Information Circular 9102

Lithium Availability—Market Economy Countries

A Minerals Availability Appraisal

By D. I. Bleiwas and J. S. Coffman

UNITED STATES DEPARTMENT OF THE INTERIOR
Donald Paul Hodel, Secretary

BUREAU OF MINES
Robert C. Horton, Director

As the Nation's principal conservation agency, the Department of the Interior has responsibility for most of our nationally owned public lands and natural resources. This includes fostering the wisest use of our land and water resources, protecting our fish and wildlife, preserving the environment and cultural values of our national parks and historical places, and providing for the enjoyment of life through outdoor recreation. The Department assesses our energy and mineral resources and works to assure that their development is in the best interests of all our people. The Department also has a major responsibility for American Indian reservation communities and for people who live in island territories under U.S. administration.

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PREFACE

The Bureau of Mines is assessing the worldwide availability of selected minerals of economic significance, most of which are also critical minerals. The Bureau identifies, collects, compiles, and evaluates information on producing, developing, and explored deposits, and mineral processing plants worldwide. Objectives are to classify both domestic and foreign resources, to identify by cost evaluation those demonstrated resources that are reserves, and to prepare analyses of mineral availability.

This report is one of a continuing series of reports that analyze the availability of minerals from domestic and foreign sources. Questions about, or comments on, these reports should be addressed to Chief, Division of Minerals Availability, Bureau of Mines, 2401 E St., NW., Washington, DC 20241.

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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

°C	degree Celsius	lb	pound
cm	centimeter	m	meter
d/yr	days per year	mt	metric ton
$/lb	U.S. dollars per pound	mt/d	metric ton per day
$/mt	U.S. dollars per metric ton	mt/yr	metric ton per year
ha	hectare	pct	percent
km	kilometer	tr oz/mt	troy ounce per metric ton
km^2	square kilometer	yr	year

LITHIUM AVAILABILITY — MARKET ECONOMY COUNTRIES

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By D. I. Bleiwas[1] and J. S. Coffman[1]

ABSTRACT

The Bureau of Mines determined the costs associated with lithium production (in various products) from demonstrated resources in seven market economy countries (MEC's). This analysis evaluated the relative economic and resource position of 16 mines or deposits, including 6 producers and 1 (Bernic Lake) operating at pilot scale. The demonstrated resource of recoverable lithium within the deposits studied is approximately 2.2 million metric tons (mt). Virtually all known MEC resources and production were covered, including resources in Chile (59 pct of the total), the United States (13 pct), Australia (11 pct), Canada (10 pct), and Bolivia, Zaire, and Zimbabwe (combined 7 pct). In addition, the large potential of lithium-enriched brines is assessed, especially those in the Atacama Basin, Chile, where production began in 1984.

The lithium resource consists of lithium in spodumene, brines, and to a small extent lepidolite and petalite. Most MEC lithium trade originates from the United States, though development of brine deposits in Chile, and potential development in Bolivia, could threaten the U.S. position. Economic analysis indicated that all lithium being recovered from producing properties could be produced at less than the published market price, and that MEC resources from these properties are adequate to supply any foreseeable demand.

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INTRODUCTION

The purpose of this report is to identify and define demonstrated lithium resources and evaluate the potential production from 3 domestic mines and from 13 mines and deposits in 6 foreign countries. Another purpose was to evaluate at least 85 pct of lithium resources and 85 pct of lithium production from producing operations in market economy countries (MEC's).

The procedures for this study included the identification of lithium resources and the collection of the engineering and economic parameters that affect production or proposed production from the deposits selected for evaluation. The information, obtained by Pincock, Allen & Holt Co., Inc., on the 13 foreign mines and deposits was collected under competitive contract J0255018. Foreign data were obtained by the contractor through acquisition of publications, meetings with company officials, and, in several cases, actual site visits by their personnel. Demonstrated and, if possible, identified resources and grades were defined; capital investment and operating costs were obtained or estimated as well as transportation costs to postmill processing destinations. As necessary, the data were modified or updated by the Bureau's Minerals Availability Field Office personnel in Denver, CO. For the domestic operations, data were collected by the Bureau's Field Operations Centers.

Of the 23 lithium mines and deposits initially investigated, 7 were excluded because of the small size of the demonstrated resource or insufficient data to complete an evaluation.

METHODOLOGY

The Bureau of Mines is developing a continuously expanding data base for the analysis of mineral resource availability. An integral part of this program is the Supply Analysis Model (SAM), developed by personnel of the Bureau's Minerals Availability Field Office (*3*).[2] This interactive computer system is an effective tool for analyzing the economic availability of world resources.

The geologic aspects particular to the lithium operations included in this study were determined in order to develop estimates of the demonstrated resources, in situ grades, and production costs. For each operation evaluated, actual or estimated capital expenditures were included for exploration, acquisition, development, mine plant, mine equipment, and mill plant and equipment. Capital costs for the mining and processing facilities include expenditures for mobile and stationary equipment, construction, engineering, infrastructure, and working capital. Infrastructure is a broad category that includes cost for access to the mine and its associated facilities, ports, water supply and treatment, power supply, and personnel accommodations. Working capital is a revolving cash fund intended for covering operating expenses such as labor, supplies, insurance, and taxes. All costs are in terms of January 1984 U.S. dollars.

The initial capital costs for producing mines and developed deposits have been depreciated according to the actual investment year, and the undepreciated portion was treated as a remaining capital investment in 1984. Reinvestments varied according to capacity, production life, age of facilities, and company philosophy. All costs were originally in January 1982 dollars but have been updated to January 1984 U.S. dollars by the use of local currency factors and individual country inflation indexes, weighted proportionately by the effect of labor, energy, and capital in the lithium industry on a countrywide basis.

The total operating cost estimated for a mining operation is a combination of direct and indirect costs. Direct operating costs include those costs associated with operation and maintenance, labor, supplies, supervision, payroll overhead, insurance, local taxation, and utilities. The indirect operating costs include those costs associated with technical and clerical labor, administrative costs, maintenance of the facilities, and research. Other costs in the analyses include standard deductibles such as depreciation, depletion, deferred expenses, investment tax credits, and tax loss carryforwards.

After the engineering parameters and associated costs for the evaluated lithium deposits were established, the SAM system was used to perform economic evaluations that permit estimation of the availability of lithium.

Specifically, the SAM system is an economic evaluation simulator that is used to determine the average total cost of lithium or mineral commodity produced as specified rates over the estimated life of each operation including a prespecified discounted-cash-flow rate of return (DCFROR) on investments, less all byproduct revenues. This average total cost represents the constant-dollar, long-run price at which the primary commodity must be sold to recapture all costs of lithium production including a prespecified DCFROR.

For this study, DCFROR's of 0 and 15 pct were specified when determining the long-run cost of production over the life of a property. The 0-pct DCFROR is used to determine the breakeven cost, where revenues are sufficient to recover total investment and production costs over the operation's life but provide no positive rate of return. This rate could be adequate for a project that seeks primarily a market share or where other advantages such as social benefits, foreign exchange, introduction of new technology, or expectation of better market prices would offset the lack of profitability. A 0-pct DCFROR could also be acceptable for some government-operated mining ventures. The 15-pct DCFROR reflects the estimated minimum rate of return sufficient to compensate profit-oriented enterprises and to attract new capital to the industry.

The SAM program contains a separate tax records file for each country and state and includes all the relevant tax parameters under which a mining firm would operate. These tax parameters are applied to each evaluated mine with the assumption that each operation represents a separate corporate entity. The SAM system also contains a separate file of 12 economic indexes for each country to

[2]Underlined numbers in parentheses refer to items in the list of references at the end of this report.

Table 1.—Byproduct commodity prices used in economic evaluations

(January 1984 dollars)

Mica	per mt..	32.00
Pollucite conc (25 pct CsO_2)	per mt..	75.00
Sandspar	per mt..	30.15
Tantalum oxide	per lb..	29.00
Tin	per lb..	5.70

enable updating of cost estimates for both producing and nonproducing mines and undeveloped deposits in 95 countries.

Price tables are maintained for all coproducts and byproducts that are applicable to the availability analyses. The byproduct prices used in this study are shown in table 1.

Detailed cash-flow analyses are generated with the SAM system for each preproduction and production year of an operation beginning with the initial year of analysis in 1984. Individual deposit or region analyses were aggregated to produce a total availability curve.

Availability curves are constructed as aggregations of all evaluated operations ordered from those having the lowest average total costs to those having the highest. The potential availability of lithium can be seen by comparing an expected long-run constant-dollar market price to the average total cost values shown on the availability curves. Availability curves are explained in greater detail in the Lithium Availability section.

Certain assumptions are inherent to all analyses performed in this report:

1. All mines produce at design capacity throughout the estimated life of the operations unless they were known to be producing at reduced levels, or were temporarily shut down because of depressed market conditions. It was assumed that full capacity could be resumed after a 1- to 4-yr preproduction period.
2. Each operation is assumed to sell all of its output at no less than the determined total cost required to obtain at least the minimum specified rate of return.
3. Each operation will be able to sell all its coproducts and byproducts at the January 1984 market prices.
4. No startup date is known for the nonproducers, therefore, development was assumed to begin in year "N."
5. Unless specific data were available, time delays relating to permitting, environmental impact statements, and other factors affecting actual or potential production were minimized.

Some of the deposits evaluated could unexpectedly be prevented from development, forced to reduce production, or close owing to lack of capital, environmental problems of issues, political reasons, a poor economic climate, or other constraints not known at this time.

BACKGROUND AND USES

Lithium in pure form is a soft, silvery white metal that is the lightest of all solid elements. It is highly reactive as a pure element and has never been found as a metal in nature; instead it is always combined with stable compounds. The most concentrated forms of lithium are associated with pegmatites and salt brines. Lithium was discovered early in the 19th century but was not used until the latter half of the century. The first uses were as ceramic additives in the natural mineral form. The first important use as a chemical was for hydrogen generation (as LiH), used to inflate emergency signal balloons in World War II. Later in the war, high-temperature-resistant lithium-based greases were developed. Shortly thereafter there was a demand for lithium in fusion reaction experimentation. By 1960 lithium had come into demand for a wide variety of uses and was well established in the marketplace. Currently, lithium has broad industrial applications; it is used in its mineral forms, such as spodumene and petalite, for use in ceramics and glass, in a variety of chemical forms, and as a metal for alloying.

The ceramics industry uses an estimated 26 to 28 pct of the contained lithium consumed in the United States (*6*, p. 467). It is used in the form of mineral concentrate, such as spodumene or petalite, or as lithium carbonate (Li_2CO_3) and other forms derived through the carbonate process. Li_2CO_3 is generally used in the steel enameling (glazing) process. The glazes are used for their resistance to thermal shock. It is also used directly or as petalite for making thermal-shock-resistant glass cookware. Controlled heat treatment of the lithium-enriched glass results in nearly zero thermal expansion. Low-iron spodumene may also be used in ceramics and in rigid foam insulation to impart low thermal expansion properties. Other ceramic and glass uses include lithium in sealed-beam headlights, photochromatic glass lenses, and large telescopic lenses.

The commercial lithium compounds, including Li_2CO_3, lithium hydroxide monohydrate ($LiOH \cdot H_2O$), and lithium chloride (LiCl), may be used directly themselves, for producing other chemicals, and for lithium metal. The carbonate form is also used as a base for nearly all the chemical derivatives, including the hydroxide and chloride.

The largest use of Li_2CO_3 is in electrolytic aluminum reduction cells because it lowers the electrolytic cell temperature and thereby conserves energy in the process. In this use, lithium fluoride (LiF) comprises about 3 pct of the electrolyte. Research has recently developed a lightweight, high-strength lithium aluminum alloy that could increase the lithium metal consumption in the aerospace industry.

The hydroxide is a component of over 50 pct of greases and accounts for about 15 pct of the lithium used in the United States (*27*, p. 7). These greases contain about 2 pct Li and are effective as lubricants over a wide range of temperatures. This chemical can also be used to make LiCl. The most important use of LiCl is as a feedstock for the production of lithium metal. The metal in turn is used for the production of butyllithium, which is used as a catalyst in the production of synthetic rubber. An estimated 10 pct of lithium minerals (spodumene, petalite, etc.) are used directly in the ceramics and glass industry (*7*, p. 576).

There are a number of minor uses of lithium in various chemical forms such as bromides, chromates, sulfates, manganates, and acetates. Lithium has a relatively important but quantitatively small application in battery technology, particularly in small batteries (watches, calculators, etc.), computers, and missile guidance systems. It also has some use in large industrial batteries but has not yet been developed for use in automotive batteries where the largest potential battery market exists. In addition, research has been ongoing for many years concerning lithium as a potential fuel source for fusion reactors.

MARKET STRUCTURE

In past years, nearly all (at least 90 pct) of the lithium in the MEC's has been produced in the United States. As of 1984, however, Chile entered into the market by developing the Salar de Atacama operation. With the annual capacity of this new operation of about 6,000 mt Li_2CO_3 (12 to 14 million lb), the United States will retain about 75 to 80 pct of the market share. A relatively small facility in Australia (Greenbushes) currently produces high-grade spodumene concentrate for the ceramics and glass industry. The production from this mine started in 1982, and the spodumene concentrate is exported to Europe and Japan for applications in ceramics. The Bikita mine in Zimbabwe produces mainly petalite for use in specialty glasses and ceramics. There are also some countries that produce small amounts of lithium minerals, mainly for internal consumption.

The supply of lithium chemicals and many lithium-based products has been controlled by two U.S.-based companies. These are Lithium Corporation of America (Lithco), a subsidiary of FMC Corp., and Foote Mineral Co., controlled by Newmont Mining Corp. The Chilean Government entered into the supply side by its 45 pct ownership of the Salar de Atacama operation through the government's development company, Corporation de Fomento de la Produccion (CORFO). The remaining 55 pct of this operation is owned by Foote Mineral Co.

The market structure of lithium is relatively stable in view of the longstanding supply situation of the two companies. Lithco produces numerous products at its Bessemer City, NC, plant complex and at its subsidiary in the United Kingdom, Lithco Europe Ltd. Foote Minerals produces mainly Li_2CO_3 at its Kings Mountain, NC, plant (a few kilometers from the Lithco operation) and its brine operations in Nevada and Chile. Foote Minerals' concentrates and Li_2CO_3 are supplied to company-owned plants in Pennsylvania, Tennessee, and Virginia to produce other downstream (value-added) products. Both companies supply raw materials to European plants for the production of products for the European market. The principal producer in Europe (other than Lithco Europe) is Chemettall, a subsidiary of Metallgesellschaft, Federal Republic of Germany.

The U.S. trade balance of lithium weighs heavily in the favor of exports. In 1983 the United States exported lithium products valued at over $42 million, while the value of imports totaled about $2 million. In terms of total weight of lithium products, the United States exported about 12,600 mt and imported about 180 mt (*7*, p. 578).

This study includes three types of lithium commodities: Li_2CO_3, spodumene, and petalite concentrates. The pricing structure depends largely on the type and purity of the concentrate. Current prices are adapted from published sources (*13*) and are discussed below.

Li_2CO_3, which contains nearly 19 pct Li, is produced from spodumene at Kings Mountain and Bessemer City, NC, and from brines at Salar de Atacama, Chile, and Silver Peak, NV. It currently sells for about $1.54/lb delivered (May 1985). Spodumene concentrate can contain from about 1.86 to 3.25 pct Li and is priced from about $200/mt to $356/mt f.o.b. mine in the United States and c.i.f. in other countries, depending on the grade, purity, and volume. Petalite concentrate is produced at the Bikita, Zimbabwe, mine and sells for about $185/mt c.i.f. European ports. This concentrate contains approximately 1.86 pct Li and is used in specialty glass and ceramics.

Other mineral concentrates include lepidolite, amblygonite, and eucryptite; however, quantities used are so small that they have no separate pricing quotations.

PRODUCTION

Lithium production for the years 1980-84 is listed in table 2. The U.S. production amounted to about 69 pct of the total world lithium production in 1983. In that year, the United States produced over 90 pct of MEC production. This share decreased in 1984 and will decrease even more in 1985, with the first year of full production from Salar de Atacama in Chile.

The quantities of contained lithium were calculated from estimated percentages contained in the various mineral concentrates (i.e., spodumene, petalite, lepidolite, amblygonite, etc.) produced in each country. The non-U.S. production is used mostly as mineral concentrates, whereas the U.S. production is mostly in the form of Li_2CO_3 and other chemicals.

Table 2. — World lithium production, 1980-84[1] (*29*)

(Metric tons of contained lithium)

Country	1980	1981	1982	1983	1984[e]
Argentina	9	2	2	5	1
Australia	0	0	0	62	212
Brazil	54	60	60	54	10
Chile	0	0	0	0	481
China	362	272	279	317	454
Namibia	NA	34	27	18	14
Portugal	17	18	16	9	4
United States[2]	4,920	4,922	3,469	4,453	4,444
U.S.S.R.	1,180	1,088	1,088	1,270	1,633
Zimbabwe	398	417	290	136	159
Total	6,940	6,813	5,231	6,324	7,412
U.S. production, as pct of total	71	72	66	70	60

[e] Estimated. NA Not available.
[1] Contained lithium estimated from data on mineral concentrate production.
[2] Based on 10-K information.

GEOLOGY

The principal occurrences of lithium are in pegmatites and salt brines. Pegmatites generally occur in Precambrian metamorphosed shield-type rocks, and the brines occur in closed drainage basins in areas of low precipitation and high evaporation.

PEGMATITES

The pegmatite occurrences are relatively widespread throughout the world in shield-type rocks. Generally, the geological environment for the formation of the spodumene pegmatites also produces swarms of pegmatites that may consist of hundreds of small pegmatites. This study addresses only the larger, potentially more economically viable occurrences within an area.

Lithium pegmatites have been classified into two categories: (*23*): (1) deposits that contain a relatively consistent spodumene content throughout the pegmatite and from contact to contact (no zonation) and (2) deposits containing spodumene and other lithium minerals, such as petalite and lepidolite, in a zoned deposit. The first type is by far more important quantitatively and, where mined, the spodumene may consist of up to 25 pct of the rock. The pegmatites generally contain a greater quantity of quartz than spodumene, with the remainder of the pegmatites being made up of feldspars and micas. Zoned pegmatites generally contain other economically important minerals. The largest known zoned pegmatite is the Bikita pegmatite in Zimbabwe, which contains petalite, spodumene, lepidolite, eucryptite, and amblygonite. The principal lithium pegmatite minerals are listed in table 3.

Table 3. — Principal lithium pegmatite minerals (*23*)

Mineral	Formula	Lithium content, pct	
		Theoretical maximum	Marketed concentrates
Amblygonite	$LiAlPO_4(F,OH)$	4.73	3.7-4.2
Eucryptite	$LiAlSiO_4$	5.50	2.6-3.0
Lepidolite	$KLi_2AlSi_4O_{10}F_2$	Variable	1.4-1.9
Petalite	$LiAlSi_4O_{10}$	2.26	1.4-2.2
Spodumene	$LiAlSi_2O_6$	3.73	2.6-3.0

CLAYS

A relatively large, low-grade, lithium-bearing clay resource occurs in northern Nevada and southeastern Oregon; the lithium is contained in hectorite. The clay has only been bench tested for lithium extraction (*19*) and, since there is no reliable grade information on which to base a total demonstrated resource estimate, the deposit was not evaluated in this study.

BRINES

Most of the lithium originates from playa brines containing lithium in varying amounts. At Silver Peak, NV, and Salar de Atacama, Chile, lithium is being extracted as the primary commodity. Lithium could potentially be extracted as a byproduct from other brine operations, principally magnesium and potash at Searles Lake, CA, the Great Salt Lake, UT, and the Dead Sea (Israel and Jordan).

The playas ("salares" in Latin America) occur in closed or restricted drainage basins where the evaporation rate is greater than the precipitation. The water source for the playas can be either direct precipitation or runoff from the surrounding hills, migration through the water table or mineral rich springs; several sources could contribute to the development of a deposit.

The mineral content of a deposit is dependent on the source material; the largest evaporite content is salt (NaCl). A playa is normally composed of a salt crust that is interspersed with varying amounts of sands, clays, and other detritus. This salt crust is normally porous (more so near the surface) and the interstices contain the salt brines. Selected elemental content of some brines are as listed in table 4.

Table 4. — Estimated average element content of some brines, percent (*16*, 26)

Location	Li	Mg	K	Na
Bolivia: Salar de Uyuni	0.025	0.54	0.62	9.10
Chile: Salar de Atacama	.125	.91	1.87	6.92
Israel-Jordan: Dead Sea	.002	4.00	.60	3.00
United States:				
Great Salt Lake, UT	.006	.80	.40	7.00
Salton Sea, CA	.022	.028	1.42	5.71
Searles Lake, CA	.0083	.034	2.30	15.20
Silver Peak, NV	.03	.040	.80	6.20

An important factor in the recovery of lithium is the magnesium-lithium (Mg-Li) ratio. The higher the ratio the more difficult the extraction, since more quantities of lime must be used, resulting in larger facilities for both magnesium separation and the necessity to settle out the calcium ions introduced by the lime.

A small amount of lithium was produced from the Searles Lake playa for a short time in the late 1970's, and processes have been investigated for the extraction of lithium from the Dead Sea, the Great Salt Lake, the Salton Sea, and seawater.

RESOURCES

Lithium resources evaluated in this study are defined according to the mineral resource-reserve classification developed jointly by the Bureau of Mines and the U.S. Geological Survey (*30*). This classification is shown diagramatically in figure 1.

Total demonstrated resources evaluated amount to a little over 3.1 million mt contained lithium, with a little over 2 million mt Li recoverable. Individual deposit data (quantities, grades, ownership, and operational data) are listed in tables 5 and 6. The locations of the deposits are shown in figure 2.

Demonstrated resources shown in table 5 include measured plus indicated quantities; the identified quantities shown include measured plus indicated plus inferred resources. Evaluations are based on the demonstrated resources.

All the resources evaluated in this study are from published sources. In some cases, the quantities evaluated as demonstrated resources are the author's interpretation of more than one published estimate. A total of 23 mines and deposits were studied, but only 16 were included in the final evaluation. Five deposits were excluded because they contained very small resources (total of less than 250,000 mt ore): La Viquita and Santa Gertrudis, Argentina; Giant Volney and Mateen (SD), United States; and Mdara-Nigel, Zimbabwe. Two others, Leguna Colorado, Bolivia, and North Atacama, Chile, were not evaluated owing to a lack of demonstrated resource and cost data.

The relationship between demonstrated and inferred resources in terms of contained in situ lithium are shown in the two diagrams of figure 3.

As can be seen, the inferred resources of the brines con-

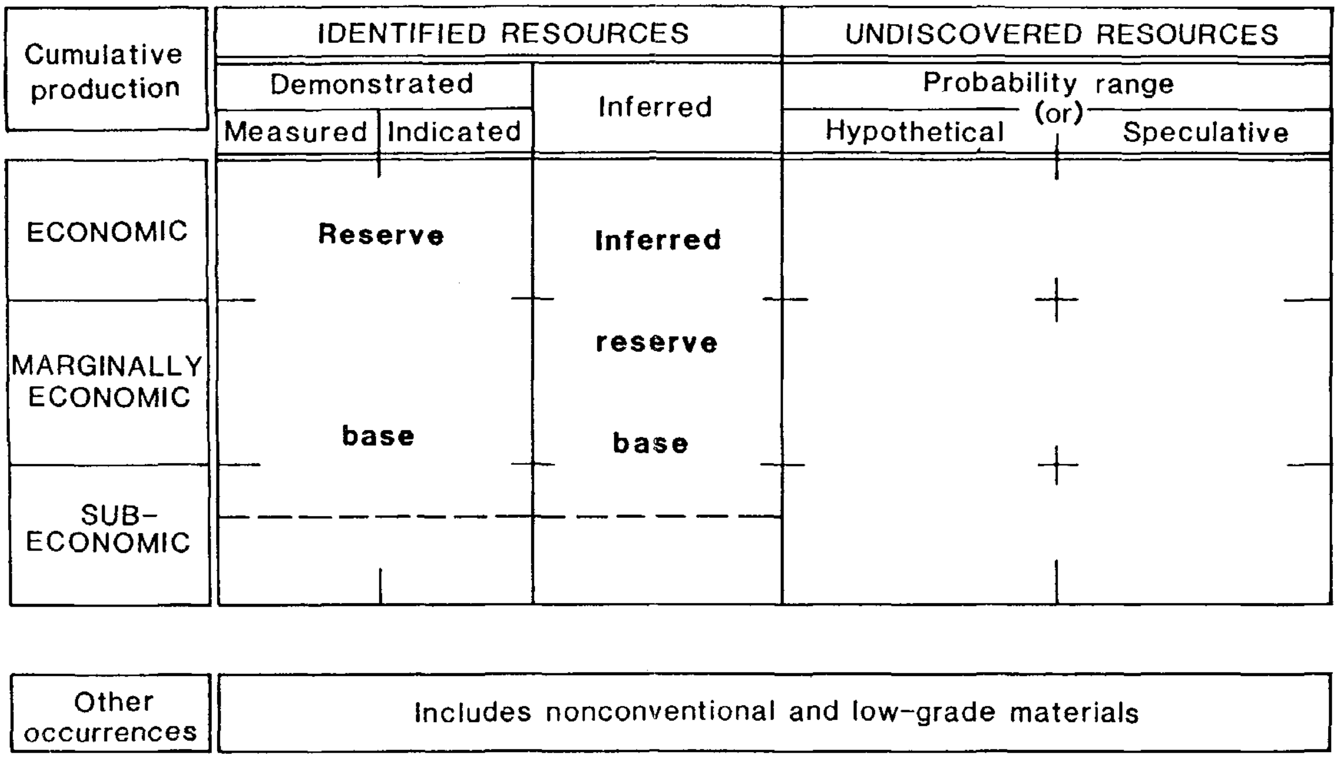


Figure 1.—Mineral resource classification categories (*30*).

Table 5. — MEC lithium resources

Country and property	Demonstrated in situ material, 10⁶mt	Grade, pct Li	Lithium resources, 10³ mt Li: Demonstrated: Contained	Lithium resources, 10³ mt Li: Demonstrated: Recoverable	Lithium resources, 10³ mt Li: Identified: Contained[1]
PEGMATITES					
Australia: Greenbushes	33.50	1.16	389	248	389
Canada:					
Bernic Lake	6.65	1.28	85	50	85
Buck-Coe-Pegli	.80	.99	8	4	8
Georgia Lake	3.20	.59	19	11	19
Jean Lake	1.50	.60	9	6	9
Lac la Croix	1.40	.59	8	5	8
Nama Creek	5.55	.48	27	16	27
Quebec Lithium	14.50	.60	88	59	120
Yellowknife	49.11	.65	319	91	320
Total or wtd av, Canada	82.71	.68	563	242	596
United States:					
Bessemer City	23.30	.68	158	109	158
Kings Mountain	22.70	.68	154	120	173
Total or wtd av, United States	46.00	.68	312	229	331
Zaire: Kitotolo	31.50	.98	307	12	495
Zimbabwe: Bikita	3.80	1.35	51	17	151
Total or wtd av, pegmatites	197.51	.82	1,622	748	1,962
BRINES					
Bolivia: Salar de Uyuni	505.00	.025	126	101	5,500
Chile: Salar de Atacama	1,300.00	.125	1,625	1,300	4,300
United States: Silver Peak	240.00	.033	72	65	124
Total or wtd av, brines	2,045.00	.089	1,823	1,466	9,924
Grand total or wtd av	2,242.51	.154	3,445	2,214	11,886

[1] Includes demonstrated and inferred tonnage.

NOTE—Data may not add to totals in text because of rounding.

Table 6. — MEC lithium mine and deposit data

Country and property	Ownership	Status[1]	Type[2]	Estimated or proposed production capacity mt/yr[3]	Product
		PEGMATITES			
Australia: Greenbushes	Greenbushes Tin Ltd	P	OP	24,800	Spodumene.
Canada:					
Bernic Lake	Tanco Mining Group	D	UG	54,000	Do.
Buck-Coe-Pegli	Lithium Corp. of Canada	E	UG	30,000	Do.
Georgia Lake	Various owners	E	UG	22,200	Do.
Jean Lake	Unclaimed land	E	UG	21,700	Do.
Lac la Croix	...Do	E	UG	21,100	Do.
Nama Creek	Cominco Ltd	E	UG	34,800	Do.
Quebec Lithium	Sullivan Mining Group Ltd	Pp	UG	49,000	Do.
Yellowknife	Canadian Superior Exploration Ltd	E	OP	45,300	Do.
United States:					
Bessemer City	Lithium Corp. of America (Lithco)	P	OP	16,300	Li_2CO_3.
Kings Mountain	Foote Mineral Co	P	OP	7,260	Do.
Zaire: Kitotolo	Geomines and Zaire Government	E	OP	39,500	Spodumene.
Zimbabwe: Bikita	Bikita Minerals (Pvt.) Ltd	P	OP	38,500	Petalite, spodumene, lepidolite, amblygonite.
		BRINES			
Bolivia: Salar de Uyuni	Government	E	B	6,350	Li_2CO_3.
Chile: Salar de Atacama	Foote Mineral Co. and CORFO	P	B	6,350	Do.
United States: Silver Peak	Foote Mineral Co	P	B	6,350	Do.

[1] P = producing, D = under development, E = explored, Pp = past producer.
[2] OP = open pit, UG = underground, B = brine.
[3] In terms of product produced; proposed capacity for nonproducers.

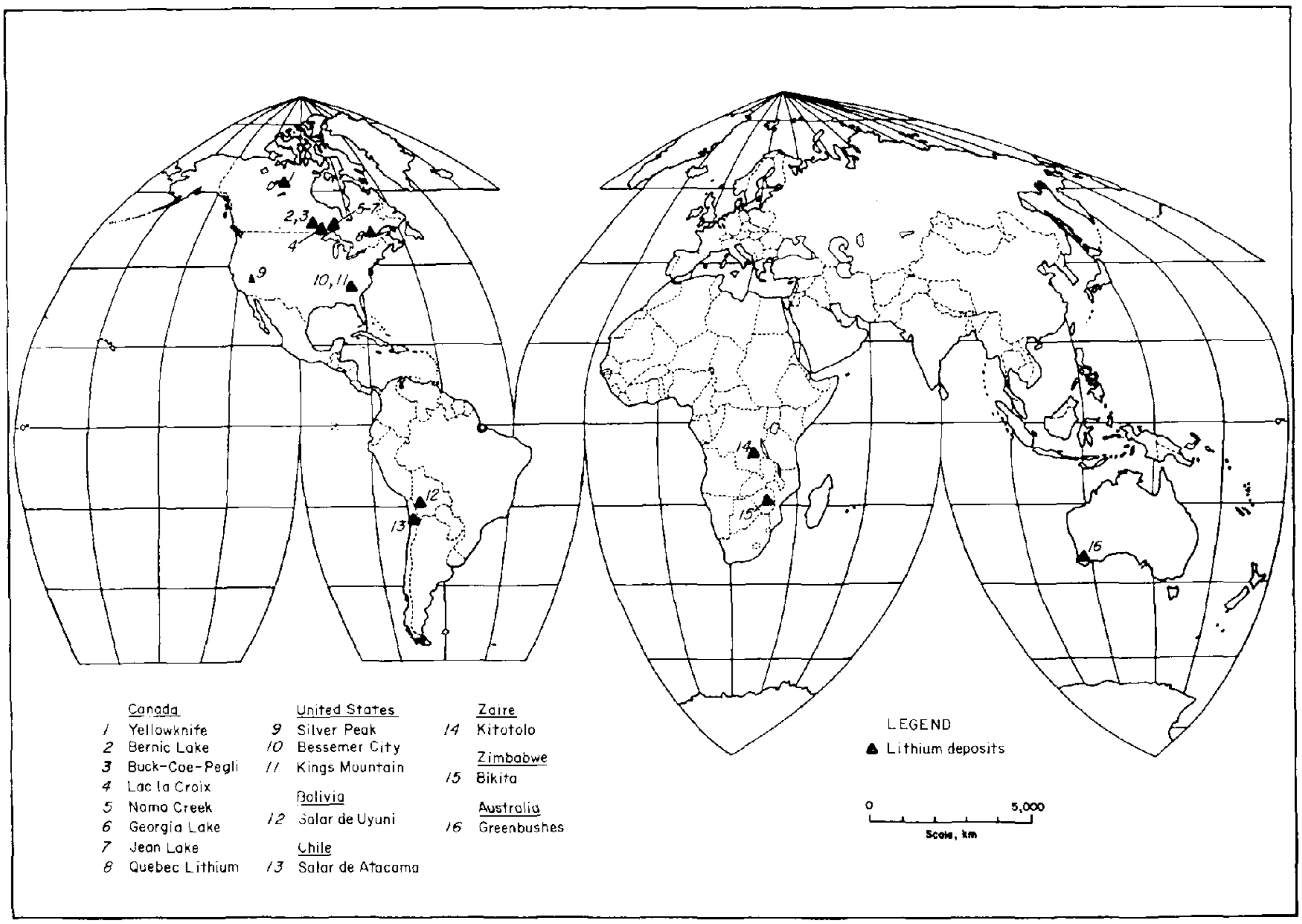


Figure 2.—Lithium mine and deposit locations.

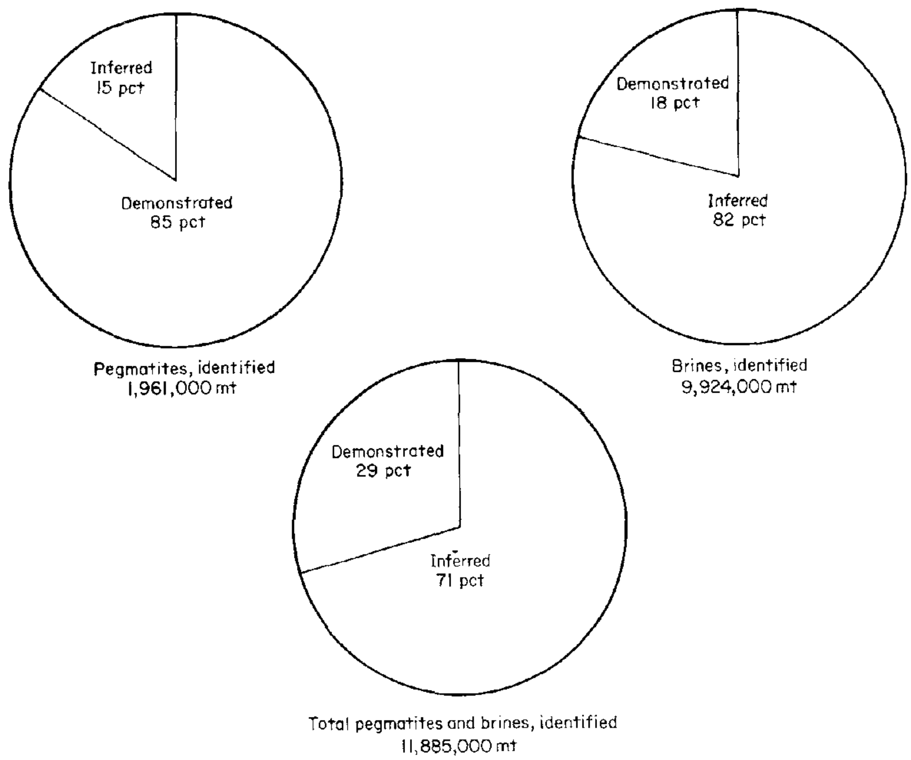


Figure 3.—Comparison of demonstrated and inferred lithium resources contained in pegmatites and brines.

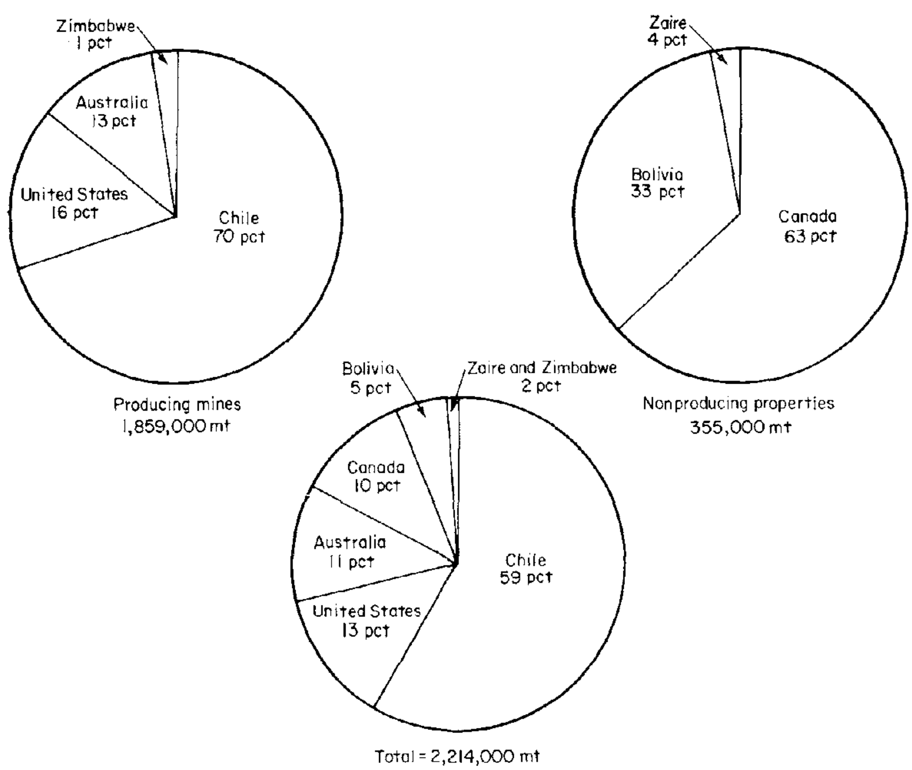
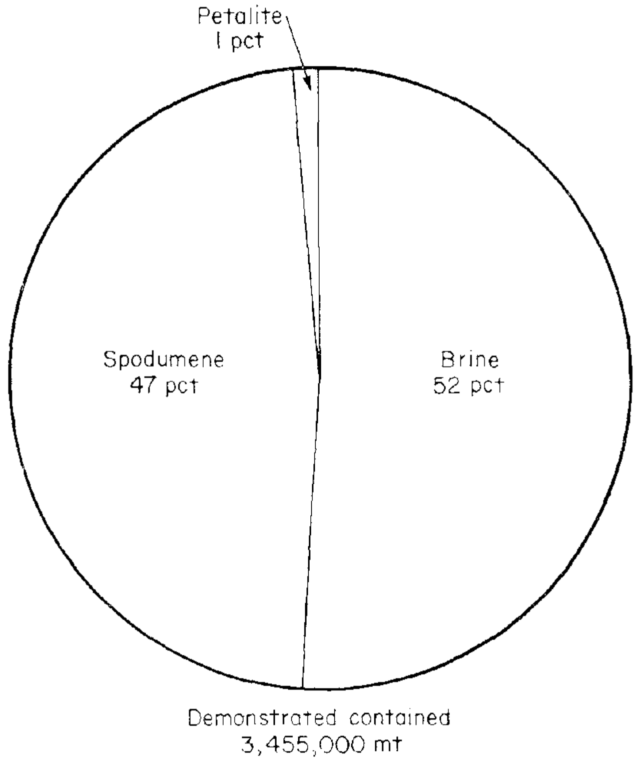


Figure 4.—Percentage share of total recoverable lithium equivalents by mine status and country.



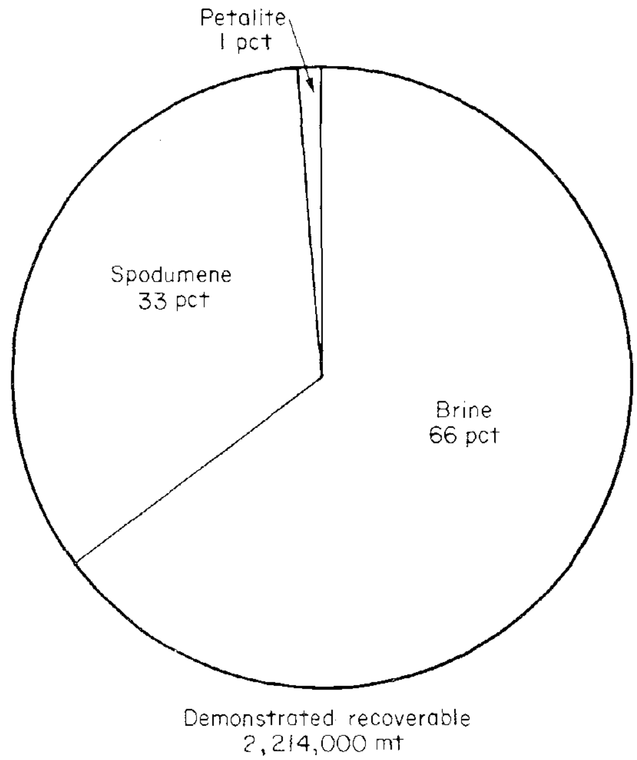


Figure 5.—Distribution of recoverable lithium equivalents within ore types.

stitute a much higher percentage of the total than do the pegmatites. This is because only a limited amount of exploration data is necessary to extrapolate large resources in playas. This is not the case in hardrock deposits.

Overall recoveries (including mine, mill, and carbonate plant) for all pegmatite deposits is estimated at 47 pct. This value is somewhat distorted because of the Kititolo deposit, which has a very low mill recovery. This is because only a small part of the spodumene ore could be recovered as a byproduct of tin and tantalum production. If this deposit were not included, the recovery would be nearly 60 pct. Overall recovery is estimated at about 70 pct for the producing pegmatite mines and at about 30 pct for the nonproducing deposits (including the Kititolo deposit).

Lithium recoveries of brines are assumed at 80 pct for Salar de Atacama and Salar de Uyuni. Recovery is assumed at 90 pct for Silver Peak, since it has been producing for many years and is likely to have developed a higher degree of efficiency. The recoverable brine resources shown in table 5 are assumed to be recoverable product.

The recoverable demonstrated resources by country and with respect to producing mines and undeveloped properties is shown in the three diagrams in figure 4. As of the date of the study, the Bernic Lake deposit was on pilot plant status, so it is included as a nonproducer.

A comparison of recoverable lithium from this type of ore is shown in the two diagrams of figure 5. The brines are a dominant source, much more so in the producing mines. Data on the producing mines are more indicative of the actual long-term situation, since with the exception of the Bernic Lake operation, there is little likelihood that the nonproducing deposits will be developed in the foreseeable future.

OPERATION SUMMARIES

PEGMATITES

Australia

The Greenbushes mining complex is located in Western Australia about 200 km south of Perth and 70 km southwest of the Port of Bunbury. (See figure 2.) The area has been producing tin and tantalum from placer deposits and weathered pegmatites for about 100 yr. The current tin-tantalum operation started up in 1964 and was modified to its present state in 1978. Exploration on the adjacent spodumene pegmatites began in 1980 when exploration for tin orebodies discovered the spodumene zone; production of spodumene concentrates started in 1982.

The Greenbushes tin field and spodumene pegmatites lie in a north-south striking belt of metasedimentary and metavolcanic rocks. The metasedimentary belt extends over an extensive area that is generally bounded on the west by sediments and on the east by granites. The belt contains a number of rock types, such as granofels, gneiss, amphibolite, schist, and various dikes and stocks. The pegmatites which contain tin, tantalum, and spodumene extend in a northerly direction for about 5 km.

The ore contains much higher grade and higher purity lithium material than is normally present in pegmatites. Demonstrated resources (measured plus indicated) have been estimated at 33.5 million mt grading 2.5 pct Li_2O (1.16 pct Li) (*9*). Since these resources were developed on limited drilling, it is quite possible that they could be increased by future exploration.

In 1982 the company operated a pilot plant that produced a small amount of concentrates, which were tested by potential customers. In 1983, the operation began on a commercial scale; the annual output capacity is projected to about 25,000 mt of spodumene concentrate. The lithium ore also contains tin and tantalum, which are produced as byproducts. There are plans to double the plant capacity if demand improves sufficiently. The possibility of building a Li_2CO_3 plant is being investigated.

Mining is by open pit, and benefication consists of recovery of the tin and tantalum by gravity methods followed by flotation to recover the spodumene. The spodumene concentrate is further upgraded by desliming along with magnetic separation to remove iron.

Canada

Canada has a number of lithium pegmatite deposits located primarily in metamorphosed Canadian Shield rocks at various locations from Quebec to Yellowknife in the Northwest Territories. There was production from the Quebec Lithium deposits between 1955–65, but none of the other pegmatites are known to have been mined. The feasibility of producing spodumene from the high-grade Bernic Lake deposit in Manitoba is currently being pilot-plant tested. The Yellowknife deposits contain the largest demonstrated Canadian lithium resource, but they are comparatively low grade and extremely remote. A discussion of individual deposits follows.

Bernic Lake Area

The Bernic Lake area consists of two lithium deposits a few kilometers apart; these are the Bernic Lake Mine and the small Buck-Coe-Pegli prospect to the east. The area is located in southeast Manitoba near the Ontario border. (See figure 2.)

Bernic Lake

The Bernic Lake Mine is managed by the Tantalum Mining Corp. (TANCO), which is a consortium formed by Hudson Bay Mining and Smelting Co. Ltd., Kawecki Berylco Industries, and Manitoba Development Corp. (a Government enterprise). The mine had been a principal world producer of tantalum concentrates; however, it was placed on standby December 31, 1982, because of the depressed tantalum market. The tantalum deposit also contains a separate spodumene zone of significant size that has not yet been exploited. The lithium content of the spodumene, at 2.7 pct Li_2O (1.25 pct Li), is considered very high grade with respect to other world spodumene resources.

The area was originally explored as a tin-tantalum deposit in 1928. Additional exploration discovered resources of tantalum, lithium, cesium, and beryl. Extensive tantalum exploration was initiated in 1967 with production beginning in 1969.

Table 7. — Bernic Lake deposit resources (*2*, p. 149)

Commodity	Quantity, mt	Grade, pct
Beryllium	834,440	0.20 BeO
Cesium	317,450	23.30 Cs_2O
Lithium:		
Lepidolite	97,684	2.24 Li_2O
Spodumene	6,662,674	2.76 Li_2O
Tantalum	1,878,722	0.22 Ta_2O_5

The Bernic Lake pegmatite is extremely complex and contains a wide assemblage of minerals. Nearly 70 minerals have been identified including 7 tantalum and 4 lithium minerals, beryl, and pollucite (a cesium mineral) (*2*, p. 147). The deposit occurs in the Archean Bird River Greenstone Belt, which is a highly metamorphosed series of sedimentary volcanic, and plutonic rocks. The complex structural nature and mineralogical association of the rocks has led to many detailed studies on the geological aspects of the area.

The pegmatite is a relatively flat-lying tabular body dipping to the north at up to 20°. The thickness ranges from 15-20 m up to 80-90 m, and the dimensions are at least 450 m down dip and 1,200 m along the strike. Most of the structure lies under Bernic Lake.

Within the pegmatite, nine mineralogic zones have been identified containing resources of tantalum, lithium, cesium, and beryl. The various resources are physically separate and could be mined separately. Resources of the various commodities are shown in table 7.

Mining for lithium began in the latter part of 1984 on a small scale. A part of the current gravity mill, once used for tantalum, was adapted to heavy media and flotation for spodumene and operated at a rate of about 100 to 150 mt/d. Expansion of the mill is expected to increase capacity to about 700 mt/d to 800 mt/d by late 1986.

The ore has been tested by the flotation process, and results have indicated that the ore could produce a concentrate as high as 7.2 pct Li_2O with a 90-pct mill recovery. The low iron content would make the concentrate advantageous for ceramics use (*2*, p. 157).

The concentrates could be used in either ceramics or glass or as feed to a Li_2CO_3 plant. The resources could support a 200,000 mt/yr (ore) operation for about 40 to 50 yr.

Buck-Coe-Pegli

The Buck-Coe-Pegli prospect is located about 5 km east of the Bernic Lake Mine and lies in a similar regional geologic setting. The mineralized area was discovered around 1920 and through the years has experienced periods of exploration, particularly when the lithium market was favorable, as in 1955. The property has had a number of owners; the longest period of ownership was by Lithium Corporation of Canada.

The deposit is composed of a series of subhorizontal dikes cropping out on the Buck, Coe, and Pegli claims. The dip is generally to the west at about 10°. The surface exposures have very limited extent; however, a lower zone was outlined by drilling and is estimated to contain about 800,000 mt of 2.13-pct-Li_2O (0.99-pct-Li) material (*32*).

The deposit would require access by shaft or shaft-decline to a depth of 180 to 200 m, and mining would probably be by room-and-pillar methods. Beneficiation would be an economic drawback in the development of the property. Even at a 400-mt/d capacity, the life of the operation would only be about 8 yr, which would not justify the expense of constructing a new flotation mill. Thus, for the purpose of this evaluation, it is assumed that the proposed mill for the TANCO operation could accommodate the ore from this mine. It is also assumed that the concentrates could be marketed similarly to those of the TANCO operation.

Lac la Croix

The Lac la Croix lithium pegmatites are located on the east end of Lac la Croix within the boundaries of Quetico Provincial Park in southwest Ontario. (See figure 2.) The deposit was discovered in the early 1950's and was explored by a series of trenches and diamond drill holes in 1956 and 1957. At that time the deposit was owned by International Lithium Corp.

The mineralized area consists of outcrops of spodumene-bearing pegmatites. The pegmatites are generally in easterly-trending Archean metasediments and dip steeply to the north. The mineralization is generally coarse with spodumene crystals ranging to over 30 cm in length. The spodumene is randomly oriented and comprises about 25 pct of the pegmatite (*25*).

Resources have been estimated at 1.1 million mt (*25*) and 1.5 million mt (*2*, p. 66) of material grading 1.3 and 1.2 pct Li_2O (0.60 and 0.56 pct Li), respectively. For the purpose of this evaluation, 1.4 million mt of 1.27-pct-Li_2O (0.59-pct-Li) material is estimated to be present.

If the deposit were mined, it would have to be by underground methods, since the nearness of the pegmatites to the shores of the lake would preclude open pit mining.

It is doubtful, however, that this deposit would be exploited except in the case of an emergency, because it is within park boundaries. In fact, claim ownership has reverted to the Government. Even if the property were open for development, the low grade and resource quantity would undoubtedly preclude profitable mining in the foreseeable future.

Lake Nipigon Region

The region north of Lake Nipigon contains a number of spodumene-bearing pegmatite exposures over an area of roughly 1,200 km². Most of these pegmatites are small and inconsistent in grade; however, three locations within the area have been explored for the possibility of spodumene production and are included in this study: Georgia Lake, Jean Lake, and Nama Creek. Each of these properties were evaluated separately. The area is located about 60 km north of Nipigon (on Lake Superior) or about 160 km northeast of Thunder Bay; the location is shown in figure 2. With respect to most other evaluated deposits, these exposures are somewhat small and relatively low grade. The low grade and small size of the resources (similar to Lac la Croix) make it unlikely that any of these deposits would be mined in the foreseeable future.

Georgia Lake

The Georgia Lake pegmatite deposits are the southernmost deposits in the area and include three exposures that are owned by various individuals or companies. Property ownership has changed through the years, and some of the claims have lapsed. Most of the exploration work has done in the middle to late 1950's.

The pegmatites are geologically similar to occurrences elsewhere in Canada. Thickness can vary from about 3 m to 20 m, and depth, as determined from drilling data, is 160 m. The total resources for the three exposures have been reported at about 3.2 million mt with a grade of 1.27 pct Li_2O (0.59 pct Li) (*25*). A mining operation of 500 mt/d would probably be proposed for this area.

Jean Lake

The Jean Lake deposits are located 8 to 10 km north of the Georgia Lake area and are currently owned by the Crown as unclaimed land. The area consists of numerous pegmatites similar to those in the Georgia Lake area. Only one pegmatite, known as the "Parole Lake Pegmatite," has been explored in this area. The pegmatite has been drilled to a depth of over 330 m and is reported to contain about 1.5 million mt of material with a grade of 1.3 pct Li_2O. Mining and beneficiation would be the similar to that at Georgia Lake; that is, a 500-mt/d room-and-pillar mine supplying a similarly sized flotation mill.

Nama Creek

The Nama Creek area is located about 20 km northeast of the Georgia Lake-Jean Lake deposits. It consists of a pegmatite zone of about 2 by 4 km. There are numerous pegmatites cropping out in the area, but most of them are quite small and have no development potential. The largest of the exposures includes the Nama Creek North and South and the Conway, about 3 km to the east. The deposits were staked in 1955, and ownership has changed several times. The Nama Creek North and South deposits are owned by York Consolidated Exploration Ltd., and the Conway area is presently controlled by Cominco Ltd.

The area was explored during 1955-58 when the lithium market was expanding. Exploration on the Nama Creek deposits included trenching and drilling and the sinking of about a 150-m shaft. The Conway deposit was drilled between 1956 and 1958.

The Nama Creek deposits are underlain by thickly bedded, metasedimentary quartz biotite gneisses. Several diabase dikes cut both metasediments and pegmatites. The Nama Creek North deposit consists of two enechelon pegmatites about 400 to 600 m in length. The Nama Creek South deposit is essentially a single pegmatite about 250 m in length. The Conway pegmatite is a little over 400 m in length. The width of pegmatites ranges between 3 and 13 m, and the depth has been tested to 300 m. The general dip is 70° to 75° to the northwest. Resources have been reported as 5,553,000 mt averaging 1.03 pct Li_2O (0.47 pct Li) (*22*, p. 50).

In the event that these deposits should be exploited, mining would be underground because of the narrow, steeply dipping veins. For the purpose of this report, it is assumed that a 1,000-mt/d flotation mill would be built to serve the three Nama Creek deposits. The mining would be coordinated to supply consistent feed to the mill for a period of 20 to 25 yr.

Quebec Lithium

The Quebec Lithium property is located in the Preissac-Lacorne District about 40 km north of Val d'Or, PQ. (See figure 2.) It is currently owned by Sullivan Mining Group Ltd.

The property was developed in 1954 and went into production in 1955 to supply spodumene concentrate to the Lithco carbonate plant in North Carolina for production of Li_2CO_3 and $LiOH{\cdot}nH_2O$. The major consumer at the time was the U.S. Government, which instituted the lithium stockpile buying program in 1955-60. Production ceased in 1959 when the stockpile was near its objective. Production resumed in 1960 at a reduced rate when a Li_2CO_3 chemical plant was constructed on the property to produce Li_2CO_3 by direct precipitation with sodium carbonate (Na_2CO_3). The plant operated until 1965 and was apparently not competitive with the established sulfuric acid (H_2SO_4) process. Research was continued by the Quebec Government, and some process improvements were later reported (*24*).

The property consists of a group of spodumene-bearing pegmatite dikes that cut an amphibolized greenstone. The dikes strike generally north of west and dip to the south at about 50°-70°. The dikes lie within a zone that is about 600 m wide by 2,400 m long (*14*).

Resources for the property have been estimated at about 20 million mt at 1.3 pct Li_2O (0.60 pct Li) (*11*). It is estimated that the demonstrated resources would be in the order of 14 to 15 million mt. This corresponds to the quantity estimated as a result of diamond drilling (*22*, p. 77); however, many dikes in the area have not been explored, so that there is potential for additional resources.

Prior to shutdown, the mine-mill capacity was rated at about 900 mt/d. The mine was accessed by a five-compartment shaft and developed on three levels. At the time of closure, the mine was employing shrinkage stope methods; however, preparations were being made to mine by long-hole stoping. This would probably be the method used if the mine were to reopen. Beneficiation was flotation; in the period 1955-60, concentrates contained between 5.5 and 5.9 pct Li_2O (2.55 and 2.74 pct Li).

Yellowknife Area

The Yellowknife pegmatites are located east of the city of Yellowknife in the Northwest Territories. (See figure 2.) Although there is ample infrastructure developed in the Yellowknife area to support development of a lithium operation, the deposits are extremely remote with respect to markets. The distance to Edmonton, AB, is about 1,600 km; this includes about 1,300 km by rail to Hay River and about 300 km to Yellowknife by road. There is also access by boat on the Great Slave Lake from Hay River (165 km) during the period June 15 to October 15. Most of the pegmatites are owned by Canadian Superior Ltd.

From Yellowknife, the westernmost deposits are accessible by approximately 50 km of existing gravel road. Access to the more distant eastern cluster of deposits would require the construction of about 75 km of new road.

During 1974-76 Canadian Superior conducted an exploration program in the area. There are hundreds of outcropping pegmatites in the region; however, most of these are very small. Canadian Superior initially screened over 30 of the larger exposures, and it was found that 14 met criteria that could lead to possible mining. Results of the exploration are summarized by Lasmanis (*18*), and the combined resources (assumed as demonstrated) of the pegmatites are shown in table 8.

The resource estimates on the individual pegmatites are based on a continuous depth of 150 m. This depth was confirmed by drilling several of the larger pegmatites (*18*, p. 406).

Table 8. — Demonstrated lithium pegmatite resources in the Yellowknife area (*18*, p. 408)

Pegmatite	Resources, mt	Grade, pct Li	Contained Li, mt
Western deposits:			
Fi	15,320,500	0.55	84,262
Big	7,888,000	.68	53,688
Jim	4,205,000	.58	24,389
Vo	3,370,500	.69	23,256
Ann	3,335,600	.89	29,686
Ki	2,812,000	.65	18,278
Nite	2,580,500	.70	18,064
Total or average	39,512,100	.64	251,623
Eastern deposits:			
Thor	9,205,000	.70	64,435
Lens	102,600	.92	944
Bin	99,100	.81	802
Mac	72,600	.93	675
Hid	50,400	.79	398
Bet	42,700	.93	397
Nut	24,600	1.02	251
Total or average	9,597,000	.71	67,902
Grand total or average	49,109,100	.66	319,525

Evaluated resources for the area are estimated at 40 pct of the total demonstrated resource value shown in the table, or about 19.6 million mt of material with an average grade of 1.42 pct Li_2O (0.66 pct Li). This tonnage value approximates the quantity that would be available by open pit mining methods to a maximum depth of 60 m.

All of the tested pegmatites are considered to be unzoned; that is, they would contain a consistent spodumene grade from wall to wall. The largest pegmatites are in the western cluster of deposits, but the smaller deposits in the east have a higher grade and occur in units easily minable by open pit.

Mining would probably begin with the western cluster of deposits, since this area has an access road. Annual ore capacity is projected at 250,000 mt. Estimated stripping ratio for mining to a depth of 60 m is 2.5.

The ore would be hauled to a mill site centrally located to all the western deposits, or about 20 to 25 km from Yellowknife. Concentration would be by flotation. Flotation tests have been conducted on some of the ore, yielding a 6-pct-Li_2O (2.79-pct-Li) concentrate with 80-pct recovery (*18*, p. 406).

For the purpose of this study it is assumed the concentrates would be hauled by truck (or barge in the ice-free open months) to Hay River and then transported by rail about 2,400 km to Prince Rupert, BC, for use in ceramics or for export for the production of lithium-based chemicals. Another option would be to construct a Li_2CO_3 plant in the area. However, in view of ample supplies of lithium near the market areas, plus the high cost of energy and materials in the Yellowknife area, such a scenario was not considered in this analysis.

To justify development of the lithium deposits in this area would require a large increase in demand that could not be met by the other currently mined resources or more economically undeveloped properties. At an estimated ore capacity of 250,000 mt/yr, the western deposits could produce for over 60 yr.

United States (North Carolina Tin-Spodumene Belt)

The principal lithium pegmatite resources in the United States are located in North Carolina in what is known as the North Carolina Tin-Spodumene Belt. Minor resources also occur in extreme western South Dakota. The South Dakota pegmatite deposits were the principal domestic lithium sources in the 1940's, but were abandoned with the development of the North Carolina pegmatites. (The South Dakota pegmatites have relatively insignificant resources and therefore were not included in the final evaluation.)

The lithium pegmatites of North Carolina, in the southwest part of the State, are being mined at two locations. Foote Mineral Co. operates a mine and chemical plant near Kings Mountain, and Lithco has a larger operation about 10 km to the northeast near Bessemer City. (See figure 2.) Both complexes have been in operation for many years — Foote Mineral since 1942 (with some interruptions) and Lithco since the mid-1950's. Since many aspects of the deposits are so similar, the following discussion is generalized to include both operations.

Geology

The lithium pegmatite zone is located in the south-central Piedmont area of North Carolina. The Piedmont is underlain by a variety of igneous and metamorphic rocks, trending north to northeast.

Attitude of the main structure ranges from nearly flat to vertical; most dips of the structure are to the northwest. In the deposit area, there is a series of weakly metamorphosed rocks that crop out in long, narrow belts. Intrusive rocks in the area include those of granitic, dioritic, and gabbroic compositions. The spodumene belt occurs in a narrow zone in the Carolina gneiss within the metamorphic rocks. The gneiss is bounded on the northwest by the Cherryville quartz monzonite and on the southeast by metasediments.

The spodumene zone is associated with various occurrences of gneiss, schist, amphibolite, limestone, quartzite, and granite. The pegmatites occur in zones of weakness in the enclosing rocks. The most persistent pegmatites generally strike northeast, and most of them are parallel with the layering or schistosity of the major rock units. The shape of the pegmatite zone varies with the structure but is generally tabular, and the contacts with the enclosing rocks vary from sharp to gradational.

Resources

The North Carolina spodumene resources have been published throughout the years of production and are generally quite well known. According to the 1982 company 10-K data, the resources of the Bessemer City holdings are estimated at about 25.7 million mt of material containing 1.46 pct Li_2O (0.68 pct Li). Similarly, the Kings Mountain resources are stated at approximately 27 million mt at a grade of about 1.5 pct Li_2O (0.70 pct Li) (*8, 10*). These quantities represent a slight increase from the 1981 data used in this study. (See table 5.) This suggests that greater quantities of resources may exist on both holdings because of the large lateral extent of the pegmatite zones.

Mining

Mining on both operations is by very similar open pit methods; both ore and waste require blasting. Usually the companies have established a drilling practice involving presplitting the bench faces to reduce overbreakage and provide a more stable pit face. The presplit holes are about 2 m apart and are not loaded.

The operations generally utilize both hydraulic shovels and backhoes. The backhoes are used for more selective mining of the smaller pegmatites. Selective mining is important in the separation of the spodumene from amblygonite because the amblygonite is deleterious to the downstream processing. In both operations, up to about half of the waste is hauled to a nearby Martin Marietta gravel plant for use as road gravel.

In 1981 Lithco expanded its Bessemer City annual ore capacity to about 680,000 mt; this would enable production of about 36 million lb (16,300 mt) Li_2CO_3 (*4*). In 1980, the annual capacity of the Kings Mountain operation was increased to about 16 million lb (7,260 mt) Li_2CO_3, which would require an ore capacity of about 310,000 mt/yr.

Beneficiation

Both operations use flotation as a beneficiation method. The spodumene concentrates average between 6.0 and 6.5 pct Li_2O (2.79 and 3.02 pct Li). One feature of the concentration is desliming after grinding. The gangue minerals are softer than the spodumene, and therefore some of them grind finer and are discarded as slimes (minus 200-mesh). A small amount of the spodumene concentrates at the Foote Mineral Co. operation are used directly in the ceramics industry; the remainder is converted to chemicals. The plants also produce a feldspar-quartz (glasspar) concentrate that is shipped to the glass industry and a mica concentrate used by local companies. Lithco has a subsidiary, Spartan Minerals Co., Spartanburg, SC, for the marketing of its mica concentrates.

Li_2CO_3 Production

The Li_2CO_3 plants at both Kings Mountain and Bessemer City use a H_2SO_4 process; the plants are located near the mines and are about 15 km apart. These plants are the only significant MEC producers of Li_2CO_3 from spodumene. A few other companies may produce a variety of lithium products in small batch operations, but their production is relatively insignificant.

The H_2SO_4 process involves treating a spodumene concentrate of about 6.0 pct Li_2O (2.79 pct Li). The concentrate is first heated to about 1,075°-1,100°C in a kiln to produce a more reactive and soft β-spodumene. This calcine is cooled, then mixed with concentrated H_2SO_4 and heated to 250°C in an acid roaster to dissolve the lithium. The acidified concentrate is neutralized with ground limestone and filtered, resulting in an impure solution of lithium sulfate (Li_2SO_4). The solution undergoes several filtering, pH adjustment, and evaporation steps and is then reacted with Na_2CO_3 to produce Li_2CO_3. Other lithium products (i.e., LiOH, LiCl, etc.) are produced in the stream process of the Lithco plant. The Foote Mineral Co. plant produces only Li_2CO_3; its other products are produced at plants in Pennsylvania, Virginia, and Tennessee.

Zaire

The Kitotolo deposit is located in the north Shaba region about 15 km southwest of the Manono tin-tantalite mine. (See figure 2). The deposit is owned by Zairetain, a company owned by the Government of Zaire (50 pct) and Companie Geologique et Miniere des Ingenieurs et Industriels Belges (Geomines).

The original discovery was in 1912 on the Manono tin-tantalum deposit, which has been operating relatively continuously since about 1919; the Kitotolo deposit has never had any production of significance. It has been explored periodically, but none of the exploration has been very intensive.

The Kitotolo deposit is located in mica schists of the highly folded and metamorphosed Kibara complex. The regional structure strikes northeast and generally dips steeply to the northwest. The pegmatite zone is massive and contains various types of individual pegmatites. The spodumene content varies but can be as much 25 pct. It occurs as small component crystals, large disseminated crystals, or as giant crystals forming spodumene bands. Cassiterite and columbite-tantalite also occur as small grains disseminated throughout the pegmatite.

A prominent feature of the area is the severe weathering that has taken place on the pegmatites. The zone of weathering on the Kitotolo deposit is between 10 and 30 m in depth. The surface has been weathered to a sandy soil, and the effects of the weathering gradually decrease downward until the unweathered pegmatite is reached.

Mining on the Manono deposit has concentrated on the weathered zone; however, as this approached depletion, mining was started on the unweathered rock from 1951-56.

The undeveloped Kitotolo deposit is regarded as being the largest spodumene pegmatite in the world. One estimate places the resources at 1.94 million mt of contained Li_2O (901,000 mt Li) (*16*). For the purpose of this study, the demonstrated resources are estimated at 31.5 million mt of material containing 2 pct Li_2O (0.98 pct Li), 0.15 pct SnO_2, and 0.0174 pct Cb_2O_5 plus Ta_2O_5 in the unweathered pegmatites. This study concentrates solely on the resources contained in the unweathered pegmatites.

If mining were to be initiated, it would probably be on the south side of the Kitotolo deposit where some mining on the weathered zone has already exposed the unweathered rock, thereby eliminating the need for preproduction stripping.

Beneficiation would require a gravity section of jigs and tables similar to the Manono flowsheet in order to recover tin and columbite-tantalite. This would be followed by spodumene flotation. The spodumene concentrates would have to be transported by a combination of truck, rail, and barge for about 2,000 km to Matadi (Zaire) for shipment to markets.

In view of the limited market for these spodumene concentrates (the market is supplied by much better situated mines) and the remoteness of the deposit, it is unlikely that there would be any development for spodumene in this area in the foreseeable future.

Zimbabwe

The Bikita operation is located in Zimbabwe about 70 km east of Masrringo, formerly Fort Victoria. (See figure 2.) It is owned by Bikita Minerals International Ltd. (51 pct), AMAX Inc., and Kerr-McGee Chemicals Corp.

Cassiterite was discovered in 1909, and along with tin, both lithium and tantalum were produced from about 1916 to 1960. Beryl production began in 1950 on a small scale. Currently, the primary commodities are the lithium minerals of spodumene, lepidolite, and petalite. A small amount of pollucite is also produced intermittently depending on contracts. From 1955 to 1960 production focused on lepidolite for shipment to Texas. This material was intended to help supply the U.S. stockpile. Lepidolite is not presently considered applicable for conversion to chemicals because of the high fluorine emissions during roasting. A certain amount of feldspar is also produced for local consumption.

The Bikita pegmatites occur in a series of greenstones, metasediments, and intrusive ultramafic rocks and have a relatively complex mineralogy. The main pegmatite strikes northwest and has a length of over 1,600 m with a width of nearly 40 m. It dips to the southeast at up to 45° and extends to at least 60 m in depth.

Two zones have been mined within the pegmatite area: these are the Bikita open pit and underground workings and the adjacent Al Hayat pit on the north. The Bikita workings have produced mainly petalite and lepidolite with lesser amounts of spodumene, amblygonite, eucryptite, bikitaite, beryl, tantalite, pollucite, and cassiterite. The Al Hayat pit produces mainly petalite with lesser amounts of spodumene and lepidolite. The mineralogy at Bikita is much more complex than that at Al Hayat, as is evidenced by the wide variety of minerals produced at Bikita.

The tin, tantalum, beryl, and pollucite zones are physically separated from the lithium mineral zones and are thus mined and processed separately. The individual lithium-bearing zones (i.e., spodumene, petalite, etc.) are most generally separate but sometimes are mined as mixed ore.

Resources have been estimated for the total Bikita pegmatite at 10.8 million mt in situ with a grade of about 3 pct Li_2O (1.4 pct Li) (*31*). An earlier study estimated the resources at about 5.4 million mt containing 2.9 pct Li_2O (1.35 pct Li) (*28*). The company has stated that resources could last well into the next century (*1*). For the purpose of this report, the in situ demonstrated resources about 3.80 million mt are assumed. The 10.8 million mt value is assumed to be at the identified level.

Mining is by open pit and selective by mineral depending on market conditions. Currently, the most important production is in petalite. Earlier underground exploration drifts under the Bikita pit are used for haulage from both the Bikita and Al Hayat pits. The ore is dumped into a raise in the Bikita pit and passes into pockets from where it is loaded into ore cars for transport to the mill.

The milling method at Bikita is very complex involving several crushing, screening, and handsorting steps where the ore is crushed and screened and sorted for one mineral at a time. The rejects from one step are recrushed and handpicked for another mineral. Spodumene and lepidolite rejects can be treated separately at a small flotation plant; the plant is used mainly for spodumene. In 1978 the company built a fine-grinding plant to provide a fine-ground product.

The minerals are generally of high quality and are in demand for specific ceramic products in Zimbabwe, Europe, and United States. Most of the pollucite (cesium) is shipped to Japan.

BRINES

Brines contain the largest lithium resource among the MEC deposits evaluated. Total demonstrated resources of the three brine areas analyzed in this study are estimated to contain over 1.4 million mt Li. Two of these, Salar de Atacama, Chile, and Silver Peak, NV, are currently producing; Salar de Uyuni, Bolivia, is being explored. Individual resources in terms of contained lithium are listed in table 9.

Table 9. — Demonstrated lithium brine resources used in this study (*16; 20; 26; 27*, p. 13)

Location	Li, 10^6mt Total identified (contained)	Li, 10^6mt Demonstrated (recoverable)	Grade, pct Li
Bolivia: Salar de Uyuni	5.5	0.101	0.025
Chile: Salar de Atacama	4.3	1.300	.125
United States: Silver Peak, NV.	.124	.065	.03

Table 10. — Element resources, Salar de Atacama, Chile (*12*)

(Million metric tons)

Boron	2.9
Lithium	4.5
Magnesium	30.5
Potassium	58.0

Bolivia

Salar de Uyuni is located in southwestern Bolivia near the border with Chile. (See figure 2.) The nearest port is Antofagasta, Chile, a distance of about 450 km. The Salar de Uyuni is the largest of the central Andes salt basins, with an area of about 9,000 km^2 and at an elevation of over 3,650 m. Detailed exploration has not been performed on the salar, but there has been some preliminary testing. An average grade of about 0.025 pct Li is generally used for this salar (*12*), although sampling has indicated grades ranging from 0.004 to 0.115 pct Li (*5*).

Resources have been reported as 5.5 million mt Li, as well as 100 million mt K, and 3.2 million mt B (*20*). It is not known how these figures were estimated, but it appears that they could be resource estimates inclusive of the total areal extent of the Salar (9,000 km^2).

The deposit was included in the evaluation principally because of the extensive resource quantity indicated and the reported interest that has been shown for exploitation. It is not felt, however, that exploration has established the entire resources as demonstrated. For this reason, demonstrated resources are limited to a proposed production life of 80 yr at a rate of about 6,350 mt/yr Li_2CO_3.

Although research into lithium recovery has been performed on the Salar de Uyuni brines, few of the data are available. The grade is roughly an order of magnitude less than that of the Salar de Atacama brines. In addition, the brine contains an extremely high Mg-Li ratio of about 21.5, compared with ratios of 6.6 and 1.5 at Salar de Atacama and Silver Peak, respectively.

Chile

The Salar de Atacama is a salt basin in northern Chile encompassing about 3,000 km^2. The nucleus of the basin, considered to be the primary lithium resource area, covers approximately 1,300 km^2. By comparison, the current operation that was brought onstream in 1984 covers an area of a little less than 170 km^2. The complex is operated by Sociedad Chilena de Litio Ltda. and is owned 55 pct by Foote Mineral Co. and 45 pct by Corporacion de Fomento de la Produccion (CORFO), the Chilean Government's development company agency. As the mining progresses, it develops a possible exploitable resource of potash as a waste accumulation in some of the ponds.

The lithium at Salar de Atacama was discovered in the early 1960's, and extensive surveys were made during 1969-74. Studies leading to the current operations began in 1975, and construction started in 1981. The projected annual Li_2CO_3 capacity of the operation is about 6,350 mt (14 million lb).

Test drilling on the nucleus ranged in depth from 40 to 390 m; the highest porosity zone is near the top, and the occurrence of the lithium-rich brines begins at an average depth of about 0.6 m (*12*, p. 34).

Within a control area of 420 km^2 with a high density of data, resources have been estimated at 1.3 million mt Li (recoverable). This is based on a depth of 20 m and a specific yield of 10 pct; that is, 10 pct porosity containing an average concentration of 0.125 pct Li. Data have been further extrapolated to the entire nucleus to indicate a resource of an additional 3 million mt Li (recoverable) (*17*).

For the purpose of this study, the control area resources are considered demonstrated and the additional nucleus resources are considered inferred, resulting in a total identified resource of 4.3 million mt Li. (See table 5.)

The demonstrated lithium resource is equivalent to approximately 7 million mt Li_2CO_3 equivalent. At a rate of 6,350 mt/yr, this quantity would last over 1,000 yr. For the purpose of estimating the potential availability of the deposit, the life is limited to 80 yr. Even this time period is extensive, given the future unknowns, such as likely expansions and potential byproduct recovery.

Another resource estimation includes other potentially recoverable commodities as well as lithium. (See table 10.) As shown, there is a difference in the lithium quantity from that used in this study. In view of the recent nature of data on the deposit, however, this difference is not considered significant.

The brine containing about 0.125 pct Li is pumped from three wells drilled to a depth of 30 to 40 m, and is then concentrated to about 4.3 pct Li (design strength) in a series of evaporative ponds ordered in three groups. The first group (four ponds) receives the brine and concentrates it to 0.4 pct Li while precipitating the salt as halite (NaCl) and the potash as sylvinite (KCl). These minerals are periodically harvested from these ponds and stockpiled for possible future processing. The second group (three ponds) is used mainly to remove the magnesium, and the last group is used for final evaporation and storage for shipment to the chemical plant. The final brine is hauled about 60 km by truck and about 265 km by rail to the Li_2CO_3 plant at La Negra (near Antofagasta).

Conversion to Li_2CO_3 from the LiCl brine is a relatively simple process. It consists of using hydrated lime ($Ca(OH)_2$) for final magnesium and calcium precipitation and soda ash ($NaCO_3$) for precipitation of Li_2CO_3. This is done under close pH and temperature controls and with attendant filtering and washing steps common to most chemical extraction processes. The 99.5-pct-Li_2CO_3 concentrate is generally packaged in bags or drums for ocean shipment.

United States

The Silver Peak (Clayton Valley) playa is located in central Esmeralda County, southwestern Nevada. The brine mining and evaporation ponds are located in Clayton Valley about 4 km from the Li_2CO_3 chemical plant in the town of Silver Peak. The operation, owned by Foote Mineral Co., has been in operation since 1966.

The first lithium exploration was undertaken in 1960, and the present company began serious work on the deposit in 1964. The chemical plant was a gold-silver cyanidation plant that was bought at auction and converted to the production of Li_2CO_3.

The Clayton Valley playa is a closed basin in which sediments consist mainly of a mixture of saline minerals and derivatives in the form of evaporates, clays, silts, and sands. The playa encompasses about 8,300 ha (83 km^2), and geophysical testing suggests the sediments may be as much as 460 m thick. Interstitial brines occur from a depth of about 9 to 180 m.

Published estimates vary from 35,000 to 2.30 million mt Li (contained) including speculative resources (*17, 23, 27*). For the purpose of this study, the demonstrated and identified resource quantities are estimated to contain 65,000 and 124,000 mt Li (contained), respectively (*28*).

The operation of the wells and evaporation ponds is very similar to that of Salar de Atacama. The main difference is in the quantity of brines pumped, which requires more wells (± 50) at a greater depth (up to about 180 m). To produce a similar quantity of Li_2CO_3 (both plants have annual Li_2CO_3 capacity of about 6,350 mt), the Silver Peak operation must pump about four times more brine and have a larger pond area. The conversion process of the LiCl in the brine to Li_2CO_3 is also similar to that used at Atacama.

The product is hauled about 80 km to a packaging plant at the Mina, NV, railhead where it is either shipped to other Foote plants for making downstream products (i.e., butyllithium, $LiOH{\cdot}H_2O$, etc.) or sold f.o.b railhead.

PRODUCTION COSTS

Operating and capital investments for the appropriate mining beneficiation and postmill processing methods were estimated for each property. Where possible, actual capital and operating costs were obtained from published material or contacts with company personnel. When actual costs were unavailable, costs were estimated, using standardized costing techniques.

Operating costs for the mine and mill are computed as a total of direct and indirect costs of production including costs associated with utilities, labor, administrative costs, facilities maintenance, supplies and research. The operating costs presented in this section are weighted averages per-metric-ton-of-ore or per pound of Li_2CO_3 over the life of the operation. Costs in parentheses represent contained lithium.

Operating cost information is presented on the basis of mine type (surface, underground or brine) and status. To standardize the evaluation, a common year dollar base was used. The cost data were collected in January 1982 dollars and updated to January 1984 dollars, for the analyses.

MINING AND BENEFICIATION COSTS

At the time of this analysis, four surface mining and two brine operations were producers; seven underground, two surface, and one brine operation were nonproducers. Except for the recovery of lithium from brines, mining follows generally applied methods. There are currently no operating underground lithium mines within the MEC's. Pegmatites, which host most lithium deposits, are relatively competent and therefore present minimal ground support problems. All of the proposed underground mines would probably utilize room-and-pillar and or sublevel blasthole stoping methods. Room-and-pillar mining generally has low dilution and high overall recovery, especially if the pillars are robbed in the later stages of the mine's life. Sublevel blasthole stoping generally results in a low dilution of about 10 pct and recovery generally exceeding 80 pct.

Underground operating costs (all nonproducers) are estimated to range from a low of $16.50/mt ore (room and pillar) to a high of $36.00 (various stoping methods). The high costs result from higher labor costs and relatively low productivity owing to complex mining and a relatively low mine capacity.

The major factors affecting surface mining costs include labor costs and productivity, energy costs, haulage distances, and stripping ratios. The surface mine operating costs for nonproducers range from $2/mt ore to $9/mt ore. The higher costs are in Canada where the remoteness of the deposits requires high labor costs. Surface mining costs for the producers range from about $5/mt ore to $18/mt ore. The variation is mainly caused by the difference in stripping ratios, which vary from 0.7 to 5.

Beneficiation of lithium ore involves mainly flotation (sometimes enhanced by gravity and magnetic methods); handpicking of complex ore is required at Bikita. Additional circuits may be necessary, however, in order to recover byproducts. Beneficiation costs for the producers range from about $7/mt ore for the simplest process, to $23/mt ore where the process includes the recovery of the more refactory byproducts. Of course the higher costs are defrayed by the byproduct revenues. Among the nonproducers, the lowest beneficiation costs are about $7/mt ore, while the highest are $23/mt. Tantalum and tin are potentially recoverable byproducts and add to beneficiation cost of the high-cost property. About 30 pct for the cost of beneficiation for the low-cost property is for ore haulage from the mine to the millsite.

Costs associated with postmill processing of spodumene concentrates are not available because of their highly proprietary nature and are therefore not discussed.

LITHIUM BRINES

The current interest in the recovery of lithium from brines in Bolivia and Chile results primarily from increasing costs associated with relatively high labor and fuel intensive requirements of hardrock mining and beneficiation. Based on the requirements of equipment, complexity of the installation, labor requirements and energy use, the cost of extraction of Li_2CO_3 from brines appear to be substantially less than extraction from spodumene.

The Silver Peak, NV, operation is the oldest and appears to have the lowest cost among all of the evaluated brine deposits, since all the initial capital costs have been depreciated. The processing of brines at the Salar de Atacama property in Chile is quite similar to that at Silver Peak except that the Chilean brines have a higher lithium content; however, the property carries the burden of capital depreciation. Based on an estimated annual output of about 6,350 mt Li_2CO_3 (1,183 mt Li) from brines in Chile, processing from brine to product is estimated at under $0.75/lb Li_2CO_3. The total capital requirement is estimated at about $48 million January 1984 dollars or approximately $3.50/lb

Table 11.—Lithium concentrate transportation costs

Country and property[1]	Destination	Distance, km	Primary mode of transportation	Cost, Jan. 1984 \$/mt[2]
Australia: Greenbushes	Bunbury, Australia	80	Truck	6
Bolivia: Salar de Uyuni	Antofagasta, Chile	450	Rail	45
Canada:				
Bernic Lake	Thunder Bay, Canada	800	Rail	45
Buck-Coe-Pegli	...do	800	...do	50
Georgia Lake	...do	145	...do	20
Jean Lake	...do	200	...do	25
Lac la Croix	...do	200	...do	20
Nama Creek	...do	200	...do	20
Quebec Lithium	Quebec City, Quebec	700	...do	41
Yellowknife	Prince Rupert, BC	2,450	...do	120
Chile: Salar de Atacama	Antofagasta, Chile	325	...do	60
United States:				
Bessemer City	North Carolina	NAp	NAp	NAp
Kings Mountain	...do..	NAp	NAp	NAp
Silver Peak	Nevada	NAp	NAp	NAp
Zaire: Kitotolo	Matadi, Zaire	2,000	Barge and rail..	60
Zimbabwe: Bikita	Masvingo to Durban, Republic of South Africa.	3,700	Rail	75

NAp Not applicable.
[1] U.S. properties process spodumene or brines on-site and distribute value-added products.
[2] Spodumene concentrate except for Bikita which produces petalite, and Salar de Atacama and Salar de Uyuni, which produce Li_2CO_3.

of annual Li_2CO_3 capacity. The costs include: (1) wells, piping, salt recovery equipment, pond liners, trucks; (2) chemical plant; and (3) infrastructure. The costs were split approximately 27 pct, 48 pct, and 25 pct, respectively. Although much of the same type of equipment would be necessary at Salar de Uyuni, technical complications produced by the brine chemistry may add significantly to the capital and operating costs.

TRANSPORTATION

Most lithium concentrate and Li_2CO_3 in MEC's is sold from main ports, generally in Europe or the United States. In this study, concentrate was shipped to either the actual or most likely port for export. If the concentrate was treated locally into downstream products, as is done at Kings Mountain and Bessemer City in North Carolina, and the brines at Silver Peak, NV, there were little or no transportation charges. Costs for transportation (table 11) are estimates only; some taxes, handling costs, special rates, or fees and other additional costs may not be included. Costs for rail, truck, or other necessary modes of transportation from mill site to port are included.

LITHIUM AVAILABILITY

An economic evaluation was performed on each of the 16 mines and deposits included in this study to determine the average total cost for the recovery of spodumene and petalite concentrate as well as Li_2CO_3 from brines over the operations' production lives. The evaluations apply DCFROR techniques to determine the constant-dollar long-run average total cost of lithium production. This average total cost is equivalent to the lithium concentrate and Li_2CO_3 price over the long run that each operation would require, so that the discounted sum of total revenues from the sale of lithium products and associated byproducts (if any) is sufficient to equal the discounted sum of all costs of production over the life of the operation. The annual cash flows are discounted at a prespecified rate of return. The economic evaluations for this study were performed at 0- and 15-pct DCFROR. A 0-pct DCFROR represents the "breakeven cost," which includes a return of but not on capital. A 15-pct DCFROR represents a minimum rate of return that might be required for a firm to develop a lithium operation and produce over the long term.

An implicit assumption in each evaluation is that each operation or proposed operation represents a separate entity or operation. The life of each property was determined by assuming that the property would operate at 100 pct of mine capacity. The mine life covers only the demonstrated resource level, which is probably a conservative figure, especially in the case of resources in South American brine deposits.

All capital investments incurred 15 yr or more before the cost date of analysis (January 1984) are treated as sunk costs. Investments incurred during the prior 15 yr have the undepreciated balances entered as a capital investment in 1984. All subsequent investments, reinvestments, and operating and transportation costs are expressed in constant (nonescalated January 1984) dollars. The resource and cost data evaluated for this study are based on January 1982 data updated to January 1984 values.

Investment and operating schedules are determined, as much as possible, from published data, actual onsite visits, or plans announced by the companies involved. For those deposits which have been explored, but where no plans to initiate production have been announced, a development plan was estimated. The preproduction period for these explored deposits allows for only the minimum engineering and development time necessary to initiate production. Additional time lags and potential costs involved in filing environmental impact statements, receiving required permits, arranging financing, etc., are not accounted for unless specific information was available.

The potential tonnage and the average total cost determined over the estimated producing life of each mine and deposit evaluated for this study have been aggregated onto availability curves that illustrate the potential quantity of lithium concentrate available at various costs. The availability curves are constructed as aggregations of the total amount of lithium potentially available from each mine and deposit, ordered from those having the lowest average cost to those with the highest.

The curve provides a concise, easy-to-read, graphic illustration of the comparative costs associated with any given level of potential output and provides an estimate of what the average long-run price (in January 1984 dollars) would likely have to be in order for a given tonnage to be potentially available to the marketplace.

Two types of curves have been generated for this study: (1) total availability curves and (2) annual curves at selected total production costs. Annual curves are a disaggregation of the total curve to show annual lithium availability at varying costs of production.

TOTAL AVAILABILITY

For this study, 16 lithium properties in seven MEC's were evaluated. The 6 that were producing at the time of the study represent over 95 pct of the MEC production; the other 10 are nonproducers. (At the time of this study, Bernic Lake had just started operating on a pilot plant basis and was therefore not evaluated as a producer.) Among these properties, 1 is primarily a petalite property, 3 are lithium-enriched brines, and 12 are spodumene properties. Combined, these properties account for over 2 million mt Li (recoverable), of which about 84 pct is in the six current producers. The percentage share of total recoverable lithium by country and the relative share of recoverable lithium from producing and undeveloped deposits was previously illustrated in figure 4. Figure 4 shows the large demonstrated resources of Australia and the United States as producers and the significance of Canada among the nonproducers. The figure dramatically illustrates potential of brines in South America. The resources of these regions have not as yet been fully demonstrated. Figure 5 illustrates the distribution of total recoverable and contained lithium in the three ore type products evaluated.

The Bikita Mine, in Zimbabwe, is the only evaluated hardrock property that does not produce spodumene concentrate as its primary mill product. The mine can produce approximately 38,500 mt/yr petalite concentrate of slightly over 4 pct Li_2O (1.86 pct Li). There is also some minor production of spodumene and lepidolite concentrates at Bikita, but they are not currently considered important as a long-term resource.

The three brine properties—Salar de Atacama, Chile; Salar de Uyuni, Bolivia; and Silver Peak, NV—contain over 7.8 million mt of recoverable Li_2CO_3 (1.466 million mt Li). As previously mentioned, Li_2CO_3 is produced from brines. Large additional lithium resources exist in these and other South American countries but have not been adequately quantified to be considered demonstrated. There is strong evidence, however, to support 80-yr operations for both Salar de Uyuni and Salar de Atacama and general acceptance that sufficient resources exist to support multiple brine operations.

The 12 spodumene hardrock properties could potentially produce over 26,169,000 mt of recoverable concentrate containing Li_2O (2.79 pct Li), or about 730,000 mt Li. Based on this study, currently producing spodumene mines account for a total recoverable resource of 16,932,575 mt of spodumene concentrate averaging 6.06 pct Li_2O (476,640 mt contained Li).

Australia's producing Greenbushes property contains the single largest demonstrated hardrock resource evaluated in this study, with 7,621,900 mt of recoverable spodumene concentrate grading nearly 7 pct Li_2O_2 (247,880 mt contained Li).

The second and third largest spodumene properties are Bessemer City and Kings Mountain, both U.S. producers; together, they could produce a total of a little over a million metric tons of concentrate at a grade of about 5.3 pct Li_2O (229,000 mt contained Li). Kitotolo, a nonproducing property in Zaire, has a demonstrated resource of about 31,500,000 mt ore that would yield only about 430,500 mt concentrate averaging 6 pct Li_2O (11,985 mt contained Li). The small concentrate production results from low recoveries during concentration owing to complexity of the ore, which also contains tin and tantalum in recoverable amounts.

Total availability curves for the 12 spodumene properties are not presented in order to avoid disclosure of proprietary cost data pertaining to the Bessemer City and Kings Mountain operations. Of the 26,169,000 mt of spodumene concentrate, 94 pct is available for less than the January 1984 published market price (approximately $330/mt) at a 0-pct DCFROR. This tonnage originates from the Bessemer City and Kings Mountain mines in the United States (33 pct), Greenbushes in Australia (36 pct), and 3 undeveloped Canadian properties — Bernic Lake, Yellowknife, and Quebec Lithium (29 pct). The remaining portion originates from the undeveloped Kitotolo property in Zaire. The Yellowknife and Quebec Lithium properties are very marginal and would be uneconomic with just a slight lowering in grade, recovery, and/or increase in estimated costs.

At a 15-pct DCFROR, 72 pct of the total spodumene concentrates from the 12 properties is available for less than the January 1984 published market price. This tonnage originates from the two U.S. mines (44 pct), Greenbushes (47 pct), and Bernic Lake (9 pct).

Canada

Separate availability curves were constructed for the eight Canadian lithium properties (all potential spodumene producers) included in this study (fig. 6). None of these properties were producing at the time of this study. In 1984 the Bernic Lake property began a pilot operation at about 150 mt/d ore.

Approximately 8,805,560 mt of spodumene concentrate, averaging 5.9 pct Li_2O (241,300 mt contained Li), is potentially recoverable from the Canadian deposits. At a 0-pct DCFROR, 82 pct of this total, all from the Bernic Lake, Quebec Lithium, and Yellowknife properties, is available for less than the January 1984 published market price for spodumene concentrate. About 75 pct of that portion (Quebec Lithium and Yellowknife) is very marginal and could become uneconomic with only a slight change in grade, estimated recoveries, concentrate qualities, or costs. The total costs for the remaining five properties range from $375/mt to $640/mt. This study indicates that the Bernic Lake property offers the best opportunity for development at the January 1984 published price of spodumene concentrate. A total of approximately 1,727,500 mt of concentrate at almost 7 pct Li_2O (nearly 50,000 mt contained Li) is available from Bernic Lake. The property's relatively favorable economic position results from currently existing infrastructure, working knowledge of the ore body (other parts of the pegmatite were mined for tantalum in the early 1970's), and a relatively high feed grade of 2.5 pct Li_2O (1.16 pct Li).

At a 15-pct DCFROR, only the resources at Bernic Lake are available for less than the January 1984 published market price for spodumene concentrate. (In the year following this evaluation, Bernic Lake began operating on a pilot

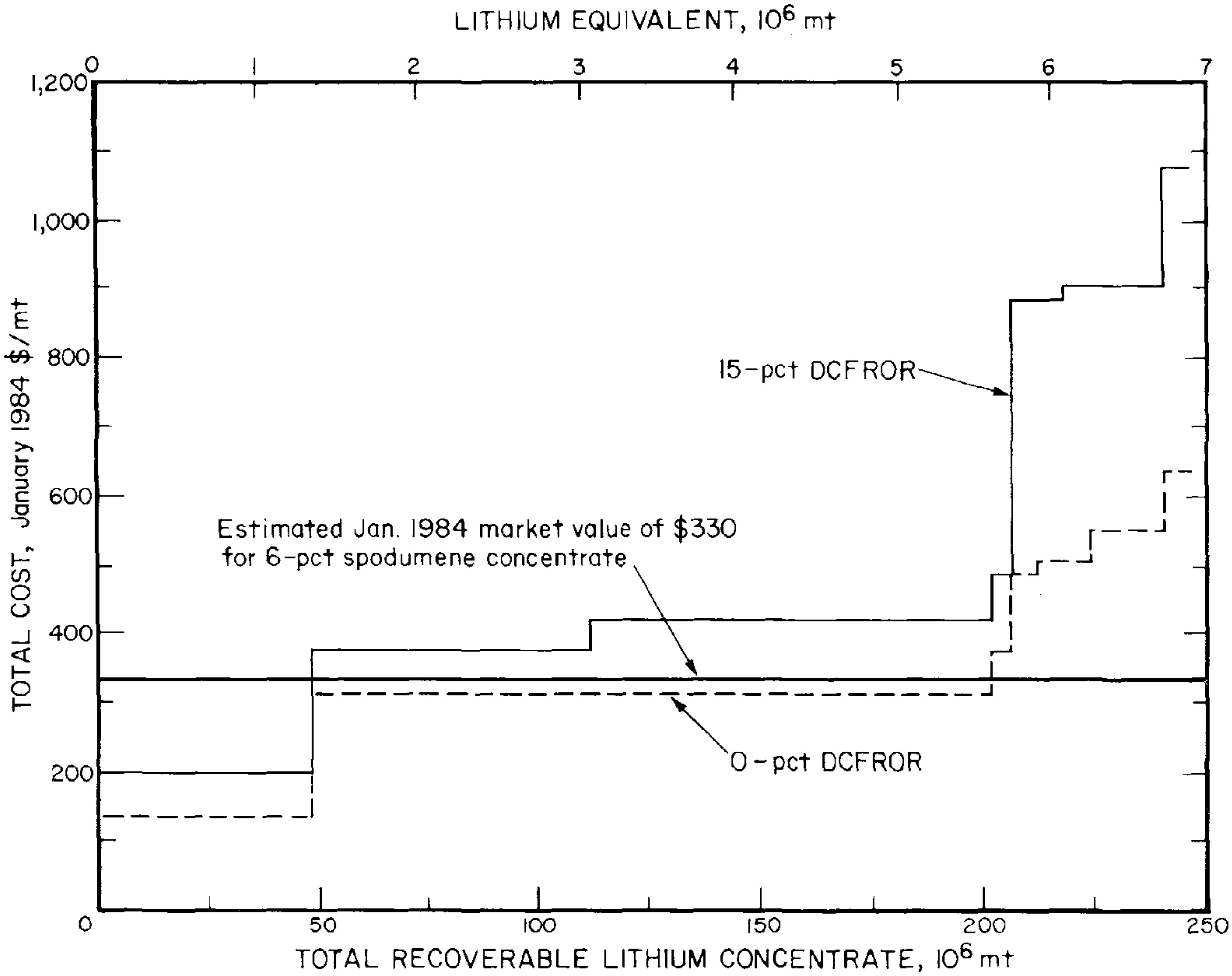


Figure 6.—Spodumene concentrate availability from nonproducing Canadian properties at 0- and 15-pct DCFROR.

plant basis. The remaining seven properties range from a total cost of $0.17/lb ($375/mt) to $0.49/lb ($1,080/mt). The weighted-average total cost for the eight Canadian properties at a 15-pct DCFROR is $0.20/lb concentrate ($445.50/mt). The estimated market value of this concentrate could be in the order of $330/mt.

Brines

The total recoverable Li_2CO_3 from brines at the three properties evaluated in this study (Salar de Atacama, Salar de Uyuni, and Silver Peak) is 6,665,000 mt Li_2CO_3 (1,466,000 mt Li), with a January 1984 market value exceeding $3 billion. Additional demonstrated resources are very likely present in the salares of Bolivia and Chile but were excluded owing to the lack of supporting data. The weighted-average total cost at 0-pct and 15-pct DCFROR for the three properties evaluated are $0.70 and $1.40, respectively. The large difference primarily results from the higher required return on newly invested capital at the South American properties. Silver Peak, NV, and Salar de Atacama, Chile, are currently operating. The two producing brine operations can produce for less than the published market price of $1.48/lb Li_2CO_3 (January 1984) at both 0- and 15-pct DCFROR. The Silver Peak operation has a significant competitive advantage resulting primarily from depreciated capital costs and low transportation charges. The nonproducer, Salar de Uyuni, would require a market price at less than $1.00/lb and $2.00/lb Li_2CO_3 in order to produce at a 0- or a 15-pct DCFROR, respectively. This economic estimate may be optimistic owing to potential metallurgical complications that could be caused by a high magnesium content. Several other properties have been investigated in the salar regions in Argentina, Bolivia, and Chile but few published data are currently available. AMAX Inc., a U.S. company, has stated that it is currently negotiating an agreement with Chile to potentially develop a new brine operation in the Atacama region.

ANNUAL AVAILABILITY

Another method of illustrating lithium availability involves disaggregating the total resource availability curve and showing potential availability on an annual basis. Separate annual availability analyses have been constructed for producing mines and proposed (undeveloped) operations in MEC's. Since no accurate development schedule can be proposed for all of the undeveloped deposits, the emphasis of these tables or curves is to indicate

Table 12.—Potential annual lithium production from producing mines and undeveloped deposits

(Metric tons Li equivalent)

Year[1]	Spodumene	Brines	Petalite	Total
Producing mines:				
1984......	5,120	1,690	770	7,580
1990......	5,550	2,380	770	8,700
2000......	5,550	2,380	770	8,700
Undeveloped deposits:				
N+1......	1,640	0	0	1,640
N+5......	7,780	940	0	8,720
N+10.....	7,300	940	0	8,240

[1] N = year preproduction development begins.

estimated future potential capacity at estimated 1984 cost levels.

Producing Mines

Potential total annual production was analyzed for six producers of lithium; three produce spodumene concentrate (Bessemer City, Greenbushes, and Kings Mountain); one produces a petalite concentrate (Bikita); and two produce Li_2CO_3 (Salar de Atacama and Silver Peak) derived from brines. These production figures could not be plotted on the same curves owing to different product types and values plus the small number of data points; however, the potential annual production in terms of lithium equivalent is tabulated in table 12.

The annual availability analysis reflects the production capacity of existing mines, including planned expansions. It was assumed that all operations produce at full (100-pct) capacity over the life of the mine. The analysis, therefore, cannot take into account sales or stockpiling, production cutbacks or unannounced expansions mandated by market conditions, or byproduct lithium potentially available from other sources. These factors vary on an annual basis and are difficult to project. A comparison of 1984 estimated production with the estimated production capacity in this study reveals that an apparent surplus capacity exists. (See tables 2 and 12.)

The three producing spodumene properties—Bessemer City and Kings Mountain in North Carolina and Greenbushes in Australia—have sufficient demonstrated resources to produce, at evaluated capacities, through the year 2000. In this evaluation, Greenbushes is assumed to expand production of concentrate at 7 pct Li_2O from a current 15,000 mt (488 mt Li) to 25,000 mt (812 mt Li) in 1987. No information pertaining to any planned expansions at the domestic spodumene properties was available, nor was any assumed.

Bikita, a petalite property that has supplied some spodumene and lepidolite in the past, can also produce petalite concentrate at 4.2 pct Li_2O through the year 2000 at an annual capacity of about 39,600 mt (773 mt Li). Although not assumed in this study, there is a likelihood that Bikita will undergo some modernization of its beneficiation facilities at some time in the near future.

Both of the evaluated Li_2CO_3 producers (Salar de Atacama and Silver Peak) have the resources to operate through the year 2000 and for some time beyond. Total annual capacity from the producing brine properties evaluated is nearly 9,000 mt Li_2CO_3 (1,690 mt Li), or about 22 pct of the total lithium among the evaluated producers. An expected increase in production at Salar de Atacama in 1985 would increase the portion of lithium from brines to nearly 30 pct of total MEC lithium production. An important consideration in anticipating future market conditions is that development of additional wells and processing facilities in the Atacama Basin is likely, and that there will be a resultant increase in supply from Chilean lithium producers. If this scenario were to occur, Chile could have a major impact on the market structure and price of the commodity.

In 1984 (table 12), the evaluated lithium producers had a total capacity of approximately 7,580 mt Li, 68 pct from spodumene, 22 pct from Li_2CO_3, and 10 pct from petalite properties. Potential annual capacity from these producers is estimated to increase to nearly 8,700 mt Li by 1990. Production at Salar de Atacama was projected to increase from 3,000 mt Li_2CO_3 (563 mt Li) in 1984 to about 6,300 mt Li_2CO_3 (1,835 mt Li) in 1985; and stepped-up production at Greenbushes, was assumed to take place in 1987, from 15,000 mt of spodumene concentrate at 7 pct LiO_2 (488 mt Li) to 25,000 mt at the same grade (813 mt Li). After the proposed increases, the percentage distribution of product types is essentially the same as in 1984. At a 0-pct DCFROR, all of the lithium products were available for less than the January 1984 published market prices. At a 15-pct DCFROR, the highest production cost was no more than 1 pct over the price.

Nonproducing Properties

The potential annual availability totals include mine nonproducing potential spodumene producers of which eight are in Canada and one is in Zaire. The Canadian properties are Bernic Lake (TANCO began operating Bernic Lake on a pilot scale basis in late 1984), Yellowknife, Quebec Lithium, Buck-Coe-Pegli, Georgia Lake, Nama Creek, Jean Lake, and Lac la Croix. The other nonproducing spodumene property, Kitotolo, is in Zaire. The nonproducing brine property, Salar de Uyuni, could produce Li_2CO_3 from lithium-enriched brine in Bolivia. The spodumene properties are included on curves at a 0- and 15-pct DCFROR in figure 7. Since no definite startup is known or available for any of these deposits, it was assumed that preproduction begins in a base year (N). Although these curves do not show a definite startup date, they do show the required lead times before production can begin and therefore are important in that they illustrate the annual production potential. In these curves, all of the undeveloped deposits are assumed to begin preproduction development at the same time, in the year "N."

Table 12 lists potential lithium production at selected time intervals for the nonproducing spodumene and brine (Li_2CO_3) properties. If development were to begin on the evaluated nonproducing lithim deposits in year "N," by the beginning of N + 1 approximately 59,000 mt of spodumene concentrate (1,640 mt Li) at an average grade of nearly 6 pct Li_2O would be produced. Nearly 70 pct of the lithium production would originate from the Bernic Lake deposit. The remaining production would come from initial production from the Quebec Lithium deposit. At a 0-pct DCFROR all of the this material would be available for less than the January 1984 market price for concentrate, although Quebec Lithium is very marginal. At a 15-pct DCFROR, only production from the Bernic Lake deposit would be economic.

By N + 5, 283,000 mt of spodumene concentrate, primarily from Canada at an average grade of 5.91 pct Li_2O (7,770 mt contained Li) plus an additional 5,000 mt Li_2CO_3 (940 mt Li) from Salar de Uyuni (not included on the curve)

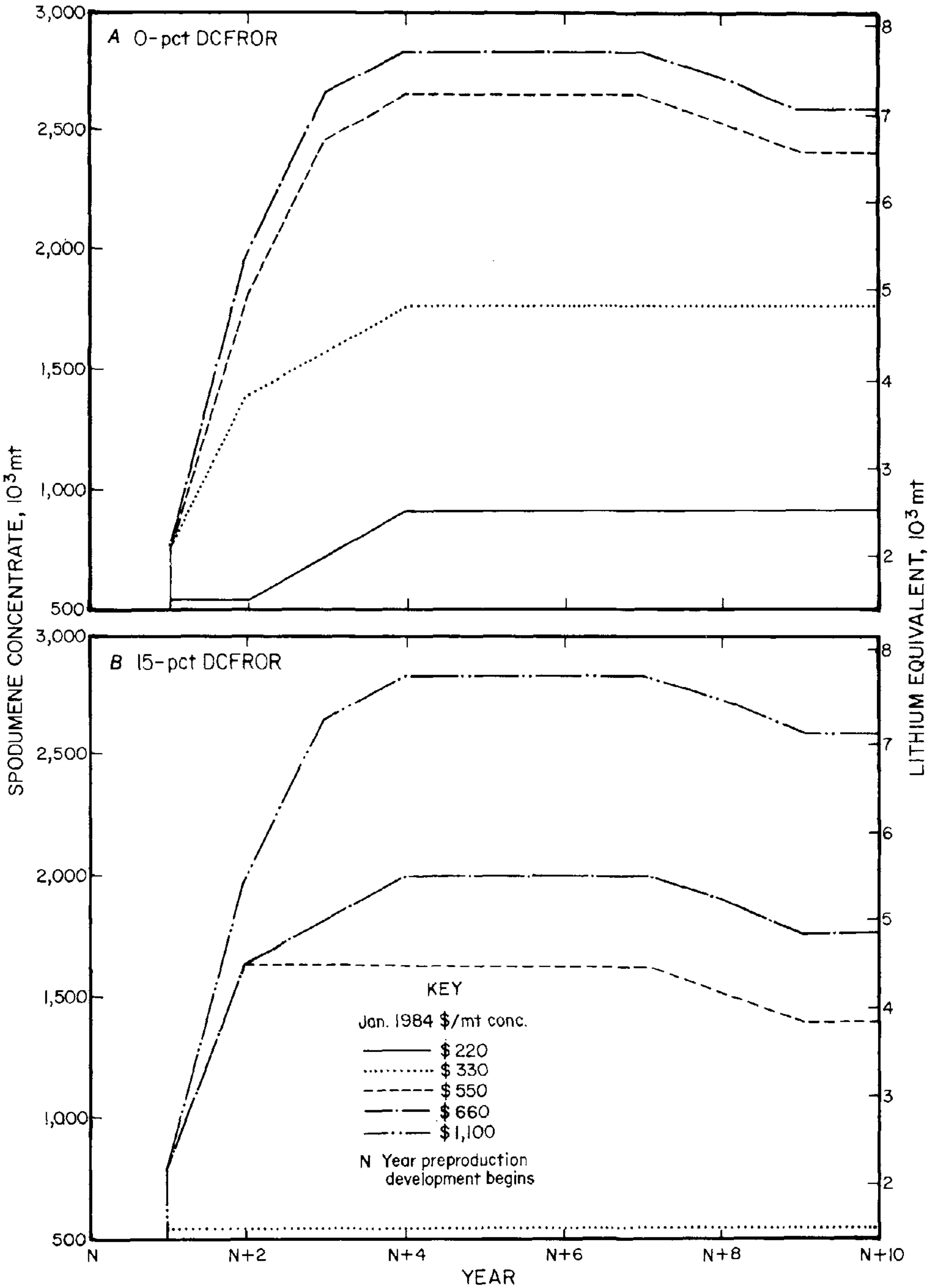


Figure 7.—Annual spodumene concentrate availability from nonproducing properties at 0- and 15-pct DCFROR.

would result in a combined total of 8,710 mt Li. This compares with an estimated 5,400 mt Li produced in 1984 by MEC's and nearly 7,000 mt worldwide. At a 0-pct DCFROR nearly 70 pct of this total is available for less than the January 1984 market price of the respective commodities. Most of the material would originate from Canada (65 pct), followed by Bolivia (20 pct) and Zaire (15 pct). At a 15-pct DCFROR only Bernic Lake can produce for less than the market price. The market price would have to exceed $0.29/lb or $639/mt of spodumene concentrate in order to allow all of the hardrock properties to attain a 0-pct DCFROR and $0.49/lb or $1,080/mt of concentrate to attain at least a 15-pct DCFROR. As previously mentioned, the Salar de Uyuni property could produce for less than the market price of Li_2CO_3 at a 0-pct DCFROR; but in order to achieve a 15-pct DCFROR, it would require a price at least 20 pct higher than the market price. Salar de Uyuni's relatively high costs result from the return required on invested capital.

In the year N + 10 approximately 8,240 mt Li is still potentially available from these nonproducing properties. The reduced tonnage is the result of the exhaustion of estimated ore resources at the Buck-Coe-Pegli Mine in Canada and declining production at Nama Creek as its demonstrated resource becomes depleted. At a 0-pct DCFROR, abut 60 pct of the total tonnage is available for at or less than the January 1984 published market price (although nearly 50 pct of this amount is essentially the same as the January 1984 market price). At a 15-pct DCFROR only about 20 pct of the total tonnage is economically available, all of which would originate from the Bernic Lake deposit.

SUMMARY

Based on the evaluation of the selected producing mines, and in terms of lithium contained in concentrates (see table 12), approximately 5,225 mt Li can currently be produced annually from spodumene properties, 1,690 mt Li from brines, and 770 mt Li from petalite concentrate, for a total of 7,685 mt Li. Production data for 1983 indicated that only about 86 mt Li was contained in concentrates produced from nonevaluated MEC deposits: 54 mt from Brazil, 18 mt from Namibia, 9 mt from Portugal, and 5 mt from Argentina. This production, mostly byproduct in origin, was believed to be about the same in 1985. In addition, about 1,270 mt was reportedly produced in the Soviet Union and nearly 320 mt in China (*9*). Production statistics for the centrally planned economy countries (CPEC's) should be considered as broad estimates. MEC production was about 80 pct of capacity in 1984. All of the producing mines evaluated have mine lives, at current design capacity, exceeding 20 yr, and there are additional undeveloped resources available at relatively low costs from Bernic Lake and from the salares of Chile. As a result, no near- or long-term shortage of lithium, in its various forms, is likely.

CONCLUSIONS

Lithium has important applications in high technology due to its ability to contribute desirable properties to a number of commercial products. Historically, the United States has dominated the production and sale of lithium products among the MEC's and is self-reliant in this commodity. The 16 lithium properties evaluated for this study in 7 MEC's represent a demonstrated recoverable tonnage of over 2,214,000 mt Li contained in brines, spodumene, and petalite ores. Producing operations account for about 84 pct of the total. At a 0-pct DCFROR all of the operating mines can produce for less than the January 1984 market price. As the Salar de Atacama property continues to produce and expand, it will most likely become more efficient and less costly to operate. This study only evaluated demonstrated resources, which does not fully reflect the potential of the Atacama region. Identified resource estimates exceed 11 million mt Li (recoverable).

As of 1984, the influx of new lithium production from Greenbushes, Australia, and Salar de Atacama, Chile, as well as the likely development of Bernic Lake, Canada, present a strong threat to the position of the United States as the major supplier to the MEC's and an increased world capacity that is already larger than current market demand. Presently, domestic producers can supply lithium, in its various forms, at competitive prices; but the hardrock mines of the United States (responsible for most of the production) could lose their competitive edge if the costs for labor, fuel, and supplies increase. These increases could provide an excellent opportunity for the further development of brines, especially those in the Atacama Basin. The tremendous potential for the low-cost recovery of lithium in brines, especially those in Chile's Atacama Basin, cannot be overlooked by companies operating hardrock mines. This potential is an important component in anticipating future market conditions, especially considering Chile's need for foreign exchange. The production of lithium from additional wells and processing facilities in the Atacama Basin could put Chile in the position to potentially control the price of lithium.

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