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RMI

TITANIUM DESIGN AND FABRICATION

This paper discusses the design and fabrication of titanium, stressing design, and how the properties of titanium lead to different kinds of applications. First, I will discuss titanium alloy characteristics and the classification of titanium alloys. Second, I will briefly discuss mill product processing and fabrication of titanium and what the mill products are used for in finished components. Third, I will show how these properties and fabrication techniques combine to produce applications. In many cases it's the unique combination of several characteristics along with fabrication capability that produce a successful application in titanium.

ALLOY CLASSIFICATION

The titanium alloys are classified into three basic systems (Fig. 1), the alpha titanium alloys which are primarily the hexagonal closed-packed crystal structure; the alpha-beta alloys, alloys which are a combination of hexagonal alpha phase, and body-centered cubic. Each of these systems has unique characteristics that are used in a variety of different applications. As a result, it is important that the proper alloy class be selected for a given application.

The alpha titanium alloys (Fig. 2) are distinguished primarily by these items. They have excellent corrosion resistance in chloride environments, especially those oxidizing in nature. They exhibit moderate strength and low density and show excellent weldability in inert gases.

Generally the alpha alloys have less than one percent alloy addition although there is a special class of alpha titanium alloys, the creep resistant alloys, which are distinguished primarily by alloy additions of aluminium, tin and zirconium.

The second class of alloys, the alpha-beta titanium alloys, have less corrosion resistance than the alpha titanium alloys. They are also distinguished by low density, indeed lower density than alpha alloys. They have moderate to high strength, are moderately heat treatable, exhibit good weldability, and possess good creep and fatigue strength (see Fig. 3).

The beta titanium alloys have not been employed to near the extent of the alpha and alpha-beta alloys, but they offer very unique characteristics which are only recently being used. They have good corrosion resistance, indeed in some applications they exhibit better corrosion resistance than the alpha titanium alloys. They have low density and high strength, are heat treatable to a wide range of strength levels and in general, are readily welded (see Fig. 4).

Reviewing all of the characteristics (Fig. 5) that these three classes of alloys exhibit, they all have low density, moderate to high strength, low elastic modulus which can sometimes be an advantage and sometimes a disadvantage as discussed later, and lower thermal expansion, typically the same as glass. They have excellent creep strength up to 600°C. They exhibit excellent corrosion resistance in oxidizing environments, discussed in more detail later.

In Figure 6 the density is compared to an aluminum alloy. Other stainless and carbon steel alloys, two titanium alloys (an alpha and an alpha-beta titanium alloy), and a typical highly corrosion-resistant nickel alloy. Titanium is approximately 60% the density of the iron and nickel base alloys, approximately

40-50% higher than the aluminum alloy. And the alpha-beta alloy Ti-6Al-4V is slightly lower than the alpha alloy.

Elastic modulus is approximately 50% higher than the aluminum alloy, as shown in Figure 7. Typically alpha-beta alloys exhibit somewhat higher elastic modulus than the alpha alloys. The beta alloys are unique in that they can exhibit elastic moduli from as low as the aluminum alloys to as high as the alpha-beta titanium alloys. By heat treatment, elastic modulus may be varied in the beta alloys.

Thermal expansion, compared in Figure 8, shows the titanium alpha alloys to be slightly higher than alpha-beta titanium alloys and in most cases lower than all other metal alloy system.

Thermal conductivity of titanium is low for titanium when compared to aluminum and copper alloys (Figure 9). In applications where titanium competes with stainless steel and nickel-base alloys, thermal conductivity is similar.

By turning to corrosion resistance, Figures 10 and 11 present a great deal of information that require explanation. In both of these figures the horizontal axis indicates the range of corrosive environments going from oxidizing (on the left) to reducing (on the right). Oxidizing includes environments such as nitric acid and oxidizing chlorides (e.g. bleach, chlorate, hypochlorate and the like). The blue vertical line represents seawater, a neutral environment, neither oxidizing nor reducing. Reducing environments, to the right of the line, include major mineral acids such as hydrochloric acids and sulfuric acid. ASTM Grade 2 titanium, which is commercially pure alpha titanium, exhibits excellent corrosion resistance in oxidizing environments. It performs rather poorly in reducing environments and as a consequence is not used to any degree in most of the reducing mineral acids. Figure 10 shows comparison with other alloy systems and Figure 11 specifically compares titanium alloys.

One of the unique things about titanium is that if you take one of these reducing mineral acids and add, for example, metal cations, such as iron or copper, the environment becomes oxidizing. So an environment that would normally attack titanium doesn't. In Figure 11, the two alloys above Ti-grade 2, Ti-grade 12 and Ti-grade 7, were developed primarily to improve titanium's resistance into reducing environments. Grade 7 is quite effective in that area, often being used in hydrochloric and sulfuric acid service. Grade 12 is less effective but has found wide application in areas where localized attack by crevice corrosion is important. Further up the vertical axis, the alpha-beta titanium alloys exhibit somewhat lower corrosion resistance in reducing environments, with the exception of Ti-6Al-2Sn-4Zr-6Mo. Because of this alloy's high molybdenum content it exhibits good corrosion resistance in reducing environments.

Of the beta titanium alloys at the top of Figure 11, Beta-C titanium has good corrosion resistance over a wide range of environments and also exhibits high strength. These two characteristics have only recently been exploited, as discussed later. Ti-13V-11Cr-3Al at the top of Figure 11 has marginal corrosion resistance in both oxidizing and reducing environments and as such is of little interest in corrosion applications.

In figure 12, various titanium alloy properties are shown. In this table, commercially pure titanium, an alpha alloy, an alpha-beta alloy, and a beta titanium alloy are compared. In general, the alpha-beta alloys exhibit the lowest density. The beta titanium alloy exhibit a wide range of strength capability by a simple heat treatment. Other properties are also provided for comparison.

Specific yield strength is given as a function of temperature in comparison to other alloy systems in Figure 13. Titanium exhibits higher specific strength than aluminum alloys and higher strength alpha-beta and beta alloys exceed the specific strength of precipitation hardening stainless steels. Commercially pure titanium has low specific strength but compares quite favorably with aluminum at about 200°C (400°F).

FABRICATION

Once you realize that titanium in ingot form behaves similarly to fabrication and other alloys systems (e.g., stainless steel), processing becomes straight forward. In practice, titanium has been found to be easier to join than many of the nickel and stainless steel alloys.

Most of the fabrication processes that are exploited for stainless steels and nickel-base alloys can be used for titanium. Hot forming may be performed over a fairly wide range of temperatures. Titanium is also unique in that it is superplastically formable where total strains exceeding 500% are possible. As a consequence, unique parts and fabricated structures may be produced using superplastic forming. All of the major cold and hot forming processes can be used with titanium on conventional forming equipment, keeping in mind the low elastic modulus. The alpha alloys and the beta alloys lend themselves to cold or warm forming, while primarily alpha/beta type alloys use hot forming. Typical process parameters are shown in figure 14.

In figure 15, typical temperatures that are employed along with the machinability and weldability ratings are presented. Weldability, as indicated, is quite good as long as it is done in inert gas. Machinability ratings are presented in a normalized fashion with carbon steel having a value 1. The alpna alloys (specifically commercially pure titanium alloys), are easier to machine and the alpha-beta alloys are somewhat harder. Beta alloys are much more difficult to machine, primarily because of their low modulus and high hardness. Nevertheless, they are machinable.

APPLICATIONS

Combining all of these characteristics and fabrication techniques, the remainder of this paper will discuss why titanium is being used and in what areas it may be used in the future. For each application the individual requirements are tabulated and any example is presented.

The first item is the largest application for titanium, primarily alpha-beta alloys, gas turbines. In a gas turbine, the requirements include high specific strength, high specific fatigue strength, low thermal expansion, and high creep strength (Fig. 16). Titanium shines in the first four and starts to fall out of the last item at about 600°C. As a consequence, titanium is used extensively in the first third of the gas turbines for all of the rotating components (Fig 17).

Figure 18 shows an engine case using various hot forming and chemical milling technologies to produce a product with significant weight savings compared to other technologies.

The second item, a major nonaerospace application for titanium, is the heat exchanger. The primary properties required are high corrosion resistance, erosion resistance and high thermal conductivity (Fig. 19). Titanium, as indicated earlier, has poor thermal conductivity. However, in Figure 20, the reason titanium is used is schematically shown. In a typical tube, there are several things that contribute to the ability of a tube material to transfer heat. Thermal conductivity of the metal is only one of these components. In addition, and of more significance, the tube and shell side corrosion deposits (scale) that form over time contribute to heat transfer.

Titanium being corrosion resistant forms essentially no scale on the surface, so that transfer is primarily controlled by metal thermal conductivity. In copper-bearing or aluminum - bearing alloys the corrosion performance is not nearly as good, and a consequence scale formation overwhelms the thermal conductivity of the tubing as the major contributor to overall heat transfer. As a result, the titanium tube with no scale will, in time, have a higher overall heat transfer rate. In addition, titanium's higher strength allows for a much thinner tube wall, thereby improving the effective thermal conductivity. Exploiting these two characteristics, higher strength and better corrosion resistance can, in many cases, reduce exchanger size by as much as 50% titanium.

Figure 21 shows a typical shell and tube type heat exchanger. In most applications only the tubes and the tube sheet are titanium because the tube inside diameter is the only component exposed to the corrosive media.

The third titanium application is in chemical process equipment (Fig. 22). In addition to heat exchangers, titanium has been used in a variety of chemical process equipment especially in contact with oxidizing environments. It is used primarily because of its corrosion resistance.

Equipment can be readily welded and conforms to most of the international boiler code requirements. Combining corrosion resistance and low density can greatly offset the increased cost of titanium. Examples include the U-bend type heat exchanger in Figure 23. In this application there is a tube inside a tube used for waste treatment where waste fluids are put into the center tube, heated with air and oxidized. The environment in very corrosive, with highly oxidizing brines at temperatures approaching 315°C. No other material can withstand this environment as effectively.

The next chemical process example shows how low density and excellent corrosion resistance combine to make an unlikely application successful.

In Figure 24, a titanium tank truck for transporting nitric acid is shown.

The tank portion of the truck is entirely titanium. The manufacturer combined the excellent corrosion resistance of titanium in nitric acid, an oxidizing mineral acid, and the low density of titanium. Together these properties allowed the weight of the truck to be reduced to the point where it could carry 40% more nitric acid offsetting the cost of the titanium compared to steel. In fact, the economic payback on these trucks is less than six months, in comparison to a carbon steel truck.

The fourth application is in electrochemical electrodes. Titanium electrodes are employed in producing other materials electrochemically.
The chief requirement for an electrode (Fig. 25) is that it must be dimensionally stable throughout its life. If the electrode moves or changes shape critical parameters in the electrochemical process are negatively effected.
Production of chlorine and chlorine compounds using dimensionally stable titanium alloy electrodes is the most obvious example of an electrochemical electrode. The titanium is more than adequate for the corrosion requirement in a highly oxidizing brine. But the high overpotential for titanium in a chlorine cell is offset using a precious metal oxide coating which dramatically lowers over-potential, allowing chlorine and chlorate-producers to significantly reduce costs compared to other technologies. A typical cell using titanium electrodes is shown in Figure 26.

Another example using titanium is the copper starter sheet shown in Figure 27. Copper-bearing electrolytes with titanium cathodes electrowin copper by electroplating copper onto the titanium surface. Titanium's thin oxide prevents the copper from wetting the titanium surface and sticking, so when the cathode is removed, the copper is casily stripped from the titanium.
Titanium is also used as a holder for aluminum anodizing.

Aluminum fixtured in titanium is anodized in a sulfuric acid solution. The titanium does not contribute in any way the power requirements for anodizing aluminum, nor does it corrode because of its stable oxide film.

The next few areas are newer applications which are either beginning to evolve now or are just around the corner.

The offshore riser is a system used to transport oil or gas from the ocean floor to the ocean surface (Fig. 28). They must be flexible because most of these platforms float on the ocean surface and the hole on the ocean floor doesn't. The riser must also have excellent resistance to corrosion and corrosion fatigue in seawater, and lastly, the riser must have moderate strength. Titanium fortunately exhibits all of these properties.

In an oil and gas system the well head is at the bottom of the ocean floor on top of a hole from the bottom of the ocean floor to depths as great as 5000 m (Figure 29). There may be several holes in the ocean floor which flow oil or gas up to a platform at the ocean surface where it is processed and subsequently sent on to refineries. If the platform moves from side to side high stresses must be accommodated by the risers to protect each well head.

Two systems that have been employed to accommodate these stresses are shown in Figure 30. The system on the right is a mechanical steel coupling. The coupling is expensive, has to operate at very high pressures, and is prone to leakage and failure because of the number of seals. The system on the left exploits the elastic modulus of titanium, the corrosion resistance of titanium and the high corrosion fatigue of titanium to eliminate this flexible coupling. A system like this has been in the Gulf of Mexico in the United States since 1987 and is working properly.

The device, termed a stress joint, is the joint at the bottom of the riser system. It is approximately 15 m long and 1 m in diameter, produced from the largest titanium extrusion ever made. Flanges at both ends were approximately 3000 kilogram forging which were electron beam welded about 250 millimeters thick to the extrusion. The entire unit weighs approximately 10,000 kilograms and supports a large floating platform in the Gulf of Mexico (Figure 31).

Another emerging application for titanium is its use in downhole oil and gas equipment. Requirements include corrosion resistance in H_2S gas and resistance to stress corrosion and cracking (Table 32). Most of the alloys have to be heat treatable because the components require moderate to high strength and they must have resistance to impact because these components take a tremendous beating in service. Titanium does very well in H_2S corrosion. The beta titanium alloys are readily welded, readily heat treated and also exhibit moderate to high strength. The remaining question right now concerns these materials resistance to stress corrosion cracking in H_2S.

The forging in Figure 33 was made for a pump intended for H_2S service. The component weighs about 18 kilograms and it is made out of a beta titanium alloy with a yield strength in excess of 1200 MPa. It is quite unique in its strength characteristics and it also has been found to exhibit excellent resistance to stress corrosion cracking up to approximately 200°C which is very unique for heat treatable materials.

Springs are a natural application for titanium (Fig. 34). Springs in general are highly loaded structures that require excellent fatigue properties. The high strength and low modulus of beta titanium alloys make for a more efficient spring. Figure 35 shows a number of titanium springs. These in general are small springs used for components in aerospace application. Figure 36 shows the characteristics used in designing a spring and where titanium has advantages.

The formula in the upper right indicates that a spring's rate is proportional to the elastic modulus divided by the number of coils. So as the modulus of titanium is 50% lower than steel, half as many coils are required for a given spring.
Fewer coils mean less weight and more efficient packaging. Figure 37 illustrates this clearly when a steel and titanium spring with the same geometry and spring rate are compared. The titanium spring has 60% more density and 50% fewer coils leading to a weight savings of nearly 75%.

Titanium is also used for structural medical implants. In Europe the medical industry is ahead of the United States in that they've been using titanium for various structural implants for a number of years (Fig. 38). The critical requirements for these components are the need for compatibility with the human body, nontoxic, moderate to high strength, and low modulus. Cold formability, surprisingly enough, is also important because the physician must often cold-form the implant while in surgery. If the implant is not cold-formable the physician cannot adjust it for proper operation.

Figure 39 shows a variety of implants used today: hip prosthesis, bone plate and screw components and a replacement knee. Most of these components function for long periods of time without trouble.

A future application for titanium stemming from experiences in gas turbines is in steam turbines. Steam turbine requirements are shown in Fig. 40 are very similar to those for gas turbines. High fatigue resistance, in this case, corrosion fatigue, high specific strength, high toughness and erosion resistance are critical for successful blading.

Figure 41 shows a picture of steam turbine blading. These turbine blades can be as long as 2 meters, so the rotating weight becomes tremendously important. Titanium’s high strength, low density can be used to great advantage here. Titanium is unique in this application because in the presence of steam, especially contaminated steam, its fatigue characteristics are the same as in air.

Titanium has also been used in the construction of submersibles. In the United States and Europe, small titanium submersibles have been made because of its low density, high strength and excellent corrosion resistance in seawater (Fig. 42). Figure 43 shows a small exploratory submersible called the Alvin. The Alvin was the first of the titanium submersibles made in the United States. The forward section of this unit is a pressure sphere approximately 2 m in diameter produced by welding two hemispherical plates together. Interestingly, many of the components on this submersible are also titanium, for example, the pumps and valve systems.

One of the most promising titanium applications on the horizon is the use of titanium in production of automobiles, especially in engine applications. Automotive companies are looking at the light weight, high strength and in some cases the low modulus, especially for spring applications. The major disadvantages, at this point, is that titanium has not been, or has not lent itself to automated fabrication (Fig. 44).
Efficiency gains from titanium engine components have been largely able to offset higher metal cost.

Figure 45 shows the most promising titanium engine component, valves. The figure shows the production sequence for making a valve using two titanium bar sizes. Surprisingly, the high creep strength titanium alloys, such as Ti-6242S, perform very well as exhaust valves at 700 – 750°C.

CONCLUDING REMARKS

Titanium has a number of properties advantageous to a wide variety of applications. However, no application can use titanium effectively without combining several of these properties. As a consequence, titanium applications depend on careful design to take advantage of its unique characteristics.

QUESTIONS:

1. Aerospace applications.

That is a good question, because that's an area of tremendous interest right now with some of these advanced aerospace applications. In general, titanium is not particularly resistant to hydrogen environments. It tends to embrittle by hydride formation or interal stress in the crystal structure. Gamma titanium aluminide alloys look interesting from a hydrogen resistance point of view. However, there is a lot of work yet to be done.

2. We hear a lot of comments from the fabricators in the United Kingdom regarding the cleanliness of the fabrication shops, particularly in relation to iron contamination on weld zones. Could you give us a few comments on that, please.

Titanium, because of its reactivity, requires clean conditions in order to weld successfully. It generally reacts with interstitials, so carbon, oxygen and nitrogen are readily picked up in the weld. I think ultra clean conditions are not required, however. Judicious application of the knowledge of potential contamination is important, but a clean room condition is not really necessary. Iron contamination may be avoided in welding through the use of stainless steel or copper bearing alloy cleaning brushes.

Titanium Design and Fabrication

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3rd Meeting on Titanium, 5 November 1987
Turin, Italy


Titanium Alloy Classification
Alpha
Alpha/Beta
Beta

Fig. 1

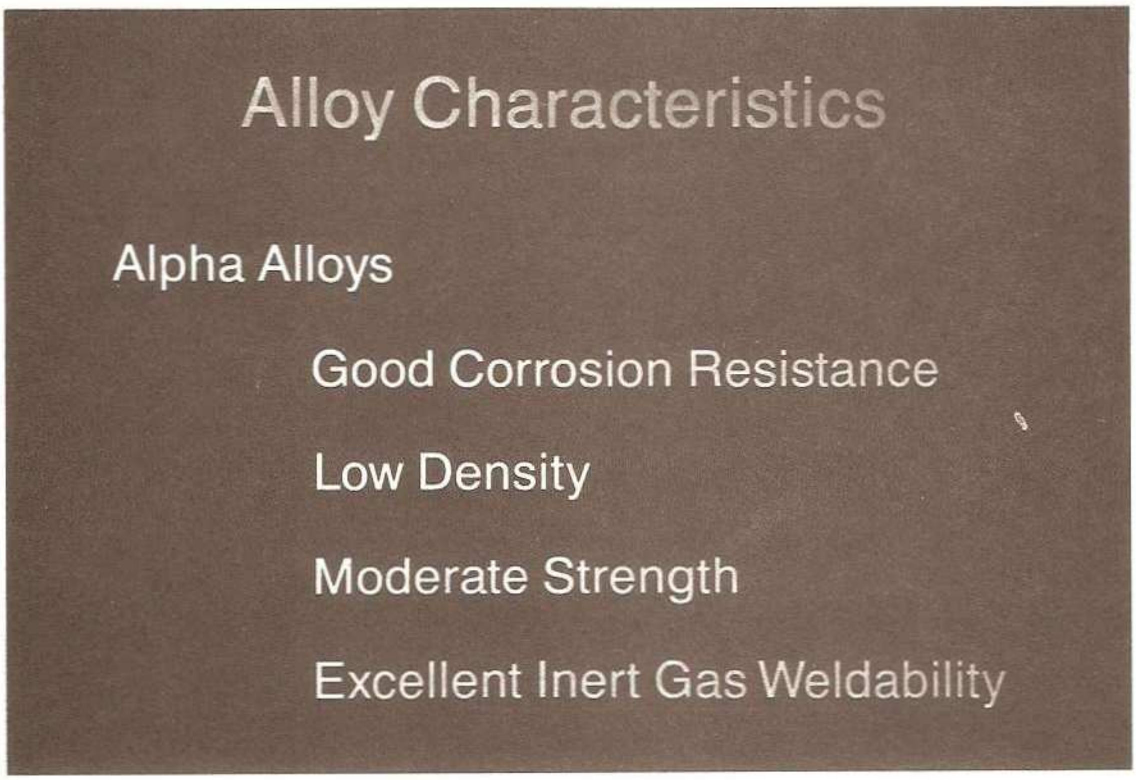

Alloy Characteristics
Alpha Alloys
Good Corrosion Resistance
Low Density
Moderate Strength
Excellent Inert Gas Weldability

Fig. 2

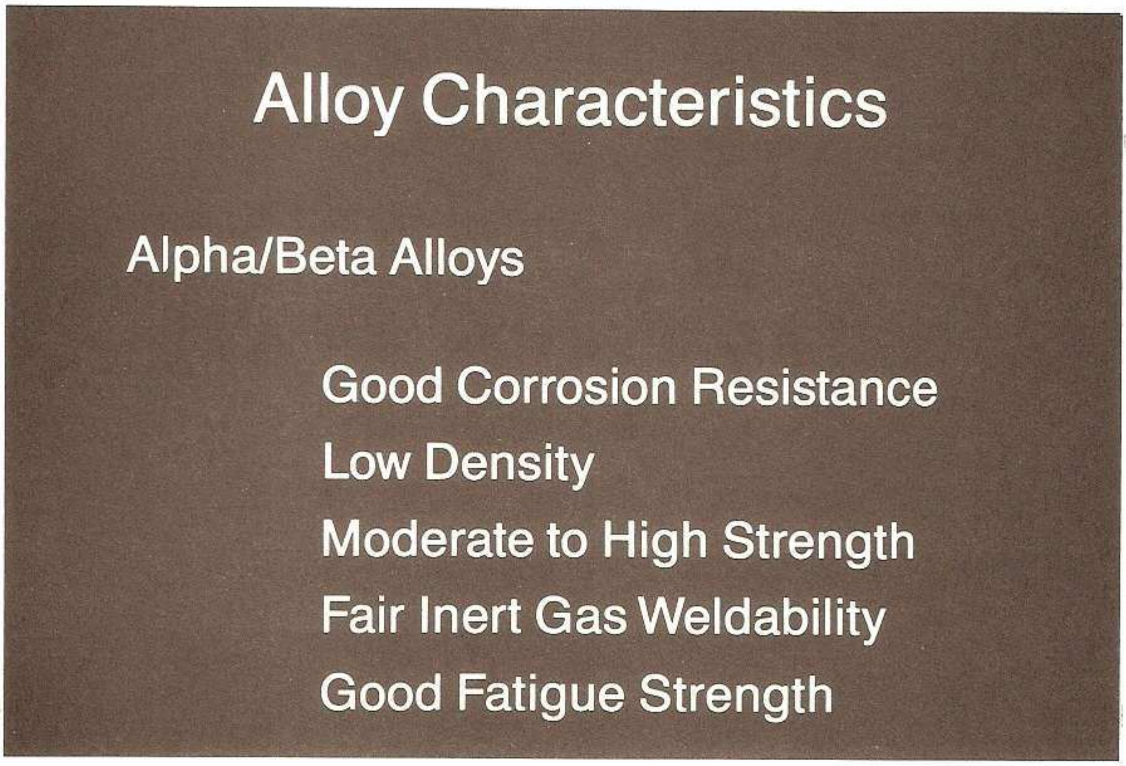

Alloy Characteristics
Alpha/Beta Alloys
Good Corrosion Resistance
Low Density
Moderate to High Strength
Fair Inert Gas Weldability
Good Fatigue Strength

Fig. 3

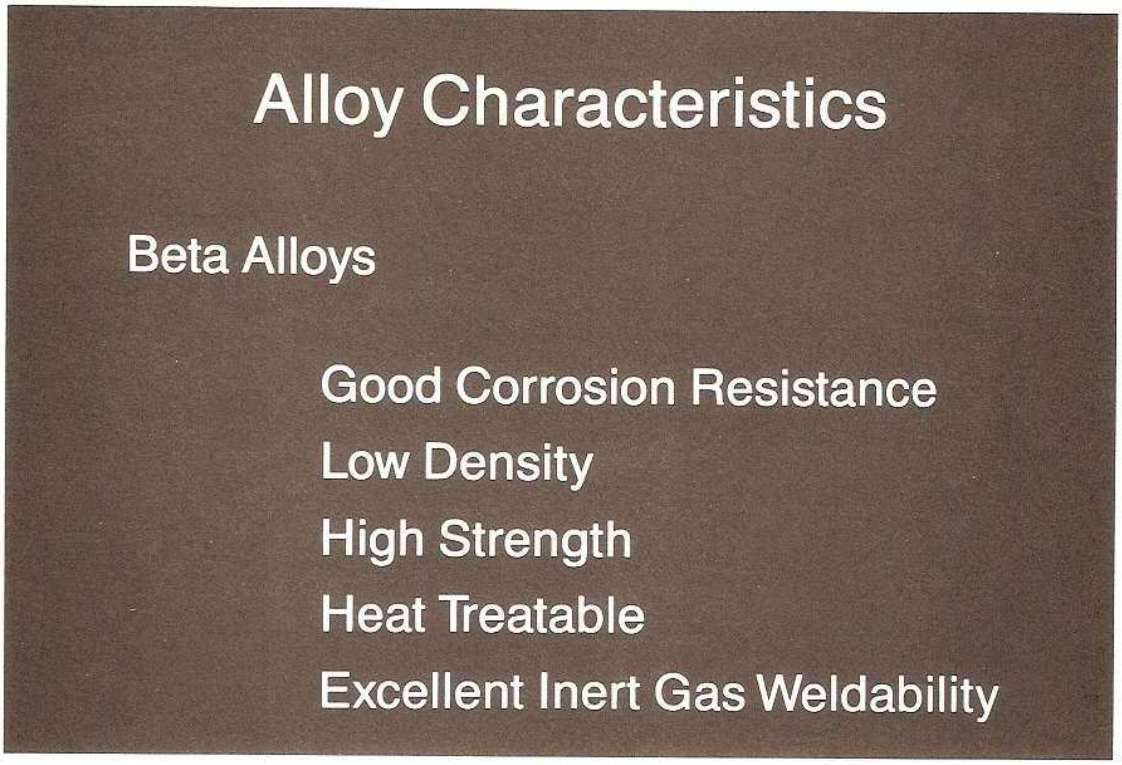

Alloy Characteristics
Beta Alloys
Good Corrosion Resistance
Low Density
High Strength
Heat Treatable
Excellent Inert Gas Weldability

Fig. 4


Titanium Alloy Characteristics
Low Density
Moderate to High Strength
Low Elastic Modulus
Low Thermal Expansion
Excellent Creep Strength to 600°C
Excellent Corrosion Resistance
Ease of Fabrication
Weldable by GTA, GMA
Fair Thermal Conductivity

Fig. 5

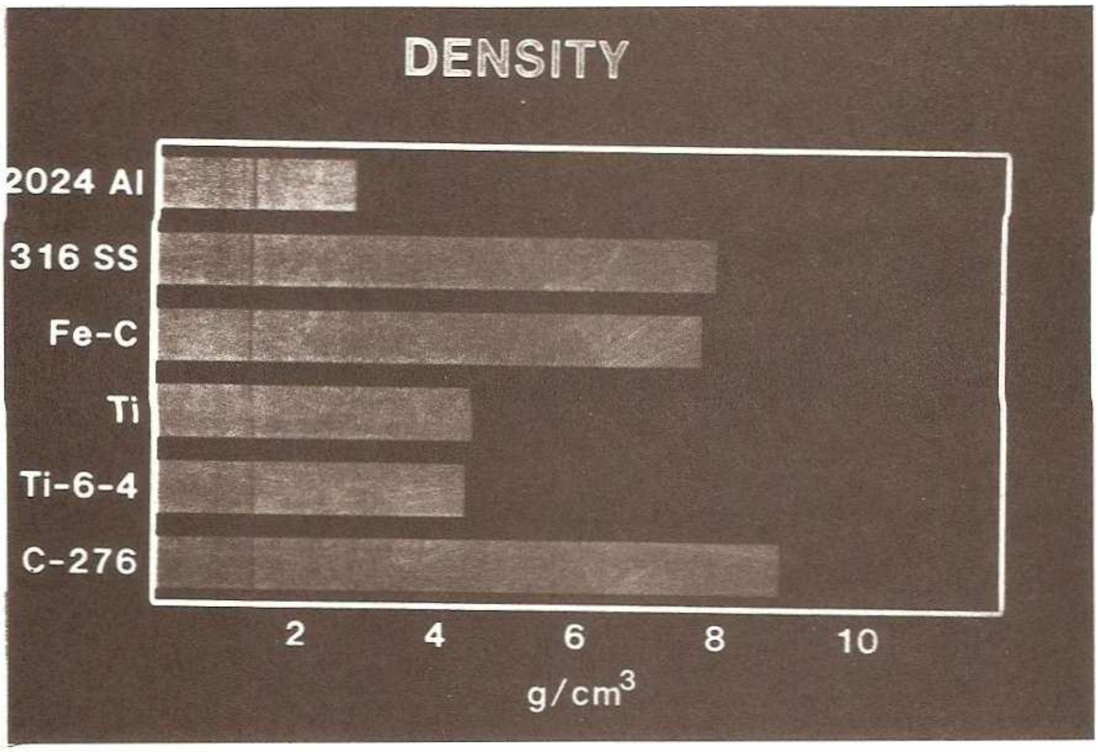

DENSITY
2024 Al
316 SS
Fe-C
Ti
Ti-6-4
C-276
2
4
6
8
10
g/cm3

Fig. 6

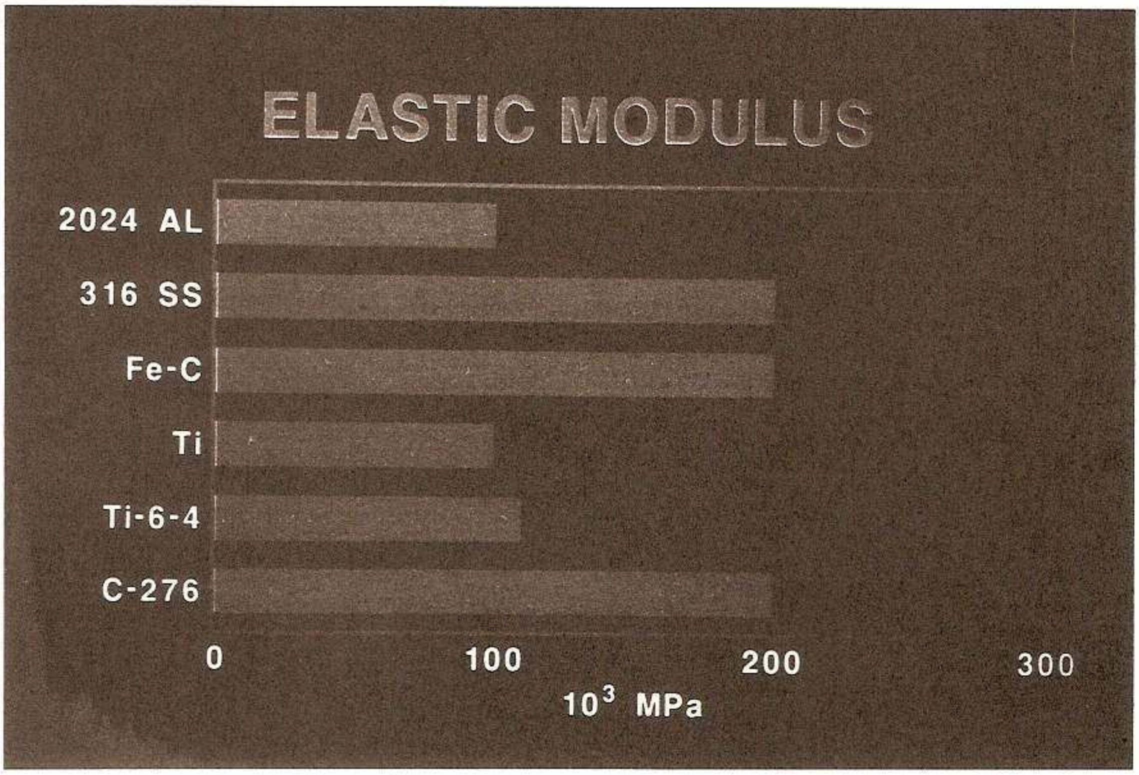

ELASTIC MODULUS
2024 AL
316 SS
Fe-C
Ti
Ti-6-4
C-276
0
100
200
300
10^3 MPa

Fig. 7

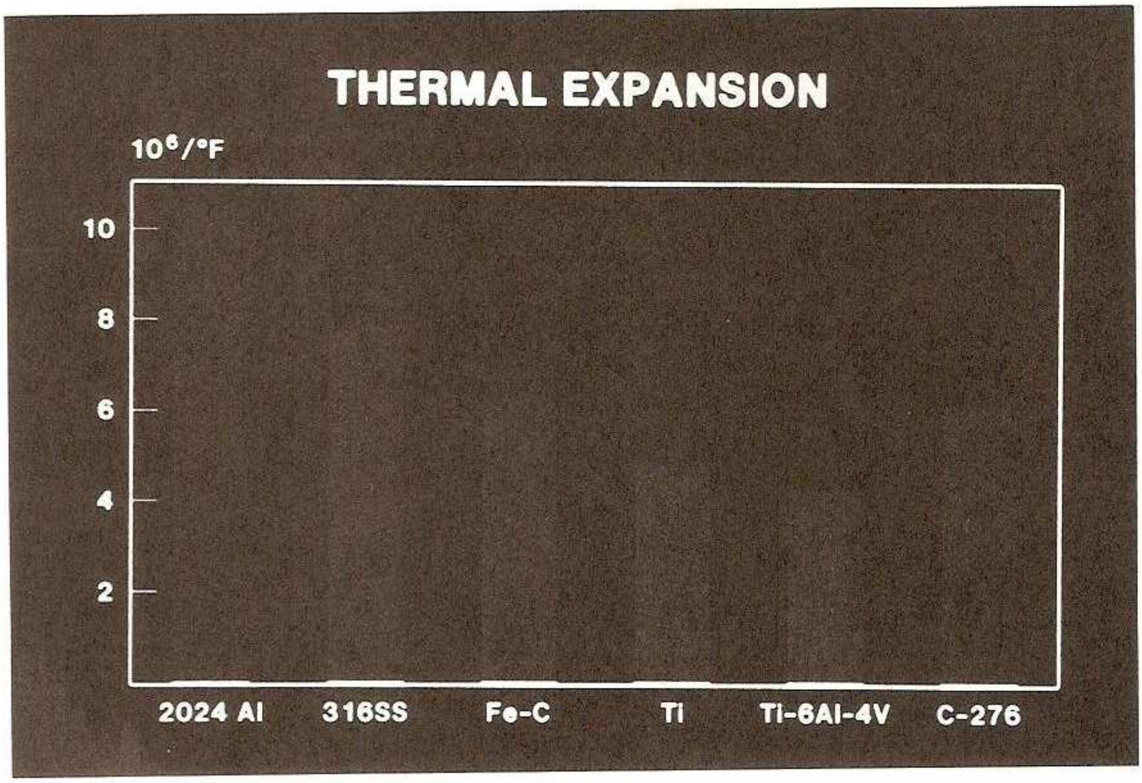

THERMAL EXPANSION
10^6/°F
10
8
6
4
2
2024 Al
316SS
Fe-C
Ti
Ti-6Al-4V
C-276

Fig. 8

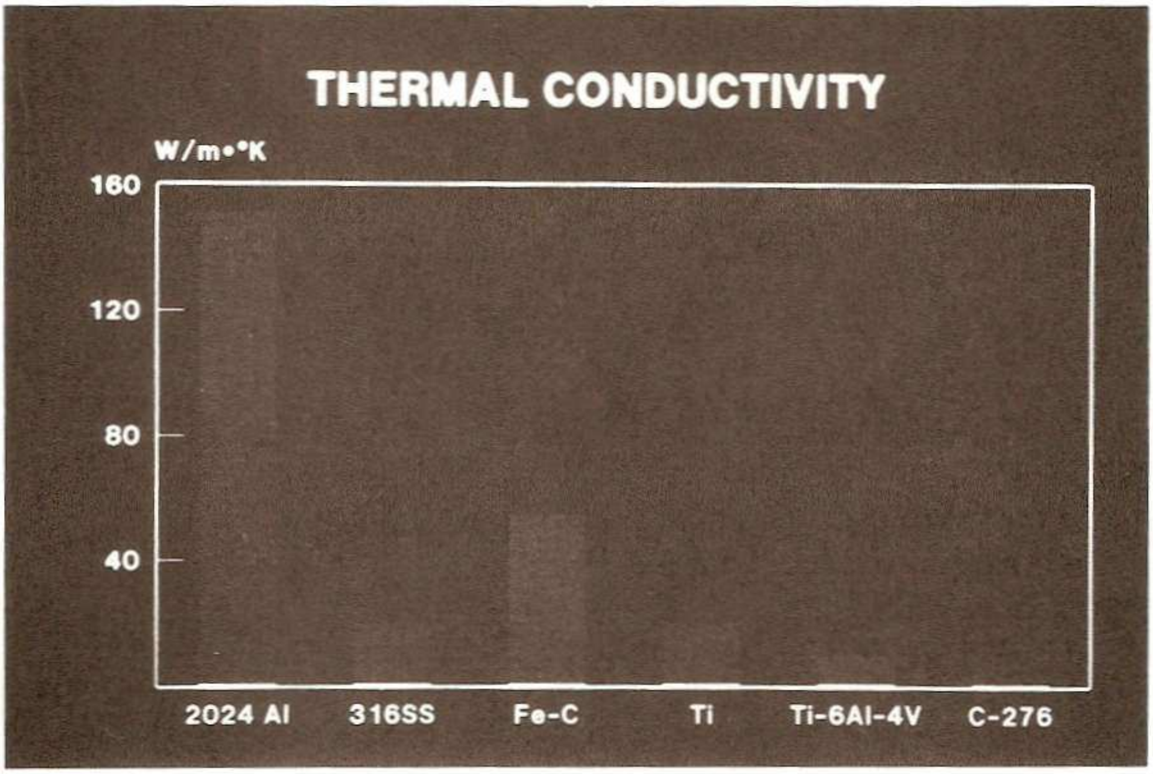

THERMAL CONDUCTIVITY
W/m•°K
160
120
80
40
2024 Al
316SS
Fe-C
Ti
Ti-6Al-4V
C-276

Fig. 9

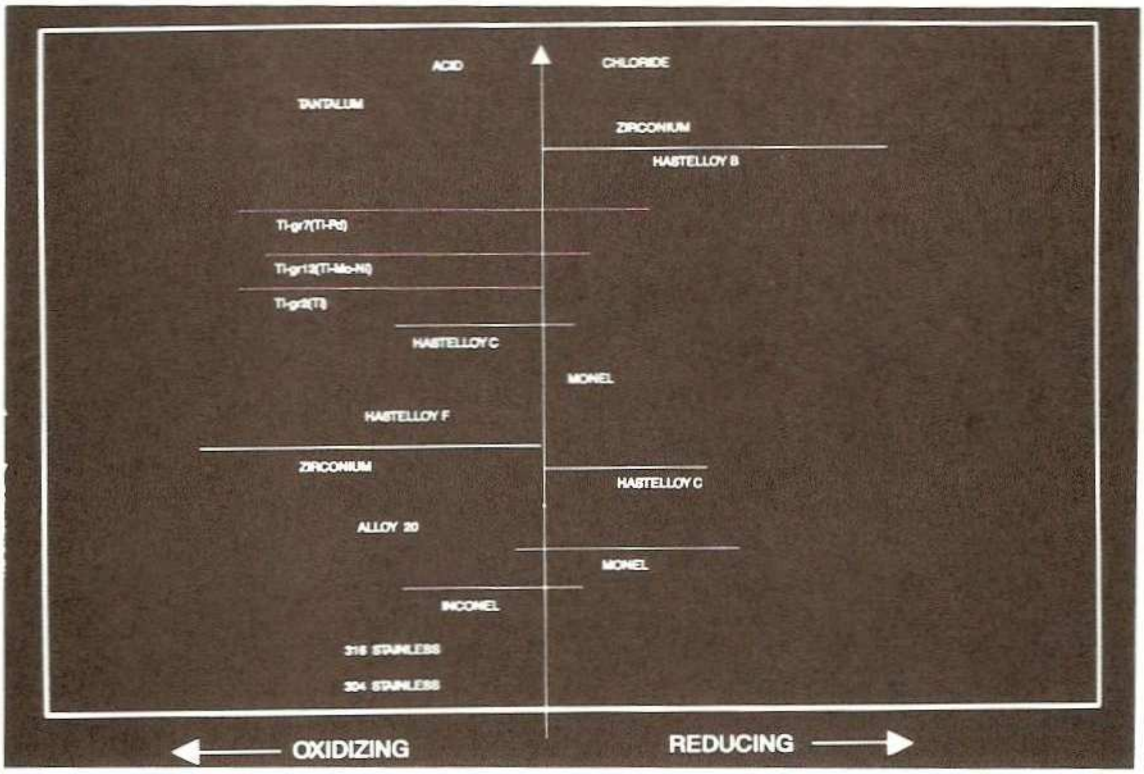

ACID
CHLORIDE
TANTALUM
ZIRCONIUM
HASTELLOY B
Ti-gr7(Ti-Pd)
Ti-gr12(Ti-Mo-Ni)
Ti-gr2(Ti)
HASTELLOY C
MONEL
HASTELLOY F
ZIRCONIUM
HASTELLOY C
ALLOY 20
MONEL
INCONEL
316 STAINLESS
304 STAINLESS
OXIDIZING
REDUCING

Fig. 10

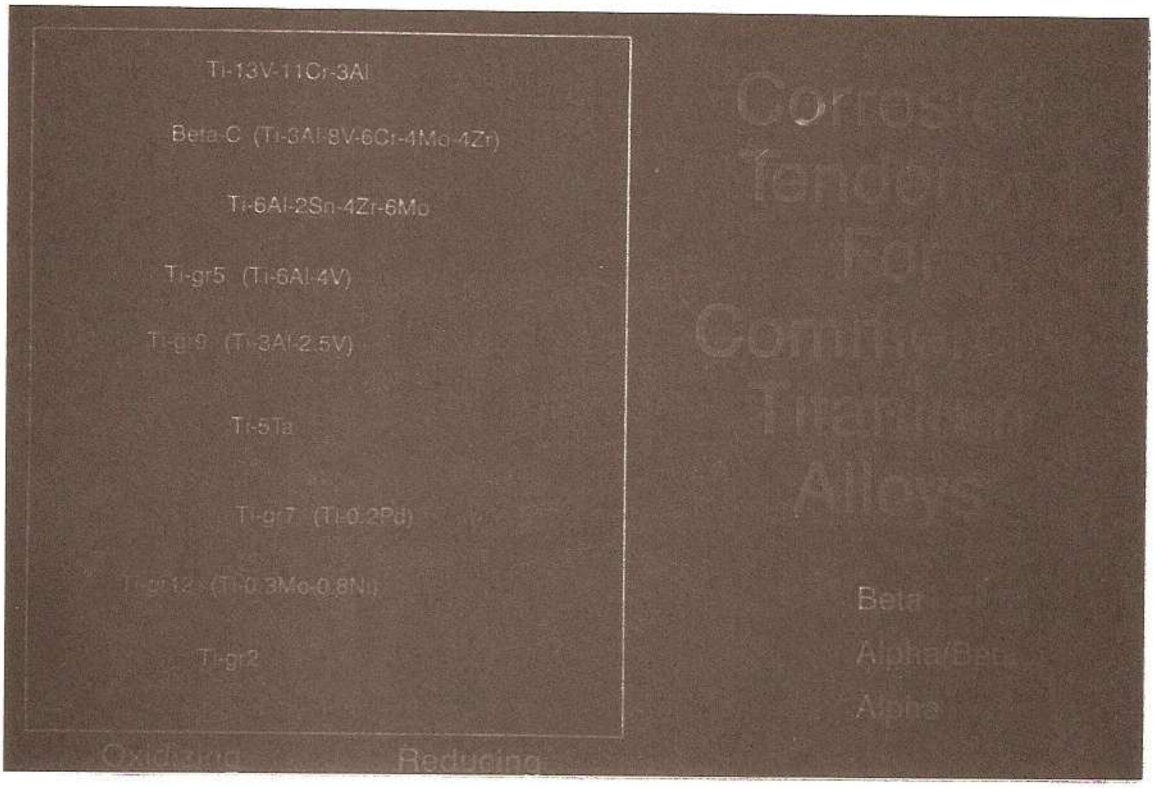


Fig. 11

Titanium Alloy Properties

	CP Titanium	Ti-3Al-2.5V	Ti-6Al-4V	Ti-38-6-44
Density (Kg/m^3)	4511	4484	4428	4816
Strength, UTS (MPa)	344	620	896	860-1250
Strength, YS (MPa)	276	517	827	840-1200
Elastic Modulus (10^6MPa)	10.2	10.3	11.3	10.1
Thermal Expansion Coefficient (10^{-6}m/m/K)	8.6	--	7.56	9.72
Thermal Conductivity (W/mK)	16.44	3.07	3.07	11.3

Fig. 12

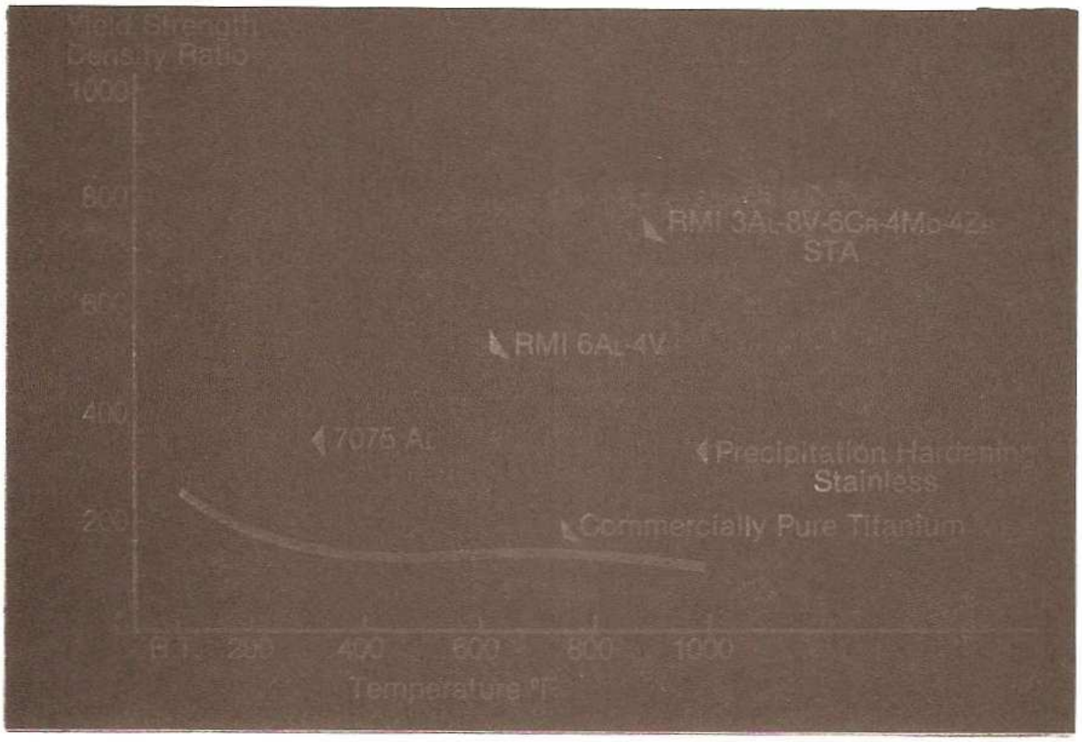

Yield Strength
Density Ratio
1000
800
400
200
RMI 6AL-4V
7075 AL
STA
Precipitation Hardening
Stainless
Commercially Pure Titanium
200
400
600
800
1000
Temperature °F

Fig. 13

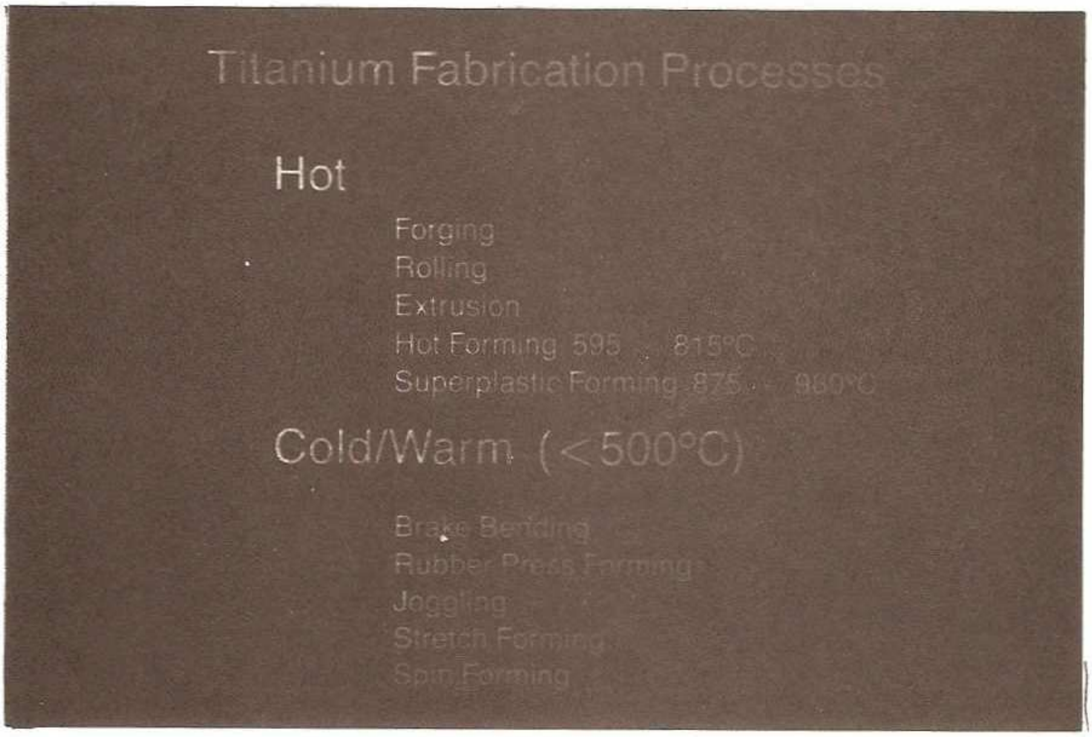
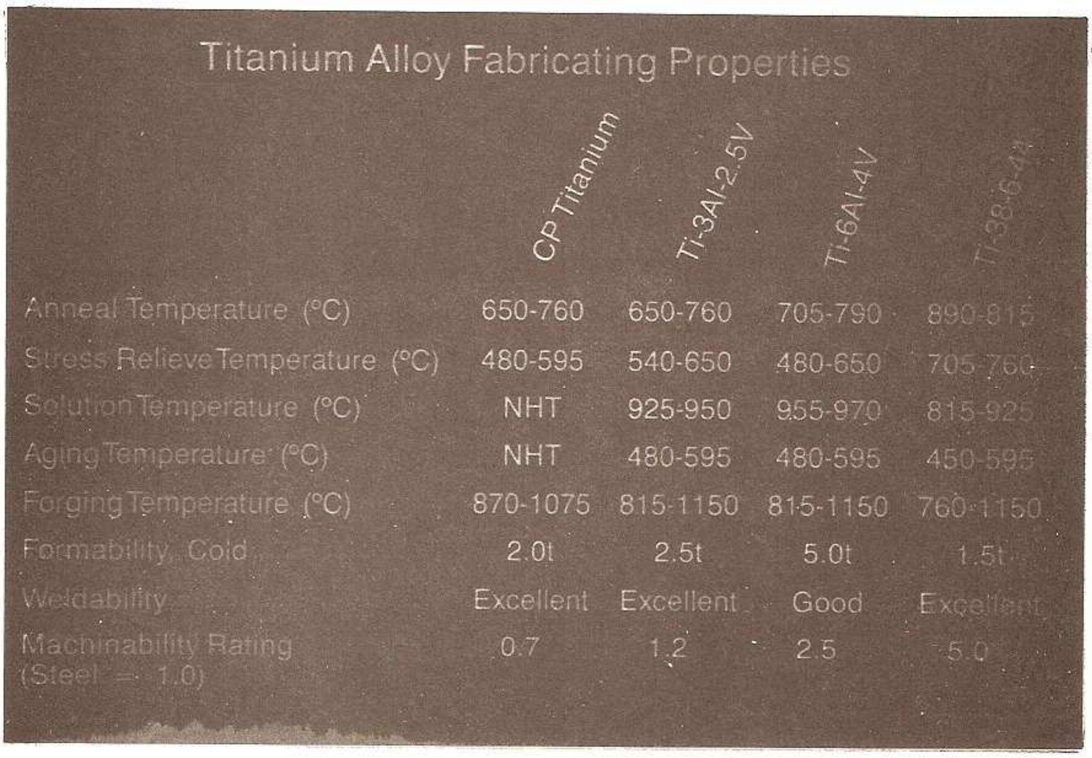

Titanium Fabrication Processes
Hot
Forging
Rolling
Extrusion
Hot Forming 595 – 815°C
Superplastic Forming 875 – 980°C
Cold/Warm (<500°C)
Brake Bending
Rubber Press Forming
Joggling
Stretch Forming
Spin Forming

Fig. 14



Titanium Alloy Fabricating Properties

	CP Titanium	Ti-3Al-2.5V	Ti-6Al-4V	Ti-38-6-44
Anneal Temperature (°C)	650-760	650-760	705-790	890-815
Stress Relieve Temperature (°C)	480-595	540-650	480-650	705-760
Solution Temperature (°C)	NHT	925-950	955-970	815-925
Aging Temperature (°C)	NHT	480-595	480-595	450-595
Forging Temperature (°C)	870-1075	815-1150	815-1150	760-1150
Formability, Cold	2.0t	2.5t	5.0t	1.5t
Weldability	Excellent	Excellent	Good	Excellent
Machinability Rating (Steel = 1.0)	0.7	1.2	2.5	5.0

Fig. 15

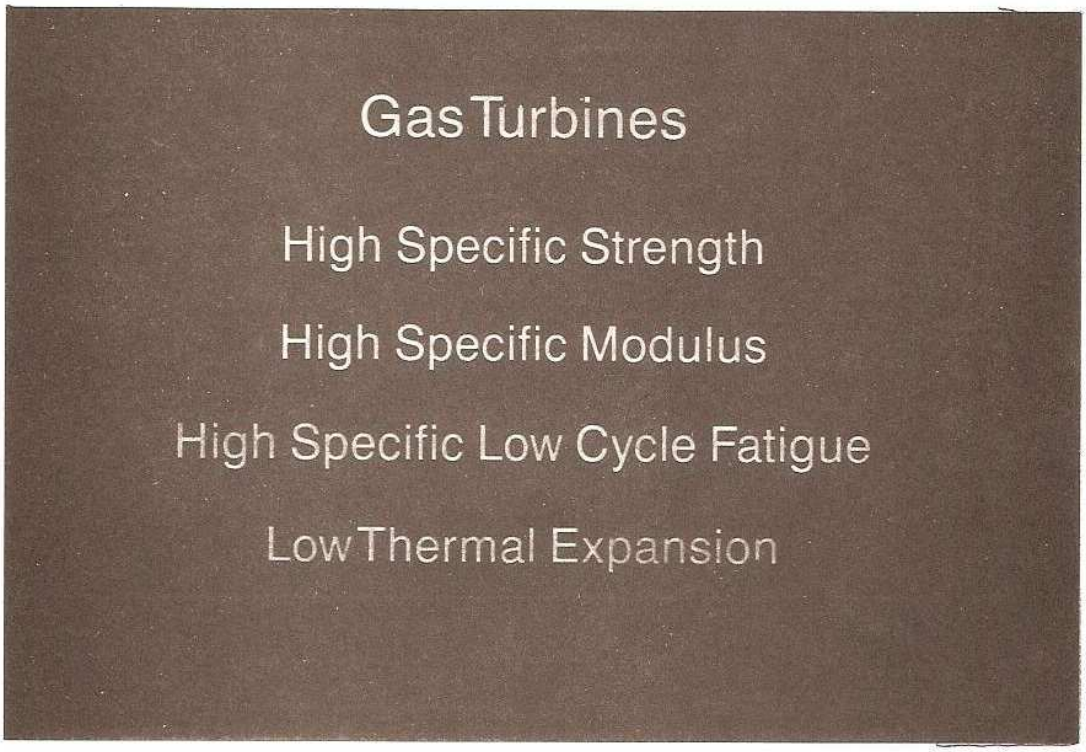


Fig. 16

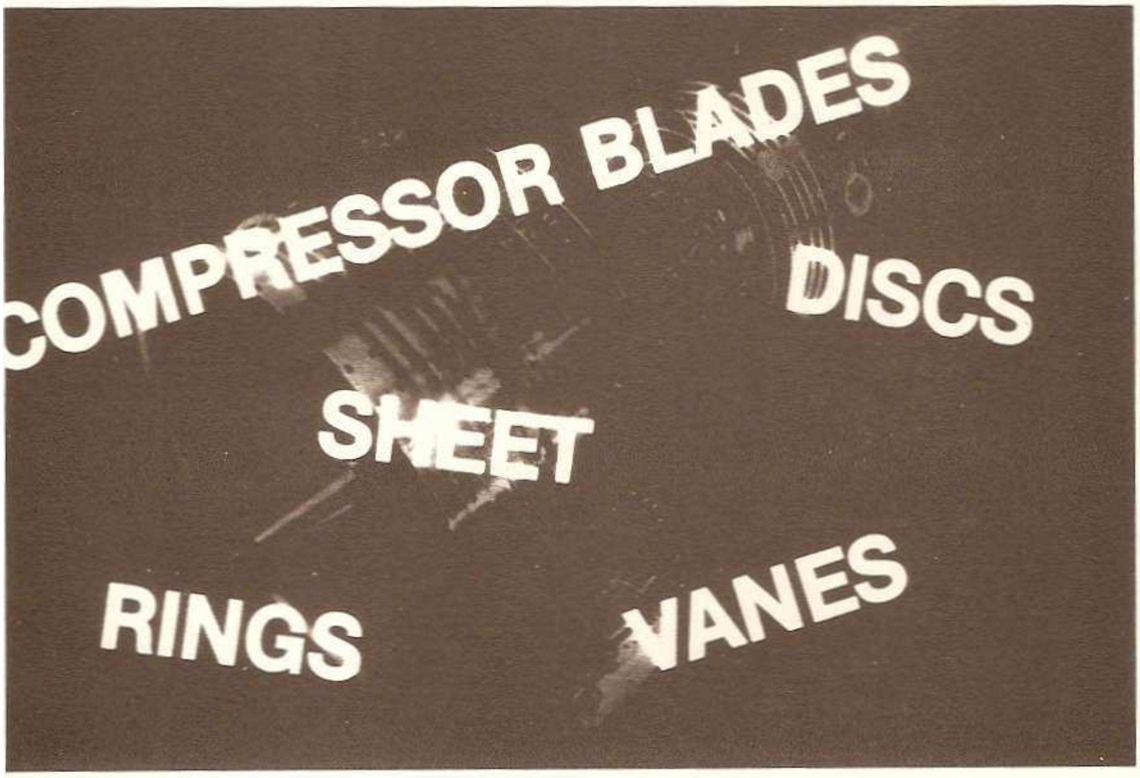


Fig. 17

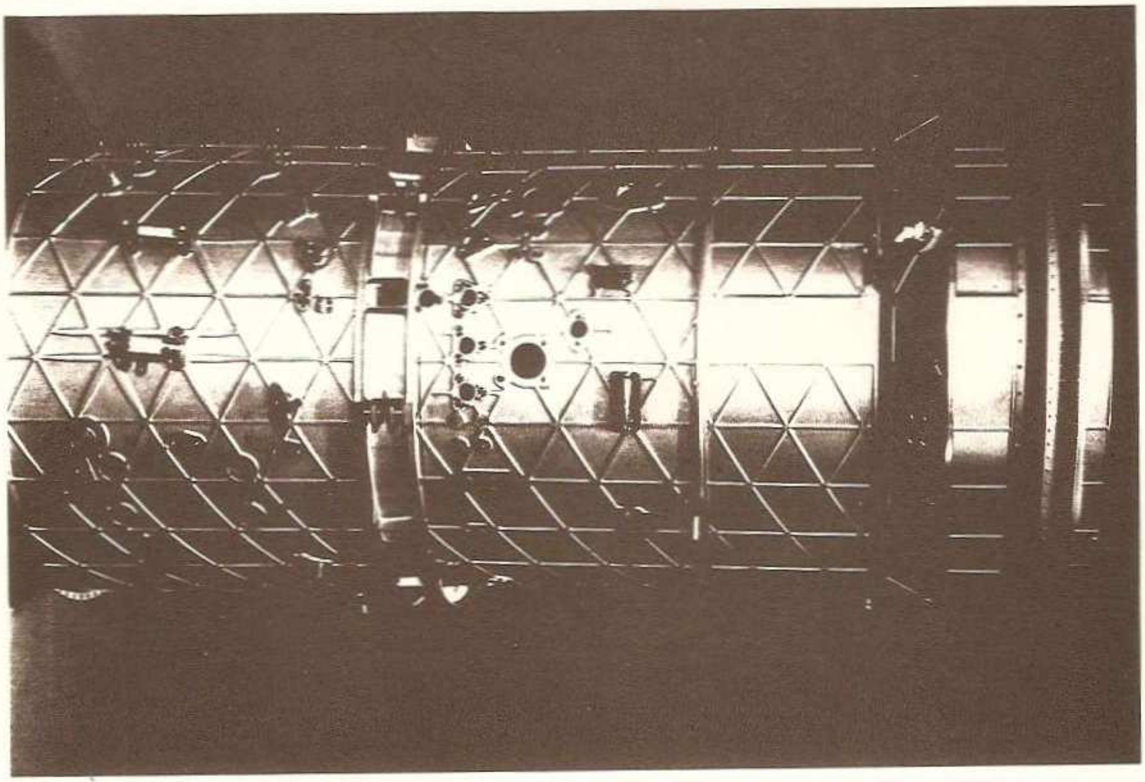


Fig. 18

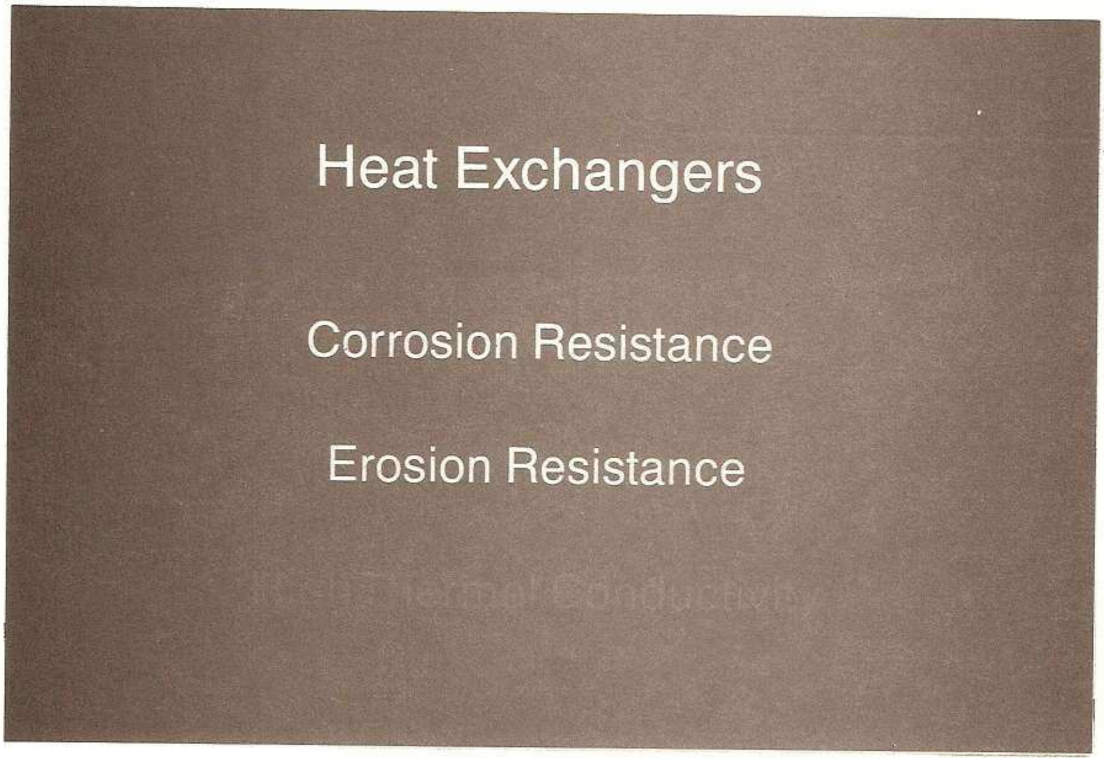

Heat Exchangers
Corrosion Resistance
Erosion Resistance

Fig. 19

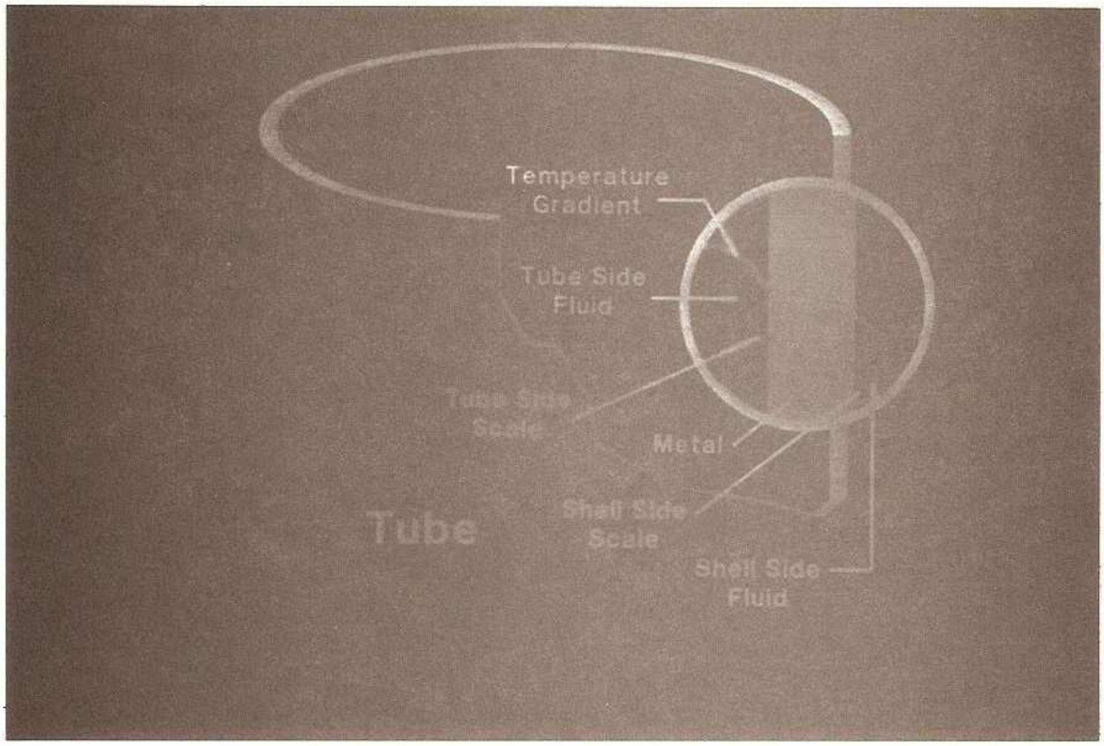

Temperature Gradient
Tube Side Fluid
Tube Side Scale
Metal
Shell Side Scale
Tube
Shell Side Fluid

Fig. 20

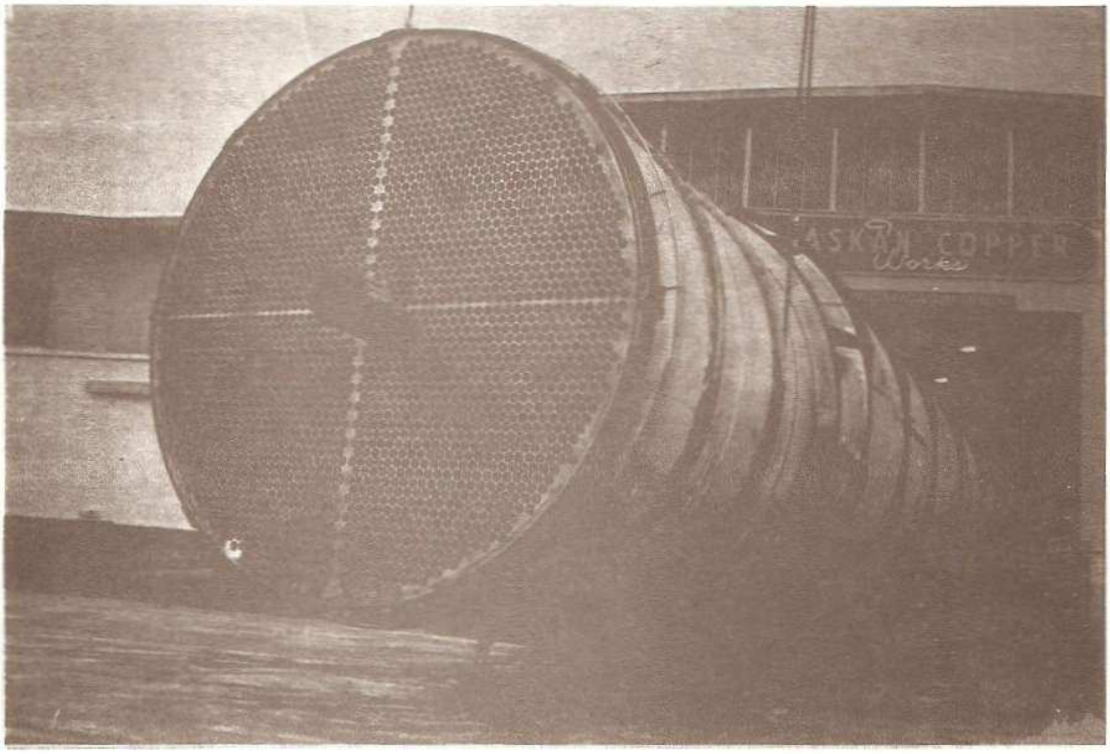

ASKAN COPPER
Works

Fig. 21


Chemical Process Equipment
Corrosion Resistance
Fabrication Ease
Weldable

Fig. 22

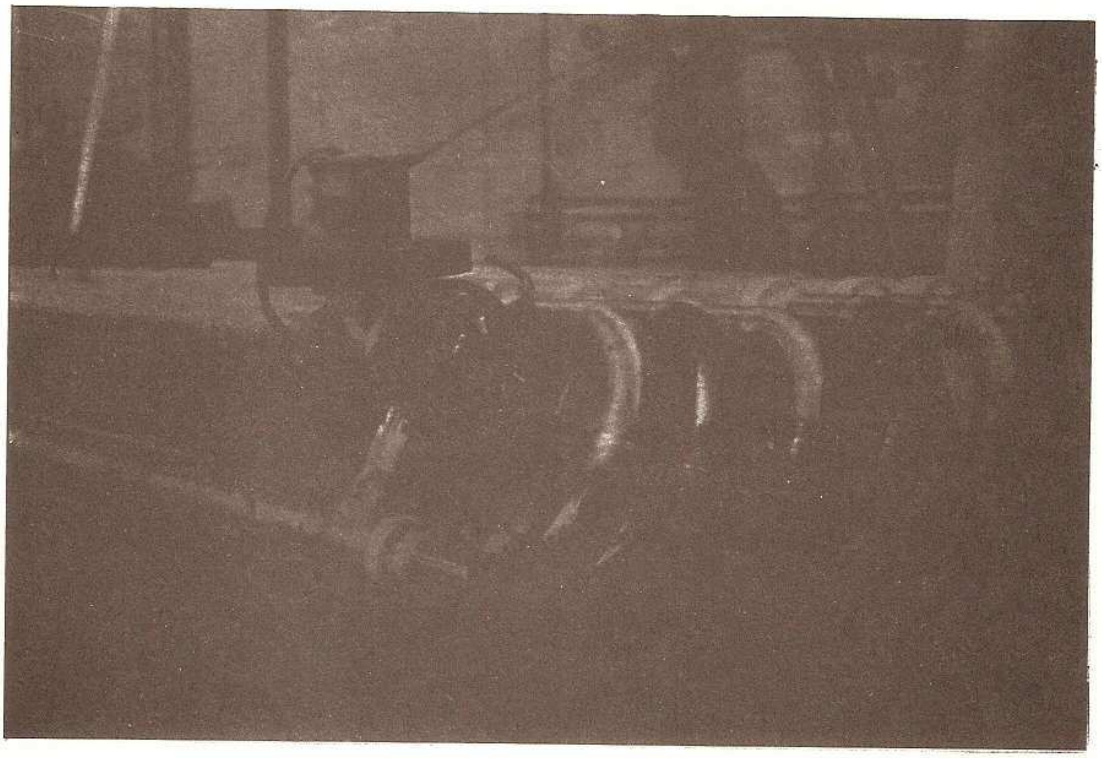


Fig. 23

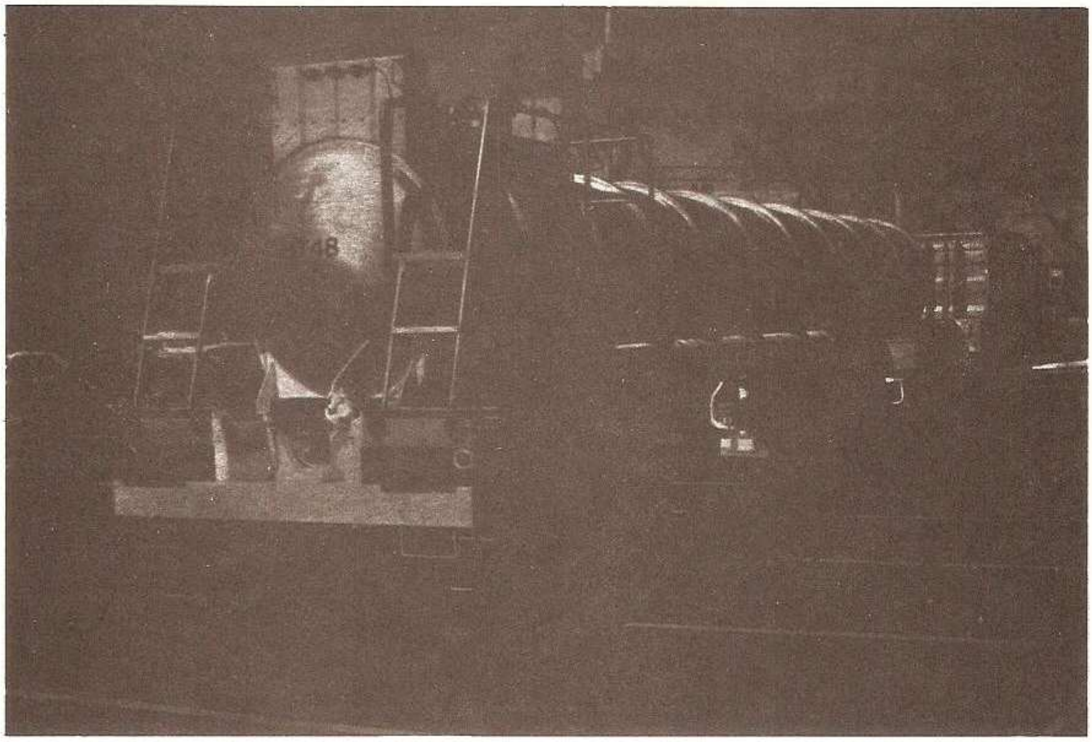


Fig. 24

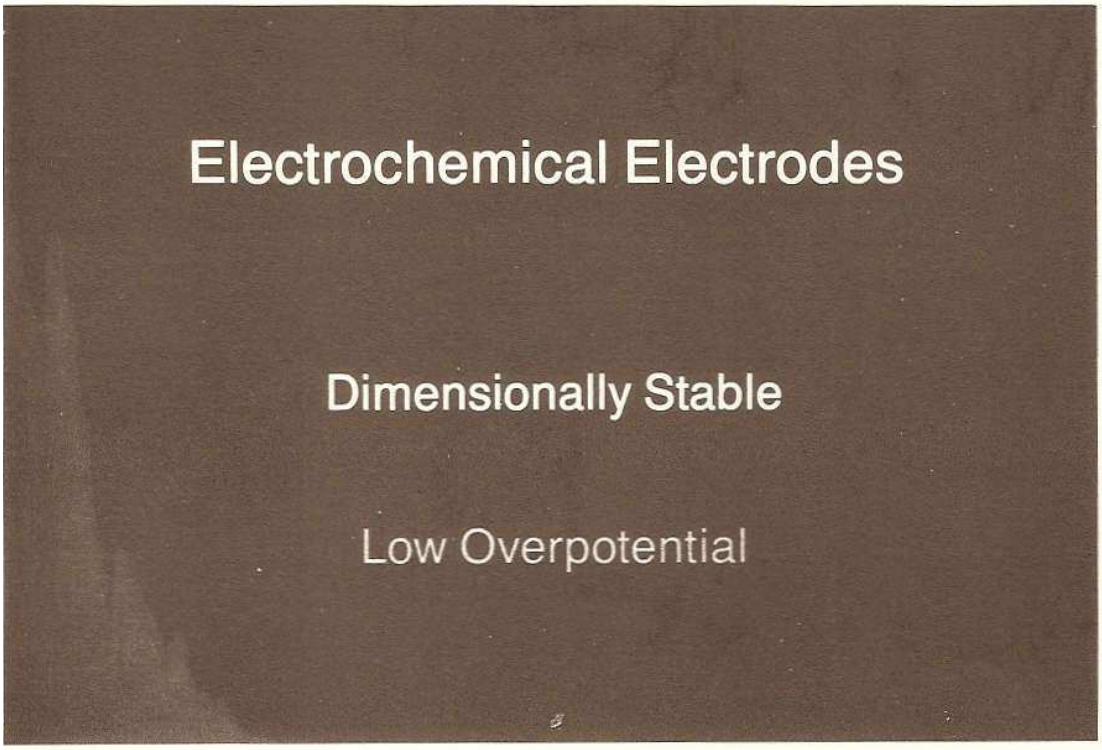

Electrochemical Electrodes
Dimensionally Stable
Low Overpotential

Fig. 25

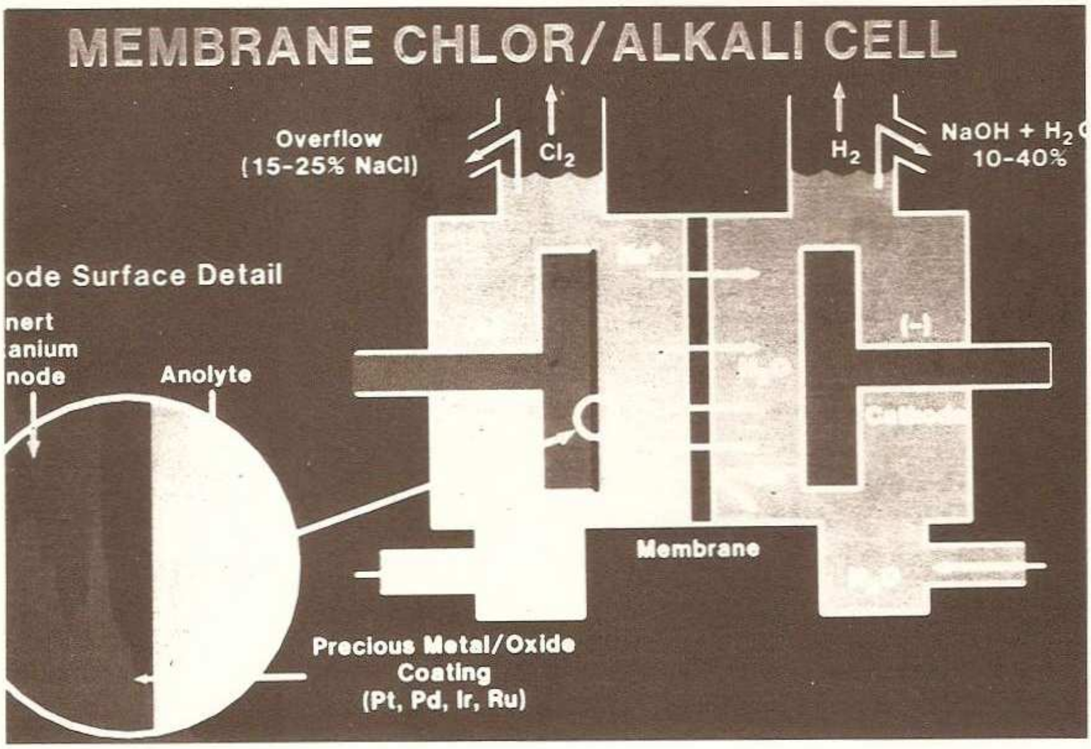

MEMBRANE CHLOR/ALKALI CELL
Overflow
(15-25% NaCl)
Cl_2
H_2
NaOH + H_2
10-40%
Anolyte
Membrane
Precious Metal/Oxide
Coating
(Pt, Pd, Ir, Ru)

Fig. 26

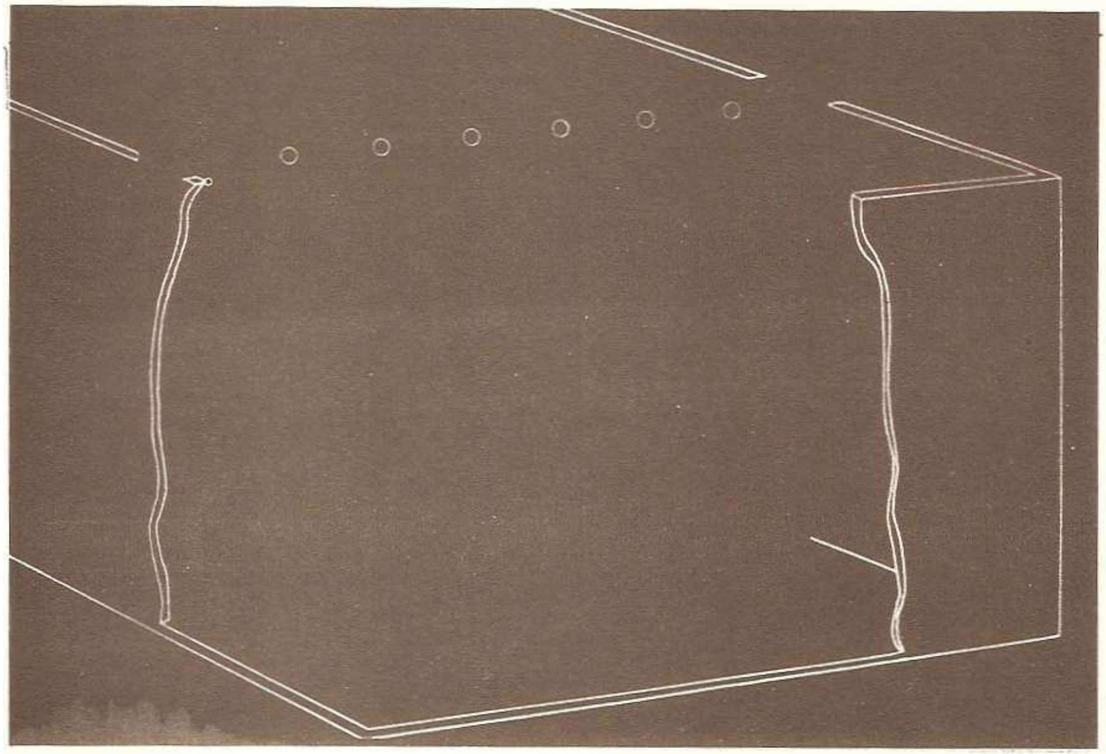


Fig. 27


Offshore Risers
Flexible
Corrosion Fatigue Resistance
Corrosion Resistance
Moderate Strength

Fig. 28

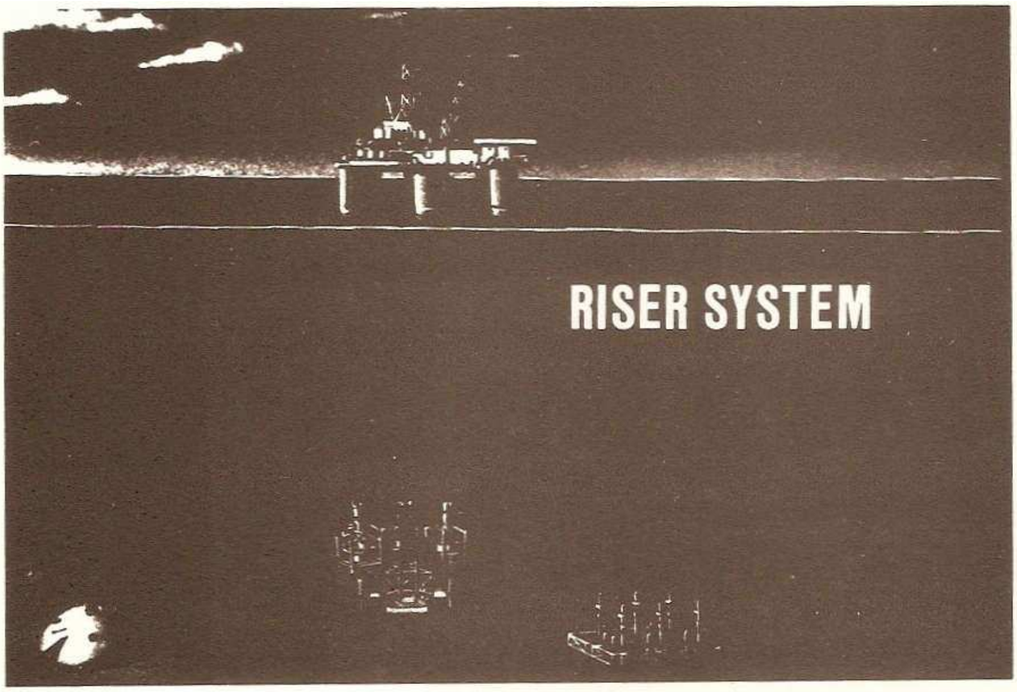

RISER SYSTEM

Fig. 29

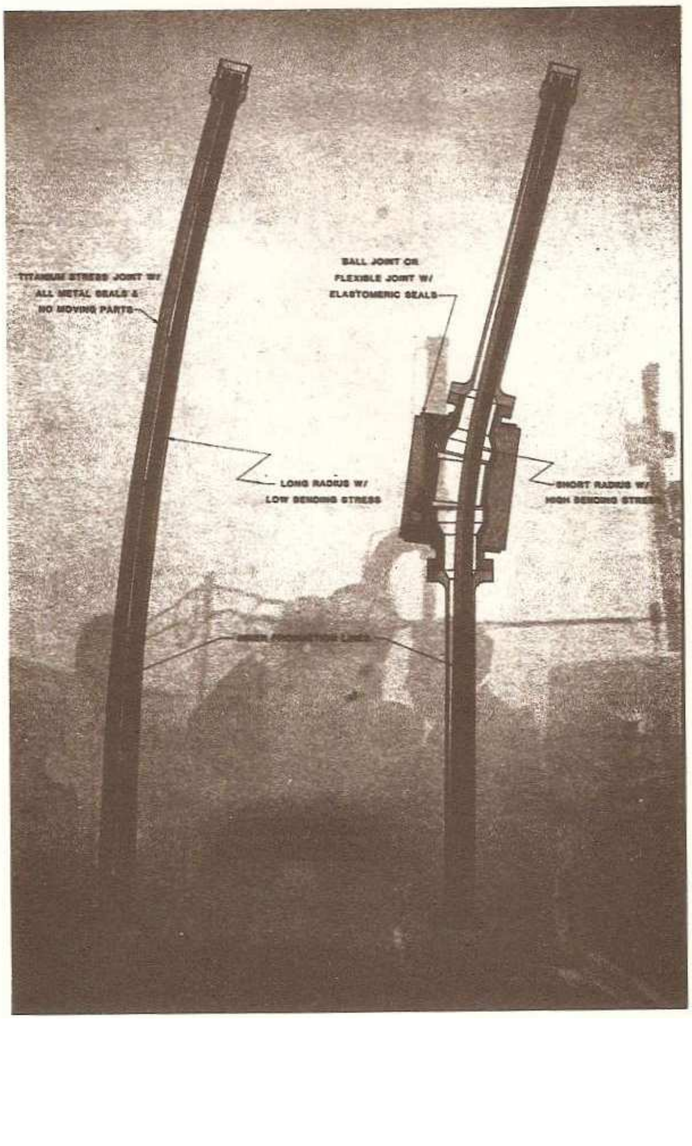

TITANIUM STRESS JOINT W/
ALL METAL SEALS &
NO MOVING PARTS
BALL JOINT OR
FLEXIBLE JOINT W/
ELASTOMERIC SEALS
LONG RADIUS W/
LOW BENDING STRESS
SHORT RADIUS W/
HIGH BENDING STRE

Fig. 30

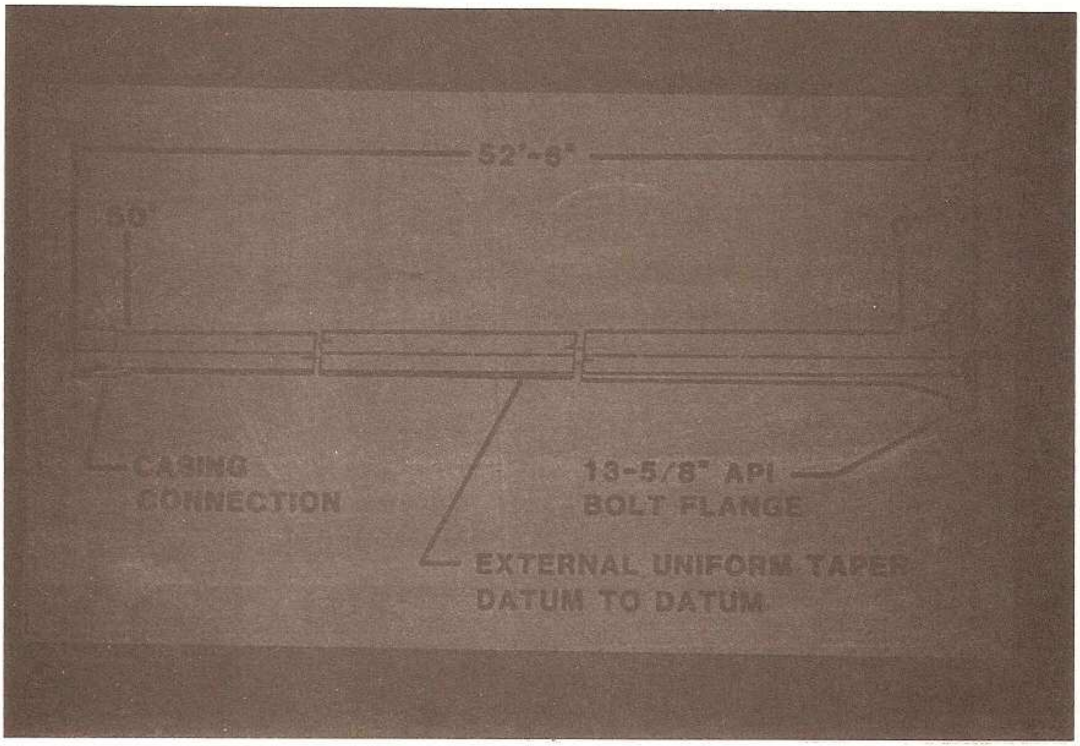

CASING
CONNECTION
13-5/8" API
BOLT FLANGE
EXTERNAL UNIFORM TAPER
DATUM TO DATUM

Fig. 31


Downhole Equipment
H2S Corrosion Resistance
Heat Treatable
Moderate to High Strength

Fig. 32

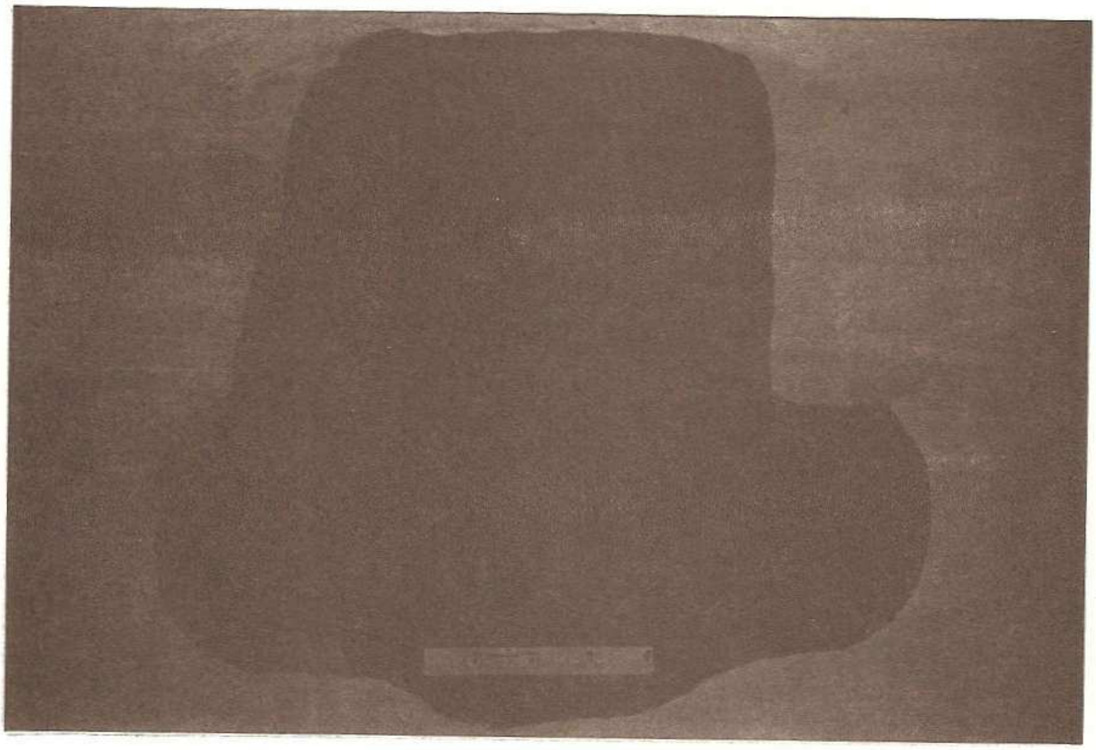


Fig. 33


Springs
Low Modulus
High Strength
High Fatigue Strength
Minimum Envelope Size

Fig. 34

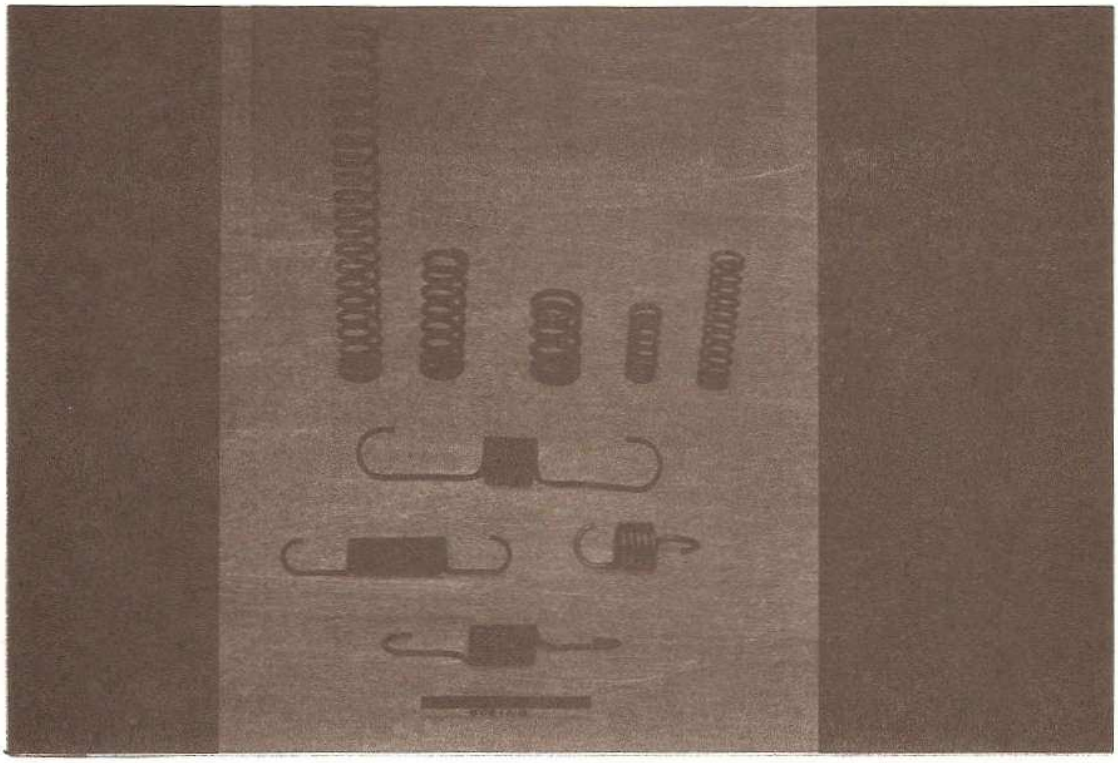


Fig. 35

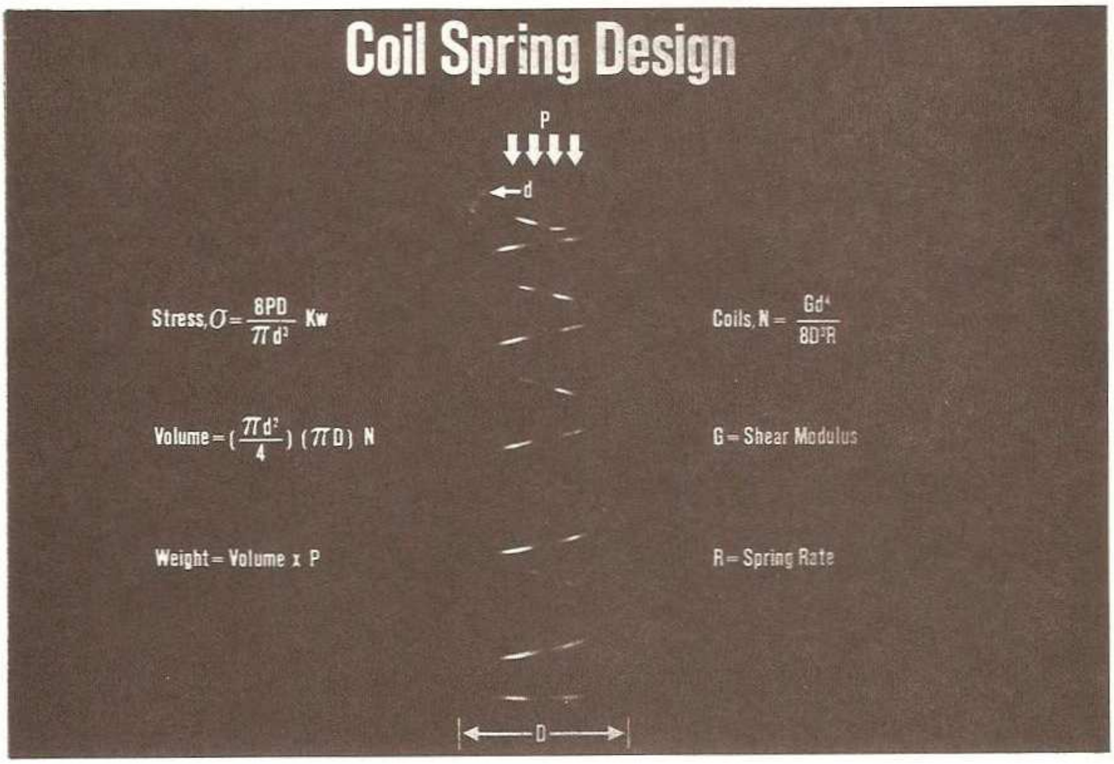

Coil Spring Design
P
d
Stress, σ = 8PD / πd³ Kw
Coils, N = Gd⁴ / 8D³R
Volume = (πd² / 4) (πD) N
G = Shear Modulus
Weight = Volume x P
R = Spring Rate
D

Fig. 36

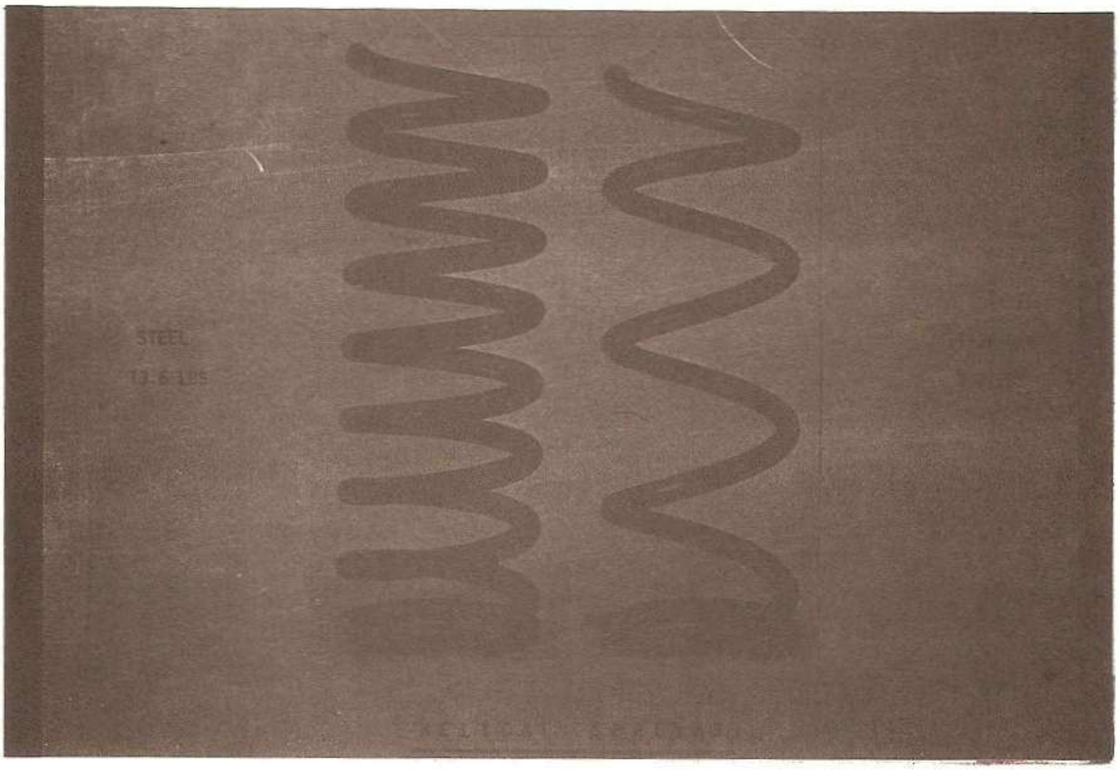

STEEL
13.6 LBS

Fig. 37

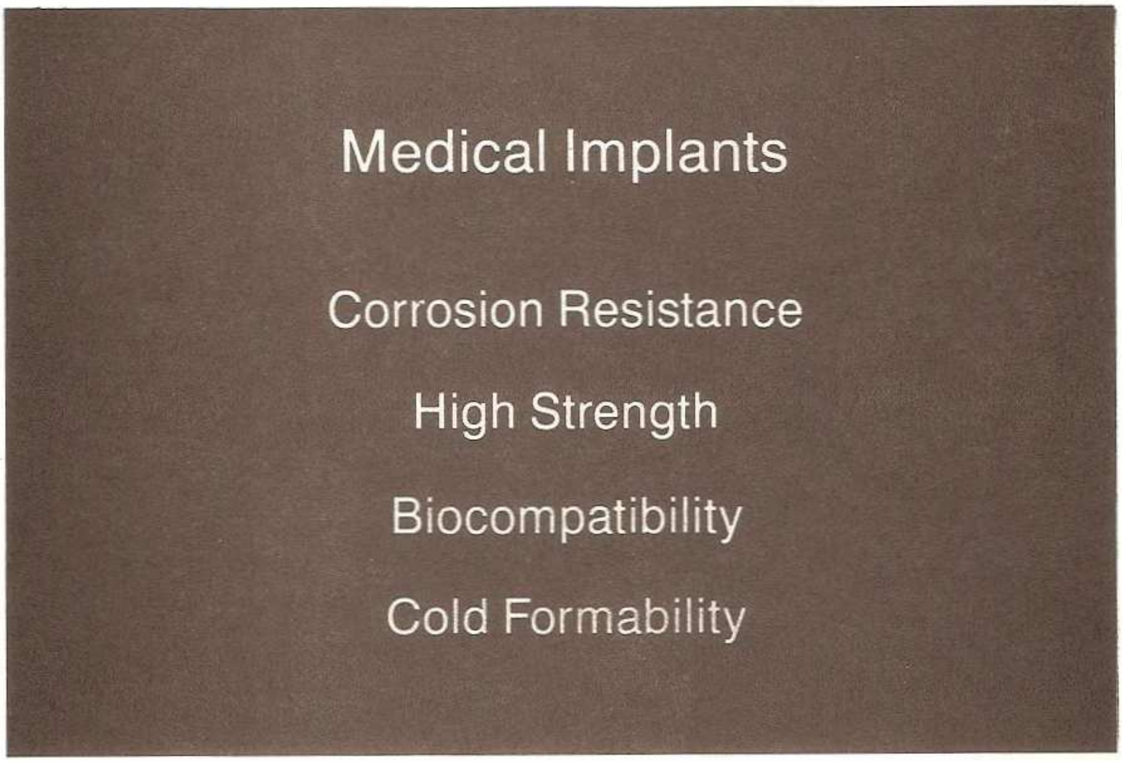

Medical Implants
Corrosion Resistance
High Strength
Biocompatibility
Cold Formability

Fig. 38

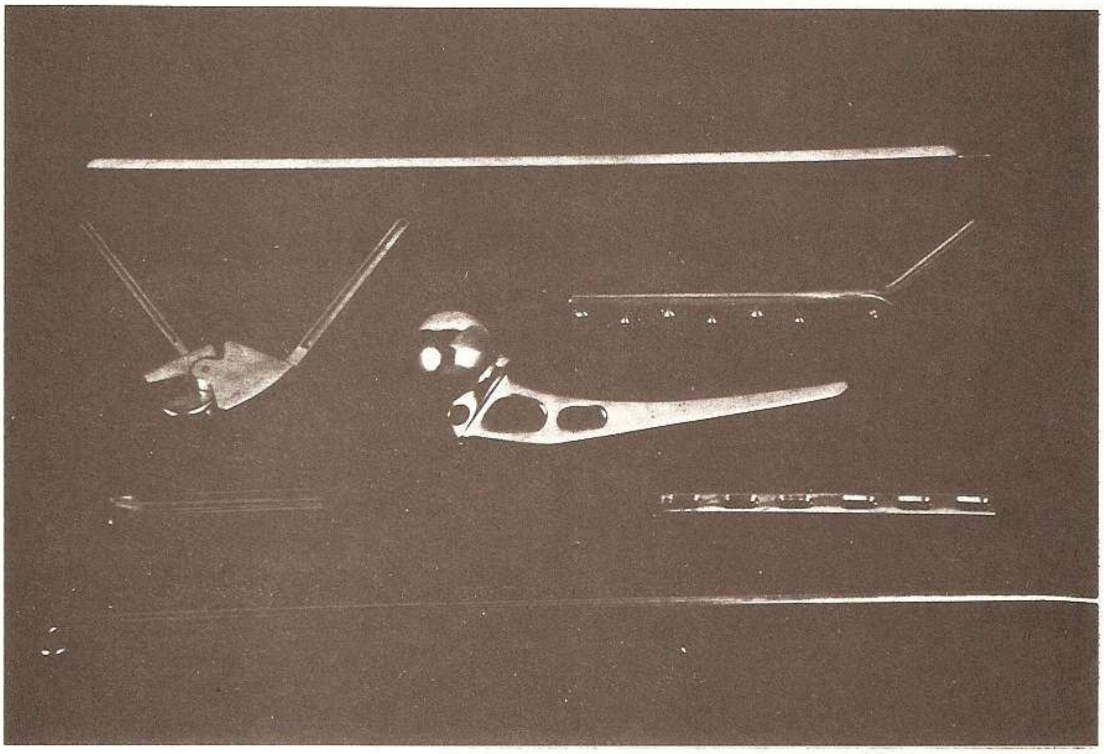


Fig. 39

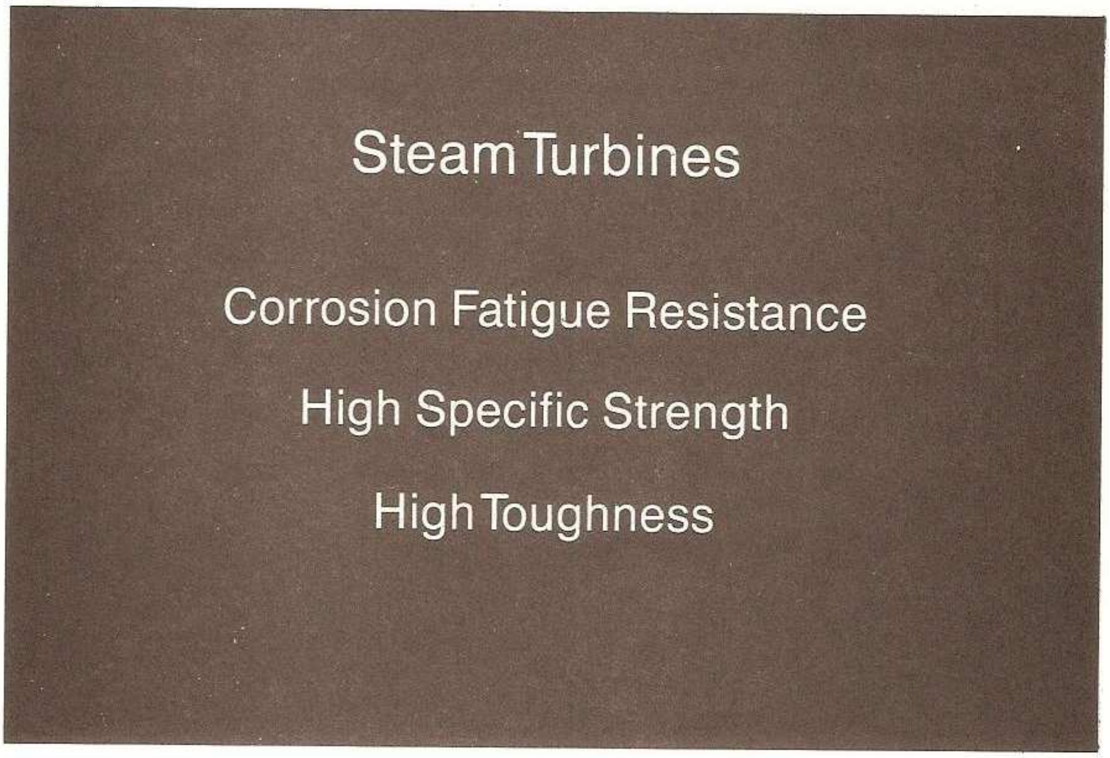

Steam Turbines
Corrosion Fatigue Resistance
High Specific Strength
High Toughness

Fig. 40

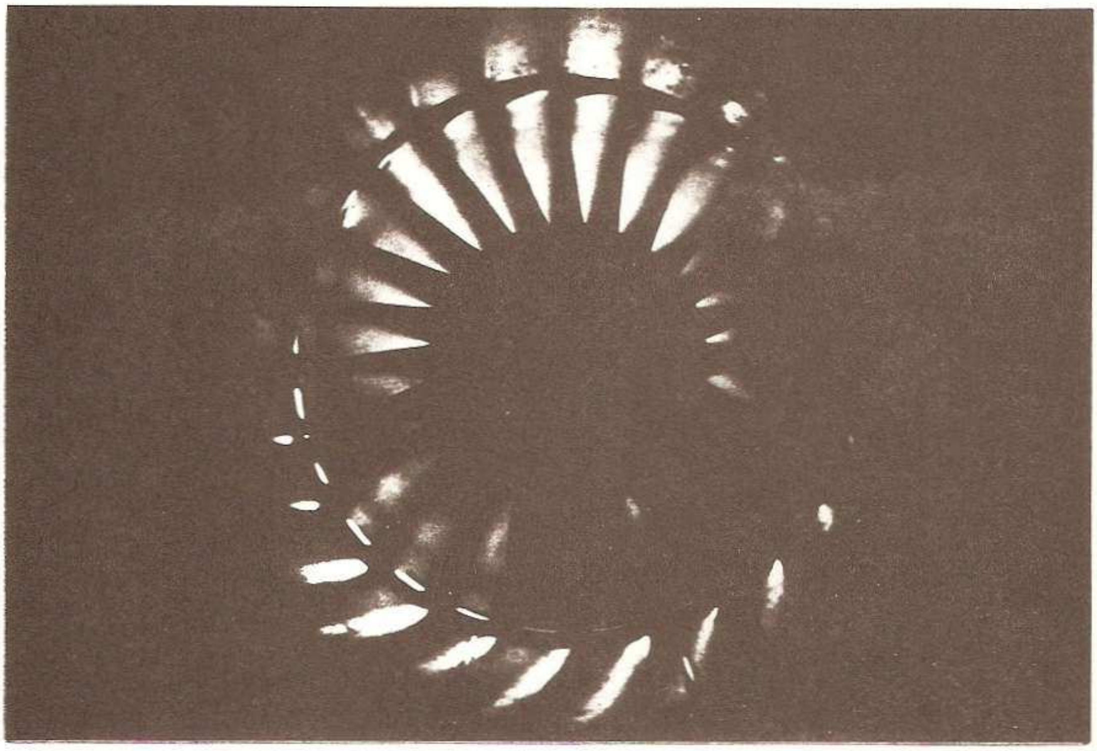


Fig. 41

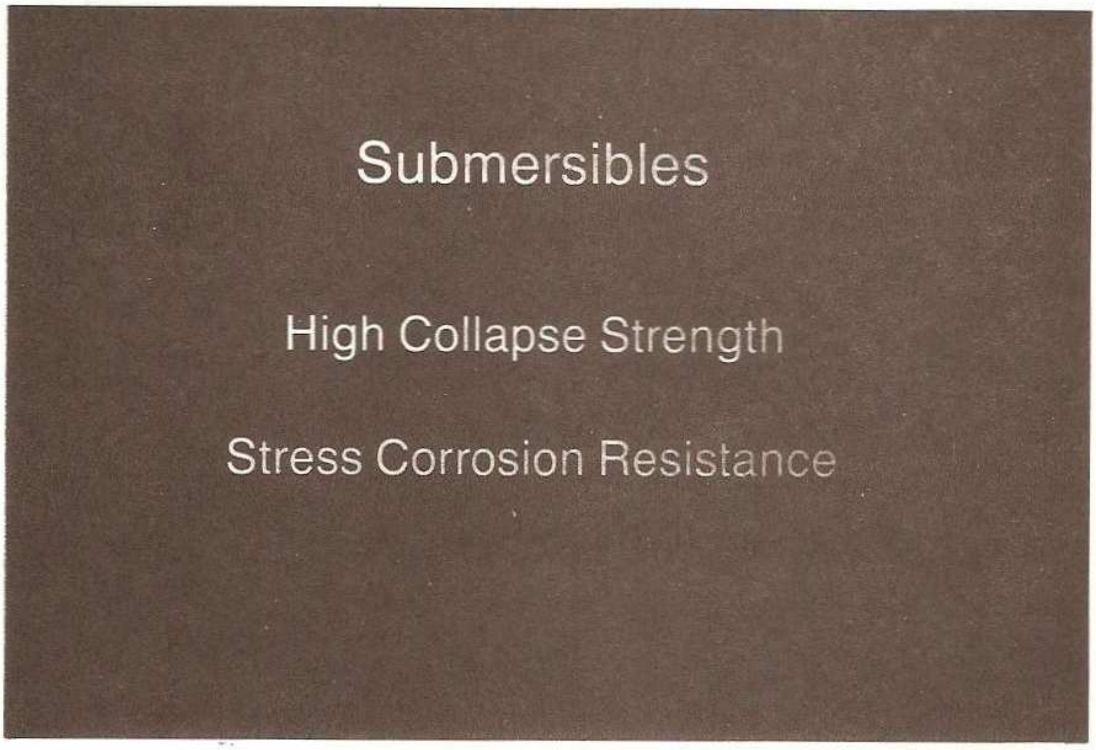

Submersibles
High Collapse Strength
Stress Corrosion Resistance

Fig. 42

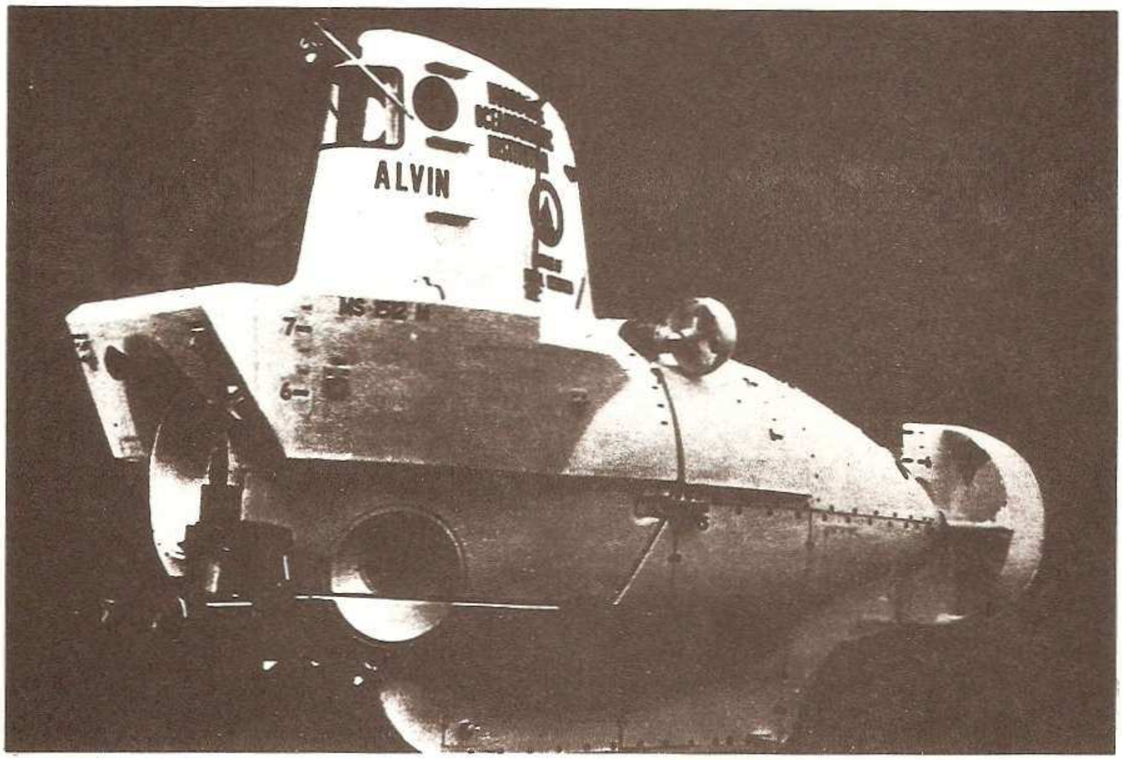

ALVIN

Fig. 43

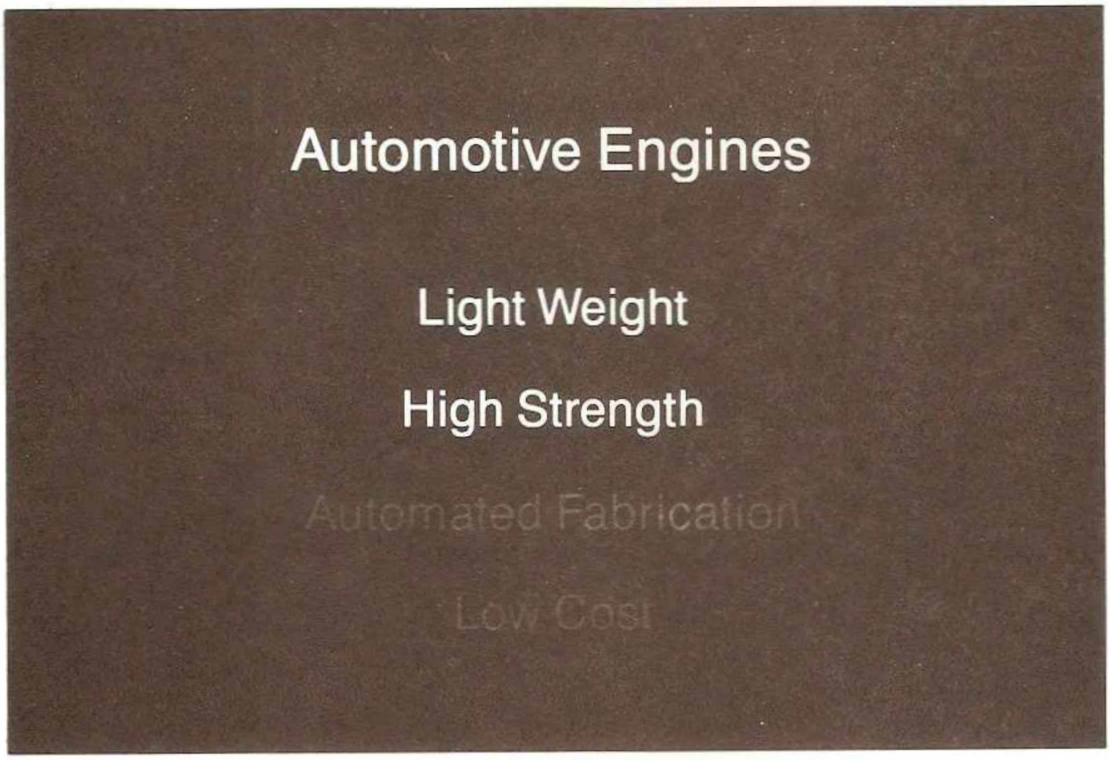

Automotive Engines
Light Weight
High Strength
Automated Fabrication
Low Cost

Fig. 44

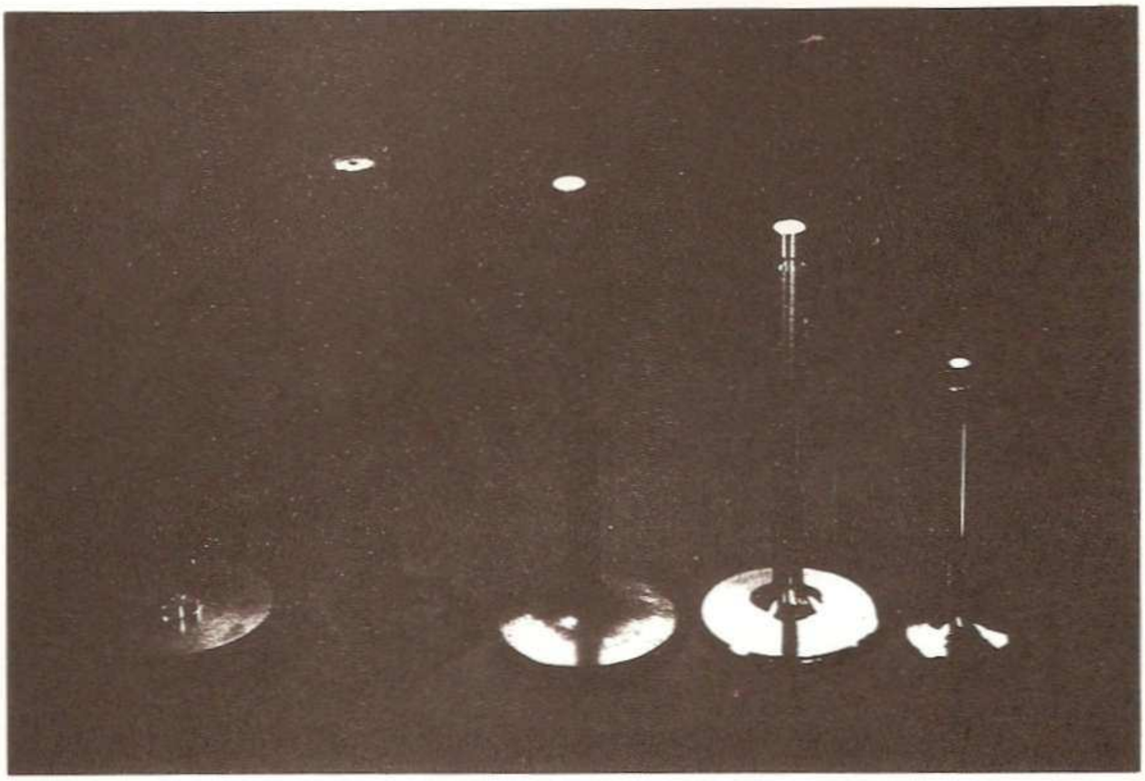


Fig. 45