Applications of Beryllium to Aircraft Gas-Turbine Engines

L. A. Corrigan,* C. E. Spaeth,† and G. J. Andreini‡
United Aircraft Corporation, East Hartford, Conn.

Beryllium is a material with a low density and a high modulus of elasticity. These factors, in combination with high strength, are of significant interest to the designer. The results of preliminary tensile testing of forged 1400 beryllium indicated a strength-to-weight advantage of 1.6:1 when compared with currently available titanium alloys. Fatigue strength is nearly as high as that for titanium alloys, but notched impact strength is extremely low. A feasibility study was made to determine the potential of beryllium in aircraft gas-turbine engines, since the material has the deficiency of extremely low impact resistance. This study showed that engine weight savings of 15% in Mach 3 supersonic engines and a savings of 36% in subsonic engines were possible. The results clearly demonstrated the need for continued effort in the development of a reliable beryllium alloy.

Introduction

BERYLLIUM has long been considered a potential structural material by the aircraft gas-turbine designer. The low density of the material (0.067 lb/in.^{3}) and its high modulus of elasticity would make possible very lightweight gas-turbine powerplants. However, applications were limited to nonstructural members because, until recently, the demonstrated strength levels were quite low.

Recent developments have changed this picture. Under Air Force sponsorship,[1] work was conducted on beryllium forgings which showed definite promise for gas-turbine engine applications. Forgings with yield and tensile strengths much higher than sintered material and with good uniaxial ductility were produced. The forgings were also found to be more economical than the hot-pressed sintered block previously used, because the amount of metal removed by machining to obtain intricate shapes was considerably reduced. The introduction of raw material with finer particle size and increased oxide content further enhanced the strength of the material, with no loss in ductility. Typical room-temperature tensile properties of sintered, cast, and forged material, illustrating the magnitude of the advances made, are tabulated in Table 1.

One sample of forged material that was severely worked demonstrated yield strength in excess of 100 ksi with good ductility. Typical tensile properties of high-strength forged beryllium compared with other structural materials on a strength-to-density ratio basis are shown in Fig. 1. Beryllium very clearly exceeds the high-strength mar-aging nickel steel and titanium alloy (AMS 4928). Commonly used compressor steel and titanium alloys are included in this figure to show that beryllium offers a strength-to-density advantage in excess of 1.6:1 for this application.

Other mechanical properties are important in the design of structural members, particularly axial flow compressor parts. Of prime importance is the high modulus of elasticity, which contributes to easier control of resonant vibration, and the basic fatigue strength, which assures the ability to withstand vibration. Figure 2 shows preliminary results of smooth and notched fatigue tests, as measured on forged beryllium. This figure also shows typical results obtained with AMS 4928 titanium alloy for comparison.

Combined stress-fatigue tests are used extensively to evaluate compressor blade and disk materials. In this type of test, a steady stress is applied to the specimen and a reversing load superimposed on it, thereby simulating the stress conditions existing in an actual compressor. Preliminary results of combined stress-fatigue tests are presented for both smooth and notched specimens in Fig. 3, along with some typical results for a widely used titanium alloy. Forged beryllium compared quite favorably with the titanium alloy in this important characteristic.

Although work on beryllium has been proceeding at a rapid pace and is yielding encouraging results, certain areas require review in order to place them in proper perspective. Lack of triaxial ductility (and, therefore, low notched-impact-strength) continues to be a major drawback to use of the material. This may be caused by the severe orientation of the crystalline structure which results when the material is worked. A joint program was undertaken with the Ladish Company to investigate the possibility of achieving improved triaxial ductility by randomizing the crystalline orientation through programed forging. However, some metallurgists contend that this may only partially alleviate the lack of triaxial ductility, and therefore impact resistance may still be a problem.

In addition to the triaxial ductility question, further experience with impact resistance, vibration, fretting, machining, salt-spray resistance, temperature sensitivity, and other related conditions is required before beryllium will have been proved practical for gas-turbine applications.

The present cost of beryllium is high, partly because only small quantities are being produced. If the demand for this material is increased tenfold, the cost is expected to be reduced drastically, and beryllium may become competitive with titanium alloy on a cost per unit volume basis.

The status of beryllium today is quite similar to that of titanium about 1950. At that time, application of titanium to aircraft gas turbines was being attempted. In the early feasibility testing, basic manufacturing problems were encountered; however, the potential weight saving and attendant improvement in aircraft performance produced by the application of titanium was great, and programs were undertaken to eliminate the problems. The potential of

Table 1 Typical room-temperature tensile properties of beryllium

Material grade	Yield strength, psi, 0.2% offset	Tensile strength, psi	Elongation, %
Cast material	20,000	20,000	0
Sintered powder	35,000	45,000	1–2
Forged powder, 200 mesh	50,000	70,000	8
Forged powder, 400 mesh	75,000	100,000	8

Presented at the AIAA/ASD (AFSC) Vehicle Design and Propulsion Meeting, Dayton, Ohio, November 4–6, 1963 (no preprint number; published in bound volume of preprints of the meeting); revision received March 25, 1964.

* Senior Design Project Engineer, Pratt & Whitney Aircraft Division. Member AIAA.

† Design Project Engineer, Pratt & Whitney Aircraft Division.

‡ Project Engineer, Pratt & Whitney Aircraft Division. Member AIAA.

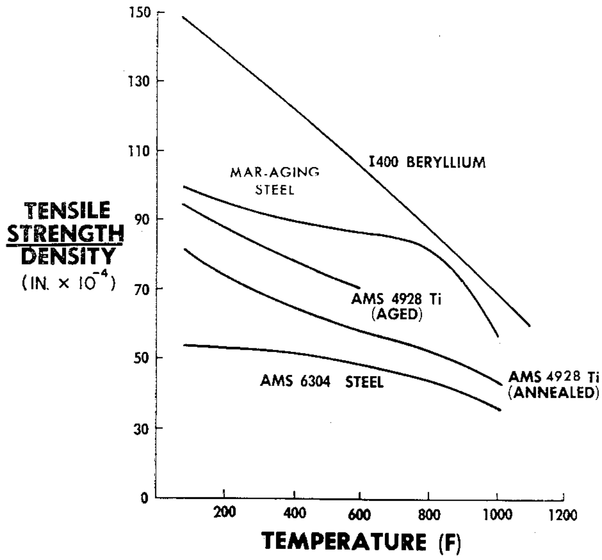

Fig. 1 Tensile strength-density ratios for I400 beryllium and competitive steel and titanium alloys.

beryllium in its application to aircraft powerplants appears to be greater than that of titanium, and it is logical to assume that the necessary effort will be made to solve the problems encountered.

Study of Beryllium Components and Engine Designs

It was assumed in this paper that the use of beryllium in aircraft gas-turbine engine components and powerplants will become feasible and that adequate impact resistance and triaxial ductility will be proved in the near future. The room-temperature mechanical properties used in the studies are listed in Table 2, along with those of titanium alloy and steel. The values used for beryllium are conservative and are based on the demonstrated properties of high-strength forged beryllium. The usable operating temperature range selected for beryllium was −70° to +900°F.

Study Approach

The study of the application of beryllium to aircraft powerplants was undertaken in two stages. The first step was to make direct substitution of beryllium for steel and titanium components in current powerplants for subsonic and supersonic applications. The second step was to investigate the powerplant configuration changes that become possible through application of beryllium to the design. The effect on weight of the application of beryllium to powerplants and components and some of the configuration changes made possible are discussed in detail in the following sections.

Table 2 Room-temperature mechanical properties for beryllium, titanium, and steel

Value	Beryllium	Titanium	Steel
UTS, psi	95,000	130,000	155,000
0.2% yield strength, psi	75,000	120,000	130,000
Density, lb/in.^{3}	0.067	0.159	0.283
Modulus of elasticity, psi	44×10^6	16×10^6	30×10^6
Endurance limit, psi	42,000	53,000	65,000
Strength/density, ultimate, in.	1.42×10^6	0.82×10^6	0.55×10^6
Strength/density, 0.2% yield, in.	1.12×10^6	0.75×10^6	0.46×10^6

Application of Beryllium to Components

General

Components may be classified from a stress-analysis viewpoint into four categories. The first category includes components that are not stress-limited; that is, their proportions are determined by considerations of deflection, natural frequency, or heat-sink capacity. The other three categories include all the members in which strength is a dominant factor in determining proportions. These members are classed according to the state of stress that exists in them, namely, uniaxial (as in a bolt), biaxial (as in a pressure vessel), and triaxial (as at the root of a notch).

Rotating components, such as the compressor rotor, are generally considered as notched members under combined stresses. As will be shown, this component places the greatest premium on strength-to-density ratio and benefits most from the application of beryllium. Therefore, notched strength (triaxial strength) is considered to be of major importance in the successful application of beryllium to gas-turbine engines.

The results of the application of beryllium to generalized components are summarized in Fig. 4. The relative weights of generalized components using beryllium are expressed in percents relative to titanium. The relative weights of steel components are also shown for comparison, and the design considerations used in preparing this weight comparison will be discussed. However, although the maximum latitude available to the designer is summarized in Fig. 4, in actual

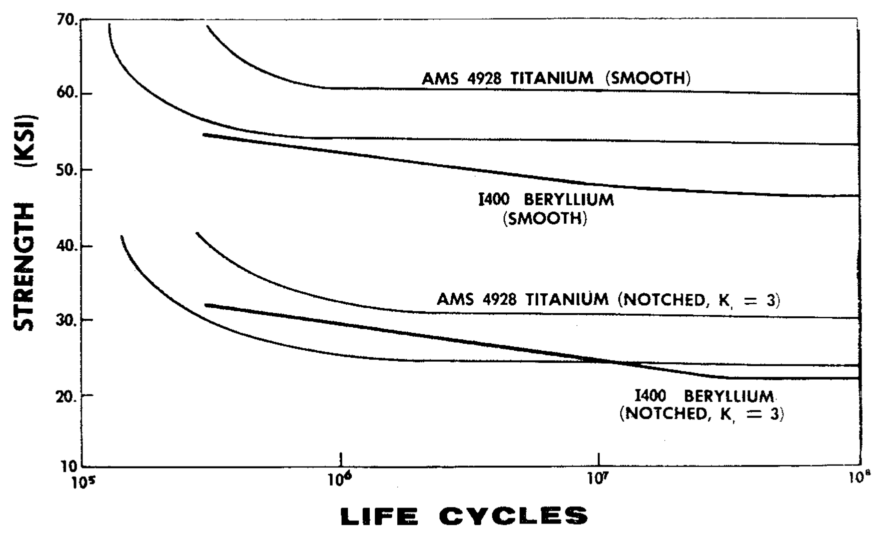

Fig. 2 Smooth and notched (K_t = 3) Westinghouse (reverse bending) fatigue data (70°F) for back-extruded I400 beryllium and AMS 4928 titanium alloy.

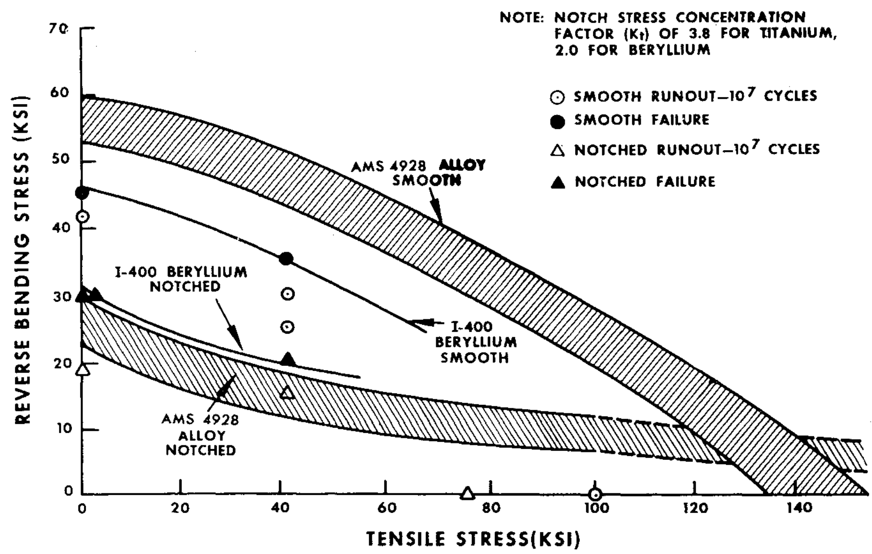

Fig. 3 Combined stress fatigue data (top) for I400 beryllium compared with annealed AMS 4928 titanium alloy.

engine design, other considerations may compromise the possible weight savings.

Shafts, Cases, and Bolts

Parts that are under direct stress, such as shafts, cases, and bolts, are sized in cross-sectional area by the allowable stress to which they may be operated. The area is inversely proportional to the allowable stress, and the weight of such parts is directly proportional to the density and inversely proportional to the stress. Beryllium parts controlled by this factor weigh 42% less than equivalent parts made of titanium.

Rotors

Disks are designed to carry a blade centrifugal pull and a body load which result from the pull of its own mass. Assuming that the design of the airfoil is fixed, the pull and resulting stress for a given disk and blade design is reduced according to the density. With no design area change, the weight of the assembly will also vary as the density. The allowable strength-to-density ratio of beryllium is larger than that for titanium, so an area reduction of the disk is permissible. A typical disk and blade assembly designed on this premise and made from beryllium would weigh about 60% less than equivalent parts made from titanium.

Compressor blades are designed so that vibrational resonances are eliminated from the engine range of operation. Also, the forward stages of a compressor must have a high frequency, so that aerodynamic-excited flutter vibration is eliminated. As noted in the introduction, an advantageous property of beryllium is the extremely high value of its modulus of elasticity. The bending frequency is a function of the modulus of elasticity, blade chord, and density as follows:

$$\omega_n \sim (1/b)(E/\rho)^{1/2}$$

where ω_n is the bending frequency, b the blade chord, E the modulus of elasticity, and ρ the density. Since the frequency must be maintained constant in substitution, the chord varies as follows:

$$b \sim (\rho/E)^{1/2}$$

The weight of the blade is directly proportional to the chord and the density, so the weight proportionality factor becomes

$$W \sim (\rho^{3/2}/E^{1/2})$$

A similar set of relationships can be derived for torsional flutter, where the flutter parameter is a function of $b\omega_t$. In this case, the flutter parameter must be maintained constant, but the torsional frequency is independent of the chord in first approximation. The resulting proportionality factor is the same as that derived for the case of bending frequency. A blade made from beryllium could be 84% lighter than a similar titanium blade designed to vibration limits. Rotor assemblies whose blades are controlled by bending frequency or torsional flutter can be made to be considerably lighter than rotors whose blades are assumed to have a fixed airfoil design, provided that the vibrational limits can be reached.

To investigate the feasibility of such a vibration-limited design, a typical rotor is shown in Fig. 5. The typical titanium stage weighs 13.2 lb. Substitution of beryllium for the titanium with no blade chord changes results in a weight of only 5.3 lb. Designing for the vibration limit would conceivably allow a reduction in weight to 2 lb. Such a rotor is not feasible when the aerodynamic convergence across the blading is taken into consideration. Also, the large number of blades required would make it impractical to produce. It is unlikely, therefore, that the mechanical limits can be reached in practical designs.

A similar situation arises in other compressor stages where the limit is a bending flutter vibration of blades. In this case, it is the practice to hold the product of $b\omega_n$ constant. Since $\omega_n \sim (1/b)(E/\rho)^{1/2}$ and the value of $b\omega_n$ is constant, it can be shown that $b \sim (\rho/E)\frac{1}{4}$, so that the beryllium chord may be 30% smaller than that required for titanium; and as a limit, the blade airfoil could be 73% lighter than that of a titanium blade. Again, factors of convergence for aerodynamic reasons or bending stress imposed by gas loads will then limit the chord to be chosen by the designer.

In the case of a first-stage compressor blade, a strength limit must be imposed. This is because the first stage must be designed to withstand foreign particle ingestion. The chord of the blade must, therefore, be set by the strength of the material in conjunction with the Z ratio of the blade (Z is the moment of inertia divided by the maximum distance from the neutral axis). In this case, the chord is inversely proportional to the cube root of allowable stress. The chord must be increased by 18%, and the weight of beryllium is 51% less than that of titanium. The effect of beryllium properties on blade chords and weights, where the limiting factors are vibration and ingestion impact, are summarized in Fig. 6. These levels of gain may be made where no other limitations are found.

Stators

Additional savings may be made in stator parts, even though the greatest weight savings are to be found in the rotors. Flanges and stator vanes which are bending-stress

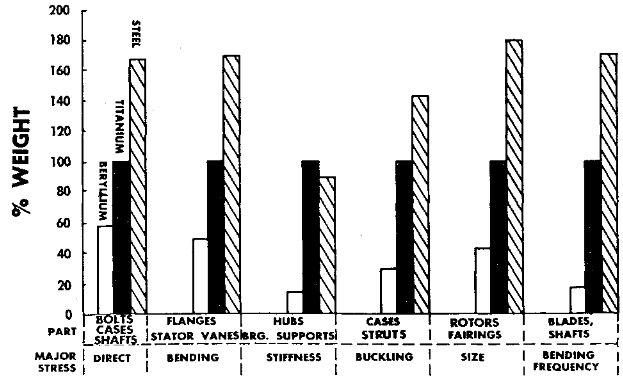

Fig. 4 Relative weight reduction for engine parts.

limited will have weights that are proportional to the density divided by the square root of allowable stress ratio. A weight saving of 50% can be achieved by direct substitution. Bearing supports where tensile stiffness is required, buckling-limited structures, and size-limited structures will all benefit from substantial savings if beryllium is used.

Effect of Beryllium on Powerplant Weight by Direct Substitution

In this section the effect of incorporating beryllium in gas-turbine powerplants of current design presently utilizing titanium is discussed.

Subsonic Gas-Turbine Engines

The weight savings made possible by direct substitution of beryllium in a current subsonic engine are summarized in Fig. 7. It will be noted that the largest proportion of the weight saving is in the compressor section. A moderate saving is possible in the diffuser-burner section and none in the turbine section, because of the arbitrarily established temperature limit for beryllium (900°F).

Supersonic Gas-Turbine Engines

In advanced engines with supersonic capability, the weight advantage of beryllium becomes smaller, as shown in Fig. 8.

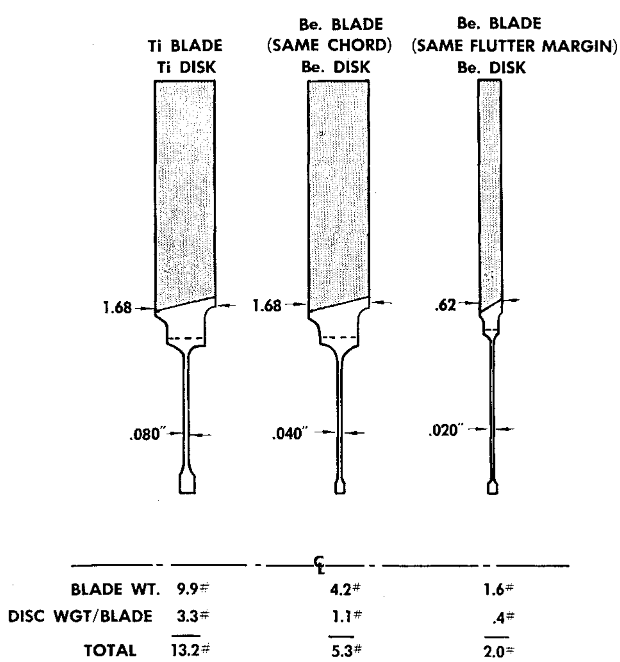

Fig. 5 Typical disk and blade.

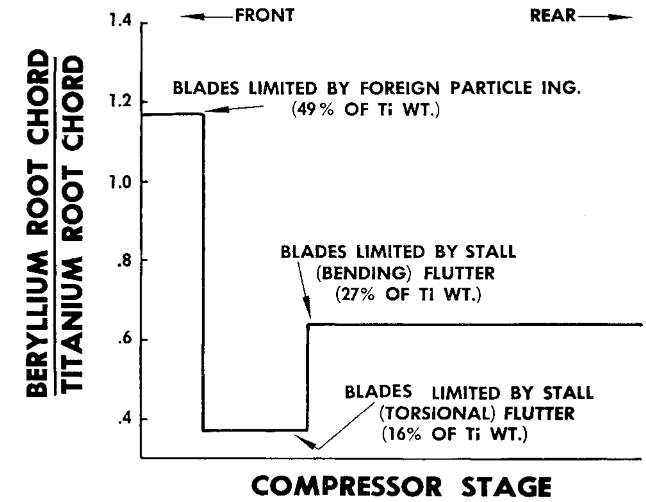

Fig. 6 Chord ratio vs blade type.

This is because 1) the temperature of supersonic engines is relatively higher than that of subsonic engines, so that fewer parts can be made of beryllium, and 2) advanced state-of-the-art engines use higher-work compressor stages, so that there are fewer stages available for substitution.

The effect of direct substitution on both current and advanced engines as a function of Mach number is summarized in Fig. 9. The greatest advantage is shown to be found in current subsonic engines; these advantages diminish for advanced supersonic engines. Figure 9 refers only to the weight of the basic gas generator. The inlet becomes an increasing proportion of the total installed weight as the Mach number increases. If beryllium is used for the engine inlet as well in a Mach 3.0 engine, the installed net weight is reduced by approximately 15%.

Effect of Beryllium on Powerplant Weight by Configuration Changes

The design of a new turbojet or turbofan engine is concerned largely with the optimization of a large number of aerodynamic and structural variables within certain constraints to achieve the best possible configuration. Examples of the constraints that exist are the allowable stress levels and the allowable level of compressor stage loading. The use of different structural materials will lead to different optimum engine configurations, because both the allowable stress level and the weight of a given component depend on the properties of the material used. Although substantial savings in weight can be achieved by the direct substitution of beryllium in existing designs, possible weight and cost savings through simplification may be optimized if the design utilizes the most beneficial properties of beryllium. For example, let us consider a turbofan engine currently popular for subsonic and

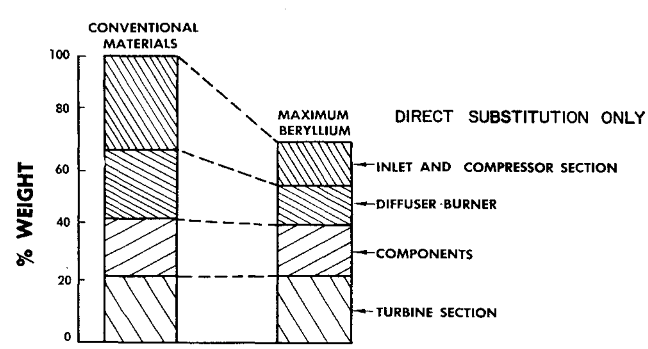

Fig. 7 Weight-saving potential of beryllium in small, subsonic, current state-of-the-art jet engine.

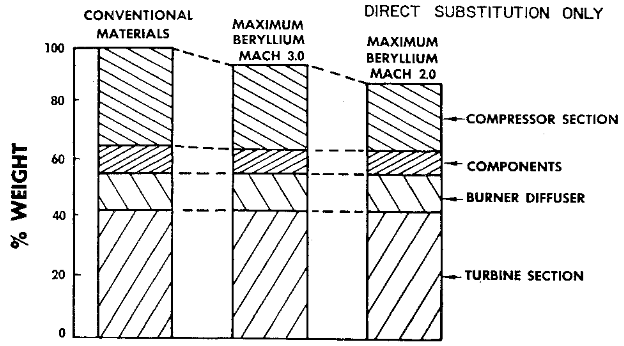

Fig. 8 Weight-saving potential of beryllium in large, supersonic, advanced state-of-the-art turbofan engine.

supersonic application. The major design considerations will be discussed first, followed by a detailed example.

Structural Design Considerations

No inherent limitations exist in the static structure of the engine. Generally speaking, a static part has certain imposed loads, either from adjoining parts or from aerodynamic loads; and the parts may be designed to accept these loads without exceeding maximum stress or deflection, or without buckling. In the case of rotating parts, however, centrifugal forces are superimposed on these other loads, and certain limits are therefore imposed. The consideration of structural design limits is therefore restricted to the rotating parts of the engine.

Compressor blades are sized so that aerodynamic loads produce very small stresses. This is because chords are usually selected to eliminate various types of flutter and vibration. The centrifugal stresses are generally large, however, and lead to high blade root stress which could be a limit on the design. It may be shown that blade root tensile stress σ_r due to this centrifugal force is given by

$$\sigma_r = \rho u_r^2[(1/\lambda^2) - 1]K$$

where

K = coefficient that depends on the change in blade cross section from root to tip
ρ = density of blade material
λ = ratio of blade hub diameter to blade tip diameter (hub-tip ratio)
u_r = blade hub (or disk rim) speed

Blade cross-section distribution is set essentially by aerodynamic considerations, whereas blade hub speed will be determined either by aerodynamic considerations or by structural limitations in the disk to which the blade is attached. Therefore, in this equation, the quantities K and u_r may be considered fixed. If the root stress is allowed to increase to the allowable stress of the blade material, then the foregoing equation involves a relationship between material properties and hub-tip ratio. It may be seen that larger values of the quantity $\sigma_{\text{allow}}/\rho$ lead to smaller hub-tip ratios. In general, small hub-tip ratios are desirable because they lead to lighter weight and more compact configurations. The value of $\sigma_{\text{allow}}/\rho$ for beryllium is 60% larger than for titanium and 160% larger than for steel.

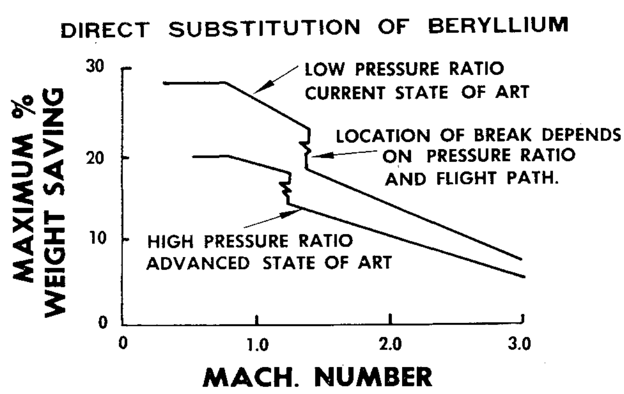

Fig. 9 Estimated potential weight savings vs flight Mach number.

Aerodynamic Design Considerations

Flow separation in the compressor may be a major problem and is influenced by the requirements of diffusion and associated adverse pressure gradients. If separation takes place, there will be an abrupt loss in efficiency. Rotors and stators are, therefore, designed to be free of separation. Separation will take place if 1) the cascade is required to do an excessive amount of diffusion, or 2) there are sufficiently strong shock-wave boundary-layer interactions. The first type of separation is defined by a so-called "loading limit" and when translated into variables associated with a compressor rotor or stator takes the following form.

Rotors:

$$\frac{\Delta h_{\text{allow}}}{u^2} = L_r \qquad L_r = f\left(\frac{Cx}{u}\right)$$

where

Δh_{allow} = allowable stagnation enthalpy rise at a given radial station of the blade
u = wheel speed at that station
C_x/u = ratio of axial velocity to wheel speed at station
L_r = rotor loading limit

Stators:

$$\Delta P_{\text{allow}}/q_i = L_s$$

where

ΔP_{allow} = allowable static pressure rise through stator at a given radial station
q_i = stator inlet dynamic pressure at that station
L_s = stator loading limit

Separations due to shock-wave boundary-layer interactions are controlled at transonic speed by keeping local cascade inlet Mach numbers lower than critical Mach numbers, i.e., the minimum inlet Mach number which produces a sonic zone at some part of the airfoil surface. Critical Mach number is a function of a number of geometric variables, but perhaps the most important is camber angle. In general, critical Mach number is reduced as camber or turning angle is increased. Consideration of these limits in the conventional compressor design reveals that the hub region of the compressor is considerably more likely to separate than the tip section, for the following reasons.

1) Rotors are usually designed to impart a constant stagnation enthalpy rise from hub to tip. Since the quantity $\Delta h_0/u^2$ will be a maximum at the hub, it is apparent that this is the radial station which will be critical with respect to the loading limit. With respect to shock-wave boundary-layer interaction, the camber decreases, which implies an increase in critical Mach number in progressing from the hub to the tip. Since the rotor inlet Mach number also tends to increase with radius, and at about the same rate as critical Mach number, no particular region of the rotor is usually considered to be limited in this respect.

2) Swirl velocities leaving the rotor are a maximum at the hub. A generally successful design practice of keeping stator exit velocity nearly uniform radially and axially implies that $\Delta P/q_i$ will be at a maximum at the hub. The hub is, therefore, the critical station with respect to loading. In addition, it is found that at the hub, both stator camber and inlet Mach number have minimum values, causing the hub section

to be critical with respect to shock-wave boundary-layer interaction.

An optimum design is obtained by selecting given variables at their limit values. In the case of a compressor stage, it is now clear that the optimum stage with respect to aerodynamic variables will be dependent on selecting blade root aerodynamic variables equal to their limiting values. For a conventional stage design, a summary of aerodynamically optimum stages may be presented, as shown in Fig. 10, on which are plotted the previously discussed limits. It is seen that the allowable stage-pressure ratio increases as rim speed is increased but that different limits set the allowable stage-pressure ratio in different ranges of rim speed. Generally, at low rim speeds, stage-pressure ratio is selected by consideration of rotor loading limits, whereas at high rim speed, stage-pressure ratio is dependent on stator critical Mach number limits.

A complete discussion of the procedures required to optimize an engine design is not essential to demonstrate the outstanding benefits to be derived by the use of beryllium. However, consideration of some of the procedures will indicate sufficiently what can be expected. Of particular importance in the design of a turbofan engine are the compressor-stage aerodynamic limits and the blade structural limits, since fan-blade root-stress limits and fan-stage aerodynamic limits usually define not only the fan configuration but, to some extent, the remainder of the engine. For example, these limits on the fan usually set the low rotor speed which may be seen if one considers the implications of the equation for fan blade root stress. This equation may be written

$$\frac{\sigma_r}{\rho} = Ku_r^2\left(\frac{1}{\lambda^2} - 1\right) = K\left(\frac{u_r}{r_r}\right)^2(R_t^2 - R_r^2)K'N^2A$$

where

R = radius
A = annular flow area
K and K' = coefficients
subscript r = hub (root)
subscript t = tip

This follows since annulus area is set by aerodynamic considerations. It is seen that optimum low rotor speed increases as the quantity $\sigma_{\text{allow}}/\rho$ of the blade material increases. Increased values of low rotor speed are desirable because they lead to lighter, more compact engine configurations, since both the fan and the turbine diameters can be reduced. For proper transition from fan to high-pressure compressor and from high-pressure turbine to low-pressure turbine, the diameter of the high-pressure spool will be reduced.

For the example which will be considered, it is useful to take the structural and aerodynamic limits one step further. These two limits will be combined by eliminating rim speed. The allowable stage-pressure ratio may be presented as a function of the quantity $\sigma_{\text{allow}}/\rho$ for the blade material and the hub-tip ratio, as shown in Fig. 11. In this figure, the material property $\sigma_{\text{allow}}/\rho$ is nondimensionalized relative to the value for titanium. Relative values of this quantity of about 0.6 and 1.6 exist for steel and beryllium blade materials, respectively. Figure 11 clearly illustrates the advantage, in terms of pressure-ratio capability, that titanium holds over steel, along with the advantage that beryllium would have over the other two materials as a fan-blade material.

Example of Weight Savings in a Specific Engine Design

The application of beryllium to a twin-spool turbofan engine was the example chosen to demonstrate the latitude in

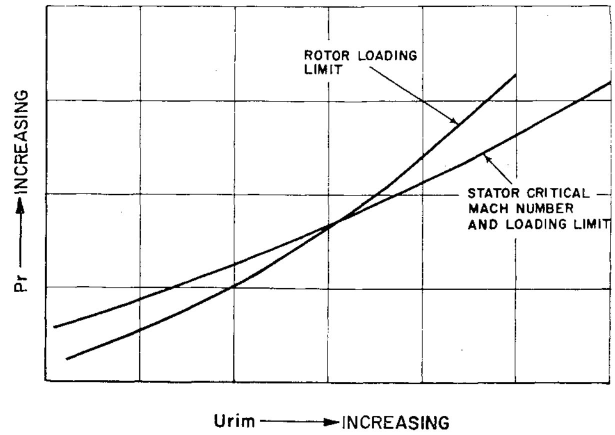

Fig. 10 Compressor stage design limits.

design allowable by the favorable properties of beryllium. The limitations imposed on the design are hub-tip ratio and allowable centrifugal stress. With titanium, the hub-tip ratio of the first-stage required for compatibility with the remainder of the engine is 0.35. This value, in conjunction with the allowable centrifugal blade stress, determines the fan rotor speed. This limits the first-stage pressure ratio, as indicated in Fig. 11, to a value which is approximately the square root of the design-pressure ratio. Two stages are, therefore, required to achieve the full design-pressure ratio. If beryllium is used in this application, a considerable increase in fan rotor speed will be allowed by the more favorable strength-to-density relationship. This speed increase results in a much higher single-stage pressure-ratio capability. In examining the detailed design, however, the hub-tip ratio of the second titanium fan stage is much higher than that of the first stage. The hub-tip ratio for a single-stage fan can, therefore, be higher than for the first stage of a two-stage fan. The combination of higher allowable speed and higher hub-tip ratio allows the designer to achieve the full design-

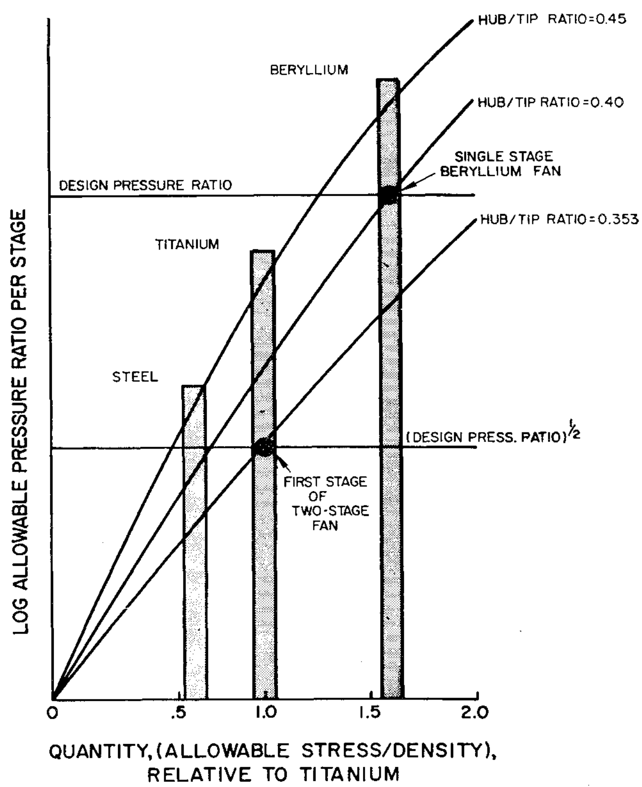

Fig. 11 Effect of material properties on allowable fan loading per stage.

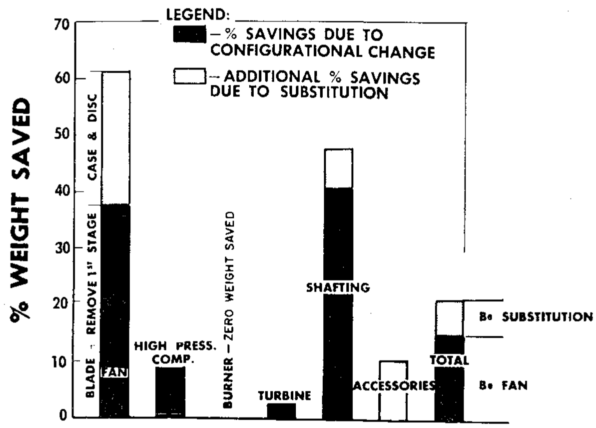

Fig. 12 Sectional breakdown of % savings in weight, single-stage beryllium fan.

pressure ratio requirement in a single-stage beryllium fan, as indicated in Fig. 11. The converse of this situation applies to the use of steel, where three stages would be required to achieve the full design-pressure ratio. Therefore, the benefits derived by the favorable properties of beryllium may allow the designer to eliminate stages as well as to reduce the weight of existing stages.

In certain cases studied, the increase in fan rotor speed permitted the engine to be designed as a single-spool engine, where the fan is coupled to the high-pressure compressor and the fan drive turbine is coupled to the high-pressure drive turbine. This configuration eliminates shafting, seals, and bearings, with a resultant reduction in weight, complexity, and over-all cost. The turbine can benefit from a higher average wheel speed, so that a reduction in turbine diameter is possible, with performance held constant. The results of a weight-saving study of a typical Mach 3 engine are depicted in Fig. 12.

Large percentage changes in weight are possible in the fan and shaft portions of the engine. However, the weight saved as a result of the aerodynamic freedom offered by the use of beryllium considerably exceeds that brought about by direct substitution. Approximately 15% of the total engine weight is eliminated by redesign, and an additional weight saving of 6% is made by substitution of beryllium. The over-all saving is approximately 21% for this particular Mach 3 engine.

Influence of Use of Beryllium on Aircraft Performance

The improvements in aircraft performance which may be achieved by the use of beryllium in powerplants are summarized in Fig. 13. In this figure, the percentage change in engine weight, takeoff gross weight (TOGW), and mission radius are shown as areas of improvement. For each of these areas, the savings that are achieved through direct substitution, plus redesign, are shown.

For the subsonic transport, supersonic transport, and subsonic STOL aircraft, the approximate reduction in TOGW is shown. The decrease in TOGW is based on the assumption that, for a given payload and range, the reduction in powerplant weight permits the aircraft to be redesigned. The powerplant for the STOL aircraft is equipped with thrust deflection nozzles for takeoff and landing. Although no VTOL aircraft was included in the chart, application of

(ALL DATA ARE IN PER CENT)

TYPICAL APPLICATION	DECREASE IN POWERPLANT WEIGHT*	DECREASE IN TOGW	IMPROVEMENT IN MISSION RADIUS
SUBSONIC TRANSPORT	36	3.5	--
SUPERSONIC TRANSPORT	15	6.6	--
STOL (SUBSONIC)	36	9	--
STOL (SUPERSONIC)	20.5	--	8

*ACCOUNTS IN PART FOR WEIGHT SAVING IN INSTALLATION DUE TO REDUCED ENGINE WEIGHT.

Fig. 13 Typical improvements using beryllium.

beryllium to lift-type powerplants was reviewed, and it is seen that a reduction in weight of approximately 35% is possible in this powerplant.

The significance of the decreases in gross weight shown in Fig. 13 is that, even in cases where the cost of the engine is increased by the maximum use of beryllium, the airplane fabrication and operational costs can be considerably reduced. Lift and STOL aircraft will be given an increase in mission radius which will allow the airplane to achieve an operational flexibility that is not possible with currently available engines. The application of beryllium to engine installation hardware and airframe components will improve further the performance of the various aircraft shown in Fig. 13.

Conclusions

The study of the application of beryllium to aircraft powerplants as discussed here clearly shows that great improvements in weight and cost are possible, if adequate impact resistance and ductility can be developed. The increase in the effectiveness of aircraft using beryllium approaches that which can be achieved with a new powerplant concept. With this large potential, it is recommended that efforts in the programs being pursued in alloying, purifying, fabricating, and developing the feasibility of application be continued and accelerated.

The arbitrary temperature limits imposed on beryllium, for purposes of this study, preclude the use of beryllium in the turbine section of the powerplant. The high melting temperature (2332°F) and excellent thermal properties (specific heat and thermal conductivity) of beryllium make it a strong candidate for a future turbine material that offers very significant additional weight savings.

It was not within the scope of this paper to describe the new configurations of powerplants which may be evolved as a result of the application of beryllium. Only the potential of the material was described, and future design work will reveal what can be produced using this important tool. It is the authors' opinion that powerplants designed with beryllium will be not only lighter and more compact than conventional powerplants but also greatly simplified, implying reduced costs and improved reliability.

Reference

[1] Hayes, A. F. and Yoblin, J. A.: "Beryllium forging program," U. S. Air Force Contract AF33(600)-36795, ASD TR 62-7-647 (March 1962).