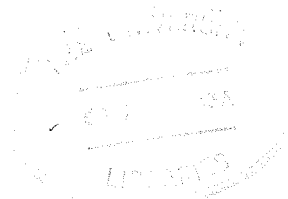AN EVALUATION OF THE POTENTIAL
FOR MANITOBA'S CESIUM

by

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A Practicum Submitted in Partial Fulfillment
of the Requirements for the Degree, Master of Natural
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"An Evaluation of the Potential for Manitoba's Cesium."

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ABSTRACT

The world's largest known reserves of cesium-rich ore (pollucite) are at the Bernic Lake mine in Manitoba. Since 1969, the mine has been operated by the Tantalum Mining Corporation of Canada Limited of which the Manitoba Government owns 25%. Tanco suspended operations as of December 31, 1982 and terminated the employment of approximately 105 full-time employees because of the poor markets for its principal product, tantalum.

The primary objective of this study was to evaluate the potential for Manitoba's cesium resource. The research methods were designed to access primary and secondary sources of information in order to collect and evaluate quantitative and qualitative data. The main objective was further delineated by investigating eight sub-objectives which included: supply-demand relationships for pollucite and its processed cesium derivatives; present and potential applications for cesium (pollucite, and cesium compounds and metal); and the cesium export ban imposed by the Government of Canada in 1976.

The report findings indicated that pollucite is the most important commercial source of cesium. Pollucite is a small tonnage but high value commodity which is processed into cesium primary products (compounds and metal). Tanco will continue to dominate the world pollucite market for reasons which include: (1) its ability to assure supply relative to its primary competitor, the Bikita mine in Zimbabwe; and (2) the two major pollucite processing countries, West Germany and the U.S., have well established trade links with Tanco. The largest user-country of cesium in the free world is the U.S., and mostly for scientific research purposes. Cesium is principally used in the form of chemical compounds and to a lesser extent in metallic form. Presently, the major applications for cesium are in photoemissive devices, density gradient solutions, and scintillation crystals. Pollucite ore is not used directly in any end-use applications, though at one time it was a candidate material for use in open-cycle magnetohydrodynamics (MHD) but was substituted by potassium. There are two potential uses for cesium compounds/metal which may increase the demand for pollucite significantly: oxidation catalyst promoters; and plasma seed in closed-cycle MHD.

Prior to 1976, the greatest demand for Tanco's pollucite was from the Soviet Union. However, this market was terminated in 1976 when the Government of Canada placed cesium in the Export Control List. Cesium continues to be in the List but its status and the status of the other entries are to be reviewed and updated during 1984-1985.

Development strategies were recommended to the Province of Manitoba in order to monitor and encourage economic opportunities, especially in industries which further process raw mineral resources into value-added products.

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I would also like to acknowledge the Manitoba Department of Energy and Mines for granting the opportunity to conduct this study by providing financial assistance and support services. Other public organizations which have contributed to this study included: Industry Technology Centre; the federal departments of Energy, Mines and Resources, and External Affairs; and the U.S. Bureau of Mines, and Bureau of the Census. I am especially grateful to Mr. Richard Burt, Manager of the Tantalum Mining Corporation of Canada Limited, for his assistance and contributions to this study.

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Chapter I

INTRODUCTION

1.1   PREAMBLE

Canada's economic performance and development continues the historical pattern of being dependent upon its vast and diverse natural resources wealth. Renewable and exhaustable resources, mostly in the primary stages of production, are exported into the international marketplace and the revenues generated from resource sales are a significant source of foreign exchange. With the help of foreign exchange earnings from the sales of primary goods, Canada tries to counterbalance its high import expenditures for many value-added fabricated and processed goods. Although Canada may be categorized as being a developed industrial nation, it still has the distinction of being a resource producer rather than a consumer such as the United States and Japan.

The practicum is primarily concerned with cesium which is classified within the exhaustable resource sector, minerals. A brief explanation about mineral jurisdiction and a general overview of the mineral industry in Canada will provide a background for the study.

1.2 MINERAL JURISDICTION

Under the Canadian Constitution, mineral resources are administered by the federal and provincial governments. Mineral rights vested in the Crown in right of Canada include those in the Yukon and the North West Territories. All Crown mineral lands within provincial boundaries (with the exception of those in Indian Reserves, National Parks, and other lands under federal jurisdiction) are administered by provincial governments. In Quebec, mining rights on federal lands are controlled by the province. Ownership of offshore resources is complex because of international law as well as the continuing debate between the federal and provincial governments about resource jurisdiction. For an in depth analysis of jurisdiction and the mineral industry in Canada refer to MacDonald (1980).

1.3 THE CANADIAN MINERAL INDUSTRY

The mineral industry in Canada is comprised of companies engaged in mineral exploration, mining, smelting, refining, and semi-fabrication. With approximately 280 mines operating in recent years, the mineral industry's economic and social contributions are substantial. Besides direct job creation in the mining sector, opportunities for employment and capital spending are also generated in industries supplying goods and services to the mines, mills, smelters, and refineries (Mining Association of Canada, 1983).

A mineral policy discussion paper presented in 1982 by the Federal Department of Energy, Mines, and Resources Canada as well as the Mining Association of Canada's 1983 publication Mining in Canada: Facts and Figures, highlight the economic importance and the characteristics of the mineral industry in Canada as follows.

Mineral production in Canada is comprised of four sectors: metallics, non-metallics, structural materials, and mineral fuels. All data presented here concerning mineral production and value pertain to the first three sectors only. Mineral fuels (crude petroleum and natural gas) are excluded because of their unique extractive and economic characteristics. Data regarding coal are included in the non-metallics sector because the methods of extracting coal are similar to other non-metallic minerals.

A principal characteristic of the Canadian mineral industry is its dependence on international markets. Canada continues to be the world's largest exporter of minerals with over 80% of production sold to more than 100 countries. However, the demand for Canadian minerals remains mostly attributed to the United States, Japan, and the European Economic Community. Of the crude minerals exported in 1982, 50.9% were sold to the U.S., 12.9% to Japan, 10.3% to the EEC, 5.0% to the U.K., and 20.9% to other nations. Because of very poor international market conditions, the sale of Canada's raw and fabricated mineral production in export

markets totaled $13.3 billion which is a decline of 17.0%
from 1981. Furthermore, the value of mining production de-
clined to $12.2 billion, a fall of 15% from 1981. Overall,
the mineral industry's contribution to Canada's Gross Na-
tional Product declined to 3.5% compared to 4.6% in 1981.

Other important characteristics of the Canadian mineral
industry are: the high risks(exploration, development, and
marketing); high energy and capital intensity; high corpo-
rate concentration; and the regional, frontier, and northern
development (job creation and infrastructure). In addition,
the industry is a major user of Canada's transportation sys-
tems. Crude minerals (44.4%) and fabricated mineral prod-
ucts (9.0%) accounted for over half of all Canadian freight
revenues in 1981. Also, minerals accounted for over half of
all cargoes loaded at Canadian seaports and about half of
Seaway and Great lakes shipping traffic (Dept. of Energy,
Mines, and Resources Canada, 1982).

1.4   FURTHER PROCESSING OF MINERAL RESOURCES
One of the continuing objectives of Canadian public policy
is the further processing of mineral resources. Further
processing provides employment, increases value-added, pro-
motes regional development, and increases tax revenues. In
1974, the Federal Government amended the Export and Import
Permits Act to support upgrading of resources. In addition,
the extent of further processing in Canada is a criterion

used by the Foreign Investment Review Agency (FIRA) in as-
sessing mineral development proposals (Dept. of Energy,
Mines, and Resources Canada, 1982). Most provincial mining
acts require further processing of resources before export,
but contain grounds for waiving the requirement.

Although there are mines acts and policies that require
or encourage further processing of mineral resources, about
half of Canada's nonferrous mine production continues to be
exported in a relatively unprocessed form (Dept. of Energy,
Mines, and Resources Canada, 1982). The reasons for export-
ing unprocessed minerals include: foreign market trade bar-
riers; high energy and capital inputs for metallurgical ex-
traction; and negative environmental effects, especially
from smelters and refineries.

1.5   EMPLOYMENT IN THE CANADIAN MINERAL INDUSTRY

The importance of mining and its effects on the Canadian
economy are evident by the employment opportunities the in-
dustry provides. However, because of a sluggish world econ-
omy in recent years, employment in the mineral industry has
been unstable. In 1982, 117,000 persons were directly em-
ployed in the production of metals, non-metals, and coal,
and also in the operation of quarries, sand-pits, non-fer-
rous smelters, and refineries (Mining Association of Canada,
1983). Because of the recent economic recession, a large
number of mining employees have lost their jobs either tem-

porarily or permanently. As of August 31, 1982, approximately 59,000 mining employees were affected by temporary shutdowns/vacation closures, and about 12,000 employees were affected by permanent layoffs (Canada, 1982).

In Manitoba, whether it be the nickel deposits at Thompson, copper-zinc at Flin Flon, Leaf Rapids and Lynn Lake, or the minor metals at Bernic Lake, thousands of mining employees are affected by mine shutdowns and slowdowns.

1.6   MINOR METALS

Within the metallics sector there is a group of minerals referred to as being less common, minor, or rare. Less common minerals are defined as: (1) minerals that would be recovered from current mining or processing operations if there were sufficient incentives; (2) metals or compounds that are possible coproducts of smelting or refining; and (3) products currently in negligible demand (Toombs and Andrews, 1976). Examples of metallic elements of the less common minerals include antimony, beryllium, mercury, tungsten, and cesium.

Demand for minor metals can be stimulated by new technologies. Research and development projects in the fields of energy, communications, and space transportation continue to introduce new materials. New materials do not only satisfy the demands of the research projects, for when incorporated into market products, they also satisfy the consumer.

Cesium is a minor metal whose unique chemical and physical properties continue to attract the attention of researchers from certain private industries and government agencies. The world's largest known deposits of cesium are mined at Bernic Lake, Manitoba.

1.7   THE BERNIC LAKE MINE

In Manitoba, there is a unique pegmatite deposit located on the north shore of Bernic Lake, 180 kilometers east-northeast of Winnipeg. The geology of the deposit has been studied extensively and continues to be the subject of several theses and technical papers. Reports include a petrological review by Hutchinson (1959), and mineralogical studies by Cerná et al. (1972), Cerný and Simpson (1977, 1978), and Cerný and Harris (1978). The deposit is significant because of the minor metals that are present, namely: tantalum, cesium, rubidium, lithium, gallium, and beryllium; along with several other mineral resources such as feldspathic sand, quartz, and dental spar (Trueman and Burt, 1983). Cesium is found in very high concentrations in the mineral pollucite.

The Bernic Lake mine is operated by the Tantalum Mining Corporation of Canada Limited (Tanco) which is jointly owned by Hudson Bay Mining and Smelting Co., Ltd., 37.5%; Cabot Corporation (Kawecki Berylko Industries Division), 37.5%; and the Manitoba Government, 25%. The Bernic Lake mine is primarily worked for its tantalum deposits which have repre-

sented most of Tanco's revenues. Tanco's sales of pollucite have accounted for less than two percent of the company's revenues (pers. comm., R. Burt, 1983). Although the cesium deposits are large, the economic impact of this commodity to the company is presently not significant because of the small quantities demanded. However, it is important to understand that the minor metals are a resource. Whether the resource is developed today or in the future, it would be advantageous for the resource owners to have current information about the possible applications and economic impacts of the resource.

1.8 PROBLEM STATEMENT

As of December 31, 1982, Tanco suspended operations at the Bernic Lake mine because of the limited demand for its minerals, especially tantalum. Employment of the approximately 105 full-time workers had been terminated because of the shutdown.

From 1969 to 1975, Tanco shipped about 1,400 tonnes of cesium-rich pollucite ore (Tanco Files). Of this total, about 1,200 tonnes were exported to the Soviet Union. Because of the Canadian export ban on cesium to Area Control List countries in 1976, the demand for cesium from the Bernic Lake mine has declined significantly.

Between 1976 and the present, only minor quantities of pollucite ore have been shipped from Bernic Lake. Most of the pollucite has been exported to processors such as Kawecki Berylco Industries Inc. (which owns 37.5% of the Bernic Lake mine) in the U.S., and to various European based companies (Tanco Files).

Other than Canada's pollucite production and export figures, information concerning the world cesium industry (production, processing, and market end-uses) is either not available, or is limited to avoid disclosing company proprietary data.

The Government of Manitoba, Department of Energy and Mines, Mineral Resources Division is interested in an evalu-

ation of the world economic and development potential for
pollucite, and cesium metal and compounds. This evaluation
is to be used primarily as an updated information base to
assist the the Manitoba Government in cesium resource devel-
opment strategies.

1.9 RESEARCH OBJECTIVES

The primary objective of the practicum is to evaluate the potential for Manitoba's cesium-rich mineral deposits. The primary objective is composed of the following sub-objectives:

1. Analyze current supply-demand in the cesium markets, and review the U.S. Bureau of Mines contingency forecasts for cesium;

2. Identify the major processors of pollucite and the major cesium distributors in the world;

3. Identify the different grades of cesium compounds and metals produced and associated prices;

4. Identify the present commercial end-use applications for cesium metal and compounds;

5. Investigate cesium-related research and development projects undertaken by private industry and government agencies;

6. Determine the availability and the effects of cesium substitutes upon the cesium industry;

7. Review toxicological/environmental studies regarding the processing and handling of cesium metal and cesium compounds; and

8. Review and investigate the export control status of cesium imposed by the Government of Canada in 1976.

1.10 METHODS

The basic information and data gathering methodology incorporated into the practicum followed the methods used in similar studies (see Chapter II, "Literature Review"). The methods were designed to investigate the two major concerns of the practicum:

1. a quantitative economic review of the cesium industry; and

2. assembling qualitative research and end-use information concerning present and potential cesium applications.

Quantitative and qualitative information have been obtained from:

1. Primary Sources: producers, processors, end-users (commercial users and researchers), and government agencies by using various communication techniques such as personal interviews, telephone conversations, and written correspondance; and

2. Secondary Sources: scientific and trade journals, patents abstracts, government reports, and consulting reports.

Most of the general information required to address the practicum objectives has been obtained from secondary sources. The areas of study which required more in depth analyses have been analyzed by communicating with primary sources, especially for qualitative information.

All the data generated were collated for interpretation. Data interpretation involved organizing and integrating relevant information and examining for significant relationships. Information addressing the practicum objectives is detailed in Chapter III, "Results and Discussion." Chapter IV, "Summary, Conclusions, and Recommendations," is a summary of the report findings and recommendations for further programs and actions.

1.11   LIMITATIONS

The collection of information was a major component of the practicum. For certain types of information, especially quantitative data, accessing and reporting restrictions were imposed by private companies and government agencies involved with cesium, therefore precluding an econometric analysis. Furthermore, several individuals who contributed proprietary information to the researcher requested that their identities be kept confidential. The names of these persons are not presented but are collectively referred to as "industry sources."

Chapter II

LITERATURE REVIEW

The primary purpose of the literature review was to:

1. present various systems used to classify metals;

2. compile and evaluate the industrial research methods
    used for data collection by the mineral industry and
    relate this information to the minor metals; and

3. outline studies concerned with analyzing minor metals
    from the mining stage to the consumer market.

2.1   <u>METALS</u>: <u>CLASSIFICATION</u> <u>SYSTEMS</u>

There are several systems used within the minerals industry
to classify the commodities that comprise the metals sector.
Five systems are presented with appropriate examples.

The American Institute of Mining, Metallurgical, and Pe-
troleum Engineers (AIME) classifies the metals as follows
(Vogely, 1976).

<u>Ferrous</u> <u>Metals</u>

| Iron Ore | - direct shipping, concentrates, and agglomerates |

| Ferroalloy Ores- ferro-(manganese, chrome, nickel, vanadium) |

<u>Nonferrous</u> <u>Metals</u>   - copper, lead, zinc, tin

Light Metals	- aluminum, magnesium, titanium
Minor Metals	- antimony, beryllium, tungsten, mercury
Precious Metals	- gold, silver, platinum group

The AIME classification system is based upon the specific metal's chemical and physical properties as well as its economic characteristics. Cesium would be considered a minor metal because of its low demand.

The U.S. Bureau of Mines (USBM) classifies the metals sector as follows (Morgan, 1983).

Steel Industry Metals	- raw steel, iron ore, ferroalloys, chromium, manganese, nickel, tungsten, molybdenum
Light Metals	- aluminum, mangnesium, titanium
Major Non-ferrous Metals	- copper, lead, zinc, tin
Precious Metals	- gold, silver, platinum group
Special Property Materials	- antimony, beryllium, cadmium, cesium, gallium, hafnium, rare-earth metals, zircon

The USBM includes cesium in the special properties category because of its special chemical and physical characteristics and its applications.

In the 1983 issue of the noted publication <u>Mining</u> <u>Annual</u> <u>Review</u>, the following metal classification system is used.

<u>Precious</u> <u>Metals</u>   - gold, silver, platinum group

<u>Older</u> <u>Major</u> <u>Metals</u>   - copper, lead, zinc, tin

<u>Light</u> <u>Metals</u>   - aluminum, magnesium, titanium

<u>Steel</u> <u>Industry</u> <u>Metals</u> - iron ore, steel, nickel, manganese, chromite
                        cobalt, tantalum, molybdenum, tungsten

<u>Nuclear</u> <u>Metals</u>   - uranium, <u>cesium</u>, rubidium, beryllium,

<u>Electronic</u> <u>Metals</u>   - mercury, cadmium, selenium

<u>Chemical</u> <u>Metals</u>   - lithium, antimony, bismuth

In this classification system, cesium is placed in the nuclear metals category because some of its applications are in highly advanced power generation systems.

Metals have also been categorized as being either abundant or scarce depending on their abundance in the continental crust (Skinner, 1976). The scarce metals have crustal abundances less than 0.1%, and the abundant metals, greater than 0.1%. Within the scarce metals category, Skinner includes three sub-groups: sulfide deposits, native state, and oxide deposits. Cesium is placed in the oxide deposits group along with chromium, tungsten, tantalum, vanadium, niobium, beryllium, and rubidium. Skinner adds that several oxide-forming scarce metals are found in a rare type of ig-

neous rock called a pegmatite. The Bernic Lake deposit is a pegmatite and contains oxide-forming cesium in the mineral pollucite.

A major contribution to the subject of minor metals was authored by David B. Brooks in 1965. In his book, Supply and Competition in Minor Metals, Brooks presents an economic study of metals which he collectively refers to as being minor metals. He begins by separating the metals into two categories, major and minor, based on volume of annual world production. World production in primary product below 75,000 tons per year is considered minor, and above is major. Brooks defines primary product as the output of the metallurgical reduction and refining stage of production, which may or may not be elemental metal. Iron, copper, lead, zinc, tin, aluminum, zinc, gold, silver, and uranium are examples of major metals.

Brooks lists 33 metals as being minor. He organizes the minor metals into a classification system based on the dominant source material from which they are produced. The criteria used for the classification are:

1. the stage of production at which a minor metal initially becomes a separate product; and
2. the joint product relationship (if any) of the metal at the stage when it becomes a separate product.

By applying the above criteria, Brooks classifies the minor
metals into four major groupings (six classes) as follows:

A. Joint Products at the Metallurgical Reduction and Refining Stage

    1) Byproducts of Major Metals

    2) Byproducts and Coproducts of Minor Metals

B. Joint Products at the Milling Stage

    1) Byproducts of Major Metals

    2) Byproducts and Coproducts of Minor Metals

C. Individually Mined Minor Metals

D. Metals Without Geologic Limitations

Byproducts and coproducts indicate the degree of influence
of the minor metal on the production of the main product
with which it is geologically associated. A metal is a by-
product if a change in its price has little influence on the
output of the main product; it is a coproduct if a change in
its price has a significant influence on the output of asso-
ciated coproducts (Brooks, 1965).

Brooks places cesium within Class B-2: subclass Pegmatite
Deposits. According to Brooks, the supply conditions of
Class B-2 are similar to those of individually mined metals
rather than metallurgical byproducts. One reason being that
Class B-2 output can be adjusted more easily than for metals
recovered during metallurgical processing.

Within the Pegmatite subclass, Brooks further states that the pegmatite vein must have a high metal concentration, must be large, and have a regular shape. The Bernic Lake mine has the above characteristics; having an average cesium oxide (Cs_2O) concentration of 23.3%, is large, and is contained within a thick sheet-like area (Crouse, et al., 1979). Given these conditions, the labor costs associated with the production of pollucite ore at Bernic Lake would be less than the costs associated with lower quality deposits (i.e., require hand sorting).

In the various classification systems presented, cesium is refered to as being a minor metal, a special property metal, a nuclear metal, and a milling byproduct and coproduct of minor metals. It is therefore apparent that cesium is typically produced from a specific type of deposit, has special properties, and is used in small amounts. Subsequently, the economic behaviour of cesium is very different from the major metals and is similar to very few of the other minor metals (e.g., tantalum, lithium, beryllium, and rubidium).

2.2 MINERAL INDUSTRY ANALYSIS

The economic issues that are of fundamental concern within the mineral industry are the economic characteristics of mineral supply and the analysis of mineral market conditions. The mineral conversion process, which is the conver-

sion of minerals as geologic resources into minerals as economic goods is outlined in Figure 1. If the relationship between mineral occurence and market demand is perceived to be favorable, investment activity flows through a number of sequential stages: exploration; development of mineral deposits; mineral processing facilities; and activity to supply market demand. Furthermore, changes in demand, depletion of deposits, and advances in processing technology constantly affect the mineral conversion process.

Ore reserves, mineral markets, and associated costs are uncertain and usually realized in future time periods. Therefore, the economic evaluation of mineral development should consider the expected profitability of the development opportunity and the associated risks (Mackenzie, 1976). An integral component for evaluating the potential of a mineral project is the development of market strategies based on market research.

2.3   MARKETING RESEARCH

Marketing research has been defined in many ways, Cox (1979), Lee (1978). Two definitions of marketing (Sharrard, 1976) that directly apply to the practicum are:

1.   the collection of facts, figures, opinions and judgements, their analysis, evaluation, and interpretation; the identification of alternatives, and the recommendation of courses of action; and
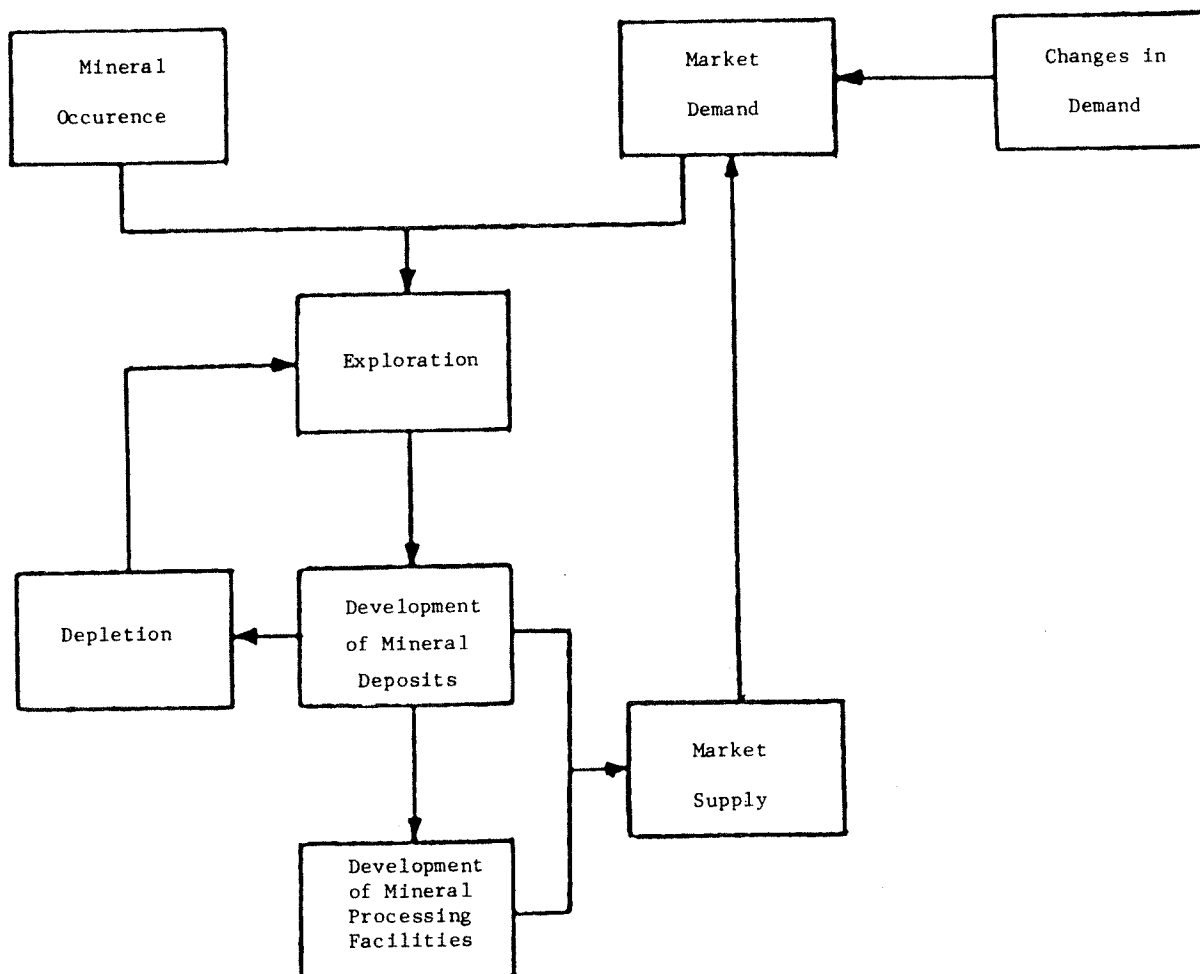
Figure 1: The Mineral Conversion Process
Source: MacKenzie, (1976).

2. the function that determines who uses the product and
    in what quantities, where it will be used and how,
    why one product and not another, and when the need
    will occur.

The above definitions relate to the marketing of industrial
goods and services of which the mineral industry is primari-
ly concerned with. Sharrard, (1976) adds that industrial
marketing research must consider several factors which di-
rectly affect the mineral industry. These factors are: size
of company, capital intensity, mine location, resource de-
pletion, international competition, secondary metal (scrap),
stockpiles, taxation policy, speculators, sensitivity to ec-
onomic conditions, technology, and sociological and politi-
cal events.

2.4   MINOR METALS MARKET RESEARCH
Market information and commodity research reports about spe-
cific minor metals are very few in number and are of a gen-
eral nature. Reports about cesium have been published by
government departments, various mining and technical jour-
nals, and consultants.

2.4.1   Government Information
The Department of the Interior, U.S. Bureau of Mines (USBM),
publishes several reports annually on mineral commodities
which include most of the minor metals. These publications

are excellent sources of general information and include quantitative data. For example, a recent USBM report on cesium, (Bascle, 1980), is presented using the following organizational format: reserves-resources, industry structure, uses, supply-demand relationships, technology, adequacy of supply, byproducts and coproducts, and outlook. Also, certain statistical information is available from the U.S. Department of Commerce, Bureau of the Census, such as U.S. export and import data regarding cesium. A standard industrial classification (SIC) exists for cesium in each of the following categories with the appropriate code numbers:

1. Ore and Concentrate (601.66) - a general category which includes cesium;

2. Cesium, Potassium, Sodium (4151000) - cesium in its purest form;

3. Cesium Chloride (4185000) - cesium chloride compounds; and

4. Other Cesium Compounds (4185200) - other cesium compounds not specifically provided for (NSPF).

Although the U.S. Government collects a wide range of information about companies involved in the cesium industry, certain types of data such as U.S. industry stocks of cesium are withheld for proprietary reasons. Likewise, production figures for pollucite, cesium metal, and compounds from most of the other relevant countries are also not available.

The USBM also forecasts U.S. mineral demand for some 88 mineral resources by end-use categories to the year 2000. The forecasting system consists of two components: (1) statistical analysis; and (2) contingency analysis. The statistical analyses (projections) are based on a standard least-squares procedure or regression analysis method. The contingency analyses (forecasts) are qualitative, based on the commodity specialists' knowledge and judgement. The demand projections and forecasts by end-use are published in the USBM Mineral Commodity Profiles (see Harris, 1979), and Mineral Facts and Problems (see Bascle, 1980) series'. These publications present an overview of current and probable future supply-demand relationships for individual mineral industries (Mo and Klein, 1980).

For each mineral commodity, including cesium, the USBM canvasses the relevant U.S. companies about their mineral usages for the commodity in question. Generally, the canvass coverage for each commodity is at least 70% and usually 80-95% (pers. comm, B. Klein, 1983). Because there are very few companies in the U.S. involved in the cesium industry, Klein considers the canvass average for cesium to be high.

In the 1980 edition of Mineral Facts and Problems, published every 5 years, the statistical projections are based on the 3 major consumption categories: chemical; electrical; and other. In each of the three categories, the USBM statistical demand projections are based on four macroeconomic independent variables. These variables are:

1. U.S. Gross National Product;

2. U.S. Population;

3. U.S. Gross Private Domestic Investment; and

4. U.S. New Construction Activity.

In addition to the above variables, each category has a sub-
set based on three Federal Reserve Board indexes of indus-
trial production as follows:

Chemical
- Chemicals and products
- Basic chemicals
- Synthetic materials

Electrical
- Electronic components
- Instruments
- Equipment, instruments and parts

Other
- Fabricated metal products
- Nonelectrical machinery
- Transportation equipment
- Instruments

Source: (pers. comm., B. Klein, 1983)

After inputting the values associated with each variable,
the statistical analysis program generates a pure mathemati-
cal projection.

Contingency factors are also considered and evaluated by
the cesium commodity specialist. Therefore, the pure mathe-
matical analysis plus contingency factor evaluation gener-
ates the final demand projection to the year 2000. Data for
the next cesium forecast is being compiled in 1984 and will
be published in the 1985 issue of Mineral Facts and Problems
(pers. comm., B. Klein, 1983).

In Canada, the Federal Department of Energy, Mines and Resources (EMR) includes a section on cesium in their annual publication Canadian Minerals Yearbook. The information presented on cesium is mostly qualitative and similar to the USBM reports. EMR also communicates with Tanco regularly regarding exploration activities, production figures, and infrastructure expansions (Tanco Files).

Statistics Canada does not have a SIC for pollucite, cesium metal, or cesium compounds. Therefore, Canadian export-import data about cesium are not directly available.

2.4.2   Non-Government Information

Apart from government publications, very few books and journal articles have been devoted exclusively to industry analysis-type information of specific minor metals. Burrows (1969) authored a book concerning an economic analysis of the tungsten industry and in 1971 about the cobalt industry. Brooks (1965), referred to earlier, presented an economic analysis of the minor metals as a group.

Brooks' sources of information for production, consumption, and trade statistics are primarily based on USBM reports, trade journals, and private correspondance with industry representatives which he considers to be the most valuable (pers. comm., D. Brooks, 1983). However, Brooks (1965, p. 128) also states that deficiencies in the information are great:

"In addition to absence of relevant data and
inconsistency from metal to metal in the data that
are available, there are the problems of incom-
plete reporting and the withholding of data from
publications because of the small number of pro-
ducers."

2.4.3   Consulting Reports

Besides government publications and journal articles, other

secondary sources of information exist in the form of con-

sulting reports.   In 1972 a report was prepared under con-

tract to the Manitoba Development Corporation by S.J.T. Con-

sultants Limited (Townsend, 1972) regarding cesium and its

possible application in a particular power generation sys-

tem.

In 1975, Roskill Information Services Ltd. (Roskill,

1975), published The Economics of Caesium and Rubidium, for

public distribution.   This first edition report was followed

by a statistical supplement in 1978 (Roskill Supplement,

1978).   The Roskill (1975) report is organized into the fol-

lowing headings:

1. Occurence of caesium and rubidium

2. Recovery, extraction, and preparation

3. Production and consumption data in main countries

4. End-uses

5. International trade

6. Prices

7. Tariffs

The report is useful because it presents information succinctly and also provides the names and addresses of companies which process/distribute cesium and rubidium metals and compounds. The Roskill Supplement (1978) presents international economic data using information from USBM and trade journal reports. Although most of the information gathered is proprietary, more references would have been useful.

2.5 SUBSTITUTION

An economic analysis that examines supply-demand relationships of a particular commodity without also including the concept and effects of substitution would be limited in scope and usefulness. Therefore, most of the published literature about cesium as well as other metals include brief discussions about substitution.

Simply defined, substitution is the preference for one material over an other (Toombs and Andrews, 1976). Two important factors that directly influence substitution are the interplay of technology and price. Toombs and Andrews do not consider price to be the only reason for an end-user to change to another mineral material. Technical suitability, quality, durability, and re-equiping costs must also be taken into consideration.

Brooks (1965) states that the reason why minor metals lack stable markets include: (1) the nearly total dependence

of certain minor metals on a single use; and (2) the devel-
opment of a more efficient substitute. In regards to cesium
substitution, there are other elements which exhibit proper-
ties similar to cesium's; for example, potassium and rubidi-
um can replace cesium in many uses (Rathjen, 1983).

2.6   SUMMARY

After reviewing the related literature, it became evident
that very few economic studies of the minor metals are pub-
lically available. Economic data specifically about cesium
are reported in government publications, however, these doc-
uments are of a general nature.

From the few studies that are available, most of the
quantitative data have been retrieved from USBM reports and
the U.S. Bureau of the Census. Additional sources of infor-
mation, both quantitative and qualitative, are available
from journal articles, consulting reports, and by private
communications with government and industry representatives.

Chapter III

RESULTS AND DISCUSSION

3.1 PREAMBLE

In reviewing the published literature, two spellings of the key word have been encountered, _cesium_ and _caesium_. To maintain consistency, the key word in this chapter is written as _cesium_. When conducting computer searches, reviewing abstracts, indexes, etc., the researcher has benefited by referring to both spellings.

Most weights in the practicum are presented using the Metric System. Because most of the raw data are not in the Metric System, standard numerical factors have been used to convert from other systems into the Metric System.

Note: Canadian EMR publications report quantitative data in metric units. The USBM reports cesium mineral data in short tons or pounds cesium content. Also, depending on resource-reserve definitions, the data changes with changing definitions (USBM: Geological Survey Circular 831, 1980). Calculation methods for converting U.S. data into metric units have been reviewed and are acceptable to the USBM cesium commodity specialist (pers. comm., T. Adams, 1984).

3.2   CESIUM

The element cesium, symbol Cs, is an alkali metal belonging to Group IA of the Periodic Table (Hampel, 1973). The element was discovered spectroscopically by Bunsen and Kirchhoff in 1860 while examining mineral concentrates from the Durkheim springs (CRC Handbook, 1983). It was not until 1881 that cesium was actually isolated (Setterberg, 1882). The name cesium, after the Latin caesius for sky-blue, refers to the element's characteristic blue spectral lines (Williams, 1979). The other alkali metal elements that comprise Group IA are lithium, sodium, potassium, rubidium, and francium.

3.2.1   Properties of the Alkali Metals

The term, metal, is applied to any substance which has a silvery luster, and good conductivity of electricity and heat. Some metals, of which the alkali metals are examples, are also relatively soft, malleable, and ductile (Sienko and Plane, 1964). Selected properties of alkali atoms are shown in Table 1.

The alkali metals are grouped together because they all have one electron in their outermost energy level. The outermost electrons, referred to as valence electrons, are important because they are primarily responsible for chemical behaviour. The energy required to remove the valence electron from a neutral gaseous atom is the first ionization po-

TABLE 1

Properties of Alkali Atoms

Element	Atomic Number	Electronic Configuration	Ionization potential, eV		Ionic radius A.(M+)
			First	Second	
Lithium	3	2,1	5.39	75.6	0.68
Sodium	11	2,8,1	5.14	47.3	0.98
Potassium	19	2,8,8,1	4.34	31.8	1.33
Rubidium	37	2,8,18,8,1	4.18	27.4	1.48
Cesium	55	2,8,18,18,8,1	3.89	23.4	1.67
Francium	87	2,8,18,32,18,8,1	--	--	(1.75)

Source: Sienko and Plane, (1964).

tential. Group IA ionization potential values are relatively small therefore the valence electrons are easily lost. However, the second ionization level, the energy required to remove a second electron, is many times higher than the first because the closed shells of the electrons are difficult to break. Ionization values for francium are not listed because the element is virtually non-existant. Francium has an unstable nucleus and is radioactive, however trace amounts have been prepared by nuclear reactions (Sienko and Plane, 1964). With only one mobile electron per atom, the metallic bonds are weak. Furthermore, the bonds become weaker with increasing atomic number because the valence electrons become more distant from the nucleus.

The alkali metals are the most reactive and the strongest reducing agents known. These metals never occur naturally in the metallic state but in combination with oxygen, chlorine, or other elements, and always in the +1 oxidation state. Water attacks all of the alkali metals and the reactions are violent and exothermic (heat releasing). Alkali metals also have the interesting property of being soluble in liquid ammonia, forming intensely blue solutions that leave behind the original metal when the ammonia is evaporated (Dickerson, et al., 1974).

Of the five naturally occuring alkali metals, cesium has the highest vapor pressure, highest density, lowest boiling point, and the lowest ionization potential (its valence electron can be ejected the easiest by light). Cesium is one of three metals (along with mercury and gallium) that is liquid at room temperature (CRC Handbook, 1983). The significance of cesium's unique chemical and physical properties will become apparent when end-use applications are discussed (see section 3.9.1). Selected physical properties of cesium are presented in Table 2.

TABLE 2

Properties of Cesium

Property	Value
atomic number	55
atomic weight (^{12}C = 12.000)	132.905
melting point, °C	28.64 ± 0.17
boiling point,°C	670
density, g/mL	
solid, 18°C	1.892
liquid, 40°C	1.827
viscosity at mp, mPa·s(=cP)	0.686
surface tension at mp, mN/m(=dyn/cm)	39.4
vapor pressure, kPa [a]	
solid, from -23°C to mp	$\log_{10}P = -4120/T + 11.321 - 1.0 \log_{10}T$
liquid, from mp to 377°C	$\log_{10}P = -4042/T + 12.051 - 1.4 \log_{10}T$
heat of fusion, J/g [b]	16.372
entropy of fusion, J/(mol·K)	7.217
heat of vaporization, J/g [b]	611
specific heat, J/(g·K) [b]	
solid, 20°C	0.217
liquid, bp	0.239
vapor, bp	0.156
thermal conductivity, W/(m·K)	
liquid, mp	18.4
vapor, bp	0.0046
ionization potential, eV	3.893
conductivity, solid (mp),S/cm [c]	4.50×10^4
specific magnetic susceptibility	0.22×10^6
neutron absorption cross section, m^2	
thermal	$(29.0 ± 1.0) \times 10^{-28}$
fast	$(15 ± 0.2) \times 10^{-31}$
thermal neutron scattering cross section,m^2	$(20.0 ± 1.0) \times 10^{-28}$

[a]. To convert kPa to mm Hg, multiply by 7.5.
[b]. To convert J to cal, divide by 4.184.
[c]. S/cm = (ohm·cm)$^{-1}$.

Source: Williams, (1979).

3.2.2 Cesium Concentrations

Cesium is the rarest of the naturally occuring alkali metals and is widely distributed in the earth's crust at very low concentrations. In terms of elemental prevalence, cesium ranks fortieth (Hill,1970). Granites contain an average of about 1 ppm (Horstman, 1957), sedimentary rocks about 4 ppm (Smales and Salmon, 1955), and sea water contains about 0.2 ppm cesium (Greenwood, 1960).

Higher concentrations of cesium, as cesium oxide (Cs_2O), are found in: lepidolite, a lithium mica (0.08 - 0.72 wt. % Cs_2O); in carnallite, a double salt of potassium and magnesium chloride (0.001 - 0.004 wt.% Cs_2O); and also in beryl, rhodonite, leucite, spodumene, petalite, potash feldspars, and related minerals (Williams, 1979). However, the most important commercial source of cesium is the rare mineral, pollucite.

3.3 POLLUCITE SUPPLY

Pollucite, a cesium aluminum silicate, $Cs_2O.Al_2O_3.4SiO_2$, was first discovered in 1846, in a pegmatite, on the Isle of Elba (Williams, 1979). Pollucite is waterclear to milky or greyish in appearance with uneven fracture and is similar to quartz (Černý, 1982). The best means of recognition in the field are the veinlets of alteration products, and a qualitative chemical test for cesium which produces a bright red reaction stain (see Mulligan (1961) for reagent prescrip-

tion). For a detailed analysis of pollucite crystal chemistry, structure, physical properties, alteration, and stability relations, refer to Černý (1982).

Pollucite is usually found in complex, well-zoned, granitic pegmatite dykes associated with lepidolite, petalite, and other lithium minerals (Hogan, 1981). The cesium content of theoretically pure pollucite is 45 wt.% Cs_2O; but naturally occuring pollucite contains from 5 to 32 wt.% Cs_2O because of the other minerals intimately associated with the pollucite (Williams, 1979).

3.3.1 Geological Characteristics

Pollucite deposits are characterized by extremely similar geological conditions of occurence and features of mineral composition. Selected features of pollucite deposits are as follows:

1. pollucite occurs in pegmatites of all ages (from early Proterozoic to Tertiary), but the largest reserves are of Proterozoic age;

2. the mode of pollucite occurence is interpreted in two different ways: (a) late metasomatic origin, and (b) as a primary constituent of the central parts of pegmatite bodies (Černý, 1982);

3. pollucite is restricted to the complex rare-element pegmatites which reached the ultimate degree of rare-alkali fractionation. These pegmatites are lithium-

rich with very low potassium (K)/rubidium (Rb) ratios
(5 to 20) in their blocky K-feldspars (Černý, 1982);
and

4. pollucite is frequently located in low-pressure, pe-
talite-bearing pegmatites (Černý and Ferguson, 1972).
In pegmatite fields with spodumene, it is also found
in bodies which are located in the relatively lowest
pressure sites (Melentyev, 1977).

3.3.2   Geographic Locations

Several pollucite occurences have been identified in numer-
ous countries. However, the largest known reserves of pol-
lucite are at Bernic Lake, Manitoba, the Bikita district of
Zimbabwe, and in the Karibib area in Namibia (Harris, 1979),
(Hogan, 1981).

The following list (Figure 2) is a compilation of known
pollucite occurences worldwide. The list was prepared with
the help of Dr. P. Černý, in the Department of Earth Sci-
ences at the University of Manitoba, a world authority on
pollucite and its crystal chemistry. Dr. Černý cautions
that very few of the pollucite deposits are described in de-
tail (exact locations, size of deposit, and grade) in the
literature, especially in the Soviet Union, East Block and
Asian Countries (pers. comm., Černý, 1983-84).

Canada

Manitoba:	Bernic Lake*, Rush Lake, Maskwa Lake, Red Cross Lake
Ontario:	Tot Lake, Lilypad Lakes
Quebec:	Lacorne Township

United States

Maine:	Greenwood, Hebron, Newry, Rumford, Buckfield
Massachusetts:	Leominster, Lithia
South Dakota:	Black Hills (Tin Mountain*)
Colorado:	Gunnison County
California:	Himalaya pegmatite district

Europe

Finland:	Viitaniemi, Luolamäki
Sweden:	Varuträsk*
Italy:	Isle of Elba
Czeckoslovakia:	Český Krumlov, Puklice, Rožná, Nová Ves at

Japan

Nagatare, Fukuoka

Africa

Zimbabwe:	Bikita*, Benson district
Namibia:	Karibib*, Helicon
Mozambique:	Alto Ligonha region

India

Several possible areas such as Bihar and Mysore States where lithium pegmatites are located.

U.S.S.R.

Kalbin Range, Sayan Mts., Kola Peninsula

Afganistan

Hindu Kush*

Other Possible Sites

Brazil, Portugal, China (Mongolian Altai)

* MAJOR DEPOSITS

Figure 2: World Pollucite Occurrences

3.3.3 Production and Export Data of Selected Countries

Between 1881, when cesium was first isolated, and the mid 1920's, cesium had almost no industrial applications. However, circa 1926, cesium came into use in electrical vacuum tube technology (Barton, 1960). Because of the anticipated increased commercial demand for cesium, interest in mining pollucite probably increased. In addition, pollucite may be associated with other economically important elements found in pegmatites, especially lithium, beryllium, tin, and tantalum. Therefore, pollucite may have acquired a byproduct or coproduct status. The following subsections are a review of pollucite production and export data of relevant countries.

3.3.3.1 United States

The mining of pollucite in the U.S. first occured in Oxford County, Maine, from 1926 to 1929, but only small domestic supplies of cesium raw materials were available (Barton, 1960). Subsequently, pollucite was also imported from Namibia (Roskill, 1975). A second important U.S. pollucite deposit was discovered in 1959, at the Tin Mountain mine in the Black Hills of South Dakota near Custer. Production from the Tin Mountain mine was approximately 45 metric tonnes (t) of pollucite (Roskill, 1975). Bascle, (1980) reported that resources of pollucite may still exist from these two mines. Currently, however, all cesium raw material requirements are imported.

3.3.3.2   African Countries

There are several pegmatite occurences in Africa. However, the most important pollucite containing pegmatites are in Zimbabwe and Namibia, and to a lesser extent in Mozambique and possibly South Africa. Barton (1960) reported that most of the pollucite production in Africa is a byproduct of lithium ores. He also stated that pollucite shipments vary erratically from year to year as importers and consumers adjust inventories. African pollucite data such as reserves, production, grades, exports, etc., are severely lacking or restricted. Therefore, the following pollucite data presented on each African country should be considered as indications of production only.

Mozambique

The pegmatite areas in Mozambique contain minerals such as tantalite, beryl, lepidolite, as well as pollucite. Roskill (1975) reported that numerous mining companies have interests in these areas, but only a few of the companies have been carrying out significant mining activities. Roskill (1975) added; in 1971 it was reported that one of the major companies in the area, Sociedade Mineira de Marropino Lda, produced about 90 t of pollucite. Furthermore, this was said to be the same level of production as in 1970, and about 45 t were exported to The Netherlands. The USBM reported 1971 production to be 100 t and estimated 100 t for

1972 (USBM: CDS[1], 1973). Prior to 1973, the USBM:CDS did
not have Mozambique listed, and subsequent to 1973, produc-
tion and reserves of pollucite have not been available.

South Africa

From the literature reviewed, there were no cited references
of any pollucite occurrences, reserves, or production in
South Africa. However, Roskill (1975) stated; the U.S. Bu-
reau of Mines reported that several tonnes of pollucite have
been recovered in South Africa as a byproduct of beryl min-
ing.

Namibia (South-West Africa)

The pegmatites containing lepidolite and petalite in the
Karibib district of Namibia are also important sources of
pollucite (Bascle, 1980). Hogan (1979) reported that Nami-
bian pollucite reserves are about 45,000 t, and Rathjen
(1983) estimated the reserve base to be 10,000 short tons of
contained cesium (about 40,000 t pollucite, 24% Cs_2O). The
Roskill (1975) report presented Namibian pollucite produc-
tion information (Table 3), however, no citations were list-
ed.

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[1] The USBM annual publication, Commodity Data Summaries
(CDS), was renamed Mineral Commodity Summaries (MCS) in
1979.

TABLE 3

Unofficial Namibian Pollucite Production Data

Year(s)	tonnes	Comments
1946-50	90	—
1951	17	26.3% Cs_2O
1952-53	unknown	reported to be major supplier to U.S.
1954-55	unknown	—
1956	67	10 t to U.S., 1 t to U.K.
1957	no production	10 t from stocks to W. Germany
1960	—	80 kg to U.K.
1961	resumed prod. to 2	—
1962	less than 1	to U.S.

Source: Adapted from Roskill, (1975).

The pollucite deposits in Namibia are thought to be of a similar nature to those of Bikita and Bernic Lake (pers. comm., P. Černý, 1983).

Zimbabwe (Southern Rhodesia)

Next to Bernic Lake, the pegmatite deposit in the Bikita district of Zimbabwe is one of the largest in the world and represents about 25% of the world's reserves of pollucite (Hogan, 1981). The pegmatite is primarily worked for its vast reserves of lithium which are mostly in the form of lepidolite and petalite (Wegener, 1981). Until the early 1970's Bikita was probably the most important source of cesium, partly from pollucite, but more importantly as a byproduct of lithium production from lepidolite (Roskill, 1975).

The Bikita pegmatite, located east of Fort Victoria, has been explored over a strike of 1,600 meters and consists of an irregular sheet striking northeast and dipping 30 ± 15° eastwards, and is from 30-60 meters thick (Wegener, 1981). The pegmatite is suited for open-cast mining by normal quarry methods because it lies at shallow depth and also outcrops. The open pit mine is operated by Bikita Minerals (Private) Ltd. of Zimbabwe which in turn is principally owned by Selection Trust Ltd. (Clark, 1982).

The petalite-lepidolite ore is extracted from the quarry and is processed at Bikita's processing facility nearby, where the ore is crushed and hand sorted into the various constituents (Clarke, 1982). The pollucite composition is shown in Table 4.

TABLE 4

Pollucite Composition at Bikita

Chemical Analysis	Theoretical	Typical	Guaranteed
Cs_2O	42.5%	25.0%	24.0% min.
Al_2O_3	15.4		
SiO_2	40.8		
H_2O	1.3		
Physical analysis:	Currently a 12 mm crusher product, but in the future, particle size (97% minus) 75 and 300 microns.		

Source: Adapted from Wegener, (1981).

Pollucite production in Zimbabwe is presented in Table 5.

TABLE 5

Reported Pollucite Production and Value for the UDI[1] Years,
(1966-1980)

Year	Production (t)	Value[2]
1966	--	--
1967	38	5,530
1968	--	--
1969	--	--
1970	38	6,720
1971	18	3,373
1972	61	10,755
1973	56	8,960
1974	--	--
1975	81	14,580
1976	281	50,474
1977	--	--
1978	--	--
1979	129	28,270
1980	--	--
Total	702	128,662

[1] UDI -   Unilateral Declaration of Independence

[2] Value - declared value in Zimbabwean dollars (assumed
to be F.O.B. source)

Source: After Clark (1982) from official statistics of
the Ministry of Mines, Zimbabwe.

Using Table 5 as a guide, Table 6 has been prepared so an estimate of U.S. dollar value per unit of pollucite may be presented. The following assumptions and procedures were used:

1. average pollucite grade - 24% Cs_2O; and

2. U.S. average annual exchange rates were compiled from International Financial Statistics (IMF) for the years 1976-81. For the years 1971, 1973, and 1975 Strack (1978) was used for reference. Exchange rates for remaining years were not available.

Also, the metric tonne unit (MTU)[2] designation is a standard way of expressing the weight of contained cesium oxide (Cs_2O) concentrate. The percent-price increases between the 1971 and 1979 figures were about 24% for both $US/t and $US/MTU.

Zimbabwean mineral exports have been very erratic because of its history of political instability. From 1967 to 1980 the U.S. as well as most other U.N. countries extended a program of economic sanctions against Southern Rhodesia to prohibit all imports from that country (Strack, 1978). Therefore, it is unlikely that U.N. member countries imported pollucite from Southern Rhodesia. After the lifting of sanctions, the marketing of Bikita's minerals simplified considerably, resulting in Bikita increasing its production schedules in an attempt to regain its position as a major producer (USBM: Other Metals, 1981).

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[2] A MTU is 1% of a metric tonne (10 kg or 22.046 lb) of pollucite concentrate (Cs_2O), e.g., 10 t Cs_2O = 1000 MTU.

TABLE 6

Reported Zimbabwe Pollucite Production and Estimated U.S.
Equivalent Dollar Values for Specific Years

Year	Pollucite Production(t)	$Z/t	$US/t	Cs_2O content(t)	$US/kg Cs_2O	$US/MTU
1971	18	187.39	262.34	4.3	1.09	10.93
1973	56	160.	283.20	13.4	1.18	11.84
1975	81	180.	288.	19.4	1.20	12.02
1976	281	177.62	290.16	67.4	1.21	12.10
1979	129	219.15	325.04	30.9	1.36	13.57

Since independence on April 18, 1980, the Republic of
Zimbabwe government has been making changes to its mineral
industry. The government seems intent on establishing a
state-controlled organization for the marketing of minerals
(Clarke, 1982). What affect such a government policy might
have on the marketing of pollucite is unclear and data re-
garding recent pollucite production in Zimbabwe is not
available. Nevertheless, industry and government sources
suggest that pollucite production is probably insignificant
because of low demand and domestic labour problems.

3.3.3.3   U.S.S.R.

Pegmatite deposits containing pollucite are known to exist
in the Soviet Union (Roskill, 1975), (pers. comm., P. Černý,
1983). Information such as deposit location, size, grade,
etc., is not published in the scientific literature. The
Roskill (1975) report suggested; because the Soviet Union

had been a major pollucite importer, especially from Bernic Lake, the Soviets wanted to delay exploiting their own resources.

3.3.3.4   Sweden

In 1938, a deposit of pollucite was discovered at Varuträsk, Sweden (Roskill, 1975). Neither the USBM nor the Canadian Department of EMR have reported of any pollucite production in Sweden. The Roskill (1975) report stated that the pollucite from Varuträsk is separated with great difficulty and therefore commercial production has rarely been done. The present status of the mine is not known.

3.3.3.5   Canada: Bernic Lake, Manitoba

Although pollucite has been identified in several Canadian locations, the most important deposit is at Bernic Lake, Manitoba. The world's largest known reserves of pollucite are at Bernic Lake and represent about 66% (350,000 t) of world reserves (Hogan, 1981), (Crouse, et al., 1979). The geology and minerology of this pegmatite deposit has been studied extensively and continues to attract the attention of geochemists from all over the world (refer to section 1.7 for references which detail its geology, minerology, crystal chemistry, etc.). The pegmatite at Bernic Lake is commonly referred to as the "Tanco pegmatite," named after the mine operating company, Tantalum Mining Corporation of Canada Limited.

Geology of the Tanco Pegmatite

The Tanco pegmatite is roughly triangular in shape, flat-lying, and has a south-pointing apex. The maximum dimensions of the pegmatite are greater than 2.2 kilometers in length from east to west, 1.4 kilometers from north to south, and its maximum thickness is about 100 meters (Trueman and Burt, 1983). From a large-scale, descriptive perspective, the pegmatite consists of nine internal zones of different mineral composition, texture, and location (Crouse, et al., 1979). Table 7 lists the major mineral reserves.

TABLE 7

Major Mineral Reserves at Bernic Lake

	Tonnes	Grade	
Tantalum	1,878,721	0.216%	Ta_2O_5
Lithium	6,622,673	2.79%	Li_2O
Cesium	350,000	23.3%	Cs_2O
Beryllium	834,440	0.20%	BeO
Lepidolite	97,684	2.24%	Li_2O
Quartz	708,186	---	

Source: Adapted from Crouse, et al., (1979).

The pollucite zone consists of three gently dipping sheet-like bodies, the largest of which ranges up to 14 m in

thickness. As of December 31, 1978, Tanco's pollucite reserves were comprised of 270,000 t averaging almost 23.9% Cs_2O in the main zone, 47,000 t averaging almost 23.9% in one westerly zone, and 55,000 t of lower grade pollucite in the second westerly zone for a total of 372,000 t. zone. These reserves estimates do not include allowances for dilution or pillars (Hogan, 1981). Furthermore, Hogan (1981) reported that exploration and drilling programs have indicated the presence of more pollucite. The discrepancy in the amount of pollucite reserves at Bernic Lake signify that the pollucite deposit has not been fully delineated.

A chemical analysis of a typical sample of pollucite ore from Bernic Lake was conducted by Parsons et al. (1963) and the results are shown in Table 8.

TABLE 8

Analysis of Bernic Lake Pollucite Ore Sample

Cs	Rb	Al	SiO_2	Li	Na	K
26.6%	1.5	8.87	48.7	0.16	1.01	0.83

Source: Parsons et al., (1963).

Tanco company records indicate the following analysis (Table 9).

TABLE 9

Typical Analysis of Tanco Pollucite in Terms of Oxides for
Analytical Assay Purposes

Cesium Oxide	(Cs_2O)	27.20%
Rubidium Oxide	(Rb_2O)	1.13
Lithium Oxide	(Li_2O)	0.36
Potassium Oxide	(K_2O)	1.14
Sodium Oxide	(Na_2O)	1.67
Calcium Oxide	(CaO)	0.10
Magnesium Oxide	(MgO)	0.01
Ferric Oxide	(Fe_2O_3)	0.10
Aluminium Oxide	(Al_2O_3)	17.40
Phosphorous Pentoxide	(P_2O_5)	0.38
Silica	(S_1O_2)	48.60
		98.09

Source: Courtesy of Tantalum Mining Corporation.

Pollucite Mining and Milling Operations

The mining method at the Tanco mine is room and pillar with the rooms being 4.5 meters square. The pillars left behind are spaced to allow a maximum extraction of ore (Crouse, et al., 1979). Both hydraulic and pneumatic jumbo drills are used to selectively mine the pollucite from the deposit. The broken pollucite ore is then hauled to the surface and crushed in a jaw crusher. The ore is screened and sized, usually between 1/2" to 1/4" (Tanco Files). Because the pollucite has a very high cesium oxide concentration (about

24% Cs_2O), further upgrading is not necessary. Before ship-ment, the ore is dried to produce a free-flowing product. The prepared ore is then loaded for transport either in 20 t containers or packed into steel drums which hold about 300 kg of pollucite concentrate each (Tanco Files).

Bernic Lake Pollucite Production

Pollucite was first discovered and mined at Bernic Lake be-tween 1956 and 1961 as a result of drilling programs in the pegmatite by Chemalloy Minerals Ltd. (Howe and Rowntree, 1967). Information about pollucite sales from Bernic Lake for the period 1960-1965 has been limited to reports pub-lished in various issues of The Northern Miner (1961), (1965). The information presented in these reports is very general but collectively suggest that about 95 t of pollu-cite were sold from 1960-1965, mostly to U.S. chemical firms and to the U.S. space program. The pollucite for these sales was mostly from stockpiles at the surface be-cause the mine was allowed to flood in 1962 and remained flooded until March of 1967 when Tanco was formed. Full-scale mining operations were achieved in September, 1969. Information about Tanco pollucite shipments from 1969 to 1983 (Table 10) were adapted from Tanco company records.

TABLE 10

Tanco Pollucite Shipments[1], (1969-1983)

Year	Pollucite Shipped (t)	Grade (%Cs$_2$0)	Cs$_2$0 Content (t)	Destination
1969	51	30.9	15.7	U.S.S.R
1970	150	22.6	33.9	U.S.S.R.
1971	251	32.1	80.5	U.S.S.R.
	2	28.6	0.5	U.S.A.
	36	27.1	9.7	W. Germany
1972*	24	25.0	6.0	U.S.A.
	52	26.2	13.6	England
1973	101	27.1	27.3	U.S.S.R.
	1	28.1	0.3	Japan
	155	28.0	43.4	U.S.S.R.
1974	254	28.3	71.8	U.S.S.R.
1975	251	26.9	67.5	U.S.S.R.
	18	27.4	4.9	U.S.A.
	18	27.0	4.8	U.S.A.
	50	17.0	8.5	U.S.A.
	1	26.8	0.2	Japan
1976	EXPORT PERMIT DENIED (intended for U.S.S.R.)			
1977	0	--	--	--
1978	254	27.2	69.0	U.S.A.
1979	53	25.0	13.2	W. Germany
1980	0	--	--	--
1981	300	24.0	72.0	W. Germany
1982	0	--	--	--
1983	200	24.0	48.0	W. Germany

*1972 shipment to U.S. was for storage and is distributed for research purposes on demand.

Source: Courtesy of Tantalum Mining Corporation.

[1] All weights and grades are approximate and shipments are F.O.B. Bernic Lake.

From 1969 to 1983 there were about 2,222 t of pollucite shipped from Bernic Lake and averaged 26.5% Cs_2O. The major importing countries were the U.S.S.R., the U.S., and West Germany.

Because of Tanco's market dominance, and for proprietary reasons, Tanco has withheld from publication the actual trade prices of its pollucite sales. Based on Tanco pollucite sales data made available to the researcher, pollucite trades have occured approximately in the price ranges listed in Table 11 for minimum grade 24% Cs_2O, F.O.B. Bernic Lake.

TABLE 11

Trade Price Ranges for Tanco Pollucite (1970-1983)

Years	$U.S./t pollucite	$U.S./MTU Cs_2O
1970 - 1973	$270 - $380	$11.50 - $13.50
1974 - 1978	$450 - $490	$16.40 - $18.00
1979 - 1983	$595 - $975	$24.50 - $40.00

Source: Courtesy of Tantalum Mining Corporation.

The average annual trade prices for Tanco pollucite increased steadily from 1969 and reached approximately $16.80/MTU in 1975. In 1976, a pollucite shipment was being arranged for the U.S.S.R. but was cancelled because of the export ban (see section 3.13).

Subsequent to 1976, shipments resumed (no U.S.S.R. sales permitted) in 1978 with the greatest demand being from West Germany. In 1979, Tanco pollucite reached a price range high between $30.00 - $40.00/MTU Cs_2O for tonnage quantities. This jump in price represented a substantial increase from the 1978 price. The explanation given for the price inceases was primarily that with limited pollucite sales opportunities, Tanco's objective was and continues to be to maximize returns in terms of price against volume for a non-renewable resource (pers. comm., R. Burt, 1984). Prices dropped in 1981 and again in 1983.

Tanco's sales representive, Natural Resources Trading (NRT) in New York stated that the sale price of pollucite is affected by several variables such as:

1. the request for kilogram lots or tonnage quantities;
2. the basis (F.O.B. or C.I.F.) and specifications such as % moisture and mesh size; and
3. the regularity of purchases by the customer (pers. comm., H. Becker-Fluegel, 1984).

Mr. Becker-Fluegel quoted a pollucite price range of $2.40 - $5.50 U.S./ kg of contained Cs_2O, F.O.B. Bernic Lake.

For the period 1969-1975, the U.S.S.R. accounted for about 86% of Tanco's pollucite sales. Since the export ban, imposed in 1976, West Germany has imported about 68% of Tanco's pollucite sales with the U.S. being the major purchaser of the difference.

Finally, an attempt has been made to compare the production and sales of pollucite from Zimbabwe and Bernic Lake (Table 12). An interpretation of the raw data suggests that for the period 1969-1983, Bernic Lake accounted for about 77% of commercial world pollucite production. In addition, the 1971 pollucite prices were competitive, however, by 1979 the Tanco price was almost three times higher in relation to Zimbabwe's. Another point of interest is that in the first year of the export controls, Zimbabwe pollucite production was very high.

TABLE 12

Comparison Between Reported Zimbabwe Pollucite Production
and Price, and Bernic Lake Pollucite Shipments and Price for
Selected Years.

	Production/Shipments[1] (t)		Price[2] ($US/MTU)	
Year	Zimbabwe	Bernic Lake	Zimbabwe	Bernic Lake
1969	–	51.		
1970	38.	50.		
1971	18.	289.	10.93	10.00 – 11.00
1972	61.	76.		
1973	56.	257.	11.84	13.00 – 14.00
1974	–	254.		
1975	81.	338.	12.02	16.00 – 17.00
1976	281.	Export Controls	12.10	---
1977	–	–		
1978	–	254.		
1979	129.	53.	13.57	30.00 – 40.00
1980	–	–		
1981	NA	300.		
1982	NA	–		
1983	NA	200.		
	---------	----------		
Total	664 or 23%	2222 or 77%		

1. Zimbabwe: reported production after Clark, (1982).

    Bernic Lake: total shipments per year.

2. Zimbabwe: estimated value F.O.B. source

    Bernic Lake: average value per year F.O.B. source.

3.3.4 Summary: Pollucite Supply

There are two major suppliers of pollucite in the world, Tanco at Bernic Lake, Manitoba , and Bikita Pvt. in Zimbabwe. In both of these mining operations, pollucite is an economic byproduct with tantalum being the major ore at Bernic Lake and lithium at Bikita. Therefore, Tanco and Bikita must compete for markets. Between Tanco and Bikita, Tanco is the more significant supplier of pollucite and has market dominance for reasons which include:

1. the pollucite reserves are larger and of equal or higher grade compared to Bikita;

2. the government in Canada is more stable (compared to the newly formed Republic of Zimbabwe), therefore supply is more assured; and

3. trade links with the two principal importers, West Germany and the U.S., are well established.

Regarding adequacy of supply, the USBM reports that the United States will probably depend on the pollucite deposits available in Canada and Africa to meet current and future industrial demand for cesium (Bascle, 1980). Although cesium occurs in several other ores, Bascle (1980) stated that no cesium is recovered from them as a commercial byproduct. Furthermore, he reported that cesium recovery from these sources in the U.S. is unlikely.

3.3.5 Pollucite Enrichment

The major commercial suppliers of pollucite guarantee a minimum cesium oxide concentration of 24%. In the U.S., there are several occurrences of pollucite but some deposits have a low Cs_2O concentration. Therefore, the USBM investigated the possibility of concentrating pollucite. By using a flotation method, an 8% pollucite ore from Maine was upgraded to 20% with a recovery of 87% of the cesium oxide (Dean and Nichols, 1962).

A Tanco research project (unpublished report) also developed a method by which a pollucite ore can be concentrated to produce a marketable grade cesium concentrate. Starting with an ore containing 13.7% Cs_2O, Tanco's method resulted in a concentrate assaying 26.9% Cs_2O with a recovery of 83.8% of the Cs_2O (Tanco Files).

The application of these methods may become necessary when the high-grade ores approach depletion. In addition, major exploration activity for new pollucite reserves is unlikely unless the demand for all forms of cesium increases substantially.

3.4 ALTERNATE RESOURCES OF CESIUM

3.4.1 Natural Sources

Besides pollucite, there are other sources of cesium (see section 3.2.2). Continental evaporitic brines and saline deposits contain cesium in very low concentrations (ppm). The major brine deposits are in Chile (Salar de Atacama), and the U.S. (Utah, Nevada, California), (Buckley, 1983). Buckley (1983) also stated that the New China News Agency reported the discovery of substantial lithium accumulations in salt lakes on the Tibetan Plateau. The News Agency reported significant quantities of sodium, potassium, boron, bromine, rubidium, and cesium in association with the lithium. Data on the size of these deposits have not been made available.

The viability of processing and marketing cesium from saline deposits has not been investigated in the practicum. However, several factors would have to be considered which include:

1. cesium concentration in the brine as well as its purity after recovery;

2. cost of extraction and the demand potential for co-products and byproducts from the brines; and

3. price competitiveness with cesium from pollucite.

Evaporitic brines and saline deposits are significant only in terms of being a potential source of cesium. The researcher has encountered only one chemical company in the

U.S. that had at one time purchased cesium compounds origi-
nating from saline deposits. However, the company's senior
chemist stated they had not made such purchases for over 15
years because the supplier was out of business and also the
final product was not of a satisfactory purity. Potential-
ly, desalinization research and development programs, espe-
cially in Israel, may lead to the marketing of various salts
including cesium.

3.4.2   Byproduct Sources

In the late 1950's an important alternate source of cesium
was marketed in the U.S. by the American Potash and Chemical
Corp. using raw materials obtained from its subsidiary, San
Antonio Chemicals Inc. San Antonio Chemicals produced a
mixed potassium-rubidium-cesium carbonate (ALKARB) from the
waste produced by an associated company, American Lithium
Chemicals Inc. which made lithium hydroxide from lepidolite.
The ALKARB analysis included two percent cesium carbonate
(Barton, 1960).

The importance of ALKARB as a source of cesium has de-
creased considerably because lepidolite, which contains ces-
ium, has been replaced by spodumene ore (lacks cesium) for
the production of lithium. Therefore, lithium residues from
lepodolite are not as plentiful and industry sources report
that cesium extraction from ALKARB is no longer done.

3.5   POLLUCITE DEMAND

Following the mining and milling stages which occur at the mine site, pollucite is shipped to various companies for further processing. It is at the processing stage that separate cesium primary products (cesium compounds and cesium metal) are produced.

Excluding the U.S.S.R., the countries of final destination of major quantities of pollucite shipped from Bernic Lake are West Germany and the United States. The purpose of this section is to present information about the cesium processors/distributors in these countries and their output of cesium products. The U.S.S.R. is excluded because there is no documented information regarding their cesium industry.

3.5.1   United States

Barton (1960) reported that eight firms comprised the cesium processing industry in the U.S. Of these eight companies, only five likely processed from pollucite. The other three companies either processed from lithium residues or recovered cesium in the form of ^{137}Cs. The cesium processors from Barton's list of companies that used pollucite are inferred to be:

1. Dow Chemical Co. .... Michigan;
2. Fairmont Chemical Co. Inc. .... New Jersey;
3. Rocky Mountain Research Inc. .... Colorado;
    (now Great Western Inorganics, Inc.,)
4. Var-Lac-Oid Chemicals Co. .... New York; and
5. Penn Rare Metals .... Pennsylvania
    (now Kawecki Berylko
    Industries Inc. (KBI)

The Roskill (1975) report stated that according to the USBM, four U.S. companies produced cesium and rubidium compounds. However, the report also stated that in the publication Chemical Week, many more cesium suppliers were listed. In addition, most of these suppliers were probably producing small quantities of cesium for research laboratories. The Roskill (1975) report tabulated the names of twenty U.S. companies as being producers of cesium metal/ compounds according to Chemical Week.

The discrepancy between the USBM figures and the total number of U.S. cesium producers listed in the Roskill report probably arose because of the confusion in using the terms 'producer', 'supplier', and 'distributor'. In the practicum, a primary producer actually processes raw materials such as pollucite ore into cesium primary products; a supplier/distributor may either further purify the cesium and/ or distribute cesium primary products to other distributors or end-users. A primary producer can also sell to the end-user directly. Therefore, it is difficult to interpret whether a company is in fact a primary producer.

Primary Producers

A practicum questionnaire was mailed to 36 U.S. companies reported to be processors/suppliers of cesium compounds or metals. Twenty-two of these companies were listed in the 1981-82 OPD Chemical Buyers Directory. Several questions

were asked; however, two specific questions were intended to
classify the companies as being primary producers, suppli-
ers, or both, and the source material used (pollucite or
other), if a primary producer. Of the 36 questionnaires
mailed to U.S. companies, there were 9 responses. Most of
the companies that did respond stated they would only answer
a few of the general questions to avoid disclosing proprie-
tary information. Again, it is difficult to determine the
number of cesium primary producers in the U.S.

Harris (1979) reported that cesium compounds and metal
were produced from imported materials by the following com-
panies in the U.S. in 1978:

1. Callery Chemical Co. .... Pennsylvania;
2. Kawecki Berylco Industries Inc. (KBI) ..... Pennsylvania;
3. Kerr McGee Chemical Corp. .... California; and
4. Great Western Inorganics, Inc. .... Colorado.

Williams (1979) stated that KBI is the only major producer
of cesium compounds in the U.S.

Kawecki Berylco Industries, Inc. (KBI)

KBI is a division of the Cabot Corporation (Boston) which
owns 37.5% of Tantalum Mining Corporation. The KBI process-
ing facility is located in Revere, PA where several minor
metal products including cesium have been processed for the
past 25 years.

Information about the processing infrastructure at KBI
has been obtained indirectly from a health hazard evaluation

report published by the National Institute for Occupational Safety and Health (NIOSH) (Maier and Lucas, 1973). Researchers from NIOSH reported that cesium at KBI is extracted from pollucite ore which is received in truck load lots of about four t. Maier and Lucas (1973, pp.7-8) reported that the pollucite ore is reacted with acid and stated that:

> "Acid reduction is carried out in a one story cinder block building approximately 32' x 42' in seven open, heated and agitated tanks holding 250 - 300 gallons. Six filter crocks are located near the tanks."

Furthermore,:

> "Purified salt production is carried out in a separate room from the raw production area. This room which occupies one end of the building approximately 28' x 32' is essentially a chemistry laboratory. Here are found laboratory benches, ovens, one ventilated laboratory hood and the usual laboratory equipment."

Maier and Lucas (1973, p.5) also stated that:

> "Twenty people including plant personnel are employed at the plant. Only three full time and one part time worker are employed in cesium and rubidium processing."

The last point about the number of plant employees involved in cesium and rubidium processing at the KBI facility is very important. KBI is one of the two largest processors of pollucite and suppliers of cesium primary products in the world, but the scale of operation is relatively small compared to traditional base metal processing facilities. Infrastructure developments at KBI since the Maier and Lucas report (1973) are probably not significant because the USBM:MCS report (1984) estimated plant employment to be 25

persons, which is very close to the 20 persons reported working at the KBI facility by Maier and Lucas (1973).

KBI's cesium production and sales information are proprietary. KBI produces a wide selection of cesium compounds (technical and high purity grades) and cesium metal in two purities (99.5% min. and 99.98% min.). The company has a national and international sales organization for the distribution of its cesium products to most free-world countries. Along with processing and marketing of minor metals, KBI has an ongoing research and development program directed towards product improvement and end-product applications (pers. comm., J. Gierschick, 1983).

Callery Chemical Company

Located in Callery PA, Callery Chemical Co. is a division of Mine Safety Appliances (MSA) in Pittsburgh, PA. Callery is involved in high energy materials and specialty products for both commercial and military applications (Industrial Research Laboratories, 1983). The alkali metals cesium, potassium, and rubidium are processed to a very high purity as are other related alkali metal products. Callery is a major world supplier of high purity alkali metals and sells its products nationally and internationally (pers. comm., J. Madaus, 1984).

As a result of the alkali metal market being weak, Callery has curtailed its cesium processing program. When pro-

cessing did occur, pollucite and ALKARB were both used as raw materials (pers. comm., J. Madaus, 1984). Callery does not process cesium compounds and company sales information is proprietary.

Great Western Inorganics Inc.

Located in Golden Colorado and previously named Rocky Mountain Research Inc., Great Western Inorganics has processed cesium compounds using pollucite ore from Bernic Lake. However, the company has not been an active processor of cesium compounds or metal for about 15 years. The company is capable of processing high purity cesium compounds but will not resume doing so on a regular basis until cesium markets improve (pers. comm., R. Aldridge, 1984).

Kerr-McGee Chemical Corporation

Kerr-McGee processed raw materials into cesium primary products at facilities located in Trona, California but has discontinued cesium production for many years. Furthermore, the processing facilities at Trona are being dismantled (pers. comm., D. Batchelor, 1983).

Other U.S. Companies

There is a company in Illinois, Carus Corporation, that has recently initiated the production of cesium compounds. A company representative stated that pollucite is the best source material for producing cesium primary products (pers.

comm., A. Nelson, 1983). There are several other companies in the U.S. that process cesium compounds on a very small scale for special orders. However, most of these other companies (suppliers/distributors) purchase technical grade cesium compounds and reprocess them into compounds of higher purity for resale. There are also some companies that are strictly traders of cesium compounds or metal.

3.5.2 West Germany

Following the placement of pollucite in the Export Control List in 1976 by the Canadian Government, thereby cutting off the Soviet Market, West Germany has since imported the most pollucite from the Bernic Lake mine (Tanco Files). The Roskill Supplement (1978) listed four West German companies considered to be the main producers and suppliers of cesium products: Metallgesellschaft A.G., E. Merck A.G., Riedel-de Haen A.G., and Dr. Theodor Schuchardt and Co. According to industry sources, Metallgesellschaft is probably the most active primary producer and distributor of cesium compounds in the world.

Metallgesellschaft A.G.

Metallgesellschaft is a large and diversified mining and chemical company with headoffices being in Frankfurt (Moody's International, 1983). One of the company's many subsidiaries is Chemetall which processes several minor metals including cesium. The size of the Chemetall processing

facility and the number of persons employed at the plant are not known. Chemetall has been a producer of cesium primary products using various ores for about 25 years; and exports cesium products wherever a demand can be identified, except for the COMECON[3] countries and the People's Republic of China (pers. comm., M. Bick, 1983).

Specific information about Chemetall's cesium sales and demand data has been withheld for proprietary reasons. Chemetall's research and development program is primarily aimed at improving production processes as a way to decrease the costs of their cesium products (pers. comm. M. Bick, 1983). Chemetall is a major world supplier of cesium compounds (99 to 99.999% purity) and also sells cesium metal (99.5% min.) Metallgesellschaft's sales representative in the U.S. is Henley and Company Inc., New York.

The Roskill(1975) report stated that in the 1950's Metallgesellschaft signed a contract with the owners of the Bernic Lake mine, at that time Chemalloy Minerals Ltd., for supplies of cesium minerals. Most of the present shipments of pollucite from Bernic Lake to West Germany are probably purchased by Metallgesellschaft.

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[3] COMECON: Communist Economy Countries.

Other West German Companies

Besides Metallgesellschaft, other West German cesium produc-
er/supplier companies are E. Merck A.G., Riedel-de-Haen
A.G., and Dr. Theodor Schuchardt and Company. These three
companies are of secondary importance compared to Metallge-
sellschaft, with E. Merck probably being the strongest of
the three in terms of cesium marketing. E. Merck is a pri-
mary producer of cesium compounds and industry sources re-
port that pollucite is used in their cesium processing fa-
cility. E. Merck's distributor in the U.S., E. M.
Chemicals, New York, is a supplier of high purity cesium
compounds. Further information about E. Merck and the other
two companies is not available.

3.5.3   United Kingdom

The Roskill (1975) report stated that cesium metal and com-
pounds have been made in the U.K. since the 1930's. Pres-
ently there are two principal U. K. firms that produce and
distribute cesium products: British Drug Houses Ltd. (BDH),
and Koch-Light Ltd. Both companies have distribution offic-
es nationally and internationally.

Koch-Light is now a part of the Genzyme Corporation (Bos-
ton). Both BDH and Koch-Light process from pollucite ore
obtained from various sources; however, amounts of ore pur-
chased annually and country(ies) of pollucite origin have
been withheld along with cesium sales information.

The only known direct shipment of pollucite from Bernic Lake to the U.K. was for about 52 t in 1972 (Tanco Files). Therefore, these U.K. companies must either be drawing from existing stocks in the U.K., or purchasing pollucite directly from countries other than Canada or through other companies. Overall, industry sources report that U.K. involvement in the cesium industry is minor compared to West Germany or the U.S.

3.5.4 Canada

Although the world's largest reserves of pollucite are in Canada, there are no Canadian commercial-scale cesium primary production facilities. A small chemical company in London, Ontario, Canadian Scientific Products Ltd., had at one time conducted some experimental work with pollucite processing, however there have been no further developments. (pers. comm., B. Weber, 1983-84). Mr. Weber explained that the current cesium market is not large enough for CSP to become actively involved in commercial-scale production of cesium primary products on a regular basis.

If a commercial scale facility were to be established in Canada for processing domestic raw materials such as pollucite into cesium and other minor metal primary products (compounds and metals), it would probably be on a similar scale to KBI's which is very small. The KBI processing facility is contained within a very small building and the

number of employees working at the plant is estimated to be only 25 (see section 3.5.1).

3.5.5   Other Countries

The most important primary producers of cesium products in the world have been reviewed. There are probably several other countries which have the capability of processing cesium products, however they are not discussed in the literature. According to industry sources, another country which might develop commercial-scale production of cesium primary products is Japan. Presently, there are companies in Japan that reprocess cesium compounds into higher purities, but specific information is limited.

3.6   U.S. CESIUM DATA REVIEW

According to industry sources and data presented by Bascle (1980), the U.S. is the largest consumer of cesium. Also, relative to other countries, the U.S. is the only country which regularly publishes cesium-related data about its cesium industry. Therefore, the objective of this section is to present salient information about U.S. production and imports of cesium raw materials (pollucite) and cesium primary products (cesium metal and compounds). Technical information regarding the processing of these commodities is presented in Appendix B. Unless otherwise noted, the information presented here has been adapted from the USBM:CDS or MCS issues published annually from 1970 to 1984.

3.6.1 Pollucite

Although pollucite reserves exist in the U.S., domestic production has been insignificant and therefore the U.S. relies on imports (see section 3.3.3.1). Pollucite import sources have been primarily from Africa and Canada; and from 1978 to the present it appears that Canada has been the only supplier of pollucite to the U.S. From 1969 to 1981, the number of pollucite processors ranged from 2 - 4 companies, and plant employment for each year of the period reported had been estimated to be 25 persons. The 1983 and 1984 USBM:MCS issues reported that one firm in Pennsylvania imported pollucite and accounted for all of the domestic output of cesium products and plant employment was still estimated to be 25. Furthermore, pollucite yearend stocks are withheld and export data are not available. Also, the U. S. Bureau of the Census does not list pollucite imports within a category of its own.

3.6.2 Cesium Compounds and Metal

U.S. production of cesium compounds and metal is withheld, and yearend stocks and exports are either withheld or not available. The commodity summaries do report imports, but the format for reporting has not been consistent over the years. For example, from 1970 to 1979 cesium imports were designated as being in all forms (pollucite, compounds, and metal). At other times there was a more specific data breakdown of product entries. If the import percentage fig-

ures alloted to Canada are excluded (Canada does not process
cesium metal or compounds), then West Germany would account
for the largest percentage of U.S. cesium imports. From
1978 to 1981, West Germany accounted for 95% of cesium com-
pounds imported by the U.S. followed by the U.K. at four
precent and collectively, Canada and France at one percent.
Although Canada is not a cesium processing country, there
might have been transshipments of cesium compounds through
Canada from another country (pers. comm., T. Adams, 1984).

U.S. imports for consumption of <u>Cesium Chloride</u> (TSUSA[4]
No. 4185000) and <u>Other Cesium Compounds</u> (TSUSA No. 4185200)
are reported and separately identifiable. The published
statistics are listed by country of origin, net import quan-
tity (wt), and value in U.S. dollars. Value is further de-
lineated into Customs value, free along side (F.A.S.) and
cost, insurance, and freight (C.I.F.).

U.S. imports of cesium chloride and other cesium com-
pounds were reviewed for the period 1972 - 1982 based on
U.S. Bureau of the Census statistics. For cesium chloride,
the data shows a steady increase in U.S. imports except for
a decrease in 1975 (Figure 3).

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[4] The Tariff Schedules of the United States Annotated
(TSUSA) is an official publication of the U.S. Tariff Com-
mission.
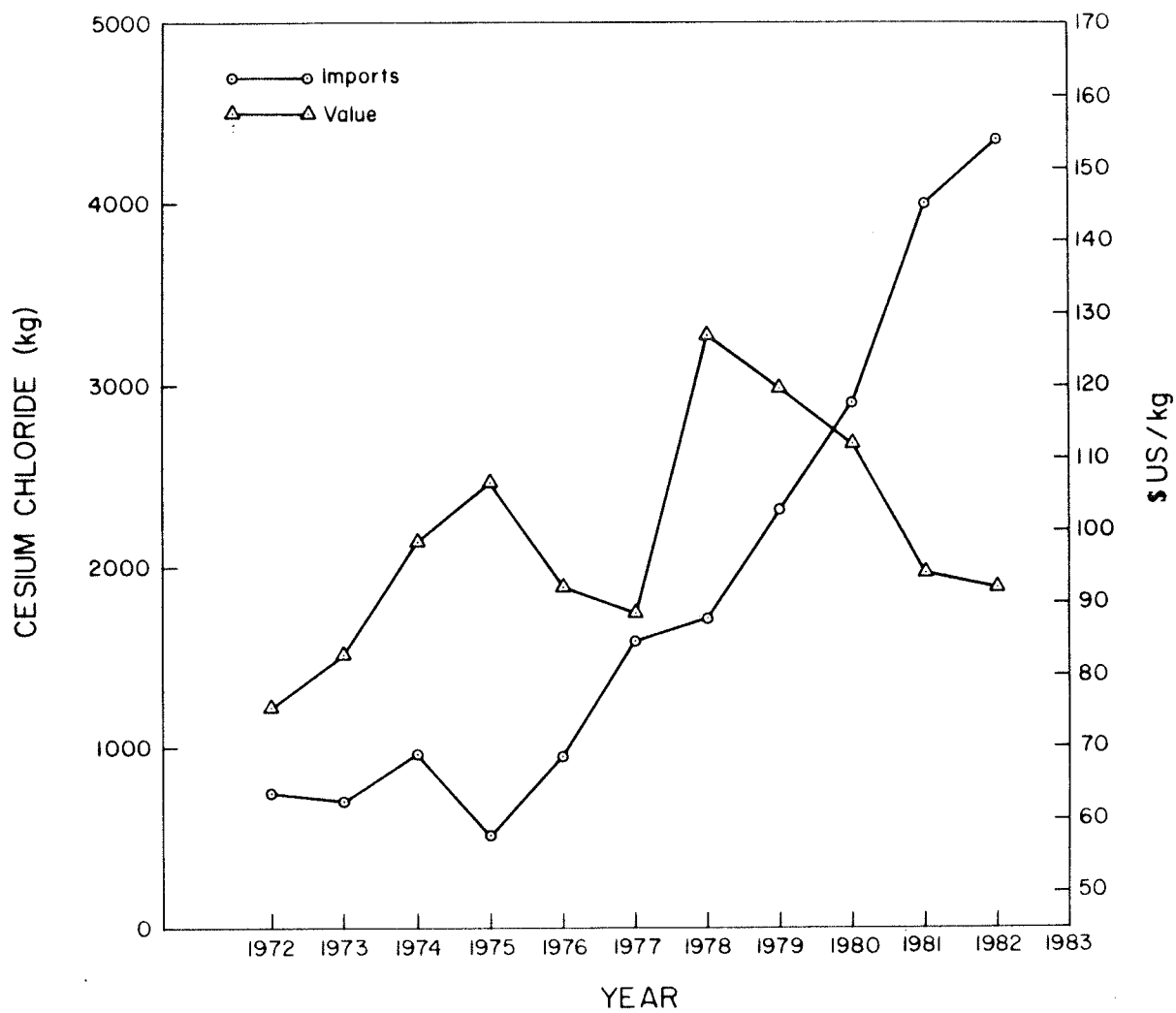
Figure 3: U.S. Imports of Cesium Chloride (1972-1982)
Source: Adapted from the U.S. Bureau of the Census,
(1972-1982).

In 1972, total U.S. imports of cesium chloride were about 753 kg and by 1982 total imports were about 4,375 kg. West Germany is the dominant country of origin, accounting for 80-100% of U.S. imports of cesium chloride. Other source countries of cesium chloride are not individually named because the import values from each country average below $5,000 per month based on cumulative Customs value figures for the year reported (U.S. Bureau of the Census, 1982).

The total F.A.S. value (transaction value of imports at the foreign port of exportation) in U.S. dollars was also reviewed for each year of cesium chloride imports. The U.S. values per kilogram of cesium chloride ranged from about $75.60 in 1972, to a high of $127.00 in 1978, and dropped to $92.10 in 1982. The West German portions of these total values tend to be higher than for the other countries, possibly because the West German product might be of a higher purity.

A similar data review was conducted for the category Other Cesium Compounds. However, there were several unexplainable inconsistencies in the data, especially for the years 1975, 1976, and 1977. By excluding the inconsistent data, the following general pattern emerges about total U.S. imports of other cesium compounds:

1. the total import quantities fluctuate erratically from year to year;

2. West Germany is the dominant country of origin
   (80-100%);

3. the total F.A.S. values in U.S. dollars fluctuate
   from year to year but also show a definite upward
   trend; and

4. the U.S. value per kilogram of other cesium compounds
   ranged from about $58.10 in 1972 to $88.20 in 1978,
   and was $125.30 in 1982.

Industry sources and U.S. import data suggest that the
U.S. imports a substantial portion of their cesium require-
ments in the form of cesium compounds. However, U.S. im-
ports of cesium metal are probably insignificant because of
the low demand and existing domestic production capabili-
ties.

Other U.S. Cesium Data Information

The following list of points regarding U.S. cesium data are
also worth noting:

1. The USBM:CDS,MCS reports stated there have been no
   U.S. government incentive or procurement (stockpile)
   programs;

2. The 1976 issue of the USBM:CDS included a new cesium
   heading titled "Recycling." According to the CDS/MCS
   reports from 1976 to the present, there has been no
   recycling of cesium; and

3. The 1979 issue of the USBM:MSC included a new cesium heading titled "Net import reliance as a percent of apparent consumption[5]." Collectively, the 1979 and 1984 issues stated that net import reliance was 100% for the years 1974 to 1984.

3.7 CESIUM COMMODITY PRICES REVIEW

The purpose of this section is to review cesium commodity pricing information as presented in the public literature. The prices are based on U.S. markets and the commodities reviewed are pollucite, cesium compounds, and cesium metal.

3.7.1 Pollucite

Barton (1960) reported that in 1957, pollucite (25 to 30% Cs_2O) was valued at about \$1.10/kg of Cs_2O (not stated but assumed to be F.O.B. source). Barton also included the price of ALKARB which traded at \$9.55 per 100 pound bag (about \$0.21/kg) F.O.B. San Antonio, Texas (ALKARB analysis included two percent cesium carbonate).

For the period 1969 to 1976 the USBM:CDS reports listed the price of pollucite at \$331/t which converts to \$1.39/kg of contained Cs_2O (assuming a grade of 24% Cs_2O). For the 1976 yearend, Metal Bulletin (in USBM: Minerals Yearbook, 1977) quoted the nominal price of pollucite concentrates containing a minimum of 24% Cs_2O, F.O.B. source, at \$12.40

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[5] Defined as imports – exports + adjustments for Government and industry stock changes.

to $13.00 per MTU (about $1.24 to $1.30/kg Cs_2O). From 1977 to 1981 the USBM:CDS/MCS reports listed the price of pollucite at about $441/t (or $1.84/kg Cs_2O, 24%). Crockett (1983) reported that Metal Bulletin quotations for pollucite remained constant during 1982 at $12.40 to $13.00 per MTU ($1.24 to $1.30/kg Cs_2O) F.O.B. for 24% Cs_2O material.

The pollucite pricing and quotation figures reported by the above mentioned secondary sources were lower and more static compared to Tanco's price range data presented earlier in Table 11.

3.7.2 Cesium Compounds

A chemical compound (or salt) is a substance which contains two or more different elements. Within the chemical industry in general, all chemical compounds must meet minimum grade standards established by the American Chemical Society. An important criterion used for the pricing of a chemical compound is its analysis, which indicates purity. To produce a high purity compound, several reprocessing steps may be required. These reprocessing steps are costly and are therefore reflected in the final sales prices.

Each major chemical company has its own jargon or marketing descriptors to indicate the different purities of their compounds. KBI, the largest U.S. primary producer and supplier of cesium compounds, publishes pricing information based on Technical Grade (99.0% min) and High Purity Grade

(99.99% min). KBI's purest cesium compound is called Optical Grade and price quotations are available on request. Table 13 shows KBI prices for selected cesium compounds in 1972 and 1983. The high purity grades are about twice the price of the technical grades. Within each grade the average price-increases between 1972 and 1983 were about 13% for technical and 6% for high purity. KBI, along with most companies, apply discounts to purchases greater than the base price quantity.

Another important factor which affects the price of compounds is the cost of packaging. Because KBI is a large primary producer, the company normally sells its compounds in kilogram units which are considered to be bulk quantities. If a cesium supplier or distributor requests packaging in smaller units, the producer price increases dramatically.

TABLE 13

KBI Cesium Compound Base Price* Comparison 1972 and 1983

Compound	Technical Grade 1972	($US/kg) 1983	High Purity Grade 1972	($US/kg) 1983
Bromide	61.70	70.55	143.30	153.25
Carbonate	63.90	70.55	147.70	153.25
Chloride	66.15	74.95	149.90	159.85
Fluoride	77.15	89.75	165.35	176.40
Hydroxide	77.15	84.90	165.35	172.00
Iodide	70.55	79.40	154.30	164.50

* Base price excludes packaging costs and quantities less than 46 kg in 1972 and less than 23 kg in 1983. F.O.B. Revere, PA.

Source: Adapted from KBI Div., Cabot Corporation, Pricing Information File No. 310

For example, if one-eighth pound packaging was requested, KBI would have added $88.20/kg to the base price in 1972 ($132.30/kg in 1983); for one pound packaging, $11.00/kg in 1972 ($22.05/kg in 1983); and for packaging in sizes greater than 10 pounds, no charges are added to the base price. The packaging cost increases, which reflect labor intensity, are much higher than the price increases for the actual compounds between 1972 and 1983.

Metallgesellschaft markets cesium compounds in purities of 99% (Pure) to 99.999% (Highest Purity). Metallgesellschaft does not distribute a published catalogue of cesium pricing information; however, price quotations may be obtained from its U.S. sales representative, Henley & Co. Inc., New York.

Both primary producers, KBI and Metallgesellschaft, sell cesium products to smaller chemical processors and suppliers, and also directly to end-users. Alfa Products, Morton Thiokol, Inc., is just one of several small U.S. chemical companies that obtains cesium primary products from various sources. Alfa reprocesses cesium compounds into higher grades and packages these products into smaller units, usually in grams.

To illustrate the different grades and prices of a single compound, cesium chloride is used as an example. Prices and grades are based on Alfa Products' published catalogue prices for the years 1975 - 1976, and 1983 - 1984. (Table 14).

TABLE 14

Alfa Products: Cesium Chloride Purities and Prices,
1975-76, 1980-81, and 1983-84

Cesium Chloride	gram units*	1975-76	1980-81	1983-84
99%	50	14.50	16.90	18.40
99.9%	25	18.30	19.90	19.20
Ultra pure	10	12.50	12.50	21.40
99.9999+%	10	25.00	29.00	31.50
Puratronic 99.999% (metal basis)	10	--	103.00	75.20

* The gram units presented are the smallest offered. Larger units are available at discounted prices.

Source: Adapted from Alfa Products, Morton Thiokol, Inc., Danvers, MA. Price Catalogues.

It is quite clear that the prices increase with increasing purity. Also, with the exception of the Ultrapure and Puratronic grades, price changes within a specific purity are not significant for the time periods reviewed. Not all companies have exactly the same specifications for their products and therefore prices do vary and are difficult to compare. It is also interesting, that over the years, a greater selection of different cesium compounds and different purities within each type of compound have become available to suit various end-use applications.

3.7.3   Cesium Metal

Cesium is a metal in its elemental form and is produced in purities ranging from 99.0 to 99.9+%. As with compounds, cesium metal is available in kilogram and gram units. Barton (1960) reported that cesium metal (no grade stated) in 1958 was priced at $1.10 to $5.22 per gram depending upon quantities and packaging. In the 1972 and 1982 issues of USBM:CDS/MCS, cesium metal prices were $220 to $826/kg, and $606/kg respectively, depending on purity and quantities purchased.

The Callery Chemical Company in the U.S. is one of the largest producers and suppliers of high purity cesium metal. In January, 1984, the company quoted a price of $1,140 U.S./kg for 0.454 kg to 1.814 kg (1-4 lb) of very high purity cesium metal. Discounts are available for larger orders

(pers. comm., J. Madaus, 1984). Furthermore, because major precautions must be taken in handling, transporting, and storing cesium metal, a special container must also be purchased or rented (depending upon the supplier) for an additional cost. KBI and Metallgesellschaft produce cesium metal but the product is of less importance, in terms of sales, compared to cesium compounds.

According to industry sources, cesium metal is more expensive relative to cesium compounds for several reasons which include:

1. higher processing costs to produce a high purity metal;

2. safety precautions necessary and special container for packaging; and

3. limited demand reduces the economy of scale.

3.7.4   Summary

Published information regarding pricing trends within each cesium product group, and price differentials among these groups, is very limited and of a general nature because of several complex variables that must be accounted (basis, purity, quantity, etc.). The following chart, Table 15, about cesium pricing over the years is also very general for the same reasons; but is intended to give an indication of value-added from the natural resource to the primary products.

TABLE 15

Estimated Pollucite Ore and Cesium Product Price Ranges for
Selected Periods in the U.S.

Year(s)	Pollucite, 24%Cs_2O $US/kg	Cesium Compounds Technical Grade, $US/kg	Cesium Metal 99.5-99.9+% $US
1958	1.10	49-61	1-5/g
1969-78	1.00-1.80	61-84	220-825/kg
1979-81	3.40-3.95	63-82	600-720/kg
1983	2.40-5.50	70-90	600-1140/kg

3.8 U.S. CESIUM DEMAND PATTERN

Cesium demand data are limited to the U.S. which is the
largest user country of cesium products. In the U.S., cesi-
um is classified into three major consumption categories:
chemical, electrical, and other, which are based on Federal
Reserve Board indicators (see section 2.4.1). Bascle (1980)
presented a numerical tabulation of the U.S. demand pattern
in each of the three categories for the period 1969 - 1979.
By calculating the demand in each category as a percentage
of total demand for each year, the general pattern is that
chemicals represent about 5%, electrical 15%, and other 80%.
A graphical presentation of the total U.S. cesium demand
pattern using the data in Bascle (1980) is shown in Figure
4, and includes cesiuml n demand for each category. Since
the low in 1973, all three categories have been steadily in-
creasing, especially for the category, other uses.
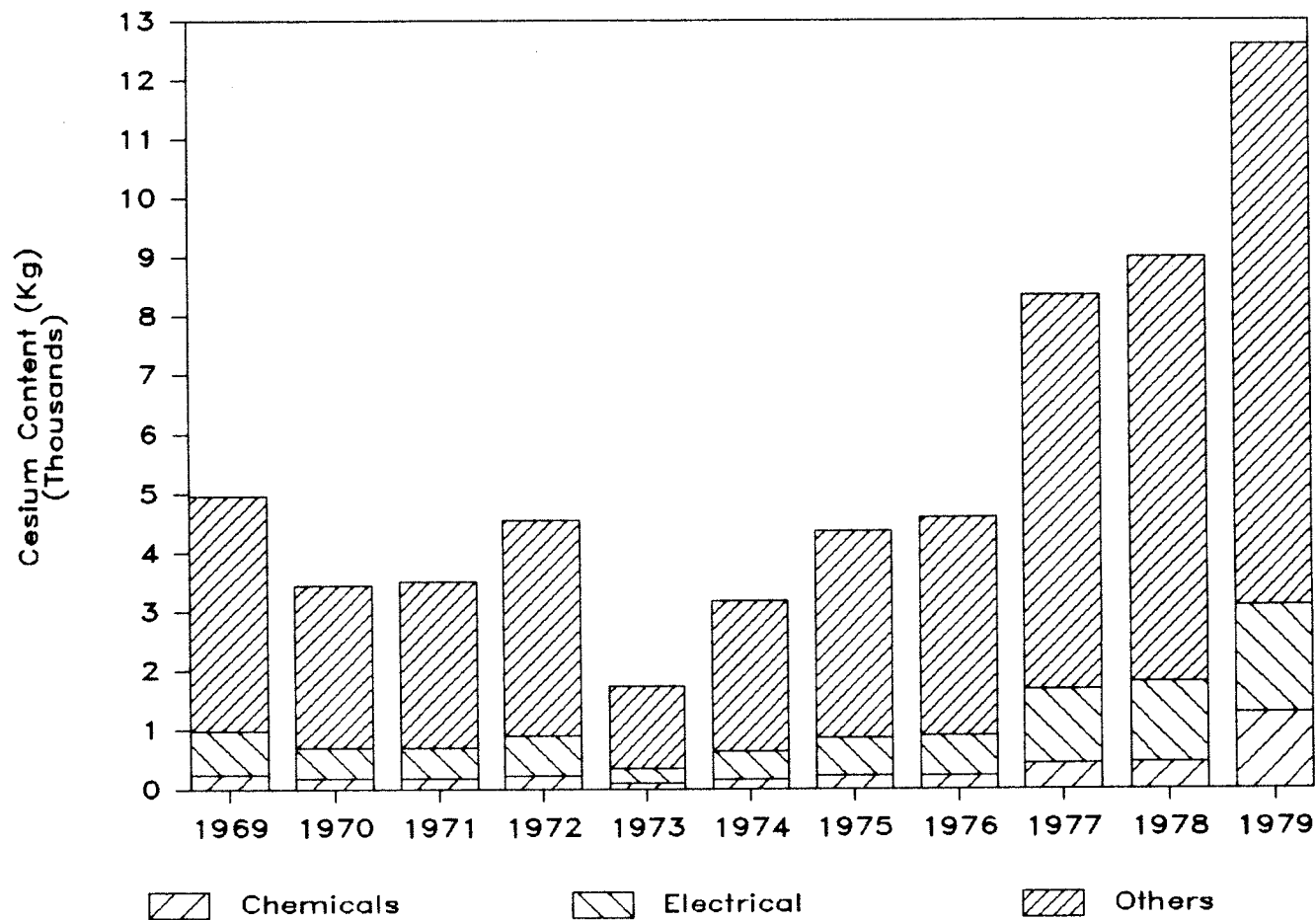
Figure 4:   Total and Per Category U.S. Cesium Demand
            Pattern, (1969-1979)
            Source: Adapted from Bascle, (1980).

U.S. cesium demand in 1978 was reported to be 8,984 kg of recoverable cesium versus 9,982 kg of cesium by the rest of the world (Bascle, 1980). A 1978 cesium world demand total of 18,966 kg of recoverable cesium is approximately equivalent to 155 t of pollucite (assuming 24% contained Cs_2O and an inferred[6] USBM cesium recovery estimate of 54% from pollucite). From 1969 to 1979, U.S. imports of pollucite concentrates totalled 101,200 lb (45,903 kg) of cesium which converts to about 376 t pollucite (24% Cs_2O). Tanco files indicate that Tanco exported approximately 366 t of pollucite to the U.S. during the same period, therefore the factor of 54% seems reasonable.

From 1969 to 1979, U.S. imports of compounds/metal totalled 65,500 lb (29,710 kg) cesium content. Assuming a cesium compound yield of 70% from Cs_2O, as indicated by industry sources, at least 177 t of pollucite (24% Cs_2O) would be required to produce 29,710 kg of cesium. Therefore, about 553 t (376+177) of pollucite would have to have been processed to supply U.S. cesium demand from 1969 to 1979.

U.S. cesium demand (chemical, electrical, and other) from 1969 to 1979 totalled 132,600 lb (60,146 kg) cesium content or at least 358 t of pollucite (24% Cs_2O). The difference between U.S. cesium import demand and total U.S. cesium demand for the period 1969 to 1979 (376+177-358) was a surplus

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[6]   See Appendix C for assumption explanations and sample calculations.

approximately equivalent to 195 t of pollucite. This surplus may indicate unprocessed pollucite/exports of cesium primary products/calculation factor errors.

3.9   CURRENT CESIUM END-USES AND CONSUMPTION

There were practically no industrial applications for cesium until _circa_ 1926 when it came into use as a coating on tungsten vacuum-tube filaments (Barton, 1960). In subsequent decades, more knowledge about cesium's properties accumulated and the availability of cesium also increased. The largest portion of cesium consumption, past and present, occurs in the field of research and development.

The published literature outlining the end-uses for cesium is mostly restricted to USBM publications such as Mineral Facts and Problems and Mineral Commodity Profiles. Other useful information sources are Van Nostrand's Scientific Encyclopedia, Kirk-Othmer Encyclopedia of Chemical Technology, and the Roskill (1975) report. Most of the cesium end-uses listed in these publications are generally the same and usually number less than twenty. Having reviewed the published literature about cesium end-uses, and after consulting with industry sources and research scientists involved with cesium, the major uses for cesium presently are:

1.   Photoemissive devices;

2.   Scintillation crystals; and

3. Density gradient solutions.

3.9.1   Photoemissive Devices

Very simply, photoemission represents the conversion of a photon (light particle) into free electrons. The phenomenon of photoelectric emission was first observed in 1887. Then in 1889, Elster and Geitel discovered that a photoelectric effect can be produced by visible light in alkali metals. The potential uses of photoemission for practical applications, especially photometry, were realized; but the low quantum efficiency of the materials limited their usefulness. After 1929, material efficiency limitations were overcome by the discovery of the silver-oxygen-cesium (Ag-O-Cs) photoemitter which exceeded the previously used materials by two orders of magnitude in quantum efficiency. Furthermore, the Ag-O-Cs photoemitter was sensitive to the whole visible spectrum including the near infrared (Sommer, 1968).

The Ag-O-Cs cathode is referred to in the industry as the S-1. The S-designation was developed in the early 1940's by the Joint Electron Devices Engineering Council (JEDEC) to indicate spectral responses. Since the S-1 cathode, there have been over thirty other photocathodes developed which contain cesium. However, all cesium containing cathodes may be grouped into five basic types with examples of S-designations:

1.   Silver-oxygen-cesium   (Ag-O-Cs)   S-1

2.	Cesium-antimony	(Cs_3Sb)	S-4,5,11,21
3.	Silver-bismuth-oxygen-cesium	(Ag-Bi-O-Cs)	S-10
4.	Potassium-cesium-antimony	(K_2CsSb)	no S-number
5.	Sodium-potassium-antimony-cesium	($Na_2KSb:Cs$)	S-20,25

Source: Adapted from Engstrom, (1980).

As a result of the Ag-O-Cs cathode, the main interest in photoemission changed from scientific research to practical applications. The first important use was the reproduction of sound from film, followed by various photoemissive devices such as the photomultiplier, iconoscope, and image orthicon in televisions. For practical applications, Sommer (1968) divided photoemissive devices into two classes: radiation detectors; and imaging tubes.

Radiation Detectors

Radiation detectors consist either of photodiodes or photomultipliers (depending on end-use), each of which also house a photocathode. In addition, photomultipliers also consist of dynodes. One of the most common dynode materials is cesium antimonide (Cs_3Sb) which is also an important photocathode material. Therefore, cesium becomes incorporated into photocathodes, which are common to photodiodes and photomultipliers, and also in the dynodes of photomultipliers.

The photomultiplier is a versatile and sensitive detector of radiant energy in the ultraviolet, visible, and near infrared regions of the electromagnetic spectrum (Engstrom, 1980). The photomultiplier is the most practical detector available for many applications. Early applications of the photomultiplier were in astronomy and spectroscopy because the effective quantum efficiency of the photomultiplier was at least 10 times that of photographic film (Engstrom, 1980). During World War II, photomultipliers were used for radar jamming and scintillation counting. A partial list of major applications for photomultipliers presently include:

- scintillation counting
- computerized tomographic X-ray scanners (C-T scanner)
- gamma-ray and positron cameras
- spectrophotometry
- colorimetry
- photometry
- densitometry
- spectrometry
- radiometry
- radioimmunoassay (RIA)
- fluorometry
- laser detection
- high speed inspection and process control
- time movement (cesium beam frequency and time standards)

Most of these devices are standard equipment in universities, hospitals, industry, and the military.

Imaging Tubes

The purpose of an imaging tube is to convert an optical (visible or invisible) image into a corresponding electron image via a photocathode (Sommer, 1968). There are two types of imaging tubes: direct viewing image tubes (image convertor tube and image intensifier tubes), and camera tubes.

The most common application for imaging tubes are television cameras. Camera tubes are used for special applications such as infrared detection which is an important military use, as well as in medical diagnostic procedures. Commercial applications for imaging devices include: (1) parts inspection; (2) reproduction of motion pictures and slides; (3) optical character recognition; and (4) scanning written or printed material, such as supermarket checkout systems (Engstrom, 1980).

3.9.1.1 Cesium Consumption

Cesium is an essential input for the production of photoemissive devices such as photocathodes and photomultipliers. Cesium compounds commonly used in the manufacture of photocathodes are cesium chromate and cesium dichromate. These compounds are reduced to produce a cesium vapor which then

coats a very thin layer (about 260-350 Angstroms) onto the cathode screen (Sommer, 1968). Although photoemissive devices are extremely important and used extensively in a variety of applications, the amount of cesium required for such purposes is not great.

There are less than 15 major companies in the free-world producing photoemissive devices. Two of the largest photomultiplier tube producers are RCA in the U.S., and Hamamatsu in Japan. According to two industry sources directly involved in the production of photomultiplier tubes, total cesium consumption by all these companies is estimated to be less than 150 kg annually. However, the Roskill (1975) report stated that at most, U.S. consumption of cesium compounds in 1972 in electronic devices was probably in the region of 1,270 kg. Petkof (1975) reported that in 1973 about 400 kg of cesium, and Bascle (1980) reported that in 1978 about 1,350 kg of cesium were used for electrical purposes in the U.S. The difference between the published and industry source demand estimates for cesium in electrical applications is large indeed and suggests that the electrical category includes more applications than photocathodes and photomultipliers alone.

The USBM (Bascle, 1980) forecast of U.S. cesium demand in electrical end-uses in the year 2000 was for a high of about 453,600 kg; and if the development of magnetohydrodynamics (see section 3.10.2.1) is excluded, then a low of about

3,600 kg is forecast. The researcher considers a cesium demand for electrical purposes approaching the low forecast more plausible.

3.9.2 Scintillation Crystals

A scintillation crystal (or phosphor) is a material able to convert energy lost by ionizing radiation into pulses of light. The light pulses produced may be amplified and used to determine the amount of energy deposited in the crystal. Scintillators, or scintillation counters are widely used in gamma-ray detection and spectrometry (Harshaw Chemical Co., 1978).

There are four general types of scintillators used for gamma-ray and charged particle detection: organic crystals, inorganic crystals, liquids, and plastics. Inorganic crystals are the most common types used because of their high gamma-stopping power and high light output. The most popular scintillator material is the inorganic crystal thallium-activated sodium iodide (NaI(Tl)) which covers a spectral range from about 350 to 500 nanometers (nm) with a maximum at about 4,100 nm (Engstrom, 1980).

Depending on application requirements, the inorganic crystal cesium iodide (thallium or sodium activated) is a rugged scintillator noted for high gamma-stopping power and resistance to thermal and mechanical shock. The Harshaw Chemical Company (1978) reported that compared to NaI(Tl),

cesium iodide (CsI) is relatively soft and plastic and is easily fabricated into a variety of useful detector geometries. Furthermore, because of its rugged character, CsI has been extensively applied to oil-well logging, satellite-borne radiation detectors, and military science where severe environmental conditions are frequently encountered. Both the thallium activated form CsI(Tl) and sodium activated form CsI(Na) are damaged by moisture, and therefore direct contact with water/high humidity must be avoided. Crystals of cesium fluoride (CsF) are also used for special scintillation applications.

3.9.2.1 Cesium Consumption

One of the largest manufacturers of scintillation crystals in the world is the Harshaw Chemical Co. in Ohio. Crystals manufactured at Harshaw are available in several dimensions such as, in inches: 1x1, 2x2, 3x3, 8x4, 8x8; custom orders are also fabricated. Harshaw sales representatives stated that the Na(Tl) crystal is the most commonly purchased crystal in the industry because of its versatility and price. For comparison, a 1x1 NaI(Tl) crystal was quoted at $142 versus $425 for CsI(Tl) or (Na). The CsI crystal is higher priced primarily because cesium salts are costlier and the crystal growth period is longer. Harshaw's purchases of compounds for crystal manufacturing and scintillator sales data are proprietary.

According to industry sources, the major end-use demand areas for scintillation crystals are medical diagnostic instruments and industrial uses such as process control. Universities and other research institutions also purchase similar type devices. Industry sources estimate that less than 10,000 kg of CsI are purchased annually for the production of scintillation crystals and that the scintillation crystal market is strengthening.

Cesium iodide is also manufactured into optical crystals such as cell windows and infrared prisms. There are over 25 different types of crystal materials to choose from with cesium-type crystals, such as CsI, being very effective in the infrared region. For a price comparison, a Harshaw sales representative quoted $92.40 for a CsI optical crystal 1" diameter x 5 mm, compared to $9.45 for a commonly purchased NaCl crystal (same dimensions). Because cesium-type optical crystals are used in a limited number of special applications, industry sources report that demand is small and estimate cesium compound requirements for optical crystals to be less than 300 kg annually.

3.9.3 Density Gradient Ultracentrifugation

Ultracentrifugation is a laboratory technique for the separation and identification of macromolecules such as proteins, subcellular organelles, and nucleic acids. Density gradient separation is a type of ultracentrifugation in

which the gradient-forming material is usually cesium chloride (CsCl) (McCall and Potter, 1973). Density gradients are used in centrifugal separations in several ways. However, they may be categorized as being either preformed (prepared with sucrose solutions), or self-generating (prepared with a salt of a heavy alkali metal). Each type of gradient has its advantages and disadvantages, and choice of gradient depends on the kind of protein being separated and the type of information being collected.

The use of self-generating gradients for isopycnic separations results in systems which are in true equilibrium (McCall and Potter, 1973). Cesium chloride was chosen initially by Meselson, Stahl, and Vinograd in 1957 because of its high solubility and high density. When a concentrated CsCl solution (8.0 molar (M)) is centrifuged to equilibrium, the CsCl becomes distributed in a linear gradient down the tube. At the top of a 1-cm column tube, the density of the solution is about 1.55 g/ml and at the bottom about 1.80 g/ml (Lehninger, 1975). When DNA is present during formation of such a gradient, it concentrates into a stable band at that position in the tube at which the buoyant density is exactly equal to the density of the CsCl solution. Lehninger (1975) explains that CsCl gradients are widely used to determine the buoyant density of DNA molecules because such measurements provide valuable information on the base composition of the DNA specimen.

3.9.3.1   Cesium Consumption

During the past decade, there have been many scientific advances in the field of genetic engineering involving both plant and animal cells. Universities, medical research organizations (especially cancer research), and private research companies are all actively conducting experiments in protein chemistry and cell biology. Because nucleic acid (DNA and RNA) separation is a fundamental procedure in these disciplines, the use of cesium compounds such as CsCl has become well established.

Standard CsCl solutions as prepared in research labs for density gradient separations range from 6-8 M (pers. comm., Dr. R. Matusik, and J. Condino, 1984). An 8 M CsCl solution is equivalent to about 1 g of CsCl/ml of solution. Therefore a 1 litre solution of CsCl will contain approximately 1.3 kg of CsCl. According to estimates prepared by researchers who use CsCl solutions, a full-time laboratory would use about 10 l of CsCl solution annually which requires about 13 kg of CsCl compound to prepare (technical grade or high purity). Furthermore, researchers and industry sources estimate that consumption of CsCl compounds for density gradient work in the U.S. and Canada alone to be approximately 10,000 kg annually.

After a solution of CsCl has been used in an experiment, the solution is usually dumped. Technical procedures are available to recover the CsCl from the contaminated solu-

tion, however, it is not a common practice because it is labor intensive and therefore costly. Demand for CsCl is expected to continue as long as there is research activity in DNA separation. A decrease in CsCl demand may occur if:

1. the recovery of CsCl from used solutions becomes a common practice; and

2. the technology of density gradient separation becomes supplanted by another separation technique which does not require CsCl.

Overall, the greatest demand for cesium is in the form of CsCl compound for end-use in density gradient ultracentrifugation.

3.9.4 U.S. Cesium Consumption Summary

The major applications for cesium are in photoemissive devices, scintillation crystals, and density gradient ultracentrifugation solutions. These applications primarily incorporate cesium compounds and to a lesser extent, cesium metal. Collectively, the above three applications for cesium currently account for approximately 25,000 kg of cesium compounds in the U.S. annually. According to the assumptions presented in Appendix C, about 150 t of pollucite (Cs_2O) would be required to produce 25,000 kg of cesium compounds. An annual pollucite consumption rate of 150 t to satisfy U.S. cesium demand is reasonable based on Tanco pollucite shipment data presented earlier in Table 10.

3.9.5 Other Reported Uses for Cesium

Several other possible applications for cesium are reported in the general literature. One application in particular, ion propulsion engines, is often reported to incorporate cesium.

Ionic Engines

Next to MHD, one of the most often reported uses for cesium was and continues to be in ion propulsion engines. The ionization of alkali vapors on hot surfaces, particularly cesium on tungsten, has been extensively studied based on the initial work by Oberth (1929). During the late 1950's and early 1960's, several types of contact ion engines were ready for preliminary testing in the U.S. as a means for reliable space propulsion (Brewer, 1966). Cesium was used because it is easily ionized by moderate heating, and its high atomic weight results in a high propulsion force (Giannini, 1961).

As promising as cesium ion engines appeared, there were also several problems. Researchers at NASA Lewis stated that experiments with ion engines during the past 10 years showed that:

1.   cesium ion engines were chemically unstable;

2.   there were difficulties in isolating the electric charge; and

3.   cesium did not have an overall performance as good as mercury, xenon, or argon.

Therefore, cesium ion engines are no longer considered to be viable for space propulsion systems (pers. comm., B. Kerslake, 1983).

Other Research

A partial list of other activities in cesium research includes the following:

1. thermionic devices: Van Nostrand's Scientific Encyclopedia (1983d), Zykov, et al. (1981), Roskill (1975);

2. single crystal infrared fibers: Mimura, et al. (1982);

3. ferroelectric materials: Plascak, et al. (1982), Lines and Glass (1977); and

4. cancer research: Pinsky et al. (1983).

Cancer research involving the use of cesium is of particular interest. As early as 1933, the stable isotope ^{133}Cs was reported as having antitumor effects (Wright and Graham, 1933). Further reports of antitumor properties were reported by Messiha, et al. (1979).

During the past few years, an interdisciplinary project initiated by researches at the University of Manitoba has been investigating the effects of ^{133}Cs and ^{132}Cs in cancer cells. Stable cesium ion (^{133}Cs) as chloride salt and the positron - emitter ^{132}Cs (produced via proton beam bombard-

ment of a $^{133}CsCl$ target) were administered to test animals in various experiments: Pinsky et al. (1983), Pinsky and LaBella (1982), Pinsky, et al. (1981). The results of these preliminary experiments have led the researchers to conclude that ^{133}Cs has a genuine antitumor effect and that cesium is taken up preferentially in malignant tissue. Furthermore, ^{132}Cs might be suitable in cancer therapy and early detection as well as a unique antitumor agent (Pinsky et al., 1983).

In several communications (1983-1984) with Dr. Pinsky, he cautioned that many more experiments must be performed, and that cesium is just one of several elements currently being investigated by cancer researchers worldwide.

3.10   POTENTIAL END-USES FOR CESIUM

The primary objective of this section is to outline the major research progects which may create substantial increases in demand for cesium. Based on information in the literature, and communications with industry sources and research scientists, there are two areas of research in which cesium is a candidate material. The research projects are: catalysts and catalytic promoters in the immediate future; and magnetohydrodynamics in the more distant future (after 2000).

3.10.1   <u>Catalyst</u> <u>Research</u>

Simply defined, a catalyst is a substance that accelerates a chemical reaction by providing an easier pathway, without itself being used up in the reaction. The catalyst is in- volved in the reaction, however it is regenerated in its original form (Dickerson, <u>et</u> <u>al</u>., 1974). Catalysts were first developed at the turn of the century and are presently a billion dollar a year business (Stiles, 1983). The two most important groups which consume catalysts are the petro- leum and chemical industries.

Cesium, as well as the other alkali metals, is used in catalytic processes which include: oxidation, amination, alkylation, and dimerization, to name a few. One of the earliest processes that included the use of cesium was the synthesis of methanol, and was patented by Fischer and Tropsch in 1922 (Stiles, 1982). The catalysts which were claimed by Fischer and Tropsch were elemental nickel, sil- ver, copper and iron, and more specifically, iron plus cesi- um and rubidium hydroxides.

Presently, both the petroleum and chemical industries are actively involved in either the development of new catalysts for novel purposes, or catalyst modifications for existing processes (Van Nostrand's Scientific Encyclopedia, 1983a). After reviewing the current scientific literature and U.S. Patent Abstracts, as well as communicating with industry sources, there are at least two principal chemical processes

in which cesium is receiving serious attention. In the petroleum industry, cesium is being investigated as a catalytic promoter in the reaction: ethylene to ethylene oxide (EO). In the chemical industry, cesium is being tested for use in the synthesis of methyl methacrylate (MMA).

Ethylene to Ethylene Oxide

Although there are few direct end-uses for ethylene (C_2H_4), it is a very important petrochemical feedstock in terms of quantities used and economic value. Ethylene is the feedstock for ethylene oxide, ethyl alcohol, ethylbenzene, ethyl chloride, ethylene dichloride, and polyethylene -- most of which are used to produce hundreds of other end-products (Van Nostrand's Scientific Encyclopedia, 1983b).

A commercially important production reaction is the conversion of ethylene to EO. EO is a very high-tonnage chemical with about 1.8 million t consumed annually as follows:

1. 60% for the manufacture of ethylene glycol -- glycol being an antifreeze compound as well as a raw material for the production of polyethylene terephthalate used in the manufacture of polyester fibers;

2. 12% for preparation of surfactants;

3. 8% for the manufacture of ethanolamines;

4. 10% for the production of ethylene glycols for use in plasticizers, solvents, and lubricants; and

5. 10% for making glycol ethers which are used as jet-
    fuel additives and solvents (Van Nostrand's Scientif-
    ic Encyclopedia, 1983c).

The conversion of ethylene to EO is by an oxidation reac-
tion which occurs in the presence of a silver catalyst. The
major petroleum companies are trying to enhance the conver-
sion process by improving the catalyst. The silver catalyst
is supported by porous alumina, with cesium or other types
of alkali metals such as K and Rb used as promoters (U.S.
Patents, 4374260, 4356312, 4350616). Detailed information,
such as the amount of alkali metal used, its form (compound/
metal), and catalyst life, is proprietary and therefore the
cesium requirements are difficult to determine.

An indication of the amount of alkali metal used in a
silver catalyst is presented for U.S. Patent 4356312. In
the patent abstract the inventors stated:

> "when supported silver materials are being pre-
> pared, deposits of from about 4.0×10^{-5} to about
> 8.0×10^{-3} gram equivalent weights per kilogram of
> finished product of ionic, higher alkali metals,
> i.e., ionic potassium, rubidium, or cesium simul-
> taneously with the deposit of silver improves the
> selectivity of these materials as catalysts for
> ethylene oxide production."

For U.S. Patent 4350616, the inventor stated that the silver
catalyst can be improved by impregnating the silver-contain-
ing support with a solution of cesium compound.

For silver catalysts which have already been used, the
inventors for U.S. Patents 4335014 and 4391735 stated that 1

to 1000 parts, per 1 million parts of catalyst of cesium, rubidium, or a mixture thereof, is deposited on the washed catalyst.

The amounts of cesium required to promote the silver catalyst, as indicated by the patent abstracts, are minute. But for large processes such as ethylene to EO, there is a potential for increased cesium demand. Other alkali metals such as potassium and rubidium are also being investigated. Therefore, to effectively employ alkali metals in the silver catalyst, the economic and performance factors of each alkali metal will have to be evaluated by the catalyst manufacturers.

Methyl Methacrylate

Methyl methacrylate (MMA) is an organic compound with end-uses which include cast sheet, surface coatings, and molding and extrusion compounds. MMA is also used in the automotive industry and in commercial construction for display cases, signs and lighting (Chemical Marketing Reporter, 1983). The Chemical Marketing Reporter (1983) also stated that MMA is about a 544,000 t business per year in the U.S. alone.

MMA is typically manufactured by the acetone cyanohydrin (ACH) process which makes use of surplus hydrogen cyanide which is generated in acrylonitrile plants (Nakamura and Ichihashi, 1980). Nakamura and Ichihashi (1980) also stated that the demand for acrylonitrile is expected to be weak,

therefore less hydrogen cyanide will be produced, and an oxidation process will probably replace the ACH process. Ai (1981) stated that increased attention has been given to improving oxidation catalysts for the direct oxidation of methacrolein (MAcr) to methacrylic acid (MAA) and ultimately to MMA. Ai (1981) further reported that more than 100 patents have appeared concerning oxidation catalysts for MMA production.

Most of the catalysts proposed for the direct oxidation of MAcr to MAA are heteropoly compounds containing both molybdenum and phosphorous as essential elements. The most important heteropoly compound being investigated is 12-molybdophosphoric acid $H_3PMo_{12}O_{40}$, (12-MPA). Of particular importance is that 12-MPA is a reasonable catalyst on its own, but Nakamura and Ichihashi (1980) found that it showed the highest performance when a part of its protons were replaced by potassium, cesium, or thallium.

Specific information about the use of cesium in 12-MPA catalysts for MMA production is proprietary. In a recent (1984) communication with a catalyst researcher actively involved in MMA research, the researcher stated that various cesium compounds may be used such as cesium nitrate and cesium hydroxide -- in very small amounts, possibly a few percent. He also added that, because cesium compounds are more expensive than other alkali compounds, substitution may result.

In the early steps of MMA production by oxidation, isobutene ($i-C_4$) may be used and therefore the entire oxidation process is referred to as C_4 technology. The Chemical Marketing Reporter (1983) reported that Mitsubishi brought on stream an MMA unit that operates via C_4 oxidation at the end of 1982; and that another company, Rohm and Haas, has also been considering construction of a plant using C_4 technology.

3.10.2   Magnetohydrodynamics

Magnetohydrodynamics (MHD) is the term used to describe electric generating systems which obtain power from conducting fluids as they move through magnetic fields (Roddis, et al., 1969). Conductivity is enhanced when cesium/potassium are injected because of their high ionization potentials. The interest in MHD arises because the thermal energy in a gas or liquid is converted directly into electric power without the need for a turbine or rotating generator. The lack of moving parts in contact with the hot working fluids simplifies the system and permits higher temperatures to be used, therefore facilitating higher plant efficiencies (Volkman, 1983).

MHD electrical power generation was first recognized by Micheal Faraday as being technically feasible during his original investigation of electromagnetic induction in 1831 (Rudins, 1974). The first modern recorded attempt to devel-

op an MHD generator was conducted at the Westinghouse Research Laboratories before and during World War II. Rudins (1974) reported that several preliminary studies of the MHD power generation process were made in the U.S. in the late 1950's; and interest was expressed by commercial electric power systems organizations and the U.S. Department of Defense. In addition, with the advent of the U.S. space program, NASA also established interest. Today, MHD is being actively investigated by over 20 countries, especially the U.S., U.S.S.R., and The Netherlands. Several different power systems using MHD have been proposed depending primarily on the cycles and fluids used (Roddis, et al., 1969). The two most developed MHD systems are open-cycle and closed-cycle, and cesium is a potential input material for both, especially the closed-cycle.

3.10.2.1   Open-Cycle MHD

<u>General</u> <u>Operation</u>

In open-cycle MHD power generation, the working fluid is seeded gaseous combustion products. A fossil fuel, such as natural gas, petroleum, or coal, is burned in preheated oxygen-enriched compressed air to produce temperatures in the range of 2,700° to 3,300°C. The hot gases are seeded with an easily ionized element such as cesium or potassium to increase conductivity. The ionized gases (plasma) are then accelerated at high velocity using nozzle systems and flow into a cooled chamber called the MHD channel. The MHD chan-

nel is surrounded by a magnetic field (5-7 Tesla) produced by a super-conducting magnet. Electrodes, situated on opposing walls of the channel, provide electrical contact between the flow and an external load thereby permitting DC electric current flow. The DC power can be used directly (industrial applications), or it can be transferred to inverters and then to the external AC power system.

When the gas-flow leaves the generator channel, the electrical conductivity is too low for efficient MHD conversion, but the temperatures are still very high (about 2040°C). The remaining energy in the gas is used to generate steam which in turn is used to drive conventional turbine AC generators. Before the gas-flow is released through the stack to the atmosphere, the alkali seed is recovered and recycled (Melcher, 1977). Figure 5 is a schematic of a combined MHD (topped) and steam turbine (bottomed) electical generation system.

Efficiency

The principal reason for developing MHD technology is to increase energy conversion efficiencies. When assessing the performance of a system, efficiency may apply to thermodynamic efficiency, power plant efficiency, or the more general term, overall energy efficiency (Tsu, et al. 1976). For more information about MHD channel performance and efficiency, refer to Swallom (1981).
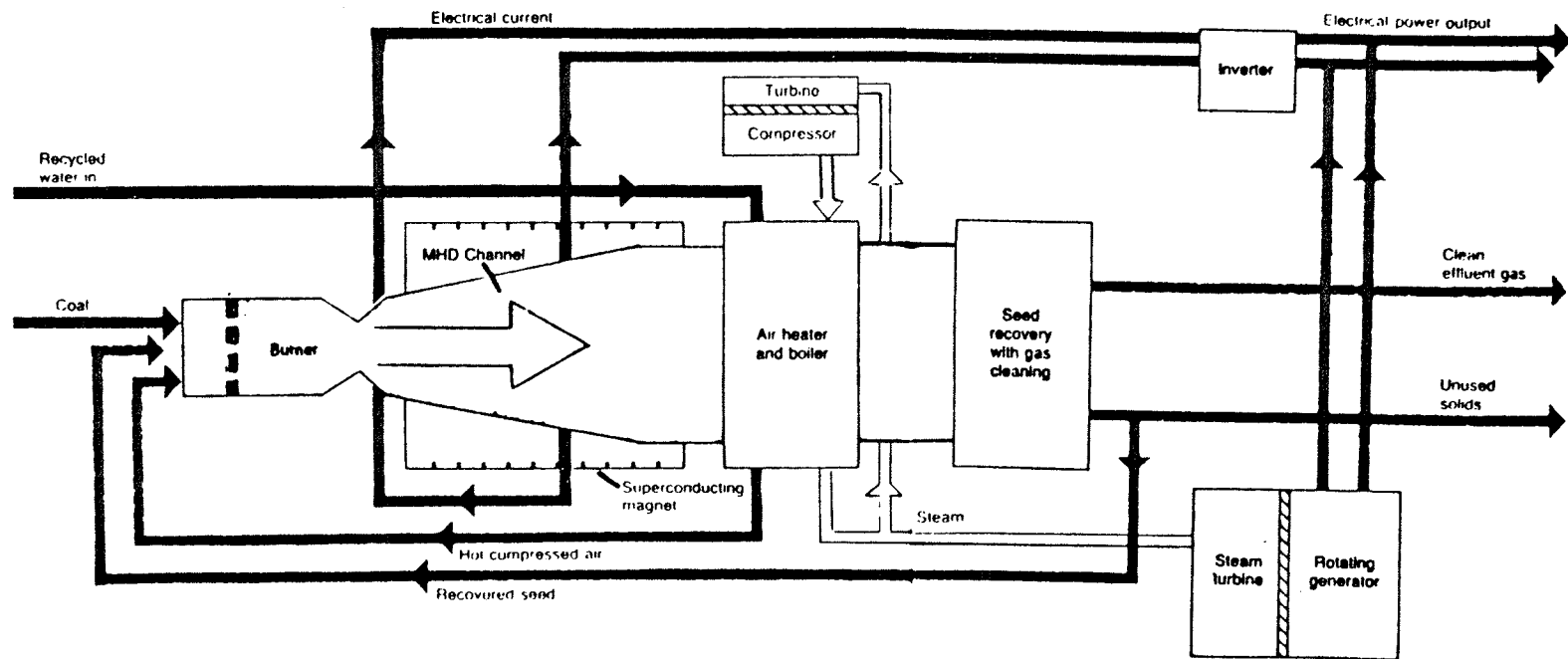
Figure 5: Schematic of a Combined Open-Cycle MHD Steam
Turbine Electrical Generation System
Source: Adapted from Freeman, (1980).

Most standard coal-fired steam generators have overall efficiencies of 30-35% depending on the size of the plant and the amount of pollution control devices incorporated into the system. Nuclear power plants have efficiencies less than 35% (Melcher, 1977). A medium scale commercial MHD powerplant of 500 Megawatts electrical (MWe), which would be a combined cycle (MHD topped and steam turbine bottomed), is expected to have an overall plant efficiency of about 45%. Gross power from the MHD section would be 18-20% of thermal input (pers. comm., R. Carrington, 1983). Dr. Carrington further explained that the larger the plant size, the greater the efficiency; and potentially, a combined cycle efficiency greater than 50% may be attained. Overall, it appears that the performance development of steam-turbine systems has reached its upper limits; and only by combining steam cycles with other conversion systems can significant efficiency increases be obtained (Rudins, 1974).

Besides increased efficiency, there are many more benefits that MHD technology offers such as: reduced sulfur, carbon dioxide, and nitrogen emissions; lower heat rejection; less cooling water; no moving parts; and improved fossil fuel utilization, to name a few. The MHD literature is voluminous and should be reviewed for more detailed information. The principal objective of this section is to review and assess the potential for cesium as a seed material in open-cycle MHD.

Cesium and Open-Cycle MHD

A critical step in the operation of the MHD cycle is the seeding of the hot combustion gases with either potassium, cesium, or both. Cesium and potassium have the ability to loose their electrons very easily hence increasing the conductivity of the working fluid. Because cesium has an ionization potential of 3.89 electron volts (eV), compared with 4.34 eV for potassium, a cesium seeded combustion plasma will exhibit a greater electrical conductivity than a potassium-seeded plasma.

For potassium seeding, various types of compounds can be used but the most common ones reported for open-cycle MHD research are potassium carbonate (K_2CO_3) and sulfate (K_2SO_3). In regards to cesium seeding, Townsend (1972) reported that cesium oxide from pollucite can be used for makeup seed rather than cesium carbonate (Cs_2CO_3) which would require very high processing costs. Hoover et al. (1976) of Westinghouse Electric Corporation used Cs_2CO_3 for the initial seed input and make-up seed was supplied as an ore containing 25% cesium. Therefore, cesium-rich pollucite ore could be used directly for open-cycle MHD.

In a major USBM report that investigated the use of cesium/potassium seeding, Bergman and Bienstock (1972) stated that on an atomic basis, mole for mole, a cesium-seeded coal combustion plasma has a 50 to 100% higher conductivity than

potassium at customary MHD open-cycle plasma seeding levels. On a weight basis, pound for pound, a cesium-seeded plasma has a 5 to 30% higher conductivity than potassium. The level of conductivity is very important because at a high conductivity level (which is attained with cesium) the working temperatures do not have to be as high, therefore material stress is reduced (pers. comm., R. Carrington, 1983). The enhanced electrical conductivity from cesium translates into savings in material costs, and improvements in equipment performance; hence, lower capital investment costs for central-station MHD power generation (Bergman and Bienstock, 1972). Although cesium is clearly the preferred material for conductivity enhancement, there are major drawbacks from using pure cesium seeding. As outlined by Bergman and Bienstock (1972), the three obstacles are:

1. higher seed cost and lower seed recovery;
2. lower sulfur removal effectiveness; and
3. limited supplies of cesium.

1. Seed Cost and Recovery

To achieve equivalent levels of conductivity, Bergman and Bienstock (1972) calculated it would cost approximately five times as much for cesium seeding compared to the cost of potassium seeding. The price factor of five was based on a cost of 5 cents/lb. K_2SO_4, and 50 cents/lb for Cs_2O from pollucite ore. Assuming a 98% seed-recovery efficiency as

being adequate for MHD, they stated that cesium recovery would have to be at least 99.6% efficient for seeding costs to be competitive with potassium. Currently, K_2SO_4 was quoted at about 10 cents/lb, and Cs_2O may range from about $1.50 to over $2.50/lb. The price differentials for these two compounds have increased several times. Therefore, cesium seed make-up costs would be uneconomic at current prices compared to potassium. In addition, present day particulate collection technology cannot satisfactorily meet such high rates of seed recovery efficiency.

Carrington stated that current projections for K recovery are in the order of 95-97%. Furthermore, Cs recovery is expected to be in the same range as K; but there is far less information concerning cesium recovery to accurately project cesium recovery efficiencies (pers. comm., R. Carrington, 1984).

2. Sulfur Removal

One of the major pollution products which result from fossil fuel combustion is the emission of sulfur dioxide (SO_2). In fossil fuel MHD, SO_2 emissions are practically eliminated because of their reaction with the seed material. In a conceptual design study of potential early commercial MHD-steam power plants, Hals et al. (1981) designed a plant that satisfied U.S. New Source Pollution Standards (NSPS) requirements which necessitate 70% removal of the sulfur contained

in the coal-type used (Montana Rosebud). The researchers stated that complete sulfur removal appears practicable because of the high chemical affinity of potassium seed to sulfur. In addition, there is a system for regenerating the seed, in this case, potassium carbonate (K_2CO_3) from the ash, and then eventually producing elemental sulfur.

With pure cesium seeding, Bergman and Bienstock (1972) reported that sulfur removal would not be as effective as with potassium because normal cesium seeding levels are too low. Therefore, a flue-gas scrubbing process would have to be incorporated into the system. The additional expense for sulfur removal would negate economic gains from plasma conductivity improvement by the use of cesium.

3. Cesium Supply

The most serious obstacle to pure cesium seeding is the limited known supply of pollucite. Bergman and Bienstock (1972) illustrated this point by explaining that a potential 1,000 MWe coal-fired open-cycle MHD power plant operating with a seeding level of 0.70 lb-mole Cs_2O/ton (0.70 kg-mole/tonne) coal and a seed recovery efficiency of 99% would annually require 3,450,000 lb (1,565,000 kg) of Cs_2O make-up seed. They also stated that the world's largest deposit, at Bernic Lake, has known reserves of 150 million lb (68,040,000 kg) of Cs_2O. Therefore, one large power plant would consume about 2.3% of the Cs_2O at Bernic Lake annual-

ly. The researcher recalculated the problem based upon the Bernic Lake reserves reported in Crouse, et al. (1979) of 350,000 tonnes of pollucite grading 23.3% Cs_2O. The recalculation of annual consumption of Cs_2O at Bernic Lake was 1.9% which is still an extremely high consumption rate. Townsend (1972) also reported that pollucite reserves at Bernic Lake would be depleted quickly if cesium were used in open-cycle MHD.

Based on further investigations by Bergman and Bienstock (1972), they concluded that a mixed potassium-cesium ratio of 85 mole % K and 15 mole % Cs would be worth pursuing because of the estimated overall cost savings, and a reduction in the pollucite depletion rate. In response to the Bergman and Bienstock (1972) report, Carrington agreed that cesium would be an effective seed material; but should only be considered if the number of MHD facilities projected to be built were few in number. However, a large number of facilities are projected to come on stream, therefore the known reserves of pollucite are not large enough to maintain MHD open-cycle technology (pers. comm., R. Carrington, 1984).

MHD technology in the U.S.S.R. is also very advanced but the type of seed material used is not definitely known. Sources report that Soviet researchers have experimented with cesium and potassium. Townsend (1972) reported that the U-02 facility, which is gas-fired, was seeded with cesium. Presently, because the Soviet MHD program is expected

to rely on coal instead of the economically important export commodity natural gas, potassium seeding will likely be used.

Major Open-Cycle MHD Projects

The major countries which have in the past, and continue presently to be the leaders in open-cycle MHD technology are the U.S. and the U.S.S.R. The MHD information that follows is based upon communications with, and literature provided by Dr. R.A. Carrington, Mountain States Energy Inc., Butte, Montana. Also, literature was provided by Dr. L.H.Th. Rietjens, Eindhoven University of Technology, Eindhoven, The Netherlands.

United States

The U.S. open-cycle MHD program, which is based on coal as the fuel source and potassium seeding, is a cooperative effort involving the U.S. Department of Energy, various universities, and private industry. The MHD program is basically structured using a two phase approach to commercialization (by year 2000). The objective of Phase I is to design and establish an advanced test facility. This facility would integrate topping and bottoming cycles into a unit approximately 80-130 MWe in size. Presently in the Phase I stage, there are two major test facilities in the U.S. involved in the engineering aspects of MHD: the Component Development and Integration Facility (CDIF) near Butte,

Montana; and the Coal Fired Flow Facility (CFFF) located at the University of Tennessee, near Tullahoma. The CFFF is capable of continuous operation at an input of 28 Megawatts thermal (MWt) and short duration testing at large scale.

The CDIF was constructed in 1976 through 1980 with the capability to test MHD topping cycle components. In November, 1980, combuster tests were performed at the facility utilizing oil as the primary fuel. The combuster is designed to burn number two fuel oil in an oxygen enriched atmosphere at a nominal input of 50 MWt and potassium is used for seeding.

On April 21, 1981, power was generated for the first time and 436 KWe (Kilowatts electrical) were produced. After several tests and modifications to the system, on October 13, 1982, a nominal 1.0 MWe was supplied to the commercial grid during an inverter test. Further testing continued during 1982-1983, and presently the CDIF is in the process of experimenting with a 50 MWt coal-fired combustor.

Federal funding for open-cycle MHD began with $600,000 in 1971 and peaked in 1980 at $79 million. For comparison, federal funding for nuclear power has been about $4 billion (Volkman, 1983). Volkman adds that the Reagan Administration, believing that viable energy technologies will find private funding, cut MHD out of the 1982 and 1983 budgets entirely. However, Congress kept the research going at a

nominal level of about $30 million per year for three years
(1982-1984). This year, the U.S. Department of Energy has
renewed its multi-year MHD program and nominal funding in
the $30 million range has been provided for fiscal year 1985
(pers. comm., R. Carrington, 1984). For historical and po-
litical perspectives about MHD technology in the U.S., refer
to Volkman (1983), Rietjens (1983), Freeman (1980), and
Melcher (1977).

Soviet Union

From the limited information available, it appears that an
MHD research development program in the U.S.S.R. began in
1961 (Rudins, 1974). Rudins adds that in 1962, at the First
International Conference on MHD in England, the Soviet con-
tingent announced that the U.S.S.R. had begun on a program
to develop commercial-scale MHD. By 1965, the Soviets com-
pleted a small-scale model of a complete commercial gas-
fired MHD plant, the U-02, near Moscow. The U-02 was fol-
lowed by the U-25, ENIN-2, and the Kiev facility (Rudins,
1974).

Rietjens (1983) reported that the U.S.S.R. National Pro-
gram on MHD Electrical Power Generation may be divided as
follows:

1. construction by 1985 of a commercial MHD combined cy-
    cle natural gas plant, followed by the construction
    of several similar plants operating on oil in metro-
    politan areas; and

2. construction of MHD power plants operating on coal, with start-up of the first commercial plant in the early nineties.

Rietjen (1983) concluded by reporting that the first commercial plant will be the U-500 Ryazan Power Station (250 MWe topping, 250 MWe bottoming cycle) and that on-site construction has begun. The U-500 station is expected to come on-line in 1988.

3.10.2.2   Closed-Cycle MHD

The closed-cycle MHD system was initiated about 20 years ago as a method through which the advantages of open-cycle MHD might be retained, while its main disadvantages -- high temperature requirements and a very chemically active flow, could be lessened (Corman, et al., 1976). As the name indicates, the closed-cycle MHD involves circulation of the working fluid in a closed loop; whereas the open-cycle working fluid (combustion gases) is not recirculated.

One of the major advantages of closed-cycle MHD is a lower inlet temperature of about 2,300°C compared to 3,000°C for an open-cycle MHD system (Rietjens, 1981). At the lower temperature, appropriate conductivity is achieved because the electron temperature is elevated over the gas temperature (Kerrebrock effect or non-equilibrium effect). In closed-cycle MHD the working fluid of the MHD generator is a noble gas (argon or helium) which is seeded with cesium or

potassium to increase the conductivity. The main purpose for developing closed-cycle MHD technology is for use as a topping-cycle in electric power generation systems fired by fossil fuels. A schematic of a closed-cycle MHD steam plant is presented in Figure 6.

Major U.S. studies of closed-cycle MHD were conducted by General Electric and Westinghouse, with final reports published in 1976 and were detailed in Grundy (1978). The best General Electric closed-cycle configuration resulted in an overall efficiency of 41.8%, and for Westinghouse 46.1%. The seed material used in both studies was cesium at levels of about 0.1%. Because the U.S. is pursuing an open-cycle MHD program, closed-cycle research is on a very limited scale, such as the program at the Southern California Edison Company.

Today, the most intensive closed-cycle MHD research program is in The Netherlands at the Eindhoven University of Technology (THE), the principal investigator being Dr. L.H.Th. Rietjens. Based on one of the conclusions presented by Marston, et al. (1975) that:

> "A blow down facility can be considered as a physical demonstration experiment for a fossil-fired closed-cycle MHD plant. In order to approach an isentropic efficiency of 50%, the power levels of this facility should be at least 5 Megawatts thermal (MWt)."
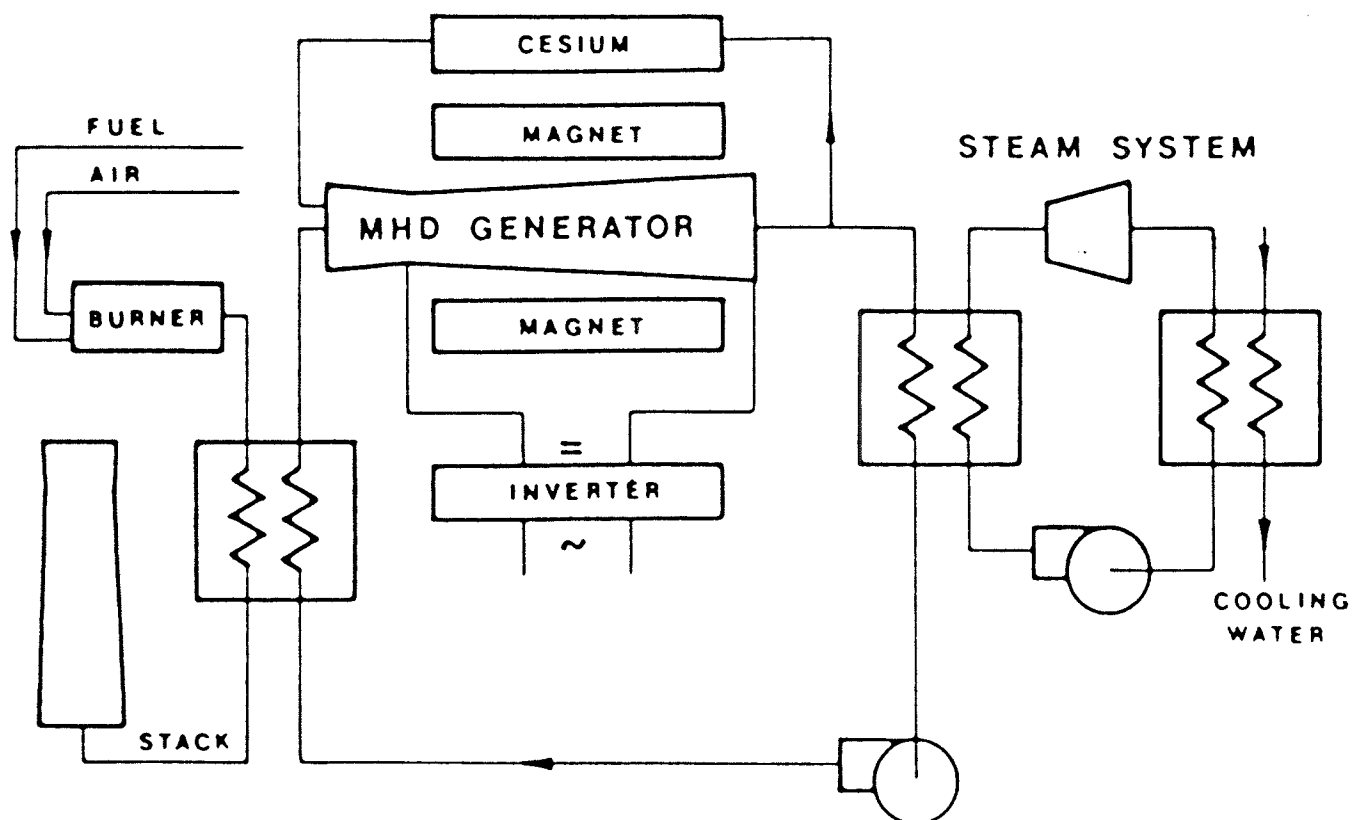
Figure 6:   Schematic of a Closed-Cycle MHD Steam Plant
Source: Rietjens, (1983).

An MHD blow down facility[7] in the 5 MWt range was designed
and built at THE and has been brought into full operation
(Rietjens, 1983). According to Rietjens (1983) the major
technical hurdle that remains in closed-cycle MHD is the de-
velopment of coal-fired heat exchangers.

The Eindhoven facility has been designed for an argon
mass flow rate of 5 kg/s. Also, an aerosol of cesium dro-
plets is injected into the argon flow at cesium concentra-
tions of about 0.10% molecular. Blom, et al. (1978) re-
ported that the appropriate cesium flow-rate in this system
is 15 g/s or 30 l/hr.

Cesium requirements, in the form of cesium metal, for
projected large-scale closed-cycle MHD power plants have not
been published. According to researchers in this field,
cesium metal will mostly be required for start-up purposes
only. Because the system is a closed-loop, and the cesium
recovery efficiency is expected to be greater than 99%, a
continuous demand for make-up cesium, as would be the case
in an open-cycle system, will unlikely occur (pers. comm.,
J. Louis, 1984). Overall, there is little doubt that
closed-cycle MHD will use cesium as a seed material and in
lower concentrations relative to open-cycle; but more stud-

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[7] A blowdown facility involves charging a heater either
thermally or electrically and then driving a gas through the
heated bed until the temperature has fallen to a minimum ac-
cepted level. Blowdown facilities are well suited for inert
gases which do not clog or damage the heater bed or elements
(Rudins, 1974, p.59).

ies are necessary before resource requirements can be estimated.

In regards to the future of closed-cycle MHD, Dr. J. Moyer at Southern California Edison stated the following:

1. U.S. electrical demand will mostly be supplied by small generating stations in the 50 - 300 MWe range. Therefore, closed-cycle topping cycles are more effective in small electrical systems compared to open-cycle which are primarily effective in 500 MWe range or greater; and

2. closed-cycle MHD is a less complicated system compared to open-cycle (pers. comm., J. Moyer, 1984).

Another advantage of closed-cycle MHD systems is their expected adaptability to combine with fusion energy technology (per. comm., J. Louis, 1984).

3.11   FORECASTS OF U.S. AND REST-OF-WORLD CESIUM DEMAND

Bascle (1980) presented data that summarized forecasts of U.S. and rest-of-world cesium demand. U.S. and rest-of-world cesium demand figures were listed for 1978 with high, low, and probable cesium demand values as well as cumulative consumption values to the year 2000. According to the data presented by Bascle (1980) and Harris (1979), U.S. cesium demand in 1977 and 1978 was approximately 48% of total world cesium demand. By the year 2000, Bascle (1980) reported

that probable U.S. cesium demand will increase to about 60%
(154 t cesium content) of total world cesium demand (256 t
cesium content).

The forecast high and low values for cumulative cesium
demand for the period 1978-2000 as presented in Bascle
(1980) are of particular interest. Bascle stated that if
MHD technology develops, the forecast high value for cumula-
tive world cesium demand in 2000 would be 10,300,000 lb
(4,672 t) cesium content. The low range value, primarily
based on negligible use of cesium in MHD, was forecast to be
only 960,000 lb (435 t) cesium content.

The forecast high value will unlikely be attained because
cesium has been substituted by potassium in open-cycle MHD
technology. Also, if cesium were going to be used in open-
cycle systems, pollucite concentrate would be used directly
with no further processing required. On the other hand, if
catalyst technology involving cesium and/or closed-cycle MHD
technology advance to commercial-scale levels, then cesium
demand will probably be higher than the forecast low value.
In addition, pollucite processing would be required to
produce cesium compounds/metal for catalyst and closed-cycle
MHD systems.

3.12 CESIUM TOXICOLOGICAL/ENVIRONMENTAL REVIEW

Toxicity studies of cesium metal and compounds are limited to two reports published in the early 1970's by the National Institute for Occupational Safety and Health (NIOSH) in the U.S. The first report by Johnson, et al. (1972) was an acute toxicity study of cesium and rubidium compounds. The report was initiated because recent and projected industrial applications indicated increased usage of the hydroxides and iodides of Cs and Rb.

The Johnson, et al. (1972) study assessed the acute toxicity of the above mentioned compounds and used the following procedures:

1. LD_{50} studies - Rats (oral);

2. Primary Skin Irritation Studies - Rabbits;

3. Eye Irritation Studies - Rabbits; and

4. Skin Sensitization Studies - Guinea Pigs.

In the summary conclusion, the researchers reported that hydroxides of cesium and rubidium are more toxic than the iodides. Also, cesium, potassium, and rubidium hydroxides are strong alkalis, and contact with the eyes or skin should be avoided.

The second NIOSH report on cesium, Maier and Lucas (1973), was a health hazard/toxicity determination study of the cesium processing facility operated by KBI at Revere,

PA. The researchers inspected the physical plant and then conducted medical tests to determine if exposure to cesium and rubidium compounds were a health hazard to the plant employees. Maier and Lucas (1973) concluded that exposure to cesium and rubidium and their salts is minor, and all exposed employees were asymptomatic.

Recent cesium acute toxicity studies have been conducted by Pinsky, et al. (1981) and Bose and Pinsky (1983). These studies were initiated, just as the NIOSH studies, in anticipation of cesium being involved in technological developments such as MHD, and the entry of cesium into the workplace and general environment. These studies are very detailed medical investigations using the most modern techniques, procedures, and instrumentation. The results address several areas of study including: histopathology, acute toxicity and general behavioural responses. Therefore, the reports should be consulted for proper interpretations and further references.

3.13   CANADIAN EXPORT CONTROL OF CESIUM

From late 1969, when Tanco began mining operations at Bernic Lake, until the end of 1975, shipments of pollucite totalled about 1,400 t with an average Cs_2O content of almost 27% (Hogan, 1981). The biggest demand for Bernic Lake pollucite during the period 1969 - 1975 was from the U.S.S.R. which purchased about 86% of the export shipments (Tanco Files),

(Hogan, 1981). However, by an Order-in-Council dated September 22, 1976, the Canadian Government placed cesium in all forms -- including ores, concentrates, chemical compounds, cesium metal and alloys containing cesium in the Export Control List (ECL: Group 5: 5674) (Canada, 1978) , established under the Export and Import Permits Act (EIPA) (Canada, 1970). Following the export ban, Tanco's shipments decreased sharply. The purpose of this section is to present information regarding the implementation of the ban, and the current status of the ban on cesium materials.

One of the earliest indications of the possible placement of cesium in the ECL was a communication in 1973 from an official representing the Federal Department of Industry Trade and Commerce to the President of Tanco. The letter stated that because of the continental energy problems and the possible future development of MHD power generation using pollucite as a raw material, concern had been expressed regarding the conservation of the Bernic Lake pollucite deposits. Also, that pollucite concentrates may become subject to export controls (Tanco Files).

Tanco continued to export pollucite. However, in April of 1976, Tanco applied for a permit to export pollucite to the U.S.S.R., but the permit was refused. In June of 1976, the Chief of Export and Import Permits Division communicated to Tanco that the application was refused because of existing Government policy (Tanco Files).

In reviewing subsequent correspondences: between the Federal Government and Tanco (Tanco Files); published Commons Debates (Canada, 1977); and newspaper reports, Northern Miner (1977), and Winnipeg Free Press (1977), it appears that the export ban on pollucite was placed for one or both of the following reasons:

1. pollucite and its derivatives were considered to have strategic applications; and

2. the government wanted to investigate and encourage further processing of pollucite to increase industrial development, especially in high technology applications.

In a correspondance with the Special Trade Relations Office of the Department of External Affairs, an official reviewed the history of the case and stated:

> "Under the Export and Import Permits Act, permits are required for the export of cesium in all forms (including ores,....) to any destination, except the United States, by virtue of the fact that this particular product falls under the Export Control List Item 5674. Applications for permits to export cesium to Area Control List countries and the People's Republic of China would require approval from the Department of National Defence in order to preserve Canadian national security interests." (pers. comm., L. Pamerleau, 1983).

Mr. Pamerleau also stated that under sub-section 15 of the EIPA, it is illegal to knowingly cause or assist the shipment or transshipment of a commodity included in the ECL to any country in the ACL.

In a discussion with the Department of National Defence (DND), an official stated that DND has no strategic policy regarding cesium[8]; and that cesium is of no concern to them as far as national security (pers. comm., Major P. Van Boeschoten, 1984). In the most recent conversation with an official at the Department of External Affairs, he stated that the entire ECL will be reviewed and updated during 1984-85. (pers. comm., R. Caux, 1984). Mr. Caux added that all entries in the ECL, including cesium, will be reviewed by various government departments. If concern(s) such as military, economic, or other are expressed to keep a commodity in the ECL, there will be a further evaluation and ultimately, a decision will be made regarding the commodity's status. In the U.S., exports of cesium commodities require an export permit (pers. comm., T. Adams, 1984). However, it is not clear whether an application for cesium exports would be accepted or refused.

After reviewing the export ban issue, and having corresponded with the federal departments of External Affairs and National Defence, no clear explanations have been given to the researcher by the Government of Canada for denying Tanco an export permit to ship pollucite concentrates to the Soviet Union.

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[8] Cesium is not listed as being a strategic material in Canada or the U.S.

3.14 MANITOBA GOVERNMENT INVOLVEMENT

The Province of Manitoba does not have jurisdiction of export trade, but in regards to resource depletion, the Province does have jurisdictional power. Important provincial legislation which has an effect on the Tanco operation is concerned with further processing opportunities and resource conservation. Section 9 of The Mines Act, being Chapter M160 of the Revised Statutes of Manitoba, provides as follows:

> "9(1) All permits or leases shall be subject to the provision that all ores or minerals mined from locations described in those permits or leases shall be treated and refined within Canada, so as to yield refined metal or other product suitable for direct use in the arts without further treatment; in default whereof the permit or leases issued for the lands is and shall become void, and the lands forthwith revert to, and become revested in, the Crown, freed and discharged of any interest or claim of any other person, and are open to disposal in such manner as the minister may decide.
>
> 9(2) The Lieutenant Governor in Council may exempt any lands from the operation of this section for such period of time as to him may seem proper."

Based on subsection 9(2), Tanco requested re-exemption in 1982 primarily for the following reasons:

1. annual world demand for cesium ore was less than 200 tonnes; and

2. there were no facilities in Canada for treating and refining cesium ore; and the cost of developing the technology to refine these small quantities of ore were not justified at the time.

Therefore, the Lieutenant Governor in Council exempted Tanco from the provision of subsection 9(1) of the The Mines Act, but also stipulated that cesium ore shipments should not exceed 1,000 tonnes in each year for a period of five years from June 1, 1982 (Tanco Files).

By regulating the annual shipment levels of pollucite, the Manitoba Government can monitor the cesium resource depletion rate. Furthermore, these actions provide the Manitoba Government with information to consider economic strategies/opportunities when significant changes in pollucite demand occur.

Chapter IV

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

There is a unique deposit of minerals located in the south-
eastern region of Manitoba at Bernic Lake. This deposit of
minerals contains ores of the following minor metals: cesi-
um, rubidium, tantalum, gallium, beryllium, and lithium.
Since 1969, the Bernic Lake pegmatite deposit has been oper-
ated by Tantalum Mining Corporation of Canada Limited (Tan-
co), of which the Province of Manitoba has a 25% interest.

Tanco suspended operations at Bernic Lake as of December
31, 1982, because of the weak markets for its primary prod-
uct, tantalum. Employment of the approximately 105 full-
time employees had therefore been terminated[9].

The Bernic Lake deposit is of special importance because
it contains the world's largest known reserves of the cesi-
um-rich ore, pollucite; and Tanco is the major world suppli-
er of pollucite. From 1969 to date, the average annual de-
mand for pollucite from Tanco has decreased. One of the
primary reasons for the decreased demand was that in 1976,
pollucite and its cesium derivatives were placed in the Ex-

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[9] In the spring of 1984, the Federal Government provided
funding for lithium studies at the mine. This program re-
sulted in the hiring of about 30 employees, most of whom had
previously been employed at Tanco.

port Control List, hence cutting off the supply of pollucite to the major purchasing country, the Soviet Union.

The primary objective of the practicum was to evaluate the potential for Manitoba's cesium-rich pollucite deposits. After reviewing the related literature, and corresponding with industry, research, and government representatives involved with cesium, the practicum primary conclusions are:

1. Tanco will continue to be the major world supplier of pollucite, and demand for pollucite will be steady with moderate increases in the short term. However, average annual demand for Tanco pollucite is unlikely to exceed 500 t to the year 2000;

2. Pollucite concentrates are not used directly in any end-use applications (except for minute amounts in certain types of MHD experiments), but are processed to produce cesium primary products (compounds and metal);

3. The largest demand for cesium primary products is for the compounds, especially cesium chloride for preparing density gradient solutions in DNA research;

4. The greatest demand for cesium was expected to be for use in open-cycle MHD technology; however, potassium has substituted for cesium. Also, if cesium were to

be used in open-cycle MHD, then it would be used in the form of pollucite concentrate and not a processed product such as a compound or metal;

5. Current research investigations which may lead to commercial levels of production and therefore signif-icant increases in the demand for cesium (compounds/ metal) are: catalysts (cesium promoters) in the im-mediate future; and closed-cycle MHD (cesium plasma seed) in the distant future (after 2000); and

6. The development of Canadian pollucite processing fa-cilities to produce cesium primary products are not warranted at this time because current demand for cesium primary products is low and therefore are eas-ily supplied by existing facilities elsewhere (West Germany and the U.S.).

7. Figure 7 shows the transformation of pollucite ore to cesium primary products, as well as present and po-tential end-uses.

```
                        ┌──────────────────┐
                        │    POLLUCITE     │
                        │       ORE        │
                        └──────────────────┘
                                 │
                                 │            ╭─────────────╮
                                 ├────────────┤    Mine     │
                                 │            │ Processing  │
                                 │            ╰─────────────╯
                                 │
                        ┌──────────────────┐
                        │    POLLUCITE     │
                        │   CONCENTRATES   │────── no anticipated end-uses
                        │    24% Cs₂O      │
                        └──────────────────┘
                                 │
                                 │        ╭────────────────────╮
                                 ├────────┤  Chemical Company  │
                                 │        │     Processing     │
                                 │        ╰────────────────────╯
                                 │
      ┌──────────────┐           │
      │  Byproducts  │◄──────────┤
      └──────────────┘           │
       - rubidium (aprox. 1%)    │
         (similar properties     │
            to cesium)           │              ╭────────╮
                                 ├──────────────┤ Wastes ├ (mostly alumina -
                                 │              ╰────────╯      silicates)
                                 ▼
     ╭──────────────────╮  ┌──────────────────┐  ╭──────────────╮
     │ Cesium Compounds │──┤      CESIUM      │──┤ Cesium Metal │
     ╰──────────────────╯  │ PRIMARY PRODUCTS │  ╰──────────────╯
              │            └──────────────────┘          │
              ▼                                           ▼
     Present End-Uses                          Present End-Uses

      - photoemissive devices                   - photoemissive devices
      - scintillation and optical crystals      - frequency and time
      - density gradient solutions                standards
              ┊                                           ┊
              ▼                                           ▼
     Potential End-Uses                        Potential End-Uses

      - catalysts                               - closed-cycle MHD
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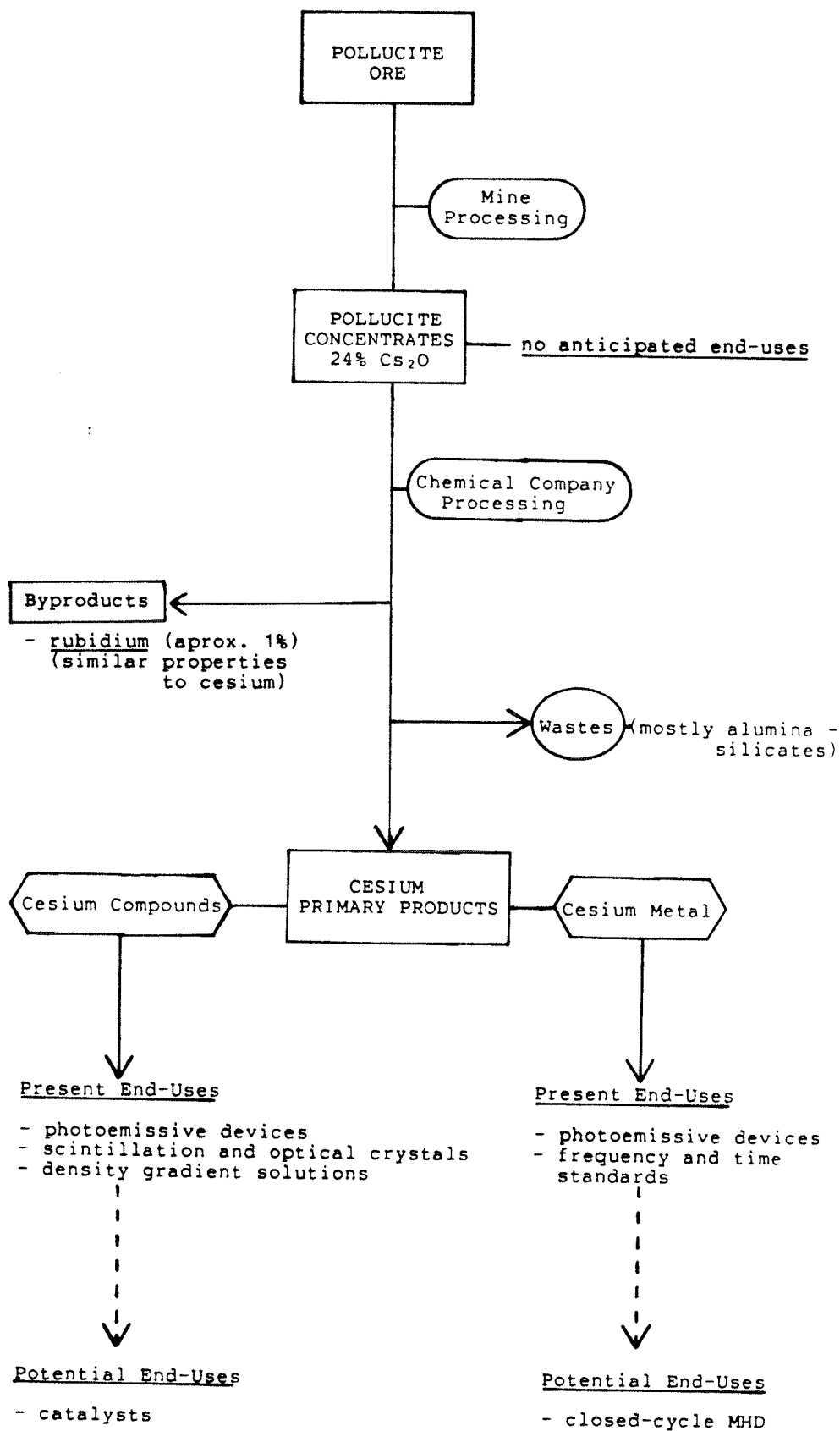
Figure 7:   Transformation of Raw Pollucite to Processed
            Products and End-Uses

The practicum sub-objectives are addressed in the following summary.

1. Supply-Demand

The most concentrated natural source of cesium occurs in the rare mineral pollucite which may contain a cesium oxide concentration ranging from 5-32wt.%. The Tanco deposit at Bernic Lake is of high grade (24% Cs_2O) and represents about 66% (350,000 t) of the known world pollucite reserves, followed by Bikita, Zimbabwe (about 25%), and Karibib in Namibia (about 8%). Although the mining operations in Bikita and Karibib have made sales of pollucite, political instabilities in these countries have disrupted commodity exports and therefore are unreliable sources of supply. As a result, Tanco dominates the pollucite market and its sales reflect pollucite demand, and ultimately cesium demand by the free-world.

Since 1977, the greatest demand for Bernic Lake pollucite has been from the major pollucite processing countries, the U.S. and West Germany. The U.S. represents the largest end-user demand (about 48%) for cesium products. Of the countries that export cesium compounds into the U.S., West Germany supplies over 90%.

The USBM forecasted cesium demand to the year 2000 and included low, probable, and high cumulative world demand levels. The high value of 4,672 t cesium content is unlikely to be attained because open-cycle MHD technology is not using cesium for a plasma seed source. The low forecast value of 435 t cesium content is a more realistic estimate and may increase if other applications for cesium are developed.

2. Major Processors and Distributors

In the western world there are only two major processors of pollucite ore: KBI (part owner of Tanco) in the U.S., and Metallgesellschaft in West Germany. Both companies produce cesium primary products (compounds and metal) as well as primary products from other minor metal ores. KBI and Metallgesellschaft supply kilogram lots of cesium primary products, especially compounds, to small supplier/distributor companies or to end-users directly. The supplier/distributor companies usually reprocess the cesium compounds to higher purities and repackage them into smaller gram lots for resale. In the U.S. there are about 20 supplier/distributor companies.

3. Cesium Grades and Prices

Cesium compounds are typically available in a standard or technical grade (99.0% min.), and high purity grade (99.9+%). Kilogram lots of technical grade compound were priced at about $US 76.60/kg, and about $US 160.70/kg for high purity. Cesium metal is available in various grades, but usually technical grade (99.5% min.) and high purity (99.9+% min.). Technical grade cesium metal was priced at about $US 600/kg, high purity about $US 720/kg, and very high purity about $US 1,100/kg. Compound and metal prices are based on 1983 figures, F.O.B. source, and for small quantities. Pollucite ore in 1981 was traded in the range of $US 3-4/kg cesium oxide (24% min.). In 1983 it was traded in the range of $US 2-3/kg. The above pollucite prices are based on F.O.B. source, and large tonnage quantities.

4. Present End-Use Applications

There are no commercial end-use applications for pollucite concentrates. Cesium primary products (compounds and metal) are used in several end-use applications, especially: photoemissive devices such as photomultiplier tubes and infrared cameras; scintillation crystals for radiation detection; and density gradient ultracentrifugation solutions for separating DNA. These three applications currently account for an estimated 20 - 25 thousand kg of cesium primary products in the U.S., and would require approximately 150 t of pollucite to produce.

5. Major Research and Development Projects

The most important research projects which might generate an increased demand for cesium (in the forms of compounds/metal) are:

1) catalyst improvements for the synthesis of ethylene oxide and the synthesis of methylmethacrylate; and

2) closed-cycle MHD, which incorporates cesium to enhance conductivity.

It was expected that research activities investigating the contact ion engine for space propulsion would lead to a significant increase in demand for cesium metal. However,

other types of propulsion systems, based on the use of
xenon, argon, or mercury, have since been developed and are
superior to the cesium contact ion engine.

6. Substitution

Most of the other alkali metals could substitute for cesium.
In fact, the alkali metal potassium, though not as effec-
tive, is substituting for cesium in open-cycle MHD technolo-
gy because potassium is more abundant and therefore several
times less expensive. However, in applications such as pho-
toemissive devices cesium is superior; and because very lit-
tle cesium is required, substitution is unlikely to occur.

7. Toxicological/Environmental Studies

Based on studies conducted in the U.S. in the early 1970's,
exposure to cesium, rubidium, and their salts was minor, and
plant employees working with cesium were asymptomatic. How-
ever, alkali hydroxide compounds such as cesium hydroxide
are very strong and contact with the eyes or skin should be
avoided. Also, cesium metal is very reactive when exposed
to air or water and must therefore be handled and transport-
ed in special containers.

8. Export Controls

Pollucite and its cesium derivatives were placed in the Ex-
port Control List in 1976 by the Canadian Government. The
export controls resulted in lost sales of pollucite to the
major purchasing country, the Soviet Union. During
1984-1985, the entire Export Control List will be reviewed
and the status of pollucite will be re-evaluated. The re-e-
valuation will be based on military (national security) and
economic (further processing opportunities) factors.

4.1 RECOMMENDATIONS

(A) The principal owners of the Tantalum Mining Corporation should expand their active market research program for all of its minor metals and industrial minerals. The program's principal objectives should be to:

1. Review and critically assess the related scientific literature (journals of various disciplines and patent reports);

2. Establish communication links with private industry and research representatives so that current "on the street" market forces can be evaluated;

3. Monitor the budgets and funding programs of those countries which are actively involved in high energy technology research in which metals such as cesium and lithium could be incorporated (e.g. MHD and fusion); and

4. Prepare up-to-date commodity market status reports on a regular basis for submission to the appropriate officials for further assessment.

(B) The sale prices of Tanco's commodities should be reviewed on a regular basis; and all factors which account for the final prices should be scrutinized in terms of new market opportunity potentials and natural resource depletion rates.

(C)   Further processing of mineral resources leads to an expanded economic base. Although pollucite processing facilities are not warranted at this time because of the low demand for cesium primary products, a response mechanism should be designed to react with pre-planned actions when appropriate key signals indicate further processing opportunities.

(D)   In principle, the Manitoba Government should assist Tanco in its pursuit to investigate the pollucite export ban issue by communicating the Province's concerns to the Government of Canada. Furthermore, Tanco should determine whether the Soviet Union continues to be a purchaser of pollucite.

(E)   Mineral exploration activities should be encouraged to discover and inventory other pollucite and minor metal deposits. These activities will lead to an increased and more diverse mineral resources base and possibly encourage more participation in research and development programs.

(F)   Cesium's unique chemical and physical properties should be further investigated by research organizations such as the National Research Council and the Industrial Technology Centre. New research initiatives may lead to the discovery of more applications for cesium and possibly also generate an increased demand for pollucite and cesium primary products.

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Appendix A

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Appendix B

STANDARD METHODS FOR MANUFACTURING CESIUM
COMPOUNDS AND CESIUM METAL

The following information regarding the manufacture of cesi-
um compounds and cesium metal was mostly obtained from Wil-
liams (1979).

Manufacture of Cesium Compounds

Pollucite is decomposed by acid digestion or by melting or
sintering with an alkaline flux. Hydrofluoric acid gives
the most complete cesium recovery from pollucite, but be-
cause of the ease of handling, hydrochloric, hydrobromic, or
sulfuric acids are used commercially. The laboratory proce-
dures for the extraction of cesium from pollucite with hy-
drochloric and sulfuric acids are detailed in Bailor (1953),
and these procedures can be scaled up easily with negligible
modifications.

According to Dean and Nichols (1962), the cesium ore is
ground to less than 149 microns (-100 mesh) in a ball mill
with sufficient water to give a 60% solid slurry. The
ground ore pulp is diluted to 33% solids in a flotation cell
and 2.5 - 7.5 kg of sulfuric acid per tonne of ore are added
to give a pH of 1.4 - 2.7. Hydrofluoric acid and then alu-
minum sulfate are added in quantities of 0.5 - 1 kg/t ore

and 250 - 500 g/t ore, respectively. After conditioning the pulp and reagents for 10 min., a cationic reagent such as Armac CD (a coco amine acetate) is added (200 - 500 g/t ore) and conditioned for 3 min. Then the non-pollucite minerals are removed by froth flotation.

Parsons et al. (1963) developed a process based on sulfuric acid decomposition of pollucite which is suitable for tonnage production of cesium chloride. Pollucite ore, ground to less than 74 microns (-200 mesh), is leached for 4 - 6 hours in 6 - 8 kg batches in glass-lined vessels with 35 - 40% sulfuric acid at 110°C. The ore residue is removed by pressure filtration of the hot leach slurry, and cesium alum is crystallized from the leach filtrate by cooling to 50°C and then to 20°C. The cesium alum is roasted with 4% carbon added to decompose the alum. The decomposed material is then leached to give a cesium sulfate solution. The cesium sulfate is converted to cesium chloride by ion exchange on Dowex 50 Wx8, and solid cesium chloride is recovered by evaporation and dehydration at 260°C. Figure 8 is a flowchart of the above process.

Depending on the process used, industry sources report that 70 - 90+% of the available cesium in the pollucite ore can be recovered. Also, rubidium values within the pollucite may be high enough to warrant recovery.
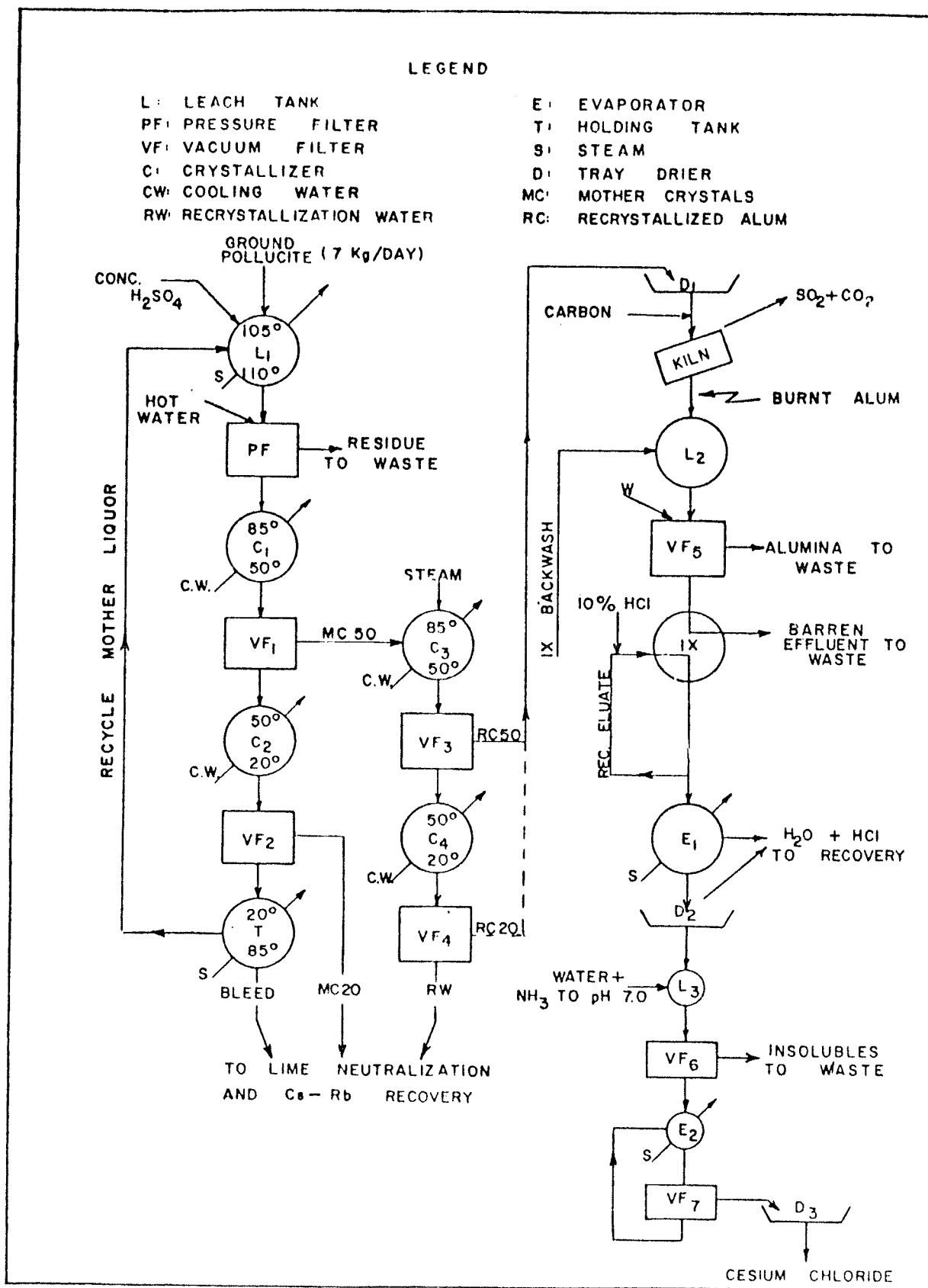
Figure 8: Batch Pilot Plant for Production of Cesium Chloride
Source: Parsons et al., (1963).

Manufacture of Cesium Metal

Williams (1979) outlined thermochemical and electrolytic reduction methods for the manufacture of cesium metal. A typical thermochemical method involves the use of calcium or barium to reduce cesium halides. A mixture of cesium chloride and calcium (50 - 60% of the weight of the CsCl) is heated to 700 - 800°C under vacuum, and 90 - 95% of the cesium metal is distilled from the mixture.

A process believed to be representative for the production of cesium metal from pollucite (Figure 9) was reported by Battelle Columbus Labs and the USBM (Battelle Columbus Labs, 1976). This report included energy input requirements for each stage of the process (mining to end product). Total energy required per ton of cesium metal, 528×10^6 BTU ±25%, was based on information obtained from the literature and from industry sources.
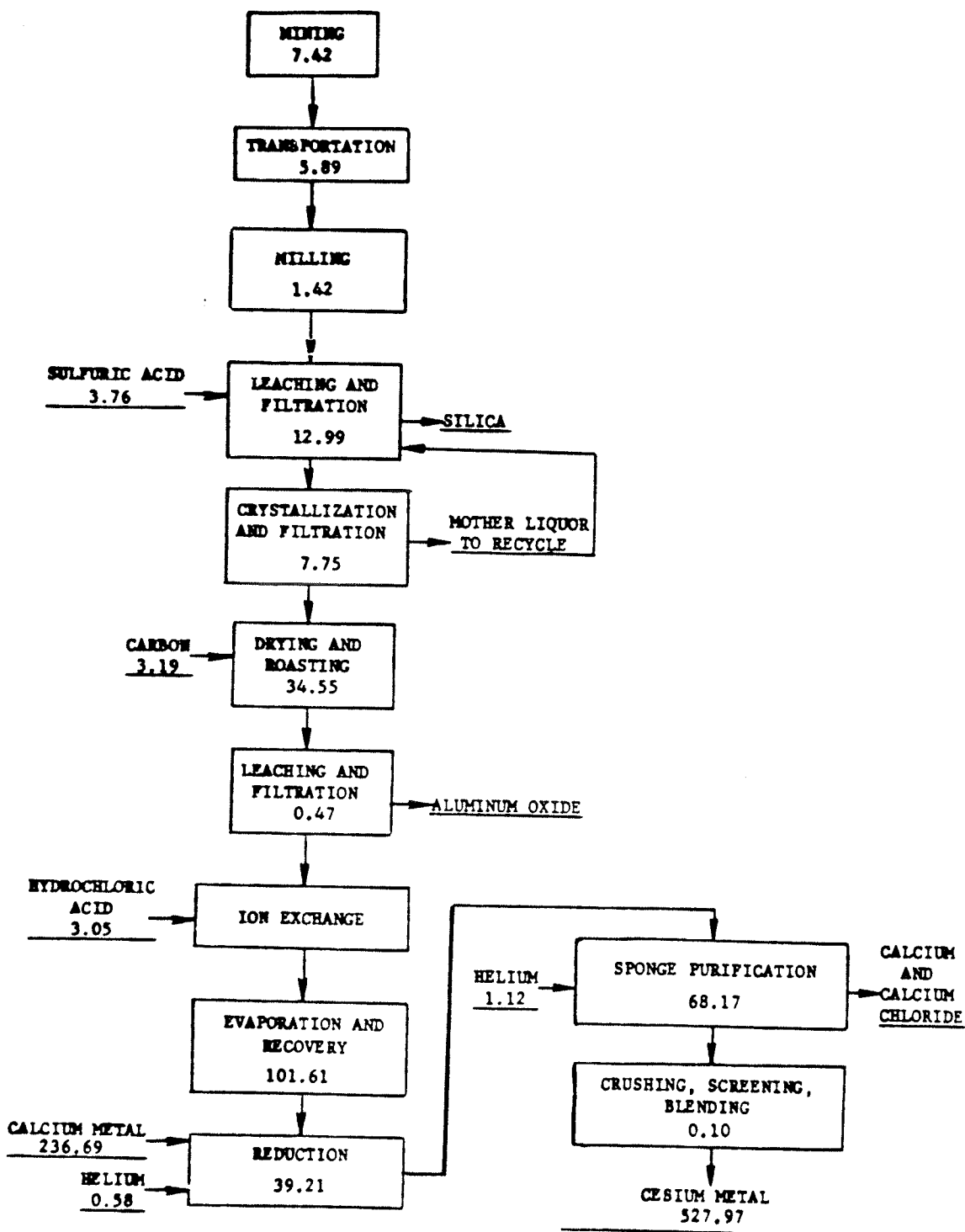
Figure 9: Production Flowsheet of Cesium Metal
Source: Battelle Columbus Labs, (1976).

Appendix C

SAMPLE CALCULATIONS AND ASSUMPTIONS

1) Cesium (Cs) atomic weight approx. = 133

   Oxygen (O) atomic weight approx. = 16

   Cesium oxide (Cs_2O) atomic weight (133+133+16) = 282

   % theoretical Cs in Cs_2O (133+133/282x100) = 94.3%

2) Pollucite (24% Cs_2O containing 94.3% Cs) contains

   approx. 22.63% theoretical cesium:

   100 t pollucite x 24% = 24 t Cs_2O

   24 x 94.3% = 22.63 t cesium

3) Assumption: there is a 54% yield of cesium from pollucite containing 24% Cs_2O.

The USBM reports cesium data in pounds cesium content. Bascle (1980) reported that in 1978 world mine production of cesium was about 68,200 lb (30,935 kg) of recoverable cesium from pollucite, and that it was all produced in Canada. Also, that U.S. imports of cesium concentrates in 1978 were 68,200 lb. Therefore, all of Canada's cesium production in 1978, which also represented world production, was exported to the U.S. Hogan (1981) reported that in 1978 Canada shipped 254 t of pollucite, all from Tanco, to the U.S. In addition, Tanco files show that this pollucite shipment con-

tained 27.2% Cs_2O. Therefore, a relationship must exist be-
tween 68,200 lb cesium content and 254 t of pollucite.

254 t pollucite (27.2% Cs_2O) = 65,150 kg theoretical cesium

68,200 lb cesium content = 30,935 kg cesium

30,935/65,150 x 100 = 47.48% estimated cesium recovery.

Assuming that pollucite typically contains 24% Cs_2O, then
estimated cesium recovery would be 54%:

254 x 22.63% x 54% x 2204.6226 = approx. 68,200 lb cesium content.

4) Assumption: according to industry sources, a factor of
70% is reasonable for estimating cesium compound yields from
Cs_2O.