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REPORT OF THE
AD HOC COMMITTEE ON BERYLLIUM

NATIONAL MATERIALS ADVISORY BOARD

DIVISION OF ENGINEERING - NATIONAL RESEARCH COUNCIL

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FOREWORD

The aim of the National Materials Advisory Board has been to present a balanced sense of perspective as to the status, the future, and the needed actions on the part of the Department of Defense in regard to beryllium. This is not a presentation of the various material options (including beryllium) open to a designer. It is assumed that the reader has a familiarity with aerospace materials. Against this background we have sketched in the place for beryllium.

The Committee held classified discussions in order to arrive at its conclusions and recommendations. The subject matter of this report (NMAB-281) is unclassified. The classified (SECRET RD) matter is available through security channels as NMAB-282.

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CONTENTS

Page

PART I

THE BERYLLIUM PROBLEM

Chapter

PART II

PRESENT APPLICATIONS

APPENDIX

TABLES

FIGURES

ABSTRACT

This review, made to examine the role of the Department of Defense in using beryllium and in advancing the technology, found numerous advantageous applications as part of important components. Improved system performance is attributable to beryllium's elastic, thermal, and nuclear properties, and its low density combined with adequate strength. The outstanding technical limitation for structural application is beryllium's low fracture toughness. It has become apparent that while few, if any, systems absolutely require beryllium, when used, performance was sufficiently improved to outweigh the expense and risks involved. Present applications, such as for guidance systems, brakes, and thrust chambers, would suffer significant performance penalties if beryllium were not available. Several design trade-offs show beryllium to be competitive with, or superior to, filamentary composites, on a stiffness-to-weight basis, in advanced applications for lightweight structures. Increased usage of beryllium, however, will be unlikely without certain necessary development work which is described. In addition to beryllium's unique capabilities, a major justification for support of beryllium technology is its usefulness as an option in the event that competitive materials prove to be unsatisfactory in critical applications.

Civilian applications (except in the form of an alloying element), now or foreseeable, are very limited because beryllium remains an expensive material. Accordingly, fulfillment of beryllium's potential advantages for military systems requires government support to ensure that beryllium in the required forms will be available, particularly for applications now being designed. Evaluation of pertinent standard cutting and forming operations and also some of the newer fabrication operations in terms of cost and applicability are recommended. In addition, the construction and evaluation of prototype hardware, based on either all-beryllium or hybrid-beryllium structures, are

I CONCLUSIONS

A. Technical Conclusions

1. Applications in which beryllium is an important factor are predominantly military:

   weapons
   nozzles
   heat shields
   space structures
   brakes
   primary missile structures
   beryllium substructures
   guidance systems

2. Space, missile and aircraft structures are the greatest potential future uses.

3. In design trade-offs comparing vehicle performances, many beryllium structures (monolithic or hybrid) are technically competitive with filamentary composites (such as of boron or carbon fibers in an organic matrix). Beryllium is generally superior for primary and secondary structures that are "modulus-critical."

4. More work is needed to develop cost-effective beryllium designs, such as hybrids, and related fabricating methods. Prototype and element development programs would supply some of the needed cost information.

5. To take maximum advantage of beryllium, there is a need for more information regarding fracture phenomena and toughness, structural reliability, and composite and hybrid structures.

6. No really extensive usage of beryllium is anticipated. Even assuming that industry becomes indoctrinated in its application and the price is lowered somewhat, it would find use in only certain applications in a limited number of systems. However, its payoff may be great in these limited applications.

B. Management Conclusions

1. There is adequate domestic beryllium mineralization available for all foreseeable applications. The unpredictability of a certain possible classified requirement precludes, in general, making a statement as to adequacy for this possible application. Availability of ore is not a hinderance to use. In the past several years, foreign sources have augmented U.S. production and earlier supplied essentially all of our requirements.

2. Current beryllium metal production capability exceeds current beryllium metal requirements. The DoD survey of 1969 detailed the future utilization and came to a similar conclusion.* The classified supplement to this report (NMAB 282) contains some forecasts as to probable future demand.

3. Beryllium producers do not look to the government, but will support their own R&D directed at improving the economics of production of mill products and the qualify of these products, as well as proprietary product development.

4. There is a priori reluctance by designers and program managers to consider beryllium for primary structures in manned systems. This is based on a lack of confidence and a concern due to low fracture toughness. Nevertheless, beryllium is being used as secondary structure in manned systems and as primary structure in missiles.

5. There is fragmentary and relatively minor government support, now and in the immediate future, for specific hardware-oriented beryllium technology. Existing support is insufficient, and inconsistent with beryllium's potential.

6. Contractors, in general, are unable to make reliable cost estimates for fabricating new hardware made from beryllium, and this is a major hinderance in getting the material introduced.

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*"Report of Interagency Beryllium Survey," March 1969, ODDR&E, Washington, D. C., Log No. 69-1349, (SRD) and proprietary information, (unavailable).

7. Current system and engineering contracts are not supporting the advancement of beryllium technology even when preliminary design studies show beryllium to be a competitive or preferred material.

8. Under present business circumstances, the future availability of a sufficient variety of beryllium mill products is not assured.

9. Up-to-date information on beryllium properties and usage is inadequately disseminated. A design guide and a processing guide are needed.

10. Available information on engineering design should be brought, and kept, up-to-date, such as by an information center.

11. For successful application of beryllium there must be a close link between the material production, process development, and product development by a direct coupling of the parties concerned, principally the system designer, the metal producer, and the end-item fabricator. The contractor, with his designers, must be the technically responsible manager and ensure the design/production/fabrication coupling.

12. If the optimum structure is to be achieved, beryllium should be considered in the basic design rather than as a last resort, thus becoming merely a substitute material. If not considered in the conceptual stage, the effective use of beryllium is compromised or made impossible because of problems with scheduling, facilities, or interfacing with the remainder of the structure.

13. There needs to be continuing recognition of toxicity limits (particularly of specific beryllium compounds). However, by adopting the necessary precautions, the numerous beryllium hardware fabricators have not been seriously deterred by beryllium's toxicity.

II RECOMMENDATIONS

The Ad Hoc Committee on Beryllium submits two major recommendations. They are summarized below and receive additional discussion in subsequent sections of the report.

1. DoD Funding of a Prototype Development Program for Beryllium Structures

To assure that the potential of beryllium structures is recognized and is maintained as a design option for future systems involving high specific modulus-critical structures, DoD should fund prototype beryllium development programs. These programs can be carried out in conjunction with a major projected DoD system. The prototype can be either an all-beryllium or hybrid-beryllium structure. (The term hybrid is used to designate structures in which beryllium is used to stiffen a conventional material, thereby achieving a major fraction of the weight saving of an all-beryllium structure at about 1/3 the all-beryllium cost.)

A major effort is needed in developing a beryllium prototype structure. This could provide the incremental jump in experience and confidence to qualify it as primary structure, where the design has not been frozen and the payoff may be great. This recommended action is based on:

- The proven technology and status of beryllium metallurgy and fabrication.
- The confirmation by the Panel on Structural Design* that beryllium is one of the advantageous primary structural materials which may be necessary to achieve an important classified operational requirement.

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*NMAB Ad Hoc Committee on Hardening of Materials for Advanced Ballistic Missile Defense Systems.

To carry this out, the responsible DoD project officers should establish prototype beryllium development contracts for the vital integration of the design, production, and manufacture of beryllium structures by the major parties (the military service, the prime contractor (designer), and the subcontractor (fabricator)). All the applied mechanics, materials testing, nondestructive testing, and evaluation necessitated by the military design requirements should be included. There is no assurance that beryllium would survive as the material of choice, but without a prototype exercise beryllium would remain only a paper possibility. Contractors are often unable to make cost estimates for structures utilizing beryllium. This problem would be eased by obtaining information on the cost and applicability of a variety of processing operations.

The essential elements in a prototype development program are:

a. The program should be run by people who are intimately conversant with both the system requirements and with manufacturing and performance problems. The source of funding should be provided by the Department of Defense.

b. Two stages are involved:

1. Work on coupons or elements is needed first to provide a basis for an efficient and economical design to establish cost and feasibility. Technical factors which need investigation encompass joining methods, and cutting and forming operations, including newly developed processes for which utility has not been established. The delineation and determination of the parameters and properties to enable rational material selection are important elements.

This stage would also involve analytic studies to define design alternatives and perform cost-weight trade-offs.

2. This stage provides for the construction of a few copies of a structure to validate the design, uncover fabrication problems, and provide additional cost data. In addition, the structure should be subjected to ground or simulated service tests and, if possible, actual service tests.

c. Determination of performance, reliability and production costs are primary goals.

2. Information Dissemination Program

An effective dissemination of cost estimates, and of production and engineering data involved in using beryllium, should be promoted, sponsored largely by the government. This should include the preparation of a processing guide, preparation of a credible design guide, and augmentation of the services provided by current information centers.

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Additional recommendations are contained in the classified supplement. Detailed recommendations will be found throughout each report, in this volume on p. 22 (processing guide), p. 23 (information centers), pp. 25-26 (research), pp. 26-37 (prototype), p. 37 (element development), and p. 39 (toxicity and labeling).

III INTRODUCTION

Beryllium has long been considered to satisfy rather specialized needs very satisfactorily; but its cost, brittleness, and toxicity constrain its wide engineering usage. The materials engineering community, particularly the Department of Defense and the Atomic Energy Commission has, during the past thirty years, made substantial investments of R&D funds to provide the scientific base and significant improvements in beryllium technology over and above that which satisfied the original requirements of the AEC for hot-pressed block.

During the deliberations of the previous MAB Committee on Beryllium Metallurgy, it became clear that the effective transfer of the newly developed beryllium technology into the market place had been hampered, among other causes, by a climate of uncertainty, which was generated by product variability and by user inexperience and the highly government-sustained but uncertain market requirements. To establish whether sufficient raw material and manufacturing facilities were available, and for related reasons, the above MAB committee recommended in 1967 that an in-depth survey be made of both classified and unclassified applications, which could be identified or projected. A government committee, under the auspices of ODDR&E, visited the producers and important users of beryllium. The findings of this group (henceforth called the "Beryllium Survey") were issued in a classified report (Report of Interagency Beryllium Survey (U) 1969).

The proven technology and availability of beryllium for primary missile structures are advantages the United States has over other countries. This is a lead of about 5 to 10 years in material technology of which we can take both pride and advantage. Failure to capitalize on the increased payloads and design allowables potentially achievable by beryllium today, despite its limitations, would be poor utilization of past investments and achievements and might penalize advanced designs.

The past years of government R&D funding (DoD, NASA, and the AEC) have accomplished what is now deemed necessary in preparing the technical base for beryllium utilization. Today there is general lack of funding for beryllium R&D with a gross shift to the potential of fiber composites. The doubt and concern among designers and fabricators who are inexperienced in beryllium technology lead them to accept currently financed composites instead of exploring the available beryllium. This report examines present usage, the importance of beryllium to the Department of Defense, and the steps necessary to advance the technology. It was not felt to be necessary or feasible to consider in detail the attributes of materials competitive to beryllium. With minor exceptions, the characteristics and performance of other metals and of boron and graphite composites have been established and documented.

Many on the Committee are not experts on beryllium but have been intimately involved with the past introduction of other new materials. It was as a problems-and-payoff, new-material-introduction point of view, that the task was approached, not one of beryllium experts looking at where else beryllium might be used.

IV PURPOSE

As one of the few major users of beryllium, the Department of Defense has an obligation, both to the industry and to itself, to make intelligent use of this resource, and to anticipate major shifts in its requirements. The Committee was asked, therefore, to delineate appropriate management and technical actions necessary to advance beryllium technology so that it may be considered as a viable material option for the designers of DoD equipment. It was recognized from the start that beryllium application was to be encouraged only to the extent that the resultant improved performance compensated for the costs and risks involved. What this report attempts to do is to assess the need for and importance of beryllium in weapons systems, and based on the need, to propose a course of action on the part of the Department of Defense to ensure realistic consideration by contractors for the use of beryllium to the same extent as that of competitive materials. "Realistic consideration" presupposes commercial supplies of mill products, availability of appropriate design data, fabrication capability, and ability to estimate costs. These are some of the considerations explored in the sections which follow.

V DISCUSSION

A. Present Usage of Beryllium and Competitive Materials

At present, there is a long list of successful applications of beryllium in Department of Defense hardware, with the expectation of many future applications. The basis for the success of these achievements results from the unique alliance of the properties of the metal, principally its nuclear and thermal characteristics, combined with high modulus and low density. System performances were sufficiently improved to outweigh the expense and technical risk involved.

These achievements have been made in spite of impressive difficulties. Principal drawbacks to the use of beryllium are relatively low ductility and low fracture toughness at the ambient temperatures, high cost, and a toxicity hazard. Typical applications, most of which are described in a section of this report, in which the use of beryllium has been successfully made are:

nuclear weapons
re-entry heat shields
rocket nozzles
guidance systems
aircraft brakes
space structures
primary missile structures
secondary aircraft structures
X-ray windows
nuclear reactors

By using design ingenuity and by sacrificing performance, almost all applications could do without beryllium. The alternate materials that could be used would depend on the nature of the application. For example, where thermal characteristics are the design criteria, ablative materials, refractory metals, ceramics, graphite, carbon composites, various steels, superalloys, etc. would be considered. In light-weight, load-carrying structures the candidates could be aluminum, magnesium, titanium, and, more recently, the various forms of fibrous composites. However, any material of construction is not without its drawbacks.

The Committee found, in a broad sense, two distinct camps — a "pro-beryllium" group with a technical background of successful applications; and a second group which, if not "anti-beryllium," is at least skeptical of the material from a variety of viewpoints. The above classifications are obviously broad and general, but further characteristics of the two groups can be distinguished. These features provide a basis for some specific observations, conclusions, and recommendations.

With respect to characteristics of the "pro-beryllium" group — the Committee found numerous, successful and frequently innovative beryllium applications, primarily in military missile and space systems. In these cases, weight, performance, and cost trade-offs usually showed distinct advantages for beryllium. Characteristically, these applications involved:

- Users with prior beryllium experience.
- An adequate physical and mechanical property data base.
- Weight savings valued at upwards of $5000 per lb.
- Non-manned systems - single mission.
- In some instances, a need, late in the program, to cut weight at nearly any cost.

The second item is important in reflecting the attitude of the system designer. Generally, the systems designer considered that there were no significant gaps in knowledge of basic properties or fabrication procedures that inhibited the use of beryllium. This is not to indicate that the programs did not involve the gathering of large amounts of property data, and significant investments in developing final production techniques, but rather to illustrate that the initial decision to use beryllium did not depend on fine points or lack of a key piece of specific data.

The second group referred to earlier is characterized by a general reluctance to consider beryllium applications. In contrast with the successful beryllium users, this group operates in a framework which can be characterized roughly as follows:

- Little or no prior beryllium experience.
- Manned systems — multi-mission.
- Weight savings valued on the order of \$100's per lb. rather than \$1000's.
- A concern over technical feasibility
  - in part due to lack of key property data, design, and fabrication experience.
  - in part as a result of lack of knowledge on the true state-of-the-art.
  - in part a concern regarding reliability of the structure.

A recurrent concern, particularly among the manned aircraft segment of this second group, is the concern over beryllium's fracture toughness, crack resistance, low ductility, etc. In the military aircraft sphere, work has been performed on prototype primary and secondary structures (e.g., F4C vertical rudder). Beryllium is sometimes included in design trade-offs for advanced structures. These trade-off studies show beryllium to be competitive with and, in many cases, superior to filamentary composites. Despite this fact, the major part of R&D funding on advanced structures is directed toward filamentary composites — raising the question of whether or not beryllium is receiving R&D support commensurate with its potential.

Another indicator of the negative attitude toward beryllium vis-a-vis filamentary composites is evidenced in requests for proposals on advanced structural systems which generally reflect a permissive attitude toward consideration of filamentary composites, and an inhibiting influence toward the consideration of beryllium.

Committee contacts with commercial aircraft producers indicate that beryllium is frequently summarily rejected for consideration in structural applications because of "low ductility, brittleness, and high costs."

The Committee's observations, perhaps somewhat overstated for emphasis, are as follows:

1. Beryllium has been accepted and used in a variety of missile and spacecraft applications.
2. Beryllium tends to be avoided in military aircraft structural applications and rejected a priori in commercial aircraft applications.
3. The need for justifying the selection of beryllium for military aircraft tends to discourage consideration.
4. Design trade-off studies for advanced structures show beryllium to be at least competitive weight-wise with, and frequently superior to, filamentary composites due to its high modulus/density ratio.
5. Development studies on beryllium are inadequately funded relative to filamentary composites.
6. The chief impediment to more extensive beryllium usage in future military aircraft stems from lack of experience and lack of confidence due to low fracture toughness.
7. Beryllium lacks a high-level champion, in the sense used in the NMAB report on Research-Engineering Interaction ("an individual who becomes intensely interested and involved with the overall goals and who plays a dominant role...by the sheer force of his will and energy.").

It is well known that support for composites has been much greater than the amounts allocated for similar end-items to be made from beryllium. The bases for this attitude are:

1. The handicap beryllium has is low fracture toughness, particularly for bending loads on sheet metal structures that require plastic deformation or thinning in the thickness direction. It is not brittleness per se that gives beryllium the handicap. Most composites are similarly brittle if we define "brittle" as a material exhibiting low strain to failure or one "unable to plastically deform." Being, in some cases, tolerant to stress concentrations, composites do not have this handicap. Beryllium's handicap is that cracks, if formed, grow at great rate, despite measured relatively high-tensile elongation.
2. Because of their anisotropic capabilities, composites also offer the designer a large number of new options. He can, within wide limits, design for combinations of stiffness and strength in different directions. Isotropic metals do not provide these options.
3. Advanced composites promise significantly lower costs than beryllium when in volume production. Industry projections show them possibly cost-effective compared with titanium structures, and certainly lower in cost than monolithic beryllium.

Viewed broadly, it has been the considered judgment that composites form the "wave of the future." In comparison, beryllium offers the following possibilities:

1. There are specific applications (particularly those involving nuclear or thermal characteristics), and for some of which no additional R&D is needed, in which beryllium is a clearly better choice.

2. In applications where composites are now the preferred material, sufficient experience in fabrication and performance has not been obtained to be sure that some fatal flaws are not present. Should substitution be required, beryllium comprises a backup.

3. Hybrid or beryllium composite construction can result in a more efficient structure compared to boron or graphite composites. This results from beryllium being available in many shapes or forms capable of being used in hybrid construction, the avoidance of an "end fitting" problem, and the ability to resort to conventional fabrication techniques, contrasted to boron or graphite, which are available only in filament form, and which suffer a weight penalty at the point where the load is transferred to a metal structure.

It is very significant that past decisions to employ beryllium have not been disappointments. A record of no DoD system failure attributable to the use of beryllium is partially a reflection of the good judgment employed in deciding when to use it.

Future use of beryllium in military hardware will follow the same paths as past applications. That is to say, it will be used when the desired form, along with corresponding design information, is available at the same time the design decision is made, and when it appears that the high cost will be justified.

Applications for beryllium, together with the properties that are significant in that application, are shown in Table 1. A careful design analysis is needed to establish the relative importance and the absolute value of any property.

TABLE 1

BERYLLIUM APPLICATIONS / PROPERTIES MATRIX

	LOAD-STRAIN-DENSITY PROPERTIES																THERMAL-PHYSICAL PROPERTIES									SPECIAL PROPERTIES											NUCLEAR PROPERTIES		
CURRENT & POTENTIAL BERYLLIUM APPLICATIONS	DENSITY	MODULUS	MODULUS/DENSITY	STRENGTH/DENSITY room temperature	STRENGTH/DENSITY elevated temperature	ELONGATION room temperature	ELONGATION elevated temperature	FATIGUE room temperature	FATIGUE elevated temperatures	PRECISION ELASTIC LIMIT	PROPORTIONAL LIMIT	CREEP RESISTANCE	STRAIN RATE RESPONSE	BALLISTIC (IMPACT STRENGTH	FABRICABILITY elevated temperature	FRACTURE TOUGHNESS	SPECIFIC HEAT	THERMAL CONDUCTIVITY	ELECTRICAL CONDUCTIVITY	THERMAL SHOCK RESISTANCE	HIGH MELTING POINT	THERMAL EXPANSION COMPATIBILITY	DAMPING CHARACTERISTICS	HEAT OF COMBUSTION (Specific Impulse)	SUPERCONDUCTIVITY (Cryogenic Properties)	DIMENSIONAL STABILITY room temperature	DIMENSIONAL STABILITY hot cyclic	EROSION RESISTANCE elevated temperature	CORROSION RESISTANCE	OXIDATION RESISTANCE	HEAT OF FUSION	DIELECTRIC PROPERTIES	POISSON'S RATIO or G	DYNAMIC SPALL STRESS	SOUND VELOCITY	HUGONIOT DETERMINATION	NUCLEAR MODERATION	NUCLEAR REFLECTION	RADIATION PERMEABILITY
1. NUCLEAR																																							
Weapons components	●					●									●	●													●				●					●	
SNAP 27 & thermoelectric PPs	●					●										●		●				●					●			●									
Rover/Nerva/Phoebus reflectors	●															●		●		●		●					●											●	
SNAP Reflectors	●				●							●															●											●	
Radiator fins & condensors	●	●	●	●	●	●			●						●	●		●				●					●						●						
Meteoroid bumpers	●		●										●	●	●	●																		●	●	●			
x-ray windows					●				●									●												●									●
Test reactors																						●					●		●	●							●		
2. SPACE OPTICS																																							
Mirrors	●	●	●							●								●				●				●													
Cameras	●	●	●	●				●		●								●				●				●													
Telescopes	●	●	●	●		●				●					●			●				●	●			●													
Shutters	●	●	●	●				●		●			●	●								●				●	●												
High-speed rotating mirrors	●	●	●	●	●			●	●	●								●				●	●			●	●												
Lens cells	●	●	●							●								●				●				●													
Instrument housings	●	●	●	●		●		●		●		●			●		●	●				●	●			●	●												
3. INERTIAL-GUIDANCE & INSTRUMENTATION																																							
Gyros	●	●	●															●				●				●			●										
Accelerometers	●	●	●															●				●				●			●										
Gimbals	●	●	●	●		●		●										●				●	●			●													
Memory discs, printing drums	●	●	●							●							●	●				●	●			●													
Supporting structure	●	●	●	●		●		●		●	●				●			●				●	●			●													
Filters and reconnaissance sensing devices	●				●				●									●				●																	●
Airborne computers	●	●	●							●							●	●				●				●	●												
Electronic-box housings	●	●	●	●	●	●		●			●				●		●	●				●	●																
Electronic component decks	●	●	●	●	●	●							●				●	●		●		●							●										●
Antennas & supports	●	●	●	●	●	●		●		●	●	●	●		●			●				●	●			●	●					●							
Wave guides	●	●	●															●				●				●	●					●							
Sound pick-up arms	●	●	●							●								●				●	●			●													
Radiation emission tubes	●	●	●		●					●								●				●				●	●												●
4. MISSILE & SPACECRAFT STRUCTURE																																							
Interstages	●	●	●	●	●	●		●			●		●		●	●	●	●		●		●							●				●						●
Fuel-cell spacer elements	●																					●					●		●	●									
Solar-array structure	●	●	●	●		●		●			●	●			●	●		●					●										●						
Space shuttle structure, STS	●	●	●	●	●	●	●	●	●		●	●		●	●	●	●	●		●	●	●	●				●	●	●	●			●						
Satellite structure	●	●	●	●		●		●			●				●	●		●				●	●						●				●						
Fittings & fasteners	●	●	●	●	●	●	●	●			●		●		●	●		●				●							●				●						
Shingles	●	●	●	●	●	●							●		●	●	●	●			●							●	●	●			●						
ABM structures	●	●	●	●	●	●		●			●	●	●		●	●	●	●		●	●	●						●	●	●			●	●					●
5. AIRCRAFT STRUCTURE & SYSTEMS																																							
Rudders & elevons	●	●	●	●	●	●		●	●		●	●	●	●	●	●						●					●		●				●						
Reinforcing stiffeners	●	●	●	●	●	●		●	●		●	●			●	●						●					●		●				●						
Fittings & fasteners	●	●	●	●	●	●	●	●	●		●	●			●	●						●					●		●				●						
Structural elements																																							
Longerons	●	●	●	●	●	●		●	●		●	●			●	●						●					●		●				●						
Honeycomb core	●	●	●												●			●				●							●	●									●
Truss core	●	●	●	●	●	●		●	●		●	●		●	●	●		●				●					●		●	●			●						
Composites		●	●	●	●	●		●	●		●	●	●	●	●	●						●					●		●				●						
Brakes	●				●		●		●				●			●	●	●		●	●	●					●		●	●									
Doors	●	●	●	●	●	●		●	●		●	●		●	●	●						●						●				●						
Landing-gear parts	●	●	●	●	●	●		●			●				●	●						●						●				●						
Push-pull rods	●	●	●	●	●	●		●	●		●				●	●						●						●				●						
Torque tubes	●	●	●	●	●	●		●	●		●				●	●						●						●				●						
Truss structures	●	●	●	●	●	●		●	●		●	●			●	●		●				●	●			●	●		●	●			●						
Pumps	●	●	●	●		●		●			●					●		●				●					●		●				●						
Heat sinks	●																●	●			●								●	●									
Actuators	●	●	●	●	●	●		●	●		●	●			●	●						●						●				●						
6. PROPULSION																																							
Engine parts																																							
Blades	●	●	●	●	●	●	●	●	●		●	●	●	●	●	●		●		●		●	●				●	●	●	●			●						
Discs	●	●	●	●	●	●		●	●		●	●	●		●	●		●				●	●				●		●				●						
Shafts	●	●	●	●	●	●		●	●		●	●	●		●	●		●				●	●				●		●				●						
Cases	●	●	●	●	●	●		●	●		●	●			●	●		●				●	●				●		●				●						
Seals	●	●	●	●	●	●		●	●		●	●									●	●				●	●		●										
Rocket nozzles & components	●				●	●	●		●				●			●	●	●		●	●	●					●	●	●	●	●		●						
Propellants (solid & liquid)	●	●																					●							●								
7. MISCELLANEOUS																																							
High efficiency electrical systems (hot or cold)	●				●				●			●							●						●					●									
Machinery Components																																							
Brakes	●				●		●		●				●			●	●	●		●	●	●							●	●									
Clutches	●				●		●		●							●	●	●		●	●	●							●	●									
Shafts	●	●	●	●		●		●			●				●	●						●	●						●				●						

B. Production of Ore

Concern has been expressed in the past for the adequacy of ore to permit large-scale applications of beryllium. This concern had been based on the scale in which beryllium is mined. It is often found by lone prospectors in scattered pegmatites. Not only has there been no decline in the supply of beryl, but the discovery and exploitation of large, low-grade non-beryl (bertrandite) deposits have changed the picture. It is the present judgment that there is adequate domestic beryllium available for all foreseeable applications and that beryllium mineralization, quantity, or quality are not limiting factors in the use of beryllium.

At present, the U.S. beryllium industry consists of two firms: Brush Beryllium Company of Cleveland, Ohio, and Kawecki Berylco Industries, Inc. of Reading, Pennsylvania. The two firms have facilities for extracting beryllium oxide from ore and for converting the oxide to metal. General Astrometals Corporation was a third producer until February 1971, when it was taken over by Kawecki. General Astrometals prepared beryllium metal electrolytically from chloride prepared from the oxide. The powder metallurgy process is used extensively for consolidating metal powder into bulk products. These products are converted to useful parts by machining, extrusion, forging, rolling, etc., either by the two metal companies or by a host of metal fabricators.

There are two commercial beryllium minerals: beryl ($Be_3Al_2(SiO_3)_6$) and bertrandite ($H_2Be_4Si_2O_9$). Beryl is not commercially mined in the United States but is imported from various countries in Africa or South America. Bertrandite is mined and processed by the Brush Beryllium Company in Utah.

Two domestic firms have extensive holdings of bertrandite ore located in the Spor Mountain area of Utah. As late as September 1970, only

Brush Beryllium Company was commercially mining and processing its ore. The Anaconda Company, parent company of General Astrometals Corp., had not begun commercial operations. There are millions of tons of bertrandite ore known to exist in Utah, containing from 0.5% to 1.0% beryllium oxide. The exact extent of the deposits is unknown since it has not been necessary to define the full potential of the mineralization. Current definition indicates that the ore deposit is ample to supply the foreseeable future needs of beryllium metal. *

Capacity figures of the commercial producers for making beryllium metal are not publicly available.

C. Special Considerations in the Use of Beryllium

In addition to the raw material question, another consideration is the availability of metal of sufficient uniformity to enable designers to designate it with confidence. There have been continuing problems, parallel to those in the handling of other reactive metals, of consistent quality control of beryllium powder, ingots, and mill products. Of greater importance, in the case of beryllium, is the need for characterization, particularly to reflect the anisotropic nature of the material. Progress in coping with these problems has been reflected in the decreased scatter in properties and in more efficient structural employment. To some extent, the degree of future use of beryllium will depend on this continuing improvement in quality control and in characterization.

For most metals, the mechanical properties are much the same in any of three orthogonal directions and are essentially the same for all mill products. This is not true with respect to beryllium, the properties of which, in fact, more nearly parallel fiber composites. This dependence on directionality (and thus on fabrication) reflects the facts that strength, ductility, and propensity to

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* See reference on page 2.

brittle fracture are highly sensitive to crystallographic orientation. Intrinsic properties can be degraded by the presence of scratches, worked metal, twins, etc. There still are fabricators who consider that beryllium applications should be satisfied by the purchase of a standard mill product which will conform to the desired shape and manufacturing convenience, without recognizing the significance of the preferred orientation resulting from the metal shaping operations. It is particularly for these reasons that programs for advancing beryllium technology must be closely related to the end-product design.

The best cost-effective use of beryllium, indeed of most materials, is dependent upon the design of parts to exploit the advantages both of specific beryllium products and of fabrication methods that are most applicable to those parts. Two types of flat rolled products are available. The common type is of powder origin but considerable process development has been carried out on sheet of cast origin. The cast wrought sheet has much lower strength and lower room temperature elongation but it is more weldable and is somewhat more formable at elevated temperature. At present KBI is the only commercial supplier of cast wrought sheet. Brush has stated that they have no plans for developing cast wrought sheet and prefers to concentrate on production of powder sheet. Commercial availability to the designer of both kinds of material is important in fostering the lowest cost end-product.

Specific methods of producing starting materials, as well as methods of processing, have very important bearings on cost-effective utilization of beryllium. Thus, for some intended applications, isostatic pressing or spark sintering can be more than competitive with pressed block. Lower cost methods of producing wire could be significant in stimulating the use of beryllium in fibrous composites. Substantial innovative work has been done developing cost-effective fabrication procedures using electrochemical and electrical discharge machining methods. Production parts are currently being fabricated by these methods.

The feasibility of shear forming both wrought ingot and hot-pressed block has been demonstrated. Reductions in thickness of eighty percent have been achieved on both wrought ingot and hot-pressed block with an accompanying improvement in properties. Improved forging and extrusion methods have been developed.

A common feature regarding all the above fabrication processes is that too few designers and materials engineers are aware of their potential.

For maximum effectiveness in reducing the cost of beryllium parts, these parts must be designed while considering simultaneously the details of processing. Pertinent facts must be available if such consideration is to be possible. Availability of the required information is dependent upon the emphasis given by the individual companies in providing materials and processing information to their design staffs, upon the efforts of beryllium producers and fabricators in technically documenting their capabilities, and upon the government in disseminating information regarding beryllium technology.

D. Communications/Information Problems in Using Beryllium

This topic was recognized as sufficiently important to be considered separately by a Panel (named on page v). This Panel identified four areas of concern.

1. Costs - Occasionally beryllium is not selected for an application because the contractors are unable to satisfy DoD requirements for a reasonably accurate estimate of costs. Both material costs and fabrication costs are uncertain. This is a major problem identified by the group.

2. Design - Much of the information that is needed by designers has not been assembled into a single source reference. The lack of a credible, comprehensive, and readily available compilation covering materials data and design methodology increases the risk-taking in the materials selection phase of preliminary design, and has resulted in the elimination of beryllium for consideration where risk-taking is not contractually encouraged. The preliminary design groups of most organizations try to be objective in estimating the worthiness of beryllium in structures. Some individuals, however, develop a sensitivity to the brittleness of beryllium that disallows objective assessments. Furthermore, top management will sometimes reject beryllium when, in their possibly unjustified estimate, the risk in reliability is too great.

3. Processing - One of the deterrents to the employment of beryllium is the lack of specific experience in processing the material. In many cases, the usual conservative approach to estimating fabricability (where little experience is available) minimizes risk-taking and forces beryllium structures out of consideration. Successful beryllium users maintain that the processing of the metal is not significantly different

from that of other materials. However, there is risk involved when a company opts for a beryllium structure, which might be reduced by the availability of a credible document which summarizes available manufacturing experience.

4. Mechanisms for the Distribution of Information - As in any technology, there is difficulty in keeping abreast of up-to-date developments. The available literature surveys, critical reviews, etc., that contribute to the awareness of the state-of-the art, are insufficient in the case of beryllium. Many potential users of beryllium have been discouraged because of the learning time required to become proficient. In materials selection procedures, questions arise regarding the suitability of beryllium which require almost immediate answers; ready access to information is the determining factor.

Concluding Remarks

Successful activities to assist other new materials should be paralleled in this field also. For example, the preparation of a processing guide would provide needed information on costs of unit operations (turning, milling, drilling, etc.). A processing guide for composites, under study by the Air Force, may provide a model. Similarly, the Air Force composites design guide will display the procedures and implementation techniques also usable for beryllium. Although there are differences of opinion as to what coverage is desired, an impressive unanimity of opinion exists in the aerospace industry as to the value and desirability of credible design and processing handbooks.

Handbooks alone are insufficient. The most useful adjunct are information centers. The Defense Metals Information Center (DMIC) at Battelle, Columbus, includes beryllium as one of many materials that it covers. Services available at DMIC range from the preparation of critical reviews of literature to "hand holding" (providing immediate answers to specific detailed questions) via telephone.

The types of services available were judged to be appropriate. However, it appeared that industry-wide knowledge, particularly of the extent of information center services, was incomplete; therefore better publicizing of the available services was warranted. It also appeared that additional personnel are needed in these centers to develop the in-depth beryllium expertise felt to be required in an information center.

Another desirable approach is the preparation of readily readable documents which distill case histories and present information on successful applications, with all the attendant qualifications and limitations. An example of this was the March 1970 NMAB Beryllium Symposium. *

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* Proceedings of the Beryllium Conference, Vol. I, NAS-NAE No. NMAB 272, Vol. II (S(FRD)), No. NMAB 273, Washington, D.C., July 1970.

E. Problems Facing DoD Contractors in the Future Use of Beryllium

The disturbing aspects of beryllium as a future material of construction are: (1) the quality and forms may not be available when needed because of a lost production capability, (2) design/fabrication/facility capacity will not be sustained in the aerospace industry, and (3) some additional property data, fabrication expertise, and confidence are needed to take full advantage of the potential of beryllium.

1. Production

We can anticipate for the near future a decreasing market for beryllium* This stems from the decrease in military spending combined with a reluctance to use relatively unproven materials. If this were to occur, it would have the effect of limiting the available product mix and probably lengthening the delivery times.

The availability of needed forms is critical, for without assurance of quality and of delivery, another solution to the materials problem will be found, but at the cost of degraded performance. It is to assure the availability of beryllium, if and when a determination has been made that it is the optimum choice, that government support is needed now.

2. Research

Theoretical and applied research on beryllium have indicated the futility of further extensive studies to purify or alloy the beryllium in order to achieve an intrinsically ductile and tough material. There are likely to be incremental improvements in metallurgy and in designing to accommodate brittle materials. Similarly, the refinement of processes and controls to tailor the metal for specific applications can be expected to

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* This was written before the absorption of General Astrometals by Kawecki Berylco Industries, Inc.

continue. However, it is clear that in the absence of novel ideas (which are not now evident), successful exploitation of beryllium is a function of development, not research.

There are three areas that overlap research and development where support is justified at this time. Each area relates not to any one specific system but affects several projected applications. Notable recent developments in composites comprising, for example, beryllium wires in a titanium matrix make this an area of considerable promise. As further discussed, beginning on page 75, beryllium is the only known "ductile" high-modulus, high-strength, low-density reinforcement material available for composite construction. Its plasticity at elevated temperatures makes it possible to fabricate composites by "conventional" metal-working techniques. Research studies of beryllium-metal matrix compatibility are required and laboratory development and structural testing of the many possible hybrid configurations should be initiated.

Two other areas relate to an important application, that of heat shields. Usual current design practice, utilizing the excellent heat capacity and heat transfer characteristics of beryllium, permits the heat shield to retain its shape (and thus its aerodynamic stability), in contrast to ablative designs that change in smoothness and in geometrical shape during flight. However, if the performance capability is expanded, at the cost of localized surface melting, it might be possible to achieve substantial performance improvement with a tolerable amount of shape change. Analytical and laboratory investigations, followed by flight tests, could establish if greater design latitude can be employed. Additional details of possible performance improvements are included in the classified supplement to this report.

3. Development

The principal shortcomings lie in the area of development. Too often beryllium will appear to be the material of choice, based on parametric studies, but is not selected because of factors such as a lack of basis for estimating cost, technical risk, capability of making nondestructive assessments of fitness for use, fabrication difficulties, etc. The exclusion is not so much due to excessive cost, or risk, etc. as it is to uncertainties. Here is an area where the Department of Defense should take the lead. The major conclusion of the Committee is that the government should fund development programs which would invigorate design teams, generate property data, and extend fabrication competence, to provide design teams the option of using beryllium where it evolves as the material of choice.

Prototype programs should develop answers to the questions that arise when systems utilization decisions have to be made. Production cost and reliability are usually the most important questions.

a. Subsidiary to these questions are issues such as:

1. Material specifications
2. Process specifications
3. NDT procedures (in-plant and in the field)
4. Repair procedures
5. Field modification procedures
6. Projected future material cost
7. Anticipated scrap rates in production

Within the limits and timing, each prototype program should address itself to these issues and, in addition, should recommend high payoff areas for additional development, if appropriate. Programs that do not accomplish the above become mere feasibility programs.

b. Property determinations that might be called for in order to design the prototype structure could include:

Fracture toughness*
High loading rate response
Biaxial yield strain criteria
Strain to failure variability

Deficiencies for which work should be undertaken to correct:

Sensitivity to test procedures
Property variability (sheet-to-sheet or lot-to-lot)
Performance of joints
Joint tolerance control
Joint residual stresses
Inspection techniques

It will be seen from the above paragraphs that some of the needed information could best be generated by the design and construction of hardware. Other kinds of information—principally property determinations and fabrication development— could preferably be obtained by specific small contracts. Information derived from prototype contracts and from small scale studies involving fabrication development and property determinations are needed and should be obtained simultaneously.

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* An ASTM committee on fracture testing is active in this area.

Prototype programs should have two principal objectives:

a. The derivation of cost and feasibility data, where these are not available, for operations involved in the fabrication of hardware. These would include forming and joining steps, inspection methods, and newly evolved procedures whose utility has not been established (such as plasma spraying and spot diffusion bonding). The kinds of information needed in this part of the program include acoustic fatigue and thermal fatigue of panels, corrosion resistance, critical crack size determinations, and measurements of high strain rate behavior. A model for a portion of this program is the Navy BuAer contract (NOw64-0456-c) with the McDonnell Aircraft Company relating to molybdenum. This overall program could be called an "Element" study in which the unit processes of fabrication and design are studied and costed.

b. The fabrication and test of a full-scale prototype. It is important that the design and fabrication of a prototype structure should relate to a real, ongoing system. Only in this way can design optimization make sense. Of the ongoing systems, one should be chosen that is at a stage in which the final design is not fixed. The B-1 bomber qualifies, but beryllium is less apt to be cost-effective here than in missile structures.

Another reason for choosing a program in an early stage is the opportunity presented to make a major advance in design. For example, such past major beryllium programs as the Minuteman interstage involved an all-beryllium structure. A prototype program, without schedule pressures and with the acceptability of some technical risks, provides the occasion to explore, as one option, hybrid structures, which offer the promise of 55 - 75% of the weight reduction of an all-beryllium structure at about 1/3 the all-beryllium cost. More than the design can be innovative. Relatively untested fabrication methods can be employed, new NDT methods can be used and their findings confirmed by subsequent examinations.

While the Committee was asked to look specifically at beryllium, the members recognized that prototype programs need not concentrate exclusively on a single material. Other developmental materials could also be incorporated. Alternatively, a case can be made for an "Advanced Materials Prototype Development Program" in which new titanium alloys, refractory metals, and structural ceramics could be introduced, each at the appropriate time, by the construction of the type of structure for which each is best fitted.

4. Proposed Prototype Program

Several large-scale applications using the specialized properties of beryllium have been successfully accomplished, e.g., the Minuteman spacer, (rolled ring forging), the Agena equipment section panels (sheet) and re-entry vehicle heat shields (block). A number of small scale applications of beryllium have also been quite successful, such as, precision gyroscopes for inertial guidance systems, mirrors for satellite telescopes, small heat sink rocket motor nozzles, torque tubes, solar array panel structure, and specialized satellite structures. Additionally, a number of developmental structural programs have successfully designed and tested individual beryllium structures, such as, the F-4 rudder, a typical wing box structure, honeycomb panels, and cylindrical equipment structures for missiles. However, no large cylindrical structures in the 70-to 100-inch diameter range have been built or tested which would represent the next generation missile structural concepts. Nor have concepts been adequately explored which consider using beryllium to reinforce traditional structures, attempting to realize significant weight savings at a fraction of the cost of an all-beryllium structure. The term "monolithic" has been employed to designate all-beryllium construction, and "hybrid" to describe designs utilizing beryllium combined with other materials, but not necessarily in the form of fibrous composites. It is apparent that no major reduction in material costs due to high volume usage can be anticipated in the near term. However, it is believed that fabrication and testing of a large-scale prototype beryllium structure could clearly demonstrate both feasibility and significant cost reductions over past beryllium concepts, thus removing one of the traditional fears associated with design, fabrication, and usage of such a structure.

It is pertinent to call attention to the recent findings of the NMAB Ad Hoc Committee on Hardening of Materials for Advanced Ballistic Missile Defense Systems. The Committee recommended the need for attention to non-destructive evaluation, fabrication, development of joint design, and failure studies. The objective of the indicated activity would be to obtain production cost data and upgrade material preparation processes and procurement specifications in order to assure ductility and uniformity.

F. Description of Needed Programs

Both the construction of prototypes and the determination of properties and fabrication characteristics have the same ultimate objectives—providing the background to enable contractors to specify it where its use provides an advantage. Since the two general programs could be handled by different organizations, they are described in turn.

Prototype Program

The design of a structure is the first important aspect. While the prototype structure might evolve as all-beryllium, certainly attention should be given to hybrid structures (which, in the extreme, could resemble the fibrous composites which are beryllium's chief competitor). Attention has been focused recently on integrating beryllium into a basically non-beryllium structure so as to gain a major portion of the advantages of beryllium at a relatively small cost. Some simple examples are the use in the F-14 aircraft of beryllium straps to stiffen an aluminum bulkhead (which supports a radar antenna), and consideration in the design of the C-5A of the use of beryllium sheet to stiffen engine support pylons. More elegant design solutions can be forecast when the problems are approached early (are not a "fix" to cope with an emergency), when more is known about the material behavior, and when a degree of technical risk can be tolerated. Another aspect of hybrid construction is that consideration can be given to not only the load-bearing concern of design, but also the thermal and possibly ablative aspects. This is especially pertinent in the recommended structure—a shell, such as for use in a re-entry vehicle.

Actual construction is the next step in the learning process. Here the proposed fabrication techniques are proven out, the acceptability of the raw material established, and the cost, time, and unexpected problems determined.

Testing of the structure will establish the adequacy of the design, particularly with regard to joints, especially those between beryllium and other materials. Any shortcomings of the interfacing of the beryllium-containing structure and the rest of the vehicle should be disclosed at this time. If tested to destruction, which is recommended, a correlation with NDT indications and actual performance would be possible. If a number of units are constructed, flight testing of some, to enhance confidence in the product, is desirable.

Finally, to capitalize on the effort and to disseminate the findings, detailed analysis, partly in the form of process specifications, should be required.

Such a program could conceivably be handled by a beryllium producer, by an aerospace contractor, or by a government laboratory. This Committee strongly endorses the idea of a collaborative effort between a government office which will be needing a high-performance unit and a contractor who ultimately might be one to build such a unit in production. Conflicting considerations of cost, desired vehicle performance, fabrication problems, etc. can best be balanced in this manner.

The major tasks, together with cost estimates, for a two-phase program, such as for a hybrid beryllium structure, are shown in Table 2 below.

TABLE 2

Estimated Cost Breakdown of a Beryllium Prototype Program

(Cost will be affected by size, shape, and complexity)

PHASE I (12 months)	
Analytical Techniques and Methodology	
Design Alternatives, Weight and Cost Comparisons	
Component Design, Analysis, Fabrication and Test	
Process Development, Standards and Specifications	
PHASE I Total Cost	$ 550,000
PHASE II (12 months)	
Prototype Design and Analysis	
Prototype Fabrication	
Prototype Test	
Elevated Temperature Investigation and Test	
Evaluation of Test Results and Comparison with Analysis	
Process Development Formulations and Design Rules	
Establish and Publish Design Criteria	
Final Documentation	
PHASE II Total Cost	$ 955,000
Phase I and II, Total Cost......................	$ 1,505,000

Alternate Prototype Structures: As previously mentioned, a shell characteristic of possible advanced missile structures, is the recommended choice of a prototype. Alternate candidates are discussed in three categories: missile (in addition to the recommended shell discussed previously), space, and aircraft. Naturally, costs would vary widely, as affected by size, complexity, risk, etc.

Missiles

The internal configuration of the aft end of an experimental missile is complicated. Construction by machining from a block would be possible, but excessively expensive. This portion of the vehicle could comprise an excellent "test-bed" for exploring a variety of methods of construction. Brazing of subassemblies, plasma spraying onto a mandrel, electroforming, and forging are examples of possible techniques. The objectives would be to establish technical feasibility and risk, and relative costs.

A structure, usable in the missiles field as well as other areas, is a spherical shape. For such a simple configuration we should be able to predict both the mode of failure and the stress level at failure. Simple shapes like this are susceptible to precise analysis. Fabrication involved would be forming and joining of hemispheres. If failure occurs as predicted, it will prove that we know how to design and fabricate beryllium.

Space

a. Tubular truss: A design could be patterned after the NASA Skylab, in which a large tubular truss (now made of aluminum tubes) supports a telescope mount. The principal concern would be the design of end fittings, since the weight of the end fittings could approximate the weight of tubes. One way to minimize end-fitting weight is to taper the tubes, but alternate means should be considered. Tubes made from rolled sheet and by plasma spraying as well as by extrusion could be included in the program.

b. Thermal protection system panels: Both the design and fabrication of panels present difficulties. Alternate designs and fabrication practices could be evaluated for cost and practicality. Some aspects to be evaluated include design of panel, design of attachments, structural close-out problems, use of panels as primary structure, acoustical fatigue response, and inspectability.

c. Miscellaneous: Booms, extendable structures, antenna structures, mirror mounts, and solar array framing are all possible candidates for prototype studies.

Aircraft

a. Structural heat shields: At 1000°F, representative of upper body soak temperatures for lift re-entry aerospace vehicles, use of other light-weight metallics becomes questionable unless additional thermal protection systems are incorporated at the expense of structural weight. Competitive configurations should be evaluated under simulated loading conditions, including cyclic thermal and mechanical loads. Attainment of creep data in the appropriate temperature range will be necessary and joining and attachment techniques must be developed and evaluated.

b. F-4 tail cone shingles: While not primary load-carrying members, these panels operate in a high-temperature vibration environment and would contribute useful data on response of beryllium structures under these conditions. These shingles are subjected continuously to the engine jet wake during flight with resulting temperatures of approximately 500°F and sound pressure levels up to 162 decibels. Because of this combined loading environment and the limited definition of actual loads, flight testing of selected configurations is recommended after simulated ground tests of competitive design. Preliminary analysis indicates a weight reduction from 64 pounds for the production titanium component to 43 pounds for the component fabricated of beryllium. While these shingles provide an opportunity to evaluate the multi-mission elevated temperature response of beryllium structures, the high acoustic fatigue environment places additional importance upon joining and attachment techniques. Creep and elevated temperature fatigue data will be required, both on mill products and on finished components.

c. F-4 rudder: Using the experience and technology attained in previous programs a second generation beryllium rudder configuration should be designed and evaluated both in ground and in flight tests. The design should emphasize economy of construction without sacrificing structural integrity. Inspection, installation, maintenance and repair procedures should be defined such that field operational units can conduct flight test evaluation of a number of these rudders with a minimum of outside assistance. It is recommended that twenty-five beryllium rudders be constructed for ground and flight test evaluation, including one each for static test, fatigue test, acoustic fatigue test, damage tolerance evaluation, and flight test by the contractor on a flight-test aircraft. The remaining twenty would be installed on operational aircraft for field evaluation.

d. Aircraft outer wing section: Both the F-4 and A-7 could serve as test-beds for evaluating the integrity and performance of highly loaded primary beryllium structure with a minimum of modification to the aircraft since both outer wing sections are hinged, thus facilitating interchangeability with production components. Six components are recommended for evaluation including one each for static test, dynamic test, acoustic fatigue test, and damage tolerance evaluation, plus two (one left and one right) sections for demonstration of flight-worthiness on a flight-test aircraft. A further option should be provided for fabrication and flight test evaluation of an additional twelve sections (6 sets) on operational aircraft. A preliminary analysis indicates a weight reduction of 24.9% for the F-4 outer wing (from 305 pounds to 229 pounds per set).

Element Program: Areas of investigation should include material development as well as solution of the fabrication problems associated with large-scale structures. Increased ductility in the short transverse direction would minimize associated design and fabrication problems. Therefore, good leads toward this end should be followed up. New developments, such as plasma spray and spark sintering used to provide structural articles, either as-formed or as starting shapes for further rolling, forging, etc., should be pursued and demonstration hardware should be produced. Corrosion-resistant surface treatments should be investigated for those applications where storage in a marine invironment is common. Load transfer methods other than mechanical fasteners, such as diffusion bonding, should be evaluated.

Two other activities would also be encompassed: determination of design data and documentation of recommended processing procedures. Beryllium's brittleness and anisotropy in certain product forms pose unique design limitations and opportunities. Part of the design problem is a knowledge of necessary mechanical properties relating to appropriate metal forms. We now lack some design data (creep, for example) on existing materials. New forms, e.g., ingot metal, call for the determination of much test data.

Because of the variety of tasks to be undertaken it is recommended that a primary contract be awarded to a group such as one of the large not-for-profit research organizations, that would subcontract and coordinate individual tasks. A program of this type could range widely in content, but could attempt reasonable coverage of essential tasks for about $500,000 - $750,000.

Such applied development could be closely coordinated with the prototype work, or alternatively, some such activity, could be carried on independently. It would be mistaken to divorce all such development from the prototype contract, as this would force the prototype contractor to use only proven methods.

VI TOXICITY COMMENTS

The Committee was constantly aware of the toxicity of beryllium and was concerned that all procedures should be performed with absolute minimum risk to the health of all personnel involved. However, since there were no industrial hygiene experts on the Committee, a draft of this report was forwarded to the National Academy of Sciences' Advisory Center on Toxicology for review concerning this important aspect. The Committee is informed that statements in this report are not in conflict with the best available information in the industrial hygiene field. The NAS Committee on Toxicology recommends that the government should protect itself by requiring an application-by-application review for health hazards.

Hazards which were not considered by the Committee concern alterations and disposal of material containing beryllium. Uninformed personnel may unwittingly come in contact with beryllium dust or fumes during maintenance or salvage (such as the melting down of a largely aluminum structure). It is understood that the producing industry has adopted a uniform labeling practice for their mill products. Serious consideration should be given by the Services to appropriate precautionary labeling of those materials for which the application review has indicated the possibility of inadvertent exposures.

The precautions and medical requirements adhered to by present manufacturers and producers of beryllium support the conclusion that toxicity has not been a deterrent to the many successful applications, as is borne out by the cases described later in this report, and in the recent Beryllium Conference of March 1970*. The rather simple techniques used for processing beryllium safely are summarized in the book edited by Herbert E. Stockinger, Beryllium: Its Industrial Hygiene Aspects, New York, Academic Press, 1966.

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*Proceedings of the Beryllium Conference, (Vol I), NAS-NAE Pub. No. NMAB-272, (Vol II), (S-FRD), NAS-NAE Pub. No. NMAB-273, Washington, D.C., July 1970.

PART II

PRESENT APPLICATIONS

The following summaries discuss each of the important generic applications. More detailed descriptions of specific applications are contained in NMAB-272, Proceedings of the Beryllium Conference, July 1970, 655 pp, and NMAB-273 (S(FRD)), July 1970, 82 pp. Particular attention is called to one of the outstanding applications of beryllium, described at that Conference. "The Use of Beryllium in Large Spacecraft Structural Assemblies," by Richard J. Switz, described beryllium usage in a 1600-pound, 25-ft-tall satellite. This is a major type of application not covered in the accounts which follow.

BERYLLIUM STRUCTURES IN MISSILE APPLICATIONS

INTRODUCTION

This section describes two successful applications of beryllium as a primary structure in missile applications. The vehicles involved are the Agena D Spacecraft which employs beryllium as a forward rack structure, and the Minuteman missile which utilizes beryllium as a spacer structure between the re-entry vehicle and missile guidance section. In both cases, the prime motive for replacing conventional materials with beryllium was to achieve vital weight reductions. Figure 1 provides an abbreviated description of both structures, together with some data on weight savings, repetitive production costs, and development spans. Although many common problems existed in each application, the designs are sufficiently distinct to warrant the separate discussions which follow.

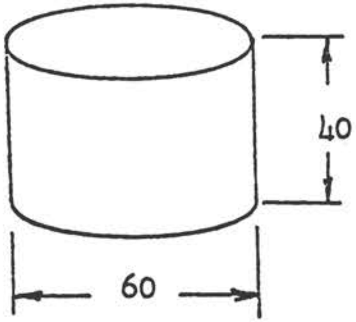
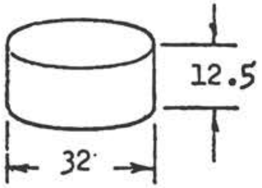
AGENA D FORWARD RACK

Description of Structure

The forward rack of the Agena D structure consists of the forward 40 inches of the 60-inch-diameter spacecraft. The structural shell of the rack carries axial and bending loads occurring during ascent flight. Detailed weight reduction studies made in August 1962, by the Lockheed Missiles and Space Co. (LMSC) led to a decision to replace the curved magnesium skin on the forward rack structure with cross-rolled beryllium sheet, while retaining the existing magnesium substructure.

The finished structure consists of nine fixed and nine removable beryllium panels which are attached to the existing magnesium alloy ring and

FIGURE 1 AGENA D AND MINUTEMAN BERYLLIUM APPLICATIONS

	AGENA D FORWARD RACK	MINUTEMAN SPACER
DIMENSIONS		
DESCRIPTION	9 FIXED PANELS & 9 REMOVABLE DOORS ATTACHED TO MAGNESIUM ALLOY RING AND LONGERON SUB-STRUCTURE WITH TITANIUM ALLOY FASTENERS	RING-ROLLED FORGED SHELL WITH FOUR HOT-FORMED SHEET LONGERONS ADHESIVELY BONDED AND RIVETED TO THE SHELL.
WEIGHT COMPARED WITH PRIOR MATERIAL	36 vs. 56 lb. 36% reduction	10.2 vs 33.5 lb. 70% reduction
REPETITIVE PRODUCTION COST ($/FINAL LB)	$360	(NOT AVAILABLE)
DEVELOPMENT TIME (GO-AHEAD-FIRST PRODUCTION UNIT)	8 months	1 year

longeron substructure with approximately 1300 titanium alloy fasteners. Removable panels are selectively chem-milled to further reduce their weight. The set of beryllium panels weighs about 36 pounds, and results in a 20-pound weight savings (36%) compared to replaced HM 21A-T8 panels.

Key Design Problems

The two major design problems associated with the structure involved the developing of an adequate joint design and fastener selection, and determining the allowable buckling load capability of the curved panels.

Joint design was somewhat complicated by the decision to use the existing magnesium substructure. This dictated the fastener edge distance in both the beryllium panels and the magnesium substructure. It also led to a simple lap joint with a single row of fasteners which naturally resulted in a substantial load eccentricity. After comprehensive investigation of various types of fasteners, a #10 titanium alloy screw, with nut plates on the magnesium substructure, was selected.

The critical design condition for the panels was axial compression load causing elastic buckling instability. The critical buckling stresses were experimentally determined using 23 panels representing several fabrication methods. These data confirmed the analytically predicted buckling load capability established during standard structural analysis procedures.

Production Experience

The entire program involved extremely close liaison between design, engineering, production process control and testing organizations, and in addition, relied heavily on the experience and capability of the beryllium sheet producers. An important factor in the program was the use of the beryllium sheet producers to form the first ten sets of panels with LMSC observation and participation while the LMSC production facility was being developed and brought into production.

One of the key in-house problems was the development of a manufacturing process to form the curved panels. A variety of methods were tried and discarded, with a creep forming procedure, using a closed die approach, ultimately being selected to simultaneously form and stress relieve the panels.

In addition to the above, significant improvements in tornetic hole drilling, cutting, routing, and chem-milling of sheet beryllium were developed and applied to production of thousands of panels.

In the production phase, panels are built in lots of 17 sets with a scrap rate of essentially zero since it is common to see over 500 panels successively fabricated without rejects. Repetitive production costs are estimated at $360 per pound of finished beryllium structure of which direct raw material cost was approximately $180 to $190 per pound of starting stock sheet. At this point in time, approximately 4,000 beryllium forward rack panels have been fabricated.

MINUTEMAN SPACER

Description of Structure

The beryllium spacer for the Minuteman missile attaches the re-entry vehicle to the missile guidance section. It contains the separation mechanism that releases the re-entry vehicle at the appropriate point in the trajectory. Since the Minuteman missile is launched from a silo, the beryllium spacer must withstand the collapse pressure loads generated within the silo due to the confined exhaust gases. Subsequently, the spacer must accept the powered flight aerodynamic and inertial loads, arising from the re-entry vehicle, that are introduced as concentrated loads from the attachment points to the vehicle. The structure is a riveted and bonded assembly made up of a beryllium ring-rolled outer shell, containing beryllium sheet longerons, five access covers, ground handling provisions and miscellaneous hardware.

The beryllium spacer design was developed and qualified by AVCO in 1963 as a means of reducing the structural weight to provide either greater missile payload or increased range. In the previously used aluminum spacer design, the structure, plus the required heat shield material, weighed 33.5 pounds. The original beryllium spacer design was very light in terms of beryllium structural weight, but a heat shield was required to control the temperature of the highly stressed structure. On the second and subsequent designs, the superior heat sink properties of beryllium were used and the heat shield eliminated by increasing the beryllium wall thickness by 0.040 inches. The weight of the final beryllium structure was 10.2 pounds and provided reduced overall weight and cost, and improved the design assurance. The spacer is 32 inches in diameter by 12.5-inches long, and is chem-milled to provide integrally thickened rings at both ends, integrally thickened pads at the longerons, and a minimum wall thickness of 0.080 inches. Five access openings with structural doors, provisions for ground handling fixture attachment and a differential thermal expansion joint at the aft end complete the spacer structure.

Design and Production Experience

Due to the paucity of beryllium design allowable data and beryllium fabrication experience at the inception of the program, extensive material testing and fabrication process development were conducted. Joint allowables and buckling criteria were established, and the basic material mechanical and physical properties were characterized for temperatures up to 1,000°F. In setting up the production program, which was the first of its kind, much attention was given to specifications and quality assurance procedures. Because the ring-rolling process for beryllium had never been used in production, there was concern about the consistency of material properties. It was early established, and still continued, that each shell is tested by both the producer, Brush Beryllium Co., and the fabricator, AVCO. The formed sheet longeron design was controversial; therefore each longeron is proof tested at design ultimate load for three minutes and periodically a longeron is cut into tensile bars to check for property degradation from the hot-forming operation.

The evolution of the formed sheet longeron and its attachment to the shell were major activities during the program and represent a case history of changes made (and risks accepted) to improve producibility. System constraints dictated the use of a hat-section to contain the separation mechanism, with a bulkhead at the forward end to react to the concentrated point load from the re-entry vehicle. The first design used a hat-section of formed beryllium sheet with a zinc-brazed block beryllium bulkhead. The second design split the hat-section into two Z-sections to reduce brazing problems and to make it easier to consistently obtain a good fit between the curved longeron flanges and the interior surface of the shell. Forming, machining, and brazing problems persisted, so the third development design consisted of one-piece longerons machined from hot-pressed block beryllium. Although these tested satisfactorily, they were heavier, and predicted production costs were higher than the formed sheet design. The fourth design, which became the final production design, was a two-piece hot-formed sheet concept even though the overall yield in making development sheet longerons was less than 10%.
It was assumed that production tooling and additional experience would provide consistent quality and a low scrap rate. After many problems were overcome this proved to be the case. The longeron assembly is then riveted and adhesive bonded to the shell. The rivets take the load when the temperature rise degrades the adhesive.

An important aspect of the total price of a beryllium assembly is the economics of production fabrication operations. After the production of several hundred assemblies, the longerons are still an important source of scrap since only about 75% of the blanks formed end up in finished assemblies. Of the ring-rolling blanks that have been prepared, 87% have been shipped as assemblies; most of those lost being scrapped in the ring-rolling operation before a large amount of labor had been expended.

The program involved production of about 700 spacers with an overall scrap rate of approximately 15% during the final stages of production. Production involved 340 man hours per spacer, on the average.

SUMMARY

The experience gained on the Agena and Minuteman programs, coupled with subsequent beryllium structural applications, indicates that additional missile, spacecraft, and ultimately, aircraft structure applications can be confidently undertaken whenever the payoff for beryllium warrants its selection.

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F-4 BERYLLIUM RUDDERS

Two F-4 beryllium rudders have been designed, fabricated, and tested under simulated and actual flight conditions to extend the structural information base and demonstrate the capability of this material to carry complex loads in a multi-mission aircraft environment. Retaining the aerodynamic envelope, attachment configuration, and design load requirements of the production aluminum rudders to achieve interchangeability, ground test and flight test beryllium rudders have been constructed with respective weight savings of 41% and 34% over aluminum rudders while torsional stiffness increased 500%.

The beryllium rudders retained the same two-cell torque box design of the production rudders, for comparison purposes, and to demonstrate that a variety of typical structural configurations can be reliably produced of this material. The designs for both materials use adhesively bonded skin-faced honeycomb core with edging members in the aft torque boxes and mechanically fastened conventional multirib-skin-spar construction in the forward torque box. Within these conceptual generalities the beryllium rudder was redesigned, as shown in Fig. 2, to take advantage of the light weight and high stiffness of this material. In addition to weight saved directly by replacing aluminum with the lighter beryllium, the number of ribs was reduced, a flutter damper was eliminated and balance weights were lightened to effect a weight reduction from 64.26 pounds for the production aluminum rudder to 37.59 pounds for the ground test beryllium rudder. Slight modification of the beryllium flight test rudder, including modification of the leading edge skin splice to eliminate interference with the aerodynamic seal, addition of a corrosion protection system, installation of flight test instrumentation, and an increase in balance

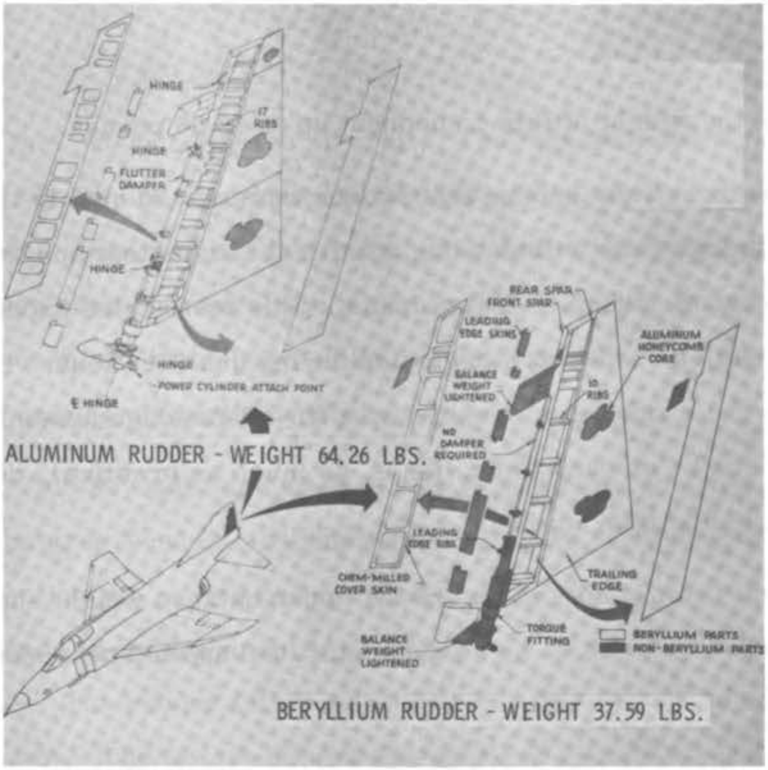

Figure 2. F-4 Rudder Structural Configurations.

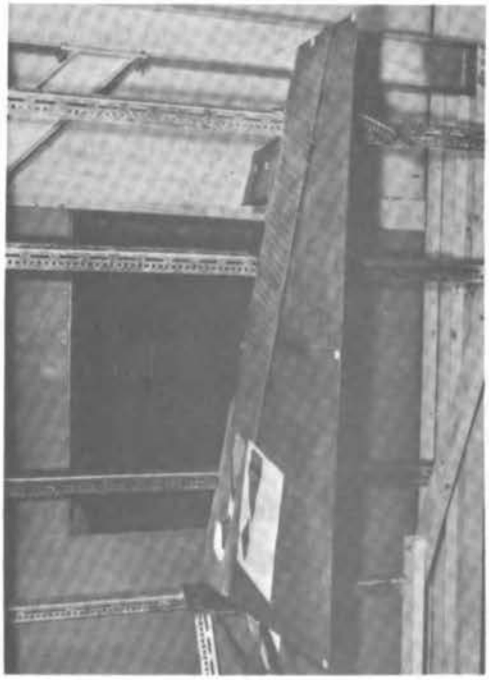

Figure 3. Beryllium Rudder Mounted in Acoustic Fatigue Test Stand.

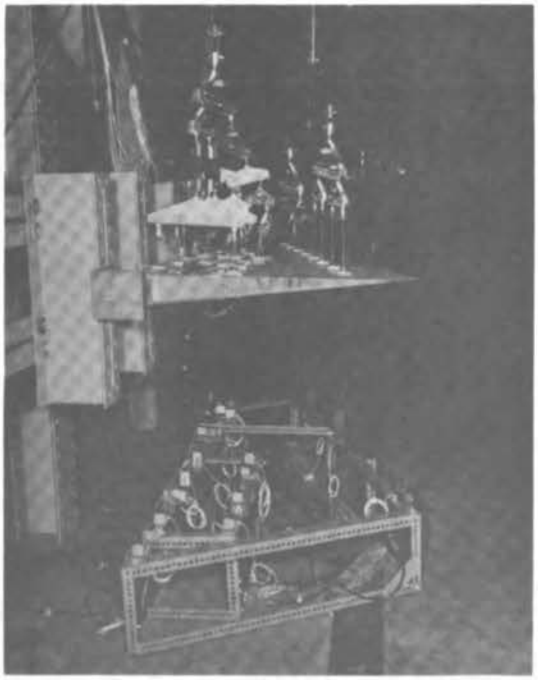

Figure 4. Beryllium Rudder Mounted for Residual Strength Test.

weight brought the weight of this component up to 42.06 pounds.

The beryllium ground test rudder was used to qualify the design for flight test by successfully withstanding a critical fatigue test and three static tests to, and beyond, ultimate design loads. This test series exceeded that to which the production rudder was subjected during qualifications. For this series of tests the rudder was mounted on a fin-aft fuselage assembly at McDonnell Aircraft Company to duplicate, as much as practical, design load conditions, including interactions.

Test 1 was a fatigue test of the upper balance weight support structure consisting of 50,000 cycles of ±40 g's inertial load applied perpendicular to the symmetry plane of the aircraft.

Test 2 was an ultimate static test representing a yaw maneuver in which the rudder was subjected to 150% of the maximum anticipated airload with center of pressure at 30% chord producing the maximum torque.

Test 3 was an ultimate static test in which the rudder and fin were subjected to 150% of maximum total load on the vertical tail simulating the rolling pullout maneuver, producing the maximum vertical tail bending and shear in the rudder.

Test 4 was a repeat of Test 2 with loads increased to 250% design limit load (167% of ultimate). This test did produce a crack in the lower closure rib but loads did not drop off and rudder appeared otherwise sound. This test on the production aluminum rudder was terminated at 225% DLL.

Following the flight qualification series, the rudder was mounted as shown in Figure 3 in the AF Flight Dynamics Laboratory Wide Band Test Facility and subjected to a high-intensity noise field with a test spectrum as similar as possible to that produced by the aircraft. The test included 12 hours at 150 dB, 10 hours at 153 dB and 45 minutes at 156 dB. When the total number of loading conditions was taken into consideration, this total acoustic test time is equivalent to about seven normal lives of the rudder. The resulting damage to the left side skin can be seen in Figure 3. Similar damage was done to the right side skin with the connecting rib virtually destroyed.

This severely damaged rudder was next mounted in a fixed jig in the AFFDL Structures Test Facility as shown in Figure 4 for a residual strength test representing the rolling pullout maneuver similar to Test 3, which produces maximum loads in the forward torque box skins, front spar, hinges, and hinge back-up ribs. The rudder failed after approximately 15 seconds at 200% DLL (133% ultimate). The failure apparently began at the crack previously created in the lower closure rib, continued through the heavily damaged lower section of the forward torque box, and ended at the leading edge just above the lower hinge attachment fitting. The ability of the beryllium rudder to support 200% DLL after such extensive testing, and in a severely damaged condition, certainly indicates the adequacy of the design and fabrication techniques used in the production of this aircraft experimental structural component.

Following flight test qualification of the original F-4 beryllium rudder, a second one was fabricated for flight test. The two were essentially the same except for modifications as previously noted. This beryllium rudder was installed on a bailed YF-4E flight test aircraft with the maiden flight occurring from Lambert St. Louis Municipal Airport on 14 May 1968, see Figure 5. No flight restrictions had been placed on the aircraft because of the beryllium rudder, rather the aircraft performed maneuvers to impose maximum loads on the rudder and data were recorded to measure the structural response. During one such rolling pullout maneuver at about the tenth hour of flight the aircraft became roll-yaw coupled resulting in an inadvertent 720° roll before the pilot regained

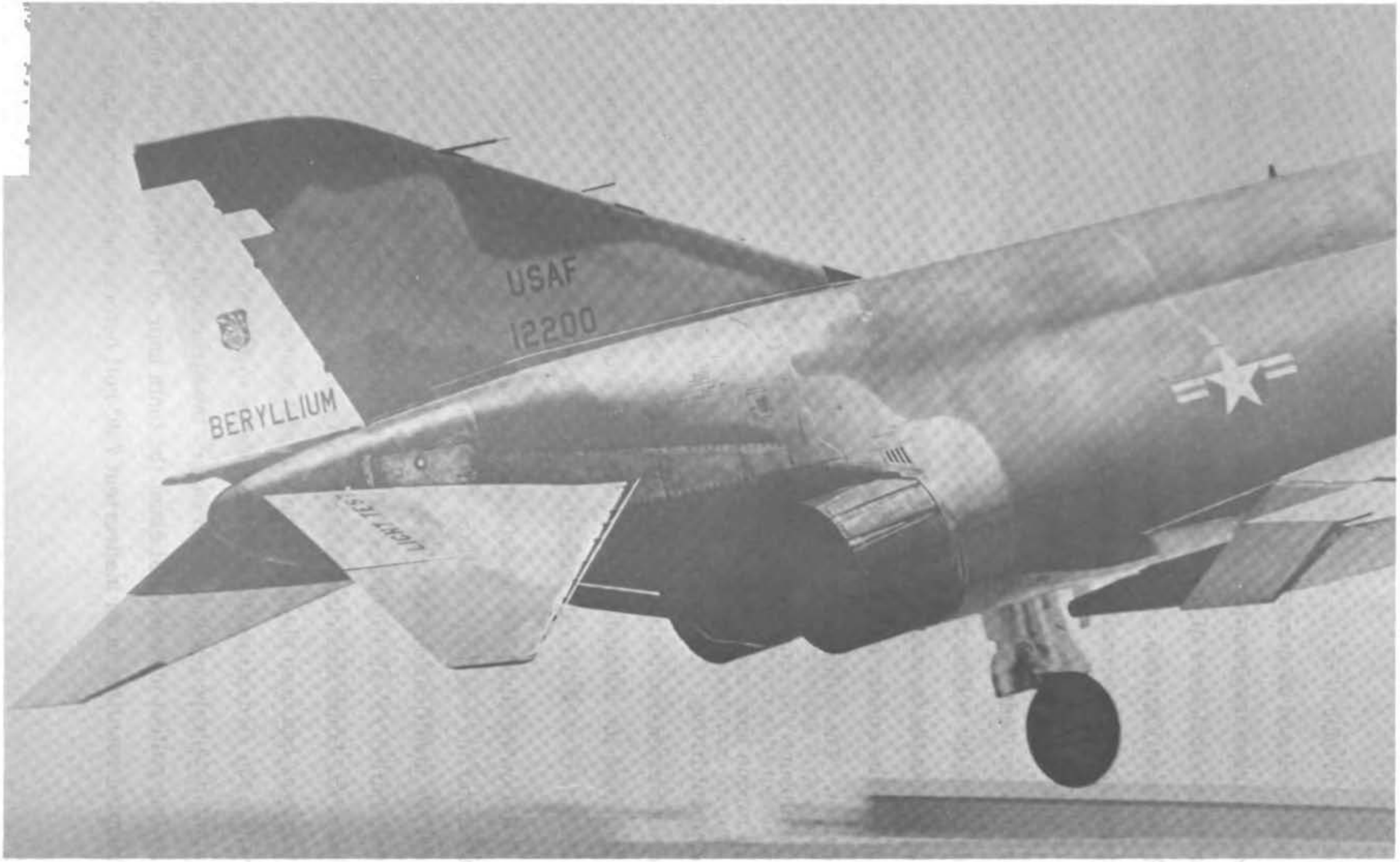

Figure 5. Flight Test of F-4 Beryllium Rudder.

control. The rudder loads exceeded design ultimate for this condition, the recorded data indicating loads estimated at 205% DLL. As a result, a permanent buckle was induced in one of the beryllium rudder cover skins. Inspection of the rudder and aircraft revealed no other damage and flight testing continued. Visual, dye penetrant, and radiographic inspections have produced no evidence of further damage except some paint flaking, a scratch in the paint but not the beryllium, and a slight debond at the lower closure rib. Through June 30 1971, the beryllium rudder has participated in a total of 151 flights, for a total flight time of 176 hours and 48 minutes, including operations from MacDill AFB, Florida, and Puerto Rico.

While the flight history of the F-4 beryllium rudder is not extensive in terms of design life of such aircraft, it does illustrate that primary load-carrying aircraft structures can be fabricated of beryllium. Experience is also being gained in handling beryllium structures under multi-mission operating conditions in a variety of atmospheric environments.

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BERYLLIUM APPLICATIONS IN GUIDANCE SYSTEMS

Superiority of Beryllium

During the past decade, beryllium, beryllium alloys, space and ceramic components containing beryllium have had steadily increasing usage in guidance hardware. Beryllium materials are most widely used in the manufacture of inertial quality gyros in both floated integrating and two degrees of freedom applications. The basis for beryllium's superiority in guidance applications stems primarily from its high modulus of elasticity since the floated assemblies of inertial quality gyros are characterized by the use of stable materials and designed for extreme rigidity.

The stiffness to weight ratio, defined as the modulus of elasticity over density, is of the order of 63×10^7 for beryllium compared with 10×10^7 for aluminum and titanium. Related to this is another factor which is of importance in instrument design, the precision elastic limit (PEL). This is a measure of the stress needed to deform the material permanently and is as high as 8000 psi for beryllium. Secondary advantages for beryllium stem from its high thermal conductivity and the fact that its thermal expansion coefficient closely matches that of irons and steels used in motors and ball bearings. Both thermal characteristics are important factors in gyro design since uniform expansion is required to minimize errors. In gyros using ball bearings the similarity of the thermal coefficients for steel and beryllium, contrasted with the dissimilarity of those for steel and aluminum, has proven of considerable value.

The overall benefit to be derived from beryllium in gyro design is perhaps best seen in the fact that, given a certain size and weight for the instrument, the use of beryllium wherever possible will allow the weight saved to be concentrated in the wheel rim, thus roughly doubling its angular momentum.

Thus, for a given disturbance torque, the gyro will drift at only half the rate it would have drifted if beryllium had not been used.

Current examples of commercially available gyros utilizing beryllium floats are the Kearfott King and Alpha gyros and the Honeywell MIG series, and it is estimated that 90% of all high quality gyros use it in one form or other.

Recent studies of a modern lightweight high accuracy guidance platform indicate that the use of beryllium in place of aluminum results in weight savings of approximately 10% (two out of twenty pounds).

In summary, beryllium is the primary material for inertial quality guidance systems primarily because of its high modulus of elasticity, low density, good thermal conductivity and system-compatible coefficient of thermal expansion.

Projected Volume

As indicated earlier, the majority of inertial quality gyros utilize beryllium for support gimbals and will continue to do so in the future. In the case of inertial quality gyros, accuracy requirements lead to the selection of beryllium because of its stiffness. At the same time, the intrinsically high unit cost of the gyro (typically $25,000) overshadows the cost of incorporating beryllium in the design. In at least one application, the Mk 25 gyro used on the Polaris missile, a cost analysis has shown that the cost of using beryllium (approximately $600) is not significantly higher than if aluminum had been used if the cost for heat treatment required by the latter is also considered.

At present it is estimated that beryllium usage in guidance systems for missile, space, and aircraft applications amounts to roughly 25,000 lbs per year. Future needs are in part dependent upon defense expenditures, but it is reasonable to expect only moderate changes in this utilization in the next five years. The projected demand, using even the most optimistic estimates, is easily within the beryllium industry's capacity.

Alternate Materials

Despite the widespread use of beryllium, other materials have also been employed in gimbal assemblies. Foremost among the alternative materials is stabilized 2024 aluminum. This material sees most frequent use in the lower-cost systems (in the \$4000-\$6000 range) and it is not anticpated that beryllium would supplant its usage in these applications, where the highest level of performance is not required.

Threats to Beryllium Usage

A review of beryllium guidance applications in missiles indicates that its attractiveness is in no way threatened by toxicity, reliability or availability considerations. For example, missile applications lead to severe vibration and shock environment conditions associated with solid propellant motor burning and stage separation, yet beryllium components have been used with safety in Minuteman, Polaris, and Poseidon guidance systems. Similarly, toxicity and safety considerations have not prevented use of beryllium in commercial aircraft guidance systems.

BERYLLIUM BRAKE DISKS

Beryllium brake disks are being used successfully on the Lockheed/ Air Force C-5A aircraft. Beryllium has been qualified for brakes for the Grumman/Navy F-14 and the S-3A aircraft. Flight evaluation has been made of beryllium brakes on the F-4, A3D, and A-6 aircraft.

Beryllium brake disks are used primarily to save weight. However, some important secondary advantages are: (1) cooler operating brakes, resulting in improved tire life and hydraulic systems, (2) improved life of the friction material, and (3) smoother operating brakes. Beryllium brakes result in a 35% to 50% weight savings, compared with steel brakes, for heavy military and commercial aircraft. For fighter-type aircraft, the weight saving is approximately 50%. The total brake weight, including the beryllium, friction material, and miscellaneous steel hardware, is about 80 to 120 pounds for heavy military and commercial aircraft. The weight of the beryllium ranges between 30 and 50% of the total weight. Beryllium brakes for fighter-type aircraft weigh between 40 to 60 pounds, and the beryllium content is about 50% of this weight.

Beryllium results in significant weight savings in brake disks because of the material's high specific heat and low density. Other properties desired of brake disk materials (which aircraft brake-grade beryllium possesses) are: (1) high elongation at elevated temperature, (2) good fatigue life, (3) high-thermal conductivity, (4) good dimensional stability, and (5) resistance to thermal shock cracking.

In order to be cost effective, beryllium brake disks must have a capability for being refurbished. It is anticipated that the full circle disks, such as the C-5A design, can be refurbished several times before they are scrapped. Some of the new beryllium disk designs which utilize segments will be very cost effective, since the segments will have a relatively long lifetime.

In competition to beryllium, considerable effort has been made to develop graphite and carbon brake disks. Molded type graphite is used in special segmented and capsulated designs, which do not impose any stresses in the graphite; i.e., the graphite acts only as a heat sink. Steel components are used in this type of design to make the disk a structural member. Reinforced carbon brakes are being studied as full circle disks. In this case, the carbon is used as a structural member as well as a friction surface. The specific heat of graphite and of carbon is about one-half the specific heat of beryllium, and the density of these materials is about 80% of beryllium. Therefore, for the same heat sink volume and braking condition, the temperature rise in the graphite and carbon brake would be about two and one-half times greater than the temperature rise in beryllium brakes. This, coupled with the extreme brittleness of the graphite/carbon materials, is the greatest deterrent to their usage as brake disk materials. The segmented or capsulated graphite brake will not result in significant weight savings because the steel structural members of the disk cannot be operated at temperatures high enough to take full advantage of the graphite heat sink. The full circle carbon brake must be operated at extremely high temperatures to be weight competitive with beryllium. This is undesirable for several reasons, including reduced tire life and hydraulic system problems.

Based on the success of the C-5A application and the recent high interest in lightweight brakes, it is anticipated that many of the future high performance military and many of the commercial aircraft will fly with beryllium brakes. The greatest deterrent to the use of beryllium brakes is lack of service experience. However, this experience is coming quickly from the C-5A program because of the large number of brakes used on each airplane. The toxicity situation is no longer considered a drawback, since the vast number of measurements made have shown that the use of beryllium brakes will not present any health hazards, even under extremely adverse operating conditions.

SPACE AND TEST REACTORS

In nuclear applications, with the exception of the weapons field, beryllium is being used to satisfy compelling needs in space propulsion reactors and in various test and research reactors. Significant quantities of beryllium have been and continue to be used as neutron reflector blocks in the nuclear rocket engines being developed under the NERVA Program. The properties that qualify beryllium for this application are its good neutron reflecting characteristics and low density. In the last four years approximately 12,500 pounds of hot-pressed beryllium have been purchased for this application. Beryllium has been used in several other space nuclear systems but the amount of material used and the potential for increased future use are low.

The use of beryllium in test and research reactors satisfies a less compelling need and has required less material than the space nuclear system applications. The major reactors which have beryllium reflectors include: the Materials Test Reactor, Engineering Test Reactor, Advance Test Reactor, High Flux Isotope Reactor, and the NASA Plumbrook Reactor. The limited amounts of beryllium used in these reactors and the low rate at which these reactors are built indicate that the future demands for beryllium for this application will be low.

X-RAY WINDOWS

One of the first major uses for beryllium was that of X-ray windows. It still is an important application today. The physical properties of the metal rather than its mechanical properties are of major concern. Beryllium permits nearly complete penetration and passage of X-rays with negligible absorption. Since structures involving X-ray windows require a vacuum environment, all metals associated with the structure must be brazable or weldable to insure vacuum tightness. To date, beryllium is the only metal that is completely satisfactory in its X-ray transparency, vacuum tightness, and brazability characteristics. The metal is employed in the form of discs or arcs varying in size from $\frac{1}{2}$-inch diameter to 4-inch diameter, and from 0.001 inch to 0.1 inch in thickness. It is guaranteed vacuum tight to 0.005-inch thick, and must be pin-hole free and light tight to 0.001-inch thick. Further, it must be inclusion free below 0.010 inch, with no inclusions that would interfere with X-ray transmission in metal thickness above 0.010 inch. The metal is occasionally coupled with nuclear devices where high X-ray transmission is desired as well as a low neutron cross section.

About one percent of total dollar sales for the beryllium industry is involved in X-ray window applications. However, the weight of metal consumed for this use is probably less than 0.1 percent of the total weight of beryllium used for all purposes.

HIGH-PERFORMANCE, LIGHTWEIGHT OPTICAL MIRRORS

In high-performance spaceborne optical systems an important requirement is usually that the mirror surface be considered diffraction-limited. Diffraction-limited performance generally signifies that the mirror surface is within $\lambda/40 - \lambda/50$ RMS (λ = wavelength) of its design geometry and this surface must remain within this limit over its expected service life and range of environmental conditions. In order to achieve the desired performance an "ideal" mirror material should have the following characteristics:

(a) Low weight - In addition to minimizing the weight of the system, lightweight mirrors are necessary to overcome inertial and/or gravitational forces. Weight reductions can be achieved by using low-density materials, or lightweight designs, or combinations of both.

(b) High-elastic modulus - In large diameter mirrors, the problem of change of surface figure due to self-weight deflection has been recognized. Deflections are reduced by increasing the thickness, with a resultant increase in weight. Optimum designs can be obtained by low-density, high-modulus materials and/or removing material from the back side of the mirror creating cellular (egg crate), arch-like, etc. configurations.

(c) Low-thermal coefficient of expansion - A very low value of this property will aid in reducing the possibility of the mirror figure deforming under temperature changes both in a localized scale (due to inhomogeneities) and over the entire surface. For materials with higher values the gross change in dimensions can be compensated for in the design of the system; however, the possibilities of localized deformation is increased.

(d) High-thermal conductivity- High-thermal conductivity is necessary to prevent warping by permitting the mirror to come to thermal equilibrium quickly both in service and during grinding.

(e) High-thermal diffusivity - This parameter determines the lifetime of a thermal transient. Rapid dissipation of localized heating is necessary for a satisfactory mirror.

(f) Strength - Although in service there are no significant stresses imposed on the mirror, the material must have a micro yield limit sufficient to prevent yielding during handling and under stresses imposed during launch.

(g) Dimensionally stable - Once generated, the mirror must retain its figure within specified tolerances during all phases of its operation. The three forms of dimensional stability that are considered applicable to mirrors are:

1. Thermal-dimensional stability - The stability of mirror figure over the range of service temperatures.
2. Temporal-dimensional stability - The stability of the mirror figure over its predicted life.
3. Thermal-cycling stability - The stability of the mirror figure after repeated cycling between the extremes of service temperatures.

(h) Polishability - The mirror material must be polishable to the desired mirror figure and be a receptive host to one or more types of special purpose optical coatings.

(i) Available in sufficiently large sizes - The most desirable mirror is of one-piece construction. Lack of adequate raw material sizes would necessitate the manufacture of large mirror structures by joining together smaller component parts. This would affect technical and cost aspects.

The list of materials that have been evaluated for mirrors includes fused silica, low expanding dielectrics such as CER-VIT (product of Owens-

-Illinois) and ULE (product of Corning Glass Works), beryllium, silicon, TZM, beryllium oxide, aluminum, and others. Of these materials the leading candidates in terms of potential availability, stability, and polishability are beryllium, CER-VIT, and ULE. CER-VIT and ULE are very attractive because of their very low thermal coefficients of expansion and excellent dimensional stability. A major disadvantage is their high density and low modulus/density ratio as compared to beryllium.

The two major concerns in the use of beryllium for mirrors are its (a) dimensional stability, and (b) availability in large sizes. During the investigation of beryllium for precision mirrors it was found that commercial hot-pressed beryllium was dimensionally unstable. The main cause of instability was the anisotropy of thermal expansion due to preferred orientation. This affects the thermal and thermal-cycle stability. In addition, residual stresses that developed from prior manufacturing and fabrication processes cause the figure to change during thermal-cycling and over extended periods of time. Once these stresses are relieved by etching away the damaged material or by annealing, the thermal behavior reverts to elastic deformations.

It has been determined that isostatic methods for producing thermally stable beryllium mirror blanks are superior to commercial hot-pressing. The methods evaluated were hot isostatic pressing and cold hydrostatically pressed followed by pressureless sintering. To further improve randomness of grain orientation with the isostatic methods, a current procedure is to recycle the powder several times through the initial compaction stage, each time breaking up the compact and sieving it out in larger agglomerate sizes. This reattritioning method of powder processing further improves the thermal stability of beryllium products.

A major problem, if the need for large beryllium mirrors should arise, is the lack of large isostatic pressing facilities to make a monolithic mirror. In an attempt to overcome this situation a preliminary investigation of joining of blanks by diffusion bonding and brazing has been made with the intent of subsequently using a mosaic-type construction for large mirrors.

In summarizing the materials criteria, there is no single material which is outstanding in all categories. Therefore, in the choice of a mirror material expected to perform over a range of temperatures, compromises must be made among weight, stiffness, thermal performances, and allied characteristics.

A survey of the optical industry and of government users of optics led to the conclusion that there is a current market for beryllium optics of about 500 to 1500 units per year, averaging 25 lb each. Indications are that the amount will be more likely to fall with time than to rise. The types of systems involved include balloon-borne optical or X-ray telescopes, infrared system scanners, and laser optics.

Another application, not optical but requiring similar properties and manufacturing, is magnetic discs for computer systems.

BERYLLIUM THRUST CHAMBERS

Beryllium has been investigated for application in thrust chambers for high-performance attitude control engines in space vehicles which are subjected to extended firing durations. These thrust chambers must be capable of reliable performance under a wide range of duty cycles such as on-and-off operation, hot and cold starts, and steady-state firing.

The properties of beryllium which make it attractive for thrust chambers are low density, high heat capacity, relatively high melting point, and high thermal conductivity. Rocketdyne Division, North American Rockwell Corporation, has been a prime investigator of beryllium for thrust chambers. Under company-funded independent research and development (IR&D) programs and Air Force and NASA sponsorship, Rocketdyne has built and tested beryllium thrust chambers at the 5-pound to 1000-pound thrust level. The thrust chambers were tested either as heat-sink material or using the Rocketdyne Interegen cooling technique when higher performance was desired. Most thrust chambers have been manufactured from hot-pressed block. Isostatic pressing, followed by pressureless sintering, has shown promising results with regard to material properties and projected cost savings. Using this method thrust chambers have been successfully fabricated and tested.

Current production hardware are the RS-14 and RS-2 thrust chambers that are used on the Post Boost Propulsion System for Minuteman III and Mariner '71, respectively. The rough machined shape for the RS-14 weighs on the order of fifteen pounds. In future space vehicles, where the trend is toward increased performance at minimum weight, beryllium thrust chambers will receive greater attention for the various types of attitude control engines.

Typically, thrust chambers of this class have been constructed of ablative materials; where these thrust chambers have operated successfully, they do have limitations in duration capability and flexibility of mode of operation. In some instances, refractory metal, radiation-cooled configurations have been used. Other materials investigated included refractories and high-temperature alloys. These materials are not as attractive as beryllium because of their greater density, high fabrication costs, and requirements for oxidation-resistant coatings. Further, since they are cooled by radiation, they cannot be used in a buried installation or where heat-sensitive components are located near the thrust chamber. These limitations are overcome with the Rocketdyne Interegen cooled beryllium thrust chambers which do not rely on radiant heat transfer to the environment for cooling.

The sizes of future thrust chambers envisioned, where beryllium could be considered, are such that they can be machined from available hot pressings. Machining the chambers from hot-pressed block is presently the most economical route. For large production runs, savings in machining costs probably could be realized by utilizing techniques such as cold isostatic pressing, followed by pressureless sintering, for making pressings closer to final shape. In order to attain optimum designs of beryllium thrust chambers and possibly extend operation to higher thrust levels and higher chamber pressures, it is necessary to improve the consistency of both room and elevated temperature mechanical properties from billet to billet and within a billet, for parts machined from large pressings, and from compact to compact and within a compact for isostatic pressings.

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BERYLLIUM ELECTRONIC COMPONENT HEAT-SINK APPLICATIONS

In many cases, beryllium is an extremely attractive material for use as electronic component heat sinks, particularly when a structural function is also involved. Its relatively low weight, small volume, high-thermal capacity, and excellent dimensional stability will frequently more than compensate for the high material and machining costs.

The properties that make beryllium desirable as a structural heat sink are:

- High-yield strength/weight ratio - approximately 1.4 times that of aluminum (6061-T6).
- High-stiffness (modulus)/weight ratio - 6 times that of aluminum.
- Good thermal conductivity - comparable to that of aluminum.
- High-thermal capacity - specific heat is twice that of aluminum.
- Nonconductive oxides - an oxide layer can be formed to provide electrical isolation between electronic components and the heat sink.
- Dimension stability - Thermal expansion is half that of aluminum.
- High-temperature strength - Although not required for normal electronic heat-sink applications, any applications requiring good strength properties above 400°F could probably benefit by using this material.
- Vibration response - Inherent stiffness and adequate fatigue properties make this material attractive for use when vibration is encountered.

The disadvantages in using beryllium are:

- High material cost - Hot-pressed block is approximately 100 times as costly as aluminum.
- Higher fabrication costs - Beryllium machining requires a special facility with provisions for controlling the toxic fumes and dust from the material, and it also requires the use of machine tools that are rigid and abrasion resistant. For structural use, beryllium requires a post-machine etch. The net result of all these factors is somewhat higher machining costs than for common aluminum alloys. A newer technique, electro-chemical machining, is a lower-cost approach to beryllium machining provided there is sufficient production quantity to pay off the high cost of ECM tooling.
- Brittleness - The low strain-to-failure value of hot-pressed block normally is compensated for by the higher stiffness of the material and by use of low-strain designs; further, conventional surface etching normally minimizes any stress-riser effects from random surface flaws. Nevertheless, beryllium is still limited to use in designs where high elongation is not a requirement.
- Forming - Beryllium powder-origin sheet will take modest amounts of forming but must be heated to 1350°F to achieve even these modest amounts. On the other hand, aluminum has good formability at room temperature.
- Joining - Beryllium heat sinks are conventionally joined by brazing, adhesive bonding, and mechanical fastening. While these techniques are reliable and well documented, they require more care and are therefore more expensive than aluminum joining.

- Conductivity - Electrical conductivity (per unit volume) is comparable to that of 6061 or other higher-strength aluminum alloys. Certain high conductivity grades of aluminum (EC and 5005) can provide 25 to 50 percent higher conductivity but at a proportionate decrease in mechanical properties.

On balance, electronic component heat sinks do not constitute a compelling application for beryllium in the sense that no other material will suffice, but there are instances where contract incentive provisions lead to the advantageous use of beryllium despite the high material and fabrication costs. An application of this type occurred in the Poseidon Flight Control Electronics Package where approximately 30 pounds of electronic modules and interconnects were mounted to a 7-pound aluminum plate. This plate provided structural support for the main package (including mounting interface) and thermal cooling by means of water circulation tubing cast into the aluminum plate. This plate was redesigned to utilize beryllium. A weight saving of approximately 3.5 pounds was achieved with no loss in thermal properties and with an increase in both rigidity and strength. Additional weight saving (approximately 1 pound) and size reduction could have been realized if the original design had been made with beryllium.

Beryllium cold plate is fabricated from hot-pressed block. Channels for water tubing and cavities to form a ribbed structure are now produced by conventional milling; however, tooling is being developed to utilize electrochemical milling (ECM) techniques. Stainless steel tubing is zinc-brazed into the channels, and final machining, drilling, and tapping of holes is performed to complete the product.

The cost of this part was tripled by using beryllium, but this cost increase was more than offset by increased missile range. Long-range costs for production units are expected to decrease, but present forecasts indicate that, at best, the cost will still be double that of the aluminum plate. Nonetheless, the range incentive is sufficiently high to justify the use of beryllium in this application.

In summary, the use of beryllium as an electronic component heat sink is strongly influenced by the application, and the incentives attached to weight reductions. For many missile and space applications, higher development and production costs associated with beryllium are easily offset by weight reduction profit incentives. It is difficult to estimate the volume of beryllium in current and future electronic heat-sink applications, but it is clear that even the most optimistic estimates represent a small fraction of the beryllium industry's capacity.

COMPOSITE BERYLLIUM-TITANIUM BLADING

Background

Modern jet engines, steam turbines, aircraft, propellers, etc. use titanium as the major blading material because of its high strength, excellent toughness, and good erosion and corrosion resistance. The major shortcoming of titanium is its relatively low modulus of elasticity which greatly limits the rigidity of the blades and necessitates design compromises. Some designs utilize a mechanical device or "bumper" which appears as a projection of the airfoil surface. These "bumpers" are designed to affix each blade to its neighbors in order to minimize bending and increase torsional stability. Other designs utilize an outer shroud to prevent bending of the long blades. The use of these mechanical devices adds greatly to the weight of the equipment and causes a loss of efficiency due to the restriction of air flow.

In an effort to eliminate external mechanical devices, recent work has been directed toward increasing the modulus of elasticity of titanium by reinforcing it with a high modulus material.

Composite Development

A truly useful composite for most structural applications must have the following characteristics:

1. Low density
2. High strength
3. High modulus of elasticity
4. Good impact and erosion resistance
5. Adequate ductility for deformation after fabrication

The above requirements are obvious with the possible exception of No. 5. The reason for this requirement is that most manufacturing operations require a final bending of a structure for fit up, or, for example, the twisting of an aircraft compressor blade for tuning. In addition, this ductility is required for redistribution of stresses in complex parts. The lack of ductility has proved to be a serious limitation in boron-aluminum, boron-epoxy, and carbon-epoxy type composites.

In order to have the above-listed characteristics, a ductile reinforcement is necessary. To date, the only known ductile high modulus of elasticity, high-strength, low-density reinforcement material is the metal beryllium. High-strength ductile beryllium wire has been developed and is presently in commercial production. It is presently being used as a reinforcement in a beryllium wire aluminum or titanium matrix high-strength ductile composites.

At present there are various studies of metal matrix composites which include boron, graphite, silicon carbide, and beryllium as reinforcing material. These studies have shown beryllium wire composites to be superior to other metal matrix composites employing brittle filaments. In comparison to these brittle filament composites, the beryllium composite is more resistant to foreign object damage and, in a blade configuration, has the capacity to bend plastically when hit without "snapping off." In addition, the ductility of the beryllium allows fabrication procedures to be employed which could not be considered for less ductile composite systems. The procedures being used allow fabrication by diffusion bonding alternate layers of thin titanium or aluminum foil and beryllium wire "mat" sections into a solid structure. The term "mat" refers to an evenly spaced array of reinforcing wires held by an organic binder in the form of a thin (one-filament diameter) sheet. This process has been highly successful. However, the present high cost of beryllium wire limits its use. Recent developments leading to a method to produce low cost solid and hollow compressor and fan blades look promising. These procedures do not utilize high cost wire and foil. The processes involve co-extrusion of beryllium rods in a titanium block into a composite rectangular bar. The extrusion is cut to the desired length and is then directly forged into a blade form or is rolled into a composite sheet, which is subsequently diffusion bonded into a hollow blade. These low cost processes are in their early development phase but could result in greatly reduced cost of metal matrix composites. In addition, the resulting composite is reinforced by beryllium ribbons which greatly increase the transverse properties, making cross-plys unnecessary. The use of beryllium as a reinforcement is unique, in that composites can be fabricated by rather conventional metallurgical processes, making it possible to control the shape of the reinforcement in addition to reducing fabrication costs.

The beryllium-wire reinforced titanium approach, developed by Allison, has resulted in the successful manufacture of a prototype TF41 third stage compressor blade. This composite blade is unique in that the beryllium reinforcement enables the fabrication of a hollow air-foil design resulting in a blade that is 50% lighter than the present monolithic titanium blade.

Recent impact failures of composite blades, such as the epoxy-boron variety, have resulted in new emphasis on impact resistance testing. In an effort to apply quantitative values to impact resistance of composite materials directly applicable to fan and compressor blading, the Detroit Diesel Allison Division of General Motors has developed a static load (dead weight) ballistic impact test. This test revealed that beryllium reinforced titanium composites (50 Vol % Be wire) have superior impact resistance to all competitive composites. Table 3 presents a greatly condensed listing of average test results of specimens which were comparable in thickness and geometry.

TABLE 3

Combined Load Ballistic Impact Test

Material	Static Stress	Impact Load for Complete Failure
Be/Ti	50,000 psi	24.6 ft. lbs.
BSiC/Ti	50,000 psi	12.0 ft. lbs.
B/Al	40,000 psi	1.5 ft. lbs.
Carbon/Epoxy	20,000 psi	0.23 ft. lbs.

In conclusion, beryllium reinforced titanium composites have the potential of producing composite fan and compressor blades that have a unique combination of properties (erosion and impact resistance, low cost, high specific torsional stability, etc.), and which are superior to all competitive materials.

Unlike the other examples, this potential application is in the planning stage. It is included here as an instance where both performance gains and cost savings may be achievable through the use of beryllium.

POSSIBLE BERYLLIUM USAGE IN THE PROPOSED SPACE SHUTTLE ORBITER VEHICLE

Introduction

The importance of weight of reusable space vehicles becomes immediately obvious when it is realized that, for a two-stage system, the addition of one pound of orbiter weight increases the total system weight by approximately 30 pounds. Conversely, the deletion of one pound of inert orbiter weight results in increased payload capability, or improved mission growth potential. Success or failure in achieving weight savings is dependent on the proper selection of structural concepts, functional arrangements, and materials. Of these, the use of unconventional materials seems to promise the most rewarding response to the technological challenges of these weight-saving studies. This approach, however, can significantly influence the cost through additional manufacturing feasibility studies and development costs, but in the long run may well provide a hardware payoff.

Working against the achievement of economy and the desired weight saving, however, are the reliability requirements imposed by the fact that the vehicle is, in fact, a manned airplane. This fact will dictate a conservative design and appropriate (and expensive) qualifying tests, such as are described in the section describing the F-4 rudder.

Basis for Weight Savings with Beryllium

Whenever weight-saving studies are made for typical aerospace structures, the weight-savings potential of beryllium, in comparison with the usual light structural alloys, often proves outstanding and even better than the prominent fiber-reinforced composites. Comparisons of the basic material properties considered in the analysis of compression or stability critical structures are shown in Table 4 for beryllium and other materials of interest. Figure 6 compares relative weights of compression-loaded or stability-critical structures. The high modulus of elasticity of beryllium coupled with an equally attractive low density provides a structural weight only 1/4 that of a similar titanium structure when stability considerations or compression loading dominate the design. The beryllium structure offers about a 30% weight savings over the graphite-epoxy material which itself is comparable to a Be-Al structure. The combined use of Be and Be-Al would still provide the least structural weight. A comparison of the modulus/density ratios, or stiffness efficiency, for the various materials is shown in Figure 7 and illustrates the outstanding position of beryllium and the still favorable position of the beryllium-aluminum alloy.

The use of beryllium in the space shuttle structure in place of aluminum offers further advantages since beryllium suffers very little loss in stiffness or strength at temperatures up to 400-600°F, and gains substantially in fracture toughness and ductility. In areas where load carrying capability, rather than stiffness requirements, is critical, beryllium offers strength/density performance comparable to that of the high-strength aluminum and titanium alloys.

The specific heat of beryllium is approximately twice that of aluminum and four times that of titanium. This greater specific heat, in the range of operating temperatures expected in the space shuttle structure, can result in a smaller temperature rise. Since beryllium's coefficient of expansion

TABLE 4 BASIC MATERIAL PROPERTIES

Material	Density Lb/In^3	Modulus (psi x 10^6)	F_{Cy} (psi x 10^3)	Elongation Percent
Aluminum (7075-T6)	0.100	10	66	7
Lockalloy (62Be-38Al)	0.076	28	28	5
Graphite-Epoxy 45° x 45° layup*	0.052	14	40	1-1.5
Beryllium (Powder Sheet)	0.067	42	46	10-12
Titanium (6Al-4V)	0.160	16	126	10

* For most thin wall structures, where buckling stresses are critical, the unidirectional composites cannot be used. The only true comparison, however, must be for a specific design, which is the case for the comparisons in Figures 6 and 7, and Table 4.

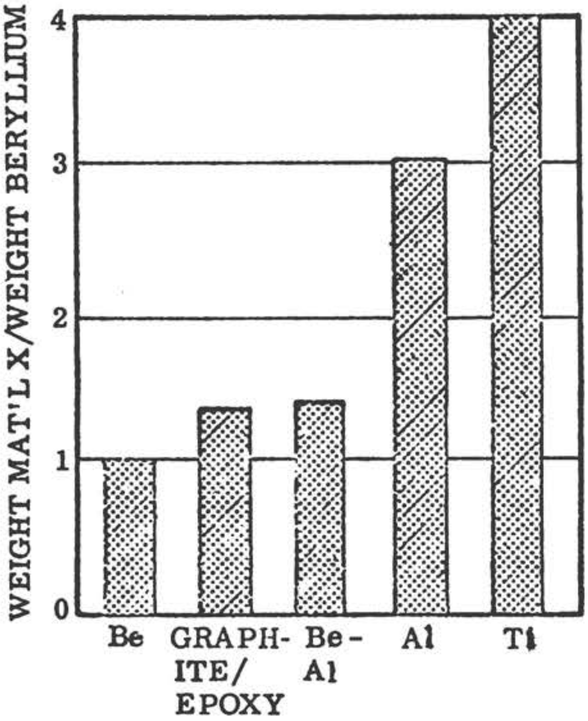


Figure 6 Weight Ratio for Stability Critical Structures

$$W_x/W_{Be} = (\rho_x/\rho_{Be})(E_{Be}/E_x)^{1/2}$$

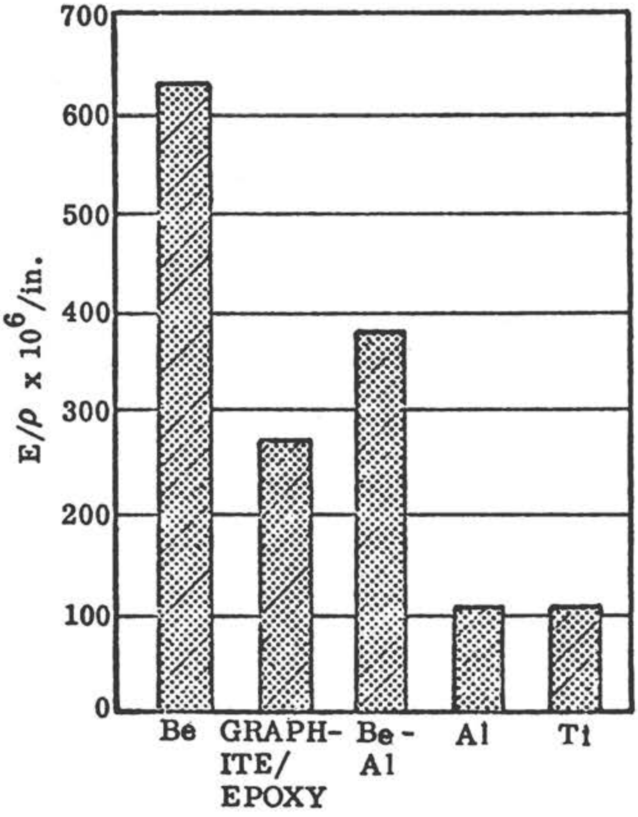


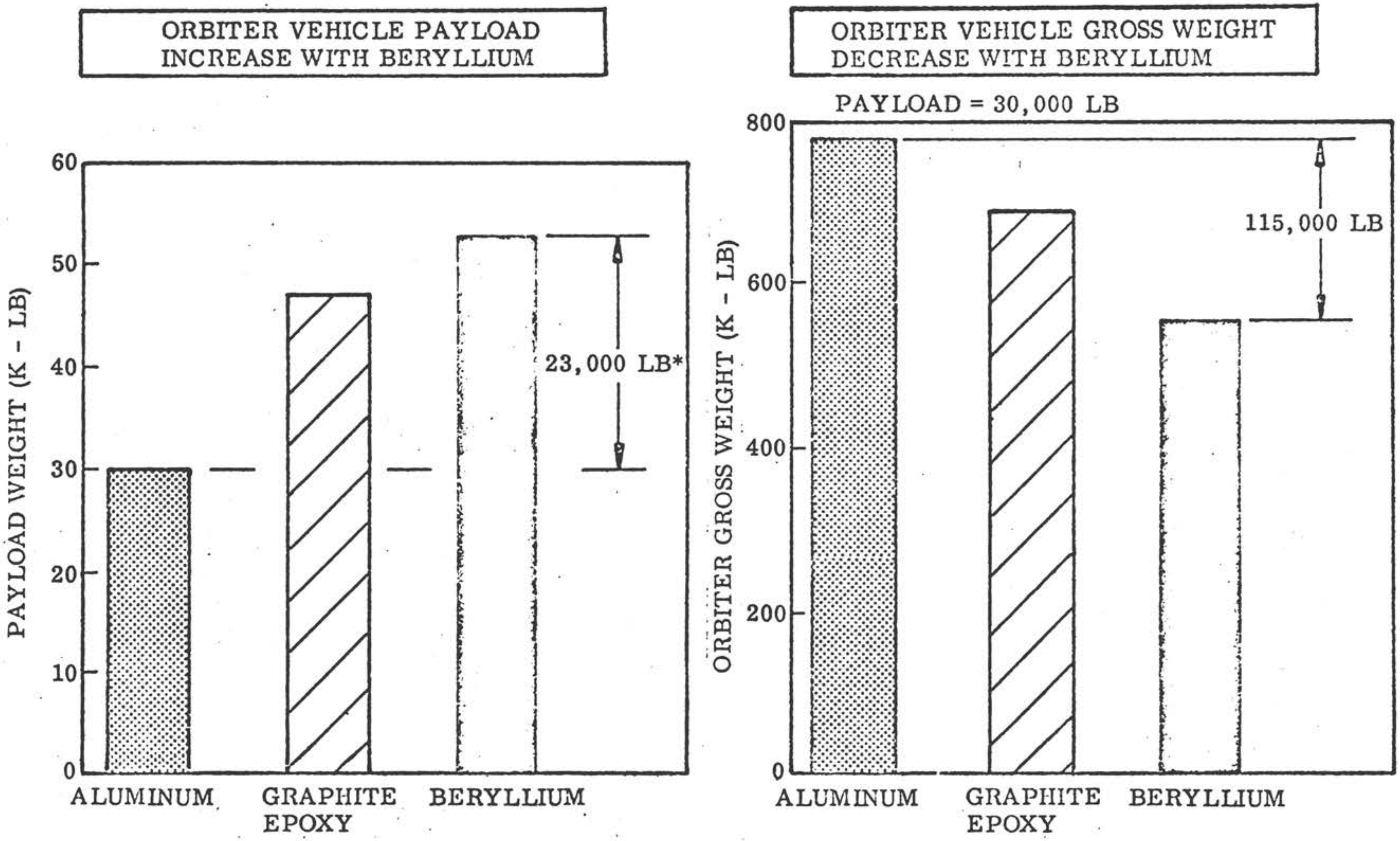
Figure 7 Stiffness Efficiency of Various Materials

is substantially smaller than that of aluminum, attendant differential thermal expansion and distortions should be significantly less.

Beryllium Space Shuttle Orbiter Applications

In terms of specific application to a point-design Orbiter Vehicle, Figures 8 and 9 show the influence of structural weight savings possible with beryllium and with graphite-epoxy, compared with an aluminum structure. A potential weight saving of approximately 23,000 pounds, equivalent to 10% of the total inert weight, in indicated. The significance of this saving in weight can be appreciated if one considers that such a vehicle would have a payload of approximately 30,000 pounds using an aluminum structure. With beryllium, this payload would be increased to 53,000 pounds. This represents a payload increase of 75%. Assuming that recurring costs would not be affected by such a material choice, it can be seen that considerable development and manufacturing costs would be justified to achieve this dramatic increase in payload. Looking at it from another viewpoint, for the same payload, the orbiter gross weight could be decreased by 5 x 23,000 = 115,000 pounds, and the system weight could be decreased by 30 x 23,000 = 690,000 pounds, with attendant cost reductions to affect the cost of using beryllium.

Further improvements in stability performance are attainable by selective beryllium substitution in the fin, space flap, and aft fuselage structure resulting in a forward center of gravity shift of the inert weight of approximately 1%. This may be of primary significance because of the desirability of a forward c.g. in the Orbiter configuration. Another area of potential weight improvement exists in fuselage regions where minimum gages for aluminum alloys occur due to low intensity compressive line loads. A direct substitution of beryllium indicates possible weight savings of 33%.



*WEIGHT SAVINGS
16,000 LB - BODY STRUCTURE
7,000 LB - AERO SURFACES

Figure 8 Impact of Beryllium Structure and Aero Surfaces on Space Shuttle Orbiter Vehicle

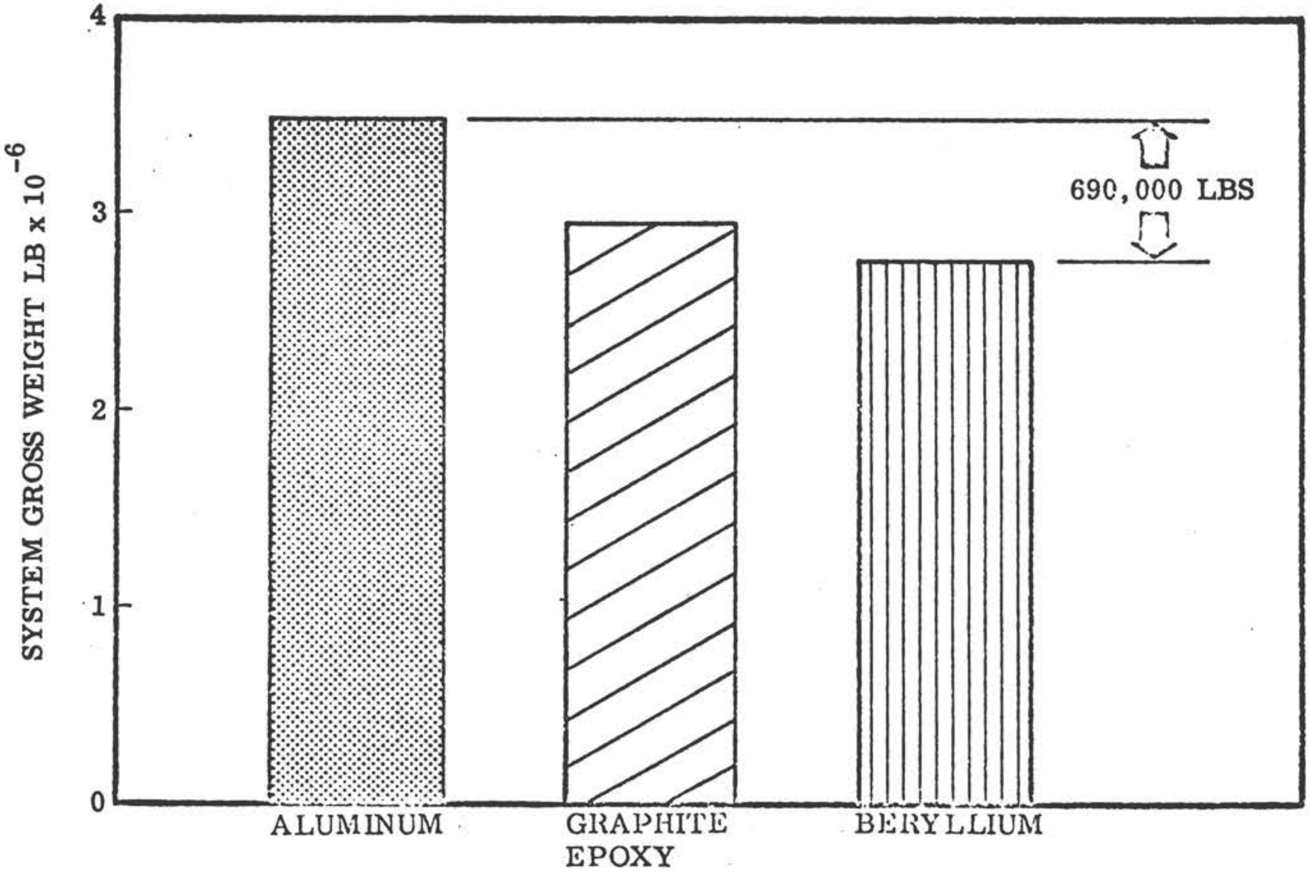


Figure 4 Impact of Beryllium Structure and Aero Surfaces on Space Shuttle System Weight

At this point it should be emphasized that there is a cardinal point in the use of beryllium for any structure under consideration. If the optimum structure is to be achieved, beryllium should be considered in the basic design rather than as a last resort where it merely becomes a substitute material. This is true, of course, for any new material. If not considered in the conceptual stage, the total effectiveness of beryllium is compromised or, in some cases, ruled out, due to design interface, facilities, or schedule problems.

APPENDIX

BERYLLIUM PROPERTIES AND HYGIENE STANDARDS

For those unacquainted with beryllium, some significant physical and mechanical properties are presented. Table 6 describes the most commonly used producer specifications. Table 7 lists the specification mechanical properties. Similarly, the American Industrial Hygiene Association guide for beryllium is reproduced. Reference is also made to the World Health Organization report, Permissible Levels of Occupational Exposure to Airborne Toxic Substances, (Joint ILO/WHO Comm. on Occupational Health, 6th rept. 16 pp. ITS Technical Rept. Series, No. 415, 1969), in which similar maximum atmospheric concentrations are recommended.

PHYSICAL PROPERTIES OF BERYLLIUM**

Table 5 below summarizes the values of the physical constants of beryllium obtained by Losano and Sawyer and Kjellgren and the values published in the 1948 "Metals Handbook" of the American Society for Metals, as well as more recent results by others.

TABLE 5

Physical Properties of Beryllium

Atomic number	4
Atomic weight	9.013
Specific gravity (x-ray)	1.8445
Melting point	1285°C (2345°F)
Boiling point (vapor pressure 1 atm)	2507°C (4545°F)
(vapor pressure 0.1 atm)	2100°C (3812°F)
(vapor pressure 0.01 atm)	1797°C (3267°F)
(vapor pressure 0.001 atm)	1557°C (2835°F)
Specific heat [30–100°C (86–212°F)] (cal/g)	0.425
Latent heat of fusion (cal/g)	250–275
Latent heat of vaporization (cal/g)	5,917
Linear coefficient of thermal expansion [20–200°C/68–392°F)]	
Parallel hexagonal axis	12×10^{-6}
Perpendicular hexagonal axis	9×10^{-6}
Thermal conductivity at 20°C (68°F)	0.35 cgs
Electrical conductivity (% of Cu*)	38.9–43.1
Reflectivity (white light) (%)	50–55
Hardness (Brinell), 1,000-kg load	90–120
Velocity of sound (m/sec)	12,600
Type of crystal lattice at 20°C (68°F)	Close-packed hexagonal
Lattice constant (Å–10^{-8}cm) 20°C (68°F)	$a_0 = 2.2851$, $C_0 = 3.5829$, $C_0/a_0 = 1.5677$
Minimum interatomic distance (Å)	2.22
Electrochemical equivalent (mg/coulomb)	0.04674
Atomic radius (Å)	1.123
Thermal neutron cross section (barns/atom)	0.0090 ± 0.005
Coordination number	12
Allotropy	None
Magnetic mass susceptibility (cgs) electromagnetic units [20°C (68°F)]	-1.0×10^{-6}
Hall coefficient (cgs emu)	0.0021 ± 0.0001
Thermoelectric power (platinum) (mv)	0.16
Electrode potential (volts)	+1.69–1.9

* International Annealed Copper Standard = 100%.

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PRODUCER SPECIFICATIONS & MECHANICAL PROPERTIES

TABLE 6

Available Grades

GENERAL DESCRIPTION	SPECIFICATION Brush	SPECIFICATION KBI	TYPICAL USES
High Purity (99% Be)	N-50	HP-8	Nuclear applications
High Purity - Structural	S-100	HP-12	Very few at present
Standard Structural	S-200E	HP-20	General purpose
Instrument Grade	I-400	HP-40	Instruments
High Strength - PEL	S-350	HP-41	High strength wrought products and instruments requiring ductility
High Strength - Structural	S-240	HP-21	Special weapons components
Brake Grade	BG-170	HP-10	Aircraft brakes and rocket thrust chambers
Sheet	SR-200	PS-20	Formed structural panels
Plate	PR-200	PR-20	Formed structural panels

Note: Producers should be consulted for newer grades.

TABLE 7

Specification Minimum Mechanical Properties of Various Beryllium Materials

Material	Form		F_{tu}, ksi		F_{ty}, ksi		e, %		PEL*, ksi
			L	T	L	T	L	T	
N-50, HP-8	Hot Pressed		35	35	25	25	1	1	--
S-100, HP-12	Hot Pressed		35	35	27	27	1	1	--
S-200, HP-20	Hot Pressed		40	40	30	30	1	1	2**
S-350, HP-41	Hot Pressed		60	68	50	50	0.3	1	5 (tentative)
I-400, HP-40	Hot Pressed		50	50	--	--	-	-	8
BG-170, HP-10	Hot Pressed	R. T.	--	50**	--	30**	-	1	--
		700°F	--	33**	--	24**	-	12	--
		1200°F	--	16**	--	13**	-	4	--
SR-200, PS-20	Sheet		70	70	50	50	5	5	--
PR-200, PR-20	Plate	.250-.450	65	65	45	45	4	4	--
		.451-.600	60	60	40	40	3	3	--
S-200, HP-20 S-350, HP-41	Extrusions & Forgings		Minimum Mechanical Properties are negotiated since extrusion or forging parameters can usually be tailored for the specific applications.						

* PEL -Precision Elastic Limit

** Typical

HYGIENIC GUIDE SERIES *

Beryllium and Its Compounds

(Revised 1964)

Significant Physical Properties

Beryllium is a silvery-white, brittle metallic element similar in appearance to magnesium.

Chemical symbol:	Be	BeO
Atomic number:	4	—
Atomic (or molecular) weight:	9.01	25.01
Density:	1.85 at 25°C	3.03
Melting point:	1285°C	2550°C
Boiling point:	2970°C	3960°C (estimated)
Solubility:	Soluble in dilute acids and alkalis.	Insoluble in water, acids (except hydrofluoric) and alkali (except fused). Attacked by water vapor at temperatures above 1300°C.

Vapor pressure (obtained graphically[1]):					
	mm Hg	7.6×10^{-6}	7.6×10^{-4}	7.6×10^{-2}	7.6
	°C	890	1080	1330	1810

Beryllium is an amphoteric element and its salts readily hydrolyze forming the beryllium cation, basic beryllium compounds or beryllates as the pH of the solution is increased.

I. Hygienic Standards

A. Recommended maximal atmospheric concentrations (8 hours): 0.002 mg per cubic meter.[2,3,4]

B. Short exposure tolerance (less than 30 minutes): 0.025 mg per cubic meter.[3,4,5]

C. Non-occupational: A monthly average concentration of 0.00001 mg per cubic meter has been used as a guide for the maximal atmospheric concentration outside the plant. This is based on epidemiological studies.[3,4,6,7]

II. Toxic Properties

A. Inhalation: Inhalation of beryllium and its compounds may produce two types of disease—acute and chronic.

1. *Acute:* Acute disease may result from relatively brief exposure to high concentrations of beryllium or its compounds. The result may be a pneumonitis where exposure is to the metal, oxide or other compounds. Nasopharyngitis or tracheobronchitis is more likely from highly soluble compounds.[8] The pneumonitis may be fulminating following massive exposure or less severe with gradual onset from lesser exposure.[9,10]

2. *Chronic:* Chronic disease may result from varying lengths of exposure to a wide range of concentrations including quite low concentrations. In some cases there is a prompt onset of symptoms while in others there may be a delay of many months or years between the last exposure and onset of symptoms.

Pulmonary manifestations usually include dyspnea and a chronic cough. Significant weight loss within a short period of time is a symptom in many cases as are anorexia, fatigue, weakness and malaise.[4] Although respiratory symptoms are most prominent and usually occur first, the chronic disease is considered by many to be a systemic disease which may involve other organs.[8] Chest x-rays are useful in

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The Committee wishes to acknowledge the assistance of Harry F. Schulte in the writing of this Guide and of the Industrial Hygiene and Clinical Toxicology Committee of I.M.A. in the preparation of the medical information section of this Guide.

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*Reproduced by permission from the American Hygiene Association diagnosis and treatment but only in conjunction with other clinical findings.

B. SKIN CONTACT: Skin contact with soluble salts, particularly acidic salts, may produce dermatitis of primary irritant or sensitization type.[4,10] Accidental implantation of beryllium or its compounds beneath the skin may cause necrosis of adjacent tissue with the formation of an ulcer. Implantation of comparatively insoluble compounds may produce a granuloma. Healing does not occur unless the beryllium-containing material is completely removed.

C. EYE CONTACT: Conjunctival inflammation may accompany contact dermatitis resulting from soluble beryllium compounds.

D. INGESTION: No harmful clinical effects have been reported from ingestion of beryllium-containing materials.

Wide variations in the effects produced by beryllium compounds of differing physical properties have been reported. Acute disease, skin and eye effects have been associated largely with soluble compounds, although the metal and the oxide also have been implicated. Chronic disease has been associated, although not exclusively, with the more slowly soluble compounds such as the oxide, beryllium metal, and the phosphors which were once used to coat fluorescent lamps (prior to 1949). Only the silicate mineral, beryl, has definitely not been found associated with beryllium disease. The degree of toxicity is associated in some manner with solubility and particle size as well as other factors but information is not adequate to exempt any beryllium-containing material except beryl from the rigid control requirements.

III. Industrial Hygieno Practice

A. INDUSTRIAL USES: Because of its low density combined with high rigidity, beryllium metal is used in the aerospace and aircraft industries as a structural material. Use of the metal powder as a rocket fuel component is under investigation. In the atomic energy industry, beryllium has a wide variety of applications, particularly as a reactor component because of its specific nuclear properties. Alloyed with copper, it produces a hard metal of high conductivity and tensile strength which is resistant to fatigue. As such, it is used for making nonsparking tools and current-carrying springs and molds. The oxide has found considerable use as a ceramic material and in neon sign manufacturing.

B. EVALUATION OF EXPOSURES:

1. *Air sampling and analysis:*
   (a) Air sampling usually is done by means of filter paper or occasionally by electrostatic precipitator.[3,4,11] Various forms of beryllium monitors have been devised for recording the air concentration of beryllium continuously after a few minutes delay.[12]
   (b) Air samples collected on filter paper or by the electrostatic precipitator may be analyzed colorimetrically,[13] fluorimetrically by the morin method[11,15,16] or spectrographically.[17,18]
2. *Sampling and analysis of biological materials:* Urine analyses of beryllium have shown little quantitative correlation with either exposure to beryllium or with clinical findings and hence are seldom done. Positive identification of beryllium in urine does indicate exposure to beryllium in some form and is of value only in establishing this fact. Tissues may be analyzed spectrographically[17] or fluorimetrically.[15]
3. *Swipe samples:* Swipe or smear samples sometimes are taken to determine the degree of cleanness of surfaces. A measured area is rubbed with a filter paper and the sample is analyzed in the same manner as an air sample. Repeated analyses of this sort can form a basis for judging whether a given surface area is in need of more frequent cleaning. A surface cleanness of less than 0.025 mg of beryllium per square foot usually can be obtained by ordinary cleaning methods and has

been used as an index of cleanliness by some.[11] It has no other health significance.

C. HAZARDS AND THEIR RECOMMENDED CONTROL:

1. *Inhalation:* Control of inhalation hazards may be accomplished by enclosure or local exaust ventilation or a combination of these. Small, high velocity exhaust pickups[4,19] or semienclosure with moderate velocity exhaust [11,20] may be used on machining operations.[21] A wide variety of combinations of enclosure and ventilation has been used on other operations.[3,20]

   Where respiratory protective devices are required, the user should refer to the *Respiratory Protective Devices Manual.*[22] Gloves and clothing worn while working with beryllium should not be worn home. All clothing and other personal items contaminated with beryllium should be laundered separately, using facilities designed to prevent contamination of the air with beryllium. Beryllium metal should be stored in such a way that it will not come into contact with moisture which causes the formation of a loosely adherent powder that may become airborne and produce an exposure by inhalation.[20]

2. *Skin contact:* Contact with soluble compounds, especially fluorides, should be prevented. Scrupulous adherence to good housekeeping practices, plant and personal cleanliness are an obvious necessity. Lacerations and abrasions with beryllium-containing materials, especially where beryllium compounds are implanted in the tissue, are difficult to heal (see Section II. B.). Special handling may be necessary to minimize the possibility of such injuries. There is no danger in ordinary skin contact with beryllium metal, alloys or fused ceramic material.

3. *Eye contact:* Eye protective devices should be worn when working with soluble beryllium compounds under conditions where splashing or mist production can occur.

4. *Ingestion:* No special precautions other than those used in handling most chemicals are required.

5. *Fire and explosion:* Bulk pieces of beryllium metal are extremely difficult to ignite and show little oxidation up to 900°C. Like most metal powders, finely divided beryllium ignites under proper conditions and can explode if suspended in air in the presence of a strong ignition source. Its low density makes it somewhat easier to create an explosive concentration in air than is the case with other metals. Powdered beryllium metal (as in a dust collector) burns quietly if ignited.

IV. Medical Information

A. EMERGENCY TREATMENT: Any person having a known exposure to a high concentration of airborne beryllium or its compounds should be given prompt medical attention and observed closely for exidence of pneumonitis. Medical management as well as signs and symptoms of overexposure simulate those of phosgene and oxides of nitrogen. (Refer to Hygienic Guide on Nitric Acid for details.) A 14- by 17-inch chest x-ray picture should be taken immediately for comparison with possible subsequent x-rays and the exposed worker put at complete rest. Follow-up observation and examination are essential for all individuals who have been exposed to hazardous levels of beryllium or its compounds.

Cuts or puncture wounds, where beryllium or its compounds may be embedded under the skin, should be thoroughly cleansed immediately by a physician. Any implanted beryllium must be excised.

B. SPECIAL PROCEDURES: X-ray pictures (14- by 17-inch) of the chest should be made on all personnel prior to job assignment. A careful history of respiratory disease should be taken. Periodic chest x-rays should be made at least annually with prompt removal from exposure at the first evidence of abnormal findings. Any dramatic unexplained weight loss should be considered as a possible first indication of beryllium disease.[4] Steroid therapy should be considered in the case of either acute or chronic beryllium disease.

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13. ABSTRACT

This review, made to examine the role of the Department of Defense in using beryllium and in advancing the technology, found numerous advantageous applications as part of important components. Present applications, such as for guidance systems, re-entry vehicles, brakes, and thrust chambers, would suffer significant performance penalties if beryllium were not available. Several design trade-offs show beryllium to be competitive with, or superior to, filamentary composites, on a stiffness-to-weight basis, in advanced applications for lightweight structures. Increased usage of beryllium, however, will be unlikely without certain necessary development work which is described. In addition to beryllium's unique capabilities, a major justification for support of beryllium technology is its usefulness as an option in the event that competitive materials prove to be unsatisfactory in critical applications. Civilian applications (except in the form of an alloying element), now or foreseeable, are very limited because beryllium remains an expensive material. Accordingly, fulfillment of beryllium's potential advantages for military systems requires government support to ensure that beryllium in the required forms will be available, particularly for applications now being designed. Evaluation of pertinent standard cutting and forming operations and also some of the newer fabrication operations in terms of cost and applicability are recommended. In addition, the construction and evaluation of prototype hardware, based on either all-beryllium or hybrid-beryllium structures, are recommended to capitalize upon available beryllium technology, and to establish the experience, data base, and confidence necessary to keep beryllium as a viable candidate for future military systems.

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