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# **Advanced High Temperature Materials for the Energy Efficient Automotive Stirling Engine**

Robert H. Titran and Joseph R. Stephens  
National Aeronautics and Space Administration  
Lewis Research Center

Work performed for  
**U.S. DEPARTMENT OF ENERGY**  
**Conservation and Renewable Energy**  
**Office of Vehicle and Engine R&D**

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Robert H. Titran and Joseph R. Stephens

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### ABSTRACT

E-2056

The Stirling Engine is under investigation jointly by the Department of Energy and NASA Lewis as an alternative to the internal combustion engine for automotive applications. The Stirling Engine is an external combustion engine that offers the advantage of high fuel economy, low emissions, low noise, and low vibrations compared to current internal combustion automotive engines. The most critical component from a materials viewpoint is the heater head consisting of the cylinders, heating tubes, and regenerator housing. Materials requirements for the heater head include compatibility with hydrogen, resistance to hydrogen permeation, high temperature oxidation/corrosion resistance and high temperature creep-rupture and fatigue properties. A continuing supporting materials research and technology program has identified the wrought alloys CG-27 and 12RN72 and the cast alloys XF-818 and NASAUT 4G-A1 as candidate replacements for the cobalt containing alloys used in current prototype engines. Based on the materials research program in support of the automotive Stirling engine it is concluded that manufacture of the engine is feasible from low cost iron-base alloys rather than the cobalt alloys used in prototype engines. This paper will present results of research that led to this conclusion.

THE STIRLING ENGINE is under investigation jointly by the Department of Energy (DOE) and the National Aeronautics and Space Administration (NASA) as an alternative to the internal combustion engine for automotive applications. The work described in this paper was conducted as a part of the supporting research and technology activities under the DOE/NASA Stirling Engine Highway Vehicle Systems program as outlined by Brogan (ref. 1).

The Stirling engine is an external combustion engine that offers the advantages of high fuel economy, low emissions, low noise, and low vibrations compared to current internal combustion automotive engines. A schematic representation of a prototype automotive Stirling engine is shown in Fig. 1. The most critical component from a materials viewpoint is the heater head consisting of the cylinders, heater tubes, and regenerator housing. The gaseous hydrogen working fluid is passed through a series of small thin-wall tubes (4.5 mm o.d. x 3 mm i.d.) which are required for efficient heat transfer from the combustion gases to the working fluid. The hot hydrogen expands in the cylinder to drive a piston which actuates the drive system. At the opposite end of the tubes is a regenerator, which absorbs heat from the hydrogen working fluid, followed by a cooler which permits contraction of the hydrogen. This process of heating and cooling the working fluid and extracting work forms the Stirling cycle. A goal of the Automotive Stirling Engine Program is to achieve a 30% increase in fuel economy over internal combustion engines of similar size and vintage. To meet this goal, a working fluid of hydrogen at a max. pressure of 15 MPa and a temperature of 820° C is required. Materials requirements for the heater head include compatibility with hydrogen, resistance to hydrogen permeation, high temperature oxidation/corrosion resistance resulting from combustion products of the fuel (diesel fuel, gasoline, coal derivatives, alcohol, etc.), high temperature creep-rupture and fatigue properties that will permit operation for at least 3500 hrs under conditions of cyclic hydrogen pressure (vehicle speed is controlled by working fluid pressure), and cyclic temperature changes resulting from intermittent engine starting and stopping. Current prototype engines use a cast cobalt base alloy HS-31 for the cylinders and

regenerator housings and N-155, a wrought iron-base alloy with 20% cobalt, for the heater tubes. Because of limited availability of cobalt and its high cost, cobalt free iron-base alloys are required for the heater head.

This paper presents experimental results of research efforts aimed at meeting the materials requirements of the automotive Stirling engine. Special emphasis is placed on the heater head cylinder and regenerator housing material HS-31, the heater tube material, N-155, and potential low-cost substitutes.

A continuing supporting materials research and technology program at NASA Lewis, Mechanical Technology, Inc., United Technologies Research Center, and United Stirling AB has identified the wrought alloys CG-27 and 12RN72 and the cast alloys XF-818 and NASAUT 4G-A1 as candidate replacements for the cobalt containing alloys N-155 and HS-31, respectively. Nominal composition of these candidate Stirling engine heater-head materials is given in Table I. The selection of these alloys was aided by concurrent investigations of the creep-rupture behavior, cyclic fatigue failure, cyclic oxidation/corrosion resistance and hydrogen permeability. All of these properties are necessary since loss of hydrogen results in loss of the engine power system.

Table II lists the manufacturers recommended heat treatment and when possible the ASM recommended heat treatment. Figures 2 and 3 depicts the resultant microstructure of these materials in their heat treated condition.

Creep-rupture tests in air and high pressure (15 MPa) hydrogen on the unaged N-155, CG-27, and the 12RN72 alloys show (figs. 4(a) and (b)) that at 760° and 815° C, and CG-27 alloy has superior stress-rupture properties than either the N-155 or 12RN72 alloys (refs. 2 to 5). Base line data derived from the creep-rupture tests on the unaged alloys tested in air and 15 MPa hydrogen was determined to be reliable by subjecting it to a simple power relationship correlational analyses of the form:

$$\ln t_r = \ln k + n \ln \sigma \quad (1)$$

where  $t_r$  is rupture life in hours,  $\ln k$  is a constant,  $n$  is the exponential stress constant, and  $\sigma$  is the applied stress. At 760° C, the stresses for a 3500 hr rupture life in hydrogen are 170, 100, and 60 MPa, for CG-27, N-155, and 12RN72, respectively. At 815° C, the corresponding stresses for a 3500 hr rupture life in hydrogen are 105, 70, and 40 MPa, respectively. Long term aging, 3500 hrs at 760° C, in either low pressure (30 to 60 kPa) flowing argon or hydrogen did not drastically reduce the creep-rupture strength of these alloys. Figure 5 shows the

effect of long time aging on 760° C stress versus rupture-life for N-155, CG-27, and 12RN72. Generally a 10 to 15% loss in rupture-stress was noted after aging in either the H<sub>2</sub> or Ar, and is not considered to be a large enough loss to affect the 3500 hr design criteria. It is concluded that the aging cycle itself has a deleterious effect on rupture strength since similar losses were noted with each environment.

The design criteria requires the allowable stress level for 3500 hrs rupture life at specific temperatures. There are many different methods (ref. 6) of analysis of creep-rupture parameters which consider both stress and temperature. A temperature-compensated analysis based on the Orowan-Sherby-Dorn method was selected for this study to determine the desired stress values. The relationship has the form:

$$\ln t_r = \ln k + n \ln \sigma + Q/RT \quad (2)$$

where  $Q$  is the apparent activation energy for creep,  $R$  the universal gas constant, (8.314 J/K mol) and  $T$  is test temperature, K.

Using multiple linear regression analysis, apparent activation energies for creep were determined along with the various material constants. The 3500 hr rupture-life stress of the candidate tube alloys was calculated over the temperature range 700° to 900° C and is depicted in Fig. 6. The present design criteria for the heater-head tube materials in the unaged condition consist of a rupture life of 3500 hrs at 870° C and at a stress of 28 MPa. At the current design maximum heater tube temperature of 870° C, Fig. 6 shows that the unaged CG-27 alloy has a 3500 hr rupture stress of 45 MPa when tested in air. It is also shown that when tested in 15 MPa H<sub>2</sub> the rupture strength is increased to 63 MPa. This implies that CG-27 has a growth potential to approximately 920° C with the present design concept. While the 12RN72 alloy does not meet the present high temperature stress-rupture criteria, it will be shown that it has qualities highly desirable for possible lower temperature designs.

Creep-rupture generally has never been observed as a major failure mode for prototype Stirling engine components manufactured from heavy wall castings. Fatigue has been identified as the major failure mode in the cylinder head manifold of engines, (ref. 7). In 3500 hrs of engine operation, the engine experiences approximately  $5 \times 10^8$  cycles of high-cycle pressure variations about the mean pressure. Growth of fatigue cracks and subsequent hydrogen leakage has lead to cylinder housing failures. The fatigue design criteria for the cylinder and regenerator housing requires a safety factor of two in the stress range produced by the number of pressure

cycles in 3500 hrs. The present design criteria for the heater-head cast cylinder heads and regenerator housings consists of a rupture life of 3500 hrs at 775° C and a stress of 120 MPa. When a safety factor of two is applied, the design criteria fatigue stress amplitude is set at a maximum of 240 MPa at 775° C. Figure 7(a) shows the results of fatigue tests at 800° C for HS-31, XF-818, and the new developmental alloy NASAUT 4G-A1. Presently, at 800° C, neither the HS-31 nor the XF-818 alloy meet the fatigue design criteria in either air or 15 MPa hydrogen. The XF-818, HS-31, and NASAUT 4G-A1 high cycle fatigue tests were conducted on smooth specimens at 800° C, however, the NASAUT 4G-A1 alloy was tested at an R ratio,  $\sigma_{min}/\sigma_{max}$ , of 0.1 at 20 Hz while the XF-818 and HS-31 were tested at an R ratio of -1.0 (fully reversed) (refs. 8 to 10). These fatigue tests show that the approximate fatigue-limit ( $>10^7$  cycles) stress amplitudes are XF-818:110 MPa, HS-31:186 MPa, and NASAUT 4G-A1:250 MPa. Figure 7(b) shows the results of strain controlled fatigue test at 800° C on the HS-31, XF-818, and NASAUT 4G-A1 alloys. The NASAUT 4G-A1 alloy is able to endure about 2.5 times the creep-fatigue strain of XF-818 and about 1.5 times that of HS-31. Whether or not the NASAUT 4G-A1 alloy will meet the fatigue strength criterion will have to wait for further evaluation at appropriate test conditions.

Although it has been identified that the creep-rupture life of the cast component is not their limiting design criteria, an assessment of their rupture life is necessary. A creep-rupture test program similar to that for the tube materials was conducted on the cast alloys. Creep-rupture tests in air and hydrogen on the unaged, aged, and following a simulated vacuum braze cycle of one hour at 1150° C were conducted on HS-31 and XF-818. The NASAUT 4G-A1 was not available for extensive creep-rupture testing. Figure 8 shows the results of creep-rupture tests at 760° C for HS-31 and XF-818 in the unaged and braze cycled condition both for air and 15 MPa hydrogen (refs. 3 to 5). Creep-rupture testing in 15 MPa hydrogen had no apparent effect on the rupture-life of HS-31 and XF-818 regardless of heat treatment. Again we see, as with tube alloys, that the test environment has very little effect on the rupture-lives and that the heat treatment or aging cycle predominates. In the case of HS-31 and XF-818, the simulated braze cycle resulted in approximately a 10% decrease in strength. Using the temperature-compensated Orowan-Sherby-Dorn relationship, and the results of a linear-multiple regression on available NASAUT 4G-A1 rupture data, a 3500 hr rupture life design curve was constructed as shown in Fig. 9. All three cast alloys meet the static stress-rupture engine design criteria of 120 MPa for 3500 hr rupture life

at 775° C. Since the results of the NASAUT 4G-A1 are considered preliminary its projected high stress value of 155 MPa will be verified both in air and hydrogen along with its high temperature growth potential.

The oxidation/corrosion resistance of candidate Stirling engine heater head tube alloys was determined under conditions that are to be encountered in automotive applications of the Stirling engine, (ref. 11). Duplicate sheet specimens were evaluated under cyclic conditions at 820° C for 3500 hrs in a Stirling engine materials simulator rig. The specimens were heated for five hour cycles in the combustion flame of the diesel-fuel fired rig. The three heater head tube alloys N-155, CG-27, and 12RN72 exhibited differing oxidation behavior, as can be seen by the specific weight change data in Fig. 10. Alloy CG-27 did not exhibit any significant spalling during the 3500 hrs of testing at 820° C, oxidizing by parabolic weight gain throughout the entire test. In contrast, N-155 and 12 RN72 both spalled after 1500 hrs into the test with alloy 12RN72 having a net weight loss at the end of the test. This behavior is characteristic of high temperature cyclic oxidation.

Oxidation/corrosion data were fitted by least squares as described by Barrett (ref. 12) to the parilinear Eq. (3).

$$\frac{W}{A} = k_1^{1/2} t^{1/2} - k_2 t \pm \text{SEE} \quad (3)$$

where W/A is specific weight change, t is time,  $k_1$  is an oxide growth constant comparable to parabolic oxidation scaling constant,  $k_2$  is an oxide spalling constant, and SEE is the standard error of estimate. An oxidation attack parameter  $K_a$  (ref. 12) was derived from Eq. (3) and is defined in Eq. (4):

$$K_a = (k_1^{1/2} + 10k_2) \quad (4)$$

In certain cases, as for CG-27 where scale spalling is insignificant, the  $k_2$  term will drop out of Eq. (4) giving the pure parabolic oxidation/corrosion case. Oxidation/corrosion attack parameters,  $K_a$  are shown in Fig. 11 for the three alloys, where lower values of  $K_a$  are indicative of better oxidation resistance. The resulting oxide attack parameter,  $K_a = 0.026$  for CG-27, quantitatively characterizes the oxidation behavior of this alloy and based on prior cyclic oxidation experience, CG-27 is considered to have excellent oxidation resistance. The  $K_a$  value of 0.11 for 12RN72 suggests that this alloy has good oxidation resistance under the conditions anticipated for the automotive Stirling engine.

Photomicrographs of the alloy specimens after testing are shown in Fig. 12. Alloy N-155 exhibits an adherent oxide scale on the specimen surface with a slight depletion zone

beneath the oxide scale. Alloy CG-27 also exhibited an adherent oxide scale on the surface. Further examination of the alloy by electron microprobe techniques revealed that internal oxidation of aluminum occurred, and that a thin aluminum rich oxide layer existed next to the metal substrate, suggesting that aluminum plays a major role in the excellent oxidation behavior of this alloy. A relatively large depletion zone characterized alloy 12RN72. Electron microprobe results showed the oxide scale to be rich in chromium and iron, pulse grain boundary penetration of oxygen to form chromium and titanium oxides. Based on the analysis of the oxidation weight change data, X-ray, metallographic, and electron microprobe analyses of tested specimens, CG-27 is considered the leading candidate heater head tube alloy.

Containment of the hydrogen working fluid during operation of the Stirling engine at high temperatures (870° C), high pressures (15 MPa) and for a period of about 175 hrs between refills is essential for the acceptance of the engine as an alternative to the internal combustion engine. While hydrogen readily permeates heater head tube alloys at 820° to 870° C, it has been shown (ref. 13), that doping the working fluid with small amounts of CO or CO<sub>2</sub> (0.02 to 1.0 vol%) reduces hydrogen permeability by as much as two orders of magnitude and to a level that will provide an acceptable recharging frequency. Figure 13 shows the results of the final five hour cycle from a 100-hr cyclic permeation study at 820° C on the N-155 alloy (ref. 13). Tubes heated externally in a diesel-fuel-fired Stirling engine simulator test rig were pressurized to 21 MPa after each five hour cycle. The results of this test show that the hydrogen permeation through hot tube walls can be substantially reduced using 1.0 vol CO<sub>2</sub> as a dopant in the hydrogen. It has been postulated (ref. 14) that the CO<sub>2</sub> or O<sub>2</sub> in the hydrogen forms a thin adherent oxide film on the inside surface of the tube, which, when coupled with the formation of a thick adherent oxide layer, on the fire side of the tube, results in the noted large reductions in hydrogen permeation. The lowest hydrogen permeation rates noted after a 3500 hr simulated engine test at 820° C were for the highly oxidation resistant alloys CG-27 and 12RN72. Figure 14 shows decreases in the hydrogen permeability by as much as two orders of magnitude for both CG-27 and 12RN72 with time (ref. 15).

Based on the materials research program in support of the automotive Stirling engine it is concluded that manufacture of the engine is feasible from low cost iron-base alloys rather than the cobalt alloys used in prototype engines. In particular, heater head tubes of alloy CG-27 offer higher creep-rupture properties than N-155. This alloy is also attractive for automotive applications

since it contains the least amount of the strategic metal chromium (13 ) of the alloys investigated, and is free of the strategic metal cobalt. This is compared to the 20 chromium and 20 cobalt contents in the N-155 alloy used in current prototype engines. The CG-27 alloy has been selected as the tube material for current design automotive Stirling engines. Also, the cast alloy XF-818 is currently being used in these engines. Its castability, weldability, and creep strength make it attractive for this use. However, fatigue resistance is in question, and continued research on the experimental NASAUT 4G-A1 alloy is in progress. It is recommended that these advanced iron-base alloys be used in future applications of the Stirling engine where high temperature, high pressures, and cyclic conditions are planned such as in stationary solar applications for domestic power systems.

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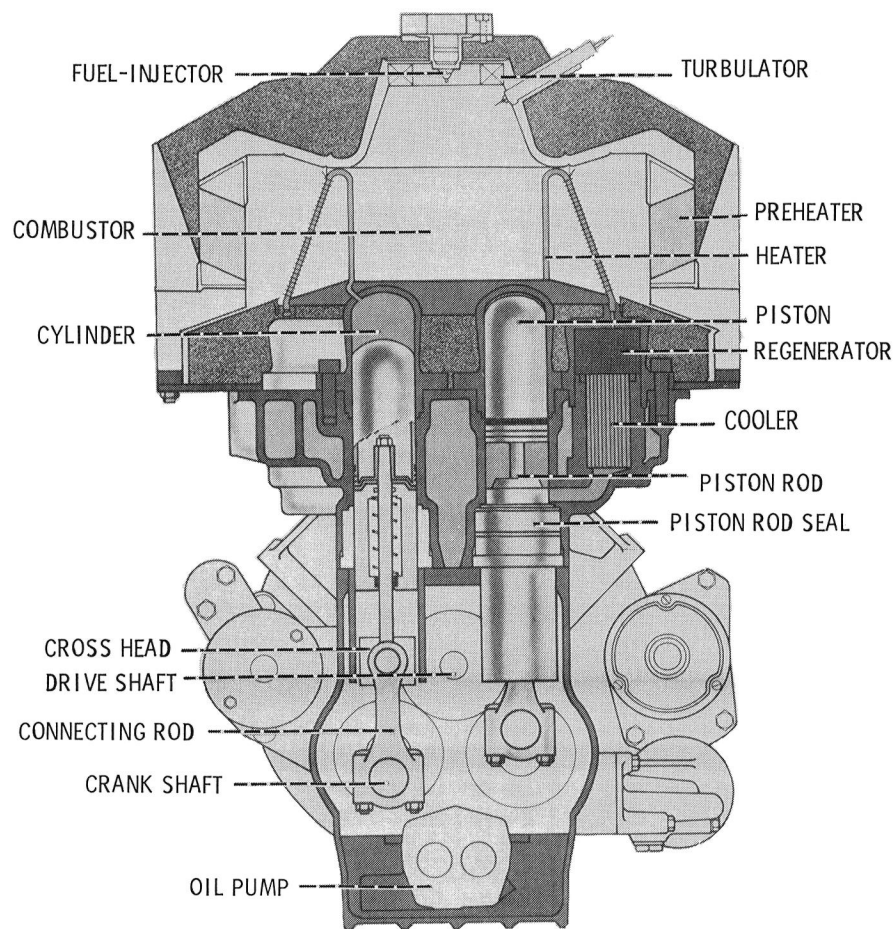


TABLE I. - NOMINAL COMPOSITION OF CANDIDATE STIRLING ENGINE HEATER-HEAD ALLOYS

Alloy	Fe	Cr	Ni	Co	Mn	Si	Mo	Cb/Ta	W	Al	Ti	C	Other
N-155	30	21	20	20	1.5	0.5	3.0	1	2.5	---	---	0.15	0.15N
CG-27	38	13	38	---	.1	.1	5.5	.6	---	1.5	2.5	.05	.01B
12RN72	52	19	25	---	1.8	.4	1.4	---	---	---	.5	.1	.015N
HS-31	1.5	25	10	54.5	0.5	0.5	---	---	7.5	---	---	0.5	-----
XF-818	55	18	18	---	.1	0.3	7.5	0.4	---	---	---	.2	0.6B
NASAUT 4G-A1	64.5	15	--	---	15	1.0	2	1.0	---	---	---	1.5	-----

TABLE II. - HEAT TREATMENT OF CANDIDATE STIRLING  
ENGINE HEATER-HEAD ALLOYS

Alloy	Heat Treatment ("unaged" condition)
CG-27	Sol'n. ann. 1150° C/10 min in vac/ fast furnace cool. Age 760° C/ 16 hr in vac/cool to 650° C/hold 24 hr/fast furnace cool.
12RN72	Sol'n. ann. 1175° C/15 min in vac/ water quench.
N-155	(AMS-5532B) Sol'n. ann. 1176° C/ rapid air cool or water quench.
HS-31	Anneal 730° C/50 hr in vac/fast furnace cool.
XF-818	None specified (as-cast).
NASAUT 4G-A1	650° C/100 hr in air/air cool.

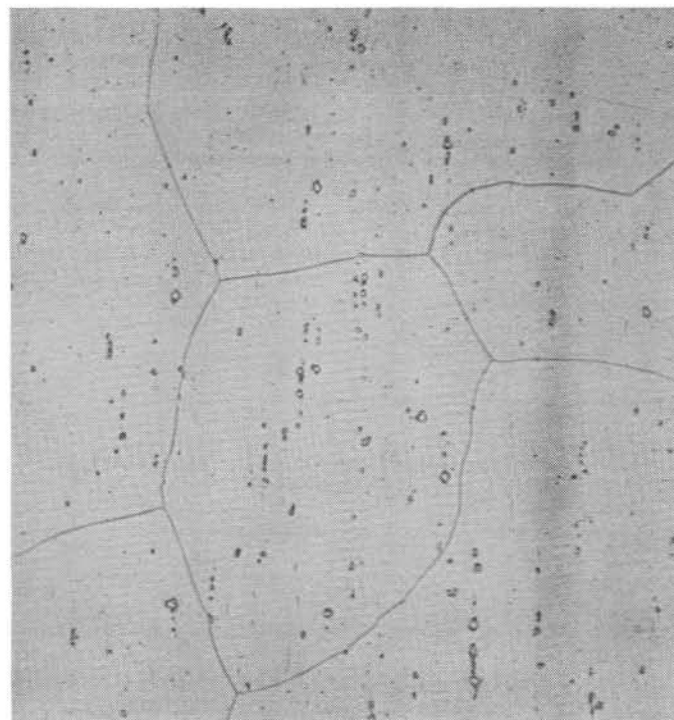


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Figure 1. - Schematic representation of automotive Stirling engine.

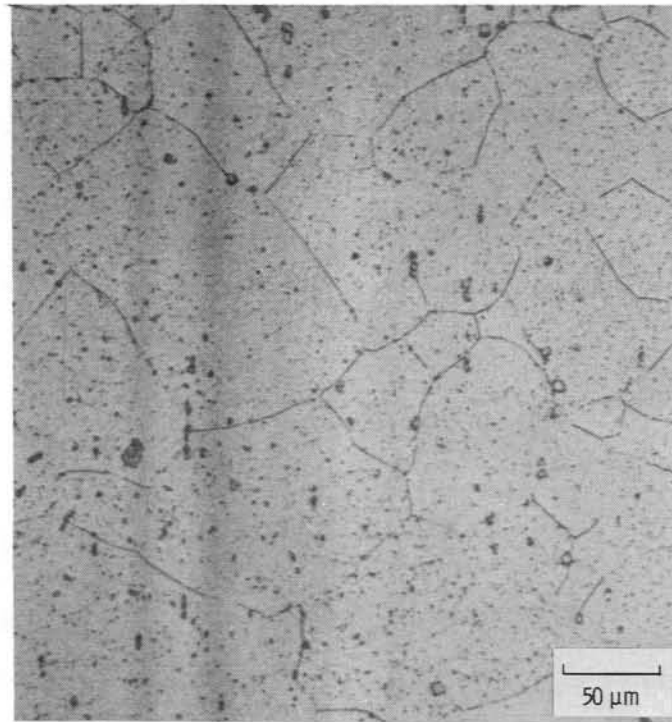


(a) N-155.



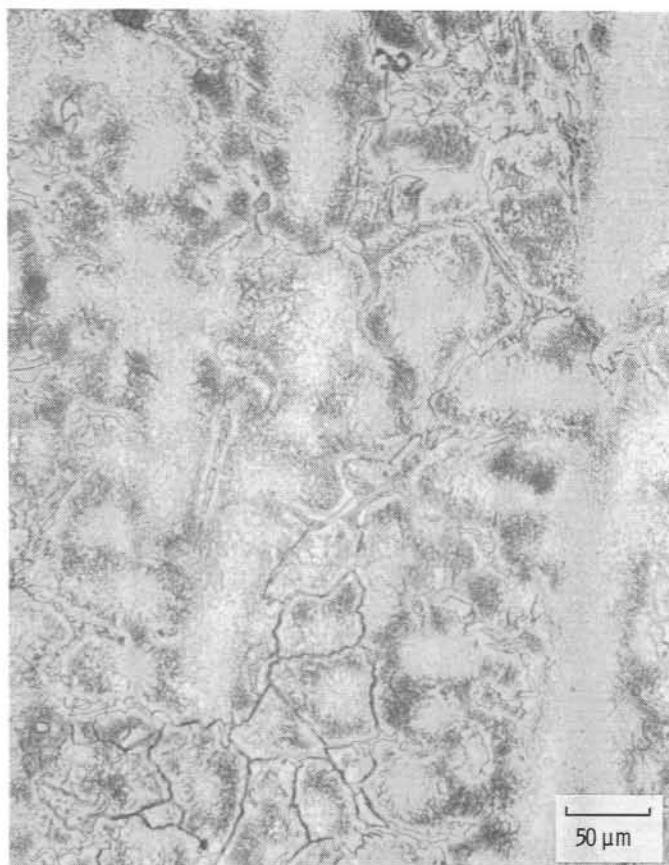
(b) CG-27.

Figure 2. - As heat-treated microstructures of heater head tube alloys.

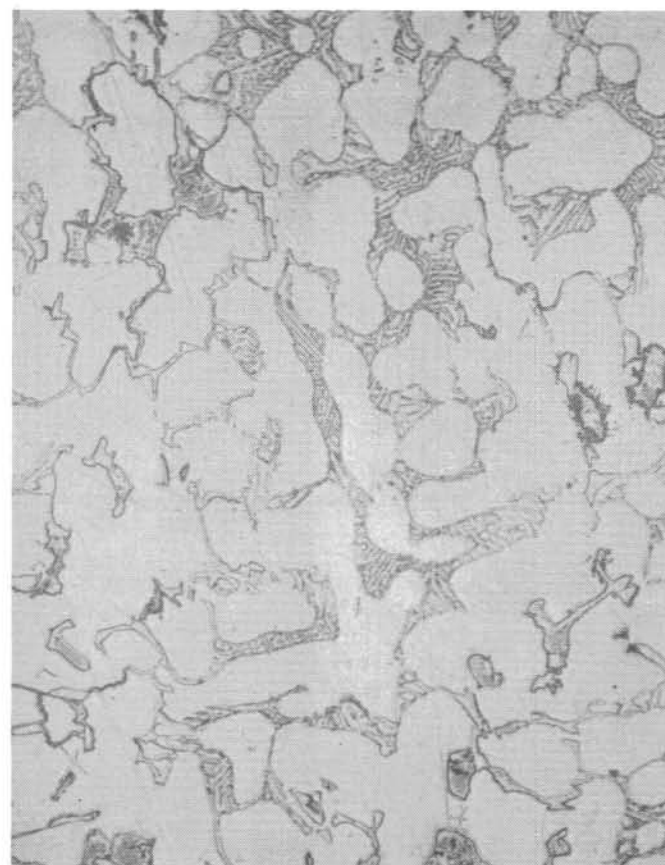


(c) 12 RN 72.

Figure 2. - Concluded.

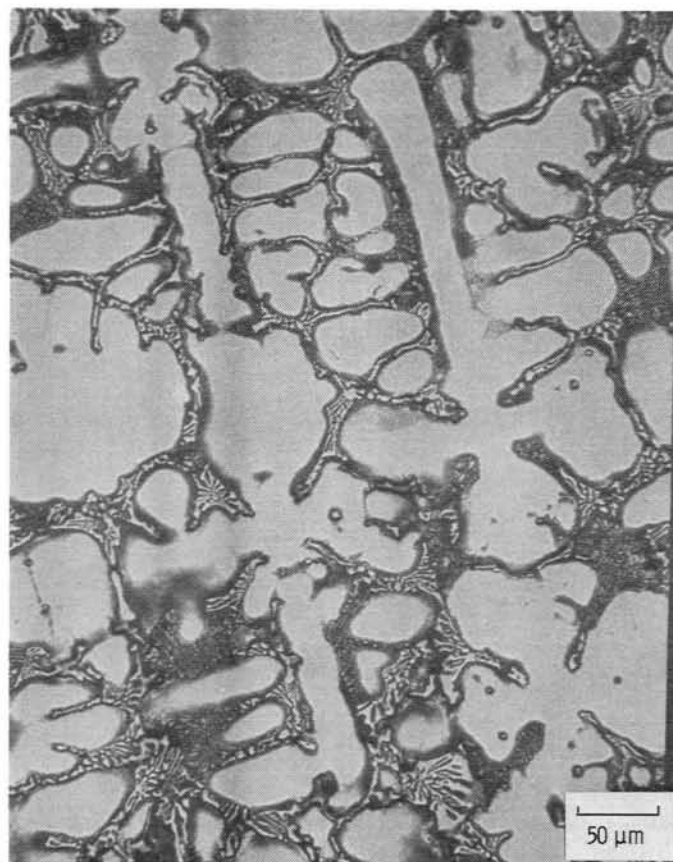


(a) HS-31.



(b) XF-818.

Figure 3. - As heat-treated microstructures of cylinder/regenerator housing alloys.



(c) NASAUT 4G-AI.

Figure 3. - Concluded.



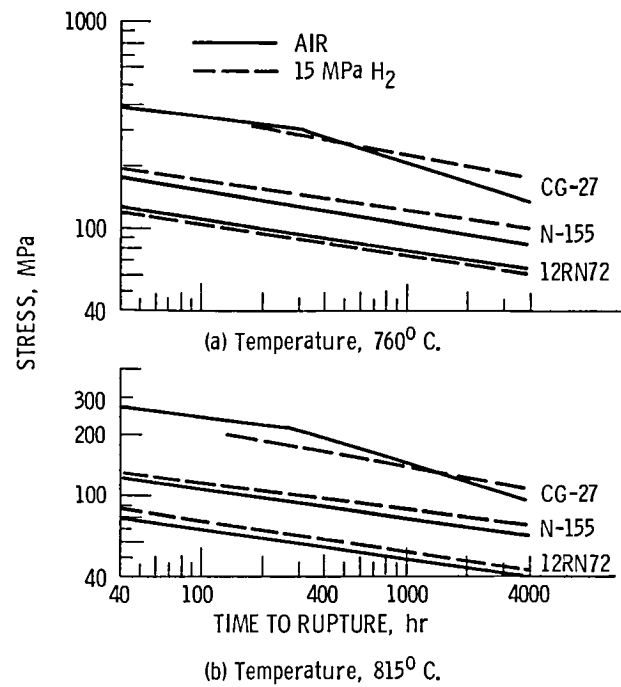


Figure 4. - Rupture lives of heater head tube alloys in air and hydrogen.

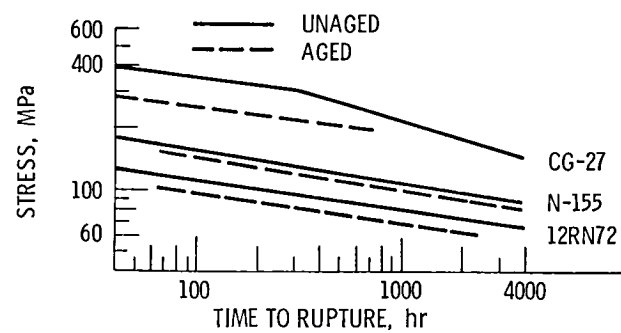


Figure 5. - Effects of long term aging on rupture lives of heater head tube alloys. Aged 3500-hour at 760°C.

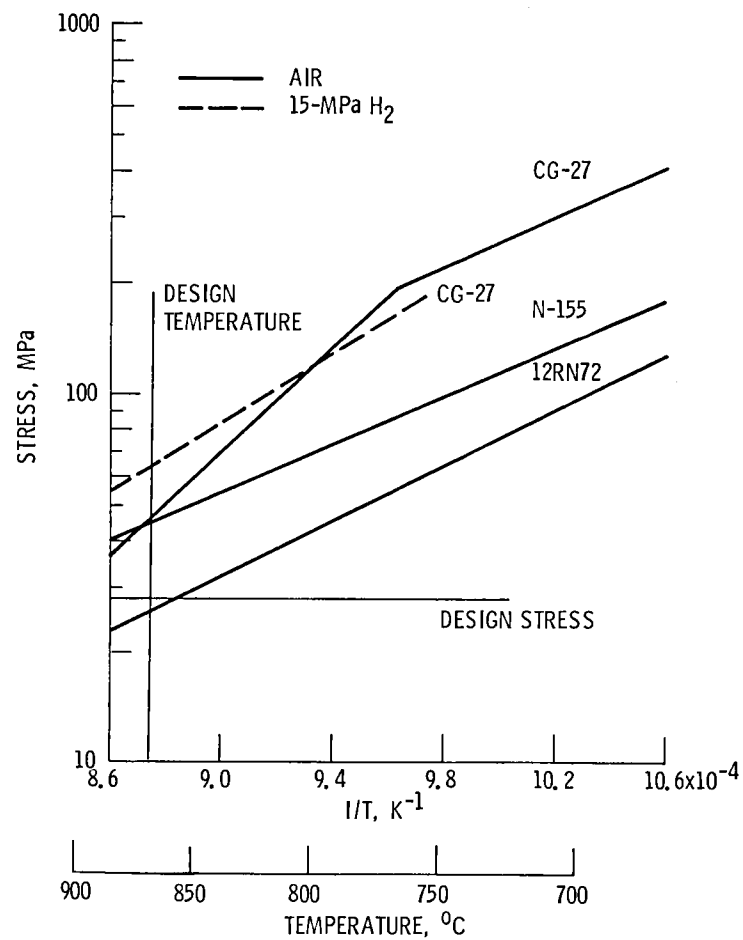


Figure 6. - Comparison of stress for 3500-hour rupture life with design criteria for heater head tubes.

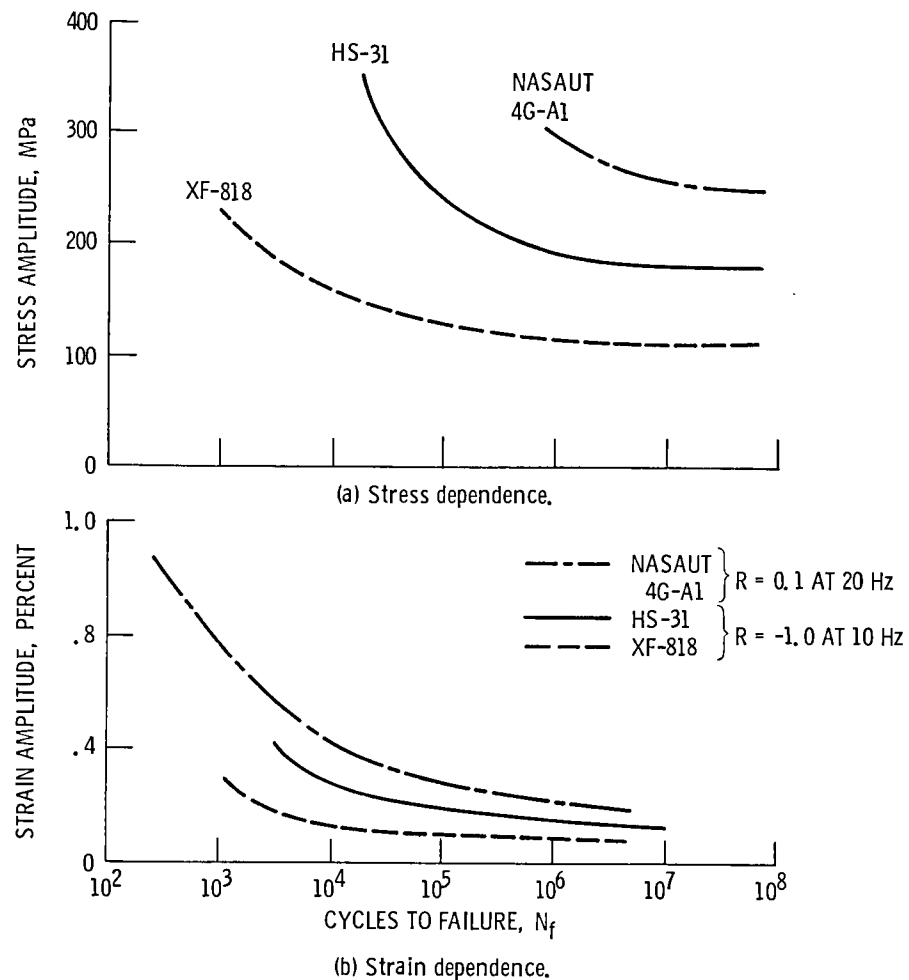


Figure 7. -  $800^{\circ}C$  fatigue resistance of cast cylinder/regenerator housing alloys.

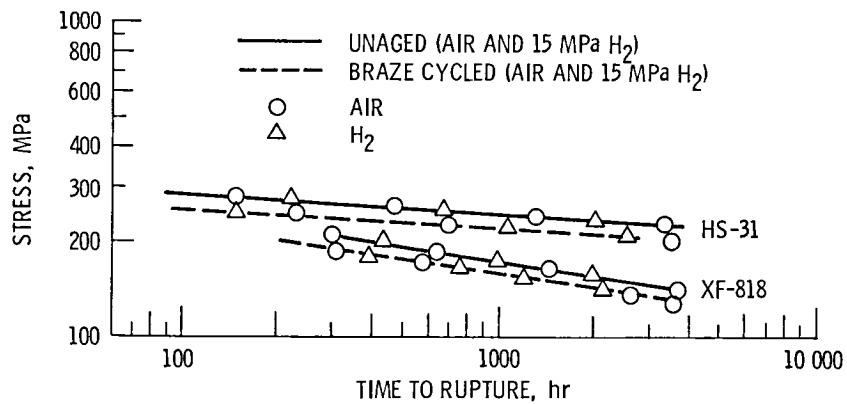


Figure 8. - Rupture lives of cast cylinder/regenerator housing alloys at 760° C.

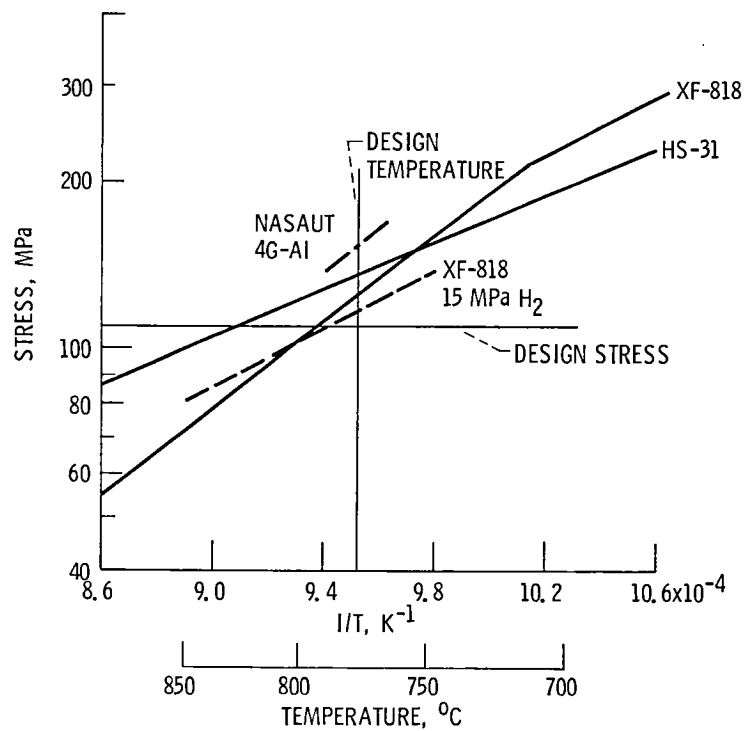


Figure 9. - Comparison of stress for 3500-hour rupture life with design criteria for heater head castings.

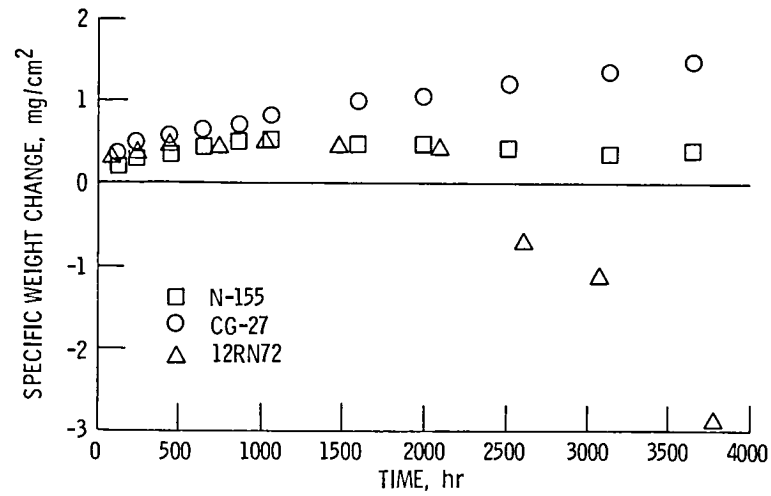


Figure 10. - Oxidation/corrosion specific weight change data for heater head tube alloys. (5-hour cycles at 820° C.)

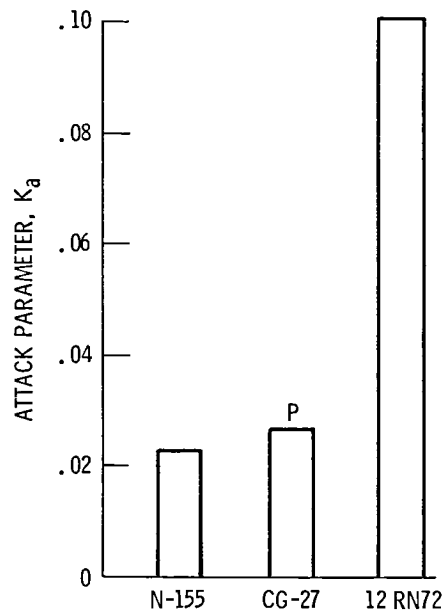
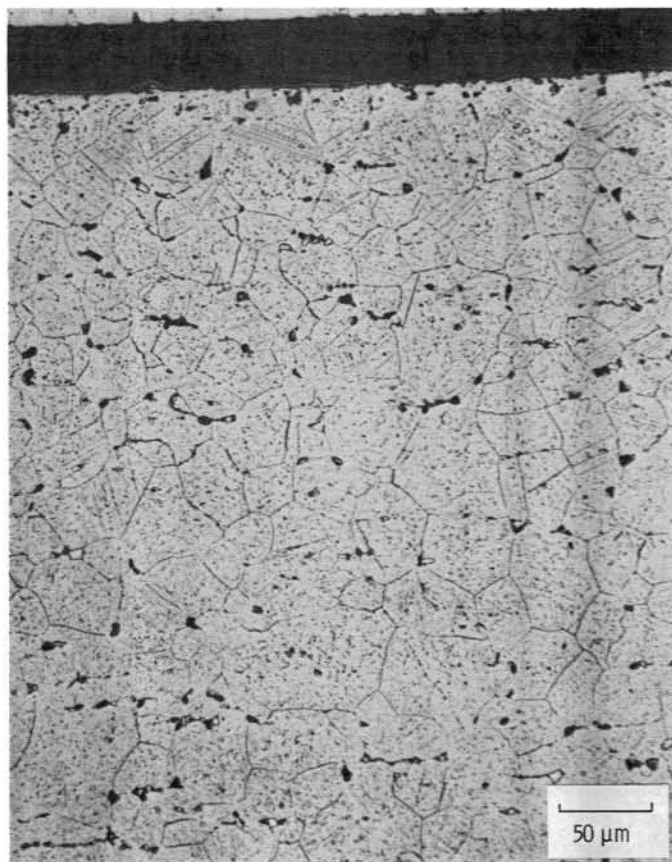
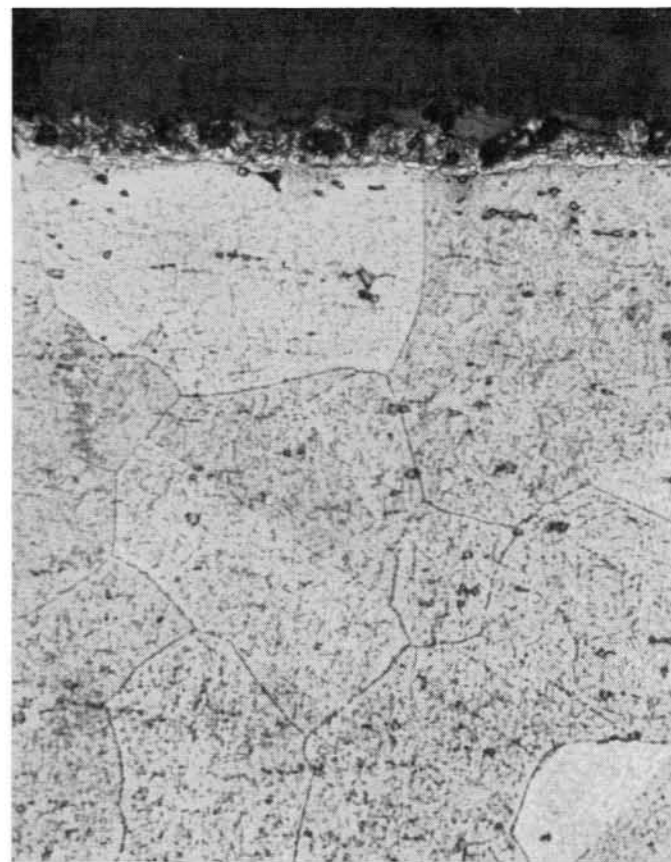


Figure 11. - Oxidation/corrosion attack parameter for heater head tube alloys after 3500-hour cycle testing at 820° C. P = parabolic weight gain - no spalling.

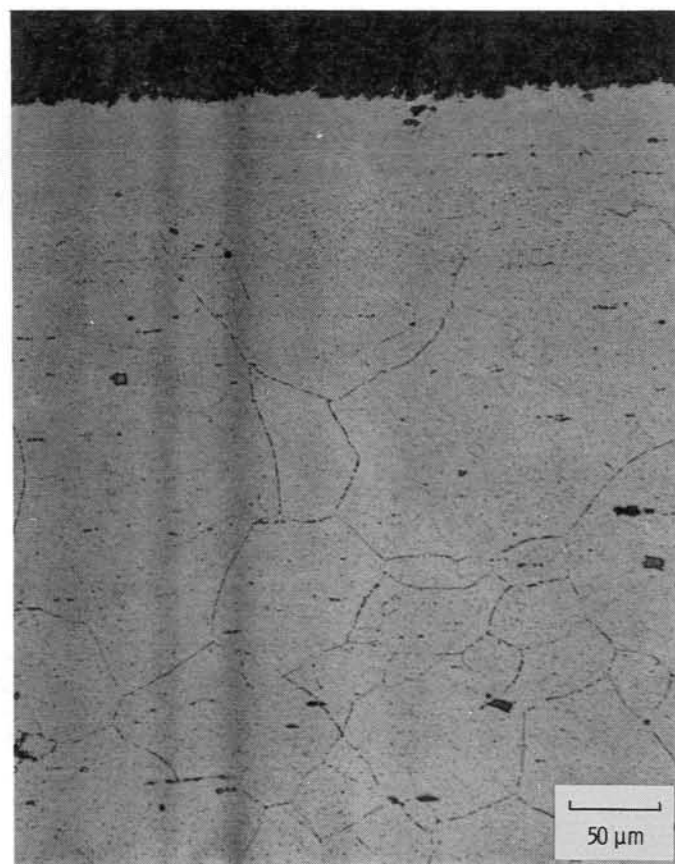


(a) N-155.



(b) CG-27

Figure 12. - Photomicrographs of 3500 hour oxidation/corrosion heater head tube specimens showing oxide scales and depletion zones.



(c) 12RN72.

Figure 12. - Concluded.

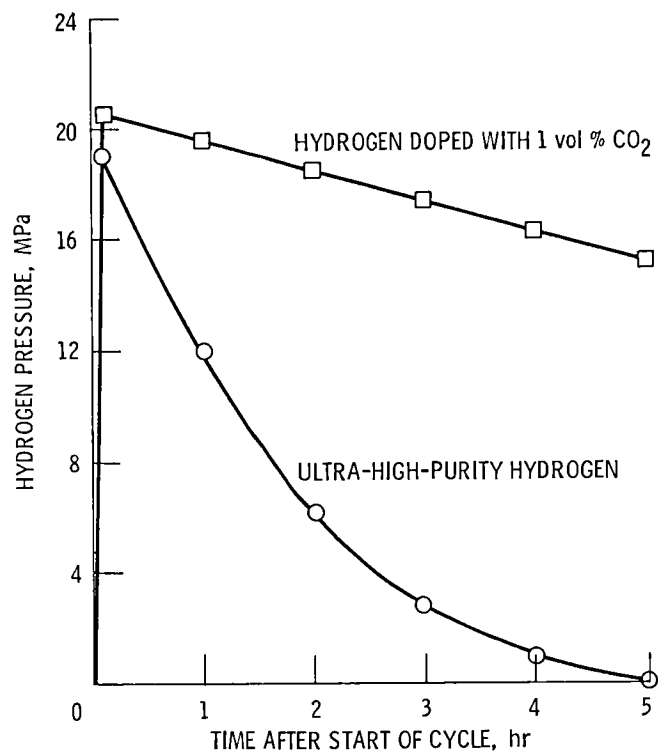


Figure 13. - Effect of doping with 1 vol %  $\text{CO}_2$  on hydrogen loss in N-155 tubes. Final 5-hour cycle of 100-cycle run.

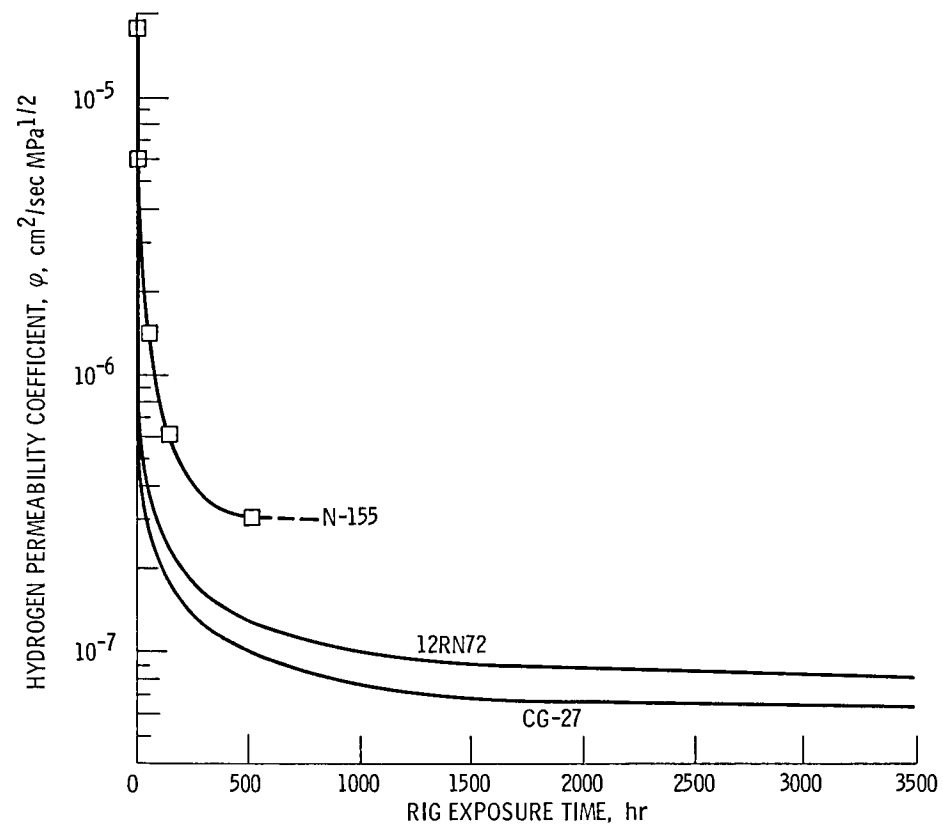


Figure 14. - Hydrogen permeability coefficient versus rig exposure time for candidate heater head tube alloys at  $820^\circ\text{C}$ . Gas,  $\text{H}_2 + 1 \text{ vol } \% \text{CO}_2$ .

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16. Abstract  The Stirling Engine is under investigation jointly by the Department of Energy and NASA Lewis as an alternative to the internal combustion engine for automotive applications. The Stirling Engine is an external combustion engine that offers the advantage of high fuel economy, low emissions, low noise, and low vibrations compared to current internal combustion automotive engines. The most critical component from a materials viewpoint is the heater head consisting of the cylinders, heating tubes, and regenerator housing. Materials requirements for the heater head include compatibility with hydrogen, resistance to hydrogen permeation, high temperature oxidation/corrosion resistance and high temperature creep-rupture and fatigue properties. A continuing supporting materials research and technology program has identified the wrought alloys CG-27 and 12RN72 and the cast alloys XF-818 and NASAUT 4G-A1 as candidate replacements for the cobalt containing alloys used in current prototype engines. Based on the materials research program in support of the automotive Stirling engine it is concluded that manufacture of the engine is feasible from low cost iron-base alloys rather than the cobalt alloys used in prototype engines. This paper will present results of research that led to this conclusion.					
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