Wind Induced Movement of Radioactive Sands from Uranium Tailings Piles

A Thesis

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Dedicated to my brother, Peter

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ABSTRACT

With the increase of electrical energy generation by fission reactors in the United States, there is a concomitant expansion of uranium mining and milling operations to provide the necessary fuel. A major environmental concern is radiation doses from inhalation of uranium tailings. The movement part of uranium tailings are similar to the Eolian transport of sand in deserts or beaches. Mathematical models developed for Eolian transport of sand particles in desert or beach areas was used to describe the transport of "sand-type" of tailings particles.

Particle-size distributions for the Anaconda Mill tailings pile in Bluewater, New Mexico, along with these determinations, gamma spectrometry using a NaI(Tl) scintillator provide data on the equivalent Ra-226 activity as a function of particle size. The activity exhibited a broad minimum near 500 μ. An increase of activity for particle sizes above 650 μ was observed for the first time. Radioactivity determination as a function of particle-size is necessary for internal dose calculations using lung models.

CHAPTER I

Introduction to Milling Operations

In recent years the generation of electricity by light-water-nuclear reactors in the United States has grown considerably. As a result of this growth of nuclear reactors in the United States, there is a parallel growth of activities that must exist to support the operation of these reactors. This activity associated with the uranium fuel cycle can be conveniently separated into seven operations: (1) mining and milling, where the ore is processed to obtain uranium oxide (U_3O_8); (2) conversion, where the uranium oxide (U_3O_8) is converted to uranium hexafluoride (UF_6), (3) isotopic enrichment, where the U-235 concentration is increased from 0.711 percent by weight to the design specification (usually 2 to 4 percent by weight of U-235 for light-water-reactors), (4) fuel fabrication where the enriched UF_6 is formed into UO_2 pellets, loaded into alloy tubing, and fabricated into individual fuel element bundles, (5) the fissioning of the uranium fuel in light-water-reactors, (6) the reprocessing of the spent fuel after it leaves the reactor, and (7) the storage and ultimate disposal of the fission products. These operations are shown in Figure 1-1 as they relate to a one thousand megawatt electrical power reactor.[1]

The area of interest of this thesis is in the milling operations. A uranium mill extracts uranium from the feed ore. The

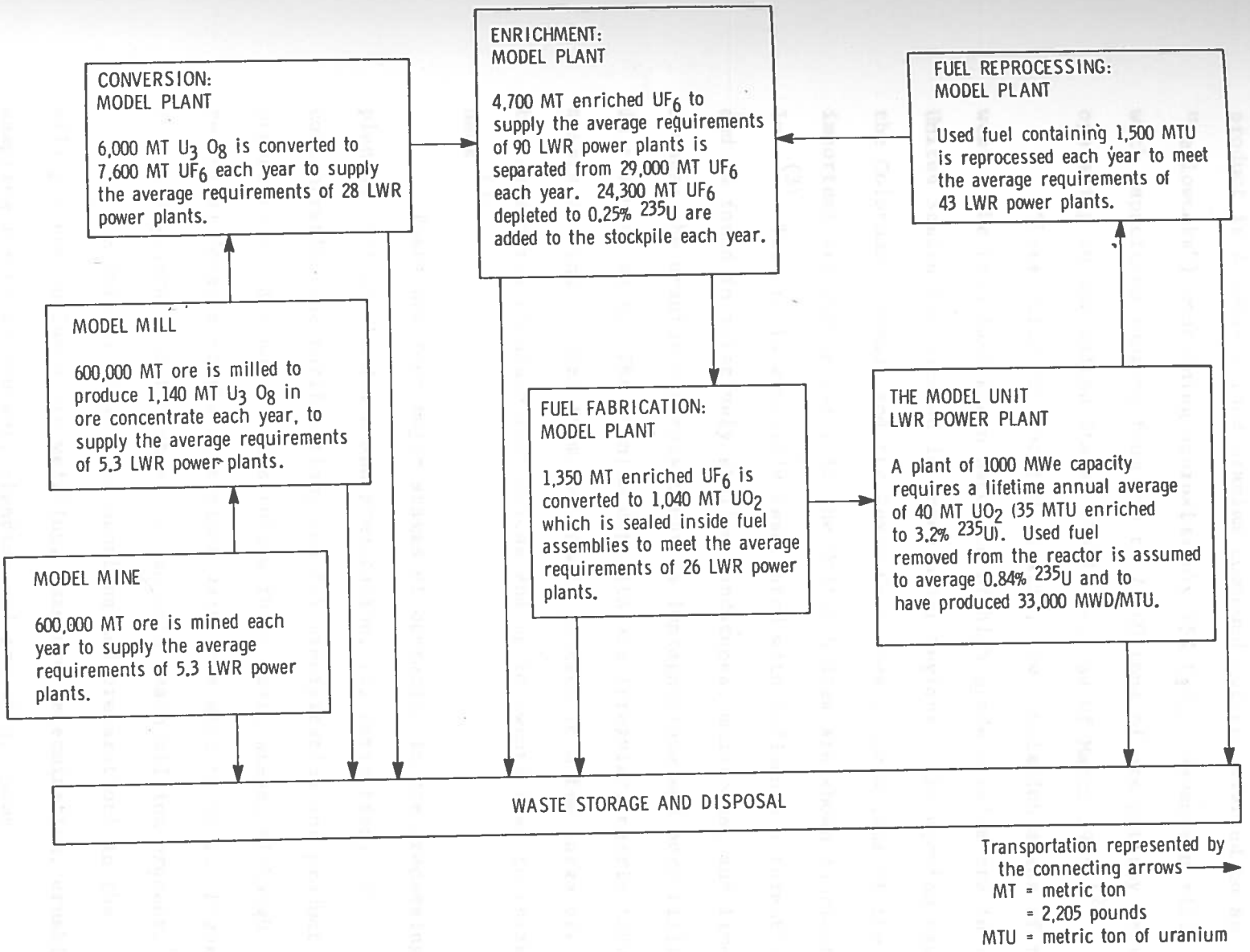


Figure 1-1. Model Facility Relationships in the Uranium Fuel Cycle for LWR Power Plants.

product is a semi-refined uranium compound (often referred to as "yellowcake") containing approximately 85% U_3O_8. Seventeen mills with capacities ranging from 250 to 7,000 tons of ore per day were operating in the United States (Table 1-1) as of March 1975.[2]

These mills are located in arid, low population areas of the west. The principal known deposits of high grade uranium ore in the United States are located in three major regions: the Wyoming Basin, the Colorado Plateau, and the Texas Gulf Coast. Locations of the more important uranium deposits in the United States are shown in Figure 1-2.[3] The ore is generally associated with sedimentary formations, and is found in relatively shallow sandstones, mudstones, and limestones; the uranium minerals occur as impregnations and pore fillings in the host rock. The uranium deposits are irregular, nearly tabular masses varying in size from very small pockets to a few large ore bodies several thousand feet across and up to twenty feet in thickness.[3]

There are four major stages of operation in ore processing plants: (1) ore handling and preparation, (2) extraction, (3) concentration and purification, and (4) precipitation and product preparation. All major mills follow these basic steps, although technical details of the operations vary from mill to mill. Figure 1-3 is a generalized flowsheet for an acid leach milling process.[4, 1]

The initial stage (ore handling and preparation) in the mill process includes ore weighing, moisture determination, crushing, sampling for metal content, blending and grinding. Some

Table 1-1

Uranium Mills in Operation as of March 1975

Company	Location	Year Operations Initiated	Nominal Capacity (Tons of Ore/Day)
Anaconda Company	Grants, New Mexico	1953	3000
Atlas Corporation	Moab, Utah	1956	800-1500
Conoco & Pioneer Nuclear, Inc.	Falls City, Texas	1961	220-1750
Cotter Corporation	Canon City, Colorado	1958	150-450
Dawn Mining Company	Ford, Washington	1957	0-400
Exxon, U.S.A.	Powder River Basin, Wyoming	1971	2000
Federal-American Partners	Gas Hills, Wyoming	1959	500-950
Kerr-McGee Nuclear	Grants, New Mexico	1958	3600-7000
Petrotomics Company	Shirley Basin, Wyoming	1962	525-1500
Rio Algom Corp.	La Sal, Utah	1972	500
Union Carbide Corp.	Uravan, Colorado	1950	0-1300
Union Carbide Corp.	Natrona County, Wyoming	1960	1000

Table 1-1 (Continued)

Company	Location	Year Operations Initiated	Nominal Capacity (Tons of Ore/Day)
United Nuclear-Homestake Partners	Grants, New Mexico	1958	1650-3500
Utah International, Inc.	Gas Hills, Wyoming	1958	750-1200
Utah International, Inc.	Shirley Basin, Wyoming	1971	1200
Western Nuclear, Inc.	Jeffrey City, Wyoming	1957	400-1200
TVA (Mines Development, Inc.)	Edgemont, South Dakota	1956	250-500

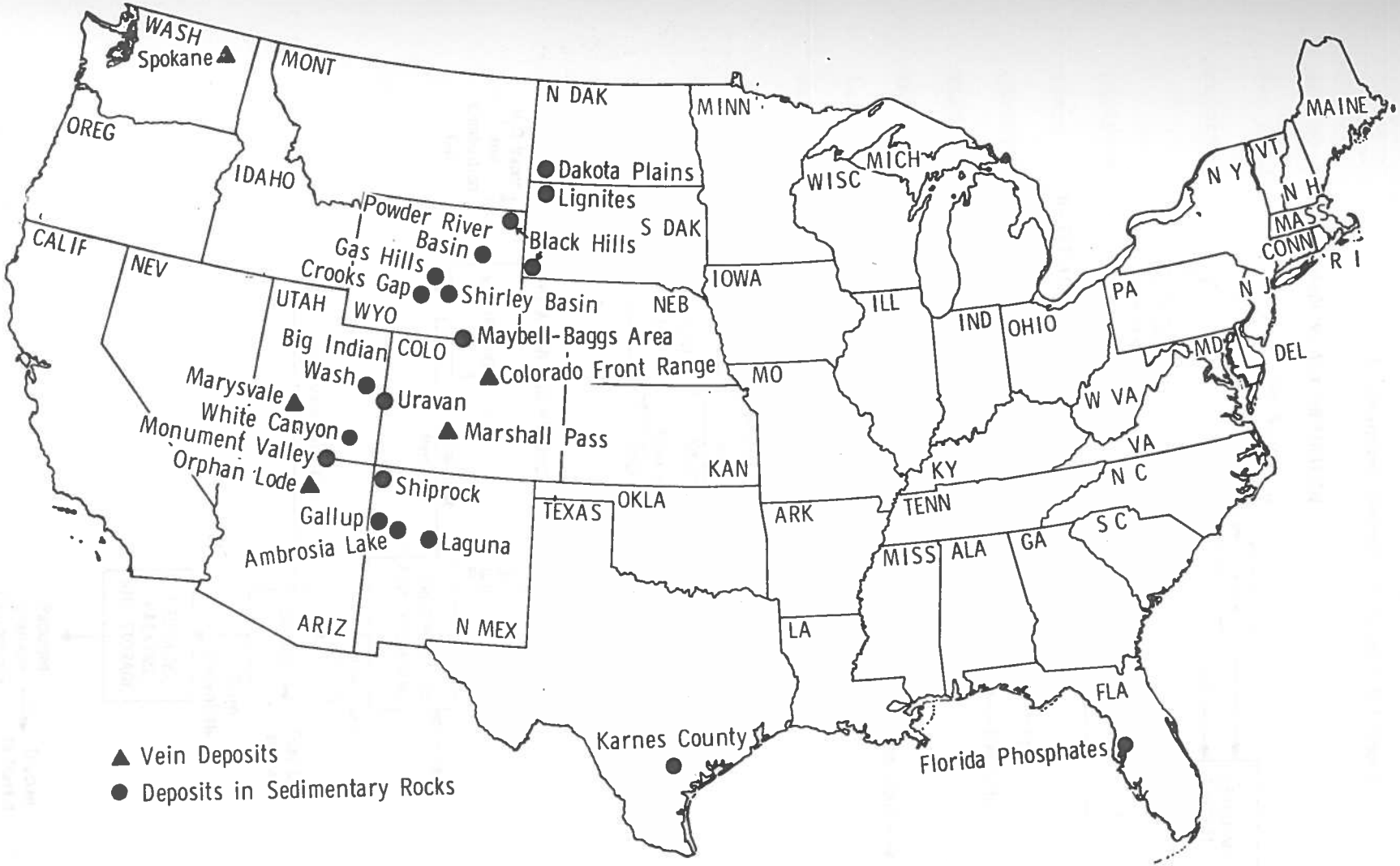
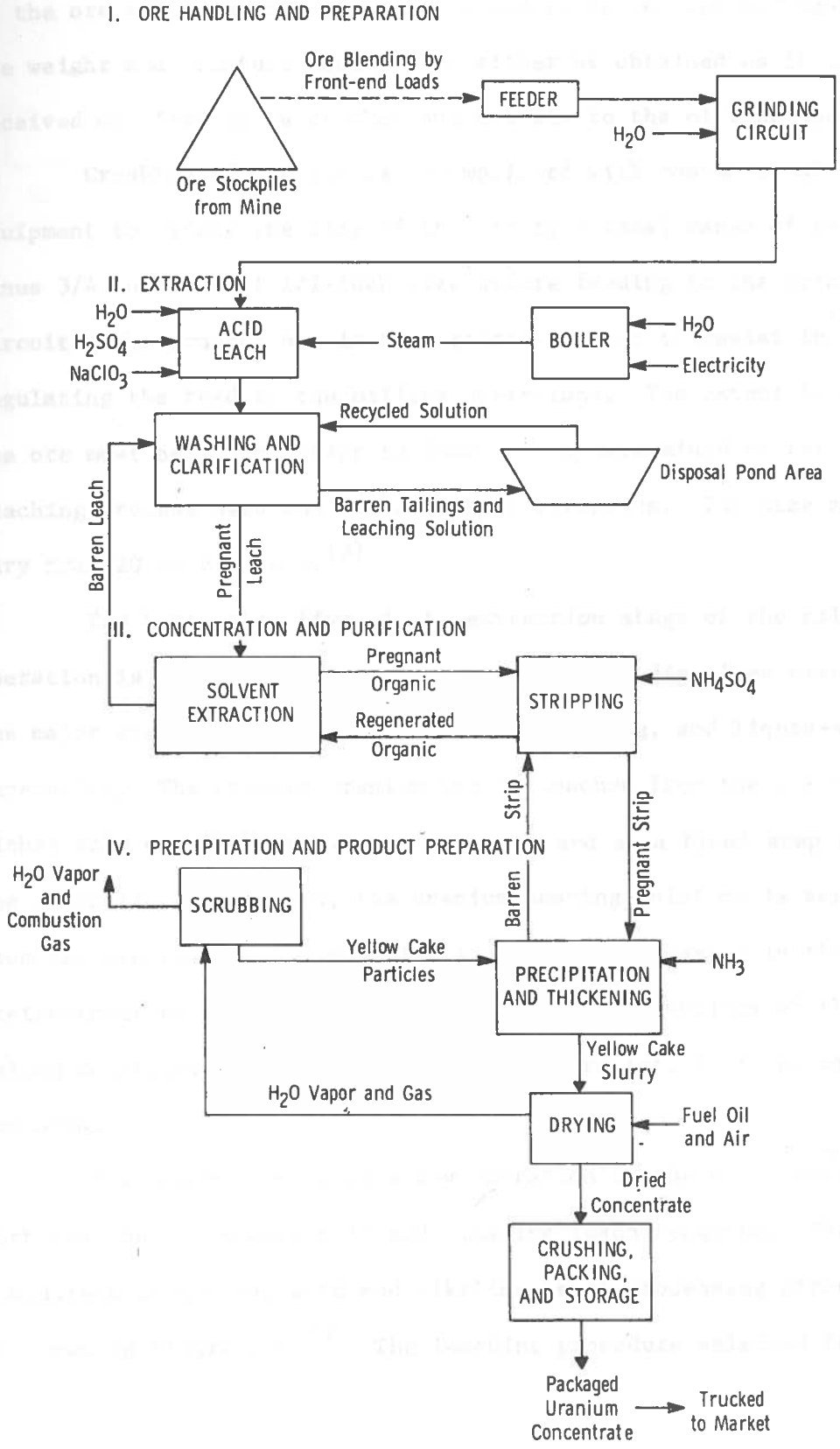


Figure 1-2. Important Uranium Districts of the United States

Figure I-3. Generalized Flowsheet of ACID Leach Mill Process



of the ore may have to be dried if found to be too wet for handling. Ore weight and moisture content can either be obtained as it is received or after it is crushed and enroute to the milling operation.

Crushing of the ore is accomplished with conventional equipment to reduce the size of the ore to a usual range of between minus 3/4 and minus 1 1/2-inch size before feeding to the grinding circuit. The crushed ore is then stored in bins to assist in regulating the feed to the milling operations. The extent to which the ore must be ground prior to leaching is determined by the leaching process used and the ore characteristics. The size may vary from 20 to 200 mesh.(3)

The basic objective of the extraction stage of the milling operation is to obtain solutions containing the dissolved uranium. The major steps involved are, roasting, leaching, and liquid-solid separation. The crushed uranium ore is leached from the ore by either acid or alkaline leach processes, and as a final step in the extraction operations, the uranium-bearing solution is separated from the ore residue. A roasting step may be necessary in the pretreatment of some uranium ores so that the solubility of the valued constituents and the physical characteristics of the ore are improved.

The leaching step is a key operation in the mill process with the choice between acid and alkaline leach reagents. The comparison of typical acid and alkaline leach processing circuits is shown in Figure 1-4.(3) The leaching procedure selected for

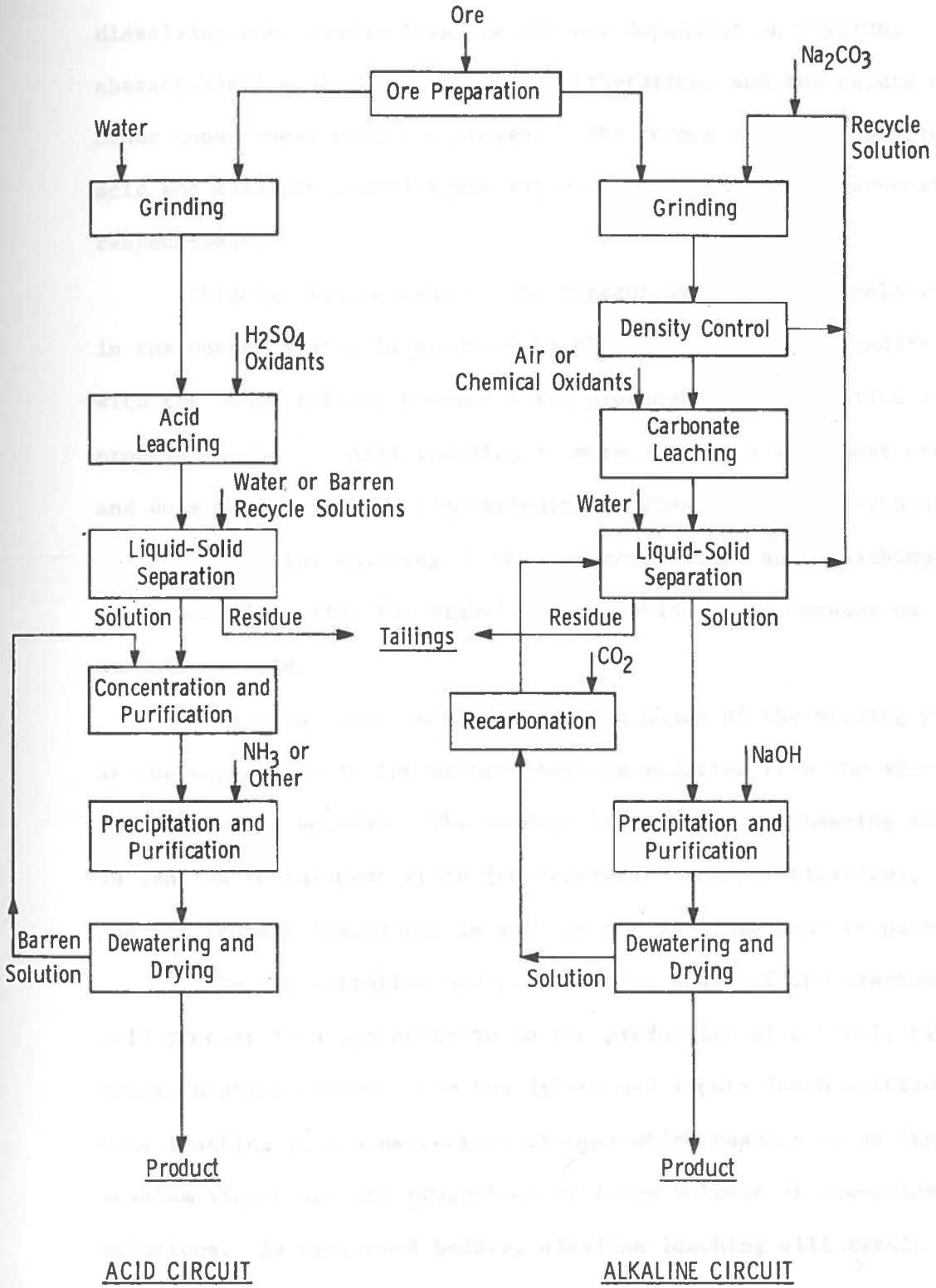


FIGURE 1-4. Comparison of acid and alkaline leach processing circuits

dissolving the uranium from the ore are dependent on physical characteristics of the ore, ease of liberation, and the nature of other constituent minerals present. The common reagents used for acid and alkaline leaching are sulfuric acid and sodium carbonate, respectively.

Eighty-five percent of the current production of yellowcake in the United States is produced by the acid leaching procedure, with the other fifteen percent being produced by the alkaline leach process.[1, 2, 5] Acid leaching is more effective with most ores, and does not require as fine grinding as does carbonate leaching. However, alkaline leaching is more selective than acid leaching and is especially useful for high-lime ores which would consume excessive amounts of acid.

The final step in the extraction phase of the milling process is the separation of the uranium-bearing solution from the spent ore residue (waste solids). The product liquor (uranium-bearing solution) is sent on to the next stage (concentration and purification), while the ore residue (tailings) is sent to the tailings pond or pile.[3]

The concentration and purification stage of the uranium mill process is a prerequisite to the production of a final, high-grade, uranium product from the dilute and impure leach solutions. Acid leaching is a nonselective process which results in an inpure uranium liquor and the production of large volumes of low-grade solutions. As mentioned before, alkaline leaching will result in a more pure liquor than with acid leaching. In either case, however,

some means of concentration and purification of the uranium solution is important to the attainment of a final uranium product which will meet all necessary specifications. The two major techniques used by the uranium mill industry are resin ion exchange, and solvent extraction, both techniques are economical and effective and have been adopted as standard practice in acid leaching mills.

Solvent extraction and resin ion exchange both involve the interchange of ions between an aqueous solution and either solid resin or a liquid organic solvent. This exchange provides the means for a highly selective and nearly quantitative recovery of uranium from the leach liquor. Each technique can be used either individually or in a two-stage series, with the solvent extraction technique used as a second stage of purification following resin ion exchange. When used in this manner, the combination is referred to as the Eluex process and will produce a very high-grade product.

The solvent extraction technique involves only liquid-liquid contacts, thus it is readily designed and operated as a continuous operation. Other advantages of solvent extraction include somewhat better selectivity and more versatility than resin ion exchange. Some problems remain, however, including the need for nearly solids-free solutions and the inability to apply solvent extraction process to carbonate leach liquors. The ion exchange process, however, is applicable to the treatment of both slurries containing appreciable amounts of solids and clarified solutions in either the acid or the alkaline circuit. Exact details of each

technique and how they are applied to uranium mills can be found in the book, The Extraction Metallurgy of Uranium by Robert C. Merritt.(3)

Final recovery of the uranium from solution is achieved by chemical precipitation from the purified liquor. In the acid process plants, the uranium is precipitated from the purified liquor by neutralization with a base such as lime, magnesia, or ammonia. In some operations, the initial precipitate may be subjected to further stages of purification. This insures product purity and produces a precipitate having desirable physical characteristics for subsequent dewatering, washing, and drying operations. In alkaline-process operations, the usual procedure involves the addition of caustic soda to clarified carbonate-bicarbonate liquors to increase the pH to nearly 12, at which point uranium precipitates as a sodium uranate.(3)

The final processes in this last stage include dewatering, drying, and packaging. High temperature drying or calcining is effective in removing ammonia, sulfate and other volatile constituents, but temperature control is critical to avoid causing the product to convert to non-reactive forms, which are undesirable in subsequent refining operations. The final product ("yellowcake") is then transferred to 55-gallon (208 liter) drums. The drum weight varies from 650 (295 Kg) to about 950 (431 Kg) pounds depending upon the product density. The final contents of each drum are sampled and sealed for shipment.

The main area of interest of this thesis deals with the spent ore residue which is sent to the tailings pile after separation from uranium-bearing liquor. The quantity of waste material generated is sufficient to warrant consideration of environmental effects by these tailings. A mill with a capacity of 2,000 metric tons of ore per day will generate about 1,800 metric tons per day of tailings solids slurried in 2,500 metric tons of waste milling solutions. Over the lifetime of the mill, some 100 to 200 acres may be committed permanently to store this material.(2) At present, it is reported that total milling operations in the United States, have produced approximately 25 million tons of tailings. The Nuclear Regulatory Commission (NRC) expects that before the end of the century there will be about a billion tons of tailings solids.(6)

From past experience, tailings management has become the major concern and source of criticism with respect to uranium milling operations. At a recent uranium industry seminar, the general atmosphere was one of dissatisfaction with current techniques.(6) Environmentalists, public interest groups, and states were dissatisfied with past examples of inadequate tailings management. Because of the uncertainty in requirements and the long licensing procedures for mills, the industry was dissatisified. Additionally, the NRC was dissatisfied with the lack of technical data and the quality of license applications.

CHAPTER II

Exposure Pathways to Man

Large scale milling operations in the United States began in the late 1940's. The function of uranium mills is to extract uranium in a concentrated form from ore deposits which contain 3 to 6 pounds U_3O_8 per ton of ore (0.15 to 0.30% U_3O_8).[7, 8] After the uranium is extracted from the ore, more than 99 percent of the ore becomes the mill waste or tailings. During operation of the mill, the liquid and solid ore tailings are pumped as a slurry to a tailings impoundment area to form a tailings pile.

Uranium mill tailings piles are a source of alpha, beta, and gamma radiation. They may be sources of airborne and waterborne contamination. Furthermore, some tailings material have been removed by individuals for private use. The major health physics concern is the nobel gas, radon. According to References 9 and 10, an uncontrolled tailings pile may be regarded as:

- A large, highly dispersed, uncontained source of radioactivity.
- A source which will yield continuous public exposure to radiation for about 10,000 years.
- A source of waste-process chemicals and toxic elements contained in the discarded ore matrix.

- An unattended source with minimal restraints to public access.

The last point is true for inactive tailings piles that have been abandoned by the operators of the mill. There are 24 such sites in the U. S.[10]

Therefore, the concern with wastes from milling operations stems from the large amounts of these wastes and the potentially hazardous nature of the radioactivity should they become distributed in the environment. Table 2-1 is an outline of pathways leading to human exposure from tailings pile radionuclides.[10] Each of the pathways in Table 2-1 should be evaluated in any assessment of the overall radiological impact of each specific mill site. A brief review of the factors that influence these processes will reveal that the Rn-222 diffusion pathway offers the greatest potential for human exposure.

Several generic radiological assessments for uranium mill sites have been made. These generic assessments have shown that Rn-222 emitted by the tailings pile constitutes the most significant health hazard.[1, 5, 7] A wide range of potential health effects have been reported. On the one hand, there are those who conclude that there are no significant health risks imposed upon the public by the uranium mill tailings. In fact, they have stated that population doses from these sources cannot be distinguished from background.[10] On the other hand, David Comey extrapolated Environmental Agency (EPA) assumptions and concluded that releases of Rn-222

Table 2-1

Principal Radionuclides Involved in Pathways
From Tailings Piles to Man

Pathway	Radionuclides	Pathway processes	Exposure hazard
Radon diffusion	^{222}Rn	Diffusion to pile surface Atmospheric transport Inhalation	Inhalation of ^{218}Po, ^{214}Pb, ^{214}Bi, ^{214}Po
Airborne activity	^{230}Th, ^{231}Pa	Resuspension from pile surface Atmospheric transport Inhalation Body surface contamination	Inhalation of airborne activity carried by respirable particles
Terrestrial	^{226}Ra, ^{210}Pb	Resuspension from pile surface Atmospheric transport Deposition on soil or foliage Uptake by plants Intake by animals Consumption of contaminated plants, meat, and milk Consumption of contaminated soil	Ingestion of ^{226}Ra, ^{210}Pb

Table 2-1 (continued)

Pathway	Radionuclides	Pathway processes	Exposure hazard
Aquatic	^{226}Ra, ^{210}Pb	Dissolution of radionuclide in pile Migration through soil to water Migration in water a. Uptake by aquatic organisms b. Consumption of aquatic organism a. Use of water for irrigation b. Uptake by plants c. Consumption of plants Consumption of contaminated drinking water Immersion in contaminated water	Ingestion of ^{226}Ra; whole body gamma irradiation
External gamma	Daughters of ^{226}Ra	Attenuation by pile material Air-distance attenuation External exposure	External exposure to gamma radiation produced by the decay of ^{226}Ra and its daughters

by uranium mill tailings will result in deaths of millions of people who will be exposed to the radon gas over a period of 80,000 years.[11]

Results obtained from a study of the inactive mill site near Salt Lake City indicate that Rn-222 accounts for about 99% of the total health risk from tailings piles to the population residing within 10 kilometers.[7] Furthermore, the tailings-pile-related exposures to this population are only about 5% of those attributable to normal background radiation.

The first step in the radon diffusion pathway is the migration of the inert gas to the surface of the tailings pile where the gas will be dispersed through the atmosphere. Migration consists of two stages: (1) diffusion of Rn-222 from its point of origination into the intergranular capillary network, and (2) migration through the capillaries to the pile surface.[10] Only the Rn-222 atoms formed by the decay of Ra-226 at or very near the surface of a particle are likely to escape from the particle. The fraction of radon which escapes from a particle is called the "Emanation Factor" or "Emanating Power". Experimental evidence suggests that the average value for this factor lies in the range of 20 to 25%.[8, 10] Radon released to the interstitial pores migrates toward the surface of the pile. This behavior results from molecular diffusion whereby Rn-222 moves from a volume of air at a high concentration (pore air) to a volume whose concentration is lower (atmosphere). The movement of the pore air itself may either enhance or retard the diffusion process. The instantaneous flux of radon across a unit area of the pile surface may be influenced by factors affecting

the movement of pore air, including atmospheric pressure, temperature differential between atmosphere and tailings, wind speed, atmospheric stability, and the presence or absence of freezing conditions.[9, 10]

The suspension of tailings-pile particles, and the transport by wind creates another potential pathway for human exposure. The quantity of radioactive material suspended is affected by such variables as the topography and physical properties of the surface, the amount and type of vegetative cover, the extent of surface contamination, local micrometerology, and the time elapsed since the surface was contaminated.[9] Previous resuspension research has been concerned mainly with agricultural erosion and resuspension of plutonium contamination. There has been little effort in determining the resuspension rates of tailings pile radionuclides. The only study on this subject was conducted by M. T. Mills, et al, whose theoretical approach had been based on instantaneous conditions.[12]

There have been other investigations conducted on airborne activity near uranium mill tailings piles. The results obtained indicate that about one-third of the total suspended activity was associated with respirable particles.[13, 14] Furthermore, about 10% of the total airborne alpha activity was determined to be water soluble. The data also suggest that the exposures attributable to airborne activity maybe less than the error associated with radon exposures. These results demonstrate the relative unimportance of the airborne activity pathway.[15] Deposition of particles between the source and the receptor will further reduce the airborne activity

pathway hazard in relation to that associated with radon diffusion pathway. The contribution of the airborne activity pathway to total exposure therefore appears to be only a small fraction of the exposure attributable to radon diffusion; hence, it has been ignored in most generic assessments studies.

The terrestrial pathway is another means by which the deposited airborne activity may reach man. Radionuclides may be deposited on edible foliar surfaces, migrate through the soil into edible crops, or be consumed by animals that provide meat or milk. The radionuclides found in uranium tailings have concentration factors in crops, meat, and milk which are generally much less than unity.[16]

Haywood, et al., indicated that the worst possible case would likely be the direct ingestion of contaminated soil.[10] This pathway provides an integrated exposure to man from previously deposited activity. The study concluded that if there is no erosional losses of deposited activity, such longer-lived radionuclides as Th-230 and Ra-226 will accumulate in the soil and may become a concern only after a century or more of wind erosion on a completely neglected tailings pile. In another study, conducted on food stuffs in the Durango and Grand Junction, Colorado, areas, the conclusion was drawn that daily dietary intakes of Ra-226 in these areas were similar to intakes reported by other U. S. cities which have no uranium mining and milling nearby.[17] Thus, based on present information, the terrestrial pathway appears to be inconsequential as a source of human exposure.

Aquatic pathways are dependent on the proximity of the site to ground- or surface-water supplies, the presence of leaky aquifiers, and the values of local geohydrologic parameters. Surface-water erosion would result in runoff water contaminated primarily by tailing particles scoured from the pile surface. The mobility of radionuclides in tailings piles is restricted by their low solubilities and the high adsorptive capacity of common soil minerals.[10] The aquatic pathway may be of importance if a leaky aquifer is in contact with the leached contamination. The adsorptive capacity of the subsoil will usually inhibit the movement of tailings radionuclides, with the exception of uranium migrating as an anionic uranyl complex. Thus, site-specific parameters affect the importance of this pathway.

Gamma radiation coming directly from the tailings pile or from wind-blown material is expected to make a minor contribution to the overall exposure of man. However, there are some areas where increased levels of gamma radiation have been observed (on the order of 1 mR/hr maximum). The external radiation may be significant in areas along public roads near the mill property, in commercial buildings built over tailings, in or near structures where tailings have been removed from the pile for private use, and on the pile itself.[9] It has been shown in several investigations at mill sites that external gamma radiation levels decrease rapidly with distance from the pile.[2, 5, 7, 18] This observed decrease with distance does not follow the typical inverse square relationship because of the large physical size of the pile. Exposure of individuals on or

near the pile result from "primary-beam" or unscattered photons from nearby tailings material, and from gamma rays which originate at other more distant points and reach the individual through "sky-shine" or air-scattering. External gamma exposure will be of minor significance and will only increase the total exposure at locations very close to the tailings pile or in close proximity to piles of wind-blown tailings particles.

CHAPTER III

Potential Impacts on Health

The Code of Federal Regulations (10CFR20) currently allows NRC licensed operations to release average concentration of Rn-222 to the air in unrestricted areas of 3 pCi/1 above natural background. Recommendations of the International Commission on Radiological Protection (ICRP), state that the annual radiation dose limits for individual members of the general public should be 1/10 of the corresponding annual occupational dose for continuous exposure as listed in the Committee II report.[19] Application of these recommendations to the occupational exposure to Rn-222 (10 pCi/1), with the radon daughters at equilibrium concentrations, leads to a value of 1 pCi/1 for continuous exposure to individuals of the general public. This concentration is in addition to the natural background radon concentration, which has been reported to be on the order of 0.1 to 0.4 pCi/1.[20]

Working level months (WLM) is a term commonly used to express a miner's calculated exposure to radon daughter products found in mine air. This unit is derived from the working level (WL), a unit which is defined as any combination of short-lived radon daughters in one liter of air that will result in the ultimate emission of 1.3×10^5 MeV of alpha energy.[18, 19] A WLM is the exposure to 1 WL concentration of radon daughters for 170 hours, or an equivalent

product of radon-daughter concentrations and time. If the concentrations of radon daughters are known (or assumed) relative to the concentration of radon, the WL concentration can be expressed in units of pCi/l of Rn-222. The relationships are summarized in Table 3-1.[18]

Off-site releases from tailings piles of radioactive materials consists of airborne dust particles, and radon gas. When a person is downwind of a tailings pile, he will inhale the dilute concentrations of radionuclides in the air. The effect that these radionuclides will have on an individual depends on the nature of the radiation emitted, on the rate at which it is emitted, on the parts of the body in which they are retained, and the period of time retained.

The radiological significance of Rn-222 is believed to result primarily from its short-lived radioactive daughters (Po-218, Pb-214, and Po-214). Radiation exposure following the inhalation of these daughters is considered to be a major cause of cancer in the tracheobronchial region of the lung.[21] EPA study assumed that an average individual chronically exposed to a concentration in air of 0.001 pCi/l of Rn-222 receives a radiation dose of 4 mrem per year to the lung from the radon daughters. This dose conversion factor is in agreement with recommendations in a report released by the United Nations.[18] The assumptions made are that a person is inside a building with adequate ventilation, that a quality factor of 10 for alpha particles applies, and that a penetration depth to cells at risk (bronchial epithelium of the lung) of 60 μm.

Table 3-1

Conversion Factors and Equivalents for
Radon-222 and Daughters

Concentration of Radon-222	Working Level	Dose Equivalent
Continuous[a] exposure to 0.001 pCi/l	Continuous exposure to 5×10^{-6} WL	4 mrem/year[b] to the lung
Continuous exposure to 200 pCi/l	Continuous exposure to 1 WL[c]	8×10^{5} mrem/year to the lung
Continuous exposure to 0.00025 pCi/l	Continuous exposure to 1.3×10^{-6} WL	1 mrem/year to the lung

(a) Assumed radon-222 and daughter ratios 1.0/0.9/0.5/0.35 (for living accommodation with normal ventilation).

(b) Dose delivered to basal cell nuclei of segmental bronchi; Q, 10; penetration depth to cells at risk, 60 μm.

(c) A combination of short-lived radon daughters in 1 liter of air that will result in the ultimate emission of 1.3×10^{5} MeV of alpha energy.

The potential health risk associated with over exposure to Rn-222 and its daughters is a form of bronchial lung cancer, which is considered to be 100 percent fatal with a latent period of 10 to 15 years. Because bronchial cancer is believed to have many possible causes, the bronchial cancer risks from radon daughters is best expressed in terms of the percentage increase in the expected cancer risk, (i.e., the relative risk), rather than the absolute number of cancers expected per person-rem of exposure. The relative risk is not considered to be a function of the level of absolute risk and is therefore the same for everyone. The absolute risk of bronchial cancer to an individual depends strongly on his personal history. As an example, a study done with uranium miners, it was found that habitual cigarette smoking increased the risk of bronchial cancer by a factor of 10.[22] Since the relative risk coefficient for bronchial cancer from radon exposure is thought to be relatively independent of smoking history, exposure to radon daughters sufficient to double the risk of bronchial cancer for nonsmokers will also double the risk for smokers.

The health risks associated with exposure to Rn-222 and its daughters cannot at this time be assessed accurately. Although studies have shown increased incidence of bronchial cancer among uranium miners who have been exposed to high airborne concentrations of radon daughters, the use of health risks derived from these results to provide estimates of risk to members of the general population involves considerable uncertainty.[21, 22] There are many differences

between the uranium miner populations and the general public, and there are critical differences between radiation exposure conditions found in mines compared to houses.

In the study with uranium miners it was concluded that exposure to 110 WLM doubles the risk of bronchial cancer in uranium mining population.[22] Uranium miners usually have chronic bronchitis and are therefore afforded alpha-particle protection to the epithelium by the increased thickness of the mucus layer; hence, an equivalent radon daughter exposure level delivers a greater dose to members of the general public than to mining populations. The BEIR report uses a factor of two to account for existing chronic bronchitis when estimating the dose to the basal cell layer of the epithelium of the larger bronchi on a probabilistic basis.[23] Therefore, despite uncertainties, 55 WLM exposure is assumed to double the risk of bronchial cancer for members of the general public. The potential risk is assumed to vary in direct proportion to exposure to radon daughter products in units of WLM.[10]

The principle exposure from airborne particles is believed to be to the non-ciliated, pulmonary region of the lung. This is in contrast to the principle exposure of radon being to the bronchial epithelium.[18] Another difference between airborne particulates and radon gas is that the exposure from particles is likely to be less indoors than out, because of removal of particles by filtration and sedimentation from the air stream entering a building.

Particulate material of respirable size carried off a pile by wind delivers a radiation dose to the lung which is less than the

radon dose. The potential health risk from wind blown particulate material from the pile is not as significant, because the radiation dose is smaller than the dose from Rn-222 and its daughters. The particulate material dose is delivered to the pulmonary region of the lung; whereas the radon dose is delivered to the bronchial epithelium region of the lung. The BEIR report indicates that the bronchial epithelium is much more radiosensitive than the pulmonary region of the lung.

The released radionuclides from the tailings pile surface are mixed into the passing airstream by local turbulences and carried off by the wind, which continually decreases the concentration by mixing and dilution. This process of airborne dispersion will eventually deliver a dilute concentration of radionuclides to down-wind locations, where people may inhale them. The particulate material transported by the wind will contain Th-230, Ra-226 and Rn-222 and their daughters. The resultant radiation doses to individuals who may have inhaled these particles will depend primarily on:

- The activity levels of the radionuclides,
- The particle size distribution of the aerosol particles,
- The solubility of the particles in fluids of the lung, and
- The energies of the alpha particles emitted in the lung.

The probability that inhaled particles would be retained in the lung is determined by the particle size distribution of the particle. Some of the particles are exhaled, and a fraction of the

rest is initially retained in the lung, but eventually is removed to the gastrointestinal tract. Those of the remaining retained particles that are insoluble will remain in the lung a long time, delivering their radiation primarily to the location of the region of the particle within the lung. However, those that are soluble are dissolved and their radionuclides will be translocated by the blood to other organs where they may be retained selectively. For example, thorium and radium are bone seekers, thus the critical organ is the bone. Dose conversion factors given in Table 3-2 are suitable for particles with a size distribution characterized by an activity mean aerodynamic diameter (AMAD) of 0.5 to 1.0 micrometer (μm).[18] Table 3-3 indicates the deposition estimate for the pulmonary region while breathing at a moderate work rate (20 l/min).[24] Thus, it can be seen that the dose conversion factor could change as a function of particle size distribution.

The potential health risk from the tailings pile's gamma radiation is of little significance as well. The conclusion is based on the fact that whole body gamma radiation dose is considerably smaller than the dose to the bronchial epithelium from the daughters of radon. While more health effects are produced per unit dose equivalent of whole body radiation than per unit dose equivalent delivered to the bronchial epithelium only, the much smaller relative dose from gamma rays causes the overall potential health risk from gamma radiation to be considerably less than the potential health risk from radon emission.[18]

Table 3-2

Dose Conversion Factors for Airborne
Thorium-230 and Radium-226

Radionuclide	Solubility (Class)	Critical Organ	Dose Conversion Factor mrem/yr per (pCi/l)
Thorium-230	Soluble	Bone	38.0
	Insoluble	Lung[a][b]	11.0
Radium-226	Soluble	Bone	0.3
	Insoluble	Lung[a][b][c]	11.0

[a] Pulmonary region of the lung.

[b] Assumes particle has an AMAD of between 0.5 and 1.0 μ, the pulmonary region of the lung weighs 450 gms, and the mean retention time of an insoluble class Y particle is 1,000 days in the pulmonary region of the lung.

[c] Assumes only radium-226 contributes to the dose and not radon-222 nor its daughters.

Table 3-3

Percent Deposition of Particles in the Pulmonary Region of the Lung as a Function of Activity Mean Aerodynamic Diameter

Particle AMAD Micrometers	Percent Deposition of Particles in the Pulmonary Region of the Lung
10	9
5	11
2	20
1	25
0.5	31
0.2	40
0.1	50

In 1975, EPA conducted a study of 20 inactive mill sites to determine the significance of the mill tailings would have on the public health.[18] While this assessment may not typify actual conditions at all uranium mill tailings sites, important implications of the potential risk were determined. The EPA stated that an individual living within 50 meters of an average inactive tailings pile could possible receive a potential dose equivalent of 8 rem per year to the bronchial epithelium. This dose is assumed to be equal to an exposure of 0.5 WLM per year of radon daughters. Thus it would require approximately 100 years of exposure to radon and its daughters at this rate of 0.5 WLM/year to double the individual's risk of bronchial cancer. This is equivalent to a one percent increase in potential risk for each year of exposure, or a 70 percent increase in potential risk over a lifetime of 70 years. Also, to be noted, 0.5 WLM/yr is approximately 1/10 of the radiation guide for the protection of underground uranium miners. Individuals at 1 km and 2.2 km will be exposed, as estimated by EPA, to 0.3 rem/yr and 0.1 rem/yr, respectively. This indicates an increase of bronchial cancer risk of about 3 percent for the individual at the one kilometer mark for a lifetime of exposure to an average inactive uranium tailings pile. For the individual at the 2.2 km mark, the increase is 1 percent.

In another independent study, an assessment was made of the radiological hazards associated with the inactive uranium tailings pile near Salt Lake City (Vitro tailings pile).[10] An evaluation was made of various pathways by which an individual could be exposed to radioactivity from the tailings. An area source model was used

in conjunction with the most recent wind profile and stability data for the Salt Lake City area in order to estimate the Rn-222 concentration attributable to the tailings pile. The results indicated that radon concentrations had decreased to less than 10 percent of background in all directions at 6.5 km from the pile. Calculations were carried out to a distance of 11.3 km. Beyond this distance concentrations of radon were less than 1 percent of natural background, where natural background was found to be 0.38 pCi/1.[20] It was assumed that no Rn-222 was lost between the source and the receptor by decay, rainout or dry deposition. Thus, the concentrations calculated by the model are conservative estimates. Comparisons were made between calculated and measured values of radon concentrations. Except for one station, the averages of the calculated and measured values were well within the stated limits of error for both sets of data. A set of airborne radioactivity measurements, made over a period of one year by the EPA, were examined carefully in this study. Results of this program is given in Table 3-4. These measurements indicate that average annual airborne activities were less than 3 percent of maximum permissible concentrations in air (MPC). The results are also compared with the measured Rn-222 concentrations in Table 3-4. The contribution of airborne activity is far less than the error associated with the radon activity. Furthermore, an interpretation of 10CFR20 Appendix B, considers that all airborne activity except Rn-222 may be administratively considered as not present.[19] Health effects attributable to

Table 3-4

Average Concentrations of Airborne Radionuclides at Suburban Sewage Treatment Plant, Salt Lake City, Utah

Radionuclide	Avg. conc. (10^{-3} pCi/l)	MPC[a] (pCi/l)	Avg. conc./MPC
^{226}Ra	0.0018 ± 0.0026	0.002 (I)	0.001
^{230}Th	0.00088 ± 0.0012	0.00008 (S)	0.011
^{210}Pb	0.010 ± 0.0056	0.004 (S)	0.003
^{210}Po	0.061 ± 0.166	0.007 (I)	0.009
^{234}U	0.00022 ± 0.00012	0.004 (I)	0.00006
^{235}U	0.000025 ± 0.000024	0.004 (I)	0.000006
^{238}U	0.00020 ± 0.00014	0.003 (S)	0.00007
^{232}Th	0.000064 ± 0.000102	0.001 (S,I)	0.00007
^{228}Ra	0.002 ± 0.002	0.001 (I)	0.002
		Σ Ci/MPC$_i$ =	0.026
^{222}Rn	4200 ± 1400	3.0 (S)	1.4 ± 0.5

[a]The most restrictive MPC$_a$ is given; S = soluble, I = insoluble.

Rn-222 progeny exposures were estimated by using data provided in the BEIR report. The health effects postulated as caused by the vitro tailings pile is given in Table 3-5. For comparison purpose the health effects which can be attributable to background radon and its daughters are shown as well. It may be noted that in every case, effects due to the tailings pile are about 10 percent of the standard deviation associated with the background estimate.

Table 3-5

A Comparison of Potential Health Effects Attributable to ^{222}Rn Progeny Exposure from the Vitro Tailings Pile and from Background from the Population Residing Continuously Within 11.3 km of the Vitro Tailings Pile

Population	Lung cancer deaths/year in the population attributable to: Vitro tailings pile	Background[a] (0.38 ± 0.26 pCi/liter)
Present (400,000)	0.4	7 ± 5
Extrapolated (1,850,000)	3	32 ± 22
Extrapolated (3,000,000)	4	51 ± 35

[a]Reference 20.

CHAPTER IV

Composition of Wind-Blown Tailings

Radioactive material may be carried from the pile by winds. This release of airborne particulates to the atmosphere is one mode of environmental contamination from tailings piles. The blowing dust and moving sand dunes from dry tailings, especially inactive piles that have completely dried, can be a nuisance to the surrounding community. Wind erosion of tailings piles brings potential health risk to locations whose distance once provided appreciable protection from the radioactivity in the pile. At one site, it has been observed that wind-blown tailings on the ground are readily visible some 150 meters beyond the original pile in the predominant wind direction. In fact, the impetus behind the Colorado regulation requiring stabilization of uranium mill tailings were complaints about the blowing dust.(18)

Sampling of the tailings indicates that essentially all of the radioactivity that was originally in the ore except for the uranium is discharged to the tailings impoundment area. However, usually less than 10 percent of the original uranium content also remains in the tailings. The principal decay chain contributing to the tailings radioactivity is the U-238 decay chain (approximately 95% of total radioactivity). The other 5% of the total activity is a result of the U-235 decay series (Actinium series).(5) The major

uranium and actinium chain members are listed in Table 4-1. There are no reports of radionuclides found in the tailings in appreciable concentrations which are not members of either of these two decay chains. The ratios of the concentration of the radionuclides in the decay chains are approximately the ratio expected under the condition of secular equilibrium. The principal radionuclides of primary interest are Th-230, Ra-226, Rn-222, Po-218, Pb-214, Bi-214 Po-214 and Po-210.[18]

Most of the uranium ores being milled are sandstones consisting of silica grains poorly cemented together with materials such as calcium carbonate. In the milling process, the sandstones are broken down and after the uranium is extracted by chemical leaching essentially the whole original mass remains as tailings. Tailings consists of the original sand grains plus slimes, made up of clay minerals from the sandstone grains and waste chemical products of the mill process.[18]

The tailings consist primarily of silica, with some silicates (i.e., sand), and, in the case of an acid-leach mill, will contain insoluble sulfates, such as calcium sulfate, from the milling process. The liquid and solid wastes are generally stored together; as the water evaporates, soluble salts crystallize from the pond and become part of the solid tailings (i.e., slime fraction). The actual density of the grain of tailings piles will vary; however, it is usually assumed to be 1.6 gm/cm^3. The tailings, in general, contain 20 to 130 pCi/g of natural uranium and 150 to 1000 pCi/g each of Ra-226, Th-230 and Pb-210.[3, 10, 18]

Table 4-1

Principal Tailings Pile Radionuclides

Nuclide[a]	Half-life	Primary decay modes α	β	γ
	Uranium series			
^{238}U	4.5×10^9 y	x		
^{234}Th	24 d		x	x
^{234m}Pa	1 m		x	x
^{234}U	2.5×10^5 y	x		
^{230}Th	8×10^4 y	x		
^{226}Ra	1.6×10^3 y	x		x
^{222}Rn	3.8 d	x		
^{218}Po	3.1 m	x		
^{214}Pb	26.8 m		x	x
^{214}Bi	19.7 m		x	x
^{214}Po	160 μs	x		
^{210}Pb	21 y		x	x
^{210}Bi	5 d		x	
^{210}Po	138 d	x		
^{206}Pb	Stable			
	Actinium series			
^{235}U	7×10^8 y	x		x
^{231}Th	26 h		x	x
^{231}Pa	3.3×10^4 y	x		x
^{227}Ac	21.6 y		x	
^{227}Th	18 d	x		x
^{223}Ra	11.4 d	x		x
^{219}Rn	4 s	x		x
^{215}Po	1.8 ms	x		
^{211}Pb	36 m		x	x
^{211}Bi	2.2 m	x		x
^{207}Tl	4.8 m		x	
^{207}Pb	Stable			

[a]Minor branches and minor decay modes are not listed.

The radioactivity distribution among the sands, slimes and other dissolved material pumped to the tailings impoundment area is divided disproportionately. The dissolved material generally contain less than one percent of the mass and less than one percent of the radioactivity of the tailings. The slimes may contain 15 to 60 percent of the mass by weight of the tailings solids, usually on the average about 25 percent. The slimes usually contain most of the radioactivity, approximately 3 to 20 times greater than the sands; on the average, the slimes commonly have about 75 percent of the total radioactivity in the tailings. Therefore, the generalization can be made that the sands will compose about three-quarters of the mass by weight but only one-quarter of the radioactivity of the tails.[1, 18] Thus, the slimes are considerably more hazardous than the sands by virtue of the greater specific activity. From a statement by Tsivoglou, it is inferred that the slime particles are as fine as minus-200 mesh (i.e., less than 74 μm in diameter), and that the sands are generally in the range of plus-200 mesh (i.e., greater than 74 μm in diameter).[25]

The "slime-type" of tailings, because of their greater specific activity and smaller size, are the major concern as wind-blown particles. Once airborne, the smaller slime particles will move farther than the larger sand particles, since the slimes can be ejected into the turbulent air stream while the sands merely creep along the surface. In fact, it is believed that particles which are less than 80 μm in diameter are ejected into the turbulent air, stream and are then dispersed beyond the mill boundary.[13, 14, 17]

Those particles that are less than 10 μm in diameter have the possibility of being inhaled, thus allowing the delivery of the radioactivity of the slime-type of tailing particles to the lung.

The transport of these solids by wind action is not significant while slimes are wet or under water. Slimes tend to form a crust as they dry, hence, dry slimes are less readily moved by the wind than the sand fraction. However, slimes can become airborne by saltation, when airborne sand grains fall and collide with the slime particles. The fine slime is not directly transported into the air because the drag forces on such small particles are spread over a large area rather than individual particles.[12, 26] Large sand particles on the other hand, are readily transported by aerodynamic forces. Consequently, the saltation mechanism, whereby large airborne sand particles collide with the smaller slime particles, causing their suspension from the tailings surface. This mechanism is considered to be the principle method for inducing transportation of the slime particles.

The investigation into the mechanism by which the "sand-type" of tailings particles are transported takes on some importance in an indirect manner. Besides providing the mechanism by which the slime particles are transported, the sand particles maybe so blown around that the source becomes enlarged. That is, the tailings pile increases in area, and, as a result, the source term area grows with the transportation of the sand particles off the pile. This may account in part for the slow decrease in exposure rate with down

wind distance. Information on the movement of these sand type particles is extremely limited, and little attention has been paid to this mode of environmental contamination. Consequently, the transportation by wind of the larger sand particles in tailings pile will be investigated within this paper.

The Eolian sand movement associated with desert and beach type of environment is a familiar problem to many investigators. There should be little difference between these sands and tailings. In fact, there is much interest in predicting effects from wind erosion of beach areas on the neighboring communities. Countries in Africa have acknowledged the importance of studying Eolian sand transport in order that the expanding deserts can be adequately controlled. Thus, many investigations have been done to study this phenomena. There are similarities between Eolian sand transport in desert or beach areas and tailings piles. Through these similarities relationships developed for Eolian sand transport of desert or beach sand particles can be directly applied to Eolian sand transport of tailings particles.

The basic topography of tailings pile itself exhibits similar characteristics as desert or beach areas. For active tailings piles, there exist a tailings pond, thus a beach area will also exist. The sandy surfaces of tailings pile that are exposed to wind exhibit sand dunes and sand ripples, which are similar to those found in desert areas.

Other similarities between desert, beach and tailings areas is the particle size distribution. For the case of desert or beach areas, the particle size distribution varies as a Gaussian Distribution, similar to the particle size distribution of tailings particles. A computer code was developed which predicted the particulate concentration downwind of a tailings pile during a wind storm.(12) The model developed was based on the physics of sand transport as developed by Baynold. Thus, other investigators of Eolian tailings sand transport also applied the principals of Eolian sand transport of desert or beach areas to tailings pile.

In all three cases (desert, beach and tailings) the substance being transported is considered to be sand. For a substance to be considered as sand, it must satisfy certain requirements. That is, the source of the grains must be plentiful. Also, the sand grain should resist the action of chemical weathering and abrasion. The material must be tough enough to resist fracture by the impact of other sand grains during transport. Of all natural substances, crystalline silica (quartz) best meets these requirements, and the bulk of sand grain found in deserts and beaches are composed of quartz.(26) However, quartz is not the only material which occurs in the form of sand. Sands which are predominantly quartz often contain grains of other materials. It is generally accepted by geologists that the bulk of the quartz sand grains found in the earth's crust, whether occurring free on the surface or in sandstones, and other sedimentary rocks laid down long ago, have originated from

the disintegration of quartz-bearing rock followed by some process of mechanical abrasion.[26] Tailings sand fits the above requirements and the composition of the tailings sand is similar to that of desert or beach sand (i.e., silica or quartz, sandstone). Much of the experimental work done has been with quartz sand but the results can be applied without change to other sands (i.e., tailing sands). Therefore, because of the similarity in composition of sand, models used for the prediction of Eolian sand transport of desert or beach sand particles can be directly applied to Eolian transport of tailings sand.

CHAPTER V

Theories of Eolian Sand Transport

Many researchers have studied the problem of the transportation of sand by wind action in the laboratory and/or in the field. The basic mechanism involved in the movement of sand by wind has not been completely resolved. One of the principal difficulties is that the forces acting on the surface vary with respect to the orientation of the particle on the surface and the different stages of motion. The flow velocity forces acting on a particular size particle will be different if the particle is part of a bed of particles composed of various sizes, than if the entire bed is composed of particles of its own size. Particles hidden in the laminar sublayers are not subjected to the same forces as those directly in the main turbulent flow.

The initial movement of a sand grain is started by sudden gusts. The sand particles are set into motion by turbulent eddies present in the air flow. The wind velocity profile and the shear velocity are the primary motivating factors in initiating and sustaining movement.[27] The velocity at which the grain starts to move is referred as the "impact threshold".[26] More energy is required to set wet sand in motion than is required to set dry sand moving, however, about the same amount of energy is required to keep wet and dry sand moving. There is no wind velocity at which

sand moves regularly, that is to say, at any wind velocity the sand always moves in an irregular pattern.

There are three basic modes of particulate movement: saltation, surface creep and suspension.(26)

Saltation: At low transport rates the main motion of the grains is in saltation. Particles will rise from the bed with very little forward speed and are accelerated and carried forward a certain distance by the wind. Finally, the effect of gravity brings the particles back to the surface again.

Surface Creep: Upon collision of moving grains with the bed grains, a portion of the energy which saltating grains have gained from the wind is transferred to the grains of sand on the surface, which are then ejected upward to continue the saltation. However, the bulk of the energy is dissipated in disturbing a large number of surface grains. The net result of the continued disturbance of the surface is that of a slow outward creeping taking place on the part of the grains composing it.

Suspension: Most sand grains are too large to be carried in true suspension. However, the motion of the smallest sand grain may, in high wind, approach suspension.

Several researchers have developed expressions for the rate of sand movement as a function of certain variables. Bagnold based his work on the assumption that the rate of sand transportation by wind depends on the change of momentum of a saltating particle.(26)

The rate of sand movement per unit width per unit time, q, is given by

$$q = C_B \, (D/D_1) \, (\frac{\rho}{g}) \, U_*^3 \, , \qquad (5\text{-}1)$$

in which

D = grain diameter in question,

D_1 = standard grain diameter (0.25 mm),

ρ = density of the air,

g = gravity, and

U_* = shear velocity.

C_B is a constant with the following values

1.50 for nearly uniform sand,

1.80 for naturally graded sand, and

2.80 for sand with very wide range of grain diameter

In our case of tailings sand, the value of the constant, C_B, is 2.80. This would be true for all tailings pile in existance.

Dr. R. Kawamura followed the same basic assumption as Bagnold, but instead used the difference between the Shear velocity U_* and the threshold shear velocity U_{*t}.[28] He obtained the following equation:

$$q = K_K(\frac{\rho}{g}) \, (U_* + U_{*t})^2 \, (U_* - U_{*t}), \qquad (5\text{-}2)$$

in which K_K is an experimentally determined constant. Kawamura found that K_K took on the value of 2.78 for sand with diameter of

of 0.25 mm. For the case of tailings sand we must determine the value of the constant.

Dr. A. W. Zingg conducted most of his experiments in the wind-tunnel.[29] From his results Zingg modified the Bagnold formula to yield,

$$q = C_z \left(\frac{D}{D_1}\right)^{3/4} \left(\frac{\rho}{g}\right) U_*^{3/2} \qquad (5\text{-}3)$$

in which $C_z = 0.83$

Drs. M. P. O'Brien and B. B. Rindlaub conducted a series of field measurements to develop an empirical formula.[30] Wind velocities were measured at elevations between 0.25 and 12 feet above the surface. The predominant sand size was approximately 0.194 mm. As a result of these measurements, they obtained the following formula:

$$G = 0.36\ (U_5)^3 \qquad (5\text{-}4)$$

(For U_5 >20 ft/sec.)

in which G is the rate of movement in pounds per day per foot width, and U_5 is the wind velocity at 5 feet above the surface in (ft/sec).

Experimental studies at the University of California, Berkeley were conducted by Pierre Yves Belly and Abdel-Lutif Kadib. Experimental results obtained in wind tunnel tests by Bagnold, Kawamura, and Zingg, and the O'Brien and Rindlaub field measurements,

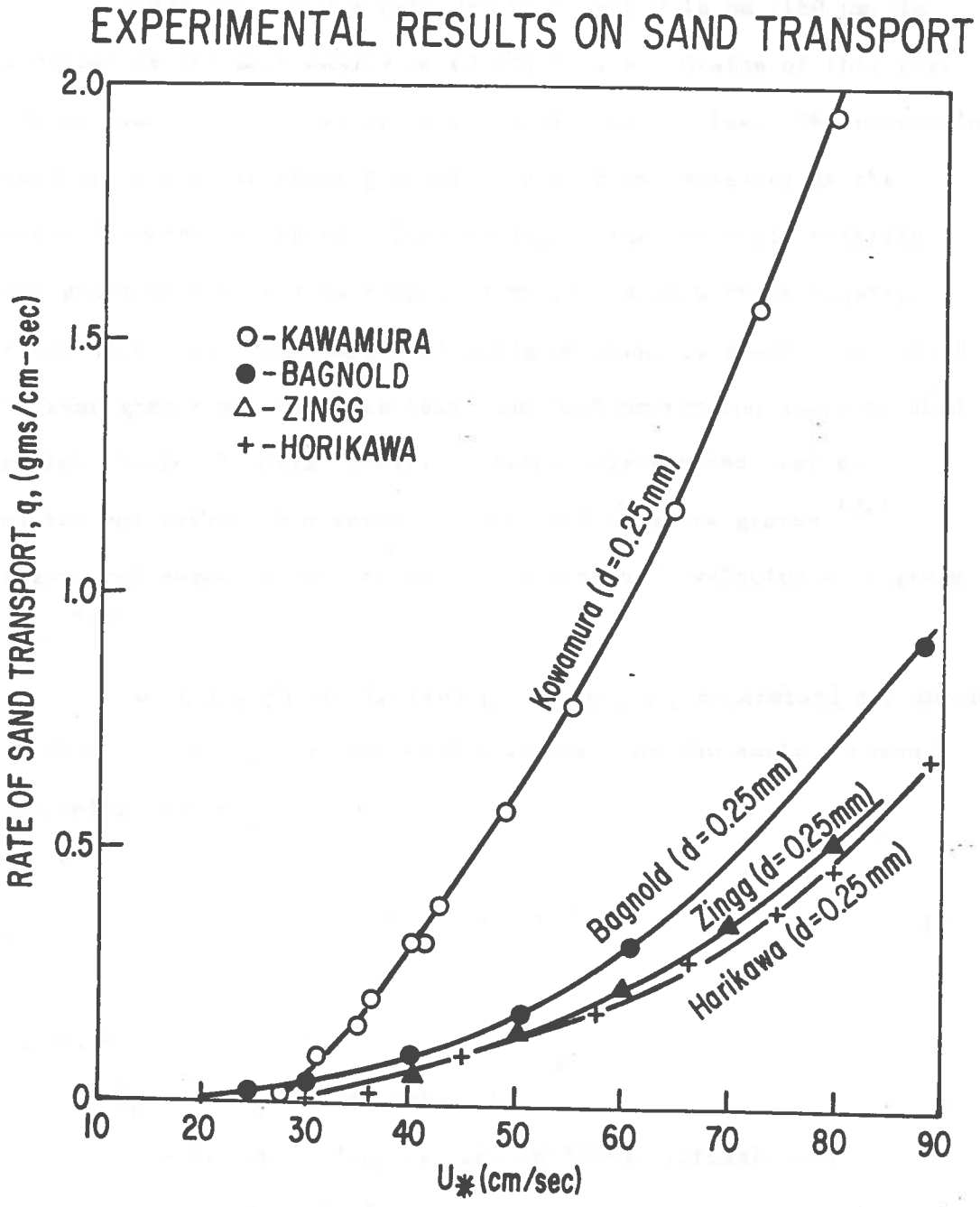
upon which Equations 5-1 through 5-4 were formulated are presented in Figure 5-1). From Figure 5-1 it is clear that the rate of sand movement obtained by these different investigators differs widely even though the sand considered has almost the same grain size.

In order to reconcile some of the apparent discrepancies in the various existing relationships for the rate of sand movement, Belly and Kadib conducted studies with three different grain diameters (sands A, B, and C) with mean grain diameters of 440 μm, and 330 μm, and 145 μm, respectively.[27] From the results of their studies the following four conclusions were drawn:

- The constant K_K in the Kawamura Equation (5-2) is not limited in range.
- For sand size B it was impossible to find a value for these constants which would permit an adequate description of the experimental data.
- The Kawamura equation includes the threshold Shear Velocity, U_{*t}, which introduces a further uncertainity in the calculations of transport rates, especially since this is influenced by personal judgement regarding when motion begins.
- The O'Brien-and-Rindlaub equation should not be used since it was shown by Belly and Kadib that their equation should be limited to sand having the same grain diameter of that tested in the field.

Figure 5-1

Comparison of Rate of Sand Transport Models



Confirmation of these formulas is not particularly good. However, these formulas are useful in the description of a particular condition when a suitable constant is chosen.

Stone and Summers observed that sand 0.18 mm (180 μm) in diameter is the most easily moved grain size. Grains of this size may be transported at relatively low wind velocities. The threshold velocity for grain sizes greater than 0.18 mm increases as the grain diameter increases. Interestingly, the threshold velocity for grain diameters less than 0.18 mm increases with decreasing grain size. This phenomenon of grain movement is readily explained in that grains of diameters less than 0.18 mm are too small to shed eddies, hence the drag (shear) is evenly distributed over the entire bed rather than being concentrated on a few grains.[32] Figure 5-2 shows the variation of the threshold velocity with grain size.[29]

Several authors (References 33 thru 37) determined the amount of drag, or shear, that the wind will exert on the surface through the relationship:

$$U_* = (\tau/\rho)^{1/2} \qquad (5\text{-}5)$$

in which

U_* = shear or drag velocity,

τ = amount of drag per sq. cm (shear stress), and

ρ = density of air.

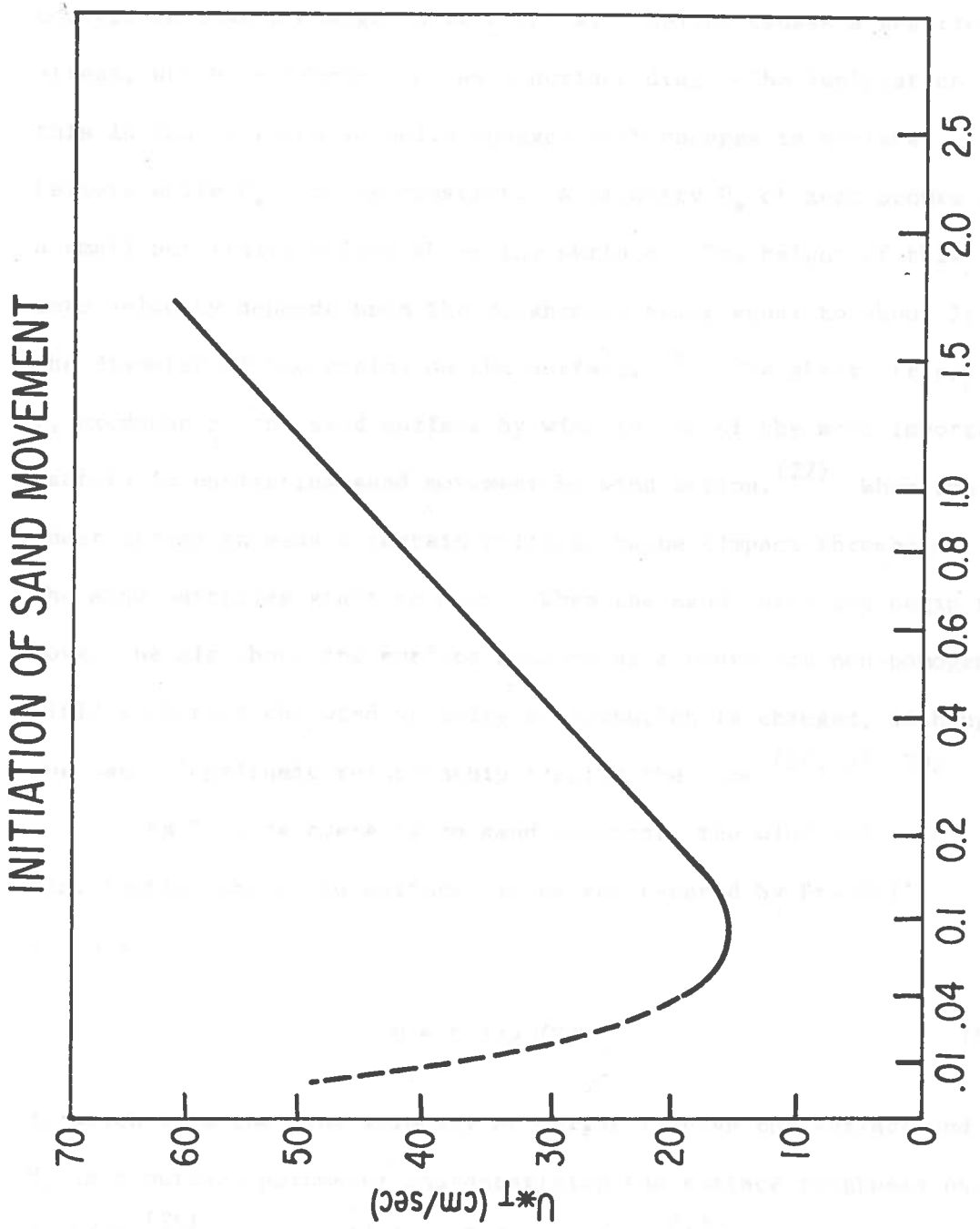


Figure 5-2. Variation of U_{*t} with Grain Size

It is possible to find the shear on the surface by measuring any two wind velocities at known heights and plotting these velocities against the logarithm of height.[35] This is an important concept in that a change in velocity with height causes a shearing stress, which is transmitted as a surface drag. The implication of this is that surface velocity changes with changes in surface texture while U_* remains constant. A velocity U_* of zero occurs at a small but finite height above the surface. The height of this zero velocity depends upon the roughness, being equal to about 1/30 the diameter of the grains on the surface.[26] The shear stress, τ, produced at the sand surface by wind is one of the most important factors in estimating sand movement by wind action.[27] When the shear stress exceeds a certain critical value (impact threshold), the sand particles start to move. When the sand particles begin to move, the air above the surface behaves as a heavy and non-homogeneous fluid such that the wind velocity distribution is changed, although the basic logrithmic relationship remains the same.[26, 27, 29]

As long as there is no sand movement, the wind velocity distribution above the surface can be represented by Prandtl's formula:

$$U = C \log (Y/Y_o) \qquad (5\text{-}6)$$

in which U is the wind velocity at height Y above the surface and Y_o is a surface parameter characterizing the surface roughness equal to D/30.[26] The coefficient C is equal to $\frac{2.3}{K} U_*$; K is the Karman

constant, equal to 0.4, and U_* is the drag velocity under the condition of no sediment motion. Thus, Equation 5-6 can be written as:

$$U = 5.75\ U_* \log\ (Y/Y_o). \tag{5-7}$$

The roughness parameter, Y_o, is also given by

$$Y_o = 0.081 \log\ (\frac{D}{0.18}), \tag{5-8}$$

with Y_o and the sand grain diameter D expressed in millimeters. This equation applies to both the smaller sized grains ($Y_o = D/30$) and to the larger grain sizes ($Y_o = D/9$). At the threshold wind velocity initiating movement of sand particles, the wind velocity distribution is slightly altered by the sand movement. It is noticed that the velocity distributions are straight lines, and, also, that there seems to be a "focus" at a certain point.[27] According to Bagnold, the velocity distribution above a surface with sand movement is given by the equation

$$U = \frac{2.3}{K} U_* \log\ (Y/Y') + U', \tag{5-9}$$

in which U' and Y' are the coordinates of the focal point for drifting surfaces. The projected focal points (U', Y') appear to bear a relation to grain size by the following equations

$$Y' = 10\ D \tag{5-10A}$$

$$U' = 20\ D \tag{5-10B}$$

Here, the grain diameters D and Y' are expressed in millimeters, and U' is expressed in miles per hour. A new value of K in Equation 5-9 was determined by Bagnold to be 0.375. From Reference 27, Equation 9 can be written as:

$$U = 6.13\ U_* \log\ (Y/Y') + U' \qquad (5\text{-}11)$$

When the wind velocity above a sand surface is great enough, the particles start moving. The initiation of sand movement has been investigated theoretically by several researchers who have derived the following equation for the threshold value of the shear velocity:

$$U_{*t} = A[(\frac{\sigma - \rho}{\rho})\ gD]^{1/2}, \qquad (5\text{-}12)$$

in which

σ = the specific gravity of the grain,

ρ = the specific gravity of the air,

g = the ravitational constant,

D = the diameter of the grain, and

A = a coefficient, the value of which in air for grains above 100 μm in diameter was found to be about 0.1.

The influence of moisture in the sand on the threshold of sand movement has been investigated by Belly.[29] Based on his study, Equation 5-12 may be modified as follows:

$$U_{*t} = A\ (1.8 + 0.6\ \log_{10} W)\ [\frac{\sigma - \rho}{\rho}\ gD]^{1/2} \qquad (5\text{-}13)$$

where W is the water content expressed in percent. At values of U_{*t} greater than U_{*t}, the particles from the bed surface are mobilized. The number of particles mobilized increases with increasing shear velocity.

CHAPTER VI

The Kadib Approach to Eolian Sand Transport

Although Bagnold's equation is generally accepted at present as the most reliable method for calculating the rate of sand movement by wind, it is based on assumptions which are open to question. Both Bagnold and Kawamura concluded that the effect of turbulence should be ignored in the study of sand movement by wind. In wind tunnel experiments Bagnold observed that sand placed at the mouth of the wind tunnel was never disturbed even when high wind velocities were used. In wind tunnels the turbulent effects do not exist at the mouth of a wind tunnel. Based on the above information, the only explanation for the lack of sand movement at the mouth of the wind tunnel is the lack of turbulent development at the mouth of wind tunnels. Bagnold unknowingly showed that the average velocity without turbulence is unable to cause movement, therefore, it is concluded that the turbulence or velocity pulsations are responsible for sand movement by wind. Thus it becomes clear that sand movement by wind can not be described by the time average values alone, and a more accurate description of the motion can be obtained only if turbulence is introduced.

Another assumption made was that an ideal path for the particle, namely, saltation, is used to describe the rate of sand transport. The rise of the grains from the bed was assumed to be

caused by the mechanical impact of the falling grains. This description applies only for low rates of transport.[27] However, at high transport rates the whole description of saltation, for initiating the motion should collapse because even the large sized particles will be suspended. Thus, it is only the direct effect of air which puts the particles in motion. Therefore, it is believed that the description of the transport rate based on the effects of saltation alone is misleading, and should be explained by the turbulent flow condition at the surface. It is also believed that the effect of saltation, especially at low transport rates, should be considered as a factor contributing to the initial disturbance of the bed particle caused by the turbulent fluctuations of the wind.

One of the important factors which should be introduced in the study of sediment motion is the grain size of the material. Bagnold assumed that the transport rate varied approximately with the square root of the grain diameter. Data obtained by Kadib (see Figure 6-1) show a family of curves of different shear velocities U_* for the change of the transport rate with the grain diameter.[27] It is clear from Figure 6-1 that Bagnold's assumption is not true.

Studies have been made on the interaction between the fluid flow and the particles of a bed. The results of these studies have led to the development of theories describing the phenomenon of sediment transport in rivers. One of the most reliable methods is the one presented by H. A. Einstein in 1950.[27] Since, in both cases of wind and water transport, one will be working with steady,

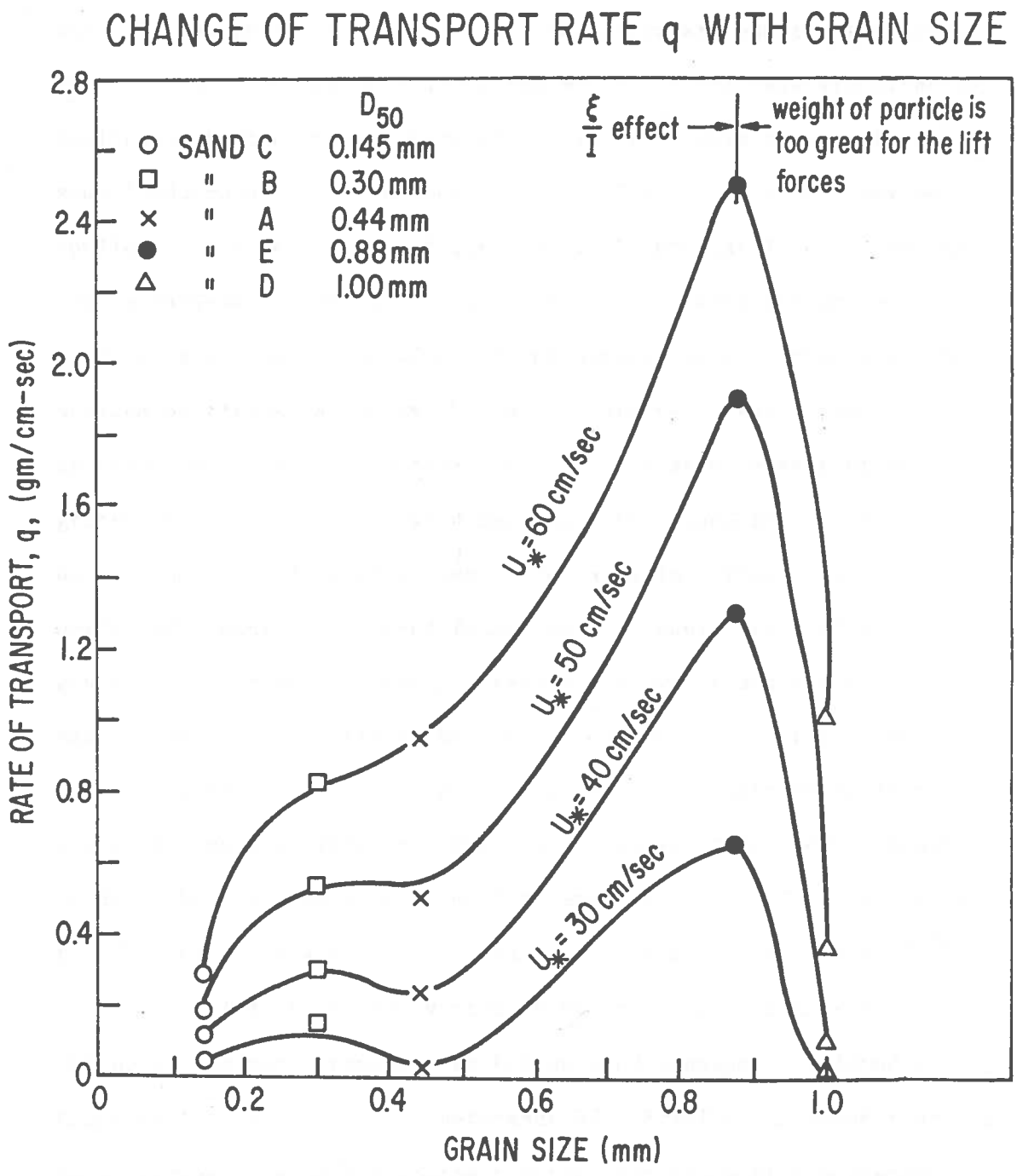


Figure 6-1. Variation of Transportation Rate with Grain Size

uniform, turbulent flow passing over a bed of loose particles, it is expected that a basic similarity exists between the motion of sediment in rivers and by wind. This, of course does not imply that the law governing the similar phenomenon are exactly the same, nor that the theories describing the motion in one case are directly applicable to the other. However, it is reasonable to assume that some fundamental concepts used in derivation of one theory may be applied in the derivation of the other. Unfortunately, in changing from a sand-water system to a sand-air system, with the enormous difference in density between air and water, the disturbance of the surface particles caused by the falling grains in saltation contributes to sand transportation. The saltation effect of the grains must be considered when dealing with a sand-air system, unlike in the sand-water system where saltation effect has been neglected. Kadib has indeed found that the basic principles governing the rate of sediment transport by water and air are the same except for the effect that saltation has on disturbing the surface particles in the case of air. With this difference in mind, especially at low transport rates, a method was developed by Kadib to describe the mechanism of sand movement by wind. This method is based on Einstein's theory of sand transport by flowing water.[27]

Details of the derivation by Kadib to apply Einstein's method of sediment transport to Eolian sand transport is found in Chapters IV through VIII of Reference 27. Briefly, he found that the basic forces causing the sediment motion are those of the average

lift $\bar{L}$ and the fluctuating lift L' caused by the turbulence. The effect of saltation, in the case of wind, can be introduced as a correction for the above basic forces. This effect of surface disturbance can be introduced as a correction, I, for the main lift force. He then goes on to show that if the Einstein correction,§ , for particle "hiding" in the laminar sublayer is combined with the above correction for surface disturbance, a new "wind correction" is obtained:

$$\psi_* = \left(\frac{\sigma - \rho}{\rho}\right) \frac{gD}{U_*^2} , \qquad (6\text{-}1)$$

in which

ψ = the new "wind correction" parameter,

σ = the specific gravity of the grain,

ρ = the specific gravity of the air,

g = the gravitational constant, and

D = the diameter of the grain.

The parameter ψ is defined to be the ratio of the submerged weight of the particle and the mean lift force caused by the fluid.

Now that the interaction between the bed particles and the fluid flow has been determined, there remains the problem of developing a method which describes the final solution. Simply, this was done by assuming that an equilibrium condition exists in the exchange of surface particles between the grains in motion and the bed. That is, for each unit of time and of surface area the same

amount of sand of a given size must be deposited on the surface as is removed from it. Thus, based on this assumption, the following relationship was developed:

$$\phi = \left(\frac{q}{\sigma g}\right) \left[\frac{\sigma}{(\sigma-\rho)gD^3}\right]^{1/2}, \tag{6-2}$$

in which

ϕ is a parameter expressing sediment transport in units of sec^2 per cm, and

q is the rate of sand movement per unit width and unit time.

Therefore, the rate of transport q can be calculated, since the above equation can be written as

$$q = \phi\sigma g \left[\frac{(\sigma-\rho)gD^3}{\sigma}\right]^{1/2} \tag{6-3}$$

The above derivation of the method of Eolian sand transport is based on uniform sand. Unfortunately, the sand particles found in the tailings piles in existance today is far from being uniform. However, Kadib believed that in the case of sand with a wide range of grain sizes, like tailings sands, a correction factor Y should be introduced to describe the change in the lift coefficient in a mixture. The correction factor Y is a function of K_s/δ, as shown in Figure 6-2.[27] The length K_s is a roughness diameter and δ is the thickness of the laminar sublayer. The value of K_s is the mean diameter of the mixture. The value of δ is calculated by

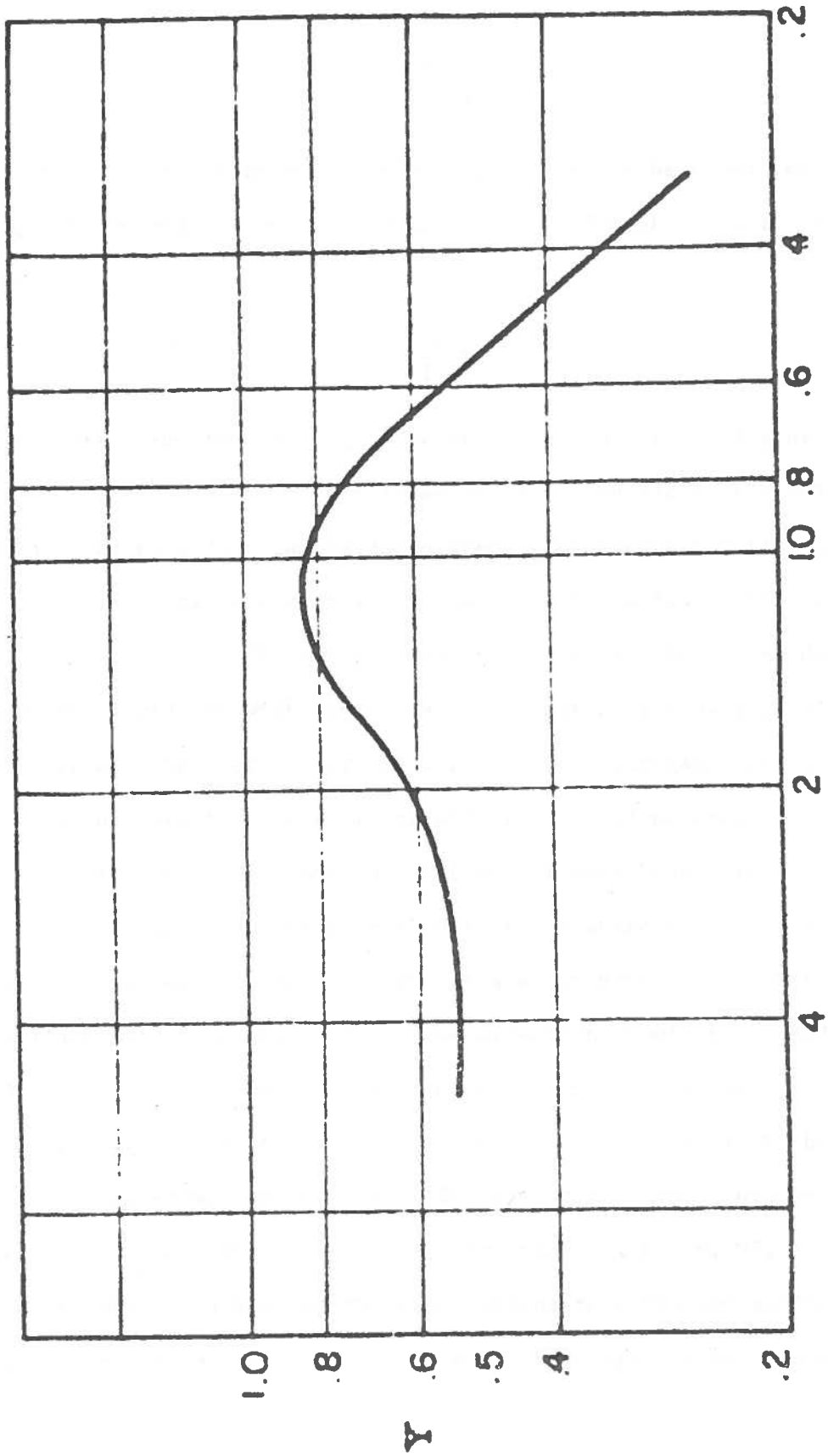


Figure 6-2. Correction Factor Y for Change in Lift Coefficient Due to Wide Variation in Particle Size Distribution

$$\delta = \frac{11.6\ \nu}{U_*}\ , \qquad (6\text{-}4)$$

In which ν is the kinematic viscosity, taken to be 0.147 cm^2/sec, and U_* is the shear velocity. Thus, the flow intensity ψ_* is written as:

$$\psi = \frac{\S\psi}{I}\ Y \qquad (6\text{-}5)$$

The correction factor Y would be unity for uniform grains of sand.

From the basic principles described by Kadib, the Eolian sand transport rate can be calculated. The greatest difficulty in applying theory to sand transport on tailings piles is the basically irregular wind conditions that exist in nature. Both wind duration and speed changes with time. Each tailings pile area generally is different from every other tailings area. Irregularities in wind speed and direction have strong effects on sand movement. Such considerations complicate calculations of sand transport.

To apply the Kadib method to the transport of radioactive sand, wind velocity measurements at a known distance above the surface should be obtained and the direction should be recorded. Also, information on the duration of this particular wind speed over the period of time for which the amount of transport is to be calculated should be recorded. The wind direction should be broken down into the eight primary wind directions (i.e., N, NE, E, SE, S, SW, W. NW), thus keeping the calculations to a minimum but yet giving reliable results. For each of these eight primary wind

directions, the longest exposed length, ℓ_r, of tailing sand particles capable of contributing to the transportation rate should be calculated and recorded.

The particle size distribution of the tailings sand should be obtained. The sampling area should be confined to surface particles only. It is important that many samples from a variety of areas of the tailings pile should be taken. From this data the mean grain diameter of the tailings particles should be calculated. The average grain diameter should be used in all calculations that need grain diameters.

Using the result of the above calculation (i.e., mean grain diameter) and Equation 5-10, the focal points U' and Y' can be calculated. Solving for the Shear Velocity U_* in Equation 5-10, the following result is obtained:

$$U_* = \frac{U - U'}{6.13 \log Y/Y'} \qquad (6\text{-}6)$$

Thus, by applying the above equation and the focal points as calculated by Equation 5-10, the shear velocity is obtained. The shear velocity should be calculated for each wind velocity.

The parameter ψ is calculated from Equation 6-1 by using U_* obtained above, the calculated average grain diameter and the accepted values of σ, ρ, and g. In the case of tailings particles, the accepted value of σ is 1.6 gm/cm^3, while for ρ it is 1.22×10^{-3} gm/cm^3. Since the parameter ψ is a function of U_*, it is necessary that ψ be calculated for each wind velocity. For each value of the

parameter ψ, the wind correction factor §/I can be obtained by use of Figure 6-3.

The correction factor Y, which is used for a wide range of grain sizes, is determined by the ratio K_s/δ. The value of δ is calculated by Equation 6-4. Since δ is a function of the shear velocity, it is necessary to calculate the value of δ for each wind velocity. As mentioned earlier, K_s is simply the mean grain diameter of the particles in the tailings pile. Thus, by using the values calculated by the ratio K_s/δ and Figure 6-2, the correction factor Y is determined for each wind velocity.

Through various graphs and equations, the following factors have been determined, the wind correction factor §/I, the parameter ψ and the correction factor Y. By applying these values in Equation 6-5, the flow intensity ψ_* can be calculated for each wind velocity. Using this value, the flow intensity, the intensity of sediment transport, ϕ, can be determined by consulting the graph shown in Figure 6-4.

As the final step in calculating the rate of transport, the Equation 6-3 is used by applying the appropriate values for σ, ρ, g, D and the values of ϕ for each wind velocity. Remembering that in the case of tailing particles the value of σ, the density of tailings particles, is usually assumed to be 1.6 gm/cm^3. In the western states where the tailings piles are located, it is usually assumed that the density of air, ρ, is 1.22×10^{-3} gm/cm^3. The value of D, as mentioned earlier, is the mean grain diameter of the

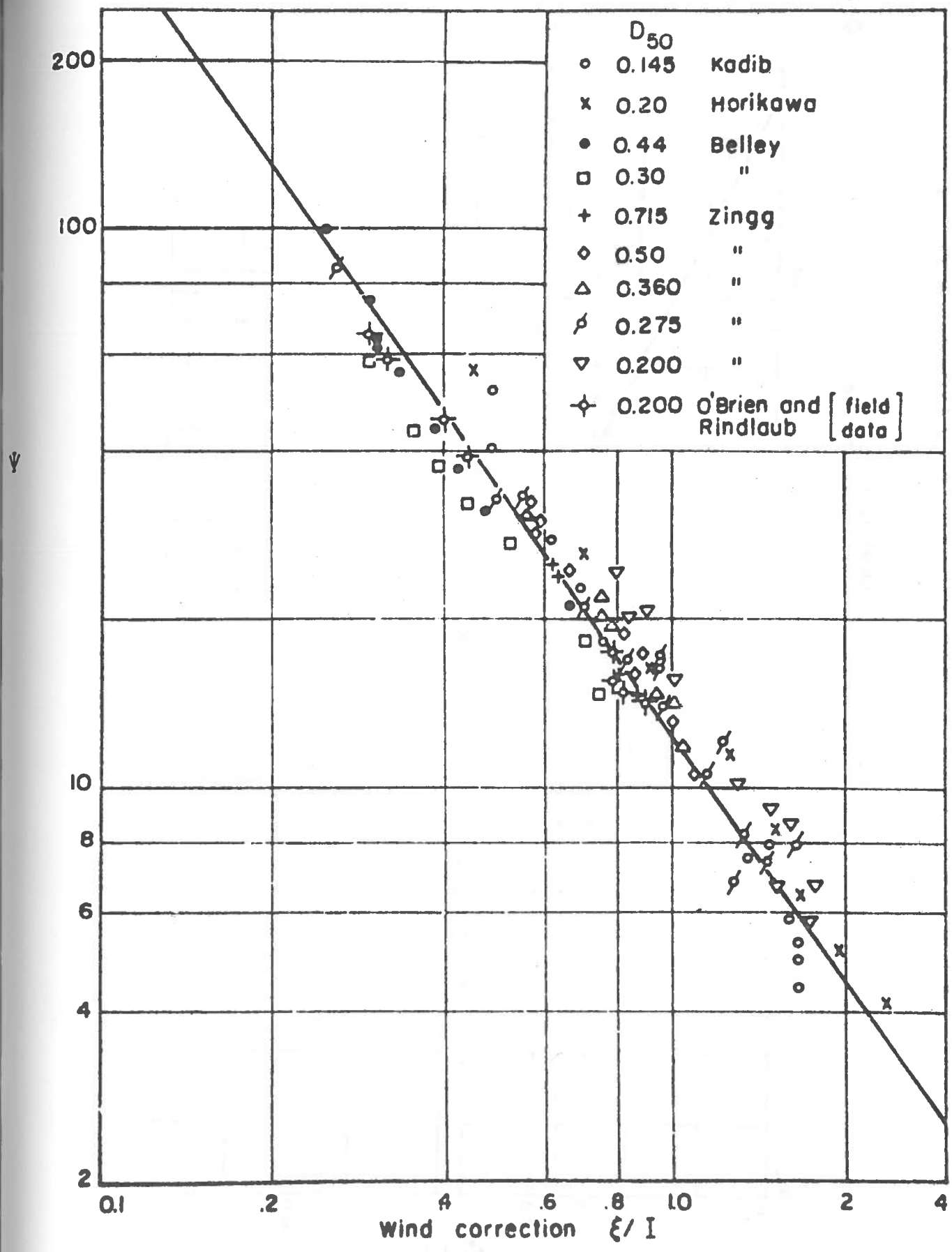


Figure 6-3. Relationship Between the Wind Correction ξ/I and ψ

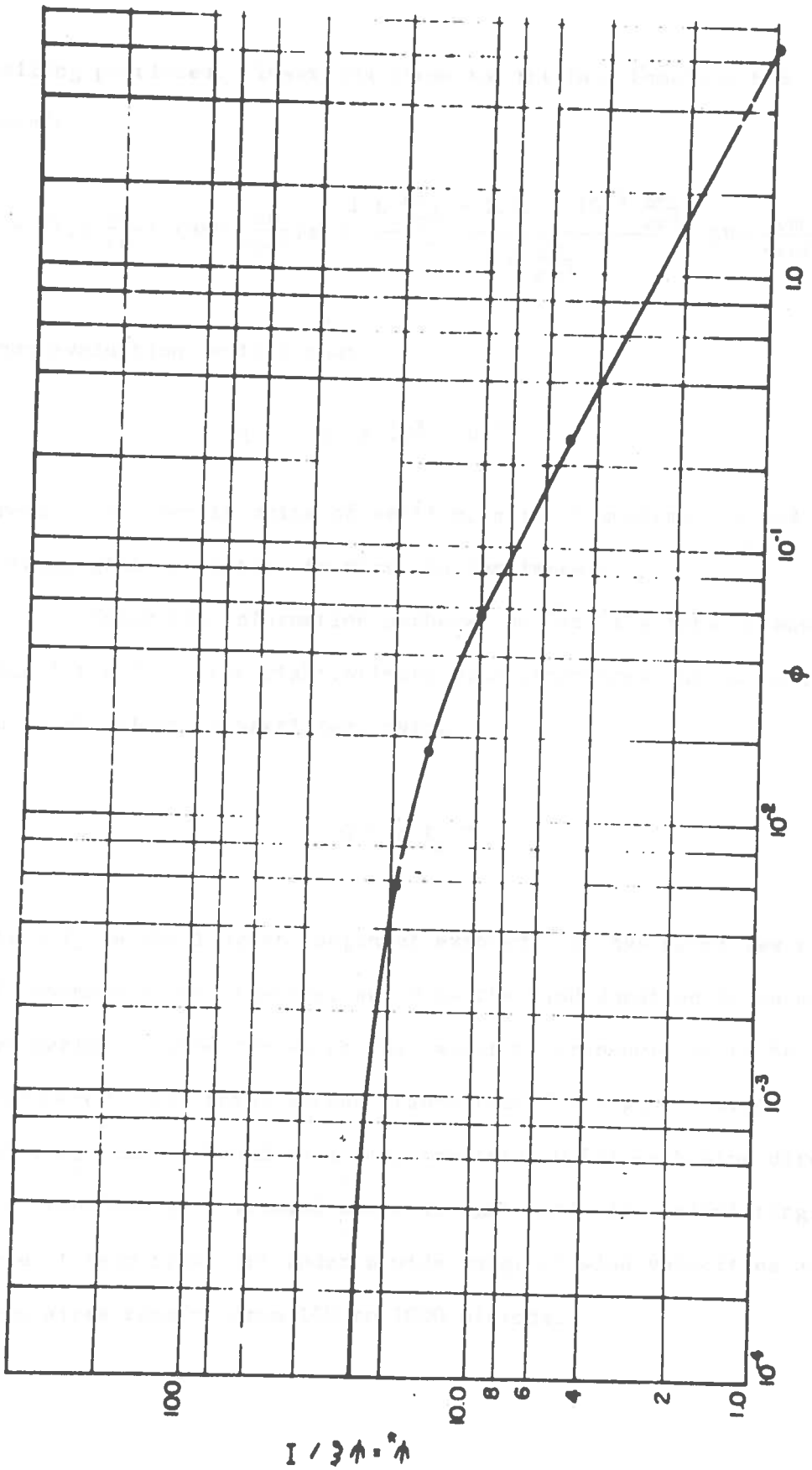


Figure 6-4. Relationship Between Flow Intensity ψ_* and Intensity of Sediment Transport ϕ

tailing particles. Inserting these values into Equation 6-3, we obtain:

$$q = \left(1.6 \frac{gm}{cm^3}\right)\left(980 \frac{cm}{sec^2}\right)\phi\left[\left(\frac{1.6 \frac{gm}{cm^3} - 1.22 \times 10^{-3} \frac{gm}{cm^3}}{1.6 \frac{gm}{cm^3}}\right) 980 \frac{cm}{sec^2} D^3\right]^{1/2}$$

Upon evaluation we find that

$$q = 4.91 \times 10^3 \phi D^{3/2} \qquad (6\text{-}7)$$

where ϕ is given in units of sec^2/cm, q is in gms/cm-sec, and D, the average grain diameter, is given in centimeters.

Using the information gathered so far, the total transport rate for each of the eight primary wind directions can be calculated in total weight of particles, using

$$Q = q \ell_r T \qquad (6\text{-}8)$$

where ℓ_r is the longest length of exposed tailings particles capable of movement in centimeters, and T is the wind duration in seconds per period of time for which the amount of transport is to be calculated. The total amount transported for a given period of time, Q_T, can be found by adding the total Q for each wind direction. The procedure as discussed above is applicable for calculating the rate of sand transport under a wide range of wind velocities and for sand sizes ranging from 100 to 1000 microns.

CHAPTER VII

Description of Experimental Apparatus and Site

Field work was conducted at the Anaconda mill site in Northwestern New Mexico. The Anaconda Company has played an active role in the uranium industry since the early 1950's when company geologists began exploring for ore in the Grants, New Mexico area. In 1952 and 1953 the company operated an ore-buying station for the Atomic Energy Commission (AEC) at the Bluewater Site near Grants, and from 1953 until 1959 processed ores by using the carbonate leaching process. The carbonate-leach circuit has been shut down since May, 1959.

In December, 1955, an acid leaching, resin-in-pulp (RIP) plant was added to the facilities at Bluewater to treat sandstone-type ores, and operations at this plant have continued until the present. This plant, which has a capacity of 3,000 to 3,300 tons per day, utilizes sand-slime separation and RIP treatment of the slime pulp to produce an eluate solution from which the uranium is recovered by a two-stage precipitation technique. The plant is arranged in two parallel sections through the RIP circuits. Operations, which are currently at a reduced rate, are using leaching and RIP facilities from both sections to increase residence times and thereby to achieve uranium recovery of nearly 97 percent. Somewhat lower recovery would be expected when operating at full mill capacity.

Sand tailings from the classifiers and slimes from the RIP circuit are combined and pumped to a 180-acre disposal area about two miles from the plant. Dust and drifting sand on the tailings pile are controlled at present by the use of drift fences and by keeping the tailings area wet. Abandoned areas are covered with local soils, which are capable of nurturing a weed cover, as a means of stabilizing the surface.(3) Figure 7-1 is the map of the Anaconda millsite area.

The primary purpose of the field study conducted at the Anaconda millsite is to measure the rate of transport of tailings particles. In this way, verification of the predicted values by the method described in Chapter VI is possible. In order to make such measurements two type of collectors were constructed. One collector was called a "horizontal trap" the other was known as a "vertical trap". The primary purpose of these two traps was to remove the tailings particles from the wind with a minimum disturbance of the wind profile.

The horizontal trap is simply a circular pan. The depth of the pan is nine centimeters, and the diameter is thirty-eight centimeters. The collector is placed in the ground such that the upper lip is level with the surface. In order to accomplish this, a shallow hole must be dug. The collector is then placed in the hole and the disturbed surface smoothed, making sure that no particles fall into the trap. The function of this collector is to give an indication of the mass of the particles that strike a

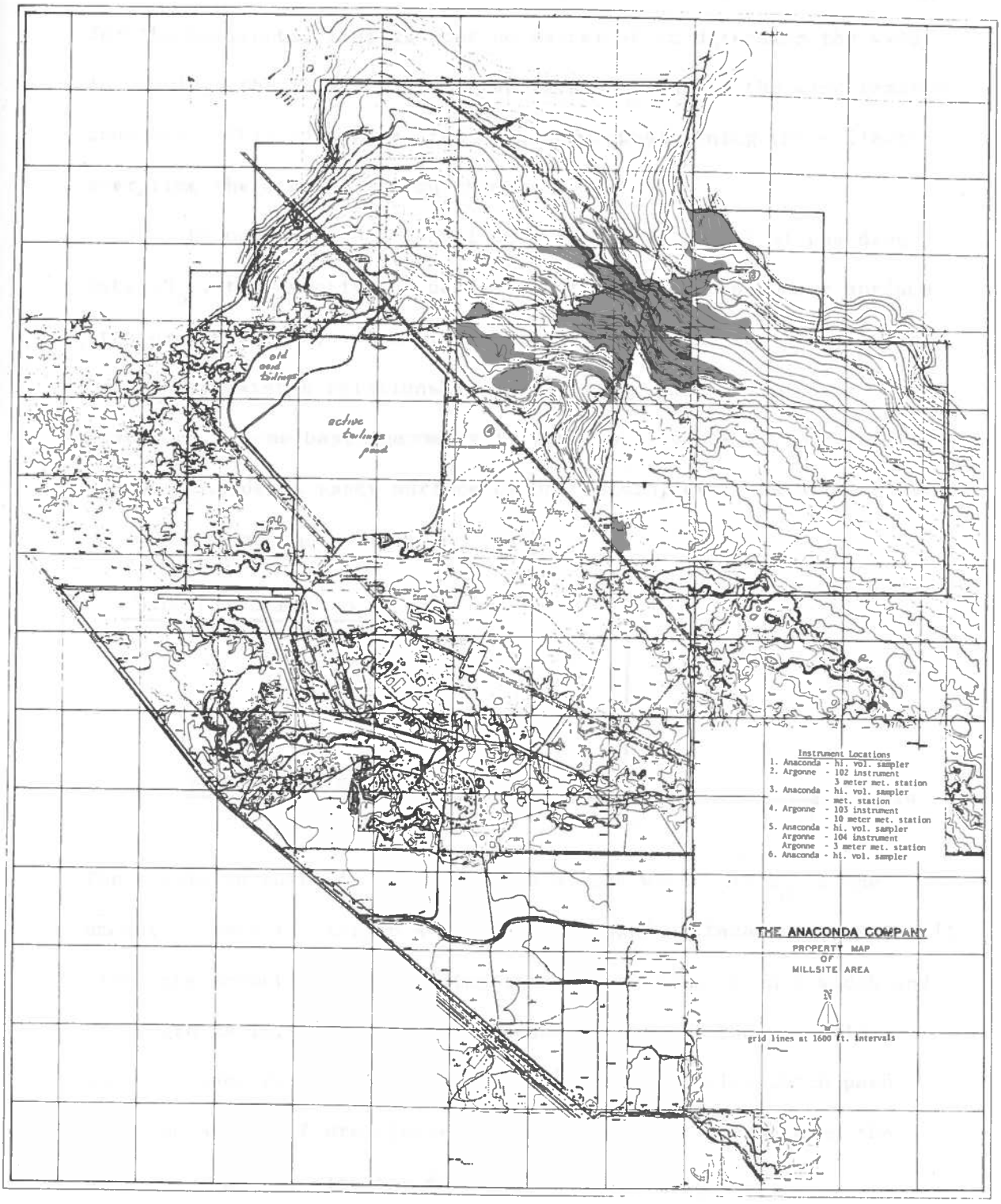
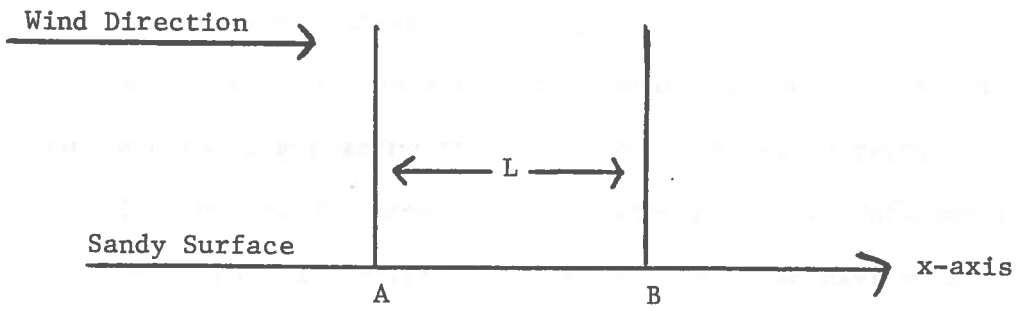


Figure 7-1. Map of Anaconda Millsite

particular surface area. The advantage of choosing a circular shape for the horizontal trap is that no matter which direction the wind is blowing, the length of the trap perpendicular to the wind remains constant. This eliminates the need for repositioning the collector everytime the wind direction changes.

By using the horizontal trap, the measurement of the drop rate (G_o), the quantity of particles dropping down per unit surface area per unit time, is easily achieved. The question then arises: Does there exist a relationship between drop rate and rate of transport? Some basic geometry is used to help answer this question. First, consider a sandy surface of unit width, over which the wind is blowing, as shown below.



The x-axis is taken in the direction of the wind. If G_o is the amount of sand falling on a unit area of sand surface during any unit time, the amount of sand jumping from the surface of unit width and of length dx is, $G_o dx$. If it is assumed that all the particles have the same flying distance, L, then sand particles which pass over the section B are ejected from the sand surface between the sections B and A, with the distance BA equal to L.

Therefore the amount of sand passing through the cross section B per unit time is,

$$q = \int_{o}^{L} G_o dx = G_o L. \qquad (7\text{-}1)$$

Thus we see that the transportation rate equals the drop rate multiplied by the length of particle travel from the point where it is projected into the wind stream to where it falls back to the surface.[29]

Figure 7-2 is a simplified drawing of the design of the vertical trap. A 200-mesh (74μ) screen is used for the back to allow the passage of wind while removing the sand type tailings particles from the wind stream.

It was hoped that the screen back would reduce the pressure drop that results from placing the collector in an air stream, thereby minimizing the disturbance of the wind profile. Unfortunately, the field experiments indicated that the vertical trap exerted a substantial influence of the wind profile. This was evident from the scouring effect of the surface that took place in front of the collector. The maximum height of the flying sand layer has been noted by several researchers to be only a few centimeters above the surface.[28] Thus the height of the collector is sufficient so that no sand particles will blow over the collector. However, for wind speeds in excess of twenty meters per second (about 45 mph) sand particles will reach heights of up to two meters from the surface.

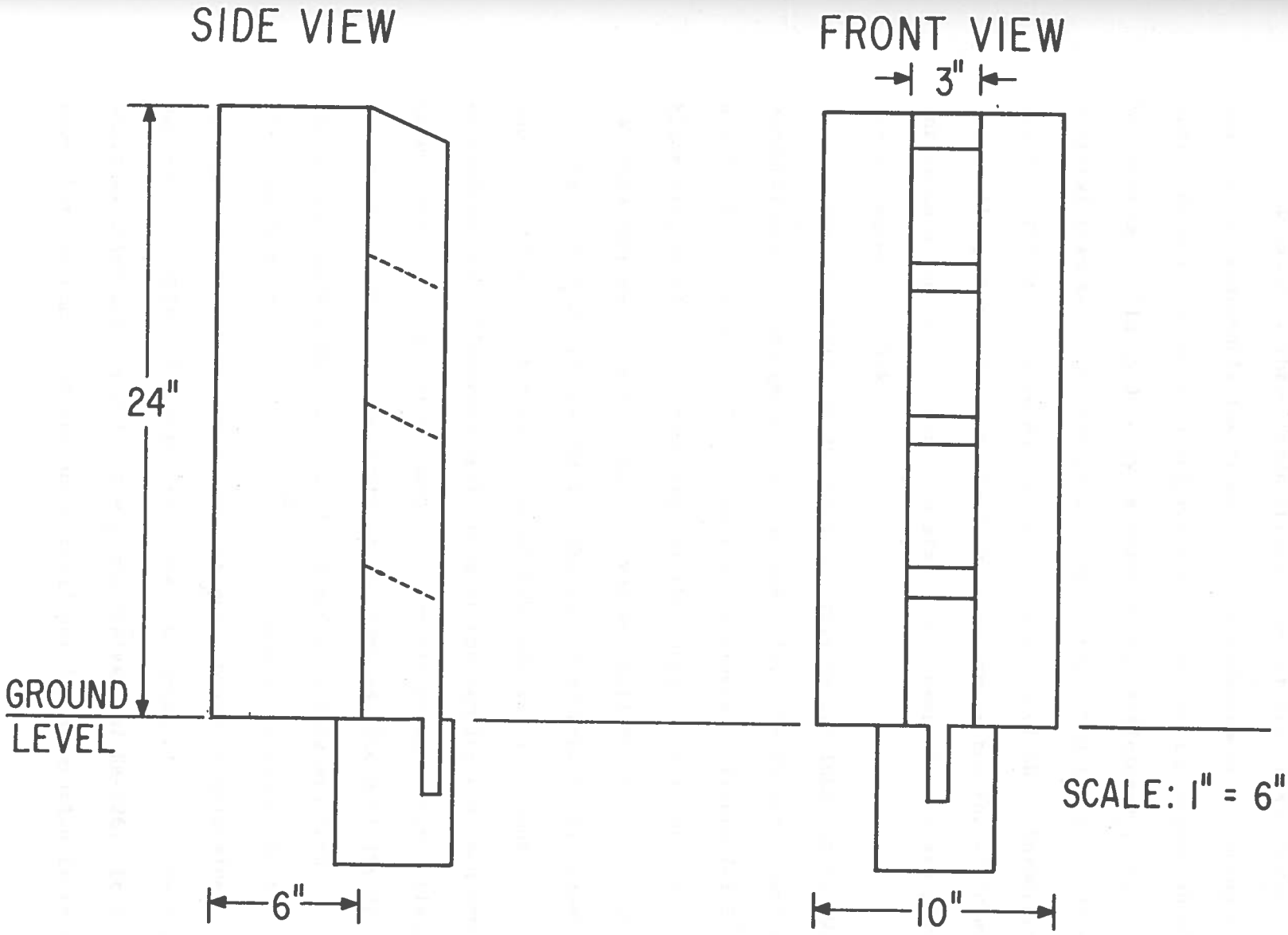


Figure 7-2. Schematic of Vertical Trap Collector

Inspite of these deficiencies, the vertical trap should serve as an reasonable instrument for the measurement of transportation rate. By calibrating this collector the inherent inaccuracy should be overcome. This is done by determining the efficiency of the vertical trap as a function of wind velocity. Thus the data collected can be corrected to give an accurate indication of the transportation rate. Also, it would be interesting to determine how the efficiency varies as a function of particle size. Such measurements are planned for the summer of 1978.

The evaluation of the radioactivity in tailings samples was accomplished through gamma spectral analysis. The detector used was a 7.62-cm x 7.62-cm NaI(Tl) scintillation crystal. Figure 7-3 is a block diagram of the system used for the gamma analysis of the tailings samples. Spectra analysis was accomplished by the unpublished computer code GASP-II, set up for the author by Drs. R. E. Toohey and P. O. Nicole of Argonne National Laboratory. This code determines the full-energy peak areas of the samples and then compared these to a reference sample for conversion to sample activity. To determine the actual activity of the samples, the activity of the samples were compared to a pitchblend reference standard obtained from Dr. C. W. Sill.[38] The standard is sealed so that the radon is retained; hence, secular equilibrium is maintained. Recorded in Table 7-1 are the relative abundances of the three photon energies which were used for the gamma analysis of Ra-226. It can be seen that the number of photons emitted per disintegration is relatively

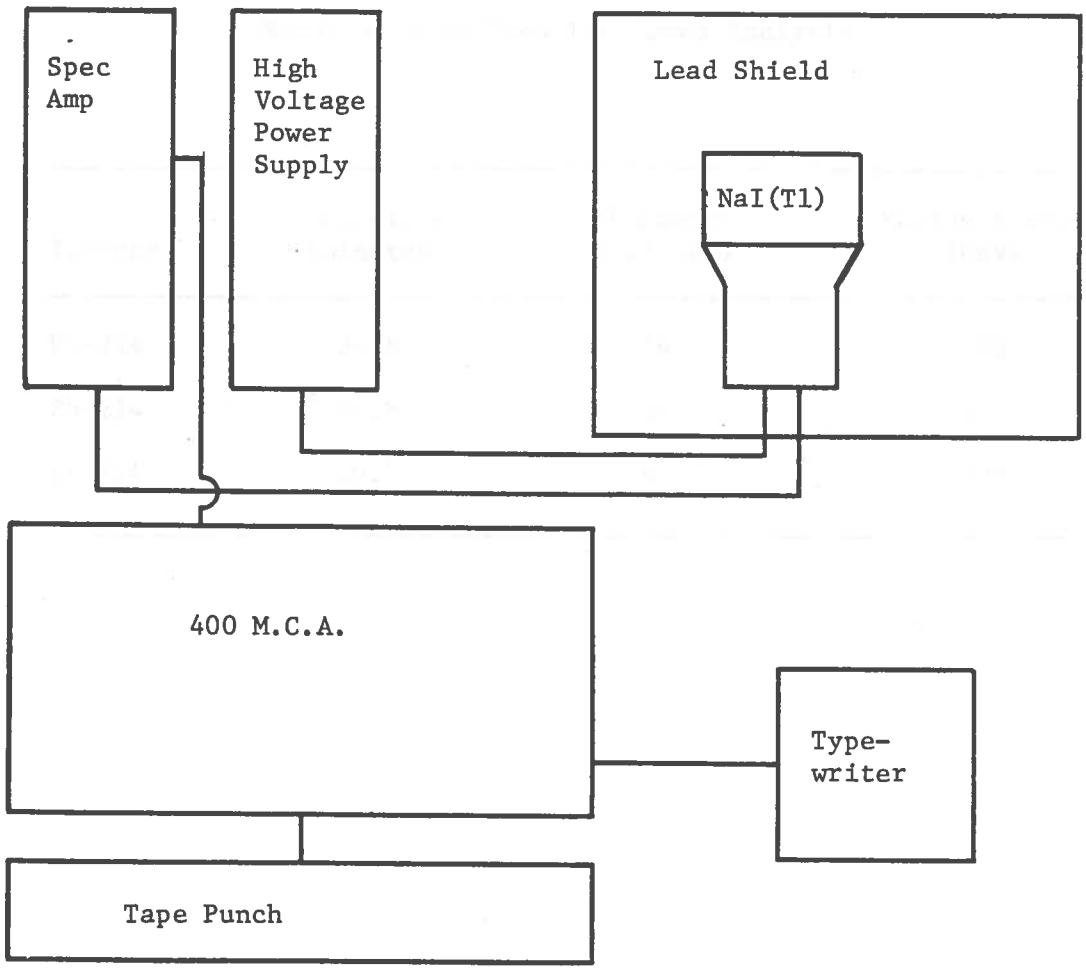


Figure 7-3. Block Diagram of Gamma Counting Equipment

Table 7-1

Radioisotopes Used for Gamma Analysis

Isotope	Half-live (minutes)	Abundance (percent)	Photon Energy (KeV)
Pb-214	26.8	19	295
Pb-214	26.8	36	352
Bi-214	19.7	47	609

low. This fact, combined with the low photon energies and the relatively poor resolution of the NaI(Tl) detector, may yield low counting efficiency. However, these low counting efficiencies need not be a deterrent to precise analysis when adequate sample is available. For example, one gram of 0.2% uranium ore contains approximately 1500 disintegrations per minute (700 pCi) of U-238 and its daughters.[39] Thus, where gram quantities of sample are available, it is possible to make reasonably accurate analysis of Ra-226 and its daughters within a reasonable counting interval.

CHAPTER VIII

Data Analysis

In order to calculate the transportation rate of sand, q, from the drop rate, G_o, it is necessary to know the flying distance, L. Kawamura derived the following relationship for the calculation of L:[28]

$$L = K_2 \frac{(U_* + U_{*t})^2}{g}, \qquad (8\text{-}1)$$

in which K_2 is a constant to be determined by experiment, and the other symbols have been defined previously. From actual measurements, it was found that the flying distance, L, varied from 1 to 45 centimeters, and the data suggested a relationship between flying distance and grain diameter.[29] Thus, it can be concluded that the Equation (8-1) is not appropriate. In fact, the average flying distance increases with grain diameter.

Furthermore, one of the assumptions made in Chapter VI for the derivation of rate of transport was that an equilibrium condition exists in the exchange of surface particles and particles in motion. This arises mainly because at a given wind velocity a limited quantity of particles can be transported. That is to say, the quantity transported will reach a saturation point. When this saturation point is reached, the equilibrium condition will exist. In experiments conducted by Kawamura, it was found that a state of saturation will be reached when the wind has blown over an area of

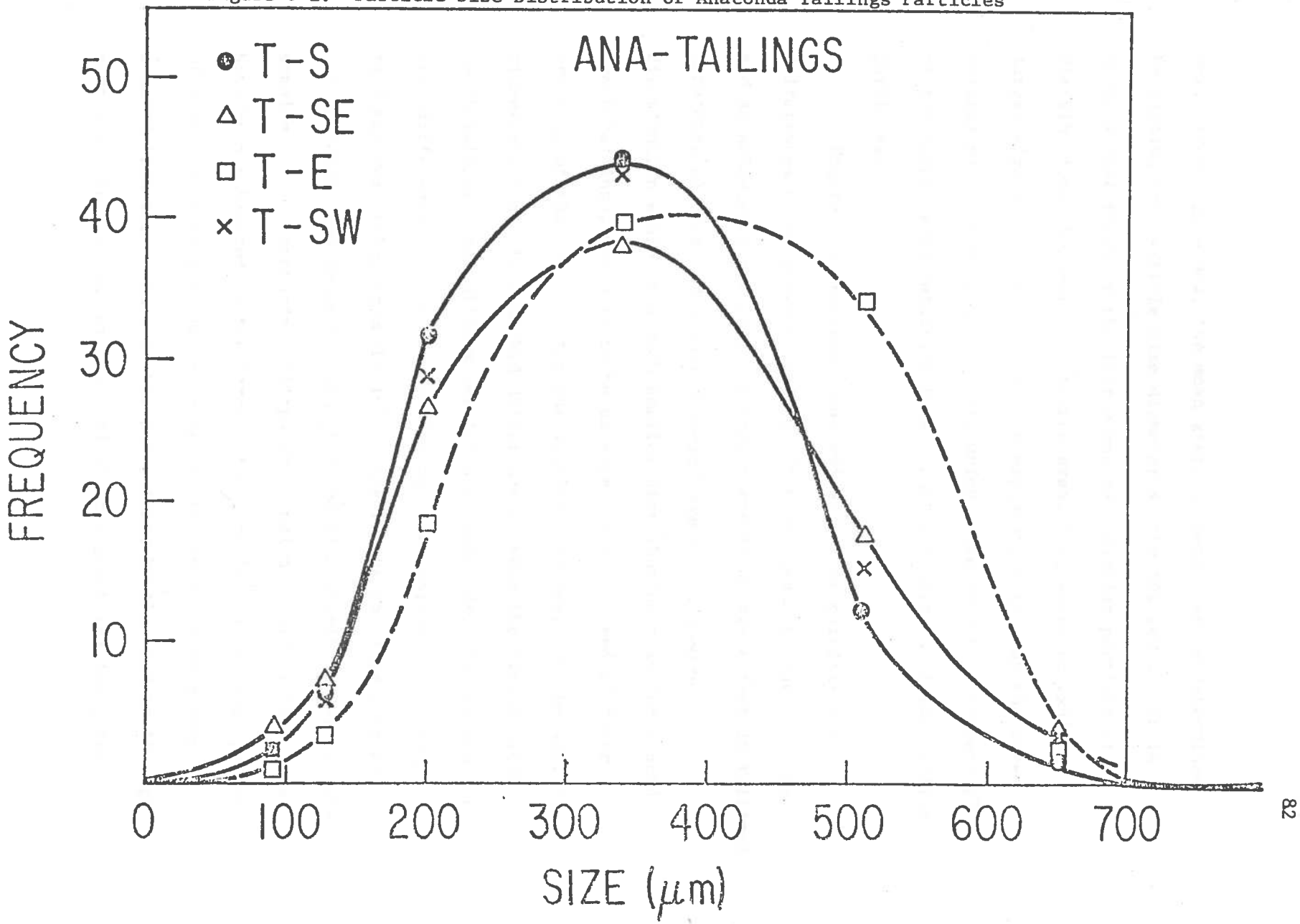
sand that is about two meters in length, even when the wind velocity is high.[28] Consequently, for tailings piles the flow of sand is considered to be in a state of saturation almost everywhere above the sandy portions of the tailings pile. It is concluded that the quantity of particles collected by the horizontal trap will equal the quantity of particles that would be transported if the surface area replaced by the collector had been undisturbed.

This still does not indicate the rate of transport, however. That is, it does not reveal the amount of particles moving per unit length per unit time. In fact, such data could only be used if the length of the area parallel to the wind is greater than the maximum possible distance that a particle could travel. There is no certainty that the horizontal trap will fulfill this necessary requirement. In any case, further studies are required to determine the correct function of L.

Knowledge of the particle-size distribution is important for the calculations described in Chapter VI. From the particle-size distribution, the mean grain diameter of the particles in the tailings pile can be calculated. Surface samples were taken from the tailings pile in four separate areas. The areas were selected on the basis of the dryness of the sandy surface; they were not covered by water, nor were they caked with dry mud. These criteria made them similar to sandy surfaces found in beach or desert areas.

To perform the analyses, standard sieves were employed, with the following mesh screen sizes: 600 μ, 425 μ, 250 μ, 150 μ, and 75 μ. The results of these analyses are shown in Figures 8-1 and

Figure 8-1. Particle Size Distribution of Anaconda Tailings Particles



8-2. From Figure 8-2, the mean grain diameter can be determined by finding the particle size diameter at the 50% level. It is obvious that three of the four areas have similar particle size distributions; however, the fourth area, T-E, seems to exhibit larger size particles. A possible explanation is that the prevailing wind blows from the west, which could lead to a "creeping" of the larger sand particles toward the east portion of the tailings particles.

Figure 8-3 provides clear evidence that particle size differences exist between tailings from an alkaline-leach process and an acid-leach process, and that there is an age effect in tailings (Anaconda's) pile. The alkaline-tailings particle-size distribution exhibits a much smaller distribution than for a acid leach tailings, which is to be expected from the need of finer grinding of the feed ore for the alkaline process. At the smaller diameters, there is a marked difference between the typical acid-leach tailings and tailings particles of Anaconda. The reason for this difference is that the samples for the typical acid-leach tailings were taken from the inlet pipe to the tailings pile and the Anaconda samples were taken from the pile itself. That is, the samples for the Anaconda tailings are considered old tailings that have been subjected to the forces of nature for an extended period of time. Most of the smaller sized particles would have been removed from the surface of the pile either by the wind or through settling. In the case of the typical acid-leach tailings, the

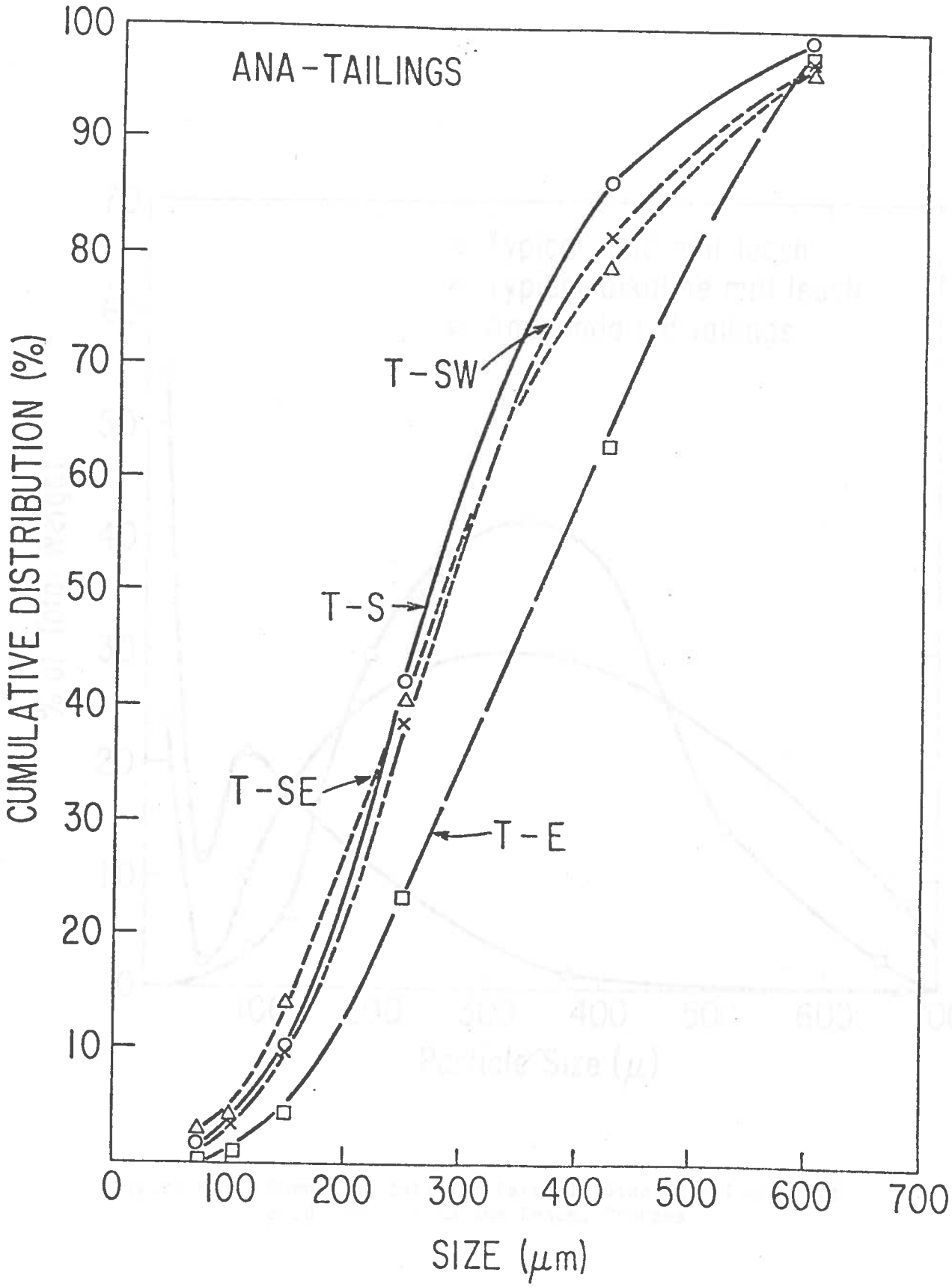


Figure 8-2. Cumulative Distribution of Anaconda Tailings Particles

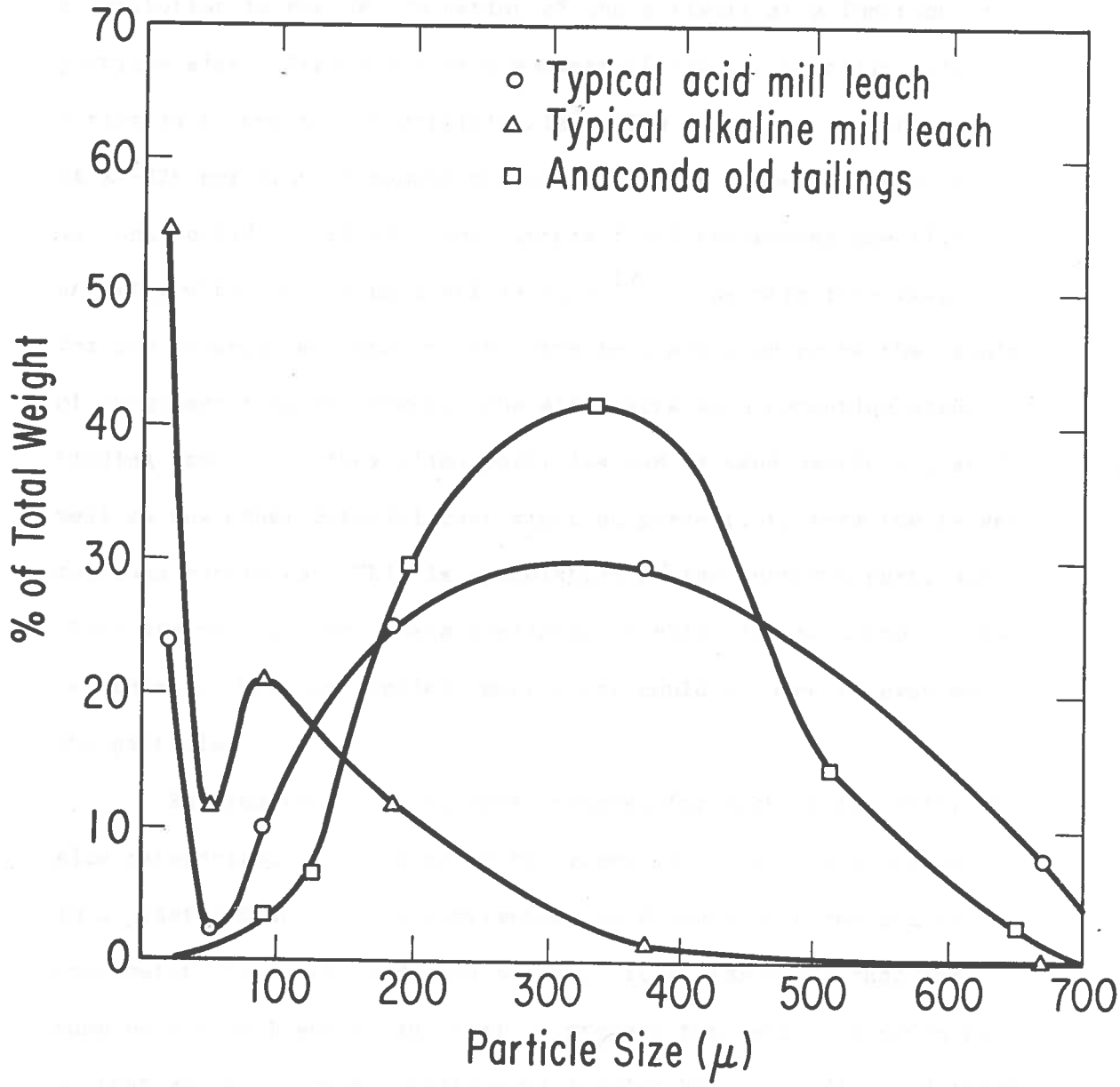


Figure 8-3. Comparing Tailings Particle Size Distribution of Acid Leach, Alkaline Leach, Process

samples taken were fresh and thus had not been exposed to the wind or had time to settle to the bottom layers of the tailings pile.

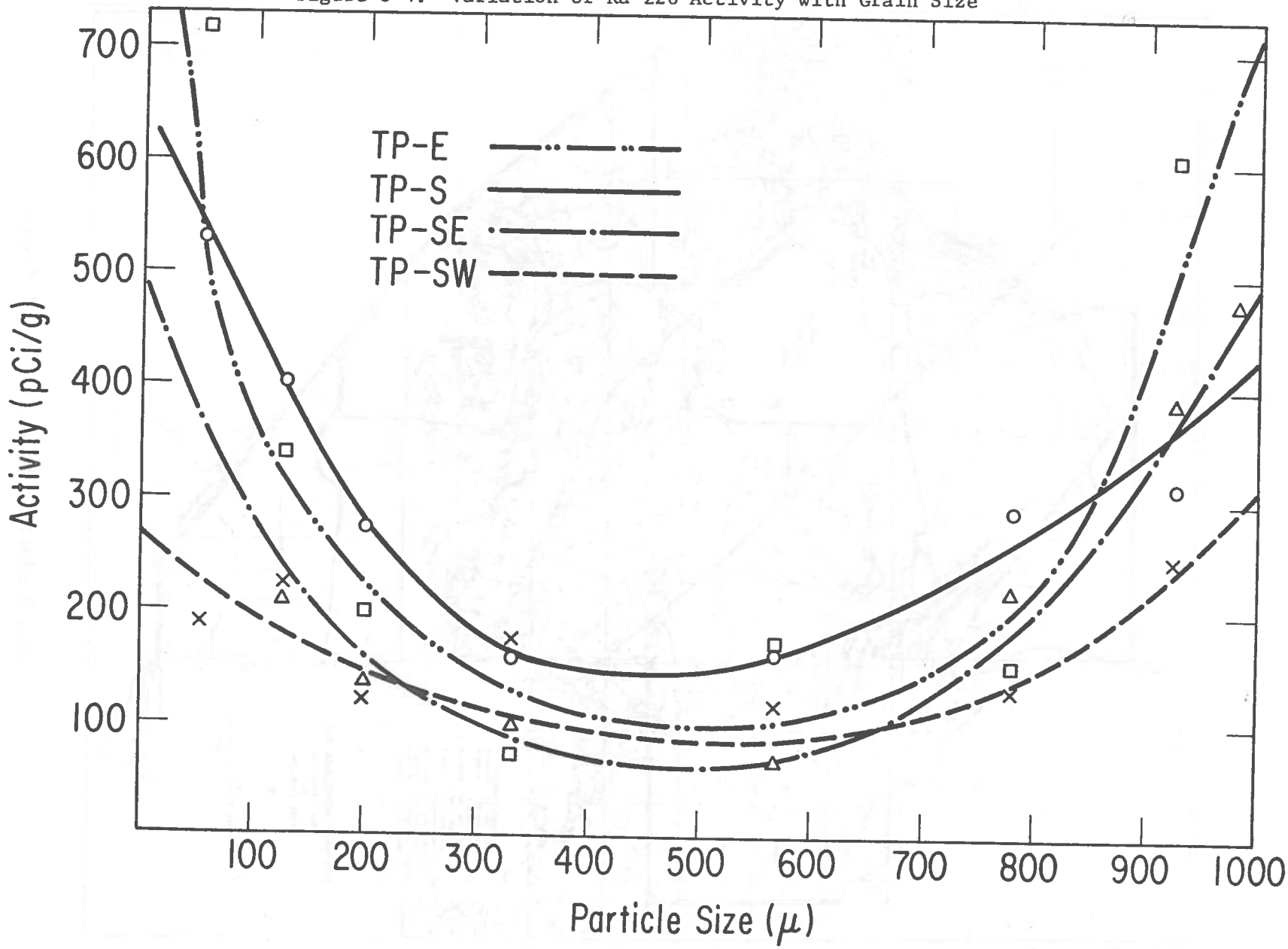
The next step after determining the particle size distribution is the determination of the activity as a function of particle size. Figure 8-4 is a summary of how the specific activity varies as a function of particle size. The units are in picocuries of Ra-226 per gram of sample and microns. The shape of the curve was unexpected. Earlier investigators found decreasing specific activity with increasing particle size.(8) The principle reason for the observed minimum in the curve is postulated to be the result of conglomeration of slimes. The slime acts as a cementing agent binding itself to other slime particles and/or sand particles, as well as any other material that might be present, to form the larger tailings particles. This is speculation on the author's part, and there are no additional data available at this time to support this hypothesis. However, optical microscopy could be used to examine the particles.

Samples for counting were prepared for each of the different size categories. Approximately ten grams of tailings were placed in a plastic dish of four centimeters in diameter and one and half centimeters in depth, and then sealed. It is important that the samples are well sealed in order to prevent the escape of radon gas so that an equilibrium condition will exist between radium and radon. Approximately fourty-five days are allowed to pass before counting the samples to assure that an equilibrium condition would be

reached between Ra-226 and Rn-222 and its daughters. The time required for Rn-222 to be within 99.9% of equilibrium with Ra-226 is about 39 days. In only five hours, Rn-222 will be in equilibrium with all of its daughters. Thus, by counting the samples with Ra-226 in equilibrium with its daughters, the measurement of Ra-226 activity is obtained by measuring the activity of its daughters. Because of the poor resolution of NaI(Tl) detectors, the only isotopes used for analysis purposes were Pb-214 and Bi-214. However, of the many gamma energies emitted by these two isotopes, only the 295-KeV and 352-KeV photons from Pb-214, and the 609-KeV photon of Bi-214 were used. The results of this gamma analysis as described, is found in Table 8-1 as well as Figure 8-4. Samples of the measured spectra are presented in the Appendix. The spectrum (A-1) from Dr. Sill's standard is included for comparison.

The results of the collections by the vertical traps analyzed is found in Table 8-2. The positions of the vertical traps within the tailings pile during the collection are shown in Figure 8-5. Field observations made help in the interpretation of the data. Note that the collection rate for samples 4 and 6 are much lower than the others, even though the wind velocity data is about the same. This could result from the position of the collectors. Both are located near the south side pump station where the surface in this region is caked mud. Thus the sand moving came from well within the tailings pile. If, during the saltation phase, there were no new particles ejected from the surface (which may well be

Figure 8-4. Variation of Ra-226 Activity with Grain Size



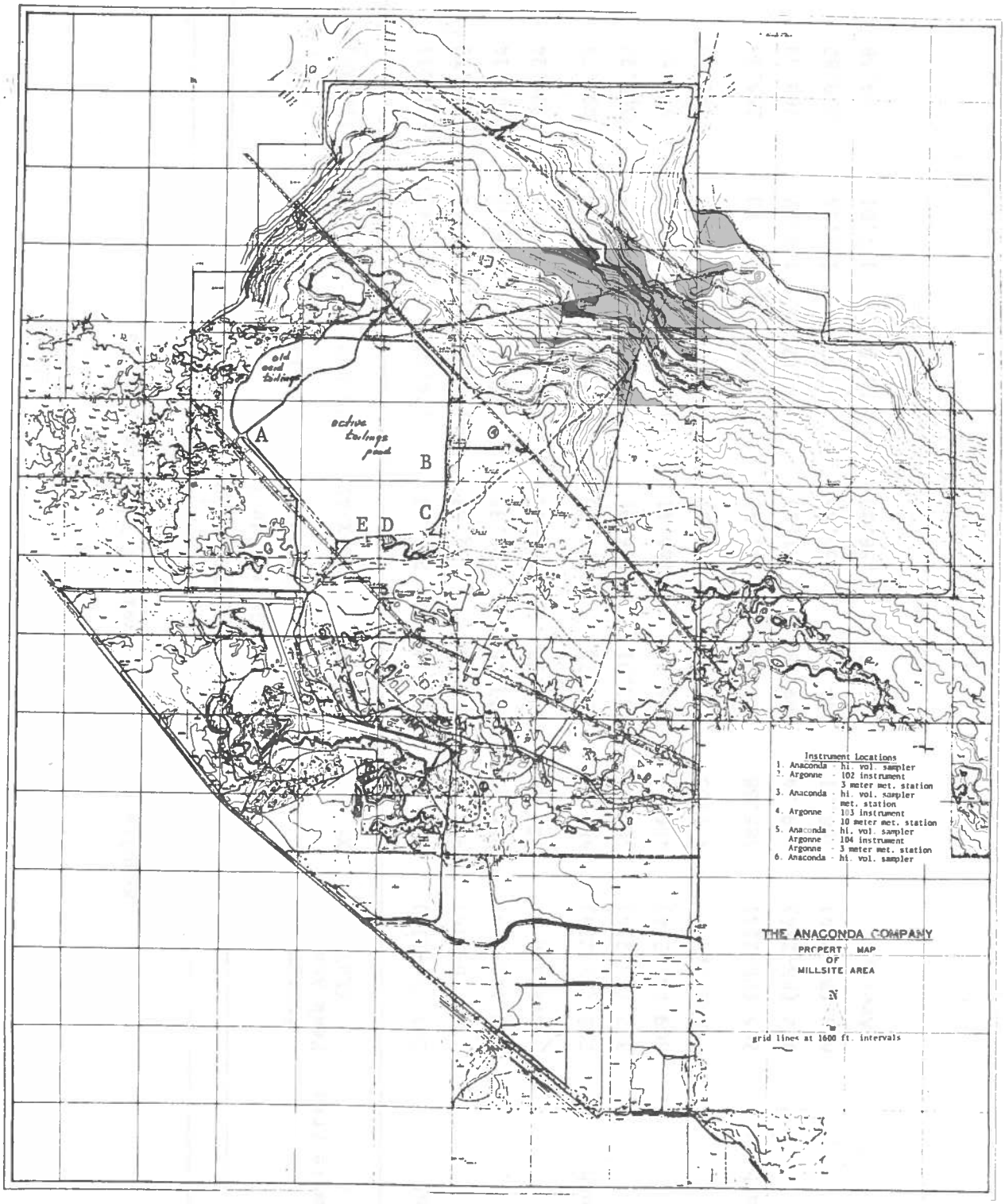


Figure 8-5. Position of Verticle Traps

Table 8-1

Results of Gamma Analysis of Tailings Samples

Sample Area	Energy of Peak Analyzed (KeV)	Activity (pCi/gm) Particle Size (μm) (A) X> 850	(B) 850>X>710	(C) 710>X>425	(D) 425>X>250	(E) 250>X>120	(F) 150>X>106	(G) X< 106
East	295 (Pb-214)	993.10	237.18	201.43	174.57	356.67	618.11	1026.53
	352 (Pb-214)	981.97	265.66	192.38	175.50	401.52	579.59	1009.62
	609 (Bi-214)	986.71	223.06	188.35	185.66	376.36	573.14	976.18
	Average	987.26	241.97	194.05	178.58	378.18	590.24	1004.11
South	295 (Pb-214)	482.45	422.78	236.35	212.45	289.20	494.74	836.98
	352 (Pb-214)	484.92	453.01	186.01	220.27	318.33	500.22	853.94
	609 (Bi-214)	466.13	416.23	185.41	195.87	272.87	481.64	845.91
	Average	477.83	430.67	202.59	209.70	293.47	492.20	845.63
Southeast	295 (Pb-214)	585.68	287.98	151.92	178.32	179.43	265.33	692.11
	352 (Pb-214)	569.24	269.59	161.63	178.17	182.27	263.53	720.81
	609 (Bi-214)	568.31	258.95	156.85	154.57	169.34	279.82	701.77
	Average	574.41	272.01	156.80	170.35	177.01	269.56	704.90

Table 8-1 (cont'd)

Sample Area	Energy of Peak Analyzed (KeV)	Activity (pCi/gm) Particle Size (μm) (A) X> 850	(B) 850>X>710	(C) 710>X>425	(D) 425>X>250	(E) 250>X>120	(F) 150>X>106	(G) X< 106
Southwest	295 (Pb-214)	334.77	168.96	174.70	189.50	225.34	329.09	404.08
	352 (Pb-214)	331.53	167.66	191.50	168.67	235.02	362.00	496.01
	609 (Bi-214)	335.74	163.45	165.06	161.64	231.64	358.65	464.48
	Average	334.01	166.69	176.92	173.27	236.67	365.11	474.86

Table 8-2

Data of Sand Transport Rates from the Vertical Traps

Position	Time (date, hr) Start		Stop		Wind Profile (mph) High	Low	Avg	Weight (gm)	Collection Rate (gm/sec)	Wind Direction
A	11/6	1126	11/6	1159	4	0	2	510.1	.258	180°
B	11/8	1520	11/8	1545	17	5	11	427.4	.285	240°
C	11/8	1525	11/8	1600	16	4	10	479.5	.226	240°
D	11/8	1530	11/8	1605	16	4	10	79.3	.038	240°
B	11/8	1635	11/8	1700	12	4	9	254.8	.170	300°
E	11/8	1645	11/8	1705	12	5	8	43.6	.036	300°

Note - The direction indicates from where the wind is blowing.

the situation in this region) then the saturation condition of the wind stream would no longer exist. Therefore, there would be a decrease in the quantity of particles being transported. Any further speculation will require additional data before a definitive test of Kadib's method can be attempted.

CHAPTER IX

Summary and Conclusion

It is desirable to know the collection efficiency of the vertical trap as a function of wind velocity. By knowing this efficiency the collector can be calibrated to give a more reliable value for sand transportation rates. Such a calibration is scheduled for the wind tunnel at the University of Colorado at Boulder for the summer of 1978. It is expected that the efficiency would increase with the wind velocity until at some point the efficiency would start to decrease. At wind velocities greater than twenty meters per second, the sand particles will start to approach suspension and may reach heights of two meters or more. After this calibration, the vertical traps will be used in the field to determine the quantity of tailings particles that are being transported by the wind into the surrounding environment. Experimental data then can be compared to the values calculated by the theoretical method described in Chapter VI.

Earlier it was speculated that the conglomeration of slimes was the reason for the shape of the curve observed in Figure 8-4. Another possible reason for this phenomenon is that the curve is a result of a superposition of two separate curves. In the one case the curve would be the result of the decrease in specific activity with the increase of particle size as is normally expected with

slimes. The other curve would be dealing with the large particles left over from the leaching process which would have cores of unleached uranium and its daughters. The result would then be an increase of specific activity with an increase in particle size. This phenomena would then suggest that during the leaching process, the extraction of uranium could be improved by the finer grinding of the original feed ore. Of course, this speculation would require further investigation before its validity can be determined.

In summary, the major contributions of this thesis project are:

- A critique of theories of Eolian sand transport and there application to the Eolian transport of radioactive materials in tailings pile.
- The development of a vertical and horizontal traps for use in the determination of transport rate and drop rate of tailing sand particles.
- The application of a gamma spectrometer in the determination of the Ra-226 activity in tailings pile.
- The determination of the particle size distribution of tailings particles of the Anaconda tailings pile. The measurement of the specific activity versus sand particle size.

The most significant accomplishment is the last contribution mentioned above. The increase in specific activity with increasing particle size above five hundred microns has not been reported previously.

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APPENDIX A

Figure A-1 is the gamma spectrum of the standard pitchblend ore obtained from Dr. C. W. Sill. Figures A-2 through A-8 are examples of spectra emitted by tailings as a function of particle size.

Figure A-1

Gamma Spectrum of Standard

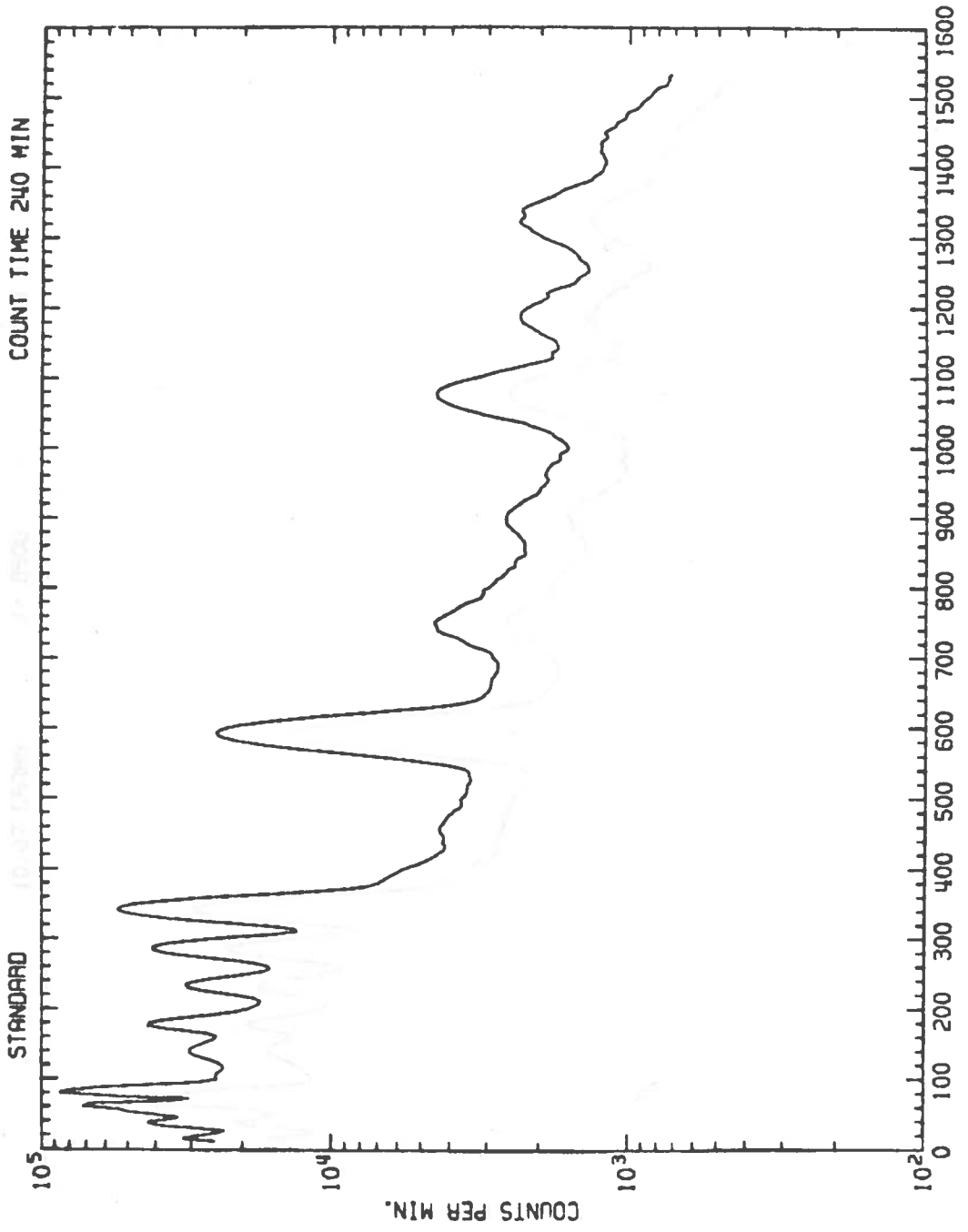


Figure A-2

Gamma Spectrum of Tailings Particles Greater than 850

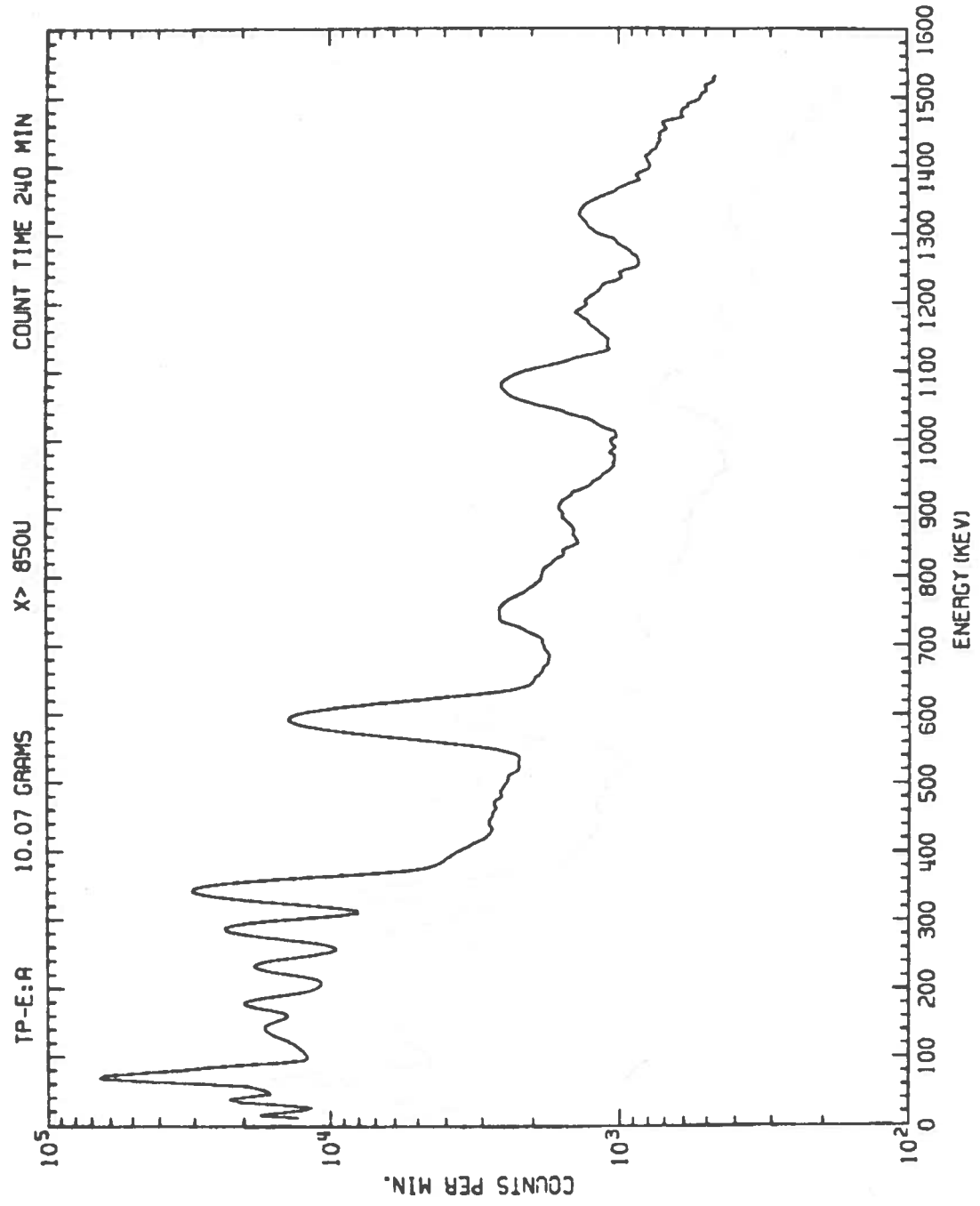


Figure A-3

Gamma Spectrum of Tailings Particles
Between 850 and 710 Microns

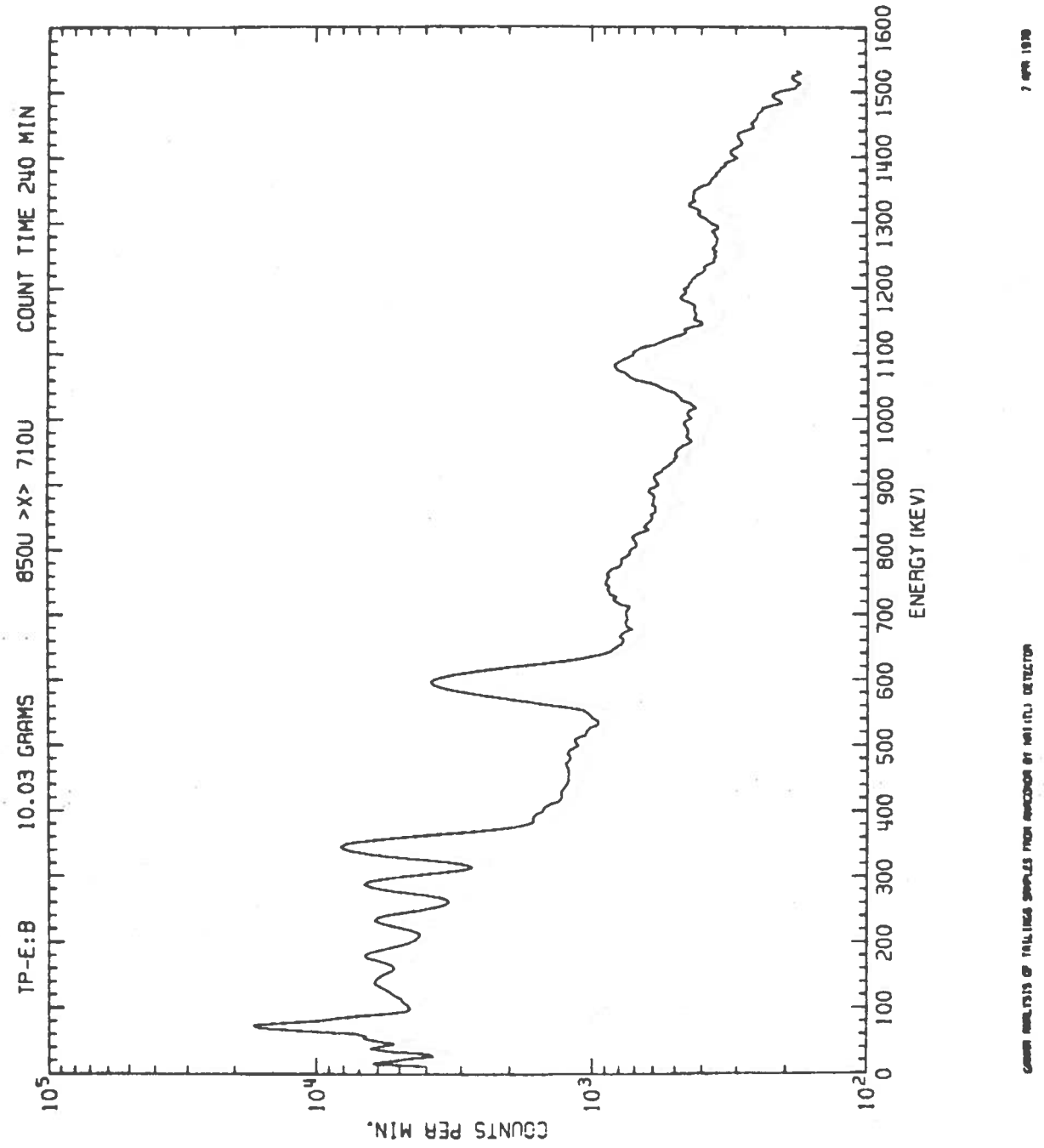


Figure A-4

Gamma Spectrum of Tailings Particles
Between 710 and 425 Microns

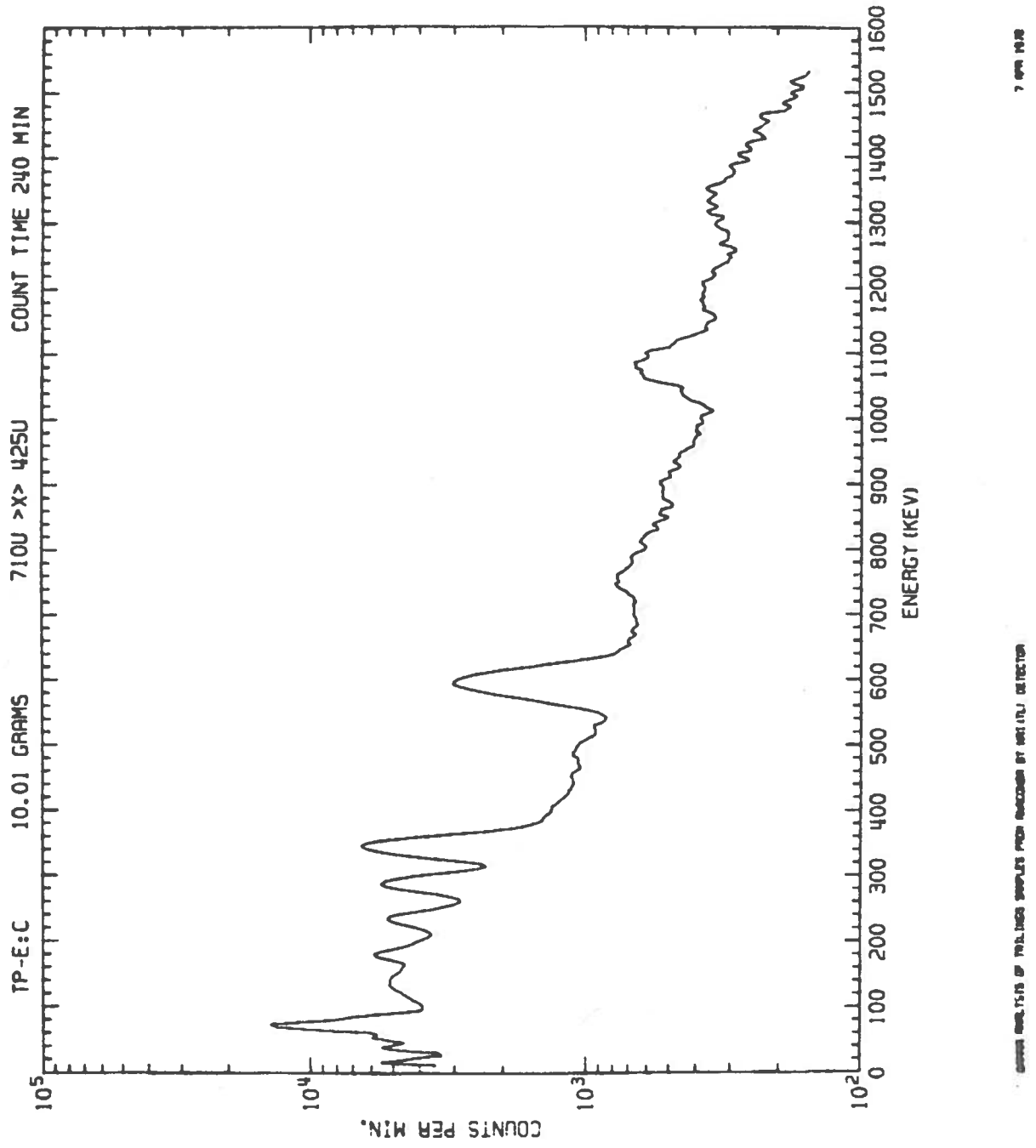


Figure A-5

Gamma Spectrum of Tailings Particles
Between 425 and 250 Microns

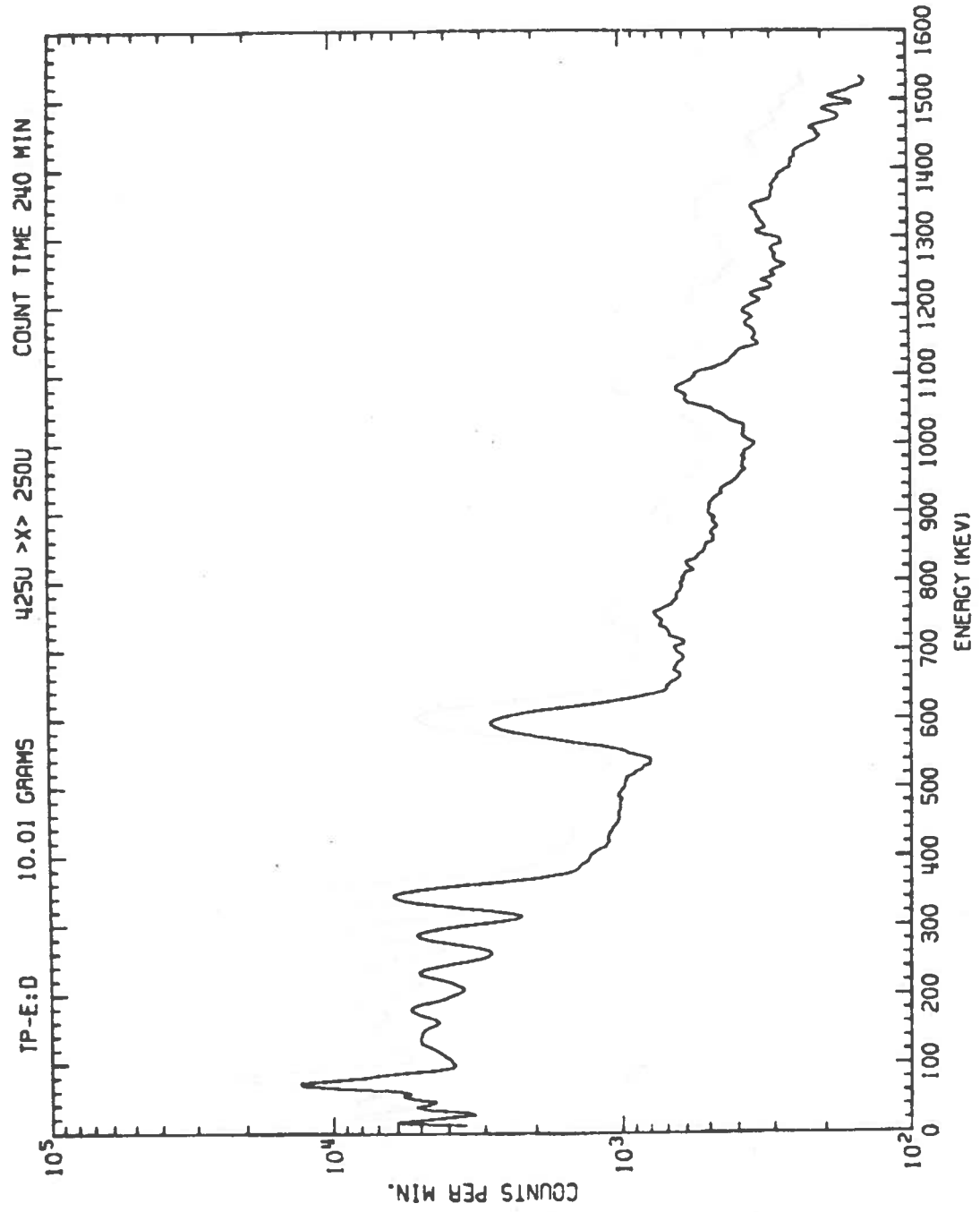


Figure A-6

Gamma Spectrum of Tailings Particles
Between 250 and 150 Microns

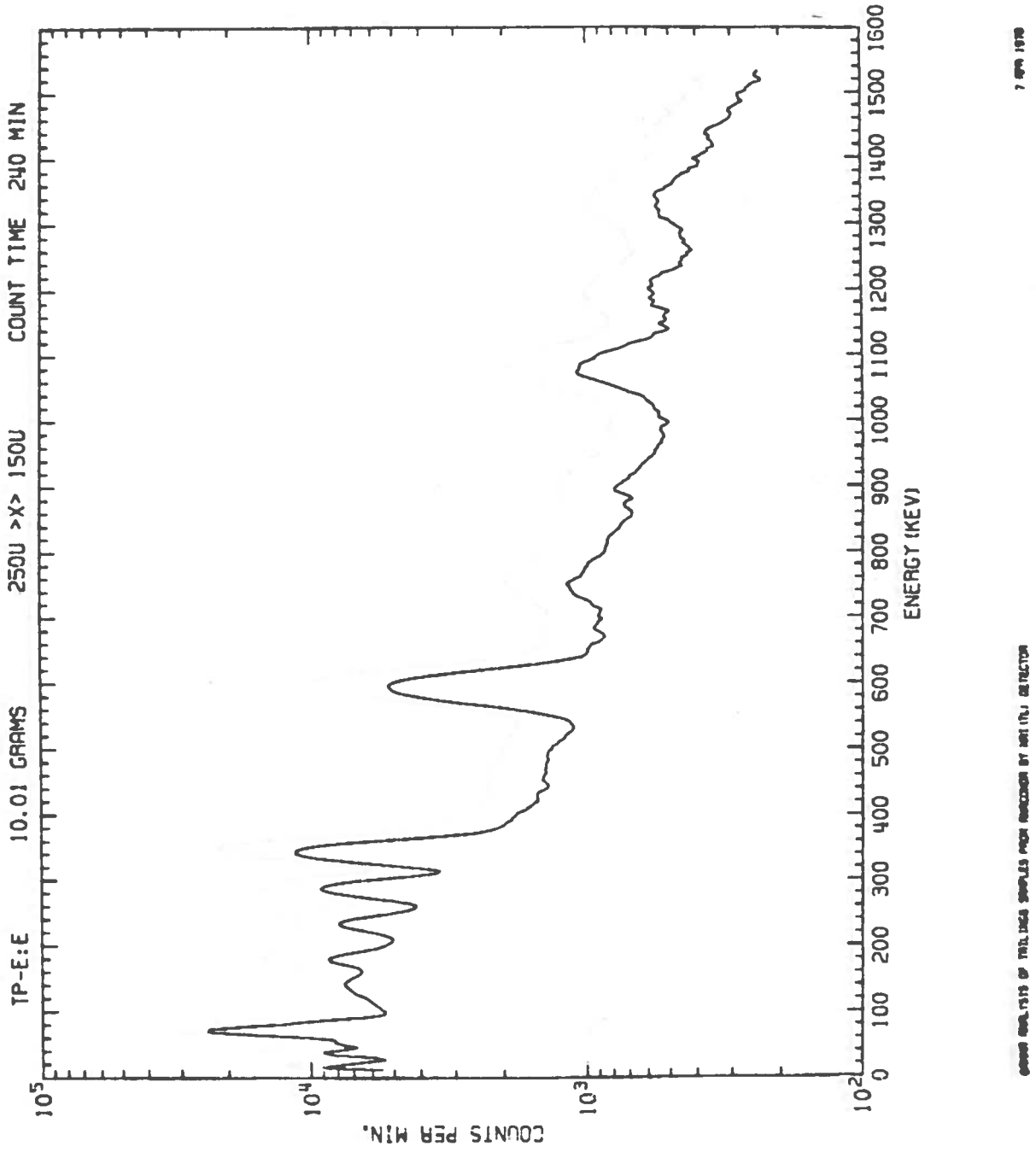


Figure A-7

Gamma Spectrum of Tailings Particles
Between 150 and 106 Microns

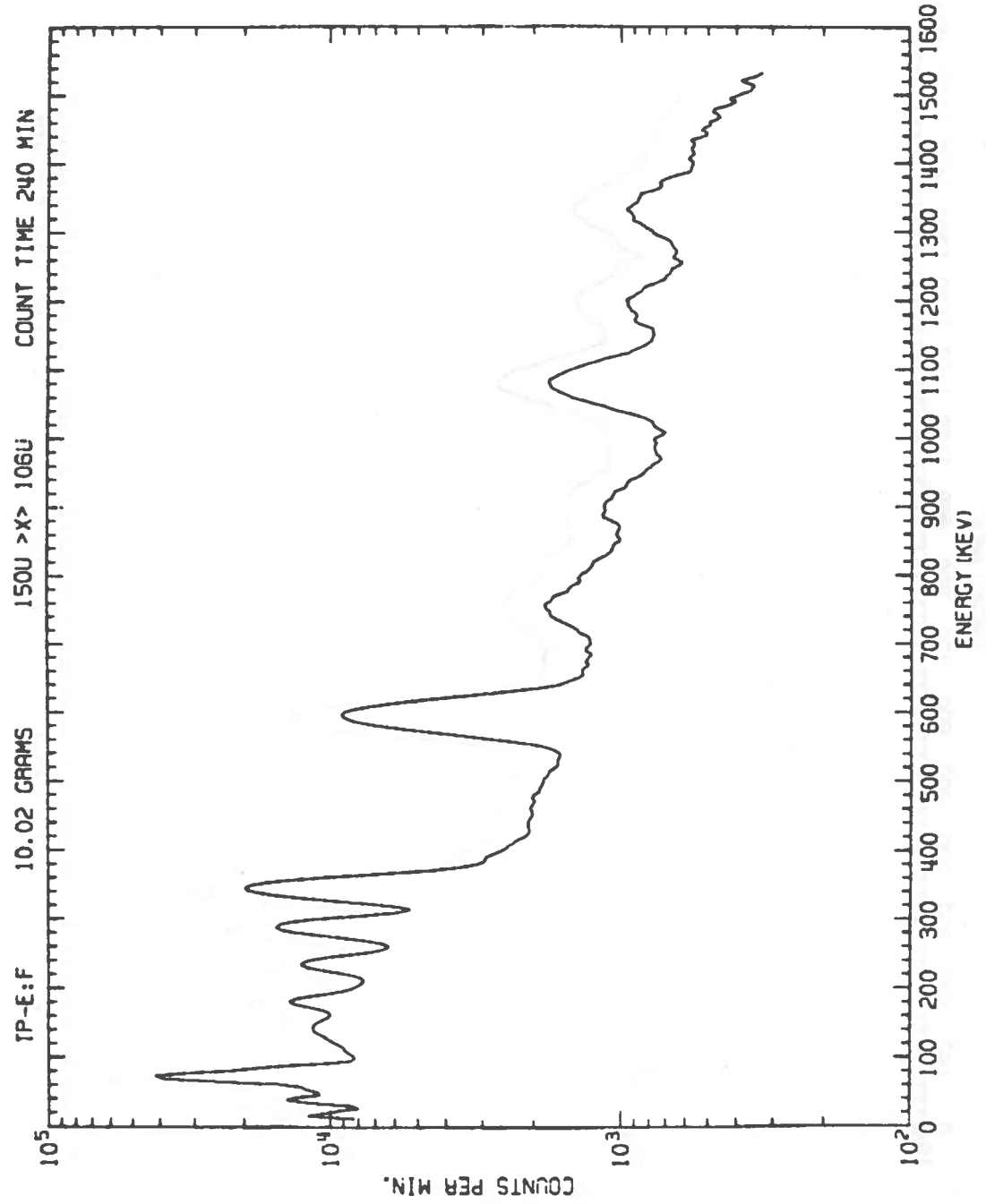
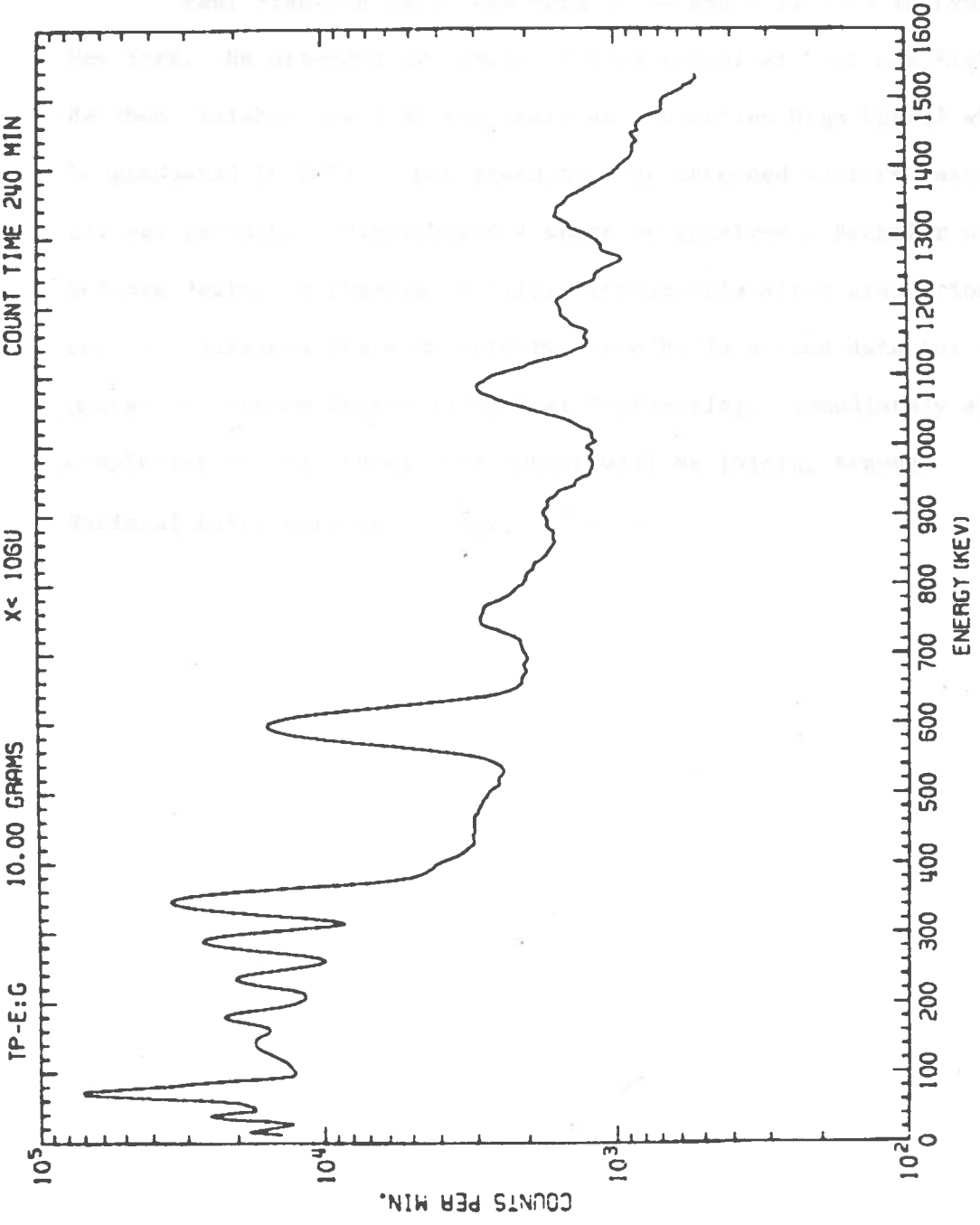


Figure A-8

Gamma Spectrum of Tailings Particles
Less than 106 Microns



VITA

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