



SOCIETY OF AUTOMOTIVE ENGINEERS, INC.
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CHRYSLER'S GAS TURBINE CAR

Materials Requirements

Amedee Roy, Frederick A. Hagen
and Claude Belleau
Chrysler Corp.

SOCIETY OF AUTOMOTIVE ENGINEERS

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CHRYSLER GAS TURBINE MATERIALS REQUIREMENTS

With the advent of the turbine engine, the materials industry has faced new requirements and the automotive engineer has been exposed to a new and more complex materials technology. The high temperature operation and the high rotational speed of the gas turbine are creating a new challenge in the selection of materials to assure adequate performance at a competitive price. In addition to the numerous material property considerations in current automotive products such as ambient temperature strength, fatigue, corrosion, wear, etc., the selection of materials for gas turbine application is found to have the added complexity of being essentially governed by stringent operating conditions of high and cyclic temperatures under high stress applications. The problem of material selection is further complicated by the need to measure accurately actual component temperatures and stresses (thermal and mechanical) under transient conditions. Furthermore, high temperature environmental effects and their interactions, which are also functions of time and stress at temperature, are found to affect markedly the life of the components. In fact, the combined effects of oxidation, thermal stresses, high frequency resonant vibrations, and low cycle fatigue can be as influential in determining the useful life of a turbine component as rupture strength, creep resistance and other common design criteria.

Actually the demands on certain materials in today's automotive gas turbine are believed to be, in some respects, more severe than on most of their aircraft counterparts. It is probable that the main obstacles to the introduction

of a practical automotive turbine did not originate from the lack of suitable materials, but rather from the inability to compete economically by the use of such materials with a well developed piston powerplant; e. g., the unavailability of relatively inexpensive materials of low strategic alloy content capable of withstanding the high temperature and high stress service conditions.

In the past, concern has been expressed as to the availability of strategic superalloys to support a world-wide shift to the use of gas turbines in the automotive and off-the-road vehicles industries. The tonnage figures of alloying elements required in commonly available superalloys to produce the critical high temperature parts would be astronomical on a mass production basis as compared with today's requirements. At this stage of development, no one can predict with certainty which family of superalloys will be used, but it appears likely that the cost of the engine is the major obstacle in the path of a mass produced automotive powerplant, especially in view of the fact that the automotive turbine has already achieved efficiency and performance comparable to the piston engine. The basic economic considerations then become essentially related to competent design for long life together with the use of low cost materials manufactured in sufficient quantities to benefit from mass production techniques.

The need for improved low cost high temperature materials was recognized at Chrysler early during the turbine development program. For many years, the Chrysler Metallurgical Research Laboratory has been engaged extensively in the development and evaluation of iron-base alloys suited for specific gas turbine components and low cost processing techniques.

From these research efforts in alloy development, a significant expansion of the operating limits of iron-base alloys has been brought about with the development of several interesting proprietary materials for turbine applications. Of equal importance has been the development of special and satisfactory regenerator seal materials which were not previously available. Commercial production of most of these new materials has already been accomplished. Furthermore, considerable operating experience has been gained with these new high temperature alloys. Although incomplete, the evaluation of some of these materials indicates performance equivalent or superior to the more expensive alloys.

It should be emphasized that high temperature alloys used in aircraft turbines are satisfactory for most automotive turbine applications except that their use in large quantities would make the engine cost prohibitive. These alloys are inherently expensive either from the point of view of the basic cost of the raw materials as in cobalt-base alloys or from that of the processing cost as are nickel-base superalloys.

In contrast, our experimental iron-base superalloy, which will be referred to as CRM-3, can be produced from low cost raw materials without special foundry techniques. To illustrate the savings made possible by this low cost material, the approximate "as cast" weights of the components requiring superalloys in the Chrysler turbine engine are listed below:

	<u>Weight of Rough Casting - Lbs.</u>	
Compressor Turbine Wheel		
One-piece design	4.5	
Blade ring design		2.0
Integral First-Stage		
Nozzle/Shroud	4.5	4.5
Power Turbine Wheel		
One-piece design	6.5	
Blade ring design		4.0
Variable Nozzle Blades -		
Second-Stage	<u>0.5</u>	<u>0.5</u>
	16.0	11.0

In the case of integral castings to obtain the total weight of metal cast, the rough casting weight should be multiplied by approximately 2.5 to account for the sprues, gates and risers. Thus raw material cost for these components at current prices would be \$80 for cobalt-base H.S. 31 (40 lbs. at \$2 per lb.) or \$120 for nickel-base Inco 713-C (40 lbs. at \$3 per lb.). On the same basis, the iron-base CRM-3 alloy would cost only \$20 at 50¢ per lb. Furthermore, when produced in larger quantities, it is expected that the price of CRM-3 alloy could eventually be reduced to less than 30¢ per lb. The raw material cost of the iron-base and cobalt-base alloys can be further reduced by recycling scrap, but with some of the nickel-base superalloys, the elemental value of the scrap would make up only a small fraction of the total processing charges. An additional charge for vacuum casting must be applied to most nickel-base superalloys. Furthermore, it has been regularly experienced that the high aluminum and titanium content of these alloys is responsible for a relatively high casting scrap rate even when vacuum cast.

As shown in the table, about 5 lbs. of superalloy can be saved by utilizing a composite turbine wheel fabricated by joining (probably by electron beam welding) a separately cast superalloy blade ring to a less expensive cast or wrought hub. This method of producing a turbine wheel offers potential cost savings and/or improved metallurgical properties. The cost of casting a blade ring can be reduced from that of an integral wheel by stacking several parts per mold. The disk material should be relatively inexpensive, have good room temperature ductility, compatible coefficient of thermal expansion, oxidation resistance, and adequate elevated temperature properties. Joining and extra machining costs would have to be added to the price of a composite wheel. In view of the above requirements, at least with our current turbine wheel designs, it has been difficult to select a disk alloy that would produce a significant cost saving without an attendant inertia penalty.

The necessity for new alloys for the automotive gas turbine might, in the earlier stages of development, have arisen from anticipated critical shortages of strategic elements. In view of today's market, the need for inexpensive alloys appears to predominate over that of low strategic alloy content. However, materials that can handle higher operating temperatures also might have to be exploited to offer higher

overall efficiency, but cost requirements would indicate that the use of expensive superalloys be kept to a minimum.

The selection of materials used in the Chrysler turbine, whenever possible, has been oriented toward commercially available alloys. In approaching the problem of material selection for a gas turbine the important considerations of economics and engineering that have been dictating for 50 years the selection of materials for the conventional piston engine are again recognized here as the only important factors. It is amazing to find a relatively large proportion of the gas turbine components for which both function and material requirements are

quite similar to that of its present counterpart.

Since it is beyond the scope of this paper to present a complete and detailed review of all materials used in the engine, our discussion will be limited primarily to: (1) the application of commercial materials in major components, and (2) the characteristics of newly developed low cost high temperature materials used in several important parts.

For convenience, these materials may be classified into three general groups:

- (a) Cast Alloys
- (b) Wrought Alloys
- (c) Special Materials.

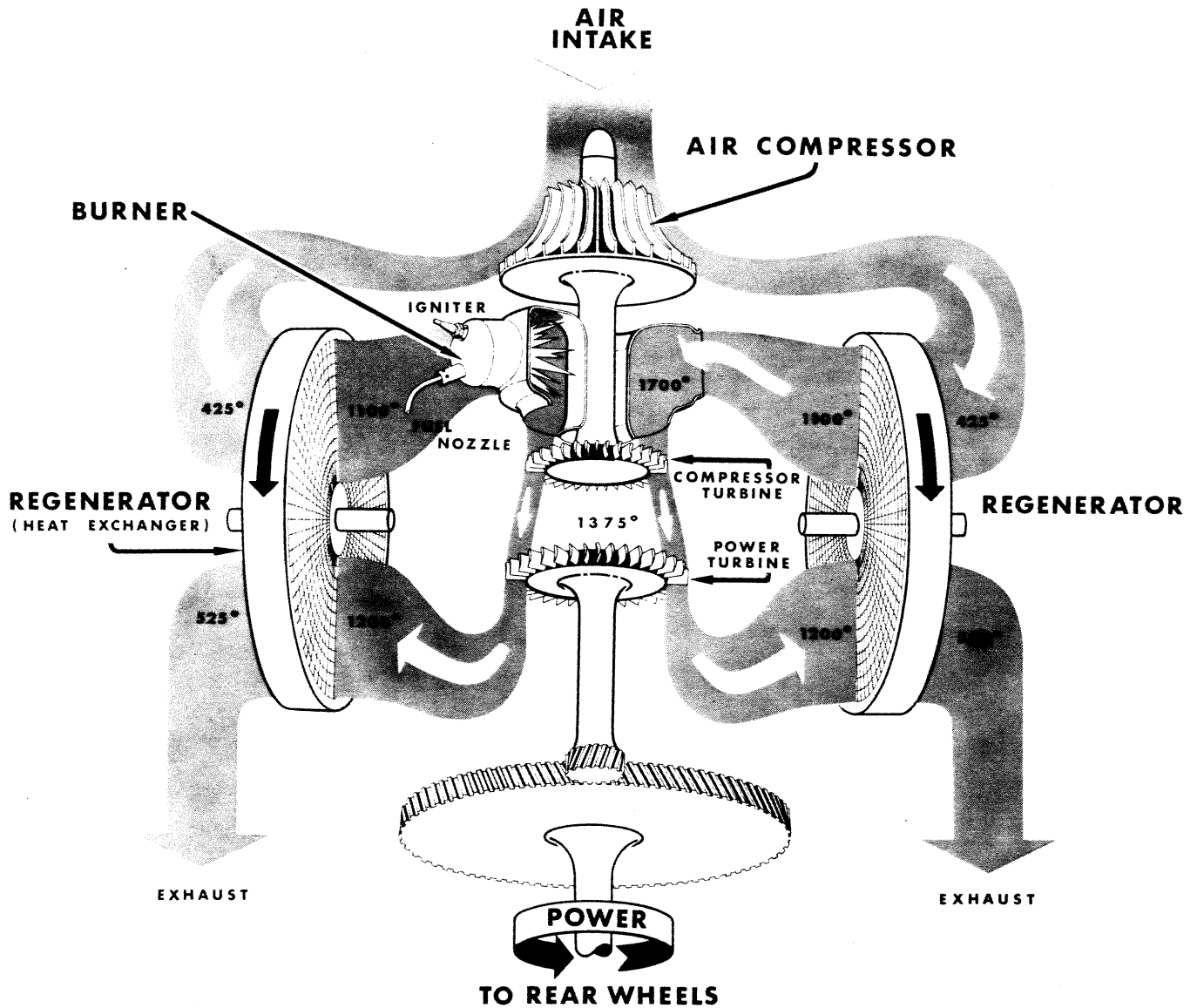
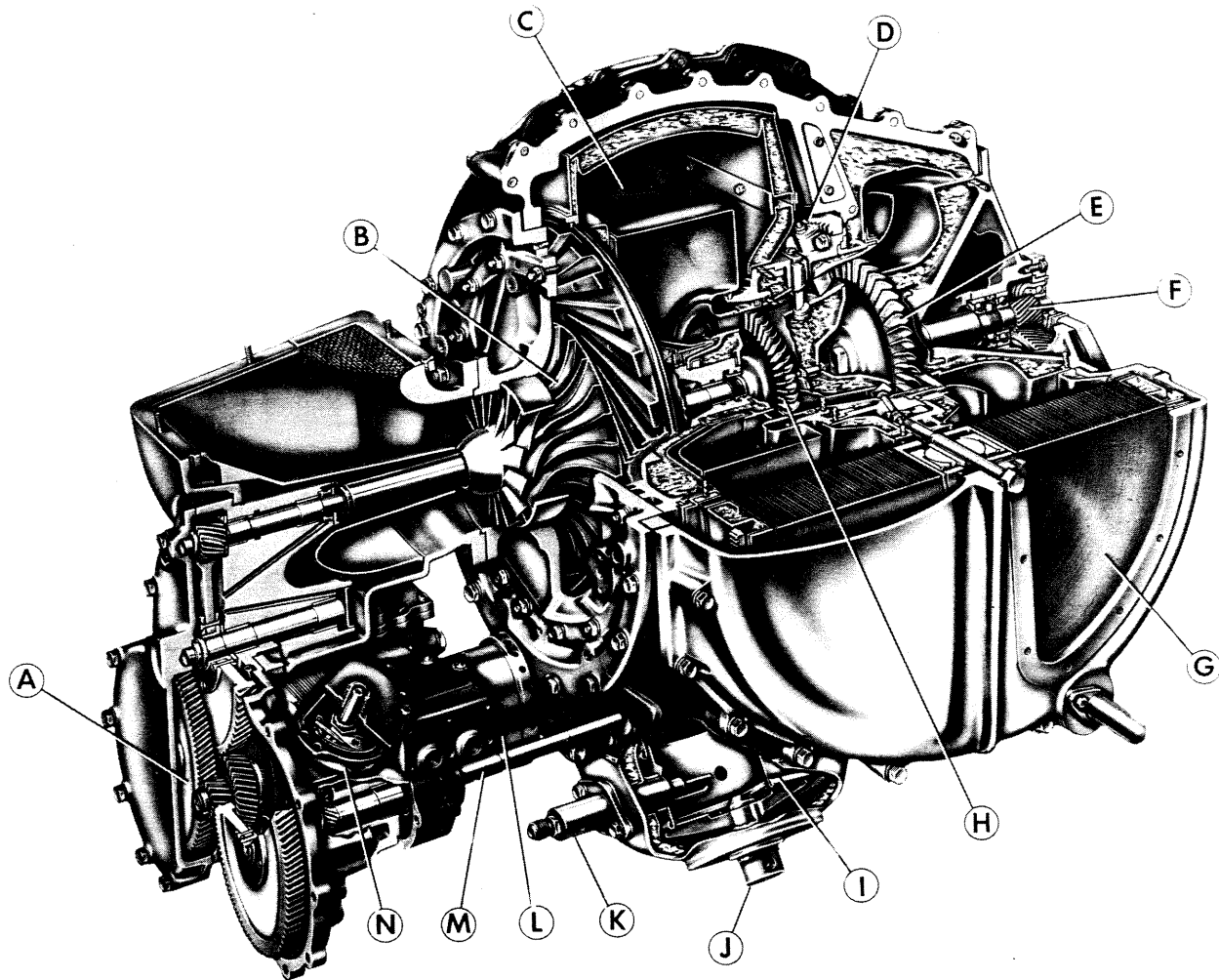


Fig. 1 - Flow Diagram of the Chrysler Turbine Engine

In order to better define the metallurgical factors involved in the design of our engine, an air flow diagram outlining the operating temperatures and speeds of various components and a cutaway view showing their physical relationship are presented.

Figure 1, a schematic of our engine, gives maximum operating temperatures and component speeds. Atmospheric air entering the engine is compressed to about four atmospheres;

this increases its temperature to 425°F. It is then directed to the outer surface of the regenerators where it passes through the front half, picking up heat from a cellular type 430 stainless steel matrix. The air, preheated to about 1100°F, then passes through the burner where the gas temperature is raised to 1700°F. The hot gas expands through both turbine stages, producing usable power, and is exhausted at about 1200°F outward through the rear half of the regenerators, giving up heat to the matrix



MAIN COMPONENTS OF THE TWIN-REGENERATOR GAS TURBINE:
 (A) accessory drive; (B) compressor; (C) right regenerator rotor;
 (D) variable nozzle unit; (E) power turbine; (F) reduction gear;
 (G) left regenerator rotor; (H) gas generator turbine; (I) burner;
 (J) fuel nozzle; (K) igniter; (L) starter-generator; (M) regenerator
 drive shaft; (N) ignition unit.

Fig. 2 - Chrysler Gas Turbine Engine

and coming out of the engine at 150 to 525°F, depending on operating conditions.

Figure 2 shows a cutaway view of the engine. The basic structure consists of a cast nodular iron housing supporting the main components. The gas generator assembly, comprising a cast aluminum radial flow compressor, a fixed nozzle, and an axial flow turbine wheel, is situated in the front part of the housing. The second stage, consisting of the variable nozzle system and the cast power turbine wheel, is coaxial with the first stage. The rotary regenerators are mounted on each side of the housing in cylindrical chambers divided by seals into high and low pressure sections. The sheet metal burner, mounted at the bottom of the housing, is fired by a single igniter. A sheet metal vortex chamber extends from the burner to the first-stage nozzle to direct the gas flow to the first-stage section.

A. CAST ALLOYS

Aluminum

The radial flow compressor impeller, which is subjected to high centrifugal stresses, is produced as a "premium quality" plaster mold precision casting in a high purity aluminum alloy, C355. The "premium quality" designation indicates that the minimum mechanical properties are guaranteed within the casting itself. The specified mechanical properties of this alloy, as well as those of another aluminum alloy that could also be used for this application, A356, are given in Table I.

TABLE I

Minimum Mechanical Properties of Test Specimens Cut from Designated Areas of Premium Quality Castings*

<u>ALLOY</u>	<u>UTS- KPSI</u>	<u>0.2% YS- KPSI</u>	<u>Elong.- %</u>
C 355-T61	41	31	3
A 356-T61	38	28	5

* Government Specification MIL-A-21180B

The typical properties of test bars cut from castings are shown in Table II. A wide range of freezing conditions is encountered in this complex casting. Actual properties are shown to be increasing with increasing cooling rate, or decreasing section size, from the thick hub

TABLE II

Mechanical Properties of Bars Cut from Impeller Castings - C355-T61

	<u>UTS- KPSI</u>	<u>0.2% YS- KPSI</u>	<u>Elong.- %</u>
HUB	42.65	33.00	6.0
(Sub-size, round specimens)	45.15 43.70	31.65 37.65	8.0 5.0
DISK	42.00	26.65	5.7
(Flat, square section specimens)	40.42 49.25	27.85 27.00	5.8 9.7
BLADES*	50.20	**	4.6
(Micro-tensile specimens)	43.68 58.47		3.5 3.4

* Tested on Chevenard micro-tensile machine.

** 0.2% yield strength could not be read accurately on the photographic plate.

to the thin blades. In the blades, the critical part of the casting, the properties are well over the minimum requirements.

Compressor impellers have also been cast successfully in magnesium. Although magnesium alloys offer significant savings in inertia, the techniques for producing premium quality magnesium castings are not as highly developed as those for aluminum. One magnesium alloy, AZ 91C, has been cast in a laboratory⁽¹⁾ with typical optimum properties of 43,000 psi tensile strength, 26,000 psi yield strength, and 6 per cent elongation.

Some of the less critical cast aluminum parts are the regenerator and burner covers, air intake housing, compressor diffuser, and other housing elements. These are currently produced as sand or semi-permanent mold castings in standard quality aluminum alloy 356 - T6.

Nodular Iron

Nodular iron meets the requirements of many of the cast components of the engine. In addition to the main engine housing, the power

(1) "Premium Quality Magnesium Castings" by M. C. Flemings and E. J. Poirier, Foundry, Oct., 1963.

turbine housing and bearing supports are cast of this versatile material. The selection of nodular iron over the other materials available, i. e., aluminum, gray iron, or low carbon cast steel, was based on the following properties: good ductility, low cost, high modulus of elasticity, growth resistance, oxidation resistance, excellent machinability, thermal shock resistance and impact resistance. Creep, stress-rupture, and short-time tensile properties are comparable to those of annealed low carbon cast steel up to 1200°F.

All of the nodular iron parts in the engine were cast of a grade similar to SAE 60-40-10. Test bars cut from the castings must meet the following properties:

Ultimate Tensile Strength 60,000 psi min.
Yield Point 40,000 psi min.
Per cent Elongation,
2" Gage Length 10% min.
Modulus of Elasticity 20×10^6 min.
Brinell Hardness Number 137 - 187

The annealed microstructure consists of a ferritic matrix containing graphite nodules and a maximum of ten per cent pearlite with no primary carbide in quantities detrimental to machining.

Stainless Steel Castings

The investment cast inducer, which directs the air into the impeller, is a rotating part with long, thin blades. It must withstand high vibratory as well as centrifugal stresses and have good corrosion resistance. Alloy 17-4 PH (currently specified), AM 355, Type 431, and Type 410 are a few of the hardenable investment cast stainless steels that are able to meet these requirements. All of these corrosion resistant alloys can be heat treated to yield strengths well over 100,000 psi with good ductility. The precipitation hardening alloys (17-4 PH and AM 355) have an advantage over a straight martensitic stainless in that they can be finish-machined in the softened condition, then age hardened at relatively low temperatures without distortion.

The power turbine shrouds are also stainless steel castings. The requirements for these parts, i. e., oxidation resistance up to 1500°F and moderate strength, are met adequately by 430 stainless steel. The thin walled 430 s. s.

shroud is produced as a centrifugal casting. Among the advantages of this process are true roundness, uniform wall thickness, and metallurgical uniformity.

Cast Superalloys

The most critical components in a gas turbine engine are the turbine wheels and nozzles. In the Chrysler engine the compressor turbine wheel and the power turbine wheel operate at temperatures somewhat in excess of 1500 and 1200°F respectively. Although the power turbine wheel is exposed to lower temperatures, it must withstand higher stresses. The stationary compressor turbine nozzle blades are exposed to gas temperatures of 1700°F and, in this case, the principal stresses are caused by thermal gradients. In addition to the above components, the first-stage shrouding and the second-stage variable nozzle blades also require the use of superalloys.

The choice of materials for these high temperature applications depends, in addition to other considerations, upon the anticipated temperature of operation. Of the commercially available cast iron-base superalloys, A-286 is considered the strongest at temperatures of 1300°F and above. The rather rapid decrease in strength of this alloy near 1300°F usually restricts its use to that maximum temperature under relatively high stress conditions. At higher temperatures, several well known cobalt and nickel-base superalloys have been widely adopted because of their ability to withstand high stresses for long periods of time at elevated temperatures. As mentioned earlier in this paper, Chrysler Metallurgical Research has developed a family of low cost iron-base superalloys for the above applications. At this time, all that can be revealed about the composition of these austenitic CRM-3 alloys is that they contain about 65 per cent iron. The two preferred compositions, which will be referred to in this discussion as CRM-3A and CRM-3B, possess relatively good strength at temperatures up to at least 1500°F.

For purposes of comparison, a tabulated and graphical description of some of the properties of these experimental iron-base alloys and of commercial superalloys will be discussed in the following pages. These are typical data obtained from investment cast-to-size 0.25 inch gage diameter test bars either in "as cast" condition or with the normally recommended heat treatment. These results summarize a great

TABLE III

Typical Short-Time Tensile Data - CRM-3 Alloys

Temp.	Ultimate Tensile Strength (KPSI)				0.2% Offset Yield Strength (KPSI)				Elongation (%)			
	CRM-3A		CRM-3B	HS-31	CRM-3A		CRM-3B	HS-31	CRM-3A		CRM-3B	HS-31
	As Cast	Heat Tr.	Heat Tr.	Aged	As Cast	Heat Tr.	Heat Tr.	Aged	As Cast	Heat Tr.	Heat Tr.	Aged
RT	105	110	115	128	65	83	91	113	3.0	2.0	2.0	2.0
1000	82	87	90	91	52	74	77	69	7.0	3.5	3.0	4.0
1200	70	77	80	81	49	67	69	60	7.5	7.5	5.0	4.5
1500	41	50	60	60	39	46	54	44	18.0	13.0	14.0	10.3
1700	27	33	38	49*	25	30	33	36*	28.0	14.0	26.0	14.3*

* Tested at 1600°F.

deal of the developmental work on these two alloys to date. We realize that these data may not be adequate for all complete design problems; therefore, thorough evaluation programs are currently underway to supplement these results.

The short time tensile properties of CRM-3A and CRM-3B obtained from room temperature to 1700°F are presented in Table III along with those of a cobalt-base superalloy H.S.31 (X40).⁽²⁾ The typical ultimate tensile strength of the CRM-3 alloys and H.S.31 are shown in Figure 3. The CRM-3A alloy has slightly lower tensile strength than CRM-3B over the whole range of temperature. The tensile strength of CRM-3B is approaching that of H.S.31 at temperatures above 1000°F. The typical 0.2% yield strength data

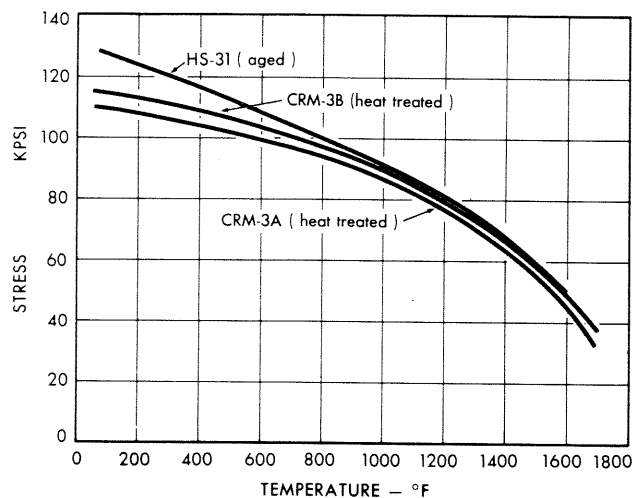


Fig. 3 - Comparative Ultimate Tensile Strength of CRM-3 Alloys

as shown in Figure 4 indicates equivalent or higher yield than published H.S.31 data at temperatures above 800°F. The typical short-time tensile elongation of these experimental iron-base superalloys as shown in Figure 5 are equivalent to that of H.S.31 over the entire temperature range.

Figure 6 has been included to show the effect of heat treatment* on the short time tensile properties of CRM-3A. Heat treatment produces a significant increase in yield strength and a 5000-10,000 psi improvement in tensile strength at all temperatures up to 1700°F. These increased properties are obtained at the expense of only a small decrease in tensile ductility.

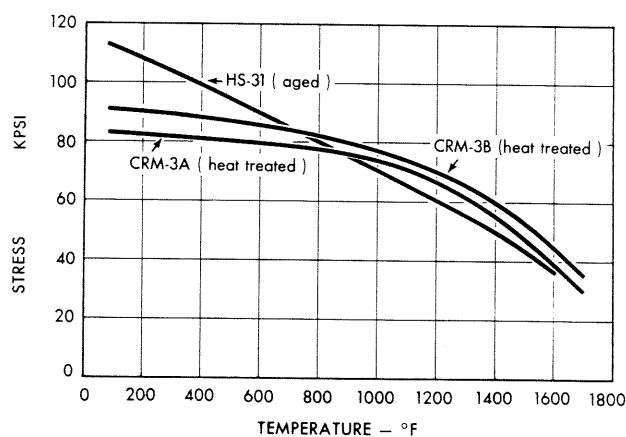


Fig. 4 - Comparative Yield Strength of CRM-3 Alloys

(2) "Alloy Digest"

* Proprietary

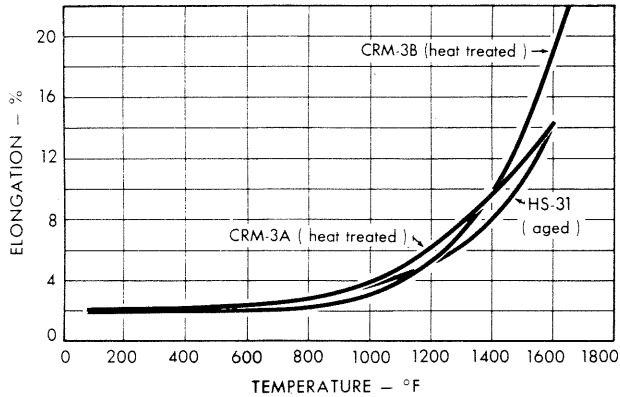


Fig. 5 - Comparative Tensile Elongation of CRM-3 Alloys

Long-time stress-rupture results for the two promising CRM-3 compositions are listed in Table IV. These data were obtained from investment cast test bars in both the heat treated CRM-3A and "as cast" CRM-3B conditions. Neither of the alloys have shown any signs of instability in rupture tests lasting from about 1000 hours to well over 5000 hours. Typical stress-for-rupture in 100 hours data from 1200°F to 1500°F for the CRM-3 alloys in the heat treated condition are shown in Figure 7. For comparison, rupture values for two cobalt-base alloys, H. S. 31 and H. S. 21, have also been included. Around 1500°F both CRM-3 alloys compare favorably with aged H. S. 31, whereas at 1200°F they have superior properties. Both of the CRM-3 alloys have higher rupture strength than does H. S. 21 over the entire temperature range.

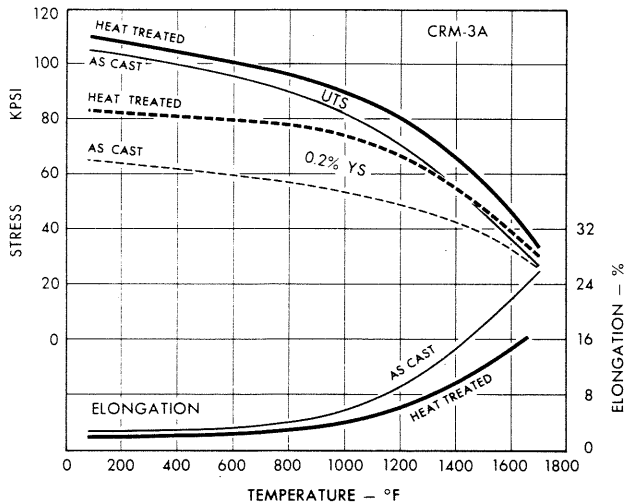


Fig. 6 - Effect of Heat Treatment on the Tensile Properties of CRM-3A Alloy

TABLE IV

Alloy	Temp. (°F)	Stress (KPSI)	Rupture Life (Hrs.)	Elong (%)	
CRM-3A Heat Treated	1000	75	641	3.5	
	1100	74	92	5.0	
		76	58	5.0	
		1200	55	1571	5.0
			60	273	5.0
			61	150	6.0
			62	105	5.0
	1300	64	44	5.0	
		67	17	6.0	
		45	387	7.0	
	1400	50	148	9.0	
		30	333	14.5	
	1500	37.5	41	18.0	
		20	1215	4.5	
		25	389	7.0	
26		306	8.5		
27.5		125	7.0		
29		86	10.5		
31		25	13.5		
CRM-3B	1200	55	901	8.0	
		60	295	6.5	
		70	70	6.0	
	1300	45	252	20.0	
		52.5	67	12.0	
		65	7	9.0	
	1400	25	5691	4.0*	
		30	271	18.0	
		37.5	45	25.0	
		42.5	20	17.0	
	1500	25	276	12.0	
		27.5	111	17.0	
		32	29	20.5	
	1600	21	118	10.0	
		22	61	18.0	
1700	17	39	12.0		
	15	127	3.0		

* Test conducted by independent organization.

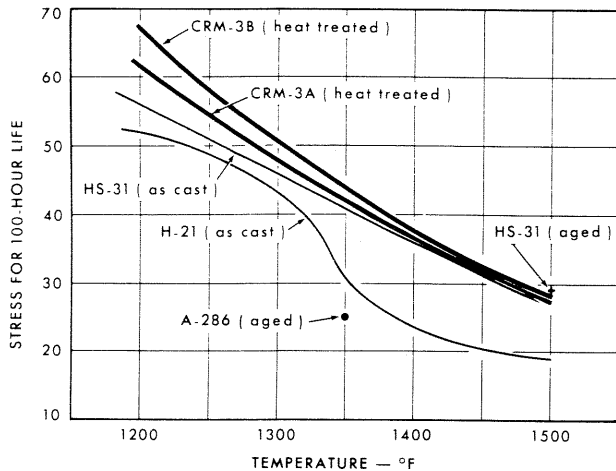


Fig. 7 - Comparative 100 Hr. Stress-Rupture Strength of CRM-3 Alloys

The rupture range for heat treated CRM-3A at 1200°F and 1500°F is presented in Figure 8. The data for these curves were obtained from 92 cast test bars and represent 57 separate heats. An evaluation of the stress-rupture properties of the CRM-3 alloys has been made through use of the function proposed by Larson and Miller⁽³⁾. Such a method allows for the estimation of long-time results from comparatively short-time data covering a wide range of stress and temperature. The function proposed by Larson and Miller is of the form:

- $P = F(S) = (T + 460)(\log t + C)$
- P = Larson-Miller parameter
- S = Stress - psi
- T = Temperature - °F
- t = Rupture time - Hrs.
- C = Constant = 20 as calculated for CRM-3 alloys.

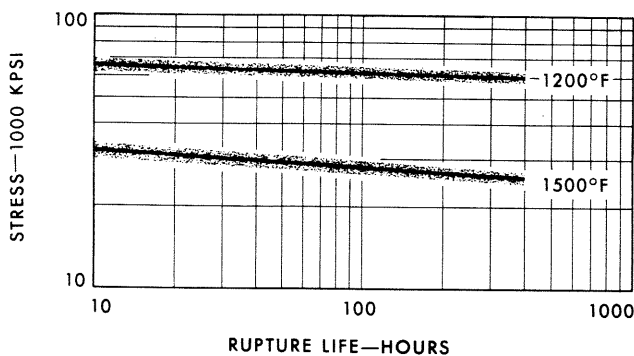


Fig. 8 - Rupture Range of CRM-3A Alloy

(3) Transactions, ASME, F. R. Larson and J. Miller, Vol. 74, No. 5, July, 1952, pp.765-771.

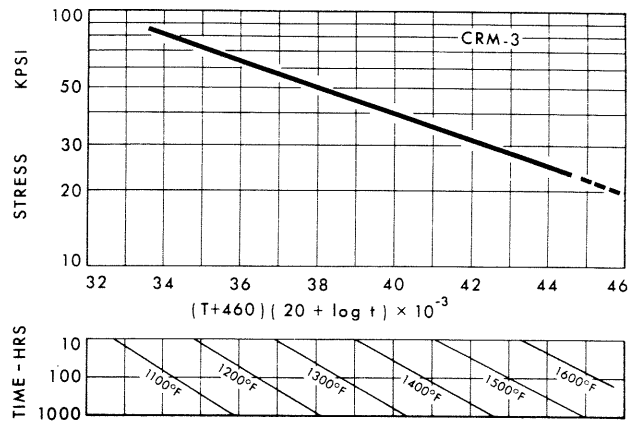


Fig. 9 - Larson-Miller Plot for CRM-3 Alloys

The generalized Larson and Miller master curve for CRM-3 alloys has been determined and is graphically presented in Figure 9. For simplicity in obtaining stress-rupture data of these alloys, the 10-hour, 100-hour, and 1000-hour life values have been calculated and are recorded along the horizontal axis of the graph.

Table V lists long-time creep data for both CRM-3A and CRM-3B in the heat treated condition. The stresses selected for these tests represent the maximum calculated turbine blade stresses at 1200°F and 1500°F.

TABLE V

Long-Time Creep Data

Temp. (°F)	Stress (KPSI)	Time (hours) for Total Creep Strain* of				Min. Creep Rate, (%/Hr.)
		0.1%	0.2%	0.5%	1.0%	
CRM-3A						
1200	40	4	15	92	400	.00155
	40	2	12	80	388	.00155
1500	20	2	6	48	344	.00143
	20	2	4	24	250	.00155
CRM-3B						
1200	40	20	80	502	1231	.000686
	40	18	70	550	1420	.000575
1500	20	1	2	18	200	.00188
	20	2	4	25	258	.00156

* Strain rates measured after extension on loading.

Some of the physical properties of CRM-3 are listed in Table VI. Included are values for thermal expansion, thermal conductivity, density, modulus of elasticity and hardness. Curves for thermal expansion and thermal conductivity are plotted in Figures 10 and 11 respectively. It is interesting to note that the density of CRM-3 is about 8 per cent less than that of H. S. 31. This becomes an important advantage for CRM-3 when the two alloys are compared on a strength-to-weight basis.

TABLE VI
Physical Properties - CRM-3

Modulus of Elasticity	Temp. (°F)	Modulus (psi)
	70	29.0 x 10 ⁶
	600	23.0
	1000	20.0
	1200	19.4
	1300	19.0
	1400	18.7
	1500	18.5

Thermal Expansion (See Fig. 10)	Temp. (°F)	Mean Coefficient (in./in./°F)
	70-200	7.5 x 10 ⁻⁶
	70-400	8.1
	70-600	8.7
	70-800	9.2
	70-1000	9.5
	70-1200	9.7
	70-1400	9.85
	70-1600	9.95
	70-1800	10.1
	70-2000	10.2

Thermal Conductivity (See Fig. 11)	Temp. (°F)	Conductivity (BTU-in/ft. ² -°F-hr.)
	200	116
	400	134
	600	152
	800	170
	1000	187
	1200	205

Hardness	
As Cast	25-29 R _C
Heat Treated	27-38 R _C

Density at 70°F	0.284 - 0.286 lbs/cu. in.
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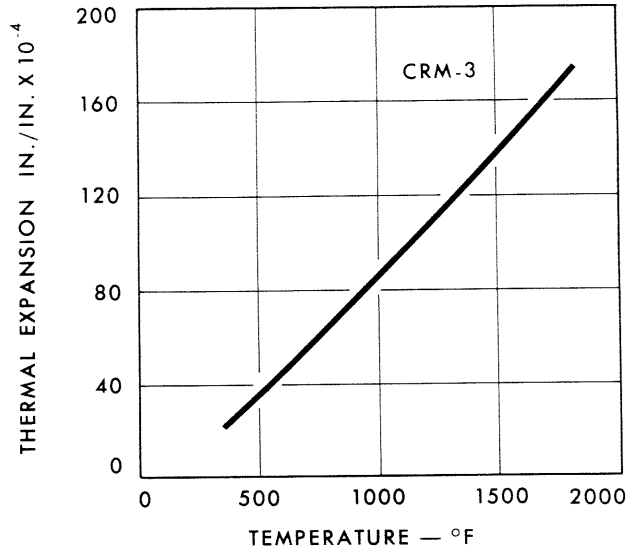


Fig. 10 - Thermal Expansion Characteristics of CRM-3 Alloys

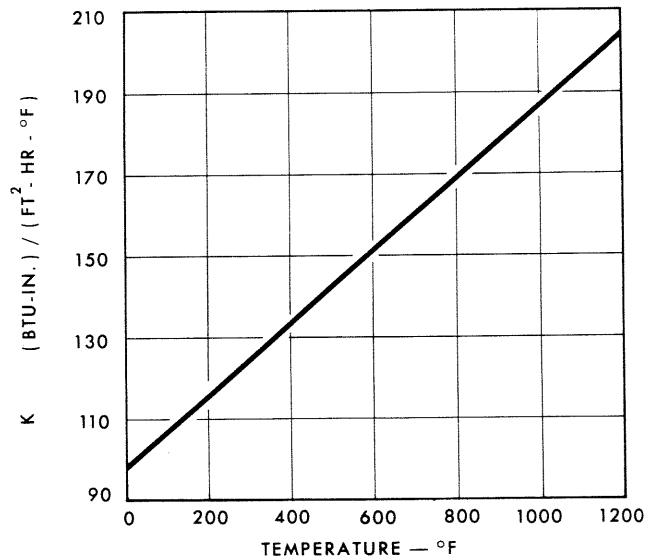


Fig. 11 - Thermal Conductivity of CRM-3 Alloys

The CRM-3 alloy also has shown excellent thermal shock resistance. Figure 12 is a graphic representation of a series of tests performed under simulated service conditions. Individually cast actual blades were tested "as cast" and after a stabilizing heat treatment simulating prior service. In both cases the CRM-3 alloy outperformed a common cobalt-base alloy. The testing apparatus is shown in Figure 13, set up for a test on another common

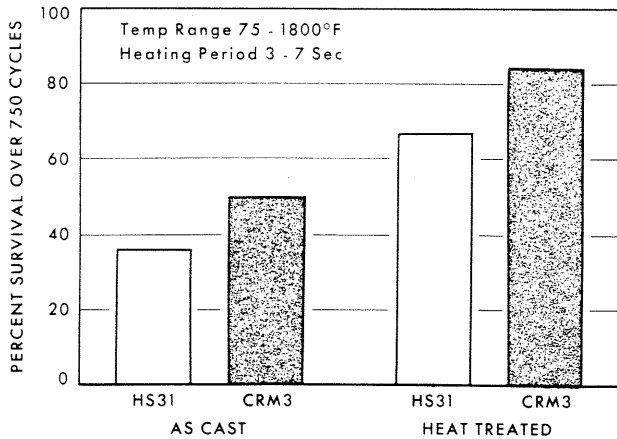


Fig. 12 - Comparative Thermal Shock Resistance of CRM-3 Alloys

type of sample. Here one edge of a triangular section prismatic sample is alternately heated in a gas flame and cooled by a compressed air blast, controlled by high and low temperature limits. The sample is periodically examined under a low power microscope and the testing discontinued when the first crack appears. The results are reported on a comparative basis.

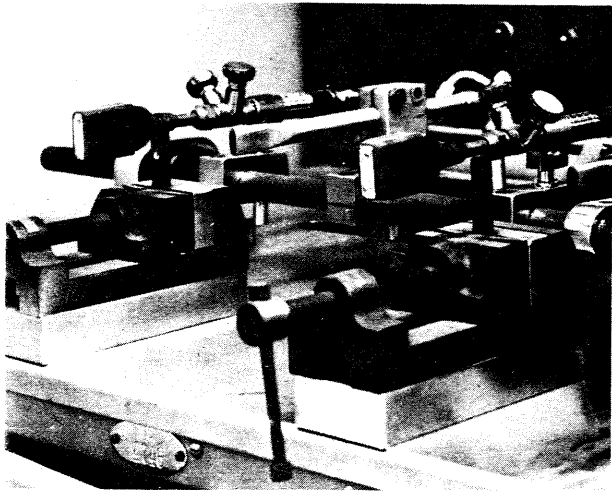


Fig. 13 - Thermal Shock Testing Apparatus

The oxidation behavior of CRM-3 at 1500°F is compared with that of H.S. 31 in Figure 14. During the 1000-hour test, the samples were removed at periods ranging from 24 to 100 hours and the loose scale was removed mechanically before weighing. Although the specific weight loss of CRM-3 is approximately twice that of H.S. 31, it has proven to have adequate oxida-

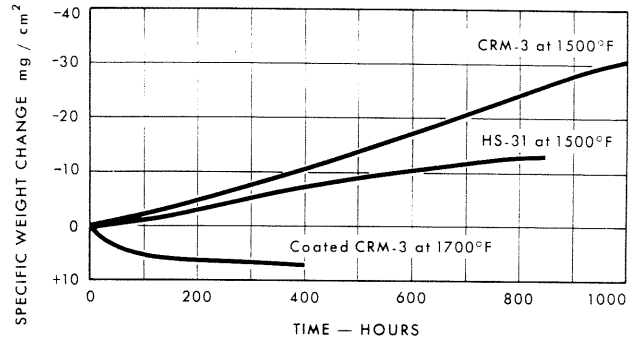


Fig. 14 - Oxidation Rate of CRM-3 Alloys

tion resistance for service at 1500°F. The lower curve in Figure 14 shows the excellent oxidation resistance of this alloy at 1700°F when protected by one of our proprietary coatings.

In our material evaluation program, the CRM-3 alloys have been used extensively. For comparative purposes, two other superalloys, H. S. 31 and Inco 713-C, are being evaluated currently. H. S. 31, which has mechanical properties comparable to the CRM-3 alloy, has been tested throughout the high temperature section. Although it appears that the CRM-3 alloys will adequately meet the superalloy requirements of our current engine, Inco 713-C has been introduced recently into the program to determine if this much stronger alloy can produce significant improvements in operating life or performance. To date, the relative cost of these three materials has not been the prime consideration. Life of the component and past experience are currently dictating which alloy is selected for the turbine program.

Blade cracking has proven to be the limiting factor in the life of the turbine wheels. Our experience has been that Inco 713-C blade life is about twice as long as that of H. S. 31 for the same type of wheel design. The life of CRM-3 blades is superior to that of H. S. 31 and apparently at least equivalent to Inco 713-C. Again wheel design is found to play an extremely important role in blade life. Turbine wheels utilizing CRM-3 alloys are being used extensively in the current evaluation program and no blade cracking or other serious problems have been encountered with the latest design.

The nozzles and first-stage shroudings have been made extensively with H. S. 31 primarily because of this alloy's long record of satisfactory performance and its outstanding oxidation

resistance. The CRM-3 alloy and several special modifications are also being evaluated with and without suitable coatings for these components.

It might be of future interest to indicate briefly here some of the preliminary results that have been obtained on other promising superalloys of the CRM-3 family. Work is moving rapidly on modified alloys which look particularly attractive for highly stressed parts and are suitable for lower service temperatures up to about 1400°F. Typical properties obtained from a limited number of test bars machined from castings are listed below:

	Stress (KPSI)	Elongation (%)
Room Temp., U.T.S.	115-135	6-10
1200°F, U.T.S.	80- 90	10-12
1200°F 100 hr. - Rupture Strength	62	5
1200°F Creep Data	40	Min. creep rate < 0.0006%/hr. *

* Total strain of 0.5% after 300 hours including elastic strain of 0.2%.

In anticipation of higher operating temperatures, work is also being carried out on other experimental iron-base superalloys for high stress application at 1600°F. Preliminary results have indicated that this alloy system offers some potential even at these relatively high temperatures.

Over 800 laboratory heats have been made in the development of the CRM-3 alloys. All of these heats, which varied between 5 and 30 lbs., were melted in a high frequency induction furnace either in air or under an argon blanket. No difficulties were encountered in the transfer from laboratory to experimental production melting operations. Approximately ten high frequency induction furnace heats of 500 to 2000 lbs. and two 6000 lbs. direct air heats have been produced from commercial grade ferro-alloys and Armco iron and/or steel scrap with properties comparable to those of the smaller laboratory heats. All of the large master heats were shotted for convenience in remelting. Gates and risers as well as scrap castings have also been remelted without detrimental effects.

The weldability of the CRM-3 alloys in both the restrained and unrestrained condition is good. Sound weldments have been made by the heli-arc, sigma and submerged arc processes. Filler wires of A-286, Hastelloy "W", N 155, L 605, Inconel 92, and 19-9 W-Mo have all been used successfully. With most of the above wires no preheat or post heat is required. Successful weldments have also been produced by electron beam welding.

B. WROUGHT ALLOYS

As shown in the flow diagram, a wide spectrum of temperatures is encountered throughout the engine. Sheet metal ducting contains and directs the hot gas stream at temperatures from 2100°F at the burner to less than 525°F at the exhaust pipe. In general, the strength requirements for these ducts are not severe, and oxidation or scaling behavior has been the main criterion for selection of the material. This wide range of service temperatures soon pointed out the desirability of a low cost alloy with outstanding oxidation resistance at elevated temperatures.

For these applications we have developed low cost ductile iron-aluminum alloys (CRM-4) that are used with suitable surface treatments depending on component service temperature. Ductility of the ferritic iron-aluminum alloys has been, until recent years, a rather elusive property, depending mostly on the control of interstitials. Our metallurgists were successful in developing processing techniques that have made the alloys commercially feasible.

The alloys are readily weldable using conventional techniques and can be drawn into complex shapes as required. The latest steel making techniques have been used to produce them on a tonnage basis at an extremely reasonable cost. The tensile properties of an Fe-6%Al alloy are shown in Table VII along with those of three common stainless steels. It compares very favorably with the 400 series ferritic stainless steels at all temperatures. Although it has inferior strength when compared to the more expensive austenitic Cr-Ni stainless steels, the oxidation resistance of the iron-aluminum alloy with suitable surface treatment is far superior above 1300°F. The lower strength of this ferritic alloy limits its use to low stress components, but it is believed that the strength limitation can be overcome by more sophisticated design.

TABLE VII
Typical Mechanical Properties of Several Oxidation Resistant Alloys

Alloy	Test Temp.	Tensile Strength (KPSI)	.2% Yield Strength (KPSI)	Elong. (%)
CRM-4 (Fe-6% Al)	RT 1300°F	65-75 15	45-50 14.5	25-35 65
Stainless Steels				
Type 304	RT 1300°F	80-95 36	35-45 11	55-60 37
Type 430	RT 1300°F	70-90 15	40-45 8	20-30 64
Type 446	RT 1300°F	75-95 18	45-60 8.5	20-30 84

All alloys in annealed condition.

The uncoated alloys will sustain long periods of service at 1200°F without excessive scaling, thereby very adequately filling the gap between mild steel and higher alloy content materials. For service above this temperature the alloys are treated to raise the surface aluminum content to a suitable level for adequate oxidation resistance*. For higher temperatures, 1500°F to 2300°F, a high surface aluminum content is built up by a dip aluminizing process. The next graph (Figure 15) shows a comparison of the scaling properties of a treated Fe-6%Al alloy

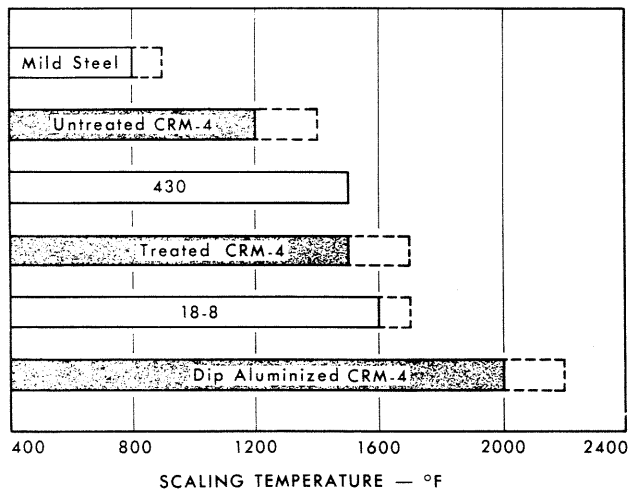


Fig. 15 - Maximum Operating Temperature of CRM-4 Alloys

with that of common stainless steels. Figure 16 shows that, on a weight gain basis, only at 1700°F does the oxidation resistance of 304 stainless steel approach that of the new alloy.

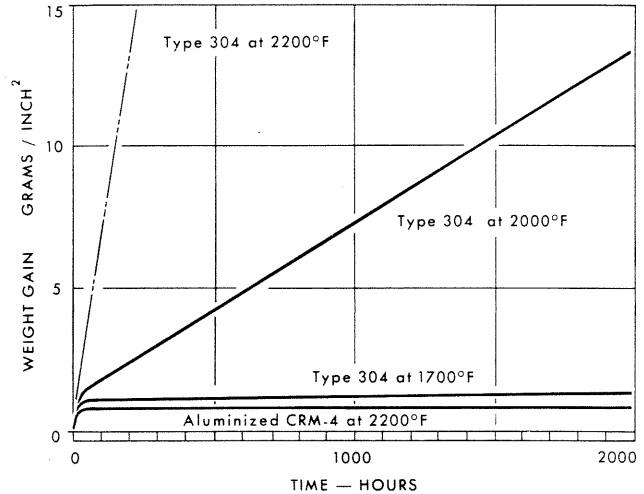


Fig. 16 - Oxidation Rate of CRM-4 Alloys

As part of our continuing materials evaluation program, wrought austenitic heat resisting alloys such as Hastelloy X and RA 333 have been tested for the sheet metal components on the gas generator side of the engine, at the burner and vortex, where temperatures up to 2100°F might be found. On the exhaust side where temperatures do not exceed 1350°F, 430 stainless steel has been used for diffusers and insulation liners. The savings realized by using our new alloy are quite substantial. They run from 10¢ to 20¢ per lb. when it is substituted for common ferritic or austenitic stainless steels to over \$1 per lb. where the austenitic heat resisting alloys are concerned.

Regenerators

Our turbine design and laboratory engineers have accepted the rotary regenerator as the best method for getting good fuel economy in automotive gas turbine engines. The Chrysler simple cycle design uses rotary disk-type regenerators which have been considered to be relatively difficult to seal. The problem of securing satisfactory seal materials has definitely been one of the main obstacles to the introduction of a practical automotive turbine engine.

* Proprietary process

High temperature rubbing seals are required to operate under severe sliding conditions at relatively high pressure with no possible lubrication. Some of the known requirements of satisfactory seal materials are tabulated below:

1. Low coefficient of friction over the range of service temperatures.
2. Low wear rate but good wear-in characteristics.
3. Dimensional and structural stability over the range of service temperatures.
4. Adequate strength, ductility, modulus, etc.
5. Adequate oxidation resistance.
6. Compatibility with the regenerator matrix material.
7. Low cost, including availability of manufacturing ease.

So far, no commercially available materials have been found to possess all of the required characteristics and be capable of operating satisfactorily over the full temperature range en-

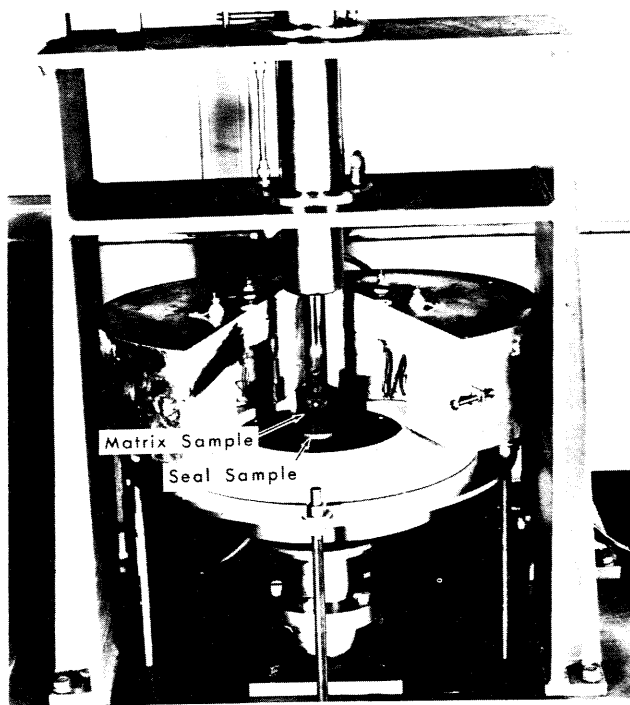


Fig. 17 - Bench Seal Wear Testing Apparatus

countered in service, i. e. ambient temperature up to about 1200°F. Common graphite-base materials have been used successfully for long period of time in oxidizing atmosphere up to about 900°F, but are short-lived at higher temperatures. Other commercial seal materials have been found to operate well in the upper temperature range, but are unacceptable at lower temperatures.

Considerable effort has been expended on this problem by our Metallurgical Research Group, resulting in the development of a new family of seal compositions having quite interesting properties. This seal development program was carried out with four similar bench test wear machines. A photograph of one of these wear machines is shown in Figure 17. This type of machine duplicated quite closely the engine design operating conditions of temperature, pressure and rotational speed. Wear rate, coefficient of friction and weight-loss measurements over the range of service temperatures recorded at regular predetermined intervals were used as evaluating criteria for satisfactory seal materials. Figure 18 illustrates the seal wear at various temperatures for one of the better graphite-base seals and one of our new rubbing seal materials (CRM-8)*. At temperatures above 900°F, rapid oxidation restricts use of the commercial seal material. The lower curve represents the satisfactory wear rate for our seal tested under the same conditions. Fur-

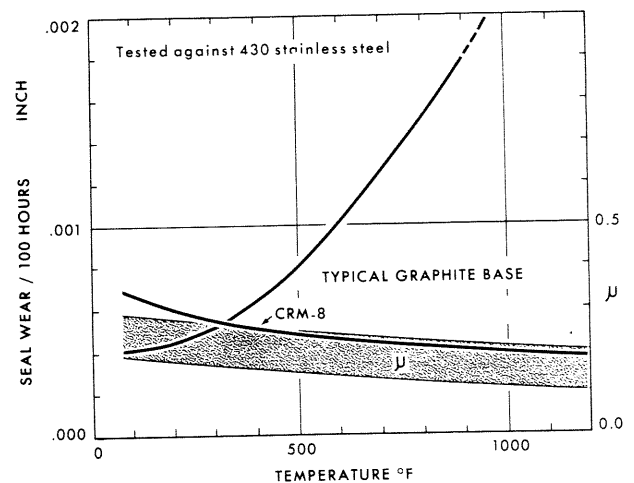


Fig. 18 - CRM-8 Seal Wear Rate at Various Temperatures

* Proprietary

thermore, this material has a relatively low coefficient of friction over the same temperature range, as shown by the shaded band.

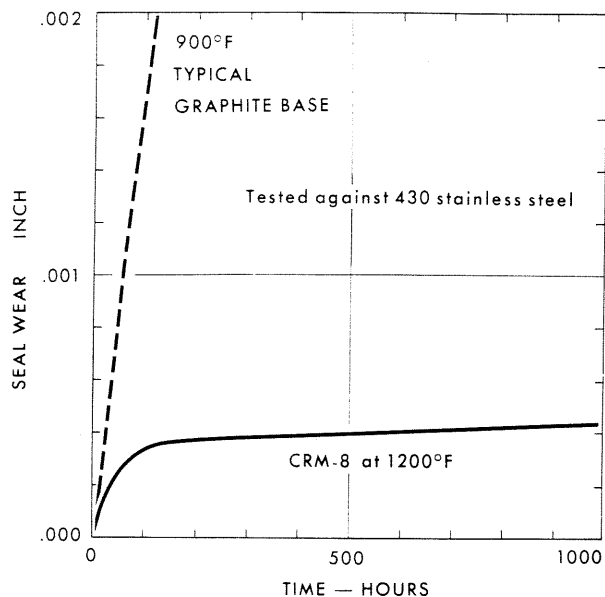


Fig. 19 - Stability of CRM-8 Seal Material

The stability and life of seal materials are compared in Figure 19. The graphite-base commercial material wears rapidly, even at 900°F. For the experimental seal, after a break-in period, the wear rate is negligible even after 1000 hours of operation at 1200°F. These laboratory results duplicate quite closely actual turbine operating conditions, as illustrated in Figure 20. Further, we have found that the experimental seal material also operates well at higher temperatures (1500°F). Another ap-

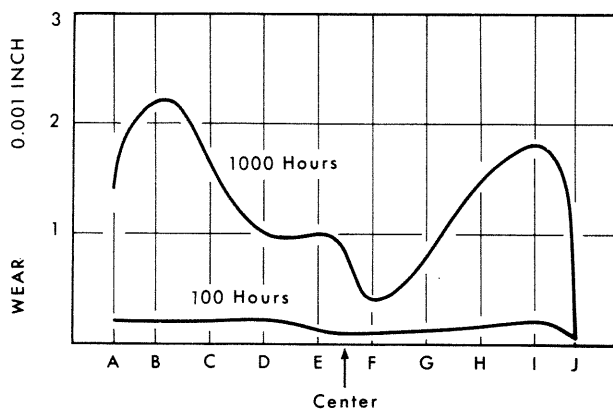


Fig. 20 - Typical Wear Profile of a CRM-8 Regenerator Seal

plication for this material is in high temperature bearings such as those used in our variable nozzle system.

We are confident today that the material problems associated with our present regenerator system have now been overcome. Contrary to general belief, this section of our engine is likely to be the source of least engine troubles. Laboratory and field experience have indicated good performance, high degree of reliability, and extremely long life.

SUMMARY

The successful development of the automotive gas turbine as an attractive powerplant has presented a real challenge to the materials engineer. Competent design has contributed considerably to making this engine a practical powerplant, but an equally large share of the success is to be attributed to the role played by conventional and newly developed materials used in unique application.

At this stage of development it appears that the cost of the engine is the major obstacle in the path of a mass produced automotive powerplant. Furthermore the severity of operation of today's automotive gas turbine appears to be more demanding than aircraft components. As a result of extensive material development programs in our Metallurgical Research Laboratories, remarkable progress has been made in the following areas:

(a) Iron-base superalloys having equivalent or superior life to aircraft type alloys, but only at 15 to 25% of the cost; (b) low-cost, heat-resisting iron aluminum alloys developed for elevated temperature service under low stress applications; and (c) low cost, long life rubbing seal materials that have been found to operate satisfactorily from ambient temperatures up to 1200°F and above.

These materials appear to meet all present or immediate high temperature alloy requirements for a competitive mass produced automotive turbine.

