11

THE POTENTIAL OF BERYLLIUM IN SUPERSONIC COMMERCIAL AIRCRAFT

GEORGE A. HOFFMAN
The RAND Corporation

ABSTRACT*

Prompted by some recent metallurgical developments, a structural comparison is made of beryllium with the best alloys of aluminum, titanium, and steel for a variety of applications in supersonic transports. Such applications include components whose design is governed by tension criteria, by compression in stiffened and sandwich panels and in unstiffened plates, and by notched behavior, all over the temperature range to be encountered in future aircraft. It is inferred that a beryllium structural part might weigh from ¼ to ½ less than the equal-function part made of more conventional metals. Calculations of the economics of beryllium usage in aircraft follow, consisting of several derivations of the worth-in-use of the weight reduction in commercial transports obtained by substituting a lighter-weight, but costlier, beryllium component. It is concluded that beryllium would offer many economic and weight-reducing advantages for transports.

PROPERTIES OF BERYLLIUM, PRESENT AND FUTURE

The use of beryllium as an aircraft structural material was proposed as early as three decades ago[1] and has been considered with increasing frequency since then,[2] but it is only recently that metallurgical developments in beryllium[3] have warranted a consideration of this metal in transport aircraft. A significant development has been the success in improving the room-temperature ductility of beryllium structural shapes under biaxial tensile stress,[4] raising the elongation before fracture in some instances to 2 percent, a level almost comparable with values for the highest-strength steel, titanium, and aluminum alloys. With this ductility, beryllium might be satisfactory for many structural applications, and

---

* This paper is based on research supported by the USAF under Project RAND and was initially reported in RM-3094-PR, *The Potential of Beryllium in Supersonic Commercial Aircraft*, The RAND Corporation, May, 1962. Views or conclusions in this paper should not be interpreted as representing the official opinion or policy of the USAF.

since its ductility also increases very rapidly with temperature to as high as 5 to 10 percent at 400°F, it appears that it might be useful to evaluate beryllium in the context of the supersonic transport (hereafter abbreviated SST). It was felt that in this possible application the obstacles in the way of beryllium—cost, availability, and toxicity hazards—could be estimated for a flight vehicle whose use is still a decade away and that must "earn" its way to successful operation. The study assumes that the lab-developed ductility attained in a few instances can be retained and enhanced through production and fabrication processes, thus permitting the other outstanding properties of this metal—particularly its low density and high modulus—to be exploited for flight structures.

Some of these unusual mechanical properties of carefully prepared samples of sheet or extruded beryllium at temperatures slightly above those encountered in steady-state flight at Mach 1, 2, and 3 are estimated in Table 1.

Table 1[a]

Density, 0.067 lb/in^3

Mechanical property	Temperature (°F)		
	70	210	500
Modulus of elasticity, psi	44,000,000	43,500,000	42,000,000
Uniaxial 0.2% offset yield tensile strength, psi	50,000	47,000	43,000
Ultimate uniaxial tensile strength, psi	90,000	83,000	70,000
Specific heat, cal/g/°C	0.45	0.5	0.57
Thermal conductivity, [(cal/sec)/cm^2]/(°C/cm)	0.38	0.34–0.38	0.30–0.37
Coefficient of thermal expansion, [(in/in)/°F] × 10^6	5.5–7	6.5–8.5	7.5–9.5

[a] From D. W. White and J. E. Burke, *The Metal Beryllium*, New York, The American Society for Metals, 1955.

It should be understood that the strengths reported occasionally in the literature are higher than shown above, but they are for a brittle material, while the lower strengths listed here are estimates for randomly oriented wrought beryllium sheet[4] that may be much altered by processing methods.

Resistance of the bare metal to the corrosive and erosive environment of the SST is quite ample, being comparable to the other aircraft metals under consideration for this application. Unfortunately, beryllium and its compounds are highly toxic—so much so that in finely divided form beryllium ranks among the dozen most poisonous elements on a weight basis. The control of these hazards in manufacturing is well known, and safe handling processes have resulted in the beryllium industry's safety record being ahead of that of other nonferrous industries. Hazard controls account for $\frac{1}{10}$ to $\frac{1}{4}$ of the present cost of beryllium sheets and extrusions, and similar proportions may be expected for the incremental cost of coping with the toxicity in the fabrication of beryllium components and aircraft structures.

Although presently there is ample capacity to produce beryllium (about 300 tons per year in the United States for 1962), there are only laboratory quantities of extrusions, sheets, and forgings that might be suitable for flight vehicle structures: for example, less than 100 sheets, 48 × 18 in. and 0.02, 0.04, and 0.06 in. thick, are scheduled to be manufactured this year. Though the present price per unit weight of powdered beryllium metal is $50 per lb, the first sheets produced that might be considered for actual use cost as much as $1000 per lb. At these price levels, it is understandable that most designers are reluctant to seriously consider beryllium.

Future properties of beryllium may be estimated by the judicious extrapolation of recent development rates. Ductility under biaxial tensile stress, which improved by an order of magnitude in the last decade, could be further improved, possibly to the levels of other lightweight high-strength metals, by several potentially promising techniques, such as removing deleterious impurities, changing to a more favorable crystal structure by alloying and/or by special heat treatment, or choosing better mechanical means of working the material.[5] One metallurgical approach has been to try to enhance ductility by attempting to retain the high-temperature body-centered cubic crystal phase down to room temperature (at which it normally would be in the highly anisotropic and brittle hexagonal close-packed phase), by alloying (nickel being a promising additive in small quantities), or by quenching or applying ultrahigh pressures. Because of the high anisotropy in mechanical properties of the beryllium single crystal, the newer fabrication processes, such as hot upset pressing, press forging, and shear spinning, are all directed toward achieving as random an orientation and as fine-grained a product as possible. As a result of these new processes, the latest sheets now might meet a tentative specification of 5 percent uniaxial elongation at 60,000 psi ultimate tensile strength. These same techniques could be effective in further raising the strength of the metal—which is today about double what it was in the early 1950s—possible by one-half in another dozen years or so.

The modulus, density, thermal properties, and toxicity of beryllium will probably not change significantly with the passage of a few years; costs, however, may be lowered by the development of new ore deposits, cheaper extraction techniques, and more efficient methods for production of the stock material.

There are numerous developments, many as yet unproven, that are directed toward reducing costs:

- Other, more plentiful but also more diffuse sources for beryllium than the conventional beryllium ore source are being studied for exploitation.
- Open-pit deposits are being eyed rather than present deep-mine ores.
- Less emphasis on manual (hand cobbling) ore extraction and benefitiation is being sought in pilot-plant experiments with flotation-concentration processes and with acid-leaching treatments.
- Continuous, rather than batch, processing for the ore-to-metal step is envisaged when and if operations are scaled up for a larger market.

STRUCTURAL EVALUATION OF BERYLLIUM

A comparison of beryllium with aluminum, steel, and titanium can be made by considering the relative weight of components that transmit tension loads, that do not buckle under compression and shear forces, that accommodate to thermal stresses, and that resist crack propagation, creep, and fatigue failure—just to name a few of the numerous criteria governing the choice of metals for the SST and other flight vehicles.

The evaluation of biaxially tensioned beryllium sheets has not yet been done, though some indication of its ranking may be had from the relative weight of sheets uniaxially tensioned to their ultimate tensile strength (UTS), customarily calculated as

$$\frac{\text{Density of alloy}}{\text{Density of aluminum}} \times \frac{\text{UTS of aluminum at room temperature}}{\text{UTS of alloy at various temperatures}}$$

This ratio is shown in Fig. 1 for present-day and future beryllium (upper and lower limits on the band) under short-time exposure to temperature, and for X2020-T6 aluminum alloy, 13V-11Cr-3Al titanium, and AM355XXH steel, the last two being promising alloys in development.[6] Also shown hereafter are the temperatures 1 ft and 100 ft behind the leading edge (the cooler and warmer bounds of the wide arrows in Fig. 1) for the two speed regimes being considered for the SST in Europe and in the United States.

Metals for thin-wall structures designed by buckling criteria—the preponderant portion of the SST—can be compared by the methods of optimal design[7,8] whether the components are unstiffened sheets and columns, sheet-stiffener panels, or sandwich plates under distributed edge compression, shear, or bending, with or without lateral pressure. Starting with the compression stress-strain diagram, one can derive the plot of the equivalent allowable stress (usually as the buckling stress times the ratio of the density of aluminum to the density of the metal) against the structural index (a parameter relating the load carried and the distance of its transmission). Then the relative weight can be calculated by ratios of allowable stresses at structural indexes representative of the SST—

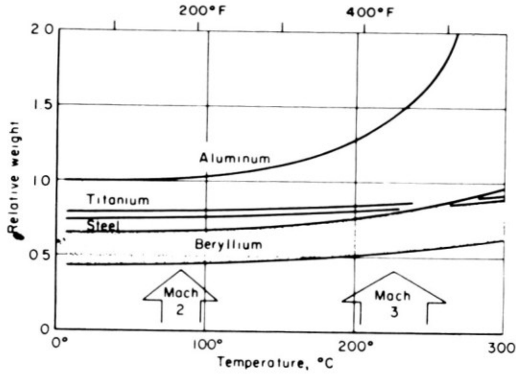

Fig. 1. Relative weight of tension elements.

these having been estimated by some industry sources to be somewhere under 200 or 300 psi for the wing[9]—and shown as the lower and upper band limit in Fig. 2 for Y-stiffened panels. For certain unstiffened plates dimensioned so as to buckle in the elastic region, the relative weight can be approximated by the ratio

$$\frac{\text{Density of alloy}}{\text{Density of aluminum}} \times \frac{\text{Modulus of elasticity of aluminum at room temperature}^{1/3}}{\text{Modulus of elasticity of alloy at various temperatures}}$$

as shown in Fig. 3, though it should be noted that unstiffened plates will constitute only a very small portion of flight structures. Far more intricate analysis is required for the allowable stress in sandwich panels, which must be compensated by the weight of core cell (honeycomb or truss), brazing, or adhesive and must reflect choices in core geometry and materials. Thus it happens that the relative weight in this case (Fig. 4) is most sensitive to the transition from the elastic to the plastic region, and to the assumptions made regarding compression prop-

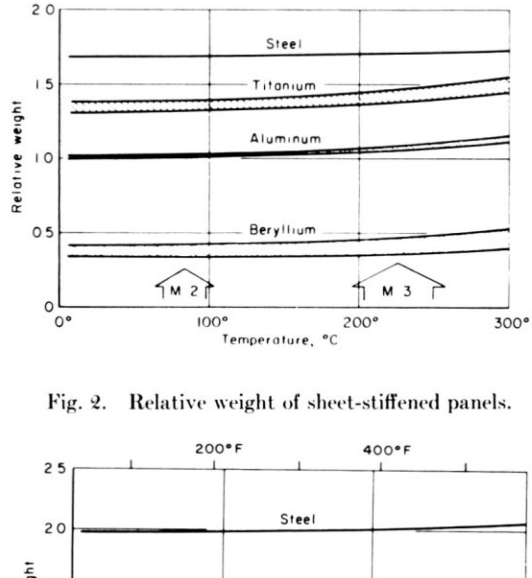

Fig. 2. Relative weight of sheet-stiffened panels.

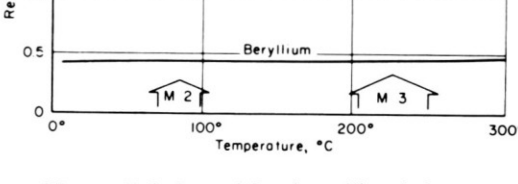

Fig. 3. Relative weight of unstiffened plates.

erties and optimum core-cell proportions. Band widths in Fig. 4 are again indicative of variations in structural index.

By the criteria considered so far, beryllium structures ranked consistently ½ to ⅓ lighter than those made of other aircraft metals. However, with respect to localized accommodation to thermal stresses, no simple and reliable index has been found for ranking various metals, and it may well be that no large differences will exist among the weights of SST components designed by thermal stresses, whether these components are made of beryllium or other more conventional metals. Since good design practice can circumvent and alleviate thermal stress problems, this consideration seems to affect but a very minute portion of the vehicle.

Current methods for comparing metals on the basis of notched strength and resistance of crack propagation are also inadequate, as are much of the data on the newer sheets of more ductile beryllium. Some preliminary information[10] seems to indicate that the weight relative to aluminum at room temperature of uniaxially tensioned notched sheets may be of the form shown in Fig. 5 if it is assumed to be proportional to

$$\frac{\text{Density}}{\text{Ultimate notched tensile strength at temperature}}$$

The upper and lower limits of the band are representative of different size discontinuities, such as fine cracks and rivet holes, respectively. Creep and fatigue data are also lacking for aircraft-quality beryllium sheets, thus precluding a comparison in this study, though no major deviation from the patterns of Figs. 1 and 5 should be expected.

Perhaps ⅔ to ¾ of the structure of an SST will be designed by the criteria shown in Figs. 1 and 4, and, to a lesser extent, by those in Figs. 2, 3, and 5, and by fatigue. It might be hypothesized from such proportions then that an all-beryllium SST structure would weigh from ¼ to ½ less than the equal-function structure composed of the appropriate proportions of aluminum, titanium, and steel. Since a more precise figure for the structural weight reduction possible from using beryllium can be derived only after the vehicle has been designed,

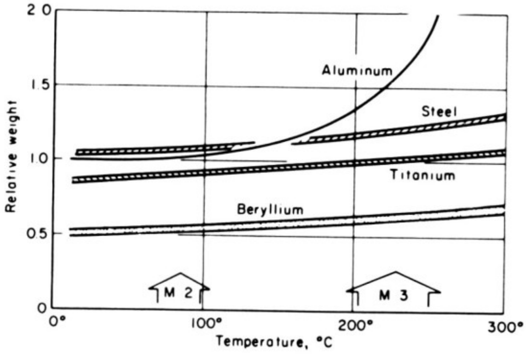

Fig. 4. Relative weight of sandwich panels.

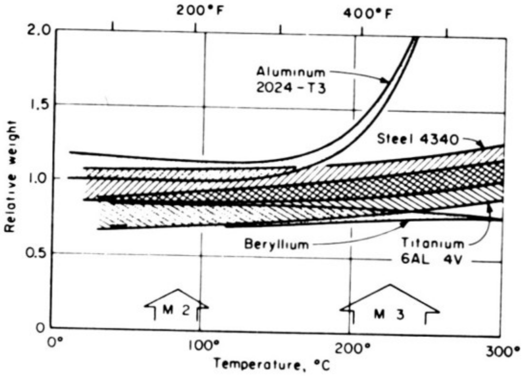

Fig. 5. Relative weight of notched tension elements.

this figure will be allowed to vary from ¼ to ⅓ to ½ in the subsequent analysis. Obviously far less than full use of beryllium must be expected for many years to come: the first generation of SST's will use minute amounts of beryllium, or perhaps none at all. Furthermore, Figs. 1–5 indicate that theoretically—in the absence of beryllium—titanium should be the metal most extensively used in the SST structure, although in actuality it will be inevitable that large portions will be designed at first from less-efficient aluminum and steel.

Beryllium is also superior to other metals in other properties which, although of no relevance in the SST, will be of importance in later flight-vehicle design. For example, calculation of the weight of meteoroid shields made of beryllium show that they might be far lighter than those made of any other material for equal protection levels, whether the design is dictated by hydrodynamic or by sound-velocity considerations. Or, as a minimum-weight heat sink for short-time high heating rates, beryllium again is superior to all the metals, being comparable to isotropic graphite, although it is inferior to pyrolitic graphite. And, finally, beryllium exceeds all metals as a neutron moderator and reflector, hence its extensive use in all types of nuclear reactors.

The combination of properties that make beryllium superior for use in large structures will place beryllium in an analogously attractive position for those small components in which minimization of inertia for a certain stiffness or strength is desired. The far-from-complete list that follows is indicative of the numerous applications that either have resulted in a manufactured and tested item or exist as contemplated uses for beryllium.

Items in Use

Brake disks
Casings, covers, housings
Aerodynamic fins and control surfaces
Memory-storage-and-retrieval disks and drums
Wave guides
Gyroscope wheels, floats, gymbals, cages, yokes, etc.
Fasteners: screws and bolts

Planned Designs

Wheel spokes, frames, and fins
Trim tabs, flaps, and fences
Helicopter blades
Radar antennas and dishes
Wind-tunnel aeroelastic models
Aerodynamic fairings
Pumps and valve bodies
Impellers
Valve disks

Items in Use

Gas-turbine compressor blades
Low-inertia linkages: tabs, fingers, links, levers, yokes, and bars
Indicator pens, needles, and styluses
Electroacoustic diaphragms
Cooling fins
Camera iris shutters

Planned Designs

Poppet valves
Electric-motor housings
Pistons and connecting rods
Low-weight clutches
Core components in vibration exciters
Astronomical-mirror frames

ECONOMICS OF BERYLLIUM USAGE IN AIRCRAFT

Even if ductile beryllium sheets, extrusions, and other aircraft shapes were to become readily available, engineers might still be reticent about using this metal in airframes because of its unusually high price and toxicity. The cost resulting from the poisonous nature of beryllium, which already accounts for ¼ or less of finished-part prices, would be a sizeable increment in the operational maintenance costs of any airframe, which may well preclude the use of this metal from the interior cabin of the SST. This application would certainly pose unusual problems wherever personnel might contact the bare metal, such as in ground-handling inspection and repair, or in decontamination of crash or skid sites. But the most important question is still whether the weight savings afforded by beryllium at its high installed price justify its use, considering its value-in-use against the increased depreciation and handling costs. The following elementary exercises in the economics of the SST and reduction of its structural weight can provide some guidance. Any economic advantage that may be derived analytically from beryllium in this commercial application is indicative of much greater attractiveness in applications where speeds or altitudes are higher (e.g., space vehicles) and a greater premium yet can be paid for weight reduction.

There are numerous ways by which designers try to ascertain the worth of eliminating weight from a flight vehicle without altering its performance. The results of such calculations are very sensitive to basic assumptions in the analysis and the number of factors considered. Figures in the literature may vary by large factors, and the three examples reported here should not be used even as guidelines.

The fourth and final calculation that will be presented here—which we believe somewhat more valid—will, instead of deriving an absolute value-in-use of beryllium, attempt to define its break-even value, i.e., the price level at which the use of beryllium components would give SST performance and operating costs identical to those of an SST built of conventional materials.

One way of looking at the incremental value to the operator from installing a beryllium component in a transport has been consideration of the lowering in fuel and operating costs due to the weight eliminated. This value increase from a unit-weight beryllium structure can be calculated[11] to be

$$\text{Operational life} \times \text{Specific fuel consumption} \times \text{Drag-to-lift ratio} \times \text{Fuel cost} \times 2 \times r/(1 - r)$$

where the factor 2 is the assumed ratio for (direct operating costs)/(fuel costs), and r is the weight-reduction factor for beryllium usage. This rough estimate is

Table 2. ASSUMPTIONS OF TRANSPORT CHARACTERISTICS FOR CALCULATION OF BERYLLIUM VALUE-IN-USE[12]

(Capacity: 125 passengers; Range: 3,000 to 4,000 miles)

Characteristic	Mach number				
	0.9	2	2.5	3	3.5
Total operational life, hr	45,000	38,000	32,000	30,000	25,000
Specific fuel consumption × drag/lift ratio, hr^{-1}	0.067	0.195	0.22	0.24	0.26
Fuel cost,* \$/lb	0.023	0.026	0.028	0.030	0.035
Initial cost of one aircraft,** \$ × 10^{-6}	6	13	16	18	24
Airframe unit cost, \$/lb	40	70	90	100	110
Growth factor,† (increment in gross weight)/(increment in payload)	10	13	14	15	16

* Derived from Fig. 14 of Symposium 24, p. 19, and Symposium 35, p. 13, of Ref. 12.

** Including research and development costs leading to production of 100 vehicles.

† From Table 1, Symposium 16, p. 9, and Fig. 3, Symposium 41, p. 10.

meaningful only as a lower limit since it does not account for the additional weight saving elsewhere in the aircraft resulting from the substitution of a lightened part; that is, the negative growth factor has been neglected. The incremental values of beryllium computed by this method from the assumptions listed in Rows 1 to 4 of Table 2 are shown in Fig. 6 for $r = \frac{1}{4}, \frac{1}{3}$, and $\frac{1}{2}$.

Another approach has been to stipulate that enough beryllium be used in an SST to permit the installation of at least one more passenger seat, allowing 300 lb per passenger. This amount of beryllium is $300 \times (1 - r)/r$. Then for a 125-passenger airplane, the incremental values of a pound of beryllium are postulated to be

$$\frac{\text{Initial cost of vehicle (from Table 2)}}{[125 \times 300 \times (1 - r)/r]}$$

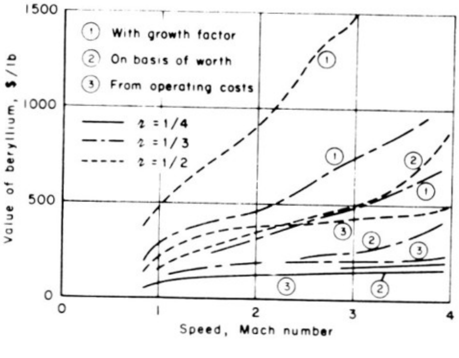

Fig. 6. Incremental value of structural beryllium installed in commercial transports.

and are also plotted in Fig. 6. This worth-basis approach neglects much of the additional weight that could be eliminated, though it already assumes some seating and space flexibility in the design of the craft.

The highest increments in values are those given by the procedure that considers the historical trends in airframe manufacturing costs and in growth factors (Table 1), resulting in

$$\begin{array}{c}\text{Incremental value of a}\\ \text{unit-weight of beryllium} = \text{airframe unit cost} \times \text{growth factor} \times r/(1 - r)\end{array}$$

also shown in Fig. 6.

The poor or incomplete criteria of analysis account for the large discrepancies in the estimated value of this metal exhibited in Fig. 6 and suggest a more meaningful computation—that of the break-even level of beryllium structural costs. This can be done as shown in Table 3, where, in essence, operating costs of beryllium-structured SST's are estimated for arbitrary values of "x," the unit cost of beryllium airframes expressed as a multiple of the unit cost of an all-titanium structure.

While substituting beryllium for aluminum or titanium, the payload, external dimensions, speed, altitude, range, and crew cost were kept constant, while structural cost and weight, power-plant size, fuel weight, takeoff gross weight, maintenance, and depreciation costs were allowed to vary.

Table 3. ASSUMPTIONS OF TRANSPORT CHARACTERISTICS FOR CALCULATING OPERATING COSTS OF BERYLLIUM SST'S

(Payload of 125 passengers with 300-lb allowance each, or 37,500 lb; range of 3,000 to 4,000 miles)

Characteristic	Cruise speed (Mach No.)		
	0.9	2.0	3.0
	Transport structure made of conventional metals		
Operating cost, ¢/seat-mile*	1.5	1.6	1.6
Composition of operating costs, %/100**			
a. Fuel	0.33	0.44	0.49
b. Maintenance, spares	0.22	0.16	0.14
c. Crew, personnel	0.14	0.11	0.09
d. Depreciation, insurance	0.31	0.29	0.28
Weight composition, %/100			
e. Payload	0.13	0.09	0.07
f. Structure	0.33	0.34	0.35
g. Fuel	0.47	0.50	0.52
h. Engines	0.07	0.07	0.06
i. Maximum takeoff gross weight = 37,500/*e*, lb	290,000	416,000	535,000

Table 3. (Continued)

	Transport structure made of beryllium								
Weight-reduction factor, r	¼	⅓	½	¼	⅓	½	¼	⅓	½
Weight composition, %/100									
j. Payload, $r \times f + e$	0.21	0.24	0.29	0.17	0.20	0.26	0.16	0.19	0.24
k. Structure, $(l - r) \times f$	0.25	0.22	0.17	0.26	0.23	0.17	0.26	0.23	0.18
l. Fuel, g	0.47	0.47	0.47	0.50	0.50	0.50	0.52	0.52	0.52
m. Engines, h	0.07	0.07	0.07	0.07	0.07	0.07	0.06	0.06	0.06
n. Gross weight, $37{,}500/j$, lb	179,000	156,000	129,000	220,000	188,000	144,000	234,000	198,000	156,000
Operating cost, ¢/seat-mile									
o. Fuel, (1.5 or 1.6) $\times a \times n/i$	0.31	0.27	0.22	0.37	0.32	0.24	0.34	0.29	0.23
p. Maintenance (1.6 or 1.5) $\times b \times n \times x(3 + x)/4 \times i$	0.15+ $0.05x$	0.13+ $0.04x$	0.11+ $0.04x$	0.10+ $0.03x$	0.09+ $0.03x$	0.07+ $0.02x$	0.07+ $0.02x$	0.06+ $0.02x$	0.05+ $0.02x$
q. Crew, personnel, (1.5 or 1.6) $\times c$	0.21	0.21	0.21	0.18	0.18	0.18	0.14	0.14	0.14
s. Depreciation, insurance†	0.05+ $0.18x$	0.04+ $0.14x$	0.04+ $0.09x$	0.04+ $0.16x$	0.04+ $0.12x$	0.03+ $0.07x$	0.03+ $0.12x$	0.02+ $0.09x$	0.02+ $0.06x$
Total $= o + p + q + s$	0.72+ $0.23x$	0.65+ $0.18x$	0.58+ $0.13x$	0.69+ $0.19x$	0.63+ $0.15x$	0.52+ $0.09x$	0.58+ $0.14x$	0.51+ $0.11x$	0.44+ $0.08x$
Nominal breakeven value of beryllium structure relative to titanium, x	3.4	4.7	7.1	4.8	6.5	12	7.3	10	14

* Averaged from estimates[12] of four transport manufacturers and an airline operator.

** From Symposium 13, Ref. 12, p. 47.

† $s = (1.5 \text{ or } 1.6) \times d \times (xk + m) \times n/(f + h) \times i$.

The results of such calculations seem to indicate that beryllium in the SST appears to break even with conventional metals at a cost per pound somewhere above four times the cost of titanium components—how much above depending on the actual weight savings finally achieved after designing with beryllium. For example, if a ⅓ weight reduction could be achieved in a Mach 3 SST, beryllium would break even at about ten times the cost of titanium.

CONCLUSIONS

From this study, it may be concluded that if the imparting of ductility to beryllium aircraft shapes can be continued, its great technical advantages could be exploited. This could result in eliminating ¼ to ½ of the weight of SST components that it replaces, concomitant with economic advantages, if its installed price can be kept well under five times that of titanium. Although not analyzed here, the problem of coping with the toxicity, and of gearing up a small industry to much greater production in a short time, appear as the major obstacles yet to be faced.

REFERENCES

1. Tuckerman, L. B., "Beryllium—A Dream of Possibilities," in *Aircraft: Materials and Testing*, American Society for Testing Materials Reprint, vol. 35, Part 2, 1935.
2. Hoffman, G. A., "Beryllium as an Aircraft Structural Material," *Aeronautical Eng. Rev.*, February 1957, pp. 50–55.
3. "The Metallurgy of Beryllium," Proceedings of the International Conference, Oct. 16–18, 1961, London, sponsored by The Institute of Metals.
4. Yans, F. M., A. K. Wolff, and A. R. Kaufmann, "Development of Randomly Oriented Wrought Beryllium Sheet," WADD Technical Report 60–403, December 1960.
5. Gelles, S. H., J. J. Pickett, and A. K. Wolff, "Recent Advances in Beryllium Metallurgy," *Journal of Metals*, October 1960, pp. 789–792.
6. Brown, W. F., Jr., G. B. Espey, and M. H. Jones, "Considerations in Selection of Wing and Fuselage Sheet Materials for Trisonic Transports," Society of Automotive Engineers Reprint No. 341 D, 1961.
7. Shanley, F. R., *Weight-Strength Analysis of Aircraft Structures*, New York, Dover, 1960.
8. Gerard, G., *Minimum-Weight Analysis of Compression Structures*, New York University Press, 1956.
9. Kiddle, P. F., and P. J. McKenzie, "Material Trends in the United Kingdom for Structures Operating at Temperatures up to 700F (380C)," Society of Automotive Engineers Reprint No. 420A, October 1961.
10. Riedinger, L. A., "Beryllium for Aerospace Structures," *Space/Aeronautics*, December 1961, pp. 64–67.
11. Hoffman, G. A., "Optimum Tolerances of Sheet Materials for Flight Vehicles," Transactions of the American Society of Mechanical Engineers, *Journal of Engineering for Industry*, vol. 82, Series B, No. 4, November 1960, p. 368.
12. Symposium on Supersonic Air Transport, vol. 2, Working Papers of the 14th Technical Conference of the International Air Transport Association, Montreal, Canada, April 1961.

DISCUSSION

Author: G. A. Hoffman

Discussor: Dr. N. J. L. Megson, British Ministry of Aviation

The possibility of using beryllium as a structural material depends greatly on whether the ductility of the metal can be improved. Can the author give more detailed information about the way in which improvements have been achieved, as claimed in his paper?

Author's reply to discussion:

Reference 4 of the paper reports how the ductility of certain beryllium structural shapes—such as sheets—has been improved in the U.S. by new rolling techniques and texture controls, achieving in certain instances a third-dimensional ductility of 1.75 percent.