility, especially at the higher temperatures. Both alloys are satisfactory in this regard.

EFFECTS OF SPACE ENVIRONMENT ON NERVA MATERIALS

R. E. Clausing

A committee composed of representatives of Aerojet General Corporation, Westinghouse Astronuclear Laboratory, NASA Space Nuclear Propulsion Office at Cleveland, Oak Ridge National Laboratory, and Thompson-Ramo-Wooldridge has been reviewing the

possible effects of the space environment on the material and components to be used in NERVA. The goal of the committee is to define the possible problem areas and to establish suitable means of assuring the satisfactory operation of materials and components in space.

The committee has recognized the tendency of atomically clean surfaces to adhere strongly to each other as one of the most important phenomena to be considered. Because adherence itself and its relationship to friction are only beginning to be understood, the committee decided to support a basic experimental program to better define the importance of various environmental parameters and lay the groundwork for future materials and component testing.

This program is being conducted through an ORNL subcontract with the Syracuse University Research Corporation. Dr. R. G. Aldrich is the principal investigator, and the contract is being monitored by R. E. Clausing of the ORNL Metals and Ceramics Division. The initial emphasis is on the influence of controlled surface contamination from gaseous environments upon the adhesion of various types of graphite to themselves and to other materials. The adherence of type 440C stainless steel to itself and to other materials is also being determined. Next year the program will be expanded to include additional combinations of materials.

The experiment is based on a technique developed by D. V. Keller of Syracuse University.⁶ The experiment is based upon (1) starting with surfaces that are initially atomically clean, (2) measuring the adherence, (3) exposing the surfaces to known gaseous contamination, and (4) measuring changes in adherence as contamination proceeds. The gases presently being used are oxygen and hydrogen. Hydrogen will be a naturally occurring contaminant in the NERVA system and oxygen could be supplied in some circumstances.

The experimental program is well begun; however, the initial data on PO3 graphite vs PO3 graphite is not sufficiently complete to allow definite results to be reported.

⁶K. I. Johnson and D. V. Keller, "The Effect of Contamination on the Adhesion of Metallic Couples in Ultrahigh Vacuum," *J. Appl. Phys.* **38**, 1896-904 (March 1967).