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ORNL-TM-3563

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BY J H Kahn/amb
DATE 1/7/72

DATE - November 11, 1971

AVAILABILITY OF NATURAL RESOURCES FOR MOLTEN-SALT BREEDER REACTORS

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ABSTRACT

An investigation has been made of the availability of, and the anticipated demand for, materials of importance to the MSBR program. Materials considered included the constituents of Hastelloy-N, coolant salt, fuel salt, and materials required for construction and operation of the processing plant. It was found that the world reserves of beryllium, fluorine, and bismuth are being rapidly depleted by non-MSBR uses, and that these reserves can be expected to be exhausted by the turn of the century. Ample resources of beryllium and fluorine are available to sustain a large MSBR industry, but development of an improved mining technology will be required to make their recovery economical. Ore from which thoria is recoverable for $10/lb will be available into the middle of the twenty-first century. MSBR demands for all materials, with the possible exception of hafnium used in modified Hastelloy-N, comprise only a small fraction of the predicted world primary demand for these minerals. The fuel cycle cost was found to be relatively insensitive to the price of raw materials; an increase in the cost of carrier salt to ten times its present level, or an increase in the price of thoria or Hastelloy-N to three times their present levels, would increase the fuel cycle cost by 0.1 mill/kWhr.

Key Words: *Availability, *Materials, *Natural Resources, beryllium, bismuth, fluorine, thorium, MSBR.

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1.0 INTRODUCTION

The Molten-Salt Breeder Reactor is being developed by the Oak Ridge National Laboratory as a thermal breeder reactor that will produce low-cost electrical power, while conserving the nation's fuel resources. Fuel for this type of reactor consists of $^{233}UF_4$ dissolved in a carrier salt which has the composition 72-16-12 mole % $^7LiF-BeF_2-ThF_4$. The reactor vessel, heat exchangers, drain tank, piping, pumps, and most equipment which contact either the fuel salt or the coolant salt are fabricated of a modification of the nickel-base alloy Hastelloy-N. Fuel salt is withdrawn from the primary reactor system on a 10-day cycle for chemical processing by fluorination-reductive extraction to remove uranium and to isolate protactinium. The resulting salt is treated by the metal transfer process, a sequence of reductive extraction steps developed at ORNL, to remove Sr, Y, Ba, and the rare-earth fission products. The reductive extraction steps consist of contacting the fuel salt or the metal transfer acceptor salt (^7LiCl) with lithium-bismuth solutions. The current development program anticipates that the vessels for the salt-metal contactors will be constructed of, or lined with, molybdenum. The purpose of this report is to examine the availability of materials which are required to sustain an expanding MSBR power economy, to indicate materials for which natural resources are in short supply, and to anticipate the possible impact of such shortages on the MSBR concept. Data for the world reserves and world primary demands of various minerals have been obtained from U.S. Bureau of Mines[1,2] and U.S. Geological Survey Reports.[2] The author would like to acknowledge the generous cooperation of W. O. Fulkerson, H. E. Goeller, P. R. Kasten, and R. C. Robertson, of ORNL, in compiling the information presented in this report.

2.0 MATERIAL INVENTORIES IN AN MSBR POWER PLANT

The inventories of fuel salt and Hastelloy-N in an MSBR power plant have been considered previously by Kasten and Robertson.[3] The fuel for an MSBR is $^{233}UF_4$ dissolved in a mixture of molten fluoride salts of nominal composition 72-16-12 mole % ^7LiF-BeF_2-ThF_4. Hastelloy-N is a nickel-base alloy, designed specifically for use in molten fluoride systems, with the composition given in Table 1.

Table 1. Chemical Composition of Modified Hastelloy-N for Use in MSBRs[a]

Element	Composition (wt %)
Nickel	Balance
Molybdenum	12
Chromium	7
Iron	0-4
Manganese	0.2-0.5
Silicon	0.1 max
Boron	0.001 max
Titanium	0.5-1.0
Hafnium or Niobium	0-2
Cu, Co, P, S, C, W, Al (Total)	0.35

[a] MSR Program Semiann. Progr. Rept. Feb. 28, 1970, ORNL-4548, p. 45.

The amount of molybdenum required to construct the salt-metal contactors in the processing plant, in addition to the amount of molybdenum already present in the Hastelloy-N, is estimated to be 16 tons. The present processing flowsheet also requires a bismuth inventory of 17.4 tons and a salt discard rate of 0.3 ft^3/day.[4] Table 2 summarizes the inventories of various materials in an MSBR power plant, and compares the MSBR inventories with the estimated world reserves and world resources for these

Table 2. Material Inventories for a 1000-MW(e) MSBR, and World Reserves and Resources of MSBR Materials[a]

	Element	MSBR Inventory (tons)	World Reserves[b] (tons)	Reserve to Inventory Ratio	World Resources[c] (tons)
Fuel Salt (225 tons)	Li	17.9	7.5×10^5	4.2×10^4	6×10^6
	Be	5.1	1.2×10^4[d]	2.3×10^3	1.6×10^6[d]
	Th	99.1	5.9×10^5[e]	5.9×10^3	9.5×10^5[e]
	F	102.9	2.2×10^7[f]	2.1×10^5	4.4×10^7[f]
Hastelloy-N (1.12×10^3 tons)	Ni	874	7.4×10^7	8.5×10^4	g
	Mo	150[h]	5.4×10^6	3.6×10^4	g
	Cr	78	8.0×10^8	1.0×10^7	large
	Fe	22	1.0×10^{11}	4.5×10^9	5×10^{11}
	Mn	2.2	7.3×10^8	3.3×10^8	1.5×10^{10}
	Ti	5.6	1.5×10^8	2.7×10^7	large
	Nb[i]	1.1	1.0×10^7	9.1×10^6	g
	Hf[i]	1.1	3.1×10^5	2.8×10^5	g
Other	Bi	17.4	1.0×10^5[j]	5.7×10^3	8.2×10^4[j]
	B	50	7.2×10^7	1.4×10^5	g

[a] U.S. Geological Survey, <u>Geological Survey Professional Paper 600</u>, "Mineral-Resource Appraisals" (1968).

[b] Reserves are known materials that may or may not be completely explored, but that may be quantitatively estimated; considered to be economically exploitable at the time of the estimate.

[c] Resources are materials other than reserves that may be ultimately exploitable; they include undiscovered but geologically predictable deposits of materials similar to present reserves as well as known deposits whose exploitation awaits more favorable economic or technologic conditions.

[d] Includes deposits containing at least 1% equivalent beryl (0.1% BeO).

[e] Ores from which ThO_2 is recoverable for $10/lb.

[f] Ores which contain at least 35% CaF_2 or equivalent value in combined fluorspar and metallic sulfides.

[g] Data not available.

[h] Molybdenum inventory includes 16.0 tons required for salt-metal contactors in processing plant.

[i] Niobium and hafnium are being considered as alternate additives for modified Hastelloy-N.

[j] F. H. Persse, <u>Bismuth in the United States</u>, USBM Information Circular 8439 (1970).

materials. Throughout this report, the definitions of "reserves" and "resources" given by the U.S. Geological Survey are employed.[2] Reserves are known materials that may or may not be completely explored, but that may be quantitatively estimated, and that are considered to be economically exploitable at the time of the estimate. Resources are materials other than reserves that may be ultimately exploitable. Resources include undiscovered but geologically predictable deposits of material similar to present reserves as well as known deposits whose exploitation awaits more favorable economic or technologic conditions. The ratio of the world reserves of a material to the MSBR inventory of that element can be interpreted as the number of 1000-MW(e) MSBRs that could be built if the entire world reserves of the various elements were committed to MSBR construction, and if no materials were recycled. The world reserves of beryllium, bismuth, and thorium are adequate to construct only a few thousand MSBRs, while the world reserves of lithium, nickel, and molybdenum are sufficient to construct a few tens of thousands of MSBR power plants.

The world resources of the elements lithium and beryllium are quite large, and these elements will be available for use in MSBRs, although at an increased price. World resources of $10/lb thoria are estimated to be equally as large as the world reserves, and higher priced thorium ores are very plentiful. Bismuth resources are not reported to be large, but the foreign potential bismuth resources are not well known. World resources of MSBR materials are sufficient to construct many hundreds of thousands of reactors if the processing flowsheet is modified to reduce the bismuth inventory.

3.0 WORLD PRIMARY DEMAND FOR MSBR MATERIALS

In addition to the consumption of natural resources by the MSR program, the present and future non-MSBR uses of these materials must also be considered. Table 3 compares the world primary demand for MSBR materials in the year 1968 with the known world reserves of these materials. The data show that the world reserves of fluorine, beryllium, and bismuth are being rapidly depleted. In the case of fluorine, the world reserves will be depleted in about twelve years based on the 1968 primary demand, and the estimated world resources of ores containing 35% fluorspar will be consumed in 25 years. The Bureau of Mines anticipates, however, that as fluorspar reserves are depleted, technological advances will be made in exploring for fluorspar and in recovering fluorine from phosphate rock, so that U.S. production will be maintained to the year 2000 at approximately the current ratio of production to demand. The USBM anticipates approximately a 33% increase in the cost of fluorine, however.

Table 3. Year 1968 World Primary Demand for MSBR Materials and World Reserves of MSBR Materials

	Element	1968 World Primary Demand[a] (tons/year)	USGS Estimated World Reserves[b] (tons)	Reserve to Demand Ratio
Fuel Salt	Li	4400	7.5×10^5	170
	Be	478	1.2×10^4	25
	Th	200	5.9×10^5	3000
	F	1.8×10^6	2.2×10^7	12
Hastelloy-N	Ni	4.7×10^5	7.4×10^7	158
	Mo	6.9×10^4	5.4×10^6	78
	Cr	2×10^6	8.0×10^8	400
	Fe	4.3×10^8	1×10^{11}	230
	Mn	8.2×10^6	7.3×10^8	89
	Ti	1.4×10^6	1.5×10^8	105
	Nb	4.4×10^4	1×10^7	2300
	Hf	43	3.1×10^5	7200
Other	Bi	3800	1.0×10^5	27
	B	2.4×10^5	7.2×10^7	300

[a] U.S. Bureau of Mines, Mineral Facts and Problems, Bulletin 650, 1970 ed.

[b] U.S. Geological Survey, Geological Survey Professional Paper 600, "Mineral-Resource Appraisals" (1968).

The cumulative world demand for beryllium and bismuth also cannot be met by known world reserves. Heindl[1] concludes that mechanical techniques must be developed to replace the present hand-cobbing of pegmatite ores to recover beryl, if the cumulative world demand for beryllium to the year 2000 is to be met. Such improved mining techniques would make available 100,000 tons of beryllium at ore prices 50% greater than the present cost.

Current world reserves of bismuth are inadequate to meet the cumulative world demand to the year 2000. Bismuth does not occur in high concentration in the earth's crust and is recovered as a byproduct in refining other metals, principally lead and copper. In order to meet the demand, it is necessary that new base metal ores, from which byproduct bismuth can be obtained, be developed, and that more effective recovery and recycle techniques be employed. Current ore reserves are inadequate to meet the high range of the cumulative 1968-2000 primary demand for lead, so that development of new base metal ores may be expected to occur. It should be noted, however, that the development of these additional lead resources will require a continued expansion of the use of tetraethyl lead in gasoline, which is in contradiction to current trends.

4.0 PREDICTED GROWTH IN DEMAND FOR MSBR MATERIALS

Table 4 summarizes the estimated growth in MSBR installed electrical capacity, and the requirements for Hastelloy-N and carrier salt, through the year 2000. The MSBR installed electrical capacity is assumed to grow according to the relation:

$$P = 5180\ (T - 1985)^{1.5} ,$$

where P is the megawatts (electrical) generated by molten-salt breeder reactors at time T, in years, after 1985. This function is an attempt to represent growth in MSR generating capacity predicted by the Systems Analysis Task Force for a power economy in which gas-cooled fast breeder reactors and plutonium-fueled molten-salt converter reactors constitute a large fraction of the generating capacity.[5] The MSBR demand for natural resources in the year 2000 as a result of this growth function is compared with the estimated world demand for these materials in Table 5. Except for the two elements thorium and hafnium, the MSBR demand for

Table 4. Estimated Growth of MSBR Installed Electrical Capacity and Demand for Hastelloy-N and Carrier Salt to the Year 2000

Year	New Capacity [10^3 MW(e)]	Installed Capacity [10^3 MW(e)]	Hastelloy-N[a] (10^3 tons)		Fuel Salt[b] (10^3 tons)	
			Per year	Cumulative	Per year	Cumulative
1986	5	5	5.6	5.6	1.2	1.2
1990	16	58	18.1	63.2	4.0	14.1
1995	24	164	26.7	176.3	6.6	43.6
2000	30	301	33.6	323.7	9.1	91.6

[a] Includes 1.12 x 10^3 tons of Hastelloy-N per 1000 MW(e) installed capacity plus replacement of reactor vessel head every four years.

[b] Includes 225 tons of salt inventory of nominal composition 72-16-12 mole % LiF-BeF_2-ThF_4 plus replacement of 8.8 tons/yr of fuel salt per 1000 MW(e) installed capacity operating at a 0.8 load factor.

Table 5. Range of Year 2000 Estimated World Primary Demand for MSBR Materials

	Element	MSBR Demand[a] (tons/year)	USBM Estimated[b] World Primary Demand (tons/year)	MSBR Demand / World Demand
Fuel Salt	Li	725	$1.5\text{-}2.1 \times 10^4$	3.4-4.8%
	Be	207	$1.6\text{-}3.0 \times 10^3$	7-13%
	Th	4000	$(1.2\text{-}8.1 \times 10^3)$[c]	49%[d]
	F	4160	$7.0\text{-}9.3 \times 10^6$	0.04-0.06%
Hastelloy-N	Ni	2600	$1.1\text{-}1.6 \times 10^6$	0.16-0.26%
	Mo	4500	$2.2\text{-}3.0 \times 10^5$	1.5-2.0%
	Cr	2500	$2.7\text{-}5.6 \times 10^6$	0.04%
	Fe	720	$6.7\text{-}9.4 \times 10^8$	$\sim 10^{-4}\%$
	Mn	72	$3.3\text{-}4.4 \times 10^6$	0.002%
	Ti	180	$1.2\text{-}4.5 \times 10^6$	0.005%
	Nb	36	$1.4\text{-}3.0 \times 10^4$	0.12-0.26%
	Hf	36	$0.8\text{-}1.7 \times 10^2$	21-45%
Other	Bi	520	$4.8\text{-}7.6 \times 10^3$	6.9-10.8%
	B	1500	$0.7\text{-}1.1 \times 10^6$	0.1-0.2%

[a] Roy C. Robertson, ORNL Reactor Division, personal communication, estimates 30 new MSBRs installed in the year 2000.

[b] U.S. Bureau of Mines, Mineral Facts and Problems, 1970 ed.

[c] Low forecast assumes the absence of nuclear reactors operating on the thorium fuel cycle. High forecast anticipates an expanding nuclear economy based on the thorium cycle.

[d] Ratio is based on high range of forecast world primary demand.

materials constitutes only a small fraction of the estimated world demand. The fact that MSBRs would account for 49% of the world consumption of thorium is simply the result of the assumption that MSBRs would represent a large fraction of the electrical generating capacity in the year 2000. The relatively large fraction of the world demand for hafnium that would result from the assumed MSR economy reflects the fact that the world demand for hafnium is very small at present and is not expected to grow rapidly. Hafnium is obtained in quantities far exceeding world demand from ores from which zirconium is recovered. It is anticipated that MSBR requirements would not, of themselves, place a severe strain on the world capacity to produce any of the raw materials shown in Table 5.

The cumulative world demand for certain MSBR materials during the rest of this century is predicted to be quite large. Table 6 compares the cumulative requirements for natural resources necessary to sustain the assumed MSBR economy, and to satisfy the anticipated range of the world primary demand. Again, except for thorium and hafnium, the MSBR cumulative demand is expected to represent only a small fraction of the world demand. However, the world demand for fluorine, beryllium, and bismuth is expected to exceed the known world reserves of these materials, and the world demand for several other materials (notably Mo, Mn, Ni, and Li) is expected to severely deplete world reserves. In the cases of fluorine and bismuth, the cumulative demand may even exceed the anticipated world resources.

5.0 DISCUSSION OF RESULTS

A survey has been made of the reserves of, and future demand for, natural resources of particular importance to the MSBR program. These data have been compared with material requirements necessary to sustain a growing MSBR power economy. It was found that sufficient reserves of beryllium, bismuth, and thorium are available to build only a few thousand MSBRs, even if all the reserves of these materials are committed to MSBR construction. Also, reserves of fluorspar ore, the principal raw

Table 6. Period 1968-2000 Estimated World Primary Demand for MSBR Materials

	Element	MSBR 1985-2000 Cumulative Demand (tons)	World 1968-2000 Cumulative Demand[a] (tons)	MSBR Demand / World Demand (%)	Cumulative World Demand / World Reserves (%)	Cumulative World Demand / World Resources + World Reserves (%)
Fuel Salt	Li	7.3×10^3	$2.7\text{-}3.3 \times 10^5$	2-3	36-44	-
	Be	2.1×10^3	$3.0\text{-}4.3 \times 10^4$	5-7	250-360	1.9-2.7
	Th	4.0×10^4	$2.3\text{-}8.4 \times 10^4$	49[b]	4.5-16	1.7-6.3
	F	4.2×10^4	$1.2\text{-}1.4 \times 10^8$	0.03-0.04	500-600	180-210
Hastelloy-N	Ni	2.5×10^5	$2.4\text{-}2.9 \times 10^7$	0.8-1.0	32-39	-
	Mo	3.9×10^4	$4.2\text{-}5.0 \times 10^6$	0.8-0.9	78-93	-
	Cr	2.3×10^4	$0.9\text{-}1.1 \times 10^8$	0.02	11-14	-
	Fe	6.5×10^3	$1.7\text{-}2.1 \times 10^{10}$	$<10^{-4}$	17-21	3-4
	Mn	6.5×10^2	$3.9\text{-}4.6 \times 10^8$	$<10^{-5}$	53-63	2-3
	Ti	1.6×10^3	$1.9\text{-}4.4 \times 10^6$	0.04-0.08	1.2-2.9	-
	Nb	3.2×10^2	$2.7\text{-}4.0 \times 10^5$	0.08-0.12	2.7-4.0	-
	Hf	3.2×10^2	$1.9\text{-}2.9 \times 10^3$	11-17	0.6-0.9	-
Other	Bi	5.2×10^3	$1.4\text{-}1.8 \times 10^5$	2.9-3.7	140-180	78-100
	B	1.5×10^4	$1.4\text{-}1.8 \times 10^7$	0.08-0.1	20-25	-

[a] U.S. Bureau of Mines, Mineral Facts and Problems, 1970 ed.

[b] Ratio based on high range of forecast world cumulative demand.

material for recovery of fluorine, are being rapidly depleted by non-MSBR applications. The following sections summarize United States Bureau of Mines information on reserves, mining technology, applications, and potential resources of these four materials.

5.1 Beryllium

Beryllium occurs at an average concentration of about 6 parts per million in the earth's crust, and is an essential constituent in some 40 minerals. Beryl, bertrandite, phenacite, barylite, and chrysoberyl are the most common beryllium minerals, but beryl ($3BeO \cdot Al_2O_3 \cdot 6SiO_2$) is the sole commercial source of beryllium. When pure, beryl contains about 14% beryllium oxide or about 5% beryllium metal. Commercial beryl is hand sorted to obtain crystals and lumps of beryl containing about 11% BeO, or 4% beryllium.

The world's principal commercial sources of beryl are heterogeneous granite pegmatites, where the mineral occurs in rich zones, usually containing only a few thousand tons of pegmatite rock. Occasionally pegmatites are mined for beryl alone, but more often beryl is recovered as a byproduct of feldspar, mica, and other minerals. Pegmatite deposits are mined by drilling or blasting, then hand-cobbing the blasted rock, a procedure by which barren rock is broken off with hand hammers and discarded, and the valuable minerals, including beryl, recovered. Beryl, feldspar, and some other pegmatite minerals have densities so nearly the same that it is difficult to separate beryl by mechanical means. Thus, all commercial beryl is hand-cobbed, and crystals less than one inch in size are not usually recovered. It is estimated that only one-third of the beryl in an average deposit is recovered by the hand methods now in use.

The United States primary demand for beryllium in 1968 was 328 tons, and the rest-of-the-world demand was 150 tons. The range of the United States demand for beryllium in the year 2000 is expected to be 1250 to 1740 tons, and the range of rest-of-the-world primary demand in the year 2000 is predicted to be 400 to 1300 tons. Beryllium is used, principally in the form of beryllium-copper alloys, in switchgear, welding apparatus, computer equipment, and radio and television equipment. Few data are available on world beryllium reserves, which are roughly estimated to be 12,000 tons. Domestic reserves of pegmatite ores containing at least 1% beryl are only about 400 tons. However, there are some 50,000 tons of beryllium contained in lower-grade pegmatite ores found in North Carolina, and 27,000 tons of contained beryllium in bertrandite deposits in Utah. In this country, attention is being given to recovering beryllium from these latter deposits. It is estimated that 15,000 tons of the beryllium in bertrandite at Spor Mountain, Utah, could be recovered at no change in ore price, and that an additional 25,000 tons could be recovered at a 50% increase in ore price. The cost of the ore is a small part of the cost of the metal, so that the price of the metal is actually expected to decrease about 20% by the year 2000 as the result of improved extractive technology and from economies of scale. The cost of the fluoride, which is intermediate between the cost of the contained beryllium in the ore and the cost of the refined metal, should show no large price increase during this period.

5.2 Fluorine

The principal fluorine-containing minerals are fluorspar (CaF_2), cryolite (Na_3AlF_6), and phosphate rock. Fluorspar, the principal fluorine mineral, is mined in this country and abroad, with domestic resources of about 5.4 million tons of contained fluorine and rest-of-the-world resources of 33.4 million tons. The only known natural cryolite deposit at Ivigtut, Greenland, was exhausted in 1963, but stockpiled ore is available to supply needs for 15 to 20 years. Fluorine compounds may be recovered from phosphate rock, but, because of the high cost of recovering the fluorine, most of this material is neutralized and discarded. Thirty-five percent of the fluorine consumed in 1968 was used in the form of HF to manufacture fluorocarbon compounds. Thirty-three percent of the fluorine consumed was in the form of fluorspar for use as a flux in the steel industry, where from 3 to 12 lb of fluorspar is required per ton of steel produced, depending on the process. Fluorine, in the form of cryolite, is used by the aluminum industry to dissolve alumina for electrolysis. This use accounted for 18 percent of the 1968 fluorine demand. The domestic demand for fluorine was 646,000 tons in 1968 and is expected to rise to 2.1 to 2.7 million tons by the year 2000. Rest-of-the-world demand for fluorine in 1968 was 1.2 million tons and is expected to rise to 5.0 to 6.6 million tons. Domestic resources of fluorine are expected to be depleted in 25 years, and rest-of-the-world resources are expected to be exhausted in less than 20 years. However, it is believed that technological advances in exploring for fluorspar deposits will be made so that a sufficient supply of fluorspar will be available to meet the demand through the year 2000 at an increase in ore cost of about 33%.

5.3 Bismuth

Bismuth is a relatively rare element, occurring in the earth's crust at a concentration of about 0.1 part per million. It is found in the minerals bismite (Bi_2O_3) and bismuthinite (Bi_2S_3), which occur in low concentration in ores throughout the world. As a result of the low concentration of bismuth in most ores, deposits are not mined for the bismuth content alone. Most bismuth is recovered as a byproduct of the mining and processing of other minerals containing small amounts of bismuth. The technology of bismuth extraction and refining is well established in connection with lead-refining plants. The bismuth in lead ores, concentrates, and flue dust is collected in the lead bullion, from which it is recovered. About 50% of the bismuth consumed is used as an alloying material in fusible alloys, specialty aluminum, and malleable iron and steel. Another 40% of the bismuth consumption is for use in pharmaceuticals and cosmetics. The United States and rest-of-the-world primary demands for bismuth in the year 1968 were 1100 and 2700 tons, respectively. The range of the U.S. primary demand for bismuth in the year 2000 is expected to be 1400 to 2300 tons. The rest-of-the-world requirements for the year 2000 are expected to grow to 3400 to 5300 tons. World reserves of bismuth are estimated to be 100,000 tons, a quantity which is insufficient to satisfy the cumulative world demand for bismuth to the year 2000. Potential bismuth resources in the U.S. and fifteen foreign countries surveyed by the Bureau of Mines total 82,000 tons. In order to meet the cumulative world demand for bismuth through the year 2000, it is necessary that new base metal ore reserves (from which bismuth is obtained as a byproduct) be developed. Domestic reserves of bismuth from lead ores total 14,000 tons. Potential domestic bismuth resources of 5000 tons are associated with marginal lead ores, and additional resources totaling 14,000 tons are associated with other base metal ores. The production of bismuth is closely related to the demand for lead, so that it is necessary for the demand for lead to increase in order that additional lead and associated bismuth resources be developed. Since 20% of the lead demand in the year 1968 was for use as tetraethyl lead in gasoline, the trend toward low-lead gasoline may retard the development of bismuth resources. In this case, bismuth demand would have to be met by developing resources associated with copper and zinc ores.

5.4 Thorium

Thorium is a widely distributed element, having an abundance of 10 to 20 parts per million in the earth's crust. It is found in the form of the minerals thorianite, ThO_2, and thorite, $ThSiO_4$, and may be associated with varying amounts of UO_2 and UO_3. Monazite, an important thorium-bearing mineral, is a rare-earth phosphate which may also contain up to 18% ThO_2. Monazite deposits are found in India, Brazil, Australia, Ceylon, Indonesia, Malagasy Republic, Malaysia, the Republic of South Africa, Canada, and the United States. Monazite is generally recovered from river and beach sands by placer mining methods. The monazite is concentrated, chemically processed to separate the rare earths, and purified by solvent extraction. The principal uses of thorium are in the manufacture of incandescent gas mantles, the production of magnesium-thorium alloys, other metallurgical applications, and as a catalyst in the petroleum and chemical industries. World primary demand for thorium in 1968 totaled 200 tons. Should nuclear reactors operating on the ^{232}Th-^{233}U fuel cycle prove successful, the high range of the world thorium demand for the year 2000 is predicted to be 8100 tons, and the cumulative demand for the period 1968-2000 is expected to be 84,000 tons. World reserves of thorium at $10 per pound of ThO_2 are 590,000 tons, and world resources at this price are predicted to be almost one million tons. Although it is apparent that inexpensive thorium ores will be available well into the next century, even larger quantities of thorium will be available at higher prices. Table 7 summarizes the magnitudes of the thorium resources in the United States as a function of the cost of ThO_2. While data on the amount of ore available in foreign countries at higher prices are not available, it is believed that analogous quantities would be recoverable at increased prices.

Table 7. Domestic Thorium Resources as a Function of Price of ThO_2[a]

Price Range per Pound of ThO_2 ($)	Reasonably Assured Resources (tons)	Estimated Total Resources (tons)
under 10	100,000	400,000
10-30	100,000	200,000
30-100	7,000,000	35,000,000
100-500	1,000,000,000	3,000,000,000

[a] AEC, Civilian Nuclear Power, a Report to the President, 1967, as presented to the Joint Committee on Atomic Energy, 88th Cong., Feb. 20 and 21, 1963.

6.0 CONCLUSIONS AND RECOMMENDATIONS

The elements beryllium, bismuth, and fluorine have been identified as materials whose mineral reserves are insufficient to satisfy the predicted world demand for these elements by the year 2000, thus creating an economic situation which might not favor the growth of an MSBR power economy. Of these three elements, the outlook for beryllium is most promising. The domestic demand for beryllium is met, at present, almost entirely by imports of beryl, which is mined from pegmatite ores by primitive, hand sorting methods. While this country does not have large resources of hand-cobbable beryl, the mineral bertrandite is found in large quantities in the western part of the United States. Unlike beryl, bertrandite occurs in deposits associated with minerals whose densities differ sufficiently from bertrandite that mineral beneficiation techniques are feasible. If the western U. S. bertrandite deposits are developed successfully, the demand for beryllium through the year 2000 can be met with no increase in the cost of beryllium metal or beryllium fluoride.

The element fluorine, in the form of fluorspar and cryolite, is used extensively in the steel and aluminum industries. Fluorine is mined in the form of fluorspar, a mineral whose mining technology is already well developed and highly mechanized, so that greater production via improved mining technology is unlikely. The U. S. Bureau of Mines believes that technological advances in exploring for fluorspar deposits and recovery of fluorine from phosphate rock will result in an adequate supply of fluorspar to the year 2000 at about a 33% increase in price. The resources of fluorine contained in phosphate rock deposits in this country alone are estimated at 2.8×10^8 tons, a quantity which far exceeds the resources of fluorspar. As the price of fluorspar increases, it is likely that more efficient use of the mineral will be made in the steel industry, where the quantity of fluorspar consumed per ton of steel varies from 3 to 12 lb. Within the MSR Program, it will be necessary to make efficient use of fluorine. The complete recycle of fluorine in the uranium removal system of the present flowsheet is an example of the type of improvements required. Consideration should also be given to discarding a chloride waste salt rather than a fluoride salt. In the year 2000, replacement of discarded salt will account for 25% of the fluorine consumed by the MSR economy, based on the present flowsheet. Also, at the end of the thirty-year life of a reactor, the carrier salt as well as the fissile material should be recovered and recycled to other reactors. Recovery is possible by means of low-pressure distillation, a process whose technology has been demonstrated by Hightower _et al._[6]

Bismuth reserves are also insufficient to meet the world cumulative demand for this metal through the year 2000. Bismuth supply is closely linked to and limited by resources and production of lead and copper. The supply varies, therefore, according to the demand for these metals, rather than according to the independent requirements for bismuth. The relatively limited and inelastic supply has prevented use of bismuth for applications requiring substantial quantities. In order to meet the demand for bismuth, more effective recovery techniques, increased secondary bismuth recovery, and development of new base metal ores are required. Substitution of alternate materials for bismuth in pharmaceuticals and cosmetics may reduce demand somewhat. A large fraction of the bismuth inventory in the MSBR processing plant is employed to dissipate the radioactive decay heat from the rare-earth fission products in the metal transfer system. The bismuth inventory necessary to operate the metal transfer process could be significantly reduced if another means is used for dissipating the fission product decay heat.

Bismuth and fluorine appear to be the two elements in the MSBR fuel cycle which are most vulnerable to depletion of low-cost natural resources. Present estimates by the U. S. Bureau of Mines are that reserves will be expanded to meet the demand for these materials through the year 2000. The availability of these materials beyond this point at prices near present costs appears quite uncertain. Although beryllium reserves which can be recovered by today's hand mining techniques are small, large resources are known to exist, and it is expected that mechanical mining techniques can be developed to recover beryllium from these ores at no increase in the cost of beryllium fluoride or beryllium metal. Reserves of $10/lb thoria are adequate to supply an MSBR economy well beyond the year 2000, and large resources of higher priced thoria are available, so that fertile material will not be in short supply in the foreseeable future.

A large fraction of the world reserves of elements Li, Mo, Ni, and Mn will also be consumed by the year 2000. In all cases, the MSBR demand for these materials will be a small fraction of the world demand. Increases in the costs of nickel and molybdenum that result when these reserves are depleted will have a greater adverse effect on the MSBR program than on competing reactor types, because of the relatively high content of these materials in Hastelloy-N and the use of molybdenum as a material of construction in the processing plant. (A typical 1000-MW(e) LMFBR power plant would require about 15% of the Ni and less than 1% of the Mo in an MSBR.) It is possible, however, that reserves of these materials will be expanded sufficiently rapidly that large increases in price will not occur until well beyond the year 2000.

Consideration has been given to the effect of large increases in the price of raw materials on the fuel cycle cost of power produced by an MSBR. The inventory and replacement charges for a number of materials are given in Table 8 for a 1000-MW(e) MSBR as presently envisioned.

Table 8. Inventory and Replacement Charges for Materials in a 1000-MW(e) MSBR

Material	Price ($/lb)	Inventory (tons)	Replacement (tons/yr)	Inventory and Replacement Cost[a] (mill/kWhr)
^{7}Li	55	17.9	1.0	0.055
Be	39.2[b]	5.1	0.2	0.010
Th	8.6[c]	99.1	6.3	0.050
F	0.5	102.9	2.9	0.0025
Hastelloy-N	10.80[d]	1120	10	0.514
Bi	6	17.4	0	0.004

[a] Assume inventory charge of 14% per annum and 0.8 plant factor.

[b] Cost of contained beryllium based on a cost of BeF_2 of $7.50/lb.

[c] Cost of contained thorium based on a cost of ThF_4 of $6.50/lb.

[d] Average cost of Hastelloy-N based on finished shapes costing $8 to $20/lb.

These data show that an increase in the price of beryllium, fluorine, or bismuth by an order of magnitude would increase the fuel cycle cost by at most 0.1 mill/kWhr. If the price of ThO_2 rises to $30/lb, the increase in fuel cycle cost would also be about 0.1 mill/kWhr. The cost of natural lithium is about $1/lb which, compared to the price of isotopic separation, is quite small. An increase of an order of magnitude in the cost of natural lithium would result in an increase in fuel cycle cost of only 0.1 mill/kWhr. The case is similar with the components of Hastelloy-N, which has a value of about $1/lb, but which is estimated to cost $8 to $20/lb when fabricated into finished shapes. An increase of 100% in the cost of nickel, the major constituent of Hastelloy-N, would result in an increase in fuel cycle cost of only 0.05 mill/kWhr.

In summary, there is no natural resource in such short supply that it would render the development of molten salt reactors unattractive. World reserves of some materials required for the MSR Program are being depleted, but new resources of these materials must be developed in order to supply a wide variety of consumers. Several areas are indicated where efficient recycle of materials within the MSR economy is desirable, but such recycle is probably in the direction of lower fuel cycle costs, even at present market conditions, and will be included in the MSR fuel cycle for reasons other than conservation of natural resources.

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