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Report of Beryllium Committee



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NATIONAL ACADEMY OF SCIENCES— NATIONAL RESEARCH COUNCIL

The National Academy of Sciences—National Research Council is a private, nonprofit organization of scientists, dedicated to the furtherance of science and to its use for the general welfare.

The Academy itself was established in 1863 under a Congressional charter signed by President Lincoln. Empowered to provide for all activities appropriate to academies of science, it was also required by its charter to act as an adviser to the Federal Government in scientific matters. This provision accounts for the close ties that have always existed between the Academy and the Government, although the Academy is not a governmental agency.

The National Research Council was established by the Academy in 1916, at the request of President Wilson, to enable scientists generally to associate their efforts with those of the limited membership of the Academy in service to the nation, to society, and to science at home and abroad. Members of the National Research Council receive their appointments from the President of the Academy. They include representatives nominated by the major scientific and technical societies, representatives of the Federal Government, and a number of members-at-large. In addition, several thousand scientists and engineers take part in the activities of the Research Council through membership on its various boards and committees.

Receiving funds from both public and private sources, by contributions, grant, or contract, the Academy and its Research Council thus work to stimulate research and its applications, to survey the broad possibilities of science, to promote effective utilization of the scientific and technical resources of the country, to serve the Government, and to further the general interests of science.

MATERIALS ADVISORY BOARD

The Materials Advisory Board is a part of the Division of Engineering and Industrial Research of the Academy-Research Council. It was organized in 1951 under the name of the Metallurgical Advisory Board, with assignments from the then existing Research and Development Board of the Department of Defense. At that time, the Research and Development Board requested the Board to accept tasks covering a broad spectrum of metallurgical science and technology as related to the Armed Services, and to include certain other areas such as collection and dissemination of information, and cooperation with professional societies in publication of significant metallurgical data.

Since the organization date, the above scope has been expanded to include organic and inorganic nonmetallic materials, and the name has been changed to the Materials Advisory Board. Concurrently, the Board's membership, staff, and operations have been adjusted to encompass the greater diversity of materials and to concentrate on materials research and development, excluding other activities except to the extent that they support and strengthen the Board's fulfillment of its primary responsibility.

The Office of the Director of Defense Research and Engineering, Office of the Secretary of Defense, is the government agency which now requests specific consulting and advisory services under this broadened program. Under a contract between the Office of the Secretary of Defense and the National Academy of Sciences, the Board's assignment is:

"... at the written request of the Director of Defense Research and Engineering, or his designated representative, to conduct studies, surveys, make critical analyses, and prepare and furnish to the Director of Defense Research and Engineering advisory and technical reports, with respect to the entire field of materials research, including the planning phases thereof; and shall, in addition, perform such other services as may be agreed upon in writing, from time to time, by the Director of Defense Research and Engineering and the President of the Contractor.

"Task assignments under this contract will be as mutually agreed by the Director of Defense Research and Engineering or his designated representative and the Contractor. Recommendations for tasks may be proposed to the Director of Defense Research and Engineering by agencies of the Military Department, the Office of the Secretary of Defense, or the Contractor."

NATIONAL ACADEMY OF SCIENCES
NATIONAL RESEARCH COUNCIL

MATERIALS ADVISORY BOARD
OF THE
DIVISION OF ENGINEERING AND INDUSTRIAL RESEARCH

August 1, 1962

MAILING ADDRESS
2101 CONSTITUTION AVENUE, N.W.
WASHINGTON 25, D. C.

OFFICES
1155 16TH STREET, N.W.

Dear Sir:

I am forwarding herewith the report entitled "Report of Beryllium Committee," which has been submitted through the National Academy of Sciences-National Research Council to the Director of Defense Research and Engineering. This report has been reviewed by the Beryllium Committee and by individual members of the Materials Advisory Board who have competence in the field.

In accordance with an agreement with the Office of the Director of Defense Research and Engineering, this report is being distributed on the same date it is being transmitted to the Department of Defense. Therefore, as of this date, it has not been reviewed by the Office of the Director of Defense Research and Engineering.

Very truly yours,



C. S. Marvel, Chairman
Materials Advisory Board

Enclosure

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REPORT OF
BERYLLIUM MITTEE

This document contains information affecting the national defense of the United States within the meaning of the espionage laws, Title 18, U.S.C. Sections 793 and 794, the transmission or revelation of which in any manner to an unauthorized person is prohibited by law.

Division of Engineering and Industrial Research
National Academy of Sciences
National Research Council
Washington 25, D.C.
August 1, 1962

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No portion of this report may be published without prior approval of the contracting agency.

This report prepared and submitted to the Office of the Director of Defense Research and Engineering under ARPA Contract SD-118 between the Department of Defense and the National Academy of Sciences.

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BERYLLIUM

THE PROBLEM

Beryllium has a potential for very large pay-off in the performance of aerospace vehicles. This possibility was discussed in a number of articles during the late 1950's, and was the subject of an MAB report (MAB-129-M, June 25, 1958). Nevertheless, the utilization of beryllium has continued to remain at a modest level. The question being asked is whether the Department of Defense can take action to accelerate the applications of beryllium and thus reap some of the promised benefits. A second consideration is that the types of beryllium ore presently utilized occur in local deposits of limited size, and nearly all such ore is imported. For this reason, unusual increases in demand should be anticipated in time to permit supply to keep pace. Especially significant in this regard are experiments now being intensively pursued looking to the utilization of beryllium powder as an additive to solid rocket propellants.

RECOGNIZED DIFFICULTIES

Cost. The high cost of beryllium has limited and will continue to limit applications. The cost of the mill product is high relative to more common metals, and the cost of a beryllium part tends to be high also because of the intractability of the metal compared to room temperature ductile alloys, such as aluminum, and the need to provide specialized hygienic precautions because of the problem of toxicity.

With sheet selling in the \$200-\$350 range, it is obvious that the possibility of use of beryllium in conventional aircraft is no better than marginal. Use of such an expensive material, however, can be fully justified on satellites and upper stages of missiles. There is no clear-cut answer as to the direction

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that prices would take upon an increase in production. Operating economies could be offset to a degree by the possibly increased cost of ore, which would result from utilizing lower grade deposits. In any case, it is not expected that the cost of beryllium or beryllium mill products will change very substantially, and certainly will never approach the price of metals like aluminum and steel. The cost barrier exists also for beryllium powder as an additive to propellants. Theoretical and experimental studies have shown that the specific impulse of propellants could be improved appreciably by substituting beryllium for aluminum powder now commonly added. This substitution (at a beryllium cost of about \$80 a pound) would result in a propellant cost of about \$12.00 compared with the present 50 cents. In this arbitrary example, 15% of Be is assumed compared to 20% Al, nevertheless resulting in a propellant with a higher specific impulse.

Availability. The delicate balance between supply and demand of beryllium ore was studied in some detail in the MAB report previously mentioned. Since that time, non-beryl deposits are being exploited. While production from this source is low, such United States deposits will tend to stabilize the price of imported beryl. The ease with which supplies have been made available to meet the demands of the past few years indicates that for production of the present order of magnitude, supply will pose no particular problem. Furthermore, there are no specific indications that there will be unusually large requirements for beryllium for structural or nuclear uses. In addition, the two producers are now operating at a rate of 25-35% of capacity. The only concern as to supply is due to propellant applications. Hundreds of pounds of beryllium can be used in a single motor, and if such use became prevalent within a brief time span, a shortage of supply might ensue. Information supplied by Defense Metals Information

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Center and Solid Propellant Information Agency had indicated that, while considerable attention is being given to this possibility, there is no military system committed to the use of beryllium as fuel. (Although it is being used in the fourth stage NASA Blue Scout, and in experimental Air Force firings.) The fuel application picture is a very fluid one, and a rapid swing to such utilization is conceivable. Nevertheless, widespread use had not materialized at the time of this writing (mid-1962). Explorations on the use of beryllium in fuels are largely at the research phase, with development only starting. Therefore, the necessary time (of the order of two years) presumably will be available to take action on increasing supply if such action is indicated. A further corollary is indicated. This is, that designers should not hesitate to use beryllium because of the belief that the metal is in very limited supply, when in fact, present supply far exceeds demand.

Going beyond the availability of the metal, a major problem exists with regard to availability in the desired finished forms. Principal airframe interest is in sheet. While this is for sale commercially, essentially on a special order basis, production has been too small to permit the use of optimum equipment and to develop well-trained crews. Therefore there tends to be some variability in quality. To be considered for use in aircraft, a comprehensive list of physical and mechanical properties must be available, and these must define the properties which will be present in the mill product to be delivered later.

Concerning powder for fuel use, an entirely new production process may be needed. Present experiments are run on a fine-particle portion of a pure lot of powder prepared in the usual manner. Such a procedure is uneconomic when large quantities are involved. The producers are now exploring on the laboratory level

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new production procedures (to yield a pure, spherical, fine-particle product), or alterations in conventional production to enhance the yield of fine grain fractions. No such methods are now being used commercially, so far as is known.

Ductility. The brittleness of beryllium has long been a serious deterrent to the structural use of the metal. This problem is now commonly recognized, and is also much better understood. Many uses for beryllium of anisotropic ductility are possible if beryllium's peculiarities are recognized during design.

During the past year, high ductility on the basal planes of highly refined single crystals was demonstrated. Through purification, the glide on prism planes also improved, but to a smaller degree. However, translation of such improvements to polycrystalline metal will probably be difficult.

The amount and kind of ductility required in a structure is not well understood. Because of expense and press of schedules, there has not been extensive experimental and prototype work.

Toxicity. The toxicity of beryllium is now well recognized, and means for coping with it are well understood. Installation of sophisticated ventilation facilities and other control measures are required, which, in effect, adds to the cost of the final product. The problem has the result of tending to eliminate employment of beryllium in facilities which would have only a small use for the metal, which would not justify installation of expensive control measures.

The toxic products of combustion tend to limit the use of beryllium in fuel to upper stages in missile systems, and even then some hazard is present (due to ground testing of these upper stages, for example).

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FINDINGS

A meeting of the Committee on Beryllium (See Appendix I) was held in April 1962. A comprehensive survey of the research and development involving the metal was presented by representatives from the Defense Metals Information Center and the Solid Propellant Information Agency. Additional comments were made by liaison members from the Services, National Aeronautics and Space Administration, and the Atomic Energy Commission. The presentations by the Defense Metals Information Center, the Solid Propellant Information Agency, and National Aeronautics and Space Administration are appended to this report (Appendices II, III, and IV).

The relatively low level of effort of research at the Atomic Energy Commission has declined even farther. A rather substantial amount of work on BeO, however, is being carried on.

Comment was made by the Army representative that a research plan has been prepared, and that operation of a new facility for nuclear and other hazardous metals is expected to be operational by the end of summer. Contracted research will follow later.

The principal interest of the National Aeronautics and Space Administration was outlined by Mr. J. H. Diedrich of the Lewis Laboratory in a prepared talk (Appendix IV). This interest derives from the favorable properties of beryllium as a "meteor bumper" over radiator and similar tubing of space power systems. Such an application could employ thousands of pounds of beryllium per 10-kilowatt system.

Discussion quickly established that the problems of ore supply and structural utilization were relatively unchanged compared to a few years ago, and reasonably well understood. Major attention was given to the application of beryllium powder

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in propellants. The technical feasibility of such use has already been demonstrated. In addition to the major consideration of toxicity, the extent of application in the near future will depend largely on the development of methods of making fine-particle powder at a cost which is not prohibitive. The question of powder production capacity is one which bears watching, as it might constitute, for a time, the limiting factor.

Some discussion pointed up the need for improving the quality of commercial beryllium sheet, and the demonstration of design and fabrication problems by the construction of structural elements.

CONCLUSIONS

1. The supply of beryllium ore is adequate for foreseeable requirements. With the two major producers operating at less than one-third capacity, a shortage of metal is unlikely. Potential users should not hesitate to incorporate beryllium because of a question of availability. A trend to use beryllium as a propellant additive has begun, but such uses are not expected to upset the market for at least the next few years.

2. The use of beryllium in propellants can be expected to increase, despite the cost and health hazards involved. There is no single system making such use extensively, and there are no known plans to incorporate beryllium in a major missile system. To the degree that this can be forecast, it appears that there will be time to expand ore supply in order for production to keep pace with added usage, if that proves to be called for. If substantial quantities of powder for fuel are called for suddenly in the near future, the powder preparation step would probably constitute the bottleneck.

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3. In most cases cost, rather than ductility or toxicity, is the major factor limiting more widespread use of beryllium.

4. The Atomic Energy Commission has a continuing interest in the immediate applications of beryllium to nuclear reactors, but foresees no important immediate use. However, a continuing effort in basic beryllium studies, such as purification and irradiation effects, is envisioned. Atomic Energy Commission metal requirements over the next several years can be met from existing plant capacity and on a straight commercial basis; no metal production contracts are anticipated. Although the Atomic Energy Commission has historically provided extensive support to the beryllium industry, this support has lessened to a point where the beryllium industry has now come to rely on the military services.

RECOMMENDATIONS

1. The presently used specifications for powder for fuel additives are questioned as being possibly unnecessarily stringent. Fine particles burn more readily, but as the particle size decreases the oxide content rises. Production of very fine size powder low in oxygen can be quite expensive. In addition, beryllium is a reactive element and may interact with the propellant unless protected, as with the naturally occurring surface oxide. More performance data should be obtained, and compared with price quotations on powders of various particle sizes and oxide maxima to arrive at optimum values.

2. Most experiments with beryllium additions to rocket fuel employ unalloyed metal powder. Other development programs beyond one known at the Naval Ordnance Test Station at China Lake should be instituted to investigate alloy powders of beryllium and other reactive metals, such as aluminum, zirconium, and magnesium. It may be possible to find a composition, which, compared with pure beryllium,

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will have improved bulk density, particle size, and oxide content. The use of beryllium additives in forms other than powder (foil or wire, as examples) should also be investigated as a means of incorporating the desired reactivity and also adding to the strength of the solid propellant aggregate.

3. In view of the possible impact of fuel use of beryllium on demand for the ore, close liaison between the Services and the Bureau of Mines is recommended.

4. One reason for the lag in use of structural beryllium is the long lead-time required to obtain many mill products. Additionally, the available mill products tend not to be of high aircraft standards of uniformity. This committee, over the years, has consistently refused to endorse a sheet rolling program if such a program consisted largely of the mere production of fixed quantity of sheet of certain sizes. The time is drawing near, however, when enough will be known about the metal that consideration can be given to sheet rolling development in which the important variables, such as billet quality, amount of hot and cold work, finishing procedures, etc., can be optimized. It is clearly important that when this point is reached, effort should also be expended to determine the physical and mechanical properties of metal so produced, to facilitate the incorporation of beryllium by designers.

5. Beryllium is not yet developed sufficiently to permit extensive air-frame application, but the construction and testing of small components at this time would reduce the total development time for beryllium aerospace structures by indicating more specifically those characteristics of the material which need improvement, and those which do not. Such work would also encourage the development of designs which accommodate the lack of ductility of the material, a

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necessary step since present indications are the customary metallic ductility will probably never be achieved, at least so in a relatively short time. A program such as the above will also facilitate the development of fabrication techniques for this material.

6. The committee has proven useful in the past in keeping the participants informed of work in progress and applicational requirements; through these members their respective organizations are apprised of these matters. Future use of the committee should be to act as a forum for the discussion of present activities and to exchange views on promising activities for the future. Additional meetings will be scheduled at 6 to 12 month intervals as the need arises.

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APPENDIX I

BERYLLIUM COMMITTEE

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* Designated from committee and moved to Department of Defense
(Special Assistant for Materials, Office of the Director
of Defense Research & Engineering) May 24, 1962

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APPENDIX II

SUMMARY OF GOVERNMENT-SPONSORED RESEARCH AND
DEVELOPMENT PROGRAMS ON BERYLLIUM

August 15, 1962

by

R. J. Bunck, E. W. Cawthorne, G. W. Cunningham
S. W. Porembka, R. J. Lund, and A. Levy

DEFENSE METALS INFORMATION CENTER
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SUMMARY OF GOVERNMENT-SPONSORED RESEARCH AND

DEVELOPMENT PROGRAMS ON BERYLLIUM

August 15, 1962

SUMMARY

Beryllium as a structural metal has received considerable attention by the Department of Defense during the past four years because of its potential usefulness in military systems. The principal (non-nuclear) properties of beryllium that account for interest by the Department of Defense are high stiffness (high modulus of elasticity), high heat capacity, and high chemical energy, all outstandingly high relative to its low density.

The principal factors that appear to deter the use of beryllium are high cost and fear of toxicity. Additional deterrents to the use of beryllium as a structural material are lack of ductility and lack of availability of desired forms (long lead time).

Because of the high heat capacity per unit weight, beryllium has been useful as a heat sink in aerospace systems. However, in re-entry bodies, beryllium has now been largely replaced by ablative plastics.

Beryllium continues to be of interest as a structural material. While significant advances have been made in the past two years in producing beryllium mill products with optimum mechanical properties, the relatively low ductility of these products and the absence of ductility in welds still leave much to be desired. Designers are, of course, being pressed to develop new concepts which will utilize materials of low ductility. However, a gap still exists between the available and desired properties in beryllium, which accounts for reluctance to use the metal in numerous potential applications.

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Initial research programs to develop beryllium for structural applications were directed primarily toward fabrication techniques to obtain high strength and retain as much ductility as possible in commercial grades of material. Initially, only moderate efforts were made to produce high-purity metal. It was not only difficult to make high-purity metal, but the efforts to do so were also plagued by lack of suitable analytical techniques to determine the degree of purity obtained.

Programs on fabrication of commercial grades of beryllium have been continued and methods of obtaining the optimum properties of this material have been fairly well established. Recent research programs, however, now emphasize the development of high-purity forms of the metal, although these programs have not yet established whether or not the high-purity metal will be more ductile or have better properties than commercial grades of metal.

Programs on welding have improved the consistency of obtaining good joints, but the lack of consistency in properties of joints still leaves much to be desired, and welds are still brittle. Most programs on joining have been terminated with the exception of a last look at electron-beam welding.

Because of its high chemical energy, beryllium is potentially useful in rocket fuels. This potential has been recognized for several years, but recently a sharp increase in interest in the use of beryllium metal powder in solid rocket propellants has occurred. Calculations have been made of the gains in specific impulse available by substituting beryllium metal powder for aluminum in presently used propellant formulations. Experimental programs are now under way to verify the calculated

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advantages. If beryllium-containing propellants are introduced into major military systems, a special grade of powder in very large quantities will be required.

Beryllium metal powder, however, does not offer as much potential increase in the specific impulse of rocket propellants as beryllium hydride. Consequently, numerous programs are also under way to develop the hydride for possible use in more advanced propellants.

The application of beryllium in nuclear reactors is still of major interest, but the oxide rather than the metal appears to have the greatest potential. The use of beryllium metal in gas-cooled reactors, which was viewed with optimism a few years ago, has been deferred because of the unpredictable corrosion resistance of beryllium to CO₂ coolant gases and the undesirable combined effect of high creep at high temperatures and low ductility at room temperatures.

In contrast with the outlook four years ago, beryllium resources now appear to be sufficient to meet potential military requirements. The development of beryllium resources, potential applications for beryllium, and costs are closely interrelated, however. Beryllium is now manufactured principally from imported beryl even though large reserves of beryllium-bearing ores have been identified on the North American Continent in recent years. The development of facilities to process these reserves, however, awaits an assured market. The development of a larger demand for beryllium (particularly as a structural material) is in turn deterred by high cost. It is hoped by the beryllium industry that the use of beryllium in rocket propellants will create the demand to break the present cost-demand dead-lock.

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In most of the potential applications for beryllium, fear of toxicity continues to be an overriding objection to its use. Toxicity of beryllium, while real, has had more than its share of publicity. Procedures for the safe handling of beryllium have been developed and the material can be used safely. The most troublesome factor related to the toxicity of beryllium is the fact that there are several maladies which have symptoms similar to those caused by exposure to beryllium. In victims exposed to beryllium, it is not possible to prove that such symptoms, when they occur, are not caused by beryllium. Government-sponsored research on beryllium is being continued not only to study the nature of beryllium toxicity but also to determine safe maximum levels of exposure to various beryllium compounds.

INTRODUCTION

This summary of programs on beryllium was prepared at the request of the Department of Defense, for use by the Committee on Beryllium of the Materials Advisory Board.

The work summarized and the programs listed represent primarily those on beryllium metal which are supported by Government funds. Included also, however, is some information on work supported by industrial funds, some information about work on beryllium being done under systems projects, and also some information on applications of nonmetallic forms of beryllium. DMIC is not in a position, however, to obtain a comprehensive collection of information from these latter sources.

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RESOURCES

The situation with respect to beryllium ore resources has changed quite substantially since the 1958 report of the MAB Panel on Beryllium. In 1958, self-sufficiency in beryllium in the United States was in doubt. Since that time, large deposits of bertrandite-bearing tuffs have been discovered and explored in the Topaz Mountain District near Delta, Utah; beryllium mineralization has been explored in the Mount Wheeler, Nevada, fluorite-tungsten deposits; and drilling has indicated large reserves of beryllium in the unusual mineral berylite in the Seal Lake, Labrador deposit. Other significant domestic and foreign discoveries and developments have also occurred.

Total tonnage of ore (detailed below) in the three new discoveries named above amounts to around 8 million tons with a grade of 0.5% of BeO or better. This amounts to about 80 million pounds of BeO or almost 30 million pounds of contained Be. The Topaz Mountain deposit accounts for about half of this.

This compares with estimates of U. S. reserves of 8,800 tons of beryl (2,460,000 pounds of BeO or 880,000 pounds of Be) in pegmatitic ores containing 1% beryl (0.14% BeO) or better. Thus, the reserve picture for the U. S. alone has been boosted by a factor of about 18. It might be noted, too, that these new ore reserves have a much higher grade cut-off point (0.5% BeO, compared with 0.14% BeO), although it is not known how strictly comparable these two figures are.

Not included in any of the above figures are the additional substantial reserves of beryl-pollucite pegmatite at Bernic Lake, Manitoba,

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Canada; or the huge reserves of disseminated beryl in the tin-spodumene belt of Kings Mountain, North Carolina. However, the Be content of the latter is so low (0.4 lb per ton of rock, or 0.02%) as to make its economic recovery dependent on production of lithium and possibly other co-products. Even so, the Be output would amount to only about 3 per cent of the lithium output. Thus, even though work continues on possible methods of beryl recovery from Kings Mountain, the chance of this contributing any major amount to future beryllium supplies is very slim.

Major recent interest has been focused on the Topaz Mountain deposits, and heavy expenditures have been made in drilling these and in developing methods for extracting the contained beryllium. Economics of concentrating techniques have not yet been proved. But reliable reports from companies that have been active in this work indicate that products such as beryllium oxide, hydroxide, or powdered metal can definitely be produced at costs comparable with those prevailing now for these products as obtained from imported beryl. Mid 1962 prices for these various products are as follows:

	<u>Per Pound</u>	<u>Equivalent Per Pound of Contained Be</u>
Hand-cobbled beryl (10-12% BeO)	\$.20	\$4.60
BeO Powder		
High purity (400 ppm metallic impurities)	\$15-25	\$42-72
Alloy grade (98.5-99% BeO)	\$ 8-10	\$22.50-28
Be(OH) ₂ (58% of \$20. oxide price)	\$11.60	\$55.50
Be Powdered Metal	\$54-60	\$54-66

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Furthermore, knowledgeable parties active in work on beryllium extraction from the Topaz Mountain ores estimate that with expanded operations—say upwards of one million pounds of Be annually—price of oxide equivalent to alloy grade could be lowered to less than \$5 per pound, and that for metal powder to around \$30 per pound.

These reports and opinions of responsible parties active in researching the Topaz Mountain deposits appear reliable and reasonable.

The U. S. Bureau of Mines is continuing to support a search for beryllium-containing ores in the United States. (6,7,8,9,10) **Emphasis** has been placed on new and non-pegmatitic sources.

The following is a breakdown of the beryllium reserves based on type of deposit:

Beryl pegmatites

New England, S.D., Colo., Idaho, Nev., N. M.
8800 tons of beryl
440 tons of Be (over 1% beryl, 0.14% BeO)

Disseminated beryl in pegmatites

N.C. tin-spodumene belt only
823,000 tons of beryl
41,000 tons of Be (0.4% beryl, .056% BeO)

Beryl pegmatite

Boa Vista, Brazil
350,000 tons of beryl
av. 3% beryl

Beryl-pollucite pegmatite (a U.S. source)

Bernic Lake, Manitoba, Canada
600,000 tons of ore (now one million tons)
av. 0.21% BeO

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Bertrandite-bearing greisen deposits

Lake George area, Colorado
Large reserves, not established
Assay data variable

Bertrandite-bearing tuff

Topaz Mountain area, Utah
4,500,000 tons of ore (probably)
av. 0.5% BeO

Phenacite-bertrandite-fluorite-tungsten shoots

Mt. Wheeler area, Nev.
Approximately 50,000 tons of ore
av. 0.5% BeO or better

Primary bertrandite with fluorite in limestone (potential U. S. source)

Aguachile, Mexico
Large reserves not yet estimated
av. 0.27% BeO

Helvite-bearing skarn

Iron Mt. area, N. M.
Data not immediately available

Chrysoberyl-bearing sills

Clark County, Nev.
New discovery
est. 7000 tons of BeO

Berylite in metamorphic complex (potential U. S. source)

Seal Lake, Labrador
3,000,000 tons of ore (probably)
av. 0.5% BeO

Minification

Work is being continued by the Bureau of Mines on the extraction
of beryllium from low-grade source materials.^(1,3) Work to improve the

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procedures for recovering beryl from the tailings of processed spodumene at Kings Mountain, North Carolina, is continuing. Hydrometallurgical methods to produce pure beryllium salts from various beryllium ores and concentrates are being developed. (4)

New beneficiation processes have been, or are being, designed for fine-grained ore as follows:

Flotation:

- (1) Van Dornick process
 - (a) Topaz Mountain bertrandite
 - (b) Brazilian beryl
- (2) USBM process, N. C. fine beryl
- (3) USBM process, Nev. phenacite, bertrandite

Chemical processes based on solubility of beryllium minerals in sulfuric acid:

- (1) Vitro process, Topaz Mt., Utah, bertrandite
- (2) USBM process, Topaz Mt., Utah, bertrandite
- (3) Brush process, Topaz Mt., Utah, bertrandite
- (4) United Technical Industries process, Topaz Mt., Utah, bertrandite.

Also, the "Mincon" process, including thermic flotation, pelletizing, sintering, and chemical treatment—designed for the Lake George, Colorado, bertrandite and beryl.

Private beryllium activity:

U. S. Beryllium Corp., with United Technical Industries

ore: Topaz Mt., Utah
treatment: sulfuric acid leach
product: BeO
present capacity: unknown
proposed capacity: 50-75 tons BeO/mo.

U. S. Beryllium Corp., with Mineral Concentrates and Chemical Co.

ore: Badger Flats, Lake George, Colorado
treatment: flotation and chemical processing
product: 20% concentrates BeO
present capacity: 7 - at Loveland
proposed capacity: 100 tons of ore/day, flotation concentrator, Badger Flats

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Beryllium Resources, Inc. (Brush Beryllium)

(project abandoned - ?)
ore: Topaz Mt., Utah
treatment: Van Dornick flotation
product: 5% concentrates
present capacity: unknown
proposed capacity: 250 tons ore/day

The Anaconda Company

ore: Mt. Washington, Nevada
treatment: USBM flotation
product: 15-20% concentrates
exploring for reserves

Topaz Beryllium Co., (Anaconda and Topaz Beryllium Joint Ventures)

ore: Topaz Mt., Utah
exploring for reserves

Vitro Minerals Corporation

ore: Topaz Mt., Utah
treatment: chemical processing
product: BeO
proposed capacity: 10 ton/day pilot plant

Beryllium Metals and Chemicals Corp. (Alloyd and Lithium Corp.)

ore: Kings Mt., N. C.
treatment: flotation, chemical processing, and Pechiney
product: Be, BeO concentrates
proposed capacity: development plant

Boots Mineral Company

ore: Kings Mt., N. C.
treatment: USBM flotation
product: beryl concentrates
proposed capacity: ?

General Beryllium Corp.

ore: Topaz Mt., Utah
exploring for reserves

Food Machinery and Chemical Corporation

ore: Topaz Mt., Utah
exploring for reserves

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International Minerals and Chemical Corporation

ore: Topaz Mt., Utah
exploring for reserves

Delhi-Taylor Oil Corporation

ore: Clark Co., Nevada
exploring for reserves

Beryllium Associates, Inc.

ore: Clark Co., Nevada
exploring for reserves

Standard Beryllium Corporation

ore: Brazil
treatment: Van Dornick flotation
product: 12% concentrates (estimated)
proposed capacity: 2500 tons/year, concentrates

Dow Chemical Company

ore: Coahuila, Mexico
exploring for reserves

Refining

The development of high-purity beryllium is considered important for two reasons: (1) high-purity materials are needed to study and evaluate mechanisms of flow and fracture and to determine mechanical and physical properties, and (2) many workers hope that the use of high-purity beryllium will solve many of the problems preventing the use of beryllium as an engineering material.

The Air Force has two programs in this area; one at Nuclear Materials and Equipment Corporation for the preparation of pure beryllium metal by the iodide decomposition method (now completed), and one at Nuclear Metals for

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for the preparation and evaluation of pure beryllium made by distillation techniques.⁽⁴⁷⁾ Nuclear Metals is also working on zone refining techniques for the AEC.⁽⁸⁸⁾ Franklin Institute is preparing and evaluating high-purity beryllium under Navy sponsorship.⁽⁸⁰⁾ Zone refining of vacuum-cast, vacuum-distilled and Pechiney SR bars has been studied. This work is being continued to study plastic flow and deformation of high-purity beryllium. Distillation and zone refining techniques have produced high-purity metal, but iodide decomposition has not been successful.

The Bureau of Mines is conducting research on preparation of high-purity beryllium by electrochemical processes in molten salts.^(2,5)

Melting and Casting

Two programs concerning this area of research have been identified. The Beryllium Corporation has conducted a study of beryllium casting for the Air Force.⁽³²⁾ The techniques developed relied on thermal gradients within the mold to control directional solidification and eliminate centerline shrinkage. Grain refining additions were also evaluated and the products extruded at 1850 F.

Electron-beam melting of beryllium along with a number of refractory materials has been investigated by the Mallory-Sharon Metals Corporation.⁽³⁸⁾ In general, the quality of the electron-beam melted material was good but no improvement in tensile properties was noted.

Primary Working

Thirteen programs have been identified as related to the primary working of beryllium. Nuclear Metals, Inc., is presently conducting

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program concerning the production and evaluation of distilled high-purity beryllium for the Air Force.⁽⁴⁶⁾ This effort is a portion of a renewal of the major Air Force program coordinated by Nuclear Metals. It is particularly noteworthy that joining studies have been discontinued in the renewed research effort and the remaining subcontracts are devoted to flow and fracture, structures, and fine-grained powder materials. It is apparent that the over-all program is directed toward a more basic understanding of beryllium metal and the effects of impurities.

The Beryllium Corporation has conducted an investigation for the Air Force on the development of techniques for producing structural shapes.⁽³⁵⁾ Oxide content of the final product was of major interest, since it was related to the tensile properties of beryllium.

The Brush Beryllium Corporation is currently studying the rolling of improved beryllium sheet in an Air Force-sponsored program.⁽³⁷⁾ The investigations are aimed at producing isotropic ductility in the sheet material. The third dimensional ductility of commercial cross-rolled beryllium sheet was 0.55%. Average biaxial ductility of 0.93% was obtained by annealing at 2020 F for one hour.

Another program at Brush Beryllium Corporation is devoted to processing and fabrication techniques for promising intermetallic compounds.⁽⁴⁸⁾ Beryllides with good high-temperature properties have been screened and the beryllides of niobium and tantalum were found particularly attractive.

A detailed study of the forging of beryllium is being conducted by the Ladish Company for the Air Force.⁽²⁹⁾ This program has involved basic forging studies, jacketed forgings, and more recently ~~have forging with~~ the appropriate support members. The developments from this program have been successful in fabricating both shallow and deep cavity items.

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A Navy-sponsored program at the Brush Beryllium Corporation concerns the drawing of fine beryllium wire.⁽⁷⁹⁾ Initially, QW material was evaluated with considerable effort in die lubricants and die design. A recent extension of this program involves the drawing of zone-refined beryllium into polycrystalline wire.

Morair has conducted a study of extruding beryllium into structural shapes for the Air Force.⁽³⁰⁾ This effort is directed toward the development of methods for providing beryllium components for spacecraft. Of particular interest was the drawing of extrusions to thin uniform complex shapes.

The extrusion of beryllium by hydrostatic pressure was investigated by Nuclear Metals, Inc., in a program sponsored by the AEC.⁽⁸⁷⁾ Attempts to use liquid lead were unsuccessful. In general, no advantage in extrusion pressure was gained in this concept.

A unique form of beryllium tubing which contained spiral fins prompted the development of several fabrication methods. In a contract with AEC, General Nuclear Engineering Corporation required this form of beryllium for their gas-cooled reactor project.⁽⁹⁰⁾ A subcontract with Sylvania Electric Products, Inc., concerned fabrication of such tubing by hot isostatic pressing of powders and also Dynapak extrusion.⁽⁹¹⁾ Both approaches were found to yield a product requiring a minimum of machining. Fabrication of such tubing by warm extrusion was studied by The Brush Beryllium Corporation and was found highly successful.⁽⁹²⁾ The reactor project was suspended in mid 1961; however, the warm extrusion program was continued under AEC sponsorship.

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An internal program at the U. S. Naval Ordnance Laboratory concerns the properties of composites of beryllium wire and epoxy resins.⁽⁸²⁾ This program will yield basic information on this system.

The Martin Company has conducted a program on the evaluation of structural beryllium.⁽³⁴⁾ The relation of bend test properties to various means of fabrication was established.

As a part of the Gas-Cooled Reactor Program at Oak Ridge, beryllium tubing from various suppliers and as-fabricated by different methods has been evaluated.⁽⁹⁴⁾ Properties of such materials to 700 C are being compared.

Secondary Working

Five contracts involving secondary fabrication of beryllium materials under sponsorship of the Air Force have been identified. A program on theoretical formability of sheet materials at Chance Vought has concerned beryllium in addition to refractory metals and high-temperature alloys.⁽⁴⁵⁾ Minimum bend radii for various thicknesses as a function of grain orientation and metal thickness have been established.

The feasibility of threading beryllium has been established by the General Electric Company in a recent study.⁽³³⁾ Their effort concerned internal thread evaluations and appropriate torque and tensile tests.

Aerona Manufacturing Corporation has investigated the preparation and brazing of curved composite honeycomb structures with beryllium facings.⁽⁵⁷⁾ Internal honeycombs considered in their research were Inconel and A-286. More recently, zirconia coatings for beryllium have been considered in composite evaluations.⁽⁵⁷⁾ This work is directed toward developing reinforced load-bearing heat shields.

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A program at The Brush Beryllium Company has concerned the fabrication of shapes from beryllide materials by mechanical working techniques.⁽⁴⁸⁾ Plastic deformation limits are being established by a variety of fabrication methods.

Powder Metallurgy

Powder metallurgy remains at present the major method of producing beryllium components. Thus, even though there are few projects which can be considered as powder metallurgy projects, the use of powder techniques may be assumed for a large number of projects listed in this report. The Naval Bureau of Weapons has sponsored work at Armour Research Foundation⁽⁷⁷⁾ on the development of ductile beryllium composites. The technique investigated consists of liquid phase sintering in such a manner that beryllium powder is enclosed in a ductile skeleton of aluminum-silver alloys. On a NASA purchase order, the American Machine and Foundry Corporation has fabricated beryllium components of beryllium powder by plasma spraying followed by isostatic pressing. The Air Force is sponsoring development work on beryllium powder at Vitro Laboratories.⁽³⁶⁾

Joining

Nine contracts have concerned the welding or brazing of beryllium components. Work done on brazed beryllium sandwich construction by General Dynamics/Fort Worth was reported to the Air Force on a contract to compile unpublished materials information.⁽⁵⁰⁾

The Brush Beryllium Company has conducted a study of fusion welding as a part of the Beryllium Management Program coordinated by Nuclear Metals

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Inc.⁽⁴⁷⁾ In this investigation, particular emphasis was placed on the effects of post heating variables and impurities. Vacuum filler wire coatings were utilized and their effects on subsequent weldments established. A portion of an internal program at Union Carbide Nuclear Company has involved the fusion welding of beryllium also.⁽⁹⁹⁾

Resistance welding of beryllium sheet (0.040-inch thick) has been investigated by Rensselaer for the Air Force.⁽⁴⁷⁾ Defect-free weldments were achieved by using a 1500 lb forging force and a long post-heating cycle. As a part of their same program, resistance brazing of 0.020-inch sheet was briefly evaluated using silver and a silver-copper eutectic alloy braze.

Forge welding has been investigated by The Brush Beryllium Company in conjunction with the Beryllium Management Program.⁽⁴⁷⁾ In their effort, improvement of welded properties was sought through the refinement of grain structure within the welds. Mechanical working by planishing and a form of ring rolling were evaluated.

Pressure bonding of beryllium components in a beryllium-uranium dioxide composite fuel plate is being investigated at Battelle.⁽⁹⁸⁾ This program, being conducted for the AEC, has yielded high integrity bonding of beryllium at 1550-1650 F and 10,000 psi. Optimum surface preparation methods and barrier coatings for UO₂ in this system were established.

Magnetic force welding of beryllium has been demonstrated by General Electric, Hanford, in an AEC contract.⁽⁹³⁾ Basic techniques developed for SAP alloys were used to briefly examine the joining of beryllium fuel rod end caps. The method was found highly successful.

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Aeroprojects, Inc., has conducted a study of ultrasonic welding of beryllium.⁽⁴⁷⁾ This contract which was part of the Beryllium Management Program concerned the effects of clamping force and power on the weld characteristics. It was concluded that crack-free welds of high integrity were possible.

A program has been initiated by the Hamilton Standard Division, United Aircraft Corporation, to investigate electron-beam welding of beryllium for the Air Force.⁽⁵⁹⁾ It is intended that high-voltage equipment will be evaluated in joining 0.040-inch sheet material.

Brush Beryllium has completed a program on the brazing of beryllium in conjunction with the Beryllium Management Program.⁽⁴⁷⁾ This effort primarily concerned the development of a silver brazing technology and a more detailed evaluation of the effects of post-brazing heat treatments.

The use of beryllium in brazing alloys for joining Zircaloy 2 has been studied by General Electric, Hanford.⁽⁹²⁾ A zirconium-base alloy containing 5 w/o beryllium has been established for production of the NFR components.

In general, the joining of beryllium components has been approached through evaluation of conventional joining methods as applied to present-day commercial beryllium. It is likely that improvement in commercial beryllium products will improve joining, primarily through increased purity. It is interesting to note that currently very little work is being done in joining.

Metallography and Structure

Most of the metallographic studies being made in active programs are in direct support of projects for improving mechanical properties. A

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fundamental study of dislocation structure at Franklin Institute, sponsored by the Navy,⁽⁸⁰⁾ has been directed toward a study of impurity precipitation and observations on the operative glide system. Two Air Force projects are concerned with the effect of grain refinement. One of these projects is being conducted at Brush to study grain refinement in weldments, and the other project involves an evaluation of fine-grained, high-purity beryllium at Nuclear Metals.^(40,47) Another Air Force-sponsored project on welding (at RPI) involves a study of silver and silver-copper eutectic brazed beryllium joints.⁽⁴⁷⁾ Lockheed is studying surface damage (twins and cracks) in both hot-pressed and hot-rolled material in another Air Force-sponsored project.⁽⁴⁷⁾ Also, studies involving electron-microscopy examination of BeO-beryllium interfaces are supported at Manufacturing Technology Laboratories by the Air Force.⁽⁴⁷⁾ Oak Ridge National Laboratory is studying the effect of irradiation on the structure of beryllium which can change due to an α reaction which forms helium in the metal.⁽⁹⁵⁾ Nuclear Metals has used metallographic and X-ray techniques to study aging and strain aging in beryllium.⁽⁴⁷⁾

Transformation and Resulting Structures

Five contracts have been identified which concern this general area of beryllium metallurgy. A program at Nuclear Metals, Inc., conducted for the AEC was devoted to a study of the stability of the high-temperature beta phase.⁽⁸⁷⁾ Partial phase diagrams were established for a number of binary systems in an effort to identify beta stabilizers and subsequently yield ductile beryllium-rich alloys. Electro-Optical Systems studied the effects of rapid quenching on various beryllium binary systems.⁽⁵³⁾

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Another program at Nuclear Metals, Inc., concerned the study of gases in beryllium as a research effort for the Air Force.⁽⁵¹⁾ Rates of absorption and diffusion were established for oxygen, hydrogen, and nitrogen. This basic study was directed toward determining conditions necessary to break down the subject gas systems.

Lockheed has completed a study of beryllium surface damage as a part of the Beryllium Management Program.⁽⁴⁷⁾ Twins and surface cracks were identified and the necessary processing to insure their removal were established.

A recent summary of radiation effects compiled by Battelle Memorial Institute for the Air Force discussed the behavior of beryllium.⁽⁵⁰⁾ Embrittling effects resulting from the n, α reaction and formation of helium bubbles at grain boundaries was noted. Heating conditions necessary to produce this effect were defined.

Physical Properties

Thirteen research contracts have been identified in the area of physical property measurements on beryllium. A compilation of aircraft materials data by North American Aviation, Inc., includes previously unpublished data on beryllium alloys.⁽⁵²⁾

The diffusion of oxygen, hydrogen, and nitrogen in beryllium has been investigated by Nuclear Metals, Inc., for the Air Force.⁽⁵¹⁾ These mechanisms were determined as a function of pressure and temperature.

A program on the thermal and electrical conductivity of irradiated beryllium and transition metals was established at Watertown Arsenal.⁽⁶⁸⁾ As yet, no work has been completed on beryllium due to the impure nature of the initial samples.

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The thermal expansion of high-temperature materials including beryllium is being investigated by the University of California, Livermore, for the AEC.⁽⁹⁷⁾

Southern Research Institute has conducted a program to measure the thermophysical properties of selected materials above 2000 F.⁽⁴⁹⁾ These properties include thermal expansion, total normal emissivity, and viscosity in the molten state. In the work to date, no beryllium materials have been evaluated although it is intended that they will be included.

An Army-sponsored program at the Arthur D. Little, Inc., concerns the high-temperature vapor-phase thermodynamics on light metals, including beryllium; it is currently active.⁽⁷²⁾ Of particular interest are the metal-oxygen-hydrogen systems.

The University of Chicago is investigating advanced energy transformation systems in an Army-sponsored program.⁽⁶⁹⁾ This effort involves quantum mechanical calculations on several beryllium compounds to provide a basis for determination of their thermodynamic properties.

Optical properties of beryllium in addition to other light metals are being investigated by the General Atomic Division of the General Dynamics Corporation.⁽³⁸⁾ The properties of interest in this effort were photon absorption coefficients and mean opacities. Both temperature and density were varied in these measurements.

Beryllium and beryllium-copper have been evaluated in a supersonic air jet in a study at Langley Research Center. A variety of conical models at 4000 F and Mach No. 2 were evaluated to establish the relative worth of the two materials as heat sinks.

The effects of nuclear radiations on beryllium have been summarized with respect to density changes in a compilation by Battelle Memorial Institute.⁽⁵⁰⁾ Post-heat treatments to 995 C after fast flux exposures of 1×10^{21} ncm⁻² have resulted in density decreases of 20 per cent.

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Several Air Force contracts are devoted to evaluations of beryllium alloys, primarily beryllide compounds. Promising compounds have been characterized by The Brush Beryllium Company with particular emphasis on alloys with niobium and tantalum.⁽⁴⁸⁾ In another contract at Brush, impact properties, thermal shock, and oxidation resistance at temperatures in excess of 2500 F have been determined for beryllide and silicide materials.

Mechanical Properties

A great deal of the research being conducted at present involves a determination of mechanical properties of beryllium and the effect of processing variables, purity, etc., on the mechanical properties. It would be expected that considerable research would be required since changes in purity, grain size, and grain orientation are known to affect the mechanical properties, and undoubtedly there are other factors as well.

Most of the research is being supported by the Air Force. The Air Force approach appears to be primarily one of determining the effect of processing variables on the mechanical properties and attempting to establish procedures whereby usable beryllium can be produced with reproducible mechanical properties. Structural design and theoretical formability data are also being collected. The Air Force-sponsored work includes one program at Brush to develop beryllium sheet with high mechanical strength and an improvement in the Z-axis ductility,⁽³⁷⁾ a program at Nuclear Metals to determine the effect of rolling variables on the yield strength of beryllium, a study of the flow and fracture characteristics of beryllium,⁽⁴⁷⁾ a program to determine the effect of voids and oxide content on the mechanical properties,⁽⁴⁷⁾ a program at Martin⁽³⁹⁾ to evaluate and characterize structural beryllium sheet made by three different techniques, and an in-house

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program⁽⁶¹⁾ to compare hot-pressed beryllium to hot-pressed and extruded beryllium. The Air Force is also sponsoring a project at Lockheed⁽⁴⁴⁾ to obtain structural design data and a project at Chance Vought on theoretical formability.⁽⁴⁵⁾ Some information on beryllium will also be obtained by the Air Force under a contract to North American Aviation to collect unpublished materials data from aircraft companies.⁽⁵²⁾ The Air Force has also supported two projects at Brush Beryllium to obtain the mechanical properties of the more promising beryllides.^(42,48)

The Navy is actively sponsoring work at Brush Beryllium to improve mechanical properties by developing high-strength beryllium wire.⁽⁷⁹⁾ At the Naval Ordnance Laboratory composites made from beryllium wire are being studied, and they also sponsored work at Armour to produce ductile beryllium composites of beryllium in a ductile metal skeleton.^(82,77)

The AEC is interested and is sponsoring work on the creep stress rupture, and fracture of beryllium with particular reference to tubes and finned tubes.⁽⁹⁶⁾ They are also supporting studies on the effects of irradiation on the strength of beryllium. This work is all being done at Oak Ridge.⁽⁹⁵⁾

Corrosion

Corrosion resistance of beryllium is important in particular applications and the research in this area is generally directed toward a particular use. Lockheed has studied the electrolytic polarization of beryllium in a number of unstirred aqueous solutions.⁽⁶⁵⁾ They found that activation and attack occurred in the presence of Cl^- , ClO_3^- , F^- , and SO_4^{--} . The AEC is sponsoring work at the University of Missouri on the corrosion of nuclear metals, including beryllium.⁽⁸⁵⁾ Basic reactions of dissolution. **CONFIDENTIAL.**

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the effect of added salts, and the extent of polarization are being studied as related to the behavior of metals, oxides, and nitrides in hydrofluoric and other inorganic acids. The AEC has also sponsored work at Atomics International to test beryllium in liquid sodium, (83) and work at Oak Ridge to resolve the unpredictable nature of beryllium corrosion in wet CO₂. (99) The reaction of beryllium with uranium carbide was also investigated. Brush Beryllium has studied the oxidation resistance of beryllides at high temperatures in an Air Force project. (48) The Marshall Space Flight Center of NASA had to develop an anodic coating for gyroscope components in order to prevent problems resulting from extremely small amounts of corrosion products. They also found it necessary to specify virgin metal powder for production of the components.

Corrosion of beryllium in marine atmospheres has been a problem in gyroscopes. This problem was studied also by the Bureau of Standards at the request of the Bureau of Ships who studied beryllium as a possible component of deep-diving submarines.

Inspection and Control

Texas Nuclear Corporation is currently investigating the activation analysis of high-purity beryllium for the Air Force. (55) Initially, a theoretical study is being made and equipment developed to yield techniques for the analysis of ultrapure beryllium.

Inspection criteria are being established in a study of beryllium tubing at Oak Ridge. (94) This work is primarily concerned with the evaluation of tubing from various suppliers.

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Toxicology

The toxicological effects of beryllium are being investigated by the Kettering Laboratory, University of Cincinnati, in a contract for the Air Force.⁽³¹⁾ In the course of developing useful information for safeguarding industrial personnel, a workshop on the subject has been conducted. Attempts have been made to identify the various beryllium materials with respect to the evidence of pulmonary disease.

Beryllium contamination resulting from its use in high explosive assemblies has been evaluated by the University of California, Livermore.⁽¹⁰¹⁾ It was established that such contamination is confined within a few hundred feet of the firing point.

Toxic hazards of beryllium in solid-propellant rocket motors are also being examined.^(21,16) Testing also has been done both in scaled chambers and in open air by various organizations such as Atlantic Research Corporation, Aerojet-General Corporation, Hercules Powder Company, Brush Beryllium Company, Dow Chemical Company, and by the Air Force. Initial tests have indicated that mixer fires or launch failures may not be a serious hazard.

Midwest Research Institute is examining the toxicity of single doses of various beryllium compounds such as the halides and the hydride.⁽⁶⁰⁾

The Kettering Laboratory examined beryllium-containing glass fiber and determined that this material presented no toxicity hazard.

Nonmetallic Forms

The most important nonmetallic form of beryllium is the oxide, and this form probably accounts for more consumption of beryllium than the metallic form.

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Other beryllium compounds of interest are the refractory inter-metallics, beryllides, and the group of compounds—hydrides, borohydrides, and hydride-hydrocarbon polymers, which along with alloys of beryllium with lithium or aluminum are of interest as fuels for rocket propellants. These are discussed more fully in the section on propellants.

Applications of beryllium oxide are:

- (1) Refractories
 - a. Pure BeO
 - b. Composites with tungsten
- (2) Electronic components
- (3) Nuclear reactors
 - a. Fuel elements
 - b. Structural parts
- (4) Fibers for reinforcement of structural composites
 - a. Monocrystalline filaments
 - b. High-modulus glass fiber

Beryllia, because of its high melting point (2550 C), and good chemical stability is used as a refractory in many specialized furnaces and in other applications where refractoriness, particularly in oxidizing atmospheres, is important. An outstanding characteristic of BeO is very high thermal conductivity at temperatures below 1000 C. Thermal conductivity increases with decrease in temperature and becomes extremely high at cryogenic temperatures.

Composites of BeO and tungsten containing different proportions of the components have been examined for potential use as rocket nozzles or re-entry bodies. Small amounts of BeO in tungsten improves thermal shock and imparts some increase in heat capacity per unit weight. BeO and BeO-W composites have been only moderately successful in rocket nozzles, however. BeO-W composites

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were made by Bendix Products Division and were tested in several stages of Minuteman. BeO and BeO-W composites also were tested in rocket nozzle inserts in an Army-sponsored program.⁽⁷¹⁾ National Beryllia Corporation made BeO-W composites with graded compositions varying from pure BeO to pure tungsten, on a Navy contract.⁽⁷⁵⁾

Beryllia is potentially useful as insulators in high-performance electronic components because of its high thermal conductivity combined with high electrical resistivity. Armour Research Foundation, under NASA sponsorship, is working on high-temperature BeO insulators for electrical applications.⁽¹⁰⁴⁾ The Army Signal Corps is interested in this application but it is not doing work at the present time.

Some of the factors that account for the potential of BeO in nuclear applications are:

- (1) BeO is more suitable in small-sized reactors than graphite. Consequently BeO may be used as a moderator and also as structural parts in small portable nuclear reactors.
- (2) BeO is more suitable than graphite in systems employing oxidizing coolants, which are likely to be used in airbourne power plants. At temperatures above 2500 F, however, BeO reacts with water vapor to form a volatile hydroxide.
- (3) In areas at temperatures below 2000 F, BeO is stronger than graphite and would be a more efficient structural member. At high temperatures, BeO has poor creep resistance.
- (4) BeO can be combined with fuel as a reflector.

Research programs sponsored by the Atomic Energy Commission on BeO are directed toward the following problems:

- (1) Making high-purity material (less than 1000 ppm metallic impurities)
- (2) Improving uniformity (reproducibility)
- (3) Determination of mechanical and physical properties

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- (4) Improvement of thermal shock at high temperatures
- (5) Determination of the behavior of Be in radiation environment (formation of He by the $\text{Be}^9, \alpha\text{-}\alpha$ reaction)
- (6) Making powder properly
- (7) Study of decrepitation of BeO by a phase transformation above 2000 C

Areas where AEC-sponsored work is being done on BeO are:

Non-Fuel Research

Oak Ridge National Laboratory
Atomics International

Fuel Research

Livermore Radiation Laboratory
Pratt & Whitney Co., Inc.
General Electric Co.
General Atomics Division of General Dynamics.

The Air Force is sponsoring work at the National Beryllia Corporation to develop filaments of monocrystalline beryllium oxide.⁽⁵⁴⁾ It is hoped that such fibers will be useful as reinforcements for structural composites.

In work to develop glass with a high modulus of elasticity, it was found that additions of BeO were the most effective in increasing the modulus without a proportional increase in density. High-modulus glass fiber was desired for structures such as rocket-motor cases. However, work on high-modulus glass-containing BeO was essentially terminated with the completion of an Air Force-sponsored project to develop high-modulus glass fiber at Owens Corning Glass Corporation.⁽⁵⁵⁾ Owens Corning now offers a high-modulus, BeO -containing glass (YK-31A) as a commercial product, but it is expensive and the high cost, coupled with a fear of toxicity from the contained beryllium, has deterred its use.

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potential uses for BeO are as a flake or fiber reinforcement which is being investigated by National Beryllia Corporation under Air Force sponsorship.⁽⁵⁴⁾ National Beryllia Corporation has also worked on BeO radomes under Navy sponsorship;⁽⁶¹⁾ however, there is doubt that BeO can compete with Al_2O_3 for this application.

General Electric Corporation, under NASA sponsorship, is investigating BeO binaries for potential use as energy storage materials in solar thermionic power systems.

Work on beryllides, which were of interest as structural materials because of their high-temperature strength, low density, and oxidation resistance, was supported by both the Atomic Energy Commission⁽⁸⁹⁾ and the Air Force.^(42,27) However, properties such as brittleness and marginal thermal shock resistance have deterred continuation of work on these materials.

Applications

The properties of beryllium metal which make it of potential use are:

- (1) Exceptionally high modulus of elasticity to weight ratio
- (2) High heat capacity per unit of weight
- (3) Nuclear properties, including transparency to X-rays
- (4) High chemical energy per unit of weight coupled with low atomic mass.

As a result of the high modulus of elasticity-to-weight ratio, beryllium is useful in compressively loaded structures such as intermediate stages in rockets, fins, and other aerodynamic structures such as the antenna for the Telstar satellite. Beryllium is also used extensively in gyroscopes.

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~~CONFIDENTIAL~~ The high capacity of beryllium per unit weight has accounted for its application in re-entry bodies and in interest in its application as an ablative.

The nuclear properties of beryllium account for its study by the Atomic Energy Commission. However, the transparency of beryllium to X-rays probably accounts for its application in a satellite to detect nuclear explosions (Vela Hotel).

The high chemical energy of beryllium accounts for interest in its use in rocket propellants.

Some of the systems in which beryllium is employed are discussed below. Since the application of beryllium in propellants is of major interest because of the large quantities of metal required for such applications, this area is discussed somewhat extensively.

Gyroscopes

NASA has completed work and NASA and the Army are using beryllium for gyroscope components for the Pershing and Saturn rockets.

Heat Sinks

Beryllium was used as a heat sink in several of the Project MERCURY capsules. These beryllium bodies weighed approximately 1000 lbs. Capsules with beryllium heat sinks were confined to firings with the Redstone rocket and none using beryllium were orbited.

Beryllium also is used in the re-entry body of Folaris A1 and A2, but probably will not be used in A3.

Beryllium also is being used for the solar cell boards in the Orbiting Geophysical Observatory (OGO Satellite). While beryllium's high heat capacity

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was a factor, a major consideration in this application was the close match in thermal expansion with that of silicon. Approximately 72 square feet of 0.043-inch thick beryllium sheet will be used in each of 5 OGO satellites to be built by the Space Technology Laboratories.

NASA has also examined the heat-sink properties of beryllium for potential use in a 4000 F supersonic air jet.

Structural

At the Space Technology Laboratories, beryllium is being considered for use as a structural member, skins, panels, and shielding on Vela Hotel, if fabrication problems can be worked out. Beryllium may be used in honeycomb panels, as thin sheet, and as threaded fasteners.

Beryllium will probably be used by Lockheed in the booster-sustainer interconnect structure for SAMOS. This may employ structures up to 72 inches in diameter, 36 inches high, and 0.10 wall thickness.

Beryllium, when fastened to aluminum picture frames may be used as interstage structures in the Minuteman.

There is also a possibility that beryllium tubing will be used for sensor booms in the Orbiting Geophysical Observatory (OGO satellite).

Beryllium is being considered as the outer shell of nozzles for third-stage Minuteman.

Beryllium composites also are being developed by the Air Force for re-entry bodies where beryllium is not used as a heat-sink nose cone. (57)

Nuclear

The AEC has supported work at Atomic International to develop beryllium as a reflector control material for CNR reactors. ~~Positive reports~~

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of beryllium metal were supplied by the Beryllium Corporation to be used as reflector elements in the advanced test reactor to be installed at the National Reactor Testing Station in Idaho. Beryllium probably is also being used as a moderator and as shielding in the NERVA project.

The AEC also has supported work at Oak Ridge National Laboratory to develop finned beryllium tubing as fuel element cladding for the gas-cooled reactor program.

Large cones of beryllium compose parts for the Vela Hotel satellite. The transparency of beryllium to X-rays and opacity to visual light may indicate its application as shielding for photomultiplier tubes in X-ray detection systems.

Rocket Propellants

There is a very real interest in the use of beryllium and beryllium compounds in rocket propellants today. This interest is the direct result of the quest for higher specific impulse, I_{sp} , in both liquid and solid propellant motors. The current interest in beryllium is not new. It has been an accepted fact, at least since 1946, that to obtain the maximum impulse a metallic fuel had to be incorporated along with the oxidizer and binder that make up the conventional solid propellant. Specific impulse is approximately proportional to $\sqrt{\Delta H/M}$ where ΔH is the difference in enthalpy of combustion gases at the rocket nozzle and in the rocket chamber, and M is the average molecular weight of the combustion gases. It has always been obvious, therefore, from an examination of the periodic table that Be, Li, B, Al, and Mg, have, in the order shown, the most promise as metallic fuel additives for increasing the specific impulse of propellants. Until the past few years, the use of beryllium has been avoided and work has been concentrated on the other

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far most of this concentration has been with the addition of aluminum powder. It is almost standard practice to add aluminum to all high-energy solid-propellant formulations today.

With respect to Li, B, Al, or Mg, the maximum increases in specific impulse have essentially been achieved. To obtain higher impulses with present day formulations, it was therefore necessary to consider the pros and cons of using beryllium. The biggest argument against beryllium has been the toxic nature of beryllium exhaust products, namely BeO. Beryllium also is relatively expensive. The main argument for beryllium is that in solid propellants, impulses of the order of 280-285 lb-sec/lb appear possible. This is about 20 lb-sec/lb greater than is currently achievable with aluminum on comparable propellants.

Calculations also indicate that very high specific impulses are possible by additions of beryllium to liquid propellants. The Be-O-N system, which has a maximum specific impulse at 26.6 wt per cent or 88 volume per cent hydrogen, has a calculated value of 456 sec. However, the potential difficulties in using this propellant combination which involves two cryogenic materials plus a high melting toxic metal are formidable. An experimental program is under way at Atlantic Research Corporation to verify the theory involved in the tri-propellant approach. (20)

In solid propellants, beryllium can be used in essentially two ways. It can be used as a fine, metallic powder, just as aluminum is used today, or it can be compounded as a hydride, borohydride, or as a beryllium-hydrocarbon polymer. Beryllium metal powder can be substituted for aluminum powder in almost any of the presently used solid propellant formulations without serious modifications in production techniques or equipment employed, except, of course, for precautions against toxicity.

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It is estimated by the Air Force that substitution of beryllium for aluminum in some solid propellants may begin in 1962. The development of a stable form of aluminum hydride has also opened the possibility of using this type of fuel in advanced solid propellants. Beryllium metal and aluminum hydride have comparable impulse values in equivalent propellant systems. Aluminum hydride, however, is in the very early stages of development and the Air Force does not expect it to be employed in propellants before 1963.*

Most of the interest and work today is on adding metallic beryllium instead of aluminum to standard ammonium perchlorate-hydrocarbon binder, or double-base propellants. Most of the current impulse data is the result of calculations, not experiments. Calculations are carried out, using available free energy data, on the known oxidation products of beryllium. The calculations are usually for solid-propellant formulations containing 10-18 per cent beryllium and are usually compared with calculated data for aluminum-containing propellants which have about the same flame temperature. Beryllium-containing propellants generally have higher flame temperatures than aluminum propellants (when the solids-loading, metal + ammonium perchlorate, is kept constant). This means that nozzle erosion problems may be more severe with beryllium propellants.

Atlantic Research Corporation and Aerojet-General Corporation have built "scrubbing" facilities for firing beryllium propellants. Other organizations such as Hercules Powder Company at Magna, Utah, probably have also built such facilities. It is very probable that in 1962, much more firing data on beryllium

* A Review of the High Energy Solid Propellant Research Effort, J. T. Edwards, R. L. Geisler, 6503rd Test Group (Dev.), Air Force Systems Command, p. 3. Bulletin of the 18th Meeting JANAF-ARPA-NASA Solid Propellant Group, June, 1962, Vol. 1.

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propellants will be come available. These data will show how far the calculated Isp data deviate from actual firing data, and in this way indicate whether there are big, unknown gaps in present knowledge of the thermodynamic properties of beryllium oxidation products. There is, for example, indication that the burning efficiencies of beryllium are not so high as aluminum. If the firing data prove nearly as encouraging as the calculated data for the direct addition of beryllium powder, we may expect a real push on the program.

Potentially, the use of beryllium hydride or beryllium hydride-hydrocarbon (or fluorocarbon) polymers is even more exciting than the use of beryllium metal. Specific impulses of the order of 300-320 lb-sec/lb have been calculated for such propellants. The density of beryllium hydride is relatively low, about 0.66 gm/cc compared with beryllium metal at 1.85 gm/cc, but for high altitude (upper stage) use, there is still a net gain in specific impulse. This is true because impulse is related to density in accordance with the equation:

$$\text{Effective impulse, } \Delta t = I_{sp} \left(\rho_c / \rho_o \right)^K$$

The effective impulse, Δt , is not affected severely by decreased density because K is altitude dependent. At low altitude, K = 0.6 and at high altitude K = 0.2.

Although there is now considerable work under way to develop beryllium hydride, its use in propellants is not anticipated before 1965.

Beryllium aluminum hydride is another potential high energy compound which is currently being investigated.

Most of the work on beryllium propellants is now being sponsored by the Air Force. (11,12,13,14,17,18,19,21,26,41,43,50,62,23,20,69,24,66,25) NASA and the Army (73,74,78) are sponsoring some while the Army, as far as can be determined, has no programs at this time.

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NASA, in conjunction with the Air Force, is developing the XM-85 and XM-86 which are spherical motors which will be used as the fourth stage of Blue Scout, Jr. and the large Blue Scout, respectively. (13,15,22,63,103) Both may contain beryllium in the propellants. The XM-85 will contain about 135 lbs of propellant while the XM-86 will contain about 600 lbs. This application, therefore, will not create a large demand for beryllium.

If the Air Force decides to use beryllium in the propellants in second and third stage Minutemen, which it is considering doing, requirements for beryllium metal powder will be of the order of 1,000,000 pounds per year. This demand alone would be about twice the present capacity to produce beryllium powder. Furthermore, the present commercial grade of beryllium powder may not be satisfactory and new processes as well as new plants may be required to produce it. Current specifications call for powder 17 microns and less in size (50% in the 8-10 micron range) with preferably spherical shaped particles. A prominent requirement is low oxygen content (less than 0.5% BeO), although 0.5% BeO would reduce the theoretical specific impulse only about 1/4 second.

Commercial grades of beryllium powder have the following properties:

<u>Source</u>	<u>Size</u>	<u>Cost, \$/lb</u>	<u>Oxide Content, %</u>
Brush	-325 mesh	70	1-1.5
	17 micron	80	1.5-3
	17 micron	100	1.0
	(minus fines)		
General Astrometals	5 micron	150	-
Texas Instrument	1-5 micron	100	<0.5

The principal redeeming feature of propellant-grade powder is that Al, Mg, or B as impurities would not be detrimental.

In longer range programs, the Air Force is now sponsoring a considerable amount of work on the production of beryllium hydride. (14,17,21,41) **CONFIDENTIAL** alloys of Be-Al and Be-Li is being sponsored at New York University. (12)

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Research Supported by the U. S. Bureau of Mines

1. Contract No. BM 3582
Contractor: Albany Metallurgy Research Center, Albany, Oregon
Contact: A. H. Roberson
Project Monitor: Charles W. Merrill
Dates: July 1961

Title: Metallurgy--Extractive, High Purity, Gamma Radiation, etc.

Bench-scale research will be conducted on the extraction of beryllium from low-grade source materials and on reduction to beryllium.

2. Contract No. BM 3608
Contractor: Reno Metallurgy Research Center, Reno, Nevada
Contact: T. R. Graham
Project Monitor: Charles W. Merrill
Dates: July 1961

Title: Metallurgy--Extractive, High Purity, Gamma Radiation, etc.

Investigations on preparing high-purity beryllium by molten-salt electrochemical techniques, and an evaluation of promising electrolytes and physical and chemical phenomena that affect electrodeposition and purity of metals.

3. Contract No. BM 3630
Contractor: Salt Lake City Metallurgy Research Center, Salt Lake City, Utah
Contact: B. H. Clemmons, Jr.
Project Monitor: Charles W. Merrill
Dates: July 1961

Title: Metallurgy--Extractive, High Purity, Gamma Radiation, etc.

Hydrometallurgical methods to produce pure beryllium salts from various pure beryllium ores and concentrates will be developed.

4. Contract No. BM 3688
Contractor: Tusculoosa Metallurgy Research Center, University, Alabama
Contact: C. Rumpcek
Project Monitor: Charles W. Merrill
Dates: July 1961

Title: Metallurgy--Extractive, High Purity, Gamma Radiation, etc.

Beryl concentration research will be undertaken on a test plant and laboratory scale to improve procedures for recovering beryl in a product of not less than 4% BeO from pegmatite tailings of ~~Booth~~ ^{Booth} Mineral Company's spodumene plant at Kings Mountain, N. C. Thermodynamic studies will be made of beryllium and other compounds that may be significant in beryllium extractive research.

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5. Contract No. BM 3756
Contractor: Reno Metallurgy Research Center, Reno, Nevada
Contact: T. R. Graham
Project Monitor: Charles W. Merrill
Dates: August 1961

Title: Metallurgy—Extractive, High Purity, Gamma Radiation, etc.

Limited small quantities of high-purity uranium and beryllium from molten-salt electrolytic refining techniques will continue to be supplied to UCLRL for evaluation.

6. Contract No. BM 3829
Contractor: Division of Mineral Resources, Pittsburgh, Pennsylvania
Contact: G. W. Josephson
Project Monitor: Charles W. Merrill
Dates: July 1961

Title: Resource Investigations, Technologic and Economic, etc.

Intensive search of deposits in New England stages for beryllium in new and nonpegmatite sources will be concluded. Field work shall consist of examination of deposits to determine small quantities of beryllium in rock samples followed by classifying and evaluating beryllium deposits according to mineral content, size, geologic type, location, and ease of mining and beneficiation. Search of deposits in southeast United States for beryllium will be completed.

7. Contract No. PM 3831
Contractor: Division of Mineral Resources, Bartlesville, Oklahoma
Contact: R. S. Sanford
Project Monitor: Charles W. Merrill
Dates: July 1961

Title: Resource Investigations, Technologic and Economic, etc.

A study of resources of tellurium, selenium, germanium, and beryllium in the southwest area will be made. General reconnaissance of favorable areas will be carried out. Any occurrence which warrants additional work will be examined and sampled in more detail. An examination will be made of mine tailings, particularly if pyritic, and base-metal smelter slags.

8. Contract No. BM 3833
Contractor: Division of Mineral Resources, Denver, Colorado
Contact: R. W. Geehan
Project Monitor: Charles W. Merrill
Dates: July 1961

Title: Resource Investigations, Technologic and Economic, etc.

The intensive search of Region III deposits for beryllium in new and nonpegmatite sources will be concluded. Field work will consist of systematic exploration of deposits according to mineral content, size, geologic type, location, and beneficiation and ease of mining. Exploration of the Breadpan Deposits, Gila County, Arizona, for beryllium will start.

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9. Contract No. BM 3836
Contractor: Division of Mineral Resources, San Francisco, California
Contact: W. F. Dietrich
Project Monitor: Charles W. Merrill
Dates: July 1961

Title: Resource Investigations, Technologic and Economic, etc.

Search will be made for deposits of beryllium emphasizing new and nonpegmatite sources; equipment will be used to detect and examine small quantities of beryllium in rock samples, and evaluate beryllium deposits according to mineral content, size, geologic type, location, and ease of mining and beneficiation. Occurrences will be noted of other valuable minerals associated with beryllium such as columbium, tantalum, cesium, and rubidium.

10. Contract No. BM 3838
Contractor: Division of Mineral Resources, Albany, Oregon
Contact: D. M. Bishop
Project Monitor: C. W. Merrill
Dates: July 1961

Title: Resource Investigations, Technologic and Economic, etc.

The intensive search of Region I deposits for beryllium with emphasis on new and nonpegmatite sources will be continued. An intensive search will be continued for beryllium in Alaska, especially on the Seward Peninsula with emphasis on new and nonpegmatite sources.

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Research Supported by the U. S. Air Force

11. Contract No. AF 04(611)-5081
Contractor: Convair Division, General Dynamics Corporation
Contact: R. L. Jones and R. E. Carlson
Project Monitor: J. Branigan, Edwards Air Force Base
Dates: --

Title: A Theoretical Design Study Applying Beryllium to Storable
Liquid Propellant Rocket Tankage

A metallurgical and structural design study was conducted to determine the feasibility of using beryllium for storable liquid propellant rocket tankage in the near future.

12. Contract No. AF 04(611)-6356
Contractor: New York University
Contact: Dr. C. J. Mursel
Project Monitor: Lt. R. Urbanek
Dates: February, 1962

Title: High-Energy Fuel
Development of phase diagrams for Be-Al and Be-Li systems. (Funds are being supplied by Columbia Explorations, Ltd., Van Couver, B. C., who claim to have extensive beryllium ore deposits in Canada.)

13. Contract No. AF 04(611)-7017
Contractor: Atlantic Research Corporation
Contact: J. Burton
Project Monitor: W. Bacon, DGSCP
Dates: April 1961 - October 1961

Title: Tailoring of a High-Energy Solid Propellant

Development of beryllium-containing propellant for XM-85.

14. Contract No. AF 04(611)-7027
Contractor: Metal Hydrides, Inc.
Contact: Dr. S. Johnson
Project Monitor: Lt. R. Urbanek
Dates: May 1962

Title: Development of Process for Synthesis of Beryllium Hydride
and Other Pure Metal Hydrides

Contractor reports that they have produced a pure Li_2BeH_4 .

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15. Contract No. AF 04(611)-7037
Contractor: Atlantic Research Corporation
Contact: J. Burton
Project Monitor: Lt. Hasselmann
Dates: May be completed now

Title: Initial Production of XM-85 Motors

The purpose of this project is to develop a 16-inch-diameter spherical motor for fourth stage of Blue Scout, Jr. This motor will contain about 135 lbs propellant and is designated XM-85. (It may contain a beryllium propellant.)

16. Contract No. AF 04(611)-7414
Contractor: Rocket Power, Pasadena, California
Contact: Milton Farber
Project Monitor: Curtis C. Selph
Dates: June 1, 1961 - August, 1962

Title: Study of Rocket Engine Exhaust Products

17. Contract No. AF 04(611)-7430
Contractor: Ethyl Corporation
Contact: Dr. F. Conrad
Project Monitor: Lt. R. Urbanek
Dates: June 15, 1961 - August 15, 1962 (completed May 1, 1961)

Title: Preparation and Characterization of a Light-Weight Metal Hydride

Laboratory scaleup of production of 80% pure beryllium hydride. Follow up on AF 33(616)-6505.

18. Contract No. AF 04(611)-7431, Task 30312
Contractor: Aerojet-General Corporation
Contact: Dr. Shookoff
Project Monitor: W. Bacon, DGSCP
Dates: July 1961 - February 1962

Title: Research and Development of the State of the Art of High-Energy Solid Propellants

Worked with three sizes of motors (5, 10, and 15 lb total propellant weights). Hydrazine perchlorate beryllium propellant with specific impulse of 292 lbf/sec/lbm. processed successfully in 50-gram batch size. Total of 23 firings of motors at Sacramento.

19. Contract No. AF 04(611)-7442
Contractor: Aeronutronic Division, Ford Motor Company
Contact: Dr. Hildenbrand
Project Monitor: C. C. Selph
Dates: June 30, 1961 - December 1963

Title: Thermodynamic Properties of Rocket Combustion Products

Measurement of heat capacity and heat of formation of beryllium compounds.

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20. Contract No. AF 04(611)-7449
Contractor: Atlantic Research Corporation
Contact: Joseph A. Herickes
Project Monitor: William B. Wilson, DGREE
Dates: July 1961 - June 1962

Title: Evaluation of Multicomponent Propellant Systems

Development of tripropellant system (liquid oxidizer + liquid fuel + beryllium powder). To demonstrate feasibility of using tripropellant system and to check theoretical calculations. Small motors (1000 lb thrust) will be fired in chambers.

21. Contract No. AF 04(611)-7554 (ARPA)
Contractor: Dow Chemical Company
Contact: Dr. Irish
Project Monitor: J. T. Edwards
Dates: January 1962 - December 1962

Title: Beryllium Hydride Synthesis - Beryllium Toxicity

- (a) Beryllium hydride synthesis - they have made beryllium borohydride $\text{Be}(\text{BH}_3)_2$.
- (b) Beryllium toxicity.

22. Contract No. AF 04(611)-8015
Contractor: Aerojet-General Corporation
Contact: Mr. Pippin
Project Monitor: Lt. Hasselmann
Dates: December 1961 - September 1963

Title: Development of an Advanced Propellant Upper Stage Motor (XM-86)

The purpose of this project is to develop a high performance rocket motor utilizing high-energy propellants and advanced components. It will contain a beryllium propellant. Total motor weight - 621 lbs.

23. Contract No. AF 04(611)-8130
Contractor: Atlantic Research Corporation
Contact: Charles Henderson
Project Monitor: Willard S. Bacon, DGSCP
Dates: April 1962 - April 1963

Title: Development of High-Energy Propellants

Will work on ammonium perchlorate/beryllium propellant development and on development of advanced oxidizers for use in beryllium-containing propellants. Propellant weight of 50 lbs per motor.

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24. Contract No. AF 04(611)-8179
Contractor: North American Aviation, Rocketdyne Division, Canoga Park
Contact: David Golding
Project Monitor: W. Backn, DG3CP
Dates: June 1962 - June 1963

Title: Development of High-Energy Propellants

Beryllium additives and oxidizer development. Small motors (15 lbs total propellant weight).

25. Contract No. AF 04(611)-8178
Contractor: Thiokol Chemical Company
Contact: Ernie Sutton
Project Monitor: Lt. Wayne Rowe
Dates: June 1962 - December 1963

Title: Development of High-Energy Propellants

Work will be on beryllium additives and oxidizer development. Will work with small motors containing total of 5 lbs of propellant per motor.

26. Contract No. AF 04(647)-243
Contractor: Hercules Powder Company
Contact: J. W. Sherman
Project Monitor: —
Dates: —

Title: Weapon System 133A, Third-Stage Motor

Calculations were made of theoretical Isp obtainable by using beryllium in several Hercules propellants. Studies were made of safe handling procedures associated with firing beryllium-containing propellants. A pilot model for firing motors is being designed.

27. Contract No. AF 04(647)-930
Contractor: Aerospace Corporation
Contact: E. J. Kendall
Project Monitor: —
Dates: —

Title: Beryllium-Containing Materials Program

Beryllium and its compounds are being studied to determine the degree to which they will be useful for future missile and space systems. Work has been done on optical properties of beryllia and on welding beryllia to itself and to other ceramics.

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28. Contract No. AF 29(601)-2807
Contractor: General Dynamics Corporation, General Atomic Division
Contact: J. C. Stewart, K. D. Pyatt, Jr.
Project Monitor: ---
Dates: ---

Title: Theoretical Study of Optical Properties

Photon absorption coefficients and mean opacities were calculated for H, Be, C, N, Si and Al over a temperature range of 1.5 to 34 ev and densities ranging from 10^{-1} g/cm³ downward.

29. Contract No. AF 33(600)-36795, Project 7-647
Contractor: Ladish Company
Contact: A. F. Hayes
Project Monitor: Campbell, ASRCTB
Dates: May 6, 1958 - November 19, 1961

Title: Beryllium Forging

Phase I - Basic forging studies were conducted over a wide temperature range (1300-2050 F). Sensitivity to interrupted forging and the need for lateral support were established.

Phase II - Press forging of mild steel jacketed beryllium was studied to establish conditions for optimum tensile properties (1375 F). With sufficient support in flat dies, forging temperature appeared to show no effect on forgeability.

Phase III - Bare forging was studied with support provided by an expendable hot steel die member. Successful for forging both shallow and deep cavities.

30. Contract No. AF 33(600)-36931
Contractor: Northrop Corporation, Morair Division
Contact: ---
Project Monitor: Felker, ASRCTB
Dates: May 14, 1959 - October 1962

Title: Extruding Beryllium into Structural Shapes

To develop improved methods for extruding beryllium into high-quality structural parts for future spacecraft. A secondary but important objective is to determine and then optimize variables of the extruding cycle which will improve the transverse ductility of the extrusion. A major effort is directed toward the development of methods for drawing beryllium extrusion to thin uniform complex shapes.

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31. Contract No. AF 33(600)-37211
Contractor: University of Cincinnati, Kettering Laboratory
Contact: L. H. Miller, M.D.
Project Monitor: L. J. Conlon, ASRCTC
Dates: July 1958 - April 15, 1962

Title: Toxicological Effects of Beryllium in Manufacturing

To develop sufficient industrial medical, toxicological, and industrial hygiene engineering information in usable form to safeguard industrial personnel working with beryllium materials.

32. Contract No. AF 33(600)-37902
Contractor: Beryllium Corporation
Contact: J. P. Denny
Project Monitor: A. H. Langenheim, ASRCTB
Dates: --

Title: Beryllium Casting

Methods were developed for production of sound 3-inch diameter vacuum cast billets. The technique relies on thermal gradients within the mold to control directional solidification and eliminate centerline shrinkage. Small additions of germanium, zirconium, and lanthanum have a grain refining effect but the extent of refinement is small compared to the effects of fast cooling. Copper and graphite molds were used. The fine grained castings can be hot extruded at 1850 F.

33. Contract No. AF 33(600)-38062, AT(11-1)-171
Contractor: General Electric Company
Contact: A. D. Feith
Project Monitor: --
Dates: --

Title: Feasibility of Threading Beryllium

Feasibility and necessary design parameters for threading holes in beryllium. Torque and tensile tests are described. It was concluded that internal threading is feasible.

34. Contract No. AF 33(600)-40648
Contractor: The Martin Company
Contact: C. J. Gienza
Project Monitor: F. E. Barnett
Dates: February 1960 - March 1961

Title: Evaluation of Structural Beryllium

The principal objectives of this investigation are (1) to establish a standard measure of merit for characterizing so-called structural beryllium, and (2) to experimentally ascertain the relative superiority in the structural sense of the beryllium sheet produced by three methods of fabrication, namely hot upsetting, hot pressing, and hot pressing with beryllium powder. Bend tests were found most useful to evaluate the plastic strain behavior of test materials. Results indicate ductile behavior depends on (1) degree of anisotropy, (2) the stress stage, and (3) temperature of reduction.

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35. Contract No. AF 33(600)-41959
Contractor: Beryllium Corporation
Contact: K. C. Taber and E. E. Weismantel
Project Monitor: Merkle, ASRCTB
Dates: —

Title: Development of Techniques for Producing Beryllium Structural Shapes

Low beryllium oxide products rolled sheet is preferred or higher oxide content because of property consistency. High B₂O₃ content causes increase in tensile and ultimate strengths. Increase in strength of low oxide sheet should be obtainable. Surface preparation, thermal treatments, etc.

36. Contract No. AF 33(600)-42916
Contractor: Vitro Laboratories
Contact: J. Holmgren
Project Monitor: L. C. Polley
Dates: —

Title: Submicron Powder Manufacturing Methods Development

Vitro Laboratories is now engaged in a state-of-the-art study on the production of fine powders largely in the 1000 to 100 Å range, i.e., 0.1 micron down to 0.01 micron diameter. The following are the materials to be studied: metals; aluminum, columbium, tungsten, titanium, lithium, and beryllium; oxides; iron oxide, SiO₂, Al₂O₃, ThO₂, ZrO₂, TiO₂, molybdenum oxide, columbium oxide, tantalum oxide, and tungsten oxide; carbides, titanium carbide, tantalum carbide, thorium carbide, tungsten carbide, columbium carbide, and molybdenum carbide. The ballarc process is the primary method used in this program. Initial studies concern SiO₂, Al₂O₃, ThO₂, WO₃, W, Al, and TaC.

37. Contract No. AF 33(600)-43037
Contractor: The Brush Beryllium Company
Contact: Dr. K. Wickle
Project Monitor: Hugh L. Black
Dates: July 1961 - November 1962

Title: Rolling Improved Beryllium Sheet

The program is concerned with the development of improved beryllium sheet with high mechanical properties in a flat condition with good reproducibility. A review of literature concerned with beryllium sheet production was made and in general did not yield much information. A detailed program outline was prepared. The investigation of rolling parameters has been initiated. Preliminary studies have been initiated on the isotropic ductility phase of the program. Finishing operations on currently produced beryllium sheet are being investigated.

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38. Contract No. AF 33(616)-5603
Contractor: Mallory-Sharon Metals Corporation
Contact: J. Perryman
Project Monitor: T. D. Cooper
Dates: April 15, 1958 -

Title: Electron-Beam Melting of Be, Boron, Boron Carbide, Tantalum Carbide, Tantalum Carbide, Tungsten and Zirconium Dioxide

It was found that beryllium could be deoxidized by adding yttrium to the melt. Beryllium was both arc melted and electron-beam melted. The quality of electron-beam melts was good but arc melt quality was poor. Electron-beam melting did not improve the tensile properties of beryllium extrusions.

39. Contract No. AF 33(616)-5602
Contractor: Owens-Corning Fiberglass Corporation
Contact: —
Project Monitor: G. P. Peterson
Dates: May 15, 1958 - April 14, 1959

Title: High-Modulus High-Temperature Glass Fibers for Reinforced Plastics

Investigate drawing of high modulus glass fibers and the properties of laminates reinforced with them.

40. Contract No. AF 33(616)-6413
Contractor: The Brush Beryllium Company
Contact: B. MacPherson
Project Monitor: Lt. S. S. Christopher
Dates: May 1959 - August 1960

Title: Fusion Welding of Beryllium

Background and standard conditions for fusion welding are described. The effects of post heat treating and fixturing on fusion welds were studied. Multiple pass and fillet welding were also investigated. Residual impurities and the development of beryllium filler wire with various coatings were studied in their relation to fusion welds.

41. Contract No. AF 33(616)-6505 (ARPA)
Contractor: Ethyl Corporation
Contact: —
Project Monitor: Lt. R. Urbanek
Dates: Completed

Title: Synthesis of Beryllium Hydride

Initial work to synthesize the compound in the laboratory was done on this contract.

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42. Contract No. AF 33(615)-6540
Contractor: The Brush Beryllium Company
Contact: J. Booker
Project Monitor: T. E. Lippart
Dates: May 1959 - December 1961

Title: Investigation of Intermetallic Compounds for Very High-Temperature Applications

An investigation was undertaken to determine the capability of refractory metal beryllides and silicides to serve as structural materials at temperatures in excess of 2500 F for short-time service. Impact thermal shock, and oxidation resistance of Ta_2Be_{17} and WSi_2 are reported. Vapor pressure measurements and oxidation rates for tantalum and zirconium beryllides are also included.

43. Contract No. AF 33(616)-6623
Contractor: Atlantic Research Corporation
Contact: Mr. Keith Rumbel
Project Monitor: W. Bacon, DGSCP
Dates: July 1959 - July 1962

Title: An Experimental Program to Evaluate High-Performance Solid-Propellant Ingredients

Work will include use of fluorine to get beryllium fluoride exhaust species.

44. Contract No. AF 33(616)-6905
Contractor: Lockheed Aircraft Corporation
Contact: R. F. Crawford
Project Monitor: —
Dates: February 1960 -

Title: Structural Design Data for Beryllium

Cylindrical shells 20-inch diameter, 10-inch long, and 0.020-inch thick were tested to determine failure under hydrostatic and uniaxial compression. The shell buckled at a differential pressure of 6.5 psi under hydrostatic compression followed by a catastrophic shattering of the shell. The design data predicted the pressure observed. Premature failure occurred under uniaxial loading but it was observed that premature buckling did not lead to catastrophic shattering.

45. Contract No. AF 33(616)-6951
Contractor: Chance Vought Aircraft, Inc.
Contact: W. W. Wood
Project Monitor: C. W. Douglas
Dates: February 1960 - July 1961

Title: Theoretical Formability

Work on beryllium has included the determination of the critical buckling radius as a function of metal thickness, temperature, and grain orientation. Some work has also been carried out to determine the maximum depth of joggling.

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46. Contract No. AP 33(615)-7065
Contractor: Nuclear Metals, Inc.
Contact: —
Project Monitor: —
Dates: October 1961 - April 1963

Title: Beryllium Research and Development

General areas of investigation are the production and evaluation of high-purity beryllium, flow and fracture characteristics of beryllium and production and evaluation of fine-grained beryllium. Past work has included resistance spot welding (RPI), surface defects (Lockheed), and electron microscopy (Materials Technology Laboratories).

47. Subcontracts: AP 33(616)-7065

Franklin Institute:

Study dislocations in beryllium (flow and fracture).

Lockheed:

Study of ductile-to-brittle transition (flow and fracture). Determination of effects of texture, composition, and strain rate on the properties of beryllium.

National Research Corporation:

Development of fine-grain beryllium powders.

New England Materials Laboratory:

Preparation of and evaluation of fine-grained beryllium.

Nuclear Metals, Inc.:

Development of methods of purifying beryllium, principally by distillation. Evaluation of beryllium fabricated from distilled metal. Identification of the elements that may account for room-temperature brittleness of beryllium.

Pechiney, France:

Study of recrystallization and grain growth. Determination of the role of BeO (or oxygen) in microstructures and properties of beryllium. Identification of impurities and methods of analysis such as electron micro-diffraction techniques.

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48. Contract No. AF 33(616)-7108
Contractor: The Brush Beryllium Company
Contact: R. S. Truesdale
Project Monitor: T. E. Lippart
Dates: April 1960 - September 1961

Title: Investigation of Processing and Fabrication Techniques for Promising Intermetallic Compounds and Effects Upon Thermal and Mechanical Properties

This program is for studies of the effects of processing variables upon the thermal and mechanical properties of promising intermetallic compounds, also studies of the feasibility of fabricating shapes by mechanical working techniques. Phase I consists of a characterization of some of the more promising intermetallic compounds in terms of the properties attainable in shapes larger than the laboratory specimens evaluated to date. Phase II concerns a feasibility study wherein the extent to which such materials can be plastically deformed, by various states of stress applied by forging, extrusion, etc., will be determined. Of particular interest in this work are the beryllides of niobium and tantalum.

49. Contract No. AF 33(616)-7319
Contractor: Southern Research Institute
Contact: C. D. Pears
Project Monitor: H. Marcus
Dates: May 1960 - November 1961

Title: Thermophysical Properties of Refractory Materials from 2000 F to Their Destruction Temperatures

The contractor will develop techniques for and measure the thermal expansion and total normal emissivity of selected refractory materials and ceramics in the temperature range from 2000 F to their melting points. Further, the contractor will develop techniques for and determine the viscosity of these selected materials in the molten state. The materials to be investigated will be selected from the following groups of materials: (1) oxides of beryllium, magnesium, thorium, zirconium, hafnium, and cerium; (2) carbides of hafnium, tantalum, zirconium, niobium, titanium, tungsten, vanadium, and molybdenum; (3) nitrides of hafnium, boron, titanium, and tantalum; (4) borides of hafnium, zirconium, tungsten, titanium, and thorium, and (5) tungsten, molybdenum-0.5 titanium, and niobium-0.5 zirconium.

50. Contract No. AF 33(616)-7319
Contractor: Battelle Memorial Institute
Contact: F. R. Shober
Project Monitor: —
Dates: —

Title: Effect of Nuclear Irradiation on Structural Materials

Summary of the effects of fast irradiation on the properties of structural metals and alloys. It was noted that beryllium is embrittled by the reaction which forms helium. On heating to 5000 C, helium precipitates at grain boundaries to cause embrittlement and possibly permeability.

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51. Contract No. AF 33(616)-7665
Contractor: Nuclear Metals, Inc.
Contact: J. P. Pensler
Project Monitor: C. D. Houston
Dates: June 1959 - November 1961

Title: Fundamental Study of Gases in Beryllium

The contractor will conduct research necessary to establish the relationship between the metal beryllium and the elements oxygen, hydrogen, and nitrogen when present in a wide range of concentrations and in various combinations. The rate of absorption of the gases at various pressures and temperatures by the metal shall be determined as well as the rate of diffusion throughout the material. The form in which each metal-gas combination exists shall be determined. The information derived from the above study will then be used to determine the conditions necessary to break down the metal-gas system.

52. Contract No. AF 33(616)-8009
Contractor: North American Aviation, Inc.
Contact: G. Keller, R. L. Schleicher
Project Monitor: F. Giese
Dates: April 15, 1961 - April 14, 1962

Title: Collection of Unpublished Materials Data from
Company-Sponsored Programs

The objective of this program is to obtain complete materials research and development data that have not previously been published and thus were not readily available to the Air Force and its contractors. Specifically, the work provides for the collection, compilation, interpretation, and transmittal for dissemination of unpublished materials information on metallic and non-metallics used in or being investigated for possible application in aircraft, aerospace and space vehicles, including fabrication and corrosion data. The program will obtain information on refractory, steel, aluminum, magnesium, nickel-base and beryllium alloys, honeycomb structures, welding, brazing, plastics, seals, fuels, electrical materials, ceramics, optics, heat transfer, and organic finishes.

53. Contract No. AF 33(616)-8011
Contractor: Electro-Optical Systems, Inc.
Contact:
Project Monitor: K. L. Kogola, ASHCOM-1
Dates: January 31, 1961 - February 28, 1962

Title: Investigation of the Effect of Ultrarapid Quenching on
Metallic Systems, Including Beryllium Alloys

The effect of ultrarapid quenching, as obtained by the technique recently described by Dupex, Willens, and Klement, upon the phase relationships in selected binary systems including at least six beryllium-based systems shall be determined. The beryllium systems specified are: Be-Ni, Be-Mn, Be-O, Be-Cu, Be-Si, and Be-Zn.

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54. Contract No. AF 33(616)-8056
Contractor: National Beryllia Corporation
Contact: —
Project Monitor: Frank J. Fechek
Dates: March 15, 1961 - December 1963

Title: New and Improved Reinforcements for Structural Composites

Research will be conducted to obtain and fully characterize beryllium oxide fibers for reinforcement in structural composites. Two routes for obtaining monocrystalline filaments, these being the controlled oxidation of beryllium metal vapors and the controlled vaporization and deposition of beryllium oxide powder, and a process for converting continuous polycrystalline BeO filaments into high-strength monocrystalline or quasi-monocrystalline fibers by a zone treating technique will be investigated. The fibers resulting from the above forming methods will be fully characterized as to mechanical, chemical, and physical properties in both the as-synthesized form and in structural composite materials.

55. Contract No. AF 33(616)-8160
Contractor: Texas Nuclear Corporation
Contact: J. A. McCrary
Project Monitor: Charles D. Houston, ASRCPA-1
Dates: April 15, 1961 - April 14, 1963

Title: Activation Analysis of High-Purity Beryllium

The various activation techniques used in quantitative analysis of metals will be thoroughly investigated and the most promising technique will be selected and applied to the analysis of beryllium metal. A theoretical study will be made to determine the sensitivity that can be expected and the effect that can be expected by combinations of elements. Various types of equipment will be investigated to determine the combination that can be expected to provide the desired results. A research and development program will then be initiated to develop and apply the technique to the analysis of ultrapure Be.

56. Contract No. AF 33(616)-8364
Contractor: Ethyl Corporation
Contact: —
Project Monitor: —
Dates: June 1961 - March 1962

Title: Research on Light-Metal-Containing High-Energy Fuels and Complex High-Energy Oxidizers

57. Contract No. AF 33(657)-7151 (replaces AF 33(616)-7050)
Contractor: Aeronca Manufacturing Company
Contact: —
Project Monitor: C. Tobin, ASRUTP
Dates: July 1961 - December 1962

Title: Insulated Sheet Beryllium-Ceramic Composite **CONFIDENTIAL**

Develop and manufacture reinforced ceramic heat shields combined with honeycomb panel load-bearing structure.

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58. Contract No.: AF 33(657)-7248
Contractor: General Dynamics/Fort Worth
Contact: C. W. Rogers
Project Monitor: D. A. Shinn
Dates: November 14, 1961 -

Title: Compilation of Unpublished Materials Information

The principal objective is to supply information on unpublished materials research and development programs. One report describes work on the development of brazed beryllium sandwich construction.

59. Contract No. AF 33(657)-7763
Contractor: United Aircraft Corp., Hamilton-Standard Division
Contact: —
Project Monitor: R. E. Bowman, ASRCMP-2
Dates: January 1, 1962 - January 1, 1963

Title: Electron-Beam Welding

Optimum high-voltage electron-beam welding techniques will be developed for joining molybdenum to tungsten, D6ac steel to itself, and B-120VCA titanium to itself. A preliminary investigation of high-voltage electron-beam welding of beryllium is included. The mechanical properties of the welds made with the optimum procedures will be evaluated.

60. Contract No. AF 33(657)-7070
Contractor: Midwest Research Institute
Contact: —
Project Monitor: Dr. K. C. Back, ASBMPT
Dates: January 1962 - November 1962

Title: Comparative Toxicity of Beryllium Compounds

To determine the acute toxicity of single doses of BeF_2 , BeH_2 , BeCl_2 , and BeOF . Animals will be exposed to beryllium compounds and working areas monitored for concentrations of beryllium compounds.

61. Contract No. Project 7351, Task 73512 (9F)
Contractor: In House
Contact: A. E. Heisen, R. T. Ault
Project Monitor: —
Dates: Completed

Title: Mechanical Properties of Beryllium

Mechanical properties of two lots of beryllium were determined. One lot was hot pressed with a H_2O content of 1.45% and the other lot was hot pressed and extruded and contained 1.55% H_2O . The hot pressed-hot extruded material was uniformly stronger. From a design standpoint, both ~~CONFIDENTIAL~~ exhibited their best behavior and higher strength under fatigue loading conditions, and appear to be weakest under static loading conditions.

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62. Contract No. Not given; In House
Contractor: Aerojet-General Corporation
Contact: D. G. Martin Shookoff
Project Monitor: —
Dates: —

Title: Development and Testing of Beryllium-Containing Propellants
63. Contract No. Not yet assigned (USAF)
Contractor: Atlantic Research Corporation
Contact: —
Project Monitor: —
Dates: Not yet started

Title: Production of XM-85 Motors
64. Contract No. In House
Contractor: Hercules Powder Company
Contact: J. N. Main
Project Monitor: —
Dates: —

Title: Development of Beryllium-Containing Propellants
65. Contract No. —
Contractor: Lockheed Missile and Space Company
Contact: D. J. Levy
Project Monitor: —
Dates: —

Title: The Electrolytic Polarization of Beryllium

Anodic and cathodic polarization behavior of beryllium was evaluated in a number of unstirred aqueous solutions. NaCrO_4 was an effective cathodic polarizer over a broad range of current densities. Activation and attack occurred in the presence of Cl^- , ClO_3^- , F^- , and SO_4^{--}
66. Contract No. In House
Contractor: North American Aviation, Inc., Rocketdyne Division
Contact: Charles Herty
Project Monitor: —
Dates: —

Title: Development of High-Energy Beryllium-Containing Propellants
67. Contract No. In House
Contractor: Thiokol Chemical Company
Contact: Ernie Sutton
Project Monitor: —
Dates: —

Title: Development of Beryllium-Containing Propellants

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Research Supported by the U. S. Army

68. Contract No. DA Project No. 5-93-32-001
Contractor: Watertown Arsenal Laboratory
Contact: Dr. Kenneth Tauer
Project Monitor: G. A. Darcy, Jr.
Dates: —

Title: Thermal and Electrical Conductivity of Irradiated Beryllium
and Transition Metals

To determine the effect of neutron irradiation on metals (beryllium and transition metals).

69. Contract No. DA Project No. 551-02-004 (TB5-5)
Contractor: University of Chicago
Contact: C. C. J. Roothan and B. J. Rancil
Project Monitor: Dr. H. Robl
Dates: —

Title: Advanced Energy Transformation Systems

Efforts will be directed to quantum-mechanical calculation of the energies and other properties of certain diatomic molecules in their ground states and excited states, to provide a basis for the determination of the thermodynamic, transport, and kinetic properties of these molecules. Calculations will be undertaken on the diatomic oxides, halides, and hydrides of the light metals, particularly LiF, BeO, BN, BeH, and LiH.

70. Contract No. DA Project No. 599-01-004 (TB2-0001)
Contractor: University of California
Contact: James R. Arnold
Project Monitor: Dr. H. Robl
Dates: Terminated June 1961

Title: Exploratory Basic Research

To investigate problems in geochemistry using radioactive tracer techniques. Studies will be made on Be¹⁰ and beryllium geochemistry, trace elements in the ocean, new natural radioactivities (e.g., Mn⁵³) natural radioactivities in meteorites, and new chemical and instrumental methods. Efforts will be made to develop the Be¹⁰ dating method and to explore the possibility of obtaining approximate dates using the most plausible geochemical model. It appears possible to measure cosmic ray intensity variations averaged over a period of one billion years to 10 to 20%.

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71. Contract No. DA-01-021-ORD-5135 and DA-01-021-ORD-11878
Contractor: Rohm & Haas Company
Contact: —
Project Monitor: —
Dates: —

Title: Advanced Solid Properties Ceramic Nozzle Evaluation Program

Standardized tests were made to evaluate on a relative basis a variety of rocket nozzle throat insert and expansion cone materials. The materials were tested for approximately 9 seconds with a high-energy, aluminized, solid propellant having a calculated flame temperature of 6650 °K and burning at a chamber pressure of 700 to 900 psi. Nozzle throat insert materials tested included graphite having a density range of 1.63 to 2.00 g-cm⁻³, molybdenum, tungsten-aluminum oxide cermet, tungsten-beryllium oxide cermet, fused silica, and silicon-nitride-bonded silicon carbide.

72. Contract No. DA-19-020-ORD-4829
Contractor: Arthur D. Little Inc.
Contact: —
Project Monitor: Alfred Buchler
Dates: February 26, 1959 - February 25, 1962

Title: High-Temperature Thermodynamics of Light-Metal Compounds

A study will be made of the high-temperature vapor-phase thermodynamics of metal-oxygen-hydrogen systems, the nature of the vapor systems present, their heats of formation, and their equilibria. In particular, the research will include such studies on light metals such as Li, Be, B, Mg, and Al.

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Research Supported by the U. S. Navy

73. Contract No. NOrd-15936, -16842, -17879, -18759, and -18771
Contractor: Atlantic Research Corporation
Contact: J. H. Grover, J. H. Wilson, K. E. Rumbel, M. L. Rice,
P. S. Shane, and A. Sloan
Project Monitor: —
Dates: —

Title: Research and Development Programs in Fields of Solid
Propellants and Interior Ballistics

The major phases are (a) propellant research and development, (b) inert materials for rocket motors, (c) rocket engineering and development, and (d) engineering consulting services.

74. Contract No. NOrd-16540
Contractor: Allegany Ballistics Laboratory
Contact: Dr. R. Steinberger
Project Monitor: S. J. Matesky
Dates: —

Title: Development and Evaluation of High-Temperature Materials
for Rockets

Materials are being evaluated for chamber insulation, jetavators, and nozzle inserts. Also for Polaris Second-Stage Program. Advanced Propellant Systems: calculations were made of theoretical Isp obtainable by using lithium, boron, or beryllium in both hybrid rockets and in double-base propellants.

75. Contract No. NOrd-18039
Contractor: National Beryllia Corporation
Contact: Eugene Ryshkewitch
Project Monitor: —
Dates: Completed

Title: Development of Tungsten-Beryllium Oxide Rocket Nozzles

76. Contract No. NOrd-18688
Contractor: Minnesota Mining and Manufacturing Corporation
Contact: —
Project Monitor: —
Dates: —

Title: Advanced Solid Propellants

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81. Contract No. NOv-62-0592-c
Contractor: National Beryllia Corporation
Contact: —
Project Monitor: —
Dates: —

Title: Fabrication of Beryllium Oxide Ceramic Experimental Radomes
82. Contract No. NRMA 02-056/212
Contractor: Naval Ordnance Laboratory
Contact: P. W. Erickson
Project Monitor: —
Dates: —

Title: Beryllium Wire Wound Composites

Objective is to develop and study the properties of composites employing high-strength beryllium wire and epoxy resins. Evaluations of properties will be made by NOL ring test commonly employed to test glass-fiber-resin composites. Applications are not yet identified.

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Research Supported by the U. S. Atomic Energy Commission

83. Contract No. AT-11-1-GEN-8
Contractor: North American Aviation, Inc., Atomics International Division
Contact: ---
Project Monitor: ---
Dates: ---

Title: Corrosion and Activity Transfer in the SRE Primary Sodium System.

Testing of stainless steel, zirconium, and beryllium exposed in the hot and cold legs of a bypass loop (sodium) is in progress. No mention of beryllium test sample results.

84. Contract No. AT-11-1-GEN-8
Contractor: North American Aviation, Inc., Atomics International Division
Contact: J. D. McClelland
Project Monitor: ---
Dates: ---

Title: Kinetics of Hot Pressing

The effect of temperature and pressure on the rate of beryllia powder compacts was obtained experimentally. The pressures ranged from 1000 to 2000 psi, the temperatures from 1200 to 1700 C, and the time from 15 to 240 min. The diffusion of Be in BeO was measured as a function of temperature.

85. Contract No. AT-11-1-73
Contractor: University of Missouri
Contact: M. E. Straumanis and W. J. James
Project Monitor: ---
Dates: ---

Title: Corrosion of Nuclear Metals

It is the purpose of this study to determine the basic reactions of dissolution, the rates of dissolution, the effect of added salts, and the extent of polarization, all as related to the behavior of metals (Hf, Zr, Ti, Be, U, Th), their oxides and nitrides in hydrofluoric and other inorganic acids.

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86. Contract No. AT-30-1-1565
Contractor: Nuclear Metals, Inc.
Contact: A. R. Kaufmann
Project Monitor: —
Dates: July 1, 1960 - June 30, 1961

Title: Fundamental and Applied Research and Development in Metallurgy:
Stability of the High-Temperature Beta Phase in Beryllium
and Beryllium Alloys

Studies of this high-temperature phase were lower on differential thermal analysis as applied to alloys of Be with Ba, Ce, Co, Cu, La, Mn, Pt, Ag, Ni-Co, Ni-Fe, Ni-Cu, Ni-Co-Fe, and Ni-Co-Mn. Beryllium regions in the Be-Co and Be-Cu systems were well established.

87. Contract No. AT-30-1-1565
Contractor: Nuclear Metals, Inc.
Contact: R. N. Randall, D. M. Davies, J. M. Siergie, and
P. Loewenstein
Project Monitor: —
Dates: Completed

Title: Fundamental and Applied Research and Development in Metallurgy:
Extrusion by Hydrostatic Pressure

Conducted experimental work on the extrusion of metals by use of a fluid under hydrostatic pressure. Experimental extrusions were made from a container in which the billets were surrounded by a fluid under hydrostatic pressure. Copper, aluminum, mild steel, yttrium, and beryllium billets were extruded at room temperature at various reductions. Attempts to extrude at 900 F from a container filled with liquid lead were unsuccessful because of the failure of the containers at pressures greater than 100,000 psi. The pressures required for extrusion of copper and aluminum were approximately the same as were required for extrusion by conventional means.

88. Contract No. AT-30-1-1565
Contractor: Nuclear Metals, Inc.
Contact: —
Project Monitor: —
Dates: Current

Title: Beryllium Purification and Deformation Studies

Primary emphasis is on getting distilled metal into rod form which is then zone refined as a purification technique. This program differs from the Air Force program in the manner of testing products.

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89. Contract No. AT-33-3-20
Contractor: The Brush Beryllium Company
Contact: W. W. Beaver
Project Monitor: --
Dates: --

Title: High-Temperature Intermetallics

90. Contract No. AT-38-i-200
Contractor: General Nuclear Engineering Corporation
Contact: --
Project Monitor: --
Dates: --

Title: Gas Cooled Reactor Project

Production of helically finned beryllium tubing by extrusion, isostatic pressing and Dynapak forming is described. Program was not completed due to de-emphasis of reactor sys

91. Contract No. AF-38-1-200
Contractor: Sylvania Electric Products, Inc.
Contact: I. Steinhart
Project Monitor: --
Dates: Completed

Title: The Fabrication of Beryllium by Hot Isostatic Pressing and by Impact Extrusion

The feasibility of producing finned beryllium tubing by the hot isostatic pressing method was demonstrated. Only a minimum of machining was required on the pressed shape. Dynapak extrusion of hot and cold pressed beryllium billets is also described. Mechanical properties were dependent on the extrusion temperature and impact density.

92. Contract No. AT-40-1-2912
Contractor: The Brush Beryllium Company
Contact: W. W. Beaver
Project Monitor: --
Dates: August 1962

Title: Fabrication of Finned Beryllium Tubing by Warm Extrusion and Drawing

Program was initiated to fabricate tubing for the Florida Gas-Cooled Reactor.

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93. Contract No. AT-45-1-1350
Contractor: General Electric Company
Contact: J. Cadwell
Project Monitor: ---
Dates: ---

Title: ---

A Zr-2-5 w/o Be brazing alloy has been evaluated for use in joining Zr-2 to uranium as applied to the NPR. Also at Hanford magnetic force welding of beryllium end closures (tubes) has demonstrated promising results. Both developments are part of a major general contract.

94. Contract No. W-7405-eng-26
Contractor: Union Carbide Company
Contact: ---
Project Monitor: ---
Dates: ---

Title: Gas-Cooled Reactor Program

The reaction of Be with VC was investigated as a part of the ORNL long-range applied metallurgy effort. At 1000 C extensive reaction was noted. Compatibility of beryllium and Be₂C with wet CO₂ is being investigated to resolve the unpredictable nature of beryllium corrosion. The inspection of finned beryllium tubing and mechanical properties of tubing up to 700 C are also being studied. In-pile stress rupture evaluations are also included. Welding by tungsten arc and electron beam as applied to beryllium fuel assemblies is also in progress.

95. Contract No. W-7405-eng-26
Contractor: Oak Ridge National Laboratory
Contact: ---
Project Monitor: D. A. Douglas
Dates: July 1, 1959 -

Title: Testing of Beryllium In Pile

To study the effects of irradiation on the structure and strength of beryllium.

96. Contract No. W-7405-eng-26
Contractor: Oak Ridge National Laboratory
Contact: ---
Project Monitor: D. A. Douglas
Dates: July 1, 1959 -

Title: Multiaxial Creep Studies of Beryllium Tubing

To determine the effect of multiaxial stresses and irradiation on the creep and fracture of beryllium.

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97. Contract No. W-7405-eng-40
Contractor: University of California
Contact: --
Project Monitor: --
Dates: --

Title: Thermal Expansion of High-Temperature Materials

98. Contract No. W-7405-eng-92 (W-7405-eng-26 Subaccount No. 2029)
Contractor: Battelle Memorial Institute
Contact: E. S. Hodge
Project Monitor: --
Dates: --

Title: Preliminary Studies of Bonding Beryllium Clad UO_2 Fuel Elements

Solid-state bonding parameters, surface preparation methods, and compatibility of beryllium with UO_2 were investigated. Grit blasting and abraded surfaces yielded surface recrystallization during bonding at 1550 to 1650 F at 10,000 psi. Chromium and pyrolytic carbon coatings for UO_2 were found most effective in preventing reaction.

99. Contract No. In House
Contractor: US AEC
Contact: --
Project Monitor: --
Dates: --

Title: Welding and Brazing of Beryllium

Develop closures for tubular fuel elements. Investigations of fusion welding, and development of brazing alloys, have been initiated.

100. Contract No. --
Contractor: North American Aviation, Inc., Atomics International Division
Contact: Dave Sinizer
Project Monitor: --
Dates: --

Title: --

As a part of the SNAP program, beryllium is being used in a reflector control mechanism.

101. Contract No. --
Contractor: University of California, Livermore
Contact: R. O. Campbell
Project Monitor: --
Dates: --

Title: A Study of Beryllium Exposure at a High-Explosive Assembly Test Facility

Beryllium included in high-explosive assemblies is vaporized, oxidized, and widely dispersed on detonation. As a result of dispersal by wind and air currents, the remaining beryllium is confined within a few hundred feet of the firing point.

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Research Supported by NASA

102. Contract No. JPL 950227
Contractor: Atlantic Research Corporation
Contact: —
Project Monitor: John F. Newton
Dates: March 1962 —

Title: Program on Combustion Efficiency
103. Contract No. JPL 950097
Contractor: Atlantic Research Corporation
Contact: T. O'Donnell
Project Monitor: John F. Newton
Dates: August 1961 - June 1962

Title: Spherical High-Energy Solid-Propellant Rocket Motor

Working on 17-inch spherical motors with design studies for larger spherical motors.
104. Contract No. NAS 8-1547
Contractor: Armour Research Foundation
Contact: R. F. Havell
Project Monitor: Y. Baskin
Dates: —

Title: Electric Insulators for Very High Temperatures

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APPENDIX II

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UTILIZATION OF BERYLLIUM IN CHEMICAL PROPULSION SYSTEMS (C)

M.T. Lyons
Solid Propellant Information Agency
The Johns Hopkins University
Applied Physics Laboratory
Silver Spring, Maryland

I. INTRODUCTION

The following analysis is narrow in that it compares beryllium with the contemporary propellants which contain aluminum, and does not consider alternative, advanced propellant ingredients. This approach is felt to be justified, however, because of the advanced stage of development of beryllium propellants relative to comparable high energy systems. These competitive formulations suffer from one or more of the following defects: incompatibility of ingredients, thermal instability, inadequate physical structure, burning rates incompatible with present grain design, chemical sensitivity to the atmosphere, and susceptibility to explosion or detonation. Beryllium propellants are no more deficient in these respects than conventional ammonium perchlorate-binder-aluminum propellants, and are therefore several years ahead of competitive and superior performance solid systems.

II. BACKGROUND

The current solid propellants employed in high performance missile systems consist of 40% to 75% ammonium perchlorate, 15% to 22% aluminum, and, either an "inert" rubber binder or a nitrocellulose-based, high energy colloidal binder. These systems have densities of 0.062 to 0.065 lb/in³, and delivered specific impulse values between 245 to 248 lbf-sec/lbm at standard conditions (1000 psi chamber pressure, expansion to 14.7 psi).

On a theoretical basis, beryllium has been known for many years to be preferable to aluminum as a propellant ingredient in certain applications, but it has only been in the last two years that confirmatory experiments have been performed at Atlantic Research Corporation and Aerojet-General Corporation. Specific impulse values as high as 255 lbf-sec/lbm have been obtained for formulations with densities of 0.059/lb/in³. This margin of superiority of beryllium propellants increases at higher altitudes.

III. LIMITS OF APPLICATION

The following three factors have played a significant role in limiting the applications of beryllium-containing solid propellants, toxicity, cost, and density.

DOWNGRADED AT 3 YEAR INTER-
VALS; DECLASSIFIED AFTER
12 YEARS.
DDI DIR 5200.10

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APPENDIX III (Continued)

A. Toxicity. Beryllium and beryllium oxide toxicity have severely curtailed the interest of both the Army and Navy in the use of these propellants. The predominant missions of both Services entail the field handling of the motors, and present some threat of exposure of personnel to the rocket exhaust. NASA and the Air Force, however, have many space and high altitude missions, for which beryllium motor upper stages could be employed. Nevertheless, there are toxicity problems associated with the development and production of beryllium-containing motors, and there is the ever present chance that a booster abort would result in the destruction of the upper stages, spreading high concentrations of beryllium and beryllium oxide over a populated area. In the case of the Air Force, the Office of the Surgeon General has had a strong tempering influence on the enthusiasm for beryllium propellants.

B. Density. Aside from toxicity considerations, the low density of beryllium propellants precludes their use in large solid propellant booster motors. Propellants containing aluminum are unequivocally superior for this application. However, the significance of propellant density diminishes rapidly with successive stages of the missile, and beryllium generally has a performance advantage over aluminum in the second and later stages.

C. Cost. The cost of the finely-ground beryllium (17 micron or less particle size) presently used in propellants is \$55 to \$80/lb. The cost of the ingredients for a conventional solid propellant is \$0.60/lb. There is no difference in the processing technique for the two types of propellant, but there would be additional costs associated with the toxicity hazards controls that would be required in the beryllium process. In many military missions, the size of the missile is fixed by previously stipulated storage and handling requirements (e.g., Minuteman silos, Polaris submarine-launching tubes), and any performance improvements must be made by tailoring of hardware weight and/or upgrading of propellant performance. Thus the cost of a beryllium propellant might be justified in many instances. NASA does not, of course, have the same incentives for using beryllium, but there will certainly be times when NASA personnel will find it less expensive to load existing hardware with beryllium-containing propellant than it would be to design and produce a larger motor to perform the same mission.

IV. PRESENT APPLICATIONS

A. Atlantic Research Corporation - The Atlantic Research Corporation presently has a contract from Jet Propulsion Laboratory for the development of a 17" spherical motor, and the loading of between 20 to 30 of these motors with beryllium propellant. This contract also requires the design of a 36" spherical motor, but the decision to produce and load this motor with beryllium-containing propellant pends the outcome of the 17" motor studies. Each 36" spherical motor would require 180 lbs. of beryllium.

In addition to the 17" motor loadings, Atlantic Research has contracted to load a miscellaneous series of motors for Naval Ordnance Test Station with beryllium propellant. The estimated beryllium requirement for these two programs is 1200 lbs. over the next year.

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CONFIDENTIAL APPENDIX XII (Continued)

B. Aerojet-General Corporation. Aerojet presently has a contract with Edwards Air Force Base for the production of three motors containing 520 lbs. of beryllium-containing propellant each. This motor is designed as a substitute for the fourth stage of the present Scout vehicle, but the three motors are to be static tested rather than flight fired. This program will require approximately 350 lbs. of beryllium.

Besides the aforementioned formal programs, it is certain that all solid propellant manufacturers are evaluating or will be evaluating beryllium in their propellant formulations on a proprietary basis. In addition, studies are presently being made of the ignition and combustion mechanism of beryllium and its alloys with metals such as zirconium and aluminum. These studies are directed toward the improvement of beryllium combustion efficiency.

V. FUTURE CONSIDERATIONS

Performance calculations have been made for beryllium-containing propellants in both the Polaris and Minuteman systems. Since the Polaris A3 propellants have already been selected, the chances of beryllium being used in this missile are negligible in the foreseeable future. If beryllium were substituted for aluminum in the second stage of the Polaris A3, a range improvement of 8% would be achieved. Each second stage Polaris motor would require approximately 1,100 lbs. of beryllium.

In the case of the Minuteman, a Wing II advanced version is presently under consideration. By employing beryllium propellant in third stage only (540 lbs. of Be/motor) an increase in range of 15% can be achieved. Current indications are that beryllium will not be used in Wing II Minuteman.

A far more tenuous and embryonic conception is the application of beryllium to liquid propulsion systems. The highest performance chemical system that is operational is the H_2-O_2 system which yields 390 lbf-sec/lbm at a chamber pressure of 1000 psi with expansion to 14.7 psi. Under comparable conditions, the Be- O_2 - H_2 system gives a value of 458 lbf-sec/lbm. This is the highest specific impulse chemical propulsion system that can be conceived on a theoretical basis, with only the H_2-F_2 (410 lbf-sec/lbm) and H_2-F_2-Li (437 lbf-sec/lbm) systems as competitors. However, the developmental problems associated with the system are formidable, and a conservative estimate of 10 years will be required to prove the feasibility of this concept. Atlantic Research and Aerojet-General presently have contracts to study the combustion efficiency of slurried metals with liquid oxygen. Additional problems that must be surmounted include the pumping and injection of metal slurries, and high temperature motor component development.

A serious development effort is presently underway to evaluate the hybrid propulsion concept. Conventionally, this system consists of a liquid oxidizer coupled with a solid fuel grain. If this system is proved desirable, beryllium is one of the logical candidates as the fuel element. The advantages and disadvantages cited previously for beryllium in solid propellants are equally applicable to beryllium hybrid formulations.

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APPENDIX III (Concluded)

Beryllium has also been considered as an ingredient in systems with fluorine as the oxidizing element, rather than oxygen. Recent thermochemical data indicates that boron and lithium are superior fuels for these applications.

Studies are also being made of the synthesis and properties of beryllium hydride. Present indications are that due to low density, beryllium hydride is not competitive as a propellant ingredient.

VI. SUMMARY

The substitution of beryllium for aluminum in present-day propellant systems offers definite performance advantages with minimum changes in propellant processing, stability, and burning characteristics. These attractive features are mitigated and circumscribed by the disadvantages of toxicity, density, and cost. The early state of development of beryllium propellants precludes a quantitative assessment of their future utilization. It is certain, however, that beryllium will be given serious consideration for all programs that entail the development of high altitude solid motors.

Looking further into the future, preliminary consideration is being given to use slurried beryllium powder in propulsion systems with liquid hydrogen and oxygen as components.

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APPENDIX IV

THE USE OF BERYLLIUM IN RADIATORS FOR
SPACE POWER SYSTEMS

By
James H. Diedrich
Research Engineer, Flow Processes Branch
NASA Lewis Research Center

INTRODUCTION

The basic purpose of this discussion is to set forth NASA's interest in the use of beryllium in radiators for space power systems. In order to establish a uniform frame of reference, the basic radiator problem will first be defined. The specific areas of application for beryllium will then be indicated and finally, the resulting problems will be tabulated. The data from which these conclusions were drawn were developed in the Fluid Systems Components Division at the Lewis Research Center in Cleveland, Ohio.

BASIC REQUIREMENTS

The major advanced space missions demand large amounts of electric power. This power will be used for both propulsion and auxiliary requirements. The level of operation for such advanced systems is in the range of 300 to 20,000 kilowatts and the power generating equipment must embody three basic requirements.

- (1) Low specific powerplant weight in pounds per kilowatt output.
- (2) Capable of long time-unattended operation, up to a year or more.
- (3) Must be capable of both startup and operation in a "zero-gravity" environment.

The need for low specific powerplant weight is emphasized by figure 1. This figure shows the relation between the ratio of payload weight to total powerplant weight plotted against the trip time in days. These curves are for a round trip to Mars but similar curves exist for other missions. The trip time is fixed

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initially by the ratio of payload weight to total powerplant weight. The trip time is reduced drastically by a lower value of powerplant specific weight. High trip times, however, would mean increased requirements on component reliabilities and increased probability of meteoroid damage, therefore a minimum weight is desirable.

To achieve the lowest value of specific powerplant weight, two systems are favorable at the higher power levels. These are the reactor-thermionic system and the reactor-turbogenerator system (fig. 2). The balance of my remarks will be confined to the reactor-turbogenerator system but the radiator is a common component in each system. The chief difference being in the radiator temperature: the turbogenerator system produces optimum weights with a radiator temperature between 1200° and 1400°F while the thermionic-emitter system requires radiator temperatures from 1800° to 2000°F . The beryllium application is visualized for the 1200° to 1400°F radiator.

The basic power cycle is shown in figure 3. It consists of the components arranged as shown. The cycle shown is a Rankine cycle having an alkali metal vapor as the working fluid (i.e., potassium, rubidium, sodium, cesium, or lithium). Such cycles have low thermal efficiencies and require large amounts of waste heat to be rejected. This brings us to the statement of the "basic radiator problem." This is briefly stated in figure 4. Item 5-B-Vulnerability to meteoroid damage - is the area where our interest for beryllium lies. Beryllium theoretically produces the lowest weight armor for a given success probability.

The radiator areas required by such systems are very large. Figure 5 emphasizes this point. This is a picture of the configuration a Mars vehicle might take. The craft is 600 feet long and the radiator measures 30 feet wide by 300 feet long.

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Many other schemes for rejecting the waste heat are being considered and these are shown in figure 6. These are the so-called "nonfluid" radiators and they reduce the prime area requirements through a continuous moving belt. However, the basic mode of waste heat rejection is still by radiation. The problem of protection against meteoroid penetration still remains.

Returning to the "fluid radiators," the basic fin and tube configuration is shown in figure 7. Basically, it consists of many parallel rows of tubes carrying the vapor. Attached to these tubes are additional heat radiating surfaces or fins. Many geometries are possible and a few of the possibilities are shown.

Utilizing the basic fin-tube configuration in a radiator panel, results in a structure similar to figure 8. Some typical dimensions for two separate power levels are tabulated in the table on page 86.

The remaining columns (Sublimation and Ultimate Tensile Strength) list other considerations in the selection of materials. The indication is that beryllium has a temperature limitation insofar as sublimation and ultimate tensile strength are concerned.

The comparative specific radiator weights for some selected materials are shown in figure 13. This curve points up the weight advantage offered by beryllium and at the same time the need for operating the radiator in the 1200° to 1400° F range. Higher temperatures would exclude beryllium from consideration and make it necessary to design with pyrolytic graphite or even molybdenum, columbium, or tantalum. These materials have disadvantages in fabrication and weight.

The final tabulation (figure 1c) lists the problem areas associated with the application of beryllium. Items (a) and (b) indicate the difficulties anticipated in bonding and joining and application of beryllium armor. Item (c) is most

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important, since the consideration of beryllium in the design is based principally on its ability to resist meteoroid penetration. One of our current research areas is the experimental verification of this property at temperature.

Items (d) and (e) list the possible problems with fatigue and corrosion resistance.

Item (f) indicates a prime area of uncertainty since the low elongation of beryllium makes it extremely difficult to use in a design. Structural loads must be predicted with great accuracy and the behavior of the material under loads must be known with equal or greater accuracy.

Item (g) indicates considerations of "off-design" operation and lists some possible problem areas.

CONCLUSION

The prime interest in beryllium in radiators for space power systems stems from its theoretical resistance to penetration by meteoroids. Beryllium radiator designs produce the lowest specific weight (lb/kw) in the 1200° to 1400° F temperature range. However, these theoretical possibilities must be borne out experimentally and a design technology for low elongation materials, such as beryllium, must be developed.

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System power level, kv	Panel size, ft	Maximum vapor header outside diameter, ft	Number tubes	Tube diameter x wall, in.	Beryllium film thickness, in.	Beryllium armor thickness, in.	Beryllium, lb	Total, lb
300	15 x 16	1.08	40	3/4 x 0.040	0.075	0.330	1140	1800
1000	30 x 39	2.03	64	1 1/4 x 0.060	.138	.500	6100	8000

The basic considerations involved in the selection of suitable materials are shown in figures 9, 10, and 11. The basic application of beryllium is found in category E - Resistance to Meteoroid Impact and Damage.

MATERIALS EVALUATION

In order to have a comparative evaluation between the various promising materials a listing is made in figure 12. The first parameter, thermal conductivity (κ) divided by density (ρ), rates the materials on their ability to conduct heat on a density basis. Beryllium ranks third best in this evaluation. The second parameter indicates the ability of the material to resist thermal stresses or a thermal shock. It consists of a breaking stress (σ) times thermal conductivity (κ) divided by the product of thermal expansion (α) and modulus of elasticity (E).

The third column is a comparison of the total hemispherical emissivities. Deficiencies in this area must be remedied by coatings.

The fourth column illustrates the prime reason for selecting beryllium. This parameter (Penetration Criteria) indicates the weight of material required for a given success probability. The indications are that beryllium offers the best promise for a minimum weight structure.

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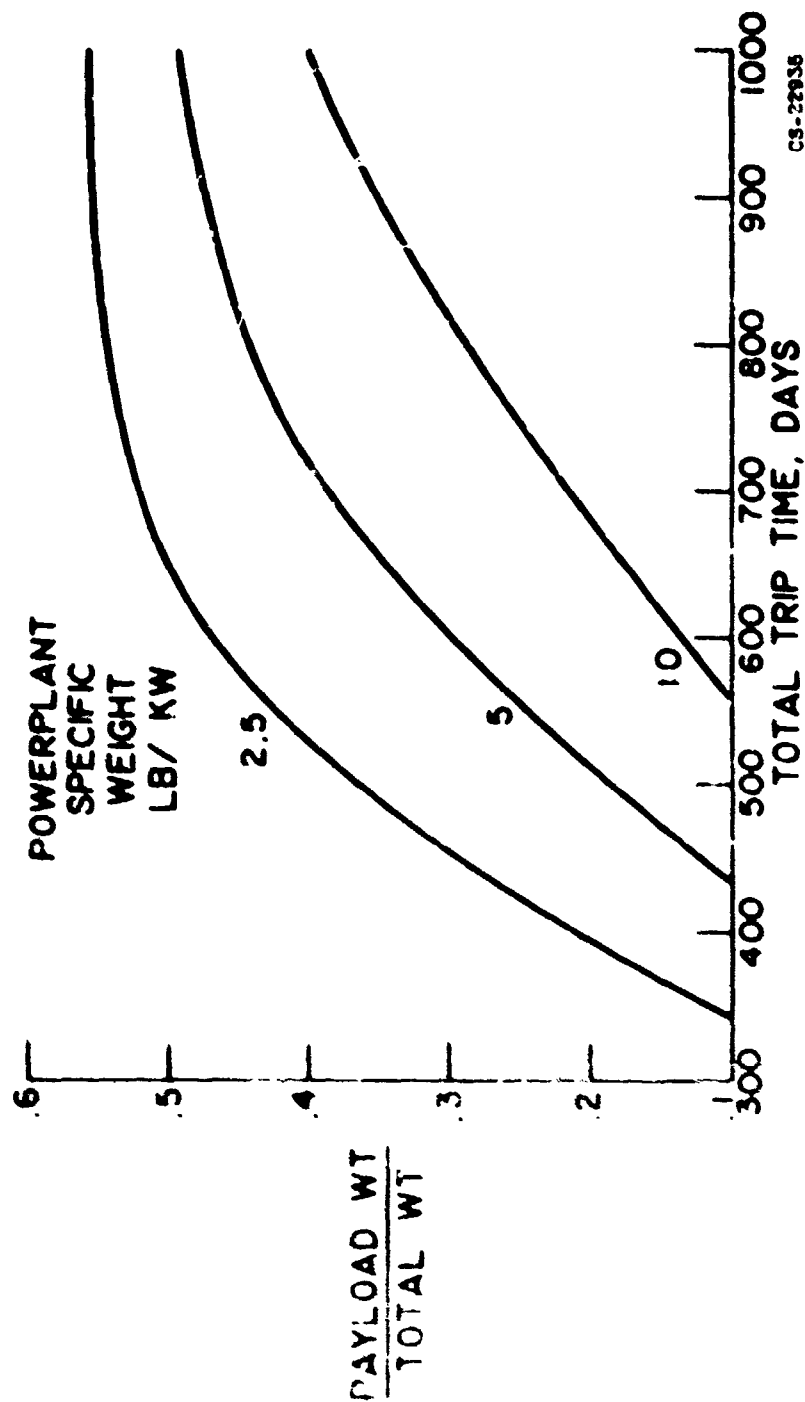


Fig. 1. Mars round trip with electric rocket.

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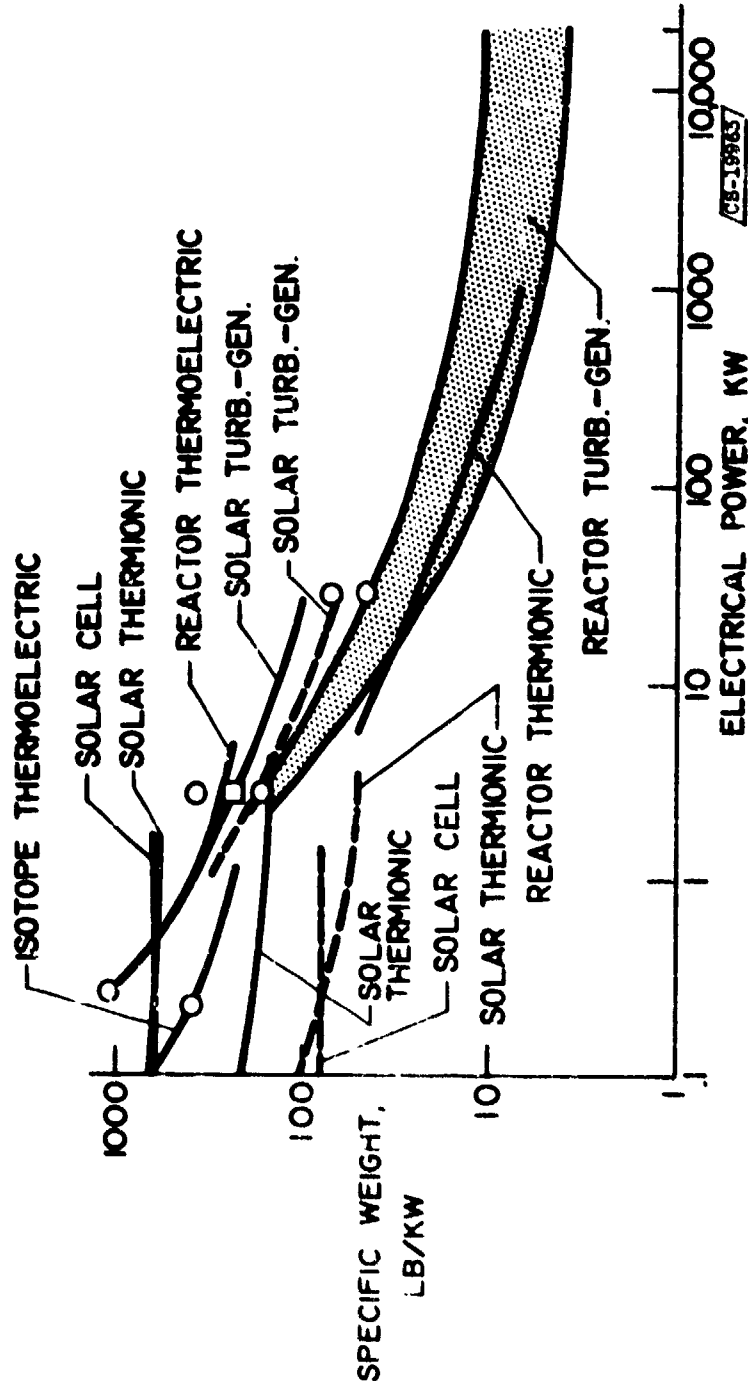


Figure 2. - Estimated specific weights of power generator systems.

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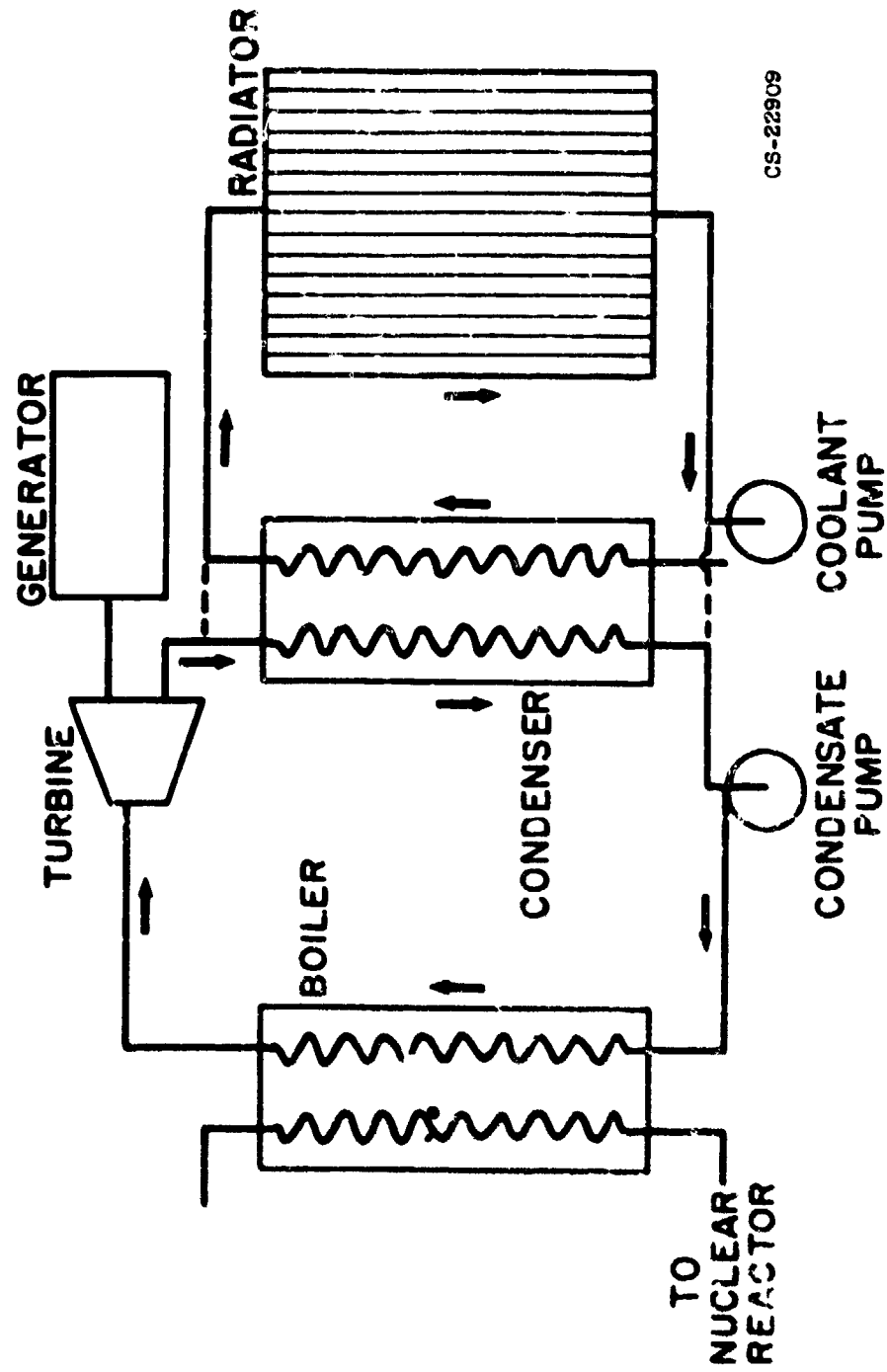


Figure 3. - Schematic of power generation loop.

THE BASIC RADIATOR PROBLEM

1. Large quantities of waste heat must be dissipated - 80% to 90% of heat generated
2. Only mechanism for heat rejection is thermal radiation to space
3. Radiation equation $Q = \epsilon A \sigma T^4$ ϵ = emissivity
 A = area T = temperature
4. Surface areas required are large for temperature limitations anticipated
 $30 \text{ kw} : 880 \text{ ft}^2 (700^\circ\text{F}) * 1 \text{ mgw} : 4000 \text{ ft}^2 (1000^\circ\text{F}) * 20 \text{ mgw} : 20,000 \text{ ft}^2 (1350^\circ\text{F})$
5. Problems created for advanced systems:
 - A. Structural complications
 1. Containment within launch vehicle, unfolding in orbit
 2. Maneuvering, vibrations, and stiffening
 3. Nuclear and thermal radiation shielding
 - B. Vulnerability to meteoroid damage
 1. Protective armor or bumpers produce heavy weight
 Radiator is 35% to 60% of powerplant weight.
 - C. Large heat capacity - starting difficulties

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Figure 4

E-1710

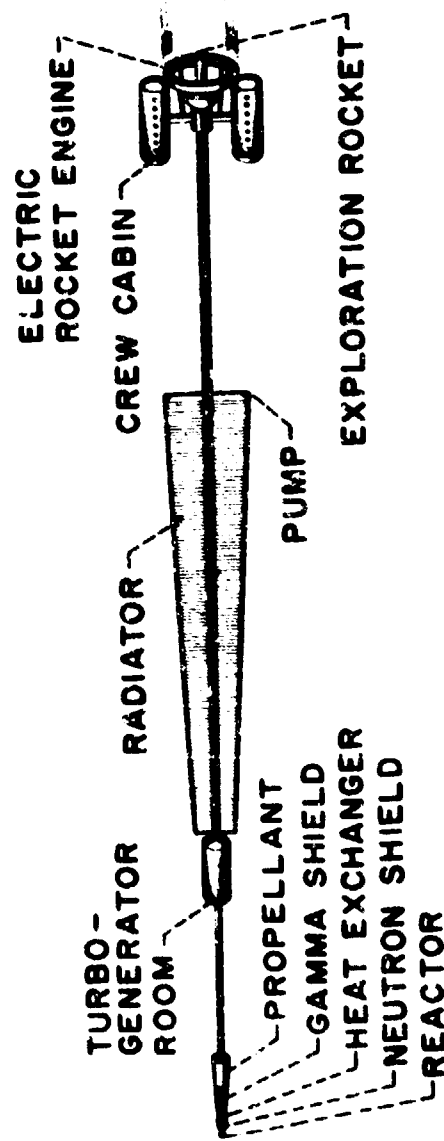


Figure 5. - Electric spacecraft for round trip to Mars.

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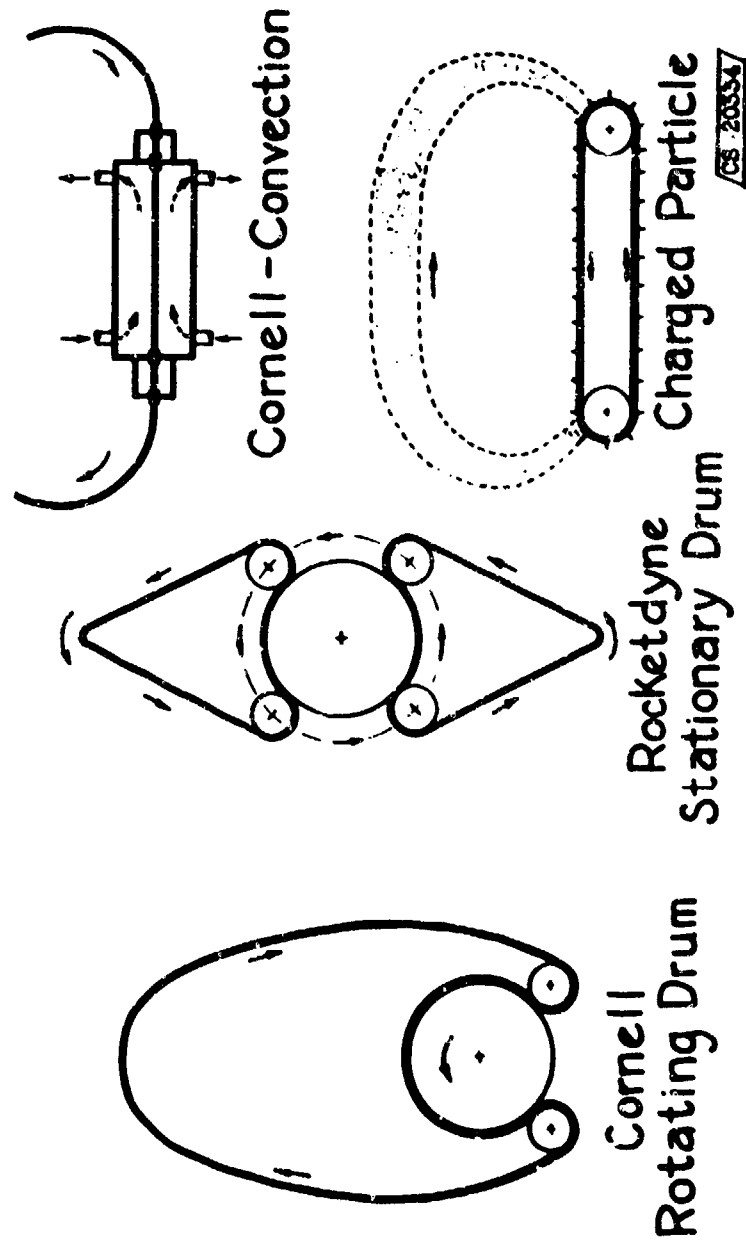


Figure 6. - Nonfluid radiators.

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PIN AND TUBE FLUID RADIATOR

- A. CONFIGURATION
 1. PIN AND TUBE BANK WITH HEADER AT EACH END
 2. SEVERAL GEOMETRIES - CENTRAL, ONE SIDE, BOTH SIDES. ALSO BLOCK FORM
- B. METEOROID DAMAGE PROTECTION
 1. ARMOR SLEEVE

$$t = \left[\frac{\text{VULNER. AREA} \times \text{TIME}}{\text{CONST. (1 - SURVIVAL PROBAB.)}} \right]^{1/3}$$

2. BUMPER CONCEPT
3. BIMETALLIC SYSTEM
- C. WEIGHT ADVANTAGES
 1. REDUCE VULNERABLE AREA
 2. LOW DENSITY MATERIAL IN PIN

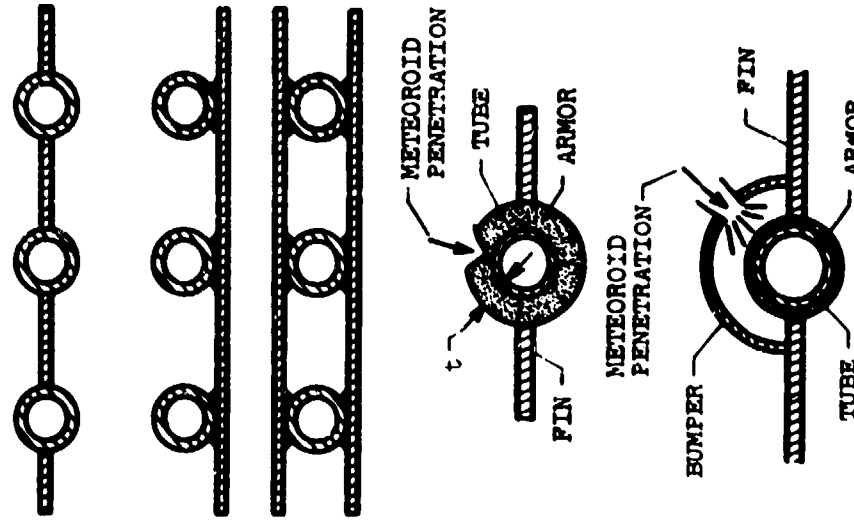
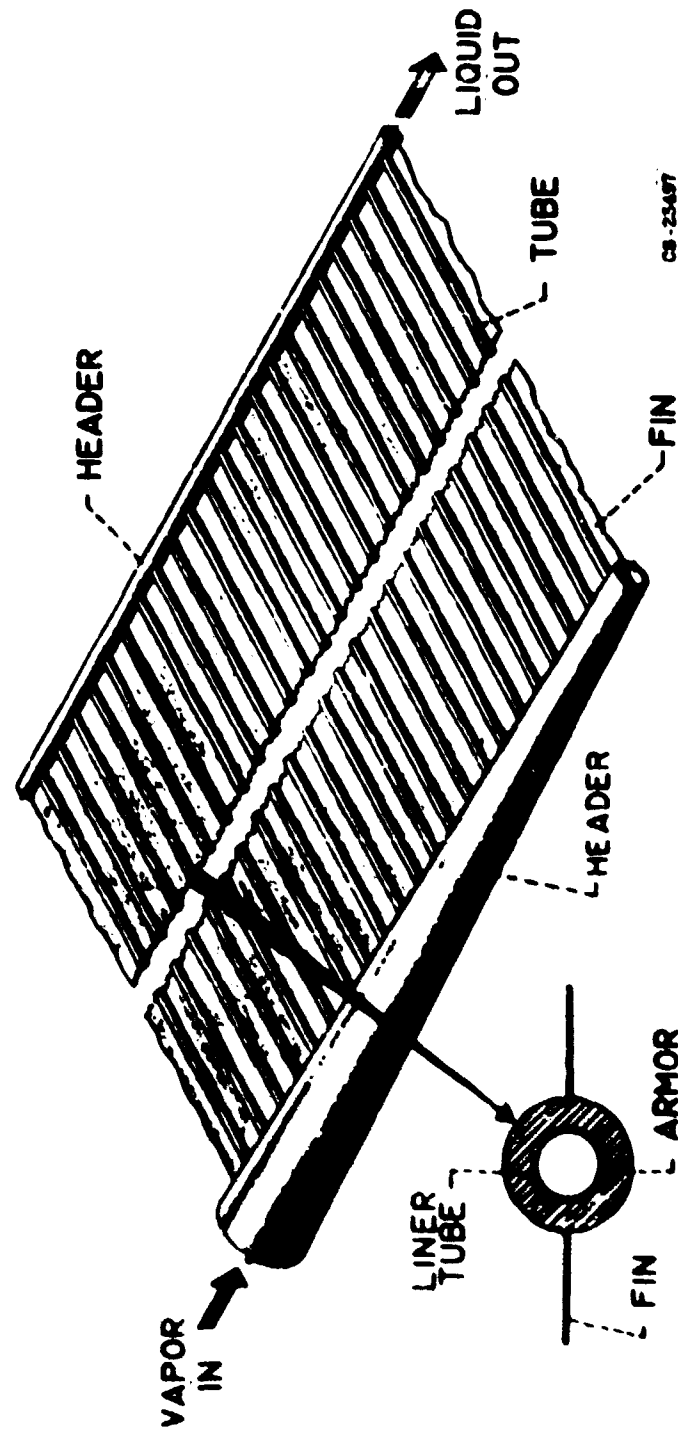


Figure 7

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Figure 8. - Fin and tube radiator.

2-1710

MATERIALS CONSIDERATIONS

A. MECHANICAL STRENGTH

1. INTERNAL FLUID PRESSURE - GENERALLY LOW
(5 TO 30 PSI)
2. THERMAL STRESSES - TEMPERATURE GRADIENTS IN FIN;
DIFFERENTIAL EXPANSION, COLD TUBE IN BANK
3. THERMAL SHOCK STRESSES - BAD DURING START-UP
4. FLEXURAL STRESSES - UNFOLDING SCHEMES
5. VIBRATORY STRESSES - POWERPLANT VIBRATIONS AND
VEHICLE MANEUVER; UNKNOWN MODES, FREQUENCIES,
AND AMPLITUDES
6. CREEP RATES - RELAXATION; DISTORTIONS
7. NEED REFRACTORIES FOR STRENGTH FOR
T > 1600° TO 1800° F

CS-22116

Figure 9

B-1710

B. CORROSION

1. COMPATIBILITY WITH ALKALI METAL FLUIDS
2. DIFFERENT FLUIDS NEEDED
AS PRESSURE INCREASES
WITH TEMPERATURE
3. BIMETALLIC SYSTEMS
4. LONG OPERATING TIMES
5. LIMITED DATA - NEED REFRACTORIES $>1600^{\circ}$ TO 1800° F

FOR 15 PSI
 1400° F - POTASSIUM
 1600° F - SODIUM
 2400° F - LITHIUM

C. FABRICATION AND BONDING

1. FIN AND TUBE JOINT - BIMETALLICS; JOINING METHOD;
JOINT STRENGTH; THERMAL SHOCK.
2. ARMOR SLEEVE OR BUMPER JOINT - TUBE AND FIN
3. TUBE AND HEADER JOINT - THERMAL AND BENDING
STRESSES
4. SHEETS OF LARGE SURFACE AREA OR LENGTH

Figure 10

CS-22117

E-1720

D. SUBLIMATION

1. MATERIAL LOSS IN VACUUM INCREASES RAPIDLY WITH TEMPERATURE

E. RESISTANCE TO METEOROID PENETRATION AND DAMAGE

F. EMISSIVITY COATINGS

1. GOOD BOND - NO INTERACTION WITH BASE MATERIALS
2. LOW VOLATILITY IN VACUUM
3. RESIST ABRASION AND OTHER LONG-TIME EFFECTS
4. METHOD OF APPLICATION - LARGE SURFACE AREAS

CS-22118

Figure 11

MATERIALS PROPERTIES

MATERIAL	K/p	THERMAL STRESS PARAMETER, of/°K		TOTAL REM- ISOTHERMAL EMISSIVITY, 2/3 E-1/3	PENETRATION CRITERIA, 2/3 E-1/3	SUBLIMATION		ULTIMATE TEN- SILE STRENGTH	
		AT 1400° F	AT 80° F			AT 1400° F	AT 1600° F	AT 1400° F	AT 1600° F
UNIT		$\frac{BTU}{(IN)(LB)(°F)}$	$\frac{BTU}{(FT)(IN)}$			$\frac{IN}{IN}$	$\frac{IN}{IN}$	$\frac{LB}{SQ IN}$	$\frac{LB}{SQ IN}$
COMMERCIAL GRAPHITE	0.57	164x10 ³	38x10 ³	0.8	4.5x10 ⁻²	<10 ⁻¹⁰	<10 ⁻⁹	2.5x10 ³	3x10 ³
NEUTRON GRAPHITE	0.4	13x10 ³	2x10 ³	.3	1.7x10 ⁻²	4.1x10 ⁻³	0.13	8x10 ³	-0
PYROLYTIC GRAPHITE	0.89	892x10 ³	192x10 ³	0.8	2.8x10 ⁻²	<10 ⁻¹⁰	<10 ⁻⁹	14x10 ³	15x10 ³
ALUMINUM	0.62	56x10 ³	4x10 ³	0.1	4.1x10 ⁻²	8.6x10 ⁻³	0.3	2x10 ³	-0
TITANIUM	0.04	8x10 ³	2x10 ³	0.25	5.2x10 ⁻²	<10 ⁻⁶	<10 ⁻⁵	5x10 ³	-0
VANADIUM	0.05	26x10 ³	1x10 ³	0.17	4.3x10 ⁻²	<10 ⁻⁷	<10 ⁻⁶	5x10 ³	-0
STAINLESS STEEL	0.04	7x10 ³	2x10 ³	0.22	4.5x10 ⁻²	<10 ⁻⁵	1.4x10 ⁻⁴	35x10 ³	20x10 ³
COBALT	0.07	21x10 ³	15x10 ³	0.6	5.1x10 ⁻²	<10 ⁻¹⁰	<10 ⁻⁹	25x10 ³	20x10 ³
COPPER	0.36	25x10 ³	-0	.06	-----	4x10 ⁻⁴	0.012	-0	-0
NICKEL	0.1	56x10 ³	30x10 ³	0.1	4.1x10 ⁻²	<10 ⁻¹¹	<10 ⁻¹⁰	70x10 ³	80x10 ³
ZINC	0.03	11x10 ³	7x10 ³	0.1	6.8x10 ⁻²	1.3x10 ⁻¹⁷	2.1x10 ⁻¹⁶	30x10 ³	25x10 ³

CS-28310

Figure 12

E-1710

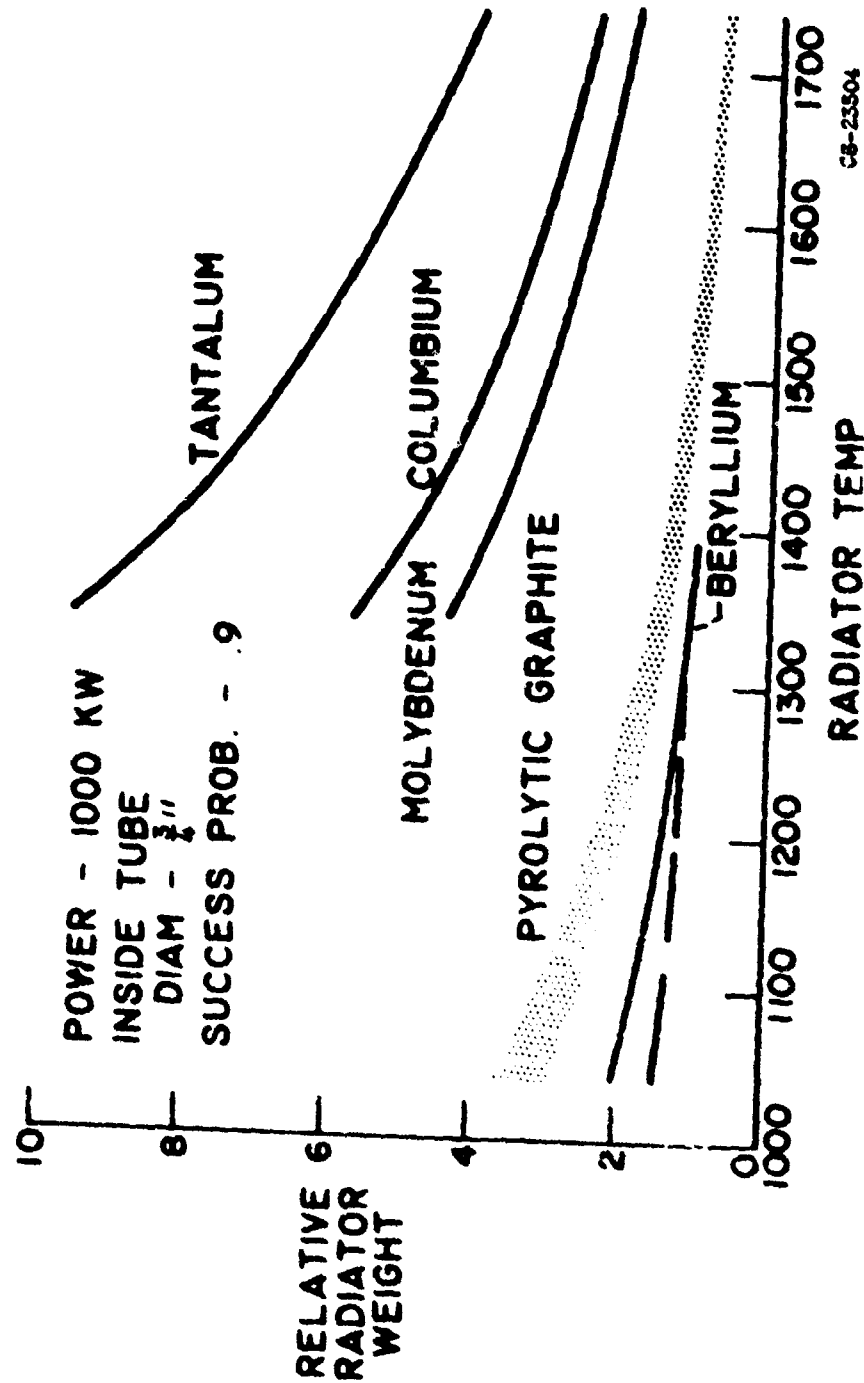


Figure 13. - Pin and tube radiator weight.

E-1710

POSSIBLE PROBLEMS WITH BERYLLIUM

- A. BONDING AND JOINING - GOOD THERMAL CONDUCTIVITY
ACROSS JOINT, DIFFERENTIAL THERMAL EXPANSION,
DIFFUSION STABLE JOINT AND COATING.
- B. APPLICATION OF ARMOR TO FULL SCALE RADIATOR.
- C. LONG TERM EFFECTS OF TEMPERATURE AND VACUUM ON
CREEP, DUCTILITY AND SURFACE EVAPORATION, -
RETENTION OF METEOROID PENETRATION RESISTANCE.
- D. FATIGUE RESISTANCE - CRITICAL AT JOINT AREAS.
- E. CORROSION RESISTANCE WITH LIQUID METALS.
- F. DESIGN FOR MINIMUM RESTRAINT.
- G. EFFECT OF OFF DESIGN CONDITIONS - STARTUP, HIGH
TEMPERATURE, VIBRATION, PLUGGED TUBE, METEOROID
HIT.

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Figure 14

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