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THE BENTONITE INDUSTRY IN NORTH AMERICA: SUPPLIERS, RESERVES, PROCESSING CAPACITY AND PRODUCTS

L'INDUSTRIE DE LA BENTONITE EN AMÉRIQUE DU NORD: FOURNISSEURS, RÉSERVES, CAPACITÉ DE TRAITEMENT ET PRODUITS

David A. Dixon, David S.J. Hnatiw, Bradley T. Walker

Whiteshell Laboratories
Laboratoires de Whiteshell
Pinawa, Manitoba R0E 1L0
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AECL RESEARCH

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RÉSUMÉ

Dans le cadre du Programme canadien de gestion des déchets de combustible nucléaire, on étudie un concept de stockage permanent géologique des déchets de combustible nucléaire à une profondeur de 500 à 1000 m au-dessous de la surface, dans la roche cristalline stable du bouclier canadien. Les conteneurs de déchets seraient entourés d'un matériau tampon à base d'argile. Ce matériau serait composé de bentonite et de sable quartzeux calibré en poids sec de proportions égales.

Pour le concept de stockage permanent de référence, on stockerait quelque $1,9 \times 10^5$ Mg de combustible usé. Ceci nécessiterait quelque $2,5 \times 10^6$ Mg de bentonite à incorporer au système de scellement à base d'argile de l'enceinte de stockage permanent. Comme il faut établir la disponibilité de ce matériau à qualité assez haute, on a étudié l'industrie de la bentonite en Amérique du nord dans le cadre de l'évaluation de la possibilité de réalisation du concept de stockage permanent. Il existe des réserves confirmées de bentonite à sodium de plus de $1,5 \times 10^8$ Mg et on sait qu'il existe des réserves beaucoup plus importantes non encore confirmées. L'enceinte conceptuelle canadienne de stockage permanent nécessiterait quelque 6×10^4 Mg de bentonite à sodium chaque année au cours de la durée de service de quarante ans d'une installation de stockage permanent. L'industrie de la bentonite de l'Amérique du nord a une capacité de production annuelle installée de 2×10^7 Mg. Une enceinte de stockage permanent nécessiterait donc à peu près 2% de la capacité de production de l'industrie.

On a étudié un certain nombre de produits commerciaux quant à leur disponibilité possible comme constituant du tampon. On a identifié dix bentonites vendues actuellement dans le commerce comme produits répondant aux normes initiales de qualité pour le tampon ainsi que deux bentonites non vendues dans le commerce comme produits pouvant être incorporés au système de scellement d'une enceinte de stockage permanent.

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ABSTRACT

The Canadian Nuclear Fuel Waste Management Program is studying a concept for the geological disposal of nuclear fuel waste at a depth of 500 to 1000 m below the surface in stable crystalline rock of the Canadian Shield. The waste containers would be surrounded by a clay-based buffer material. This buffer would be composed of equal dry-weight proportions of bentonite clay and graded silica sand.

For the reference disposal concept, some 1.9×10^5 Mg of used fuel would be emplaced. This would require some 2.5×10^6 Mg of bentonite for use in the clay-based seals within the disposal vault. Since the availability of sufficiently high-quality material needs to be established, a review of the bentonite industry in North America has been completed as part of the feasibility assessment of the disposal concept. There are proven reserves of sodium bentonite clay in excess of 1.5×10^8 Mg, and far vaster supplies are known to exist but are not yet proven. The Canadian conceptual disposal vault would require some 6×10^4 Mg of sodium bentonite each year of the 40-a life of a disposal facility. The bentonite industry of North America currently has an installed annual production capacity of 2×10^7 Mg. A disposal vault would therefore require approximately 2% of the industry capacity.

A number of commercial products have been screened for potential suitability for use as a component of the buffer. Ten currently marketed bentonite products have been identified as meeting the initial quality standards for the buffer, and two non-commercial bentonites have been identified as having the potential for use in a disposal vault.

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CONTENTS

1. BACKGROUND

The Canadian concept for safe nuclear fuel waste disposal proposes disposing of the waste in a massive geological formation. Used fuel, sealed in corrosion-resistant containers, would be placed in an underground disposal vault located some 500 to 1000 m below the surface in a stable crystalline rock formation. The containers would be emplaced either in rooms excavated in the rock (in-room disposal) or in boreholes drilled in the floor of these rooms (borehole disposal). In either case they would be surrounded by a bentonite clay-based material called the buffer. Bentonitic clay has a number of desirable properties, including the ability to swell on contact with free water and thereby limiting the through-flow of water or contaminants. Bentonitic clays also have the capacity to sorb or exclude certain radionuclides (depending on size and charge). These properties and others make bentonite an attractive potential sealant for use in a disposal vault. The details of the Canadian concept for nuclear fuel waste disposal are presented by Baumgartner (in preparation). Figure 1 presents a schematic of the general disposal concept.

Used reactor fuel will by its nature generate a gamma-radiation field and heat. The radiation field will persist until complete decay of the radionuclides contained in the used fuel is achieved. While the location of the vault would be such that this field would not be evident beyond a few metres from the vault, there would be an intense field within the buffer barrier. The preservation of the bentonite clay's swelling and hydraulic properties must be assured under such a harsh environment. Many commercial bentonite products used by the oil, drilling, and environmental industries are extended (chemically treated) or polymerized products. The polymer materials are typically large organic chain molecules that improve the sorptive or rheological properties of the bentonite. These molecules are unlikely to be stable in a radiation field, and the long-term effect of a denatured polymer on the performance of the bentonite-based buffer is uncertain. It is therefore prudent to limit the bentonites considered for use by the Canadian Nuclear Fuel Waste Management Program (CNFWMP) to untreated (no chemical treatment or polymer addition) natural bentonite products. A number of polymerized products are identified in this report for the purposes of providing a complete listing of the available materials.

Approximately 2.5 x 10^6 Mg of bentonite will be required over the 40 a of operation of the reference disposal facility (Baumgartner, in preparation). To acquire this volume of material over this extended time period, reliable suppliers and suitable products must be selected. The supplier(s) must be capable of providing some 60 000 to 100 000 Mg of consistent-quality untreated bentonite each and every year, for some 40 a. The materials and quantities required for the borehole disposal concept are outlined in Table 1, and include the volumes of material required for shaft and drift sealing during vault closure. Bentonite clay is expected to constitute approximately 17% by mass of the material to be used in sealing the vault (Table 1).

The magnitude of this project requires that resource availability must be fully examined prior to final vault design. Because of the large quantity of sealing material needed, and its geographically limited distribution, it is important to identify potential suppliers and to qualify candidate bentonite materials. For these reasons a review was undertaken to determine the available reserves and the long-term supply of bentonite material. This report provides some of the information necessary to initiate the selection and qualification process for the bentonite component of the sealing system.

2. GEOLOGICAL HISTORY AND BENTONITE FORMATION

Bentonite is a clay mineral formed by the geochemical alteration of volcanic ash deposited into shallow marine basins. Most North American deposits of sodium bentonite were formed during the Cretaceous Age (some 67 to 144 million years (Ma) ago). During this age, a combination of geological activity and environmental conditions existed that allowed the initiation of bentonite formation. Central North America had been inundated by a shallow brackish sea (Figure 2). The extent of this sea varied with time, as shown in Figure 3, especially in the northwestern reaches (now Alberta and Saskatchewan) (Shepheard and Hill 1970). Contemporary with this marine episode, there was extensive volcanic activity in the Western Cordillera. This volcanism generated vast quantities of ash that were blown east by the prevailing winds. The result was a series of ash deposits on the surface of the inland sea. The ash gradually settled to the bottom and was subsequently buried by marine or land-derived materials. With time, these deposits were deeply buried and consolidated by the more recent sediments, and many of these ancient ash layers were later altered to bentonite.

The type, thickness and quality of the subsequently formed bentonite beds are dependent on the initial ash composition and granularity, as well as the pore-fluid chemistry of the deposits. The deposits in the north and west tend to be more "ashy," with a higher grit content. This is either a function of their proximity to the volcanic sources of the ash, or the result of the inclusion of terrestrial material carried into the deposits during sea-level fluctuations. The deposits in the central basin tend to be of generally higher quality, perhaps as the result of the somewhat calmer central waters and, likely, a finer textured material being initially deposited farther from the volcanic ash sources.

The economically significant bentonite deposits of the Wyoming region of central North America are largely of Lower Cretaceous age (some 100 Ma old). In the Wyoming region these deposits are found in the Frontier, Mowry and Thermopolis shales (Figure 4). These deposits are generally exposed in the Big Horn region of Wyoming and are visible, as the result of the uplift of the Big Horn Mountains, in western Wyoming and the Black Hills region of western South Dakota (Auer and Thayer 1979). Thus the Wyoming or western-type bentonites are exposed in three localities, the Big Horn Basin to the west of the Big Horn Mountains, the Kaycee region to the east of the Big Horn Mountains, and the Black Hills region in easternmost Wyoming and into South Dakota (Figure 5).

Auer and Thayer (1979) estimated that the reserves of accessible, highest quality Wyoming bentonites were only 68 x 10^6 Mg. It was recognized that these estimates were highly conservative and represented only the very best of the bentonites available for mining. The conservative nature of this estimate is evidenced by the proven reserves of 1.8 x 10^8 t claimed by the Wyoming-based bentonite producers (see Table 2).

Vast reserves of lower quality bentonite are also known to exist within the Wyoming formations, and extensive deposits of sodium bentonite are to be found outside the traditional Wyoming deposits. These non-Wyoming bentonite deposits, normally of inferior grade, exist in large volumes in Montana, Alberta and Saskatchewan.

The second major North American geological series containing economically significant quantities of sodium bentonite are the Montana-type bentonite beds. These deposits are younger in age than the Wyoming-type bentonites and are located in regions of Montana, Alberta and Saskatchewan. They are Upper Cretaceous, normally from the Campanian Age (80 Ma) Bearpaw shales. Their geological positions are presented in Figure 6. In general, these formations contain thinner bentonite seams and are commonly believed to be of inferior quality (for use as a drilling mud or for use in the foundry industry). In some localities, where the overburden is relatively thin and the local bentonite quality high, some mining of these deposits occurs.

3. NORTH AMERICAN SUPPLIERS OF SODIUM BENTONITE

3.1 BRIEF HISTORY OF THE BENTONITE INDUSTRY

Historically, the bentonite industry has been largely associated with the petroleum and foundry industries. Bentonite is the major component of drilling mud, and so commercial viability of bentonite mining has largely been tied to the oil industry. The bentonite industry is also strongly affected by the foundry industry, since bentonite is used as a foundry sand binder in metal casting. When economic slowdowns occur, the foundry industry is one of the first affected, and so are bentonite producers. With the rise of the environmental industry in the 1980s, a new market has been, and continues to be, developed for the bentonite producers. Bentonite has a number of highly desirable swelling, sealing and chemical properties that make it ideal for use in lining disposal sites and tailings ponds, and in constructing cutoff walls for existing hazardous materials sites.

Commercial development of the vast bentonite deposits of Wyoming, Montana and South Dakota began in the 1880s for the cosmetic industry. Later in the 1920s, with the growth of the oil industry, a number of bentonite mining and processing plants were constructed, and the expansion of the industry continued through to the 1960s. During the 1960s and 1970s the bentonite industry went through a period of rapid expansion as the result of oil industry activity in North America. By the 1980s this activity had dropped off, and the bentonite industry went through a major downturn and a subsequent rationalization during the late 1980s. This reorganization led to the disappearance of a number of producers; they either combined with other companies or were purchased outright by more solvent bentonite producers. The surviving producers of Wyoming-type bentonite have also undergone operational rationalization. This was largely accomplished by mothballing or permanently closing non-profitable or outdated facilities. The basic composition of the industry as of the 1980s is outlined in Figure 7.

In recent years there have been three sodium bentonite producers in Canada, one in Saskatchewan and two in Alberta. The Alberta operations (located in Rosalind and Onoway) traditionally produced very small quantities of bentonite for local oil-industry use. As of 1989 neither of these operations was in production, although the Rosalind operation resumed limited production in 1990. The Saskatchewan bentonite mining and processing plant, located near Avonlea, is smaller than the American operations. It has undergone a number of changes in ownership in the past twenty years, some of which, including the most recent one (1989-1991), have resulted in the complete shutdown of the operation for extended periods. Customers requiring the product have had to go to the somewhat more stable U.S. suppliers. The Canadian bentonite also has some limitations in its use and availability, as discussed in later sections of this report.

3.2 MAJOR U.S. AND CANADIAN BENTONITE SUPPLIERS: MINING AND PROCESSING OPERATIONS

Following the bentonite industry rationalization of the late 1980s there were five major bentonite producers in business in the U.S. and two small processing facilities in western Canada. The milling capacity, stated or estimated reserves, and the locations of these operations are summarized in Table 2. The simplified processing flow charts for bentonite processing plants are presented in Appendix A. It must be noted that the product names referred to in this report are registered trademarks and do not refer to generic materials. Although not specifically marked in the text of this report, the tradenames used are registered trademarks and any reference to the products reported should recognize this. The following sections provide an overview of the mining and processing operations of the major bentonite producers.

3.2.1 WYO-BEN Incorporated

3.2.1.1 Geology

WYO-BEN is a privately owned company with its head office in Billings, Montana. Its mining claims and operations are mainly located in the Bighorn Basin region of south-central Montana and northwestern Wyoming, although it does have a processing plant and reserves as far south and west as Thermopolis, Wyoming. The bentonite deposits utilized by WYO-BEN originate from the Lower Cretaceous Age Thermopolis shale formation (110 Ma) to the mid-Cretaceous Age Frontier formation (90 Ma) and the Lower Cretaceous Upper Thermopolis shale (120 Ma). Some of these deposits are fairly steeply dipping, requiring somewhat different mining procedures than those used by other producers.

3.2.1.2 Mining and Processing Operations

Each mining operation is controlled from the local mill. The deposits are first surveyed in a grid pattern and then drilled to determine material quality, quantity, and necessary excavation procedures. Using in-house drilling equipment and personnel, test holes are augered and sampled for quality analysis. The overburden is then stripped by mining contractors using belly scrapers and D9 bulldozers. Once overburden removal is completed, the ore is drilled with an auger rig on 50-ft (15.2 m) centres, sampled, and logged. The ore is then removed from the pit using belly scrapers, stockpiled adjacent to the workings, and may be field-dried to remove some moisture before it is loaded and trucked to the processing plants. It has been established by drilling that WYO-BEN has at least 6×10^7 Mg of bentonite ore in its explored reserves. Considerably more ore is known to exist but has not yet been fully quantified.

WYO-BEN has three milling facilities, only two of which are currently in production. These facilities are located in Lovell, Greybull, and Thermopolis, Wyoming (Figure 5).

Sage Creek Plant - The Sage Creek Plant at Lovell has mining, milling (coarse and fine), screening and packaging capabilities and includes an on-site statistical process control (SPC) and quality control (QC) laboratory. The plant contains one rotary dryer, operating on either natural gas or coal, one 66-in. (1.68 m) Raymond roller mill, a four-bag (up to 0.045 Mg) packager, a 0.25- to 1.50 Mg-bulk sack bagger and a bulk rail/truck system. This packaging capacity is complemented with storage bins for on-site stockpiling of commercial products. The powder product part of the plant can produce more than 22 Mg/h of powder for packaging or bulk transport loading.

Stucco Plant - The Stucco Plant at Greybull has mining, milling, screening and packaging capabilities, and has an on-site SPC/QC laboratory. The plant is much the same as the Sage Creek operation except it has one 66-in. (1.68 m) and two 50-in. (1.27 m) Raymond roller mills and has a higher milling capacity of approximately 35 Mg/h.

Lucerne Plant - The Lucerne Plant at Thermopolis is the newest and most modern of the bentonite processing plants in Wyoming. Although not currently in operation, it has the facilities for milling and bagging, and has on-site SPC and QC laboratories. It operates in much the same manner as the other plants, except that it contains two 66-in. Raymond mills and no small bagging system. This plant was built with room for an extra dryer and two mills. The installed milling capacity of this facility is in excess of 50 Mg/h.

Each mill stockpiles ore according to grade, as determined by the mill QC laboratory on the basis of quality parameters established by the main QC laboratory at Stucco. Depending on the product, stockpiles may be mixed to obtain the proper grade of material. Stockpiled material is fed into the plant through a conveyor system, through a crusher to reduce the feed size, dried in a rotating dryer, milled with Raymond 66- or 50-in. mills, and then stored in tanks, packaged in bags or loaded into bulk transport systems for shipping. The Sage Creek Plant also has a second milling stream for production of aggregate-size material. This material is solar-dried, crushed, sized and then bagged for transportation.

3.2.1.3 Laboratories

Two research laboratories are maintained, one located at the head office in Billings, Montana, and the other at the Wyoming operations office at Stucco, Wyoming. These laboratories are used to test and develop new products and conduct special-application testing. In addition to the research laboratories, WYO-BEN operates a central QC laboratory at the Stucco Plant that does routine tests on raw and product samples according to API (American Petroleum Institute) or AFS (American Foundrymens Society) and other standards. Typical testing includes tests for viscosity, methylene blue (an indirect means of measuring the cation exchange capacity and surface activity of the clay), fluid loss, plate water absorption, grit size (% dry weight of sand size), moisture content and free swell. Each plant also operates an ongoing QC/SPC process to monitor the operation of the plant. This permits identification of on-line equipment adjustments necessary to ensure consistency in product quality. The tests conducted as part of the QC/SPC processes will vary with product type, but typically include tests for moisture content, dry fineness, grit content, rheology and fluid loss.

3.2.1.4 Commercial Products

A wide range of commercial untreated sodium bentonite products are available from WYO-BEN Inc., each targeted to specific industrial markets. Those products targeted to environmental and civil engineering applications are listed below. The physical, chemical and rheological characteristics of these products are summarized in Tables 3 through 5.

Naturalgel - An untreated sodium bentonite used for civil engineering applications, such as slurry trench barrier walls, and in meeting the requirements of API Specification 13A, Section 5, nontreated bentonite.

Envirogel 200 - An untreated sodium bentonite powder used for low-permeability mixed soil/bentonite horizontal membrane seals for landfill and lagoon liners and closure covers.

Envirogel 10 - An untreated, granular version of Envirogel 200 used for the same applications.

Naturalgel - Used in oil, water and mineral exploration, and in monitoring well drilling.

Enviroplug #6, #8, #16 - Medium and coarse products used for borehole sealing and plugging.

Bighorn Bentonite - A product line that includes grades for foundry, asphalt, water treatment, winery, and chemical applications.

3.2.2 M-I Drilling Fluids Company

3.2.2.1 Geology

The main operations of the M-I Drilling Fluids Company are located in the Greybull region of Wyoming. The commercial bentonite beds in this region are largely found within the Bighorn Basin region of Wyoming, and consist of units within the Mowry and Frontier formations. These deposits are Cretaceous in age, approximately 90 to 120 Ma old (Figure 4).

In many of the deposits mined in Wyoming, there is an overlying "ash" layer consisting of bentonitic materials of lower (non-economical by current standards) quality. This ash layer is normally bulldozed back into the excavations once the underlying high-grade bentonite is removed. This ash material has been sampled and the potential significance of the material is discussed later in this report. At the plant, the stockpiles are sampled during building and drilled after hauling is complete.

In Canada, M-I Drilling Fluids owns a small processing facility in Rosalind, Alberta. This plant processes sodium bentonite excavated from the Upper Cretaceous Bearpaw formation. The Alberta Bearpaw shale is contemporary with the Montana exposures of the same formation. These Montana bentonites are generally not perceived as being of as high a quality as Wyoming bentonites. They are, however, suitable for many applications, including drilling fluids and sealants for civil engineering applications. The primary difficulty with the exploitation of these deposits is that, while locally of relatively high quality, the deposits tend to rapidly grade into sandstones and shales, and hence the quality is variable.

3.2.2.2 Mining and Processing Operations

The Canadian processing plant in Rosalind is small, capable of producing 50 000 Mg/a. At this site, bentonite is removed by strip-mining techniques involving removal of 4 to 7 m of overburden to expose the approximately 3-m-thick upper bentonite bed, which is previously drilled and tested for quality and quantity. The bentonite is then removed by bulldozer and scraper and transported to the processing plant stockpiles. Processing begins with feeding the stockpile material through a slicer and into a rotary drier. From here the material is fed to a 54-in. (1.37 m) Raymond mill and an air floatation classifier. The dried and sized bentonite is then conveyed to either a bagging plant or to bulk storage and loading facilities. A QC program is in place with on-line tests for gel strength, moisture content and grind size.

The main M-I Drilling Fluids bentonite production facility is located in Greybull, Wyoming. It contains mining, milling and bagging facilities, QC, QA (quality assurance) and product-development laboratories, as well as pit reclamation facilities. Day-to-day mining operations are directed from the office complex at Greybull. The field manager is responsible for all operations associated with mining - surveying, stripping, hauling, and pit roads. The mine lease is first surveyed in a grid pattern of 61 m and drilled for quality and pit limits. The overburden is then stripped using belly scrapers and D9 bulldozers. On completion of the overburden removal, the ore is drilled with an auger rig on 15.25- to 25.9-m centres, sampled, and logged. The samples are sent to the lab for analysis and the results are reviewed by the mine superintendent. The mine superintendent then decides on the areas to be mined and the stripping method. The ore is then removed from the pit, stockpiled, partially field-dried and transported to the plant stockpiles as required.

Ore is stockpiled at the plant according to pits and grades. Depending on the product being produced, stockpile materials may be mixed to obtain the proper grade of bentonite. Following preprocessing mixing, the material is fed into the plant through a conveyor system, put through a primary crusher, dried in a rotary dryer, milled in either the Raymond roller mills or Williams-type hammer mills, and then stored in hoppers or placed in bags or bulk systems for shipping. The detailed process flow chart is presented in Appendix A (Figures A-1 and A-2). Process control samples are gathered hourly from different locations along the processing path using automatic or manual samplers. These samples are tested on site and the results are used to control the routine operation of the plant and determine necessary adjustments to equipment. Testing includes tests for moisture content, grit size, methylene blue, and fluid loss.

The Greybull plant has two independent processing streams once the material has entered the processing plant. One system uses two rotary dryers, fueled either by coal or natural gas, two Williams hammer mills to crush the dried material, bulk product storage, and packaging facilities - bag or bulk rail/truck. This processing circuit can produce >15 Mg/h. The second milling stream uses two rotary dryers, three 66-in. Raymond roller mills to crush the dried material, bulk product storage, and packing facilities. This milling operation can produce >50 Mg/h.

3.2.2.3 Laboratories

At the head office in Houston, Texas, a research laboratory has been established to conduct QC testing, develop new products, and test special-application products. In addition to the research laboratory, the company operates an on-site QC laboratory and a QA/process control laboratory, which conduct routine tests on raw and milled samples according to API or ASTM (American Society for Testing Materials) standards. This typically includes tests for viscosity, methylene blue, fluid loss, plate water absorption, grit size (dry sand %), moisture content and free swell.

3.2.2.4 Commercial Products

There are a number of products produced by this company, each with its target market. A summary of the physical, chemical and rheological characteristics of these products relative to other bentonite products is presented in Tables 3 through 5. The sodium bentonite products available include the following:

Federal Jel "CG" - This is an untreated oil-well cement-grade product used in a variety of civil engineering as well as oil-well cementing applications.

Federal Jel Natural - This is an untreated product used for a variety of civil engineering applications. This product has a slightly higher bentonite content and a higher swelling capacity than the Federal Jel "CG". Its application is mainly in the environmental and water-control industries.

Federal Seal 200 - A "construction/civil" engineering grade product. Its application is largely as a liner and cap component for lagoons or landfills.

Federal Jel "90" - This product has been included for the sake of providing a complete list of "civil engineering" products. It is a polymerized material, with very high swelling and attractive rheological properties. As the CNFWMP is interested only in untreated products, this material is not considered suitable for our application.

3.2.3 <u>Black Hills Bentonite Company</u>

3.2.3.1 Geology

Black Hills Bentonite Company is a privately owned company (as of 1991 the 49% M-I Drilling Fluids interest had been sold back to the majority owner). This company holds claims throughout Wyoming; its main processing and operating sites are located in the central part of the state at Casper (Figure 5), and a small plant is located in Worland. As with the other bentonite producers, Black Hills mines the Upper Cretaceous bentonite deposits of the Frontier formation for processing in its Worland plant. The main part of the processing capacity is located in central Wyoming (Casper) where the Lower Cretaceous Frontier and Mowry formations mined from the Kaycee Wyoming region (Figure 5) are processed. These deposits are located to the East of the previously discussed Big Horn Basin workings of WYO-BEN or M-I Drilling, and represent the eastern exposures produced as the result of the Big Horn Mountains uplift.

3.2.3.2 Mining and Processing Operations

Following initial site characterization and drilling, each mine site is grid-drilled to determine the extent and grade of the deposit. Mining is conducted by contractors using belly scrapers and bulldozers, and the excavated ore is stockpiled adjacent to the excavation. The Black Hills bentonite processing circuit includes a period of solar drying prior to transportation to the processing plant.

Black Hills has three milling facilities, all of which are in production:

Worland - This is a satellite operation; nearby mined bentonite is brought in for processing. The plant contains one rotary dryer, operating on either natural gas, coal or both, a Raymond 66-in. roller mill with air-floatation sizers, a four-bag (up to 0.045 Mg) packager, and a bulk rail/truck (up to 96-Mg railcars) delivery system. This is complemented with storage bins for on-site stock of commercial products. The plant can produce as much as 30 Mg/h of powdered material. The site contains only a small process control laboratory, which permits routine monitoring of processing.

Casper - There are two processing plants located in Casper, Wyoming, both of which are supplied by material transported from the Kaycee region. These mills both use the conventional rotary drier and Raymond mill to process the bentonite ore. Each plant operates with a routine process control procedure to ensure product consistency.

3.2.3.3 Laboratories

At the main processing plants in Casper, the company operates a QC laboratory where routine tests are conducted on raw and milled samples according to relevant API or ASTM standards. These include tests for viscosity, methylene blue, fluid loss, plate water absorption, grit size (wet and dry sieve analysis), moisture content, pH and free swell.

Each plant also operates a process control laboratory where samples are gathered hourly and tested to permit continuous monitoring of the product going through the processing circuit. The results of sampling are used to control plant operation; adjustments are made to milling equipment as determined by the ongoing SPC process. The tests routinely conducted include moisture content, grit size and fluid loss. The laboratory also monitors the rate and quantity of any additives placed into the products during processing.

3.2.3.4 Commercial Products

Black Hills Bentonite markets a large variety of sodium bentonite products. Those targeted for the drilling, civil and environmental engineering industries are outlined below. Although some of these materials have been polymerized they have been included in this discussion for the sake of completeness. The physical, chemical and rheological properties of these materials are described in Tables 3 through 5.

S-5 Natural - An unaltered sodium bentonite intended for use in oil-well cements, water-control projects, and lagoon liners.

Mineral Colloid 103 (MC-103) - A non-polymerized, extended, low-swelling sodium bentonite. It is intended largely as a binder product or for slurries where low viscosity is required. It can be specified as either a standard-grind (200 mesh), or a fine-grind (325 mesh) product.

Mineral Colloid CG (MC-CG) - An unaltered sodium-bentonite product. It is intended for oil-well cement use as well as water control and similar civil and environmental applications.

Black Hills Bond (BHB) - An unaltered sodium bentonite targeted as a general-use bentonite. It is intended for use in lagoon liners, landfill liners and caps, and other civil engineering applications.

BH Granular - An unaltered sodium bentonite. This product is the same material as the Black Hills Bond but is not as finely ground. It is targeted for civil and environmental engineering applications where a powdered material is undesirable.

BH Natural - A natural unaltered bentonite product with a high yield (API 13A) used for drilling mud.

Mineral Colloid 125 (MC-125) - A polymerized sodium bentonite targeted for use in slurry trench cut-off walls, where a very high gelling bentonite is desired. This type of material, because it has been polymerized, is not considered suitable for use by the CNFWMP.

HYG-200 - A polymerized sodium bentonite intended for use in water-well drilling, where a very high barrel-yield drilling mud is required.

3.2.4 American Colloid Company

3.2.4.1 Geology

The American Colloid Company (ACC), through its wholly owned subsidiary, Colloid Environmental Technologies Company (CETCO), is the largest single producer of bentonite and bentonite products in North America. The ACC holds claims and mineral rights for sodium bentonite materials for regions in Wyoming, Montana and South Dakota. The ACC operated six sodium bentonite mining and processing facilities as of 1989 (ACC Annual Report, 1989). Processing facilities are located in Belle Fourche, South Dakota, and in Colony (2 plants), Upton (2 plants) and Lovell in Wyoming. The sites in Belle Fourche, Colony, and Upton are all located in the Black Hills mining district and represent the easternmost mined exposures of Wyoming-type bentonite. The Lovell site is located in the Big Horn Basin mining region, and it consists of the western exposures of the Lower Cretaceous deposits of the Frontier and Mowry shales.

3.2.4.2 Mining and Processing Operations

The ACC has its own exploration, mapping, and reclamation planning groups. Proven reserves could supply the 1989 rate of production (approximately 900 Mg) for the next 25 to 30 a. Each year further field investigation is conducted to maintain this reserve. The proven reserves are estimated to be some 2.7×10^7 t on the basis of simple multiplication of the 1989 production values (actual values not provided by the ACC). The sites are explored, deposits are delineated by exploration drilling, and then prior to mining the deposits are extensively drilled. The deposit is then divided into grades, and the materials harvested from each grade are stockpiled separately. The materials so mined are fed into the appropriate processing plant, depending on the products currently in production. The same type of overburden-stripping equipment and bentonite mining techniques are used by the ACC as are in use by the other bentonite mining operations. Bulldozers and scrapers are used for overburden removal and scrapers are used to remove the bentonite beds. The removed bentonite is generally stockpiled close to the processing plants and is allowed to dry in these stockpiles until required.

In 1989, the ACC listed six bentonite processing facilities as operational; in 1991 these were still in operation. None of these plants are particularly new, all being constructed in the 1950s or earlier, but they are maintained by an in-house fabrication facility to ensure equipment reliability. It should be noted that the Belle Fourche and Lovell plants are primarily involved in production of specialty and polymerized materials. The plants currently producing sodium bentonite products are the Colony West and Colony East Plants, both located in the northeastern corner of Wyoming, only a few kilometres from the Belle Fourche processing facilities.

Colony West Plant - The Colony West Plant at Colony, Wyoming, was formerly owned by the Federal Bentonite Company. It has mining, milling and bagging facilities, and a QC and QA laboratory. At the milling plant, the ore is stockpiled according to grade, as determined at the Colony West Plant's QC laboratory. Depending on the product, stockpiles may be mixed to obtain the proper grade of material. The plant contains two rotating driers, two Raymond air-floatation mills, and three packaging lines. The finished product can be stored in hoppers, placed in bags or in bulk systems for shipping by rail or truck. The plant has an on-site storage capacity of 1800 Mg. This site is primarily involved in production of material for the foundry industry, or for granular applications.

Colony East Plant - The Colony East Plant at Colony was originally owned by International Minerals and Chemical Company (IMC). This plant has milling and bagging facilities, a QA laboratory and a process control laboratory. The plant contains one fluid-bed dryer operating on either natural gas or coal, two 66-in. Raymond air-flotation mills, a four-bag (up to 0.045 Mg) packager, and a 0.25- to 1.50-Mg bulk or bulk rail/truck (up to 96 Mg by rail) delivery system. This is complemented with storage bins for 2280 Mg of 200-mesh material and 720 Mg of granular material on site. The fine-mesh (200) facilities can produce more than 40 Mg/h of powdered material and the part of the operation that produces granular bentonite can produce at an even higher rate. A clay-processing flow chart for one of the Colony milling plants has been obtained and is presented in Appendix A (Figure A-3).

Belle Fourche Plant - The Belle Fourche Plant, at Belle Fourche, South Dakota, is only a few kilometres east of the Colony Wyoming processing facilities. This plant has it own on-site milling, bagging and bulk storage facilities, and an on-site process control laboratory. The plant has four rotating driers, three Raymond air-floatation mills, and the capability to package the products in bags, bulk bags, or bulk rail or truck carriers. This is supplemented with storage bins for approximately 5900 Mg of processed material.

Lovell Plant - The Lovell Wyoming plant is located in northwestern Wyoming. This plant is equipped with two rotating driers, four Raymond air-floatation mills, and facilites to bag, bulk bag, and bulk ship bentonite by rail or truck. There is capacity to store approximately 1500 Mg of processed product on site in storage tanks or the palletizer warehouse.

Upton Plant - This site contains two processing plants and is located in east-central Wyoming. There are three rotating driers, five Raymond mills ranging from 42 to 73 in. (1.07 to 1.85 m) in size, and facilities to bag, bulk bag, or bulk ship bentonite by rail or truck. This facility can store approximately 2400 Mg of processed material in bulk storage tanks or the palletizing warehouse.

3.2.4.3 Laboratories

At the Colony West plant, a laboratory is established to test field exploration samples and conduct QC testing of the Colony East and Colony West products. Routine tests are conducted on raw and milled samples according to relevant API or ASTM standards. These include tests for viscosity, methylene blue, fluid loss, plate water absorption, grit size, moisture content and free swell. Each plant also operates an on-site QC laboratory. The results of routine material sample analyses are used to determine what if any milling changes are necessary as part of the ongoing SPC process. These routine tests include moisture content, grit size, methyl blue, consistency limits and fluid loss.

A more extensive research and development facility is located in CETCO's head office in Arlington Heights, Illinois. This facility works on new product development, conducts QC checks on the production plants, evaluates new bentonite sources, and provides customer support.

3.2.4.4 Commercial Products

American Colloid Company stocks a large number of commercial bentonite products. On the basis of samples and technical data received on the products listed below, a general impression of the products available can be developed. What is known of these products is included in Tables 3 through 5.

Volclay MX-80 - This bentonite is a granular product that has been extensively studied by the nuclear fuel waste disposal programs in a number of European countries, including Sweden and Switzerland.

Custom Sealant 200 (CS-200) - A powdered sodium bentonite product that has not been treated with any chemicals or polymers. It is targeted for use by the civil and environmental engineering industries.

Foundry C: This product is a granular material intended for use in the metal-casting industry. It is an untreated sodium bentonite; it has not undergone any chemical alteration during processing.

3.2.5 Bentonite Corporation (Formerly NL Baroid)

3.2.5.1 Geology

Bentonite Corporation (BC) mines and holds mineral rights in two localities in Wyoming, Colony and Lovell. These operations mine the Cretaceous Frontier and Mowry formations. The Colony plant in northeastern Wyoming mines the deposits exposed by the uplift of the Black Hills region, whereas the Lovell plant (not currently in operation but expected to reopen in 1993), processed material excavated from the western exposures resulting from the uplift of the Big Horn Mountains.

For the operation of the Colony Plant, the company has a drilled and proven ore reserve of 7 x 10^6 Mg. These reserves represent materials with liquid limit >300%, and Bentonite Corporation works to maintain this reserve by exploration drilling each year. Likewise, the Lovell Plant has its own drilled and proven reserves totalling some 1.2 x 10^7 Mg of ore with a liquid limit >300%.

3.2.5.2 Mining and Processing Operations

Bentonite Corporation currently operates only its Colony plant. This operation contains mining, milling and bagging facilities; QC, QA and product development laboratories; and reclamation facilities. The day-to-day mining operation is managed from the processing plant. The mine lease is first surveyed in a grid pattern of 100-ft (30.5 m) centres, and drilled for quality and pit limits. On the basis of the expected quality and the quality of material required for current operation, sites are opened for mining. The overburden is stripped using belly scrapers and D9 bulldozers. Once overburden removal is complete the ore is drilled, using an auger rig on 50-ft centres, sampled, and logged. The samples are sent to the lab for analysis, the results are reviewed and the mining plan formalized. The ore is then removed from the pit by front-end loaders, hauled to the plant, stockpiled and air-dried to a moisture content of 25%.

Ore is stockpiled at the plant according to grades. Unlike other companies, stockpiles are not mixed to obtain a specific grade of material. The products produced are determined from testing the as-mined beds. On determination of the grade and product to be produced from each stockpile, the material is fed into the plant through a conveyor system and through a preliminary crusher.

Colony Plant - On entering the processing stream at the Colony plant, the bentonite is dried in one of three rotary dryers (coal-fired). It is then passed through Raymond roller mills (four in operation), sized using an air-floatation classifier, and sent to bulk product storage and packaging facilities - bag or bulk rail/truck. The mill capacity is estimated at 360 000 Mg/a. Process control samples are gathered hourly from different locations along the processing circuit. The routinely conducted QC tests include moisture content, grit size, methylene blue, and fluid loss. The results of these process control tests are used to ensure that consistent quality is maintained. As with most process control testing, the results are used to determine what on-line adjustments are necessary to the milling process.

Lovell Plant - The plant in Lovell used two rotary dryers, two Raymond mills for crushing, and has bulk product storage and packing facilities. This milling operation produced approximately 360 000 Mg/a of pulverized product prior to its shutdown.

3.2.5.3 Laboratories

At the head office in Denver, Colorado, there is a research laboratory established for development of new products and special-application testing. In addition to the research laboratory, Bentonite Corporation operates a QC laboratory, a QA and process control laboratory, and a specialty testing laboratory at its Colony site. The on-site laboratories do routine tests on raw and milled samples according to API or ASTM standards. These include tests for viscosity, methylene blue, fluid loss, plate water absorption, grit size (dry % sand), moisture content, consistency limits and free swell. A number of customer-required or industry-specific tests are also performed at this location.

3.2.5.4 Commercial Products

A wide variety of sodium bentonite products are available from Bentonite Corporation. The physical, chemical and rheological characteristics of these products are summarized in Tables 3 through 5.

Enviro-Seal - A polymerized product for use in fresh- and waste-water lagoon sealing, landfill liners and caps, as well as slurry trench applications. Since it is a chemically treated material it is not considered suitable for use in the CNFWMP.

Bara-Kade (B-K) 90; 125; 180 - These are all soil sealing and slurry trench products. They are powdered bentonites of differing rheological characteristics. These products have been treated with a small amount of polymer (<0.1 %) to enhance yield.

Bara-Kade Standard Bentonite - This product is intended for the environmental and civil engineering markets for use as a soil sealant. It is an untreated sodium bentonite of slightly lower bentonite content than the previously listed Bara-Kade products, but still exhibits a high swelling capacity. This is the powdered form of the soil-sealing grade of sodium bentonite. This grade of material represents approximately 70% of the reserves held by this supplier.

Bara-Kade Granular Bentonite - This is the same product as the Bara-Kade Standard Bentonite, except that it is a granular material (-30 mesh).

3.2.6 Canadian Clay Products (Formerly Ekaton, Avonlea)

3.2.6.1 Geology

This bentonite mining company, located in Wilcox, south-central Saskatchewan, is a privately held company. Canadian Clay Products (CCP) mines bentonite from the Bearpaw shale formation. This bentonite is equivalent to the Montana-type exposures in the United States. It is upper Cretaceous (approximately 80 Ma) in age and underlies much of the prairie region of Canada; its geological location is shown in Figure 6.

Across most of western Canada the Bearpaw formation is deeply buried. However, in the Avonlea/Wilcox region, it either outcrops or is close to the surface. This surface exposure is the result of extensive deep-seated block faulting of the underlying Prairie Evaporite formations.

3.2.6.2 Mining and Processing

The thin (typically <1 m thick), extensively block-faulted and deformed bentonite beds (three are mined) of the Avonlea region have been the focus of much of the historical sodium bentonite mining activity in Saskatchewan. This discontinuous exposure of the bentonite has resulted in a "hunt and peck" type of mining, and has been the source of considerable operational difficulty. These thin and variable bentonite beds are initially drilled to gain an estimate of the quality and quantity of material available. They are then stripped of overburden, and rotating-blade scrapers are used to remove the bentonite seams. The material is then spread out on the surface and tilled to reduce aggregate size and moisture content. This ore is stockpiled for later trucking to the processing plant. At the plant, the raw bentonite is first fed through a clay feeder, then into a rotating drier, and finally into a Raymond mill. The bentonite is then sized by air floatation and either bagged, bulk-loaded or stored in on-site silos for later shipment.

3.2.6.3 Laboratory

There is a small on-site quality testing laboratory, but until 1991 when the mill was purchased by Canadian Clay Products, no effective or formal QC or QA programs were in operation. This resulted in products of varying quality being sold under the same trade name. Material purchased as the same mill run in late 1989 was tested by AECL Research and its contractors. The variability of the material supplied was such that before the product could be used it was necessary to completely rebatch the order. The liquid limit of individual 40-kg bags in this 10-Mg order of Civil Engineering Grade (a.k.a. Avonseal) varied from a low of 150% to higher than 350%. The average liquid limit of the rebatched material was 240% (±7%). The new owners and operators of this facility (1991) have instituted a QC program to improve the quality and consistency of their product. It is yet to be established whether this will correct the previous variability of the product. For continuity of the CNFWMP's research program, the Saskatchewan bentonite will continue to be referred to as the reference bentonite.

3.2.6.4 Commercial Products

There is only one untreated sodium bentonite product currently manufactured by Canadian Clay Products that would meet the requirements of the CNFWMP. This is a 200-mesh sodium bentonite given the trade name GeoSeal. This product is the successor to the Civil Engineering and Avonseal products marketed by previous operators of this mine and processing plant. It is this product that is referred to as the reference sodium bentonite for the CNFWMP. The available information on this material is provided in Tables 3 through 5.

4. CHEMICAL, RHEOLOGICAL AND ENGINEERING PROPERTIES

4.1 MATERIAL SPECIFICATIONS

In order for the buffer (1:1 by dry mass of silica sand:bentonite) to provide the specified swelling potential, certain fundamental properties of the bentonite must be present. Preliminary research on bentonite-based barriers has established that the Saskatchewan sodium bentonite (if properly blended) should produce a buffer of sufficient quality to meet the currently identified swelling, hydraulic and thermal requirements of the reference buffer material. Using this bentonite and reference buffer material as a standard, minimum specifications for the reference bentonite have been identified and are outlined in Table 6.

Bentonite materials of equivalent quality to the reference Saskatchewan bentonite should therefore provide the necessary sealing and contaminant isolating properties required for the buffer. It is important to note that all bentonites are not the same, and that the specifications typically supplied by producers of bentonite are intended for their main markets, drilling and foundry use. These markets require certain properties to be present in the bentonite, but these properties are not necessarily of any significance to the civil and environmental engineering industries. For civil and environmental applications it is typically the cation exchange, chemical and hydraulic properties of the clay that are perceived to be of greatest importance. However, for completeness, the product information of interest to the drilling industry has been included in the data summaries in Tables 3 through 5.

4.2 COMPARISON OF BENTONITE PRODUCTS

A total of 34 sodium bentonite materials, 21 unpolymerized commercial products, 10 polymerized products, and 3 currently unexploited Na-bentonite materials have been identified, reviewed, and their properties summarized in Tables 3, 4 and 5.

Some of these commercial products are the same bentonite ore ground to different size specifications; therefore the number of actual different untreated commercial materials can be reduced to 16.

The three non-commercial bentonites examined consist of an Alberta bentonite found and once mined near Onoway, Alberta, and two Wyoming bentonites currently not used by the mining companies. The Wyoming materials are of particular interest because they represent low-grade "Blue Tanner Pit" bentonite or "Ash" deposits currently considered to be waste. These materials are now bulldozed back into the pits following removal of the higher grade underlying bentonite beds. While these materials are not really suitable for foundry or oil-well use, they do represent vast amounts of lower grade bentonite that has potential application in the environmental or civil engineering industries.

The variability in the measured properties of the sodium bentonites examined makes it evident that there is a wide range of materials available commercially. Most of these products meet or exceed a number of the key parameters identified for a candidate bentonite. The data also show that it is unwise to assume, on the basis of a limited number of characterization tests, that a particular product is acceptable. While certain properties may meet or exceed the standards established using Saskatchewan bentonite, the material considered may not in the final analysis be suitable because it may not exhibit adequate hydraulic or swelling properties.

Testing of the specimens supplied by the producers of sodium bentonite clay is not yet complete. It is evident, however, that the relationship between index properties and swelling and hydraulic properties is not necessarily direct. In some cases, as in the samples supplied by Bentonite Corporation and M-I Drilling, the results of index testing for consistency limits (Table 5), or free-swell tests (Figure 8), indicated that these materials should exhibit higher swelling pressures and lower hydraulic conductivities, relative to the Saskatchewan reference material. They did exhibit lower hydraulic conductivities but did not develop a higher vertical swelling pressure (Figure 9). The reasons for this are uncertain, but it may be a function of differences in material particle sizing, or in the exchangeable cation compositions of the clays (Reschke and Haug 1991). This relationship between hydraulic conductivity, swelling pressure and cation composition is currently being investigated at Whiteshell Laboratories.

Table 7 presents a summary of the physical, chemical and engineering properties of the 16 commercial and 3 non-commercial bentonite products relative to the reference CCP bentonite.

5. SUMMARY

It has been established that the bentonite requirements of the CNFWMP's conceptual disposal vault could easily be met by the current industry. The disposal centre would require approximately 2% of the maximum currently installed milling capacity of the North American bentonite industry. During the estimated 40-a life of the reference disposal centre, the required bentonite represents much less than 2% of the currently established reserve of commercial-grade sodium bentonite.

It is important that the bentonite used be of consistent quality throughout the assumed 40-a operational life of a disposal vault. All the U.S. producers of sodium bentonite have established some form of statistical process control and QC program as part of their routine operation. A number of these companies have formal QA policies and procedures. This type of process control should help to ensure that the materials supplied by these processors meet whatever material specifications are established for a particular product. For the purposes of the CNFWMP, it would be necessary to work with the manufacturer(s) to establish a set of QA standards relevent to this application.

In establishing the quantity of the bentonite reserve that would be consumed by a disposal centre, it is also important to note that the reserve figures quoted are for high-grade bentonite deposits currently mined in the Wyoming, Alberta and Saskatchewan exposures. It is well known that vast quantities of lower-grade material exist, such as the Ash and Blue bentonites. These materials are in many ways of comparable quality to the reference Saskatchewan bentonite. In terms of free swell, hydraulic and swelling-pressure properties, the lower grade materials appear to be adequate for use. However, before such non-commercial materials could be considered for vault use, extensive testing and detailed resource availability studies would be necessary. If these materials proved adequate for disposal vault use, it would be possible to use what are currently considered non-commercial materials for the disposal facility. This would not only avoid using a higher quality material than is necessary, it would probably also reduce the cost considerably.

A number of the sodium bentonite deposits known in Alberta appear to be of sufficient quality to be used in a buffer barrier. However, these deposits are extremely limited in volume, are highly variable in quality and the currently stated reserves are insufficient for a disposal vault. Unless new reserves of higher consistency sodium bentonite are identified in Alberta, it is unlikely that this source of bentonite could be used for an operational disposal centre.

A wide variety of commercial bentonite products from Canada and the U.S. have been examined for potential suitability for use in a nuclear fuel waste disposal vault. Excluding chemically enhanced (polymerized) products, there are at least 10 different commercial products (200-mesh grind) that have potential for future use in a disposal vault. Preliminary investigations indicate that at least two of these products, Baracade

Standard and Federal Jel "CG," exhibit free swell and hydraulic properties equal or superior to the reference bentonite. Before a complete list of confirmed alternative suppliers and products is prepared, a number of scoping tests must be completed to establish the swelling pressure and hydraulic suitability of each of these materials. This work is ongoing and the results will be reported in subsequent reports on alternative bentonite materials for the CNFWMP.

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TABLE 1

VAULT SEALING MATERIAL REQUIREMENTS
(Baumgartner, in preparation)

Sealing Material Components	Vault Totals ($\times 10^6$ Mg)	% of Total Material
Bentonite Clay		
- buffer	0.59	
- upper backfill	1.89	17.0
Glacial Lake Clay		
- lower backfill	0.78	15.4
Sand		
- buffer	0.59	
- container annulus	0.14	
- upper backfill	1.89	18.0
Cement		
- room bulkheads	0.07	
- grout and other	0.01	0.6
Crushed Granite		
- lower backfill	6.77	
- concrete aggregate	0.38	49.0
Total	14.58	100.0

TABLE 2

BENTONITE PRODUCERS IN CANADA AND THE UNITED STATES

Company and Mine Location	Maximum Annual Production (1000 Mg/a)	Reserves (1000 Mg)
Canadian Clay Products,		
Wilcox, Saskatchewan	100	4 000
M-I Drilling Fluids, a Dresser/Haliburton Co.		
Rosalind, Alberta	36	500
Greybull, Wyoming	650	50 000
Colloid Environmental Technologies Company		
Formerly, America Colloid Company, Illinois	estimated	35 000
Belle Fourche, South Dakota	400	
Colony, Wyoming (2 plants)	900	
Upton, Wyoming	500	
Lovell, Wyoming (shut down)	400	
Bentonite Corp., Denver, Colorado		
Lovell, Wyoming (shut down)	(360)	12 000
Colony, Wyoming	360 to 460	7 000
WYO-BEN Inc., Billings, Montana		50 000
Lovell, Wyoming	450 to 750	
Greybull, Wyoming	225	
Thermopolis, Wyoming (mothballed)	350	
Blackhills Bentonite, Casper, Wyoming		
Worland, Wyoming	200	unknown
Casper, Wyoming (2 plants)	450	
Wilbur-Ellis Company,		
Central California	35	unknown

TABLE 3

SUMMARY OF BENTONITE CHEMICAL PROPERTIES

SAMPLE	Si02	Al203	Fe203	MgO	CaO	K2O	Na2O	TiO2	H2O (Crystal)
	CHEMICAL COMPOSITION AS % OXIDE								
BENTONITE CORP. PRODUCTS									
Eviro-Seal (P)	62.56	21.18	3.63	2.32	0.63	0.31	2.45	N/R	5.72
Newcastle +	62.9	19.45	3.6	2.92	1.76	0.55	1.54	0.13	6.06
B-K Standard	63.59	21.43	3.78	2.03	0.66	0.31	2.7	N/R	5.5
B-K gran.	63.59	21.43	3.78	2.03	0.66	0.31	2.7	N/R	5.5
B-K 90 (P)	63.31	21.43	3.83	2.32	0.63	0.31	2.45	N/R	5.72
B-K 125 (P)	63.31	21.43	3.83	2.32	0.63	0.31	2.45	N/R	5.72
B-K 180 (P)	63.31	21.43	3.83	2.32	0.63	0.31	2.45	N/R	5.72
Natnl. LD-6	N/R	N/R	N/R	N/R	N/R	N/R	N/R	N/R	N/R
Natl. LD-16	N/R	N/R	N/R	N/R	N/R	N/R	N/R	N/R	N/R
M-I DRILLING FLUIDS CO.									
Blue Tanner	N/R	N/R	N/R	N/R	N/R	N/R	N/R	N/R	N/R
"ASH"	N/R	N/R	N/R	N/R	N/R	N/R	N/R	N/R	N/R
F-J Natural	61.3-64	19.8	3.9	1.3	0.6	0.4	2.2	0.1	7.2
F-J "CG"	61.3-64	19.8	3.9	1.3	0.6	0.4	2.2	0.1	7.2
F-J "90" (P)	61.3-64	19.8	3.9	1.3	0.6	0.4	2.2	0.1	7.2
Fed-Seal 200	61.3-64	19.8	3.9	1.3	0.6	0.4	2.2	0.1	7.2
WYO-BEN INC.									
Envirogel-10	60.3	19.3	3.5	1.7	0.4	0.1	2.3	0.2	<7.8
Envirogel 200	60.3	19.3	3.5	1.7	0.4	0.1	2.3	0.2	<7.8
Naturalgel	60.3	19.3	3.5	1.7	0.4	0.1	2.3	0.2	<7.8
AMERICAN COLLOID COMPANY									
CS - 200	N/R	N/R	N/R	N/R	N/R	N/R	N/R	N/R	N/R
Foundry C	N/R	N/R	N/R	N/R	N/R	N/R	N/R	N/R	N/R
Volclay MX-80	58-64	18-21	2.5-2.8	2.5-3.2	0.1-1.0	0.2-0.4	1.5-2.7	0.1-0.2	5.64
BLACKHILLS BENTONITE COMPANY									
product 404	65	20.2	2.3	1.0	1.4	0.8	3.1	N/R	7.0
B H B(regular)	64.7	17.6	4.4	1.8	1.3	0.46	2.5	0.16	5.9
B H B (fine)	64.7	17.6	4.4	1.8	1.3	0.46	2.5	0.16	5.9
BH-Natural	64.7	17.6	4.4	1.8	1.8	0.46	2.5	0.16	5.9
BH-Granular	64.7	17.6	4.4	1.8	1.8	0.46	2.5	0.16	5.9
S-5 Natural	66.9	16.3	3.3	1.5	1.8	0.48	2.6	0.12	6.0
HYG - 200 (P)	66.9	16.3	3.3	1.5	1.8	0.48	2.6	0.12	6.0
Min. Colloid CG	66.9	16.3	3.3	1.5	2	0.48	2.6	0.12	6
Min..Colloid 103	56.4	17	4.3	2.6	4.4	0.53	2.7	0.55	8.5
Min Colloid125(P)	56.4	17	4.4	1.8	1.8	0.46	2.6	0.16	5.9
CANADIAN CLAY PRODUCTS INC.									
Civil Eng.	61.4	18.1	3.2	2.3	0.6	0.4	2.2	0.1	5
Civil Eng.*	64.7	16.3	4.46	2.26	1.79	0.56	2.23	0.25	4.68
Civil Eng.**	61.4	13.7	4.63	0.79	1.76	1.56	0.75	N/R	N/R
Geoseal(1991)	59.6	15.6	4.96	1.71	1.33	1	2.31	0.81	<7
Na-Bent.(1991)	58.66	16.36	4.7	2.11	2	0.1	1.96	0.2	<8
ALBERTA BENTONITES									
MI - Autobond (Rosalind)		N/R	~2.8	N/R	N/R	N/R	N/R	N/R	N/R
(Onoway)***	N/R	N/R	N/R	N/R	N/R	N/R	N/R	N/R	N/R
*(Rosalind)****	N/R	N/R	N/R	N/R	N/R	N/R	N/R	N/R	N/R
(Rosalind)**	69-76	12-14	3.0-4.1	0.8-1.3	0.8-1.7	0.2-1.4	0.4-1.4	N/R	N/R

Note: Data presented is obtained from Manufacturers Technical Data Sheets unless otherwise noted.
* From Oscarson & Dixon (1989)
** Reschke & Haug (1991)
*** (Scafe,1975), This deposit is extremely variable, values quoted are "typical" of the material
+ Typical Wyoming bentonite (Newcastle formation, SWy-1 (Van Olphen & Fripiat, 1978)
N/R - Not reported, Data not available or not supplied by manufacturer
(P) - Polymerized Product

TABLE 4

SUMMARY OF BENTONITE RHEOLOGICAL PROPERTIES

SAMPLE	WET SIEVE ANALYSIS +200 Mesh	-200 Mesh	-325 Mesh	RHEOLOGICAL PROPERTIES (6%) Viscosity 600rpm	Apparent Viscosity	Plastic Viscosity	Yield Point (lb/100psf)	Filtrate (mL) 30 minutes	Yield 42 gal. bbl.
BENTONITE CORP. PRODUCTS									
Eviro-Seal (P)	2-4	96-98	95-97	60	9	17	25	8.5	105
Newcastle +									
B-K Standard	2-4	96-98	95-97	18	9	6	5	15	80
B-K gran.	N/R	N/R	N/R	19	9	N/R	N/A	16	80
B-K 90 (P)	2-4	96-98	95-97	34	17	12	10	11	93
B-K 125 (P)	2-4	96-98	95-97	75 (37 in 4.5%)	37.5(19 in 4.5%)	9 (in 4.5 %)	18(in 4.5 %)	11(15 in 2.8%)	130
B-K 180 (P)	2-4	96-98	95-97	(30 in 2.8%)	(15 in 2.8 %)	7(in 2.8%)	16(in 2.8 %)	20(in 2.8%)	200
Natnl. LD-6	N/R	N/R	N/R	N/R	N/R	N/R	N/R	N/R	N/R
Natl. LD-16	1.3	N/R	97.1	N/R	N/R	N/R	N/R	N/R	N/R
M-I DRILLING FLUIDS CO.									
Blue Tanner	N/R	N/R	N/R	N/R	N/R	N/R	N/R	N/R	N/R
"ASH"	N/R	N/R	N/R	N/R	N/R	N/R	N/R	N/R	N/R
F-J Natural	2.5-4.0	>96	N/R	35	17.5	10	30	13.7	N/R
F-J "CG"	2.5	>97	N/R	26-28	N/R	10	15	13	N/R
F-J "90" (P)	2.5-3	>97	N/R	35	17.5	10	30	13.5	N/R
Fed-Seal 200	N/R	N/R	N/R	N/R	N/R	N/R	N/R	N/R	N/R
WYO-BEN INC.									
Envirogel-10	N/R	N/R	N/R	N/R	N/R	N/R	N/R	N/R	N/R
Envirogel 200	N/R	N/R	N/R	N/R	N/R	N/R	N/R	N/R	N/R
Naturalgel	<4	96-98	N/R	22	11	9	4	11-12	84
AMERICAN COLLOID COMPANY									
CS - 200	N/R	N/R	N/R	N/R	N/R	N/R	N/R	N/R	N/R
Foundry C	N/R	N/R	N/R	N/R	N/R	N/R	N/R	N/R	N/R
Volclay MX-80	N/R	N/R	N/R	N/R	N/R	N/R	N/R	N/R	N/R
BLACKHILLS BENTONITE COMPANY									
product 404	N/R	90	N/R	N/R	N/R	N/R	N/R	14	95
B H B(regular)	N/R	N/R	N/R	10-15	N/R	N/R	N/R	N/R	N/R
B H B (fine)	N/R	N/R	N/R	N/R	N/R	N/R	N/R	N/R	N/R
BH-Natural	N/R	>97	N/R	35-40	N/R	10	15-20	13.5-14.4	91
BH-Granular	N/R	N/R	N/R	10-15	N/R	N/R	N/R	N/R	N/R
S-5 Natural	N/R	>97	N/R	25-27	N/R	12	N/R	11.5-12	86
HYG - 200 (P)	N/R	>97	N/R	30	N/R	N/R	N/R	16-20	>200
Min. Colloid CG	N/R	N/R	N/R	22-25	N/R	10	2-5	12-13	83
Min. Colloid 103	N/R	N/R	N/R	5-10	N/R	N/R	N/R	N/R	N/R
Min Colloid125(P)	N/R	>97	N/R	30	N/R	N/R	15	15-18	>125
CANADIAN CLAY PRODUCTS INC.									
Civil Eng.	4	96	N/R	N/R	N/R	N/R	N/R	N/R	N/R
Civil Eng.*	17	83	64	N/R	N/R	N/R	N/R	N/R	N/R
Civil Eng.**	N/R	N/R	N/R	N/R	7	4	6.5	N/R	N/R
Geoseal(1991)	N/R	N/R	N/R	N/R	N/R	N/R	N/R	N/R	N/R
Na-Bent.(1991)	N/R	N/R	N/R	N/R	N/R	N/R	N/R	N/R	N/R
ALBERTA BENTONITES		Clay	Silt	Sand					
MI - Autobond (Ro	N/R	76	22	1	6.5	6	1	22.5	70-105
(Onoway)***	N/R	44-54	40-49	2-10	N/R	N/R	N/R	N/R	36-48
(Rosalind)***	N/R	76-78	11-23	1	N/R	N/R			70-105
*(Rosalind)***		N/R	N/R	N/R	2.5-5.5	2 - 4	1 - 3	N/R	N/R

Note: Data presented is obtained from Manufacturers Technical Data Sheets unless otherwise noted.
* From Oscarson & Dixon (1989)
** Reschke & Haug (1991)
*** (Scafe,1975). *This deposit is extremely variable, values quoted are "typical" of the material*
+ Typical Wyoming bentonite (Newcastle formation, SWy-1 (Van Olphen & Fripiat, 1978)
N/R - Not reported, Data not available or not supplied by manufacturer
(P) - Polymerized Product

TABLE 5

SUMMARY OF BENTONITE PHYSICAL PROPERTIES

SAMPLE	Specific Gravity	pH 6% Soln.	Free Swell (cc/g)	Cation Exchange (meq/100g)	Surface Area (m2/g)	Liquid Limit(+) (%)	Plastic Limit(+) (%)	Plasticity Index(+)	Free Swell(++) (cc/g)
BENTONITE CORP. PRODUCTS									
Eviro-Seal (P)	2.5	9.2	29	76.2+	N/R	717	38	679	20
Newcastle +++	N/R	N/R	N/R	76.4	750	N/R	N/R	N/R	N/R
B-K Standard	2.5	9.4	28	N/R	N/R	537	41	496	13
B-K gran.	2.5		29	N/R	N/R	N/R	N/R	N/R	11
B-K 90 (P)	2.5	8.8	25	N/R	N/R	N/R	N/R	N/R	18.2
B-K 125 (P)	2.5	9.4	25	N/R	N/R	N/R	N/R	N/R	N/R
B-K 180 (P)	2.5	9.4	25	N/R	N/R	N/R	N/R	N/R	N/R
Natnl. LD-6	N/R	N/R	N/R	N/R	N/R	N/R	N/R	N/R	7
Natl. LD-16	N/R	N/R	N/R	77.9+	N/R	457	39	418	12.8
M-I DRILLING FLUIDS CO.									
Blue Tanner	N/R	N/R	N/R	56.9+	N/R	375	43	332	10
"ASH"	N/R	N/R	N/R	53.1+	N/R	374	45	329	19
F-J Natural	N/R	9.0-10.0	N/R	56+	N/R	503	41	462	26
F-J "CG"	N/R	8.5-9.5	N/R	60.7+	N/R	412	41	371	24
F-J "90" (P)	N/R	9 - 10	N/R	N/R	N/R	N/R	N/R	N/R	N/R
Fed-Seal 200	N/R	8.5-9.5	N/R	N/R	N/R	503	41	462	N/R
WYO-BEN INC.									
Envirogel-10	2.55	8.7-9.5	22-25	70-90	800	N/R	N/R	N/R	11
Envirogel 200	2.55	8.7-9.5	22-25	70-90	800	452	37	415	21
Naturalgel	2.55	8.7-9.5	22-25	70-90	800	N/R	N/R	N/R	N/R
AMERICAN COLLOID COMPANY									
CS - 200	N/R	N/R	N/R	89.9+	N/R	383	44	339	8
Foundry C	N/R	N/R	N/R	76.5+	N/R	N/R	N/R	N/R	9
Volclay MX-80	2.7	8.5-10	12-15	85-90(81.8+)	N/R	N/R	N/R	N/R	12
BLACKHILLS BENTONITE COMPANY									
product 404	2.74	8.4	15	55.4+	N/R	333	40	293	14
B H B(regular)	2.6	8.5-9.5	N/R	N/R	N/R	N/R	N/R	N/R	N/R
B H B (fine)	2.6	N/R	N/R	N/R	N/R	N/R	N/R	N/R	N/R
BH-Natural	2.6	8-10	N/R	N/R	N/R	N/R	N/R	N/R	N/R
BH-Granular	2.6	8.5-9.5	11-12.5	N/R	N/R	N/R	N/R	N/R	N/R
S-5 Natural	2.6	8-10	N/R	N/R	N/R	N/R	N/R	N/R	N/R
HYG - 200 (P)	2.6	7 - 9	N/R	N/R	N/R	N/R	N/R	N/R	N/R
Min. Colloid CG	2.6	8-9	N/R	N/R	N/R	N/R	N/R	N/R	N/R
Min. Colloid 103	2.6	8.5-9.5	7.5-8.5	N/R	N/R	N/R	N/R	N/R	N/R
Min Colloid125(P	2.6	N/R	N/R	N/R	N/R	N/R	N/R	N/R	N/R
CANADIAN CLAY PRODUCTS INC.									
Civil Eng.	2.75	9.0	10	80-85	500-850	400-450	est 40	360-410	N/R
Civil Eng.*	N/R	N/R	N/R	N/R	N/R	(150-385)+	(33-64)+	(115-330)+	9 +
Civil Eng.**	N/R	8.5-9.5	N/R	82	568	245	36	209	N/R
Geoseal(1991)	2.55	8.5-9.5	6.5-8.5	70-85	N/R	N/R	N/R	N/R	N/R
Na-Bent.(1991)	2.5	8.5-9.5	7.5-10	75-90	N/R	N/R	N/R	N/R	N/R
ALBERTA BENTONITES									
MI - Autobond (R	N/R	8.8-9.2	N/R	N/R	N/R	N/R	N/R	N/R	N/R
(Onoway)***	N/R	N/R	N/R	37-43	N/R	N/R	N/R	N/R	N/R
(Rosalind)***	N/R	N/R	N/R	85-105	N/R	N/R	N/R	N/R	N/R
(Rosalind)**	N/R	N/R	N/R	57-71	469-493	(338-440**)	(30-35**)	(306-405**)	N/R

Note: Data presented is obtained from Manufacturers Technical Data Sheets unless otherwise noted.
* From Oscarson & Dixon (1989)
** Reschke & Haug (1991)
*** (Scafe,1975), This deposit is extremely variable, values quoted are "typical" of the material
+ From WL or commercial testing laboratories
++ From WL, modified free swell test using 0.15 Molar NaCl
+++ Typical Wyoming bentonite (Newcastle formation, SWy-1 (Van Olphen & Fripiat, 1978)
N/R - Not reported, Data not available or not supplied by manufacturer
(P) - Polymerized Product

TABLE 6

PROPERTIES OF THE REFERENCE (SASKATCHEWAN) BENTONITE

Particle size		
	% Clay (<2 um)	>60%
	% Silt (76 um to 2 um)	<40%
	% Sand (>76 um)	<1%
Consistency Limits		
	Liquid Limit	>250%
	Plastic Limit	40-50%
	Plasticity Index	>200%
Confined Swelling Pressure		
	in distilled deionized water (DDW)	
	at γ_d = 1.15 Mg/m³	>700 kPa
	at γ_d = 1.30 Mg/m³	>1500 kPa
	in saline water	
	at γ_d = 1.15 Mg/m³	>500 kPa
	at γ_d = 1.30 Mg/m³	>1000 kPa
Hydraulic Conductivity		
	at γ_d = 1.15 Mg/m³	$<10^{-11}$ m/s
	at γ_d = 1.30 Mg/m³	$<10^{-12}$ m/s
Cation Exchange Capacity		
	50 to 85 meq/100 g	
Clay Specific Surface		
	500 to 650 m²/g	
Exchangeable Cation Composition		
	50% sodium	
	40% calcium	
	10% magnesium/potassium	

TABLE 7

COMPARISON OF SASKATCHEWAN AND WYOMING BENTONITES
(relative to Saskatchewan Na-bentonite)

Material	Cation Exchange Capacity	Liquid Limit	Plastic Index	Viscosity (600 rpm)	Free Swell	PS (at 1.15 Mg/m^3) (kPa)	k (m/s)
Saskatchewan Bentonite							
Civil Eng./Geoseal	55-60	250	200	---	x	<1000	$<10^{-11}$
Bentonite Corp.							
Bara-Kade Standard	>>	>>	>>	>>	1.3x	=	<=
National LD-16	>>	>	>	---	1.3x	---	---
M-I Drilling							
"Blue Tanner"	=	>=	>=	---	=	---	---
"Ash"	=	>=	>=	---	2x	=	<=
Federal Jel	=	>	>	>>	3x	---	---
Federal Jel (CG)	=	>	>>	>>	>2x	=	<=
Federal Seal	---	>	>	---	---	---	---
WYO-BEN							
Envirogel 200 (P)	=	>	>	---	2x	---	---
CETCO (Am. Colloid)							
CS-200	>>	>=	>=	---	=	---	---
Foundry C	>	---	---	---	=	---	---
Volclay MX80	>>	>	>	---	>=	=	<=
Black Hills							
Black Hills Bond*	---	---	---	>	>	---	---
Product 404	=	=	=	---	1.5x	---	---
Black Hills Nat.*	---	---	---	>	>	---	---
S 5 Natural*	---	---	---	>	---	---	---
Mineral Colloid*	---	---	---	<=	---	---	---
Alberta Bentonites							
M-I Autobond*	>=	=	=	=	---	---	---
"Onoway deposits"*	=	---	---	<	<	---	---

Notes:

PS - Swelling pressure developed
k - Hydraulic conductivity
(P) Polymerized product
> Greater than
>= Greater than or equal to
< Less than
<= Less than or equal to
= Equal to
--- Data not available
* data based on technical data sheets and literature only.

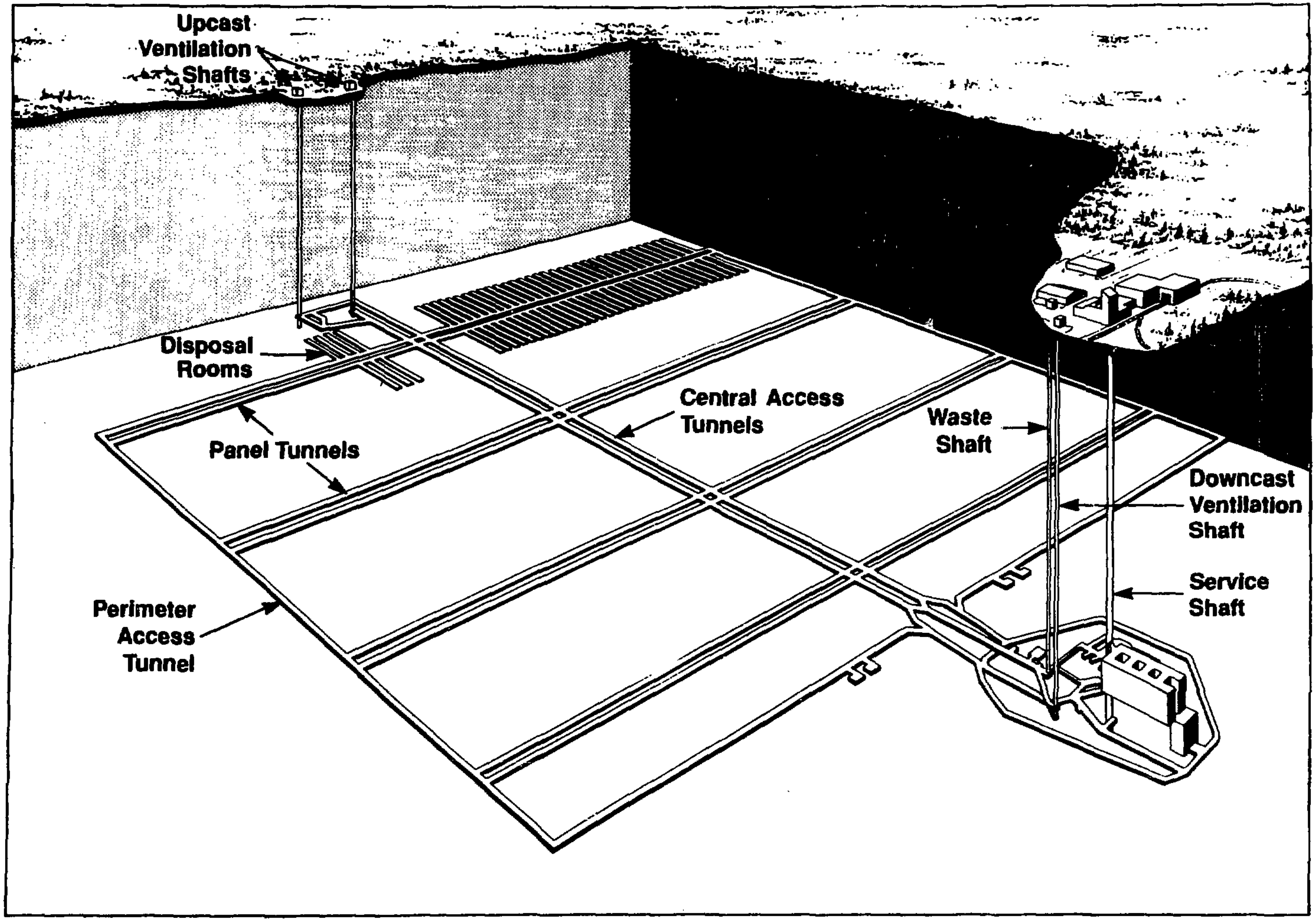

FIGURE 1: Canadian Disposal Vault Concept

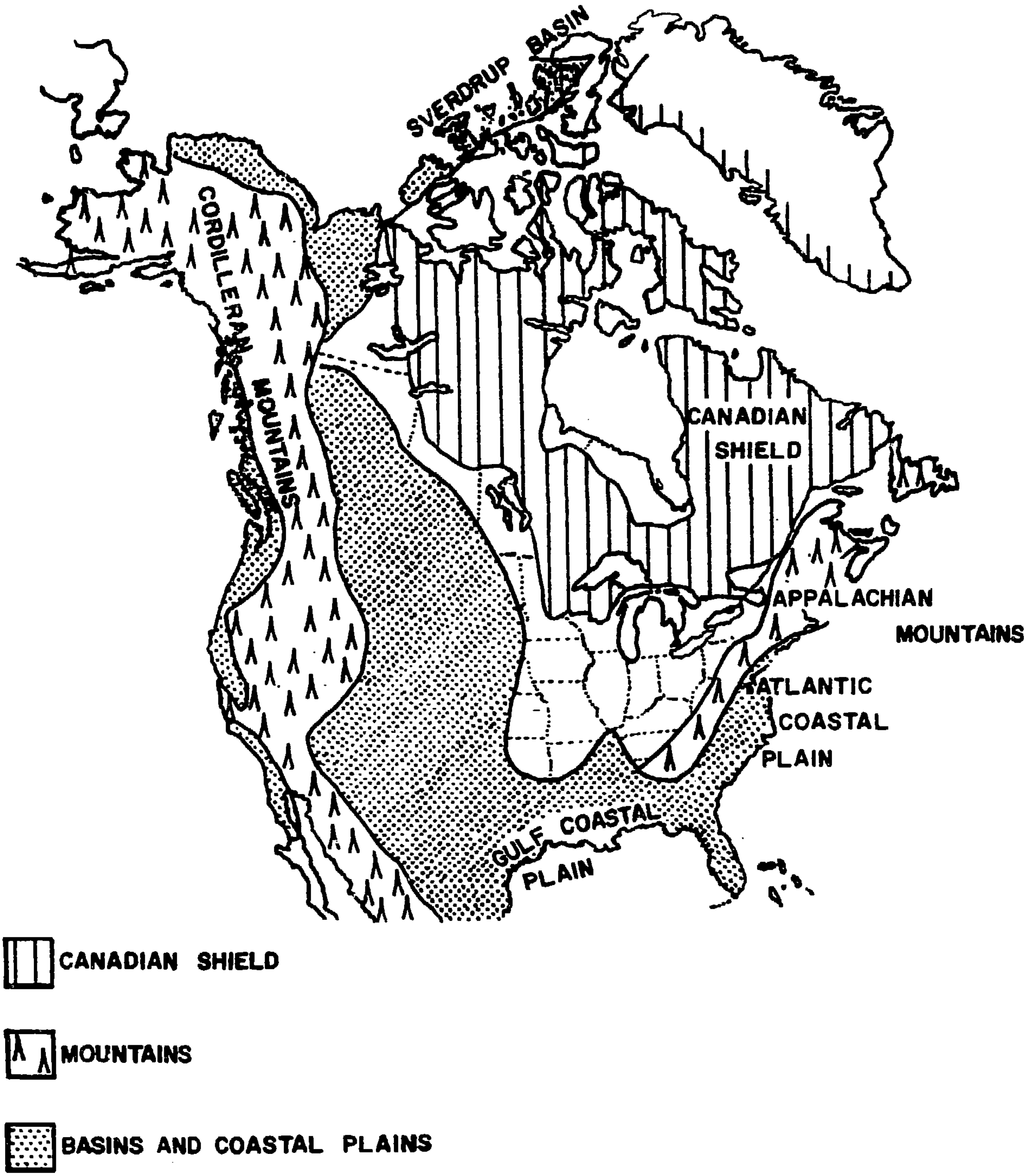

FIGURE 2: Cretaceous Inland Sea Boundaries (Sartorius 1978)

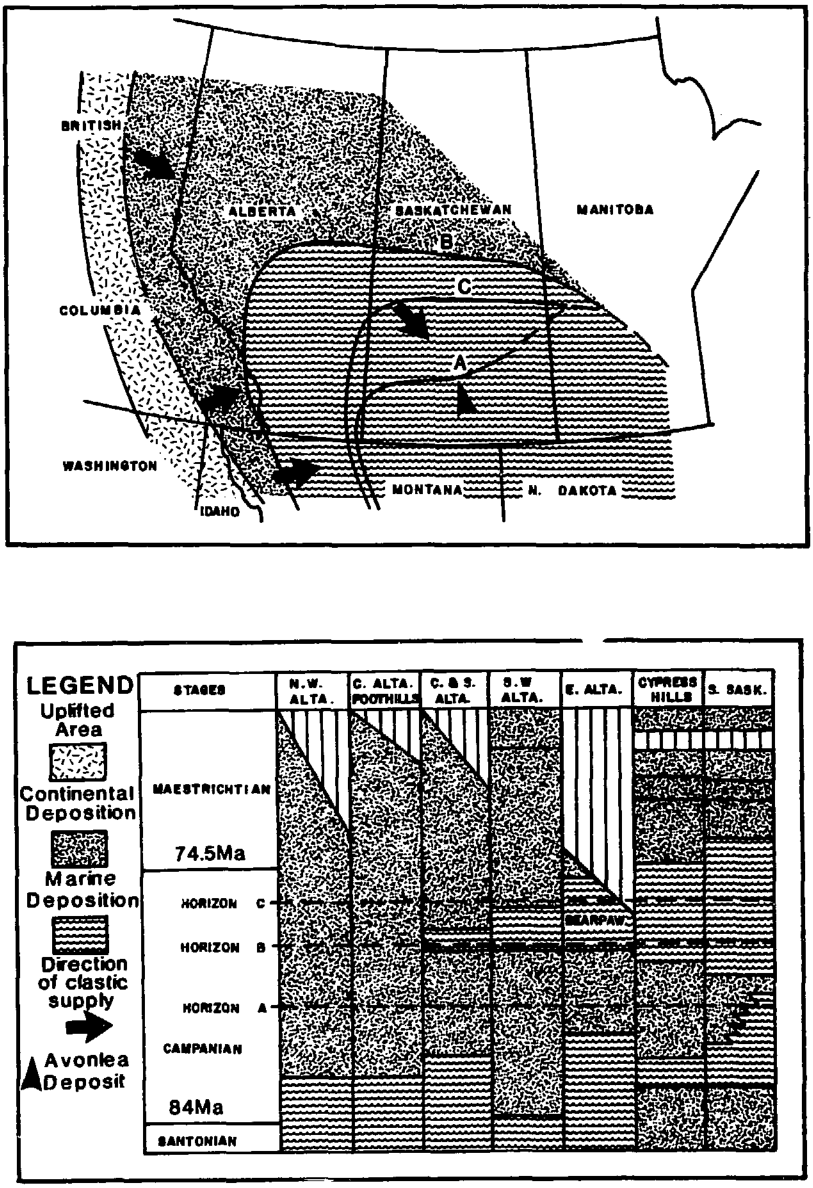

FIGURE 3: Changes in Shoreline Location During Cretaceous Age

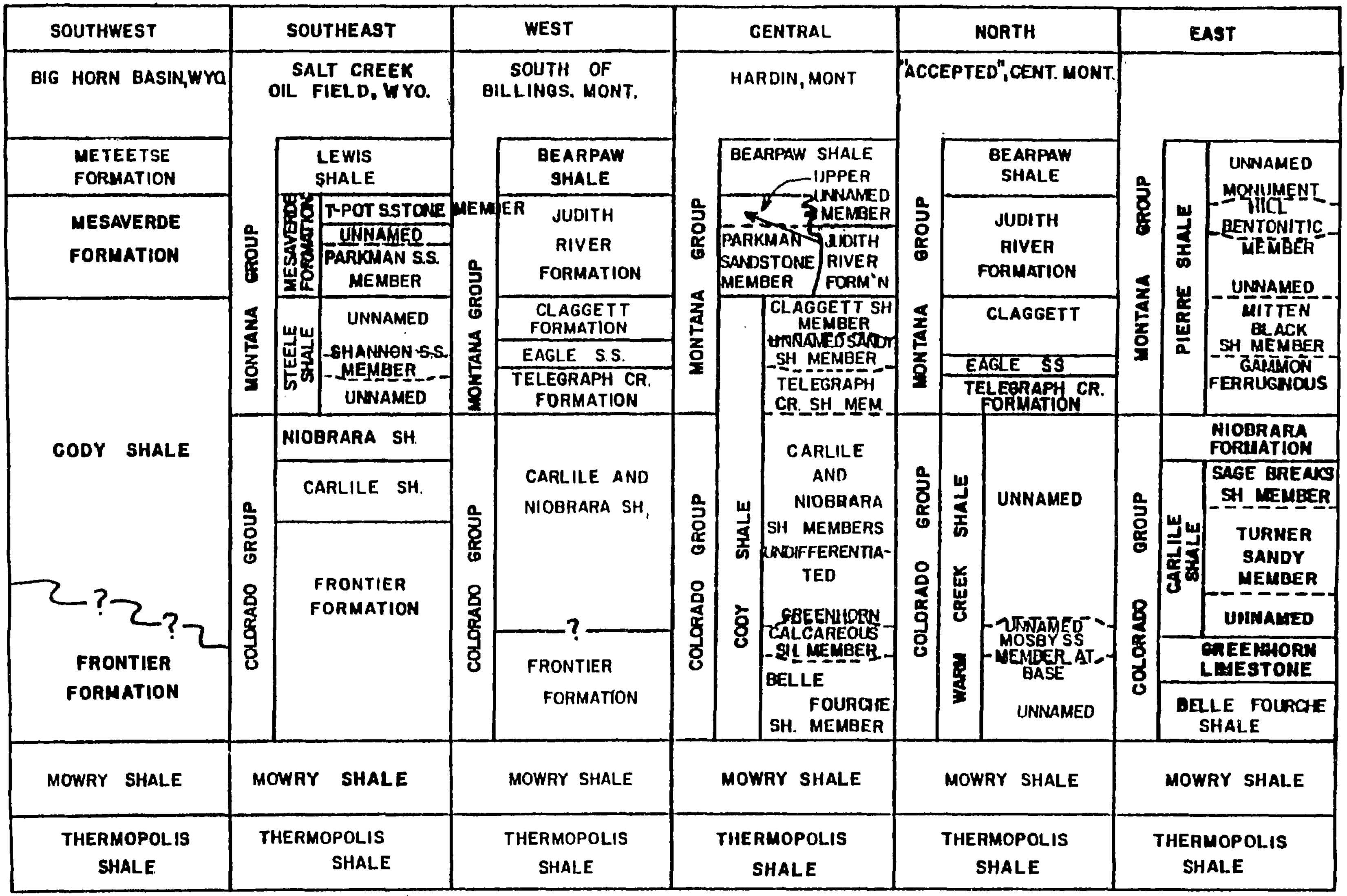

FIGURE 4: Geological Location of Wyoming Bentonitic Deposits (Sartorius 1978)

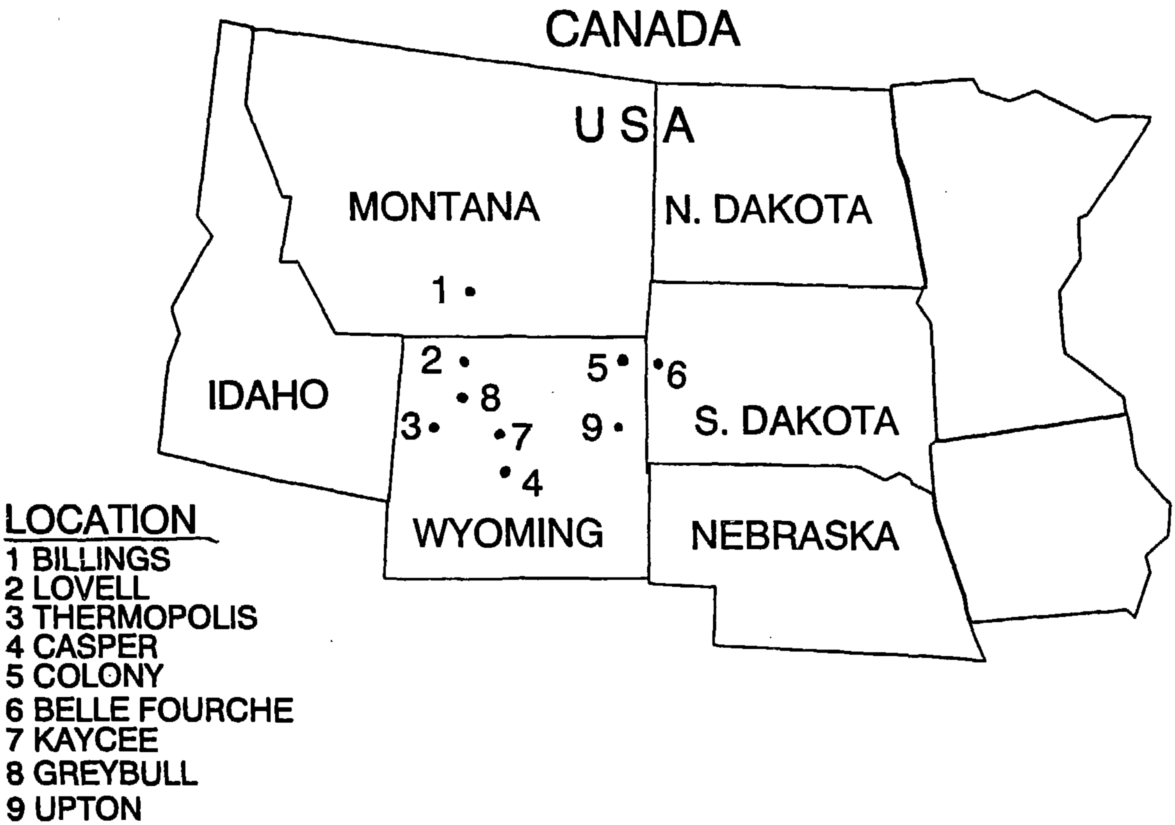

FIGURE 5: Wyoming Bentonite Exposures and Processing Facilities

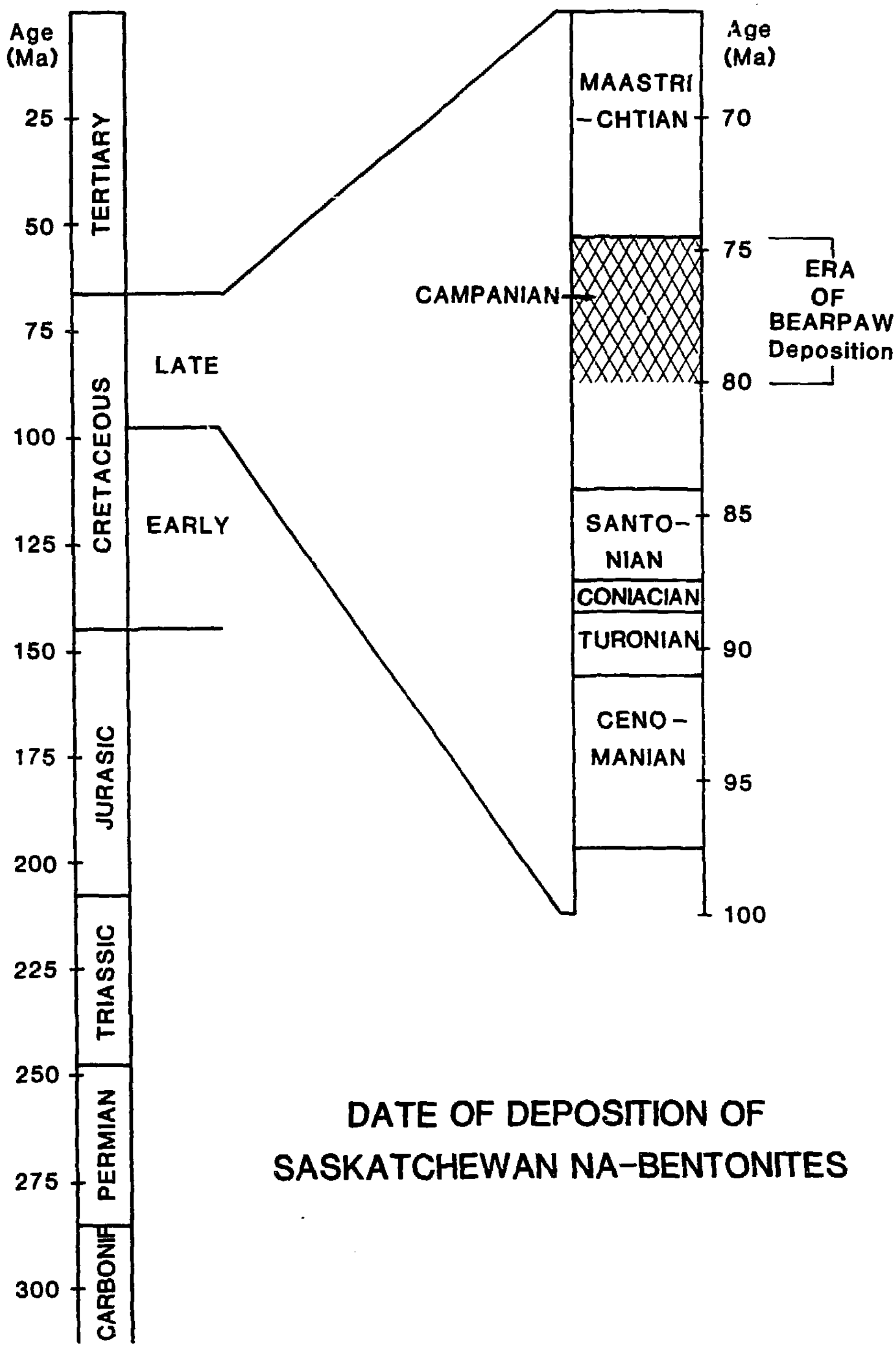

FIGURE 6: Geological Location of Bearpaw Shale

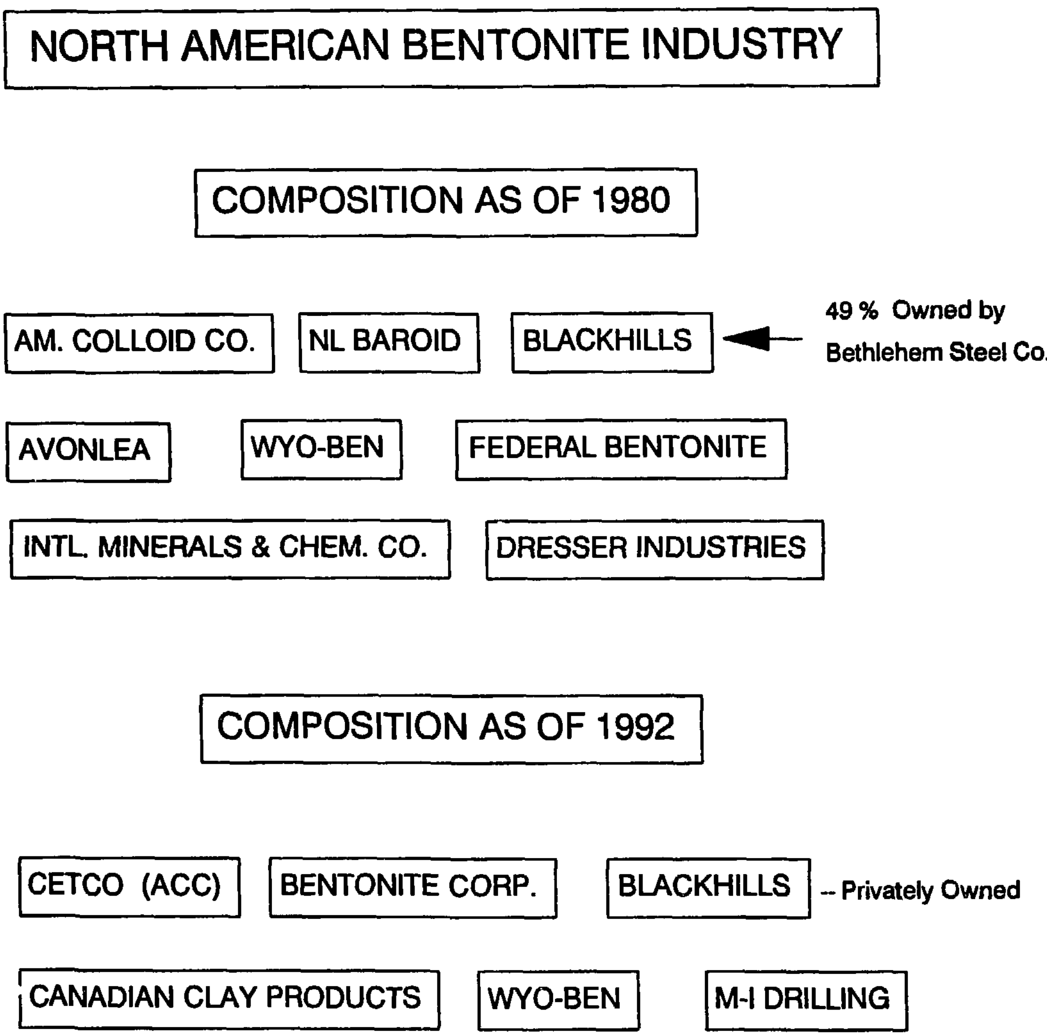

FIGURE 7: Changes in the Bentonite Industry

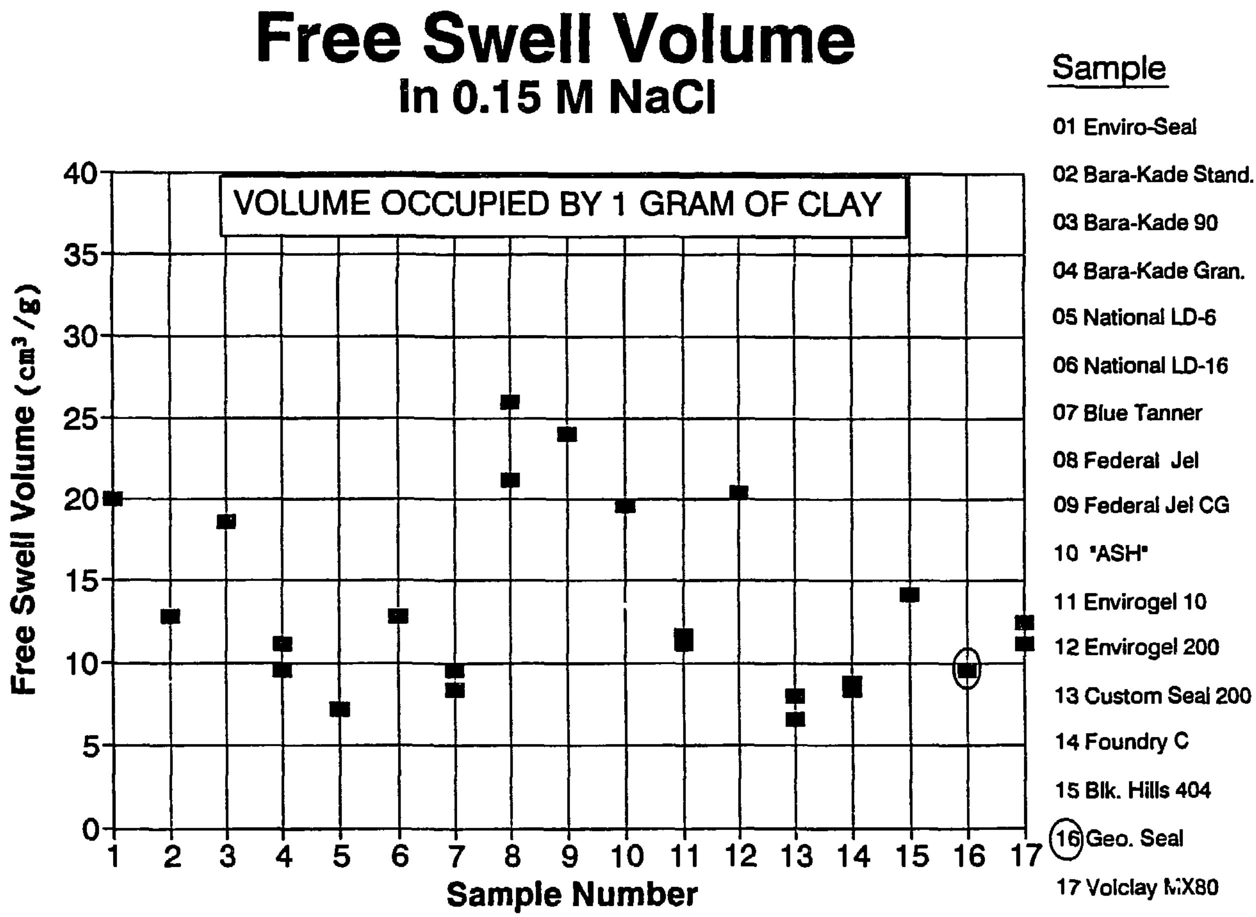

FIGURE 8: Free Swell Capacity of Sodium Bentonites

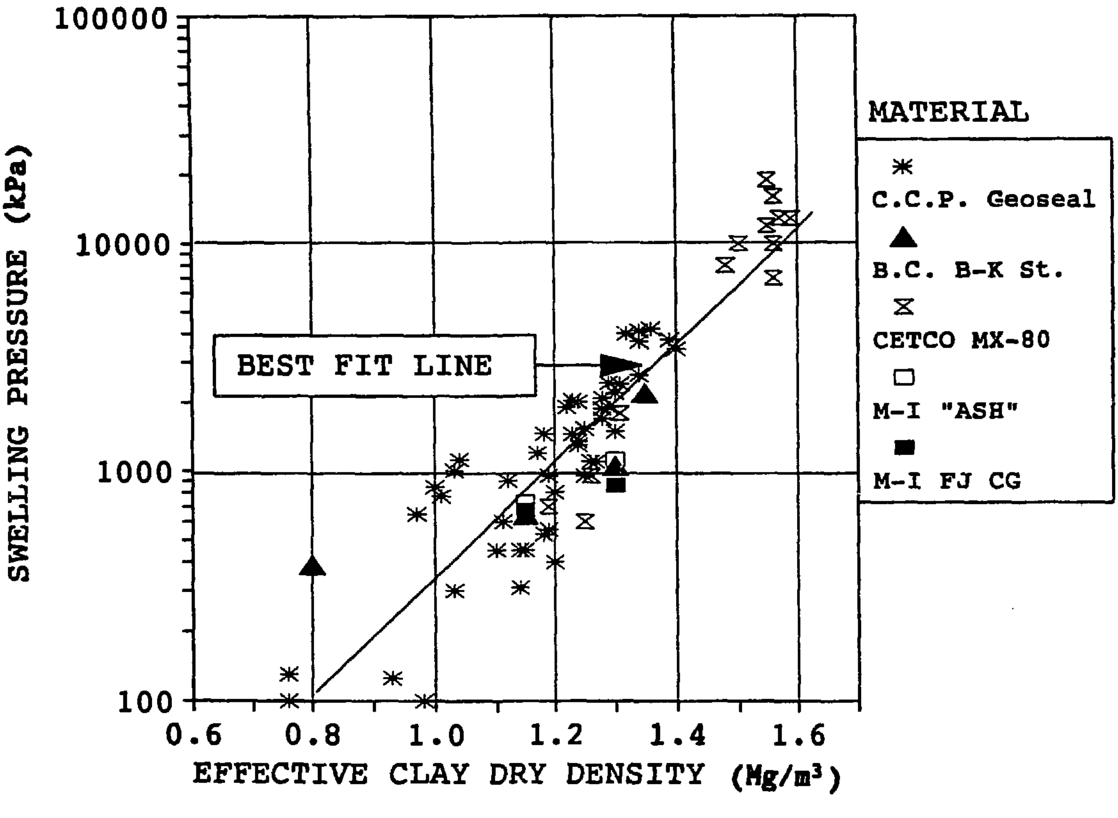

FIGURE 9: Swelling Pressure Generated by Sodium Bentonites

APPENDIX A

PROCESSING FLOW CHARTS FOR BENTONITE MILLS

The processing sequence of several of the bentonite mills are presented in Figures A-1 to A-5. They are intended to provide information on the processes involved in the conversion of bentonitic clay/shale ore to the final powdered bentonite. They also show how the processing streams can be adjusted to provide customer-specific products.

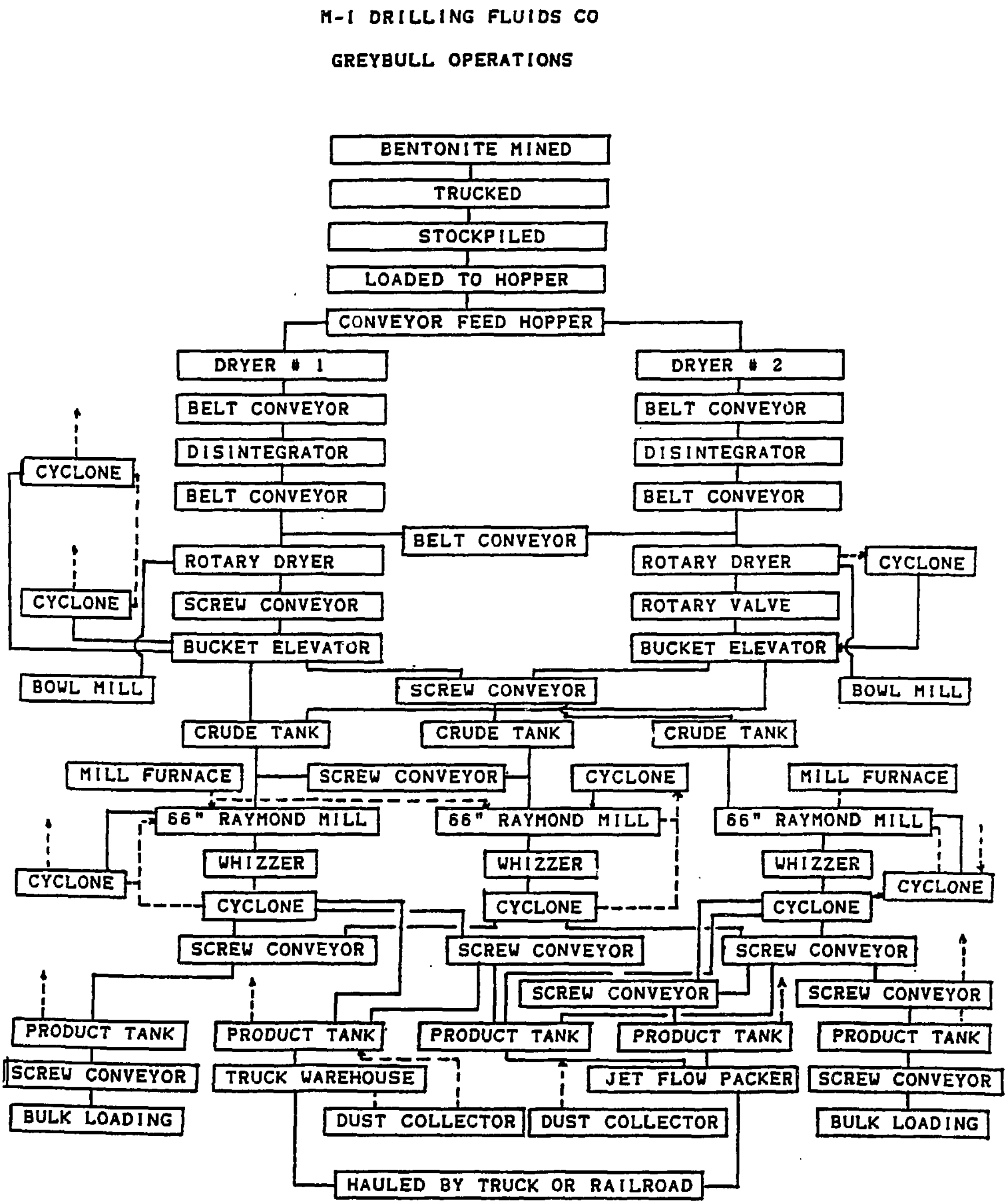

FIGURE A-1: M-I Drilling Fluids Company; Processing Using a Raymond-Type Mill

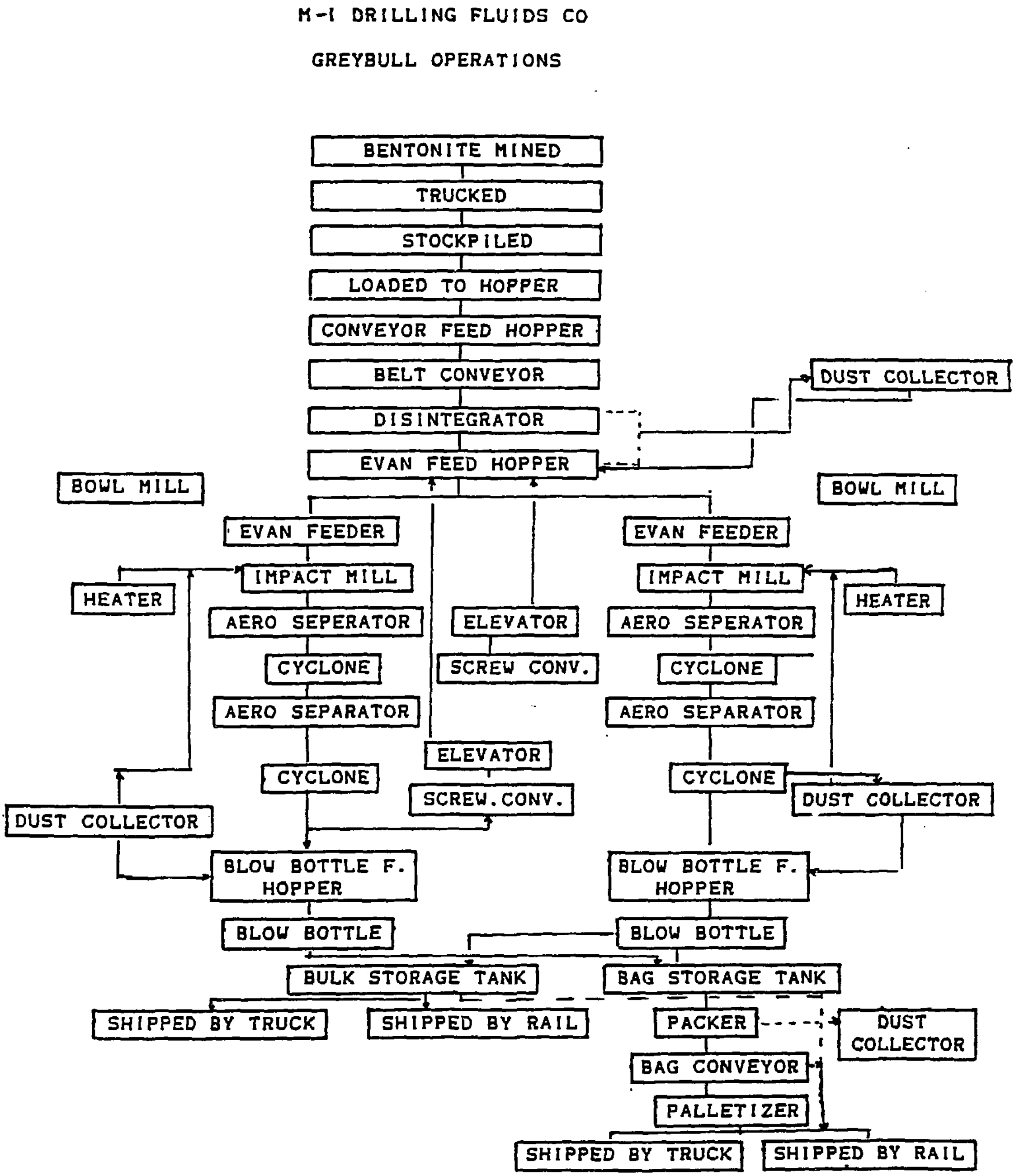

FIGURE A-2: M-I Drilling Fluids Company; Processing Using a Williams-Type Mill

CE-210:01 * MATERIAL FLOW CHART
COLONY EAST PLANT

ISSUE DATE: 03-01-90 **REVISION DATE:**

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( ) ( )

SUMMARY: THIS MATERIAL FLOW CHART DENOTES THE PROCESS FLOW AND CONTROL POINTS

PROCEDURE: IT IS THE RESPONSIBILITY OF THE PLANT SUPT. TO UPDATE THIS CHART WHEN THERE IS A CHANGE IN THE PROCESS FLOW.

= CONTROL CHARTS

= VISUAL INSPECTION, NORMAL SAMPLE

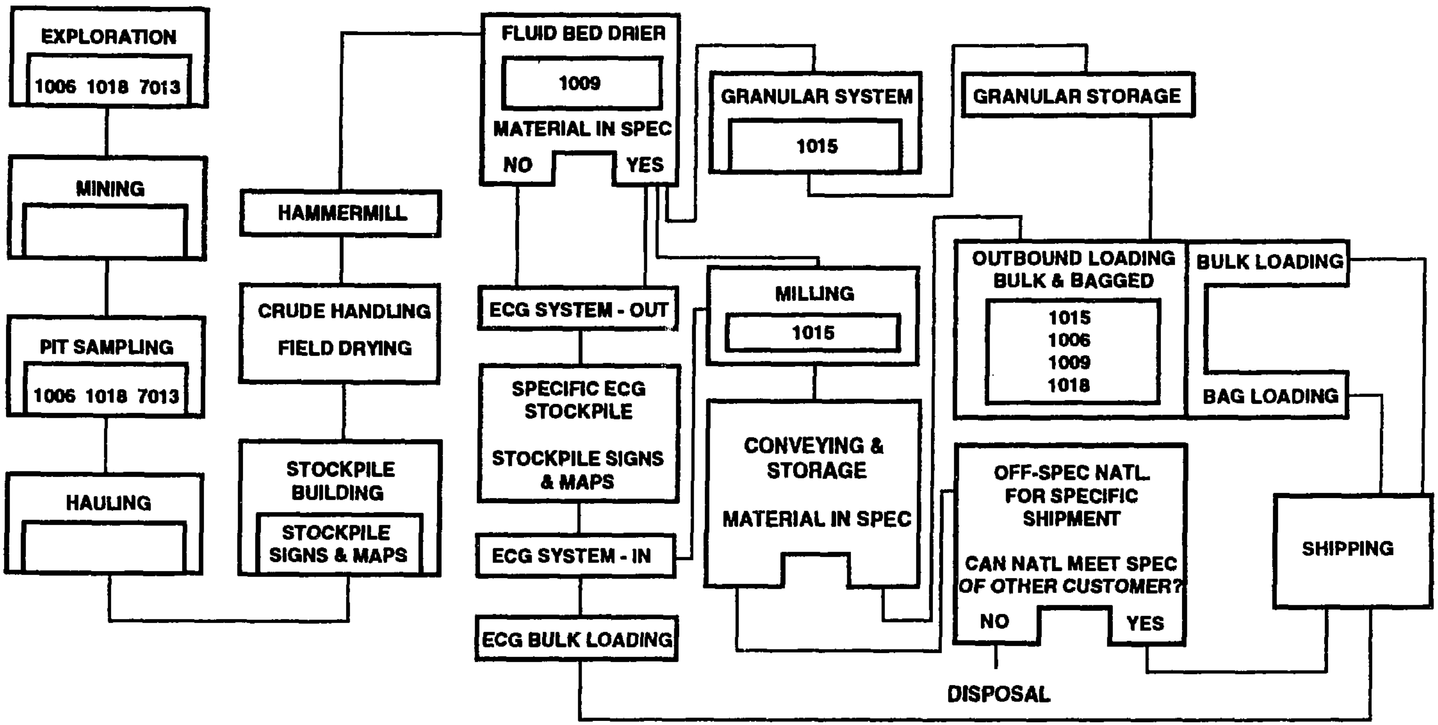

FIGURE A-3: American Colloid Company; Material Flow Chart for Fluid-Bed Drier Milling

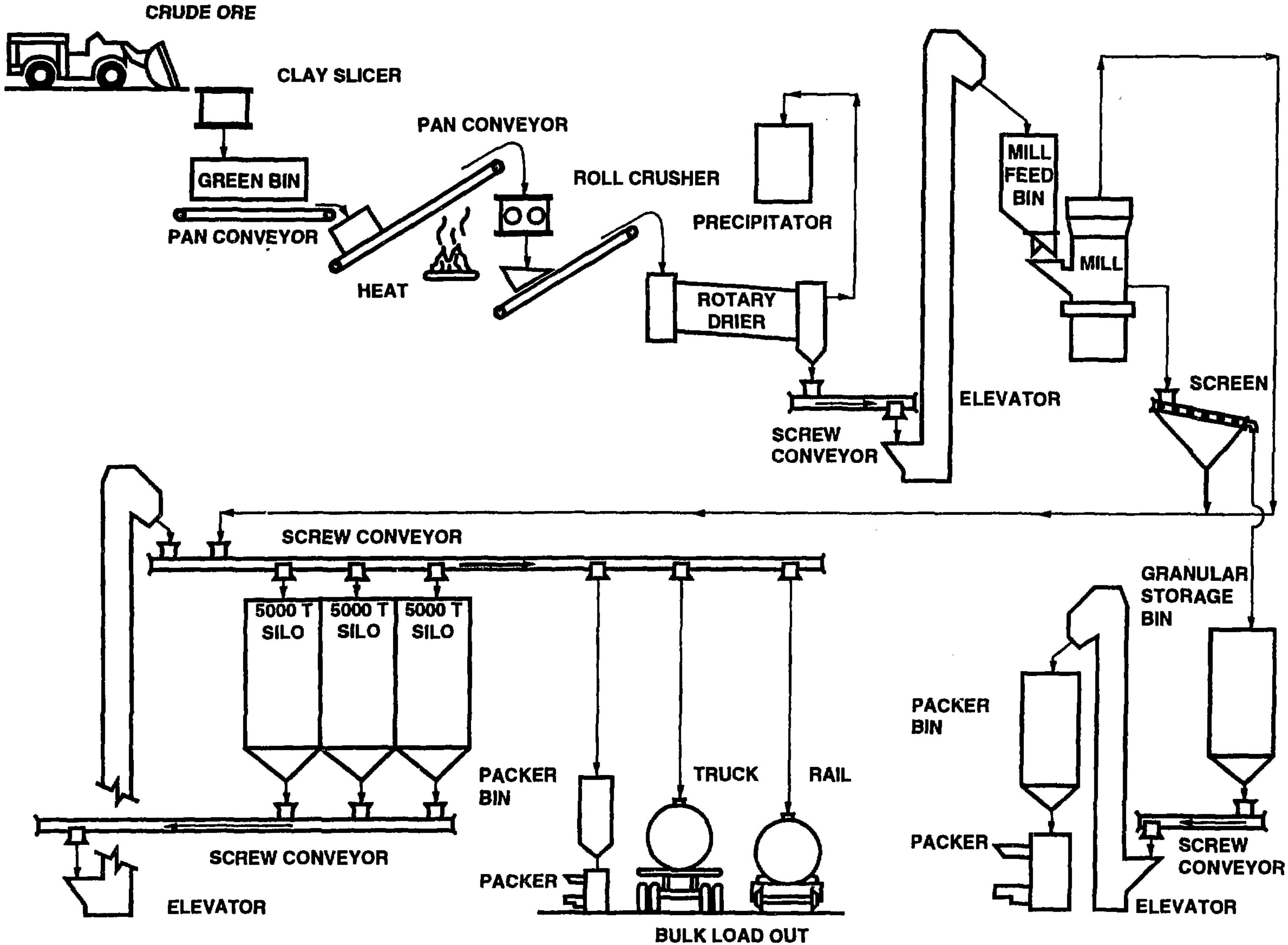

FIGURE A-4: Bentonite Corporation; Generalized Flow Chart for Raymond Mill

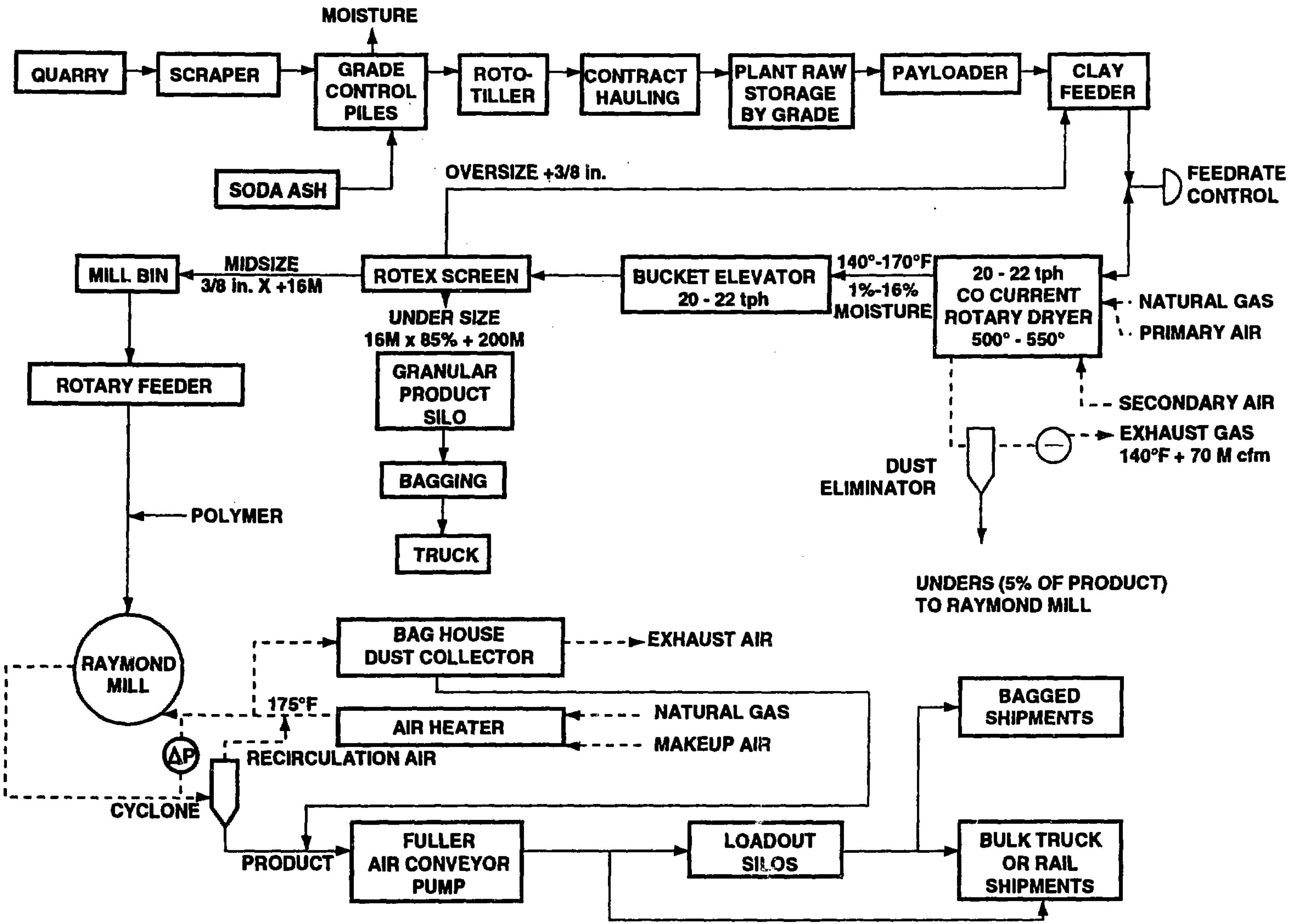

FIGURE A-5: Canadian Clay Products; Material Flow Chart for Raymond-Type Mill

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