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ENGINEERING ASSESSMENT OF INACTIVE URANIUM MILL TAILINGS

TUBA CITY SITE
TUBA CITY, ARIZONA

SEPTEMBER 1981

PREPARED FOR

UNITED STATES DEPARTMENT OF ENERGY
ALBUQUERQUE OPERATIONS OFFICE
URANIUM MILL TAILINGS
REMEDIAL ACTIONS PROJECT OFFICE
ALBUQUERQUE, NEW MEXICO

CONTRACT NO. DE-AC04-76GJ01658

BY

Ford, Bacon & Davis Utah Inc.
FB&D 1894
375 CHIPETA WAY, SALT LAKE CITY, UTAH 84108 801 583-3773
SINCE 1894

DISCLAIMER

ERRATA

ENGINEERING ASSESSMENT OF INACTIVE URANIUM MILL TAILINGS; TUBA CITY SITE, TUBA CITY, ARIZONA; SEPTEMBER, 1981; DOE/UMT-0120, FBDU 360-05.

Page 1-16, First paragraph, Fifth line should read:

"...6 mi of the Tuba City site is 3.2×10^{-6} per person per year, or about 3%...."

Page 1-16, the table showing cumulative health effects should be as follows:

25-Year Cumulative Health Effects Within 6 Miles of Edge of Pile

Projected Population Growth	Pile-Induced RDC	Background RDC
Constant 0.8% growth rate	0.25	2.0
2.5% declining growth rate*	0.28	2.2
4.0% declining growth rate*	0.33	2.6

Page 1-16, Third paragraph, Second line should read:

"...than 13%...."

Page 3-17, Fifth paragraph, Third line should read:

"...the 0.8% constant growth rate and the 2.5% and 4.0% declining growth rates.

Page 3-40, Table 3-4 is amended as attached.

Page 4-5, Figure 4-2 is amended as attached.

Page 9-9, Figure 9-3 is amended as attached.

Page 9-12, Table 9-2 is amended as attached.

inserted 7/6/82

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Contract No. DE-AC04-76GJ01658

By

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375 Chipeta Way
Salt Lake City, Utah 84108

NOTICE

This engineering assessment has been performed under DOE Contract No. DE-AC04-76GJ01658 between the U.S. Department of Energy and Ford, Bacon & Davis Utah Inc.

Copies of this report may be obtained from the Uranium Mill Tailings Remedial Action Project Office, U.S. Department of Energy, Albuquerque Operations Office, Albuquerque, New Mexico 87115.

FOREWORD

This report has been authorized by the U.S. Department of Energy (DOE), Albuquerque Operations Office, Uranium Mill Tailings Remedial Action Project Office, Albuquerque, New Mexico, under Contract No. DE-AC04-76GJ01658. The report is a revision of an earlier report dated March 1977, entitled "Phase II - Title I Engineering Assessment of Inactive Uranium Mill Tailings, Tuba City Site, Tuba City, Arizona," which was authorized by DOE, Grand Junction, Colorado, under Contract No. E(05-1)-1658.

This report has become necessary as a result of changes that have occurred since 1977 which pertain to the Tuba City site and vicinity, as well as changes in remedial action criteria. The new data reflecting these changes are presented in this report. Evaluation of the current conditions is essential to assessing the impacts associated with the options suggested for remedial actions for the tailings.

Ford, Bacon & Davis Utah Inc. (FB&DU) has received excellent cooperation and assistance in obtaining new data to prepare this report. Special recognition is due Richard H. Campbell and Mark Matthews of DOE, as well as Harold Tso and Ben Benally of the Environmental Protection Commission, Navajo Nation. Officials of the Navajo Nation, Window Rock, Arizona, contributed information, as did several local, county, and state agencies and private individuals.

ABSTRACT

Ford, Bacon & Davis Utah Inc. has reevaluated the Tuba City site in order to revise the March 1977 engineering assessment of the problems resulting from the existence of radioactive uranium mill tailings at Tuba City, Arizona. This engineering assessment has included the preparation of topographic maps, the performance of core drillings and radiometric measurements sufficient to determine areas and volumes of tailings and radiation exposures of individuals and nearby populations, the investigations of site hydrology and meteorology, and the evaluation and costing of alternative corrective actions.

Radon gas released from the 0.8 million tons of tailings at the Tuba City site constitutes the most significant environmental impact, although windblown tailings and external gamma radiation also are factors. The four alternative actions presented in this engineering assessment range from millsite decontamination with the addition of 3 m of stabilization cover material (Option I), to removal of the tailings to unspecified disposal sites and decontamination of the tailings site (Options II through IV). Cost estimates for the four options range from about $17,800,000 for stabilization in place, to about $23,100,000 for disposal at a distance of about 15 mi.

Three principal alternatives for the reprocessing of the Tuba City tailings were examined.

(a) Heap leaching

(b) Treatment at an existing mill

(c) Reprocessing at a new conventional mill constructed for tailings reprocessing

Processing the Tuba City tailings by heap leach is not feasible because of the impermeability of the tailings to leach solution. The cost of the uranium recovered would be about $56/lb of U_3O_8 by conventional plant processes. The spot market price for uranium was $25/lb early in 1981. Therefore, reprocessing the tailings for uranium recovery appears to be economically unattractive under present market conditions.

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CHAPTER 1

SUMMARY

CHAPTER 1

SUMMARY

1.1 INTRODUCTION

The U.S. Energy Research and Development Administration (ERDA) contracted in 1975 with Ford, Bacon & Davis Utah Inc. (FB&DU) of Salt Lake City, Utah, to provide architect-engineering services and final reports based on the assessment of the problems resulting from the existence of large quantities of radioactive uranium mill tailings at inactive millsites in eight western states and in Pennsylvania. In 1980, the U.S. Department of Energy (DOE) contracted with FB&DU to produce revised reports of the sites designated in the Uranium Mill Tailings Remedial Action (UMTRA) program in order to reflect the current conditions, new criteria and options, and to estimate current remedial action costs.

A preliminary survey (Phase I) was carried out in 1974 by the U.S. Atomic Energy Commission (AEC) in cooperation with the U.S. Environmental Protection Agency (EPA) and the affected states. In a summary report,(1) ERDA identified 17 sites in Arizona, Colorado, Idaho, New Mexico, Utah, and Wyoming for which practical remedial measures were to be evaluated. Subsequently, ERDA added five additional sites (Riverton and Converse County, Wyoming; Lakeview, Oregon; Falls City and Ray Point, Texas). More recently, DOE has added a site in Canonsburg, Pennsylvania, one near Baggs, Wyoming, and two sites in North Dakota (Belfield and Bowman), and deleted Ray Point, for a total of 25 sites. DOE continues to investigate the status of the site near Baggs, Wyoming. Most of the mills at these sites produced by far the greatest part of their output of uranium under contracts with the AEC during the period 1947 through 1970. After operations ceased, some companies made no attempt to stabilize the tailings, while others did so with varying degrees of success. Recently, concern has increased about the possible adverse effects to the general public from long-term exposure to low-level sources of radiation from the tailings piles and sites.

Prior to 1975, the studies of radiation levels on and in the vicinities of these sites were limited in scope. The data available were insufficient to permit assessment of risk to people with any degree of confidence. In addition, information on practicable measures to reduce radiation exposures and estimates of their projected costs was limited. The purposes of these recent studies performed by FB&DU have been to revise the information necessary to provide a basis for decision making for appropriate remedial actions for each of the 25 sites.

Evaluations of the following factors have been included in this engineering assessment in order to assess the significance of the radiological conditions that exist today at the Tuba City site:

(a) Exhalation of radon gas from the tailings

(b) On-site and off-site direct radiation

(c) Land contamination from windblown tailings

(d) Hydrology and contamination by water pathways

(e) Potential health impact

(f) Potential for extraction of additional minerals from the tailings

Investigation of these and other factors originally led to the evaluation of four potential practicable remedial action alternatives. Since that time, some remedial action alternatives have been judged unacceptable because of new criteria that have been proposed.

In this report, the remedial action alternatives are revised as follows:

(a) Option I - Stabilization of tailings on site with a 3-m cover

(b) Option II - Disposal at an unspecified site within 5 mi of the Tuba City tailings site

(c) Option III - Disposal at an unspecified site within 10 mi of the Tuba City tailings site

(d) Option IV - Disposal at an unspecified site within 15 mi of the Tuba City tailings site

1.1.1 Background

On March 12, 1974, the Subcommittee on Raw Materials of the Joint Committee on Atomic Energy (JCAE), Congress of the United States, held hearings on S. 2566 and H.R. 11378, identical bills submitted by Senator Frank E. Moss and Representative Wayne Owens of Utah. The bills provided for a cooperative arrangement between the AEC and the State of Utah in the area of the Vitro tailings site in Salt Lake

City.* The bills also provided for the assessment of an appropriate remedial action to limit the exposure of individuals to radiation from uranium mill tailings.

Dr. William D. Rowe, testifying on behalf of the EPA, pointed out that there are other sites with similar problems. He recommended the problem be approached as a generic one, structured to address the most critical problem first.

Dr. James L. Liverman, testifying for the AEC, proposed that a comprehensive study should be made of all such piles, rather than treating the potential problem on a piecemeal basis. He proposed that the study be a cooperative two-phase undertaking by the states concerned and the appropriate federal agencies, such as the AEC and EPA. Phase I would involve site visits to determine such aspects as their condition, ownership, proximity to populated areas, prospects for increased population near the site, and need for corrective action. A preliminary report then would be prepared which would serve as a basis for determining if a detailed engineering assessment (Phase II) were necessary for each millsite. The Phase II study, if necessary, would include evaluation of the problems, examination of alternative solutions, preparation of cost estimates and of detailed plans and specifications for alternative remedial action measures. This part of the study would include physical measurements to determine exposure or potential exposure to the public.

The Phase I assessment began in May 1974, with teams consisting of representatives of the AEC, the EPA, and the states involved visiting 21 of the inactive sites. The Phase I report was presented to the JCAE in October 1974. Table 1-1, adapted from Reference 1, summarizes the conditions in 1980. Based on the findings presented in the Phase I report, the decision was made to proceed with Phase II.

On May 5, 1975, ERDA, the successor to AEC, announced that Ford, Bacon & Davis Utah Inc. of Salt Lake City, Utah, had been selected to provide the architect-engineering (A-E) services for Phase II. ERDA's Grand Junction, Colorado, Office (GJO) was authorized to negotiate and administer the terms of a contract with FB&DU. The contract was effective on June 23, 1975. The Salt Lake City Vitro site was assigned as

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*The proceedings of these hearings and the Summary Report on the Phase I Study were published by the JCAE as Appendix 3 to ERDA Authorizing Legislation for Fiscal Year 1976. Hearings before the Subcommittee on Legislation, JCAE, on Fusion Power, Biomedical and Environmental Research; Operational Safety; Waste Management and Transportation, Feb 18 and 27, 1975, Part 2. The Phase I report on the Tuba City site appears as Appendix I to Reference 5.

the initial task, and work began immediately. Work at Tuba City was begun early in 1976, and the original Phase II - Title I Engineering Assessment was published in March 1977.[2]

On November 8, 1978, the Uranium Mill Tailings Radiation Control Act of 1978 (PL 95-604) became effective. This legislation provides for state participation with the Federal Government in the remedial action for inactive tailings piles. Pursuant to requirements of PL 95-604, the EPA has the responsibility to promulgate remedial action standards for the cleanup of areas contaminated with residual radioactive material and for disposal of tailings. The U.S. Nuclear Regulatory Commission (NRC) has the responsibility for enforcing these standards.

In 1979, DOE established the UMTRA Program Office in Albuquerque, New Mexico. Work on the program has since been directed by personnel in that office. The supplementary field work by FB&DU in support of this report was performed during the week of June 22, 1980.

1.1.2 Scope of Phase II Engineering Assessment

Phase II A-E Services are divided into two stages: Title I and Title II.

Title I services include the engineering assessment of existing conditions and the identification, evaluation, and costing of alternative remedial actions for each site. Following the selection and funding of a specific remedial action plan, Title II services will be performed. These services will include the preparation of detailed plans and specifications for implementation of the selected remedial action.

This report is a continuation of the assessment made for Title I requirements and has been prepared by FB&DU. In connection with the field studies made in 1976, the Oak Ridge National Laboratory (ORNL) at Oak Ridge, Tennessee, under separate agreement with DOE, provided measurements of the radioactivity concentrations in the soil and water samples and gamma surveys. The EPA staff provided the results of radiation surveys they previously had made at the Tuba City site.

The specific scope requirements of the Title I assessment may include but are not limited to the following:

(a) Preparation of an engineering assessment report for each site, and preparation of a comprehensive report suitable for submission to the Congress on reasonable remedial action alternatives and their estimated cost.

(b) Determination of property ownership in order to obtain release of Federal Government and A-E liability for performance of engineering assessment work at both inactive millsites and privately owned structures.

(c) Preparation of topographic maps of millsites and other sites to which tailings and other radioactive materials might be moved.

(d) Performance of core drillings and radiometric measurements ample to determine volumes of tailings and other radium-contaminated materials.

(e) Performance of radiometric surveys, as required, to determine areas and structures requiring cleanup or decontamination.

(f) Determination of the adequacy and the environmental suitability of sites at which mill tailings containing radium could be disposed; and once such sites are identified, perform evaluations and estimate the costs involved.

(g) Performance of engineering assessments of structures where uranium mill tailings have been used in off-site construction to arrive at recommendations and estimated costs of performing remedial action.

(h) Evaluation of various methods, techniques, and materials for stabilizing uranium mill tailings to prevent wind and water erosion, to inhibit or eliminate radon exhalation, and to minimize maintenance and control costs.

(i) Evaluation of availability of suitable fill and stabilization cover materials that could be used.

(j) Evaluation of radiation exposures of individuals and nearby populations resulting from the inactive uranium millsite, with specific attention to:

  (1) Gamma radiation

  (2) Radon

  (3) Radon daughter concentrations

  (4) Radium and other naturally occurring radioisotopes in the tailings

(k) Review of existing information about site hydrology and meteorology.

(l) Evaluation of recovering residual values, such as uranium and vanadium in the tailings and other residues on the sites.

(m) Performance of demographic and land use studies. Investigation of community and area planning, and industrial and growth projections.

(n) Evaluation of the alternative corrective actions for each site in order to arrive at recommendations, estimated costs, and socioeconomic impact based on population and land use projections.

(o) Preparation of preliminary plans, specifications, and cost estimates for alternative corrective actions for each site.

Not all of these items received attention at the Tuba City site.

1.2 SITE DESCRIPTION

1.2.1 Location and Topography

The Tuba City site is about 105 acres in size, of which 22 acres are covered by the tailings pile and 44 acres are former evaporation ponds. The site is on the Navajo Indian Reservation, 5.5 mi east of Tuba City in Coconino County, Arizona, and 85 mi north of Flagstaff. The site is at 5,000 ft above sea level. The tailings pile and surrounding terrain are shown in the aerial photograph in Figure 2-2. The site is located in the typical type of terrain found in the desert areas of the American Southwest: occasional dry washes, mesas, and rolling hills; sparse vegetation (about 15 to 20%), and few trees.

1.2.2 Ownership and History of Milling Operations and Processing

The Tuba City mill was built in 1955-1956 by Rare Metals Corporation of America. The company constructed 10 houses and a trailer court on the north side and 16 houses and a trailer court for employees on the south side of U.S. Highway 160 at the millsite. The Rare Metals Corporation merged with El Paso Natural Gas Company in July 1962. Before and during the milling operations, the site land was owned by the Navajo Nation. Shortly after the mill was shut down in 1966, full control of the site reverted to the Navajo Nation.

The mill began operation in 1956 and treated ores obtained principally from the Cameron area, located about 25 mi to the southwest. Initially, the plant processed 300 tons/day using an acid leaching, sand-slime separation, and resin-in-pulp ion-exchange operation. By 1962, the major ore supply was from the Orphan Lode mine located near the village of Grand Canyon, Arizona. This high-lime content ore was not well suited to acid-leaching; consequently, the mill was converted in 1963 to the carbonate leach process. Using this process, approximately 200 tons/day were processed from April 1963 until the plant was closed permanently in September 1966. During its total operating life the Tuba City mill processed 800,000 tons of ore with an average grade of 0.33% U_3O_8, and produced 2,348 tons of U_3O_8 in concentrate.

1.2.3 Present Condition of the Site

Figure 2-5 is a descriptive map of the site as it now exists showing the layout of the tailings area and the locations of the millsite and housing areas. There are 26 houses which are partially occupied, located on both sides of U.S. Highway 160, immediately north of the tailings; the houses are occupied on a random and changing basis. A survey(3) in 1967 found the housing area habitable and no evidence that surrounding ground or surface water had been affected by leaching of radioactive materials from the tailings area.

The kind of material dumped into the area noted as the "emergency dump pit" is not known. All of the mill equipment and some of the buildings have been removed. The shell of the main mill building remains, although it has been severely cannibalized. None of the mill buildings are now in use. The buildings or portions of buildings remaining in the mill area appear structurally sound, but loose sheet metal is a hazard. The site has been fenced, but the fence is covered by sand in places and is undermined or torn down in other places. The fence on the northeast side of the site has been buried in windblown tailings by the prevailing southwesterly winds. The fence along the northwest side of the tailings area has been undermined by wind erosion and only a small portion of this fence remains intact. It appears that the fence was built originally on naturally migrating dune sand, not on tailings. Gates are missing or are open, and no radiation warning signs are readily apparent.

1.2.4 Tailings and Soil Characteristics

The tailings are composed of finely ground particles easily carried by the wind. They have a high-clay content, are relatively impermeable, and can hold water. The tailings were not deposited evenly throughout the pond areas. The subsoil is uniform beneath the entire site and consists mainly of sand and small aggregate eroded from the underlying Navajo Sandstone.

Figure 2-6 is a cross-section of the site. Table 2-1 includes weights and volumes of the tailings and materials in the evaporation ponds and dikes.

1.2.5 Geology, Hydrology, and Meteorology

The Tuba City site lies about 2 mi north of Moenkopi Wash. The tailings rest on loose sand derived by wind erosion from the underlying Navajo Sandstone. This loose sand layer varies in thickness from less than 1 ft to 20 ft. The Navajo Sandstone is a weakly cemented, medium-grained, crossbedded sandstone. It dips at a low angle (2 deg) away from the town of Tuba City towards the axis of the Tuba City syncline. This axis runs in a northwest-southeast direction about 1 mi east of the tailings site. The Navajo Sandstone is exposed south of the millsite along Moenkopi Wash. The Kayenta Formation (a series of silty mudstones with intertongues of sandstone) underlies the Navajo Sandstone. A simplified stratigraphic cross-section of the site is illustrated in Figure 2-8.

There are no surface waters of consequence near the Tuba City tailings site. Surface drainage runs to the Moenkopi Wash about 1.5 mi south of the tailings. There is some drainage potential from precipitation falling in the area between the highway and the tailings pile. There is evidence of sheet erosion in this area of steeply sloping land due to thunderstorm runoff, but the erosion has been small. To the north of the highway, a large depression known as Greasewood Lake collects surface runoff in that area. Surface drainage from the Greasewood Lake depression drains to the west-southwest and does not cross the highway until well past the tailings site.

The principal aquifer in the Tuba City-Moenkopi area is a multiple aquifer system consisting of the Navajo Sandstone and some sandstone beds in the underlying Kayenta Formation. This aquifer is recharged by winter and spring precipitation in the Kaibito Plateau highlands some distance north of Tuba City. Water in the multiple aquifer system moves southward from the highlands; its principal discharge area is along Moenkopi Wash. Thus, the tailings are situated in the discharge rather than the recharge area of the aquifer system. Water in this multiple aquifer system is unconfined because the Navajo Sandstone is covered only by windblown sand over almost all of the areas of concern. Most of the water is produced by gravity flow where the water table intersects the land surface along Moenkopi Wash and its tributary gullies. Springs and shallow wells in the vicinity of the site were checked in 1967 by the U.S. Public Health Service for radioactive contamination,(3) and results of this sampling showed no contamination in ground water from the mill tailings.

The tailings are protected from inflow or outflow of surface water by dikes. The only water that can reach the tailings comes from precipitation directly onto the pile. However, surface runoff from severe thunderstorms can cause erosion of the dikes. Because of the large moisture deficiency in the present tailings and the high rate of evaporation, any rain falling on the pile would penetrate the tailings a few feet at most, then return to the surface as evaporation takes place, causing an upward soil moisture gradient.

The average annual precipitation at Tuba City, as reported by the U.S. Department of Commerce, is 6.1 in. based on a 62-yr period of record. The 24-hr precipitation would be expected to be at a rate of 1.3 in. once every 2 yr, with a "maximum observed" 24-hr storm at Tuba City of 4 in.

Analysis of the records at Tuba City over a 25-yr period indicates that the maximum daily precipitation usually occurs during the 3-mo period of August through October. This pattern is typical of much of the southwest desert area, being the time of most frequent thunderstorm activity.

There are no records of wind measurements at the Tuba City site, but data from Flagstaff, Arizona, have been used in health effects calculations. Dune and cross-bed orientation indicate that past and present wind directions prevail from southwest to northeast. The large area of deposited windblown tailings to the northeast of the site confirms the existence of strong southwesterly winds.

1.3 RADIOACTIVITY AND POLLUTANT IMPACTS ON THE ENVIRONMENT

About 85% of the total radioactivity originally in uranium ore remained in the tailings after removal of the uranium. The principal environmental radiological impact and associated health effects arise from the ^{230}Th, ^{226}Ra, ^{222}Rn, and ^{222}Rn daughters contained in the uranium tailings. Although these radionuclides occur in nature, their concentrations in tailings material are several orders of magnitude greater than their average concentrations in the earth's crust. Because of the chemical treatments these radionuclides have experienced, it appears that ^{226}Ra is more soluble and, therefore, more mobile.

1.3.1 Radiation Exposure Pathways, Contamination Mechanisms, and Background Levels

The major potential environmental routes of exposure to man are:

(a) Inhalation of ^{222}Rn and its daughter products, resulting from the continuous radioactive decay of ^{226}Ra in the tailings. Radon is a gas which diffuses from the pile. The principal exposure results from inhalation of ^{222}Rn daughters. This exposure affects the lungs. For this assessment, no criteria have been established for radon concentrations in air. However, the pathway for radon and radon daughters accounts for the major portion of the exposure to the population.

(b) External whole-body gamma exposure directly from radionuclides in the pile.

(c) Inhalation and ingestion of windblown tailings. The primary health effect relates to the alpha emitters ^{230}Th and ^{226}Ra, each of which causes exposure to the bones and lungs.

(d) Ingestion of ground and surface water contaminated with radioactive elements (primarily ^{226}Ra) and other toxic materials.

(e) Contamination of food through uptake and concentration of radioactive elements by plants and animals is another pathway that can occur; however, this pathway was not considered in this study.

1.3.1.1 Radon Gas Diffusion and Transport

Measurements of radon flux from the tailings made in 1976[2] using the charcoal canister technique[4] ranged from 11 to more than 400 pCi/m^2-s on the tailings pile. Radon flux depends principally on radium content of tailings; however, it also varies considerably because of moisture, soil characteristics, and climatological conditions.

Short-term radon measurements were made in 1976 with continuous radon monitors supplied by ERDA at two locations in the vicinity of the Tuba City tailings pile. The locations and values of the radon measurements are shown in Figure 3-3. The background ^{222}Rn concentration for a 24-hr period was determined to be 0.7 pCi/l. One set of measurements on the tailings indicated an average ^{222}Rn concentration of about 22 pCi/l for a 24-hr period. At the mill housing area, the ^{222}Rn concentration averaged 1.3 pCi/l for 24 hr. The concentration was 2.1 pCi/l at a location 0.13 mi east of the site during a 24-hr period.

1.3.1.2 Direct Gamma Radiation

Background values of gamma radiation around the Tuba City site averaged 10 μR/hr.[5] The range of background values was between 6 and 13 μR/hr. Above the surface of the tailings and the former evaporation ponds, gamma rate readings ranged from about 20 to 2,600 μR/hr. Background levels of gamma radiation were reached about 200 yd from the tailings pile in the northwest and southwest directions.

1.3.1.3 Windblown Contaminants

Prevailing winds in the area are from the southwest, and there is a large area of windblown tailings northeast of the pile. In most directions the maximum distance of tailings transport is about 200 yd. However, northeast of the site there are indications that the tailings material has been deposited out to about 1 mi. These estimates of the extent of windblown tailings were determined by analyses of soil samples completed as part of the Tuba City effort by ORNL. In 1980, the extent of the area around the site contaminated in excess of 5 pCi/g of ^{226}Ra in soil was estimated as shown in Figure 3-13.

No particulate measurements were performed at the Tuba City site during this field survey. Previous measurements(6) in Tuba City indicated that airborne concentrations of ^{226}Ra, ^{230}Th, and natural uranium were two to three orders of magnitude less than the guidelines established in the Code of Federal Regulations, Title 10, Part 20. Measurements in the downwind direction indicated substantial transport of ^{226}Ra in concentrations exceeding recommended concentration guidelines.

1.3.1.4 Ground and Surface Water Contamination

Four water samples taken within a 2-mi radius from the pile during this assessment contained dissolved ^{226}Ra concentrations ranging from 0.37 to 1.24 pCi/l.(5) These values are less than the 5 pCi/l level for ^{226}Ra and ^{228}Ra in the EPA Interim Primary Drinking Water Regulations for radionuclides.(7)

The only water that can now reach the tailings comes from precipitation directly on the pile. Because of the high upward soil moisture gradient, there is little potential for future infiltration of contaminants to the ground water of this area. However, periodic monitoring of nearby springs and wells should be continued during the next few years to determine if water, which may have been contaminated during the operation of the mill, has seeped into the underlying sand and sandstone.

Surface erosion of tailings due to thunderstorms is possible. Sudden thunderstorms with large runoffs could further erode the tailings dike.

The wind has eroded the tailings material severely, breaching the tailings dikes in several places. The amount of tailings material that has been transported away by the wind is considerable. The light-colored tailings material can been seen over an area as much as 0.5 mi in a northeasterly direction away from the residences along U.S. Highway 160 and in the opposite direction from Tuba City. There are no residences nearby in the northeasterly (downwind) direction.

1.3.1.5 Soil Contamination

The leaching of radium from the tailings into the subsoil has been measured to depths of 2 to 5 ft below the tailings-subsoil interface. In the mill area, soil contamination was generally limited to less than 1 ft deep, although a few locations were found where contamination reached a depth of 2 ft.

1.3.2 Remedial Action Criteria

For the purpose of conducting the original engineering assessment,(2) provisional criteria provided by the EPA were used. The criteria were in two categories, and applied either to structures with tailings present or to land areas to be decontaminated. For structures, the indoor radiation level below which no remedial action was indicated was considered to be an external gamma radiation level of less than 0.05 mR/hr above background and a radon daughter concentration of less than 0.01 WL above background. Land could be released for unrestricted use if the external gamma radiation levels were less than 10 μR/hr above background. When cleanup was necessary, residual radium content of the soil after remedial action should not exceed twice background in the area.

Since enactment of the Uranium Mill Tailings Radiation Control Act of 1978 (PL 95-604), which was effective November 8, 1978, the EPA has published interim (45 FR 27366) and proposed (45 FR 27370) standards for structures and open lands. These standards establish the indoor radon daughter concentration, including background, below which no remedial action is indicated at 0.015 WL. The indoor gamma radiation limit is 0.02 mR/hr above background. The EPA has also published proposed disposal standards for inactive uranium processing sites (46 FR 2556).

For open land, remedial action must provide reasonable assurance that the average concentration of ^{226}Ra attributable to residual radioactive material from any designated processing site in any 5-cm thickness of soils or other materials within 1 ft of the surface, or in any 15-cm thickness below 1 ft, shall not exceed 5 pCi/g.

Environmental standards have been proposed by the EPA (46 FR 2556) for the disposal of residual radioactive materials from inactive uranium processing sites. These standards require that disposal of residual radioactive materials be conducted in a way which provides a reasonable assurance that for at least 1,000 yr following disposal:

(a) The average annual release of ^{222}Rn from the disposal site to the atmosphere by residual radioactive materials will not exceed 2 pCi/m^2-s.

(b) Substances released from residual radioactive materials after disposal will not cause:

(1) the concentrations of those substances in any underground source of drinking water to exceed the level specified below,* or

(2) an increase in the concentrations of those substances in any underground source of drinking water where the concentrations of those substances prior to remedial action exceed the levels specified below for causes other than residual radioactive materials.*

Substance	mg/l
Arsenic	0.05
Barium	1.0
Cadmium	0.01
Chromium	0.05
Lead	0.05
Mercury	0.002
Molybdenum	0.05
Nitrogen (in nitrate)	10.0
Selenium	0.01
Silver	0.05

	pCi/l
Combined ^{226}Ra and ^{228}Ra	5.0
Gross alpha particle activity (including ^{226}Ra but excluding radon and uranium)	15.0
Uranium	10.0

(c) Substances released from the disposal site after disposal will not cause the concentration of any harmful dissolved substance in any surface waters to increase above the level that would otherwise prevail.

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*These requirements apply to the dissolved portion of any substance listed above at any distance greater than 1.0 km from a disposal site that is part of an inactive processing site, or greater than 0.1 km if the disposal site is a depository site.

Since the passage of PL 95-604, the NRC has published final regulations for uranium mill tailings licensing in the Federal Register (45 FR 65521). They include the requirement that the stabilization method must include an earth cover of at least 3-m thickness and sufficient to reduce the radon emanation rate from the tailings to 2 pCi/m^2-s above background. In addition, seepage of materials into ground water should be reduced by design to the maximum extent reasonably achievable.

While these standards may undergo further revisions, the interim and proposed standards as indicated above form the basis for determining required remedial actions and their associated costs.

1.3.3 Potential Health Impact

Radon gas exhalation from the pile and the subsequent inhalation of radon daughters account for most of the total dose to the population from the Tuba City site under present conditions. The gamma radiation exposure from the pile is very small since the number of people who live or work within 0.3 mi of the pile (where gamma radiation is above background in all but the northeast direction) is small.

Gamma radiation can be reduced effectively by shielding with any dense material. However, experience has shown that it is very difficult to control the movement of radon gas through porous materials. Once released from the radium-bearing minerals in the tailings, the gaseous radon diffuses by the path of least resistance to the surface. The radon has a half-life of about 4 days, and its daughter products are solids. Therefore, part of the radon decays en route to the surface and leaves daughter products within the tailings pile. If the diffusion time can be made long enough, then, theoretically, virtually all of the radon and its daughter products will have decayed before escaping to the atmosphere. Calculations using the theoretical techniques of Kraner, Schroeder, and Evans(8) earlier indicated that 13 ft of earth cover would be required to reduce the radon diffusion from the Tuba City tailings by 95%. Later experimental work(9) has demonstrated that 2 to 3 ft of compacted clay may be sufficient to reduce radon flux to less than 2 pCi/m^2-s, assuming the continued integrity of the clay cover.

The health significance to man of long-term exposure to low-level radiation is a subject that has been studied extensively. Since the end results of long-term exposure to low-level radiation may be diseases such as lung cancer or leukemia, which are also attributable to many other causes, the determination of specific cause in any given case becomes very difficult. Therefore, the usual approach to evaluation of the health impact of low-level radiation exposures is to make projections from observed effects of high exposures on the premise that the effects are linear. A considerable amount of information has been accumulated on the high incidence of lung cancer in uranium miners and others exposed to radon and its daughters in mine air. This provides a basis for calculating the probable health effects of low-level exposure to large populations. (The term "health effect" refers to an incidence of disease; for radon daughter exposure, a health effect is a case of lung cancer.) This is the basis of the health effects calculated in this report. It should be recognized, however, that there is a large degree of uncertainty in such projections. Among the complicating factors is the combined effect of radon daughters with other carcinogens. As an example, the incidence of lung cancer among uranium miners who smoke is far higher than can be explained on the basis of either smoking or the radiation alone.

The risk estimators used in this report are given in the report of the National Academy of Sciences Advisory Committee on the Biological Effects of Ionizing Radiation (BEIR-III report).[10] This report presents risk estimators for lung cancer derived from epidemiological studies of both uranium miners and fluorspar miners. The average of the age-dependent absolute risk estimator for these two groups as applied to the population at large is 150 cancers per year per 10^6 person-WLM of continuous exposure, assuming a lifetime plateau to age 75. The term WLM means working level months, or an exposure to a concentration of one working level of radon daughter products in air for 170 hr, which is a work-month. A working level (WL) is a unit of measure of radon daughter products which recognizes that the several daughter elements are frequently not in equilibrium with each other or with the parent radon. Because of the many factors that contribute to natural biological variability and of the many differences between exposure conditions in mines and residences, this estimator (150 cancer cases per year per 10^6 person-WLM of continuous exposure) is considered to have an uncertainty factor of about 3. Another means of expressing risk is the relative risk estimator, which yields risk as a percentage increase in health effects per 10^6 person-WLM of continuous exposure. However, this method has been shown to be invalid[11] and is not considered in this assessment.

For the purpose of this engineering assessment, it was assumed that about 50% equilibrium exists inside structures between radon and its daughter elements resulting in the following conversion factors:

$$1 \text{ pCi/l of } {}^{222}\text{Rn} = 0.005 \text{ WL}$$

For continuous exposure:

$$0.005 \text{ WL} = 0.25 \text{ WLM/yr}$$

On the basis of predictions of radon concentrations in excess of the background value under present conditions, it was calculated that the average lung cancer risk attributable to radon released from the tailings pile in the area within 6 mi of the Tuba City site is 9.2×10^{-7} per person per year, or about 1% of the average lung cancer risk due to all causes for the Navajo Nation (1.02×10^{-4}).[12]

The 25-yr health effects were calculated for three population projections using the present population of about 2,800 in the 0- to 6-mi area. The results for pile-induced radon and background radon for this area were as follows:

25-Year Cumulative Health Effects Within 6 Miles of Edge of Pile

Projected Population Growth	Pile-Induced RDC	Background RDC
Constant 0.8% growth rate	0.066	1.9
4% declining growth rate*	0.083	2.3
6.4% declining growth rate*	0.10	2.9

Pile-induced radon daughter health effects are less than 4% of the background radon daughter health effects for the 0- to 6-mi area. The exposure and consequent risk will continue as long as the radiation source remains in its present location and condition.

1.3.4 Nonradioactive Pollutants

Ground and surface water in the vicinity of the tailings pile contained only selenium in concentrations above the level specified in the EPA Interim Primary Drinking Water Regulations (0.01 mg/l). The high selenium content was found in all water samples located in drainage areas above and below the tailings indicating a natural condition not attributable to the presence of the tailings.

1.4 SOCIOECONOMIC AND LAND USE IMPACTS

Because all reservation land is owned in common by the Navajo Tribe, there is no conventional market for Navajo properties. However, there are several criteria that might be used to assess the value of the site land. For example, recent exchanges of tribal land for off-reservation land is one basis. Lease payments for Navajo lands is another; comparisons with similar use off-reservation is another criterion, and

*Declines linearly from its initial value to zero in 25 yr and remains constant at zero thereafter.

the monetary value assigned to sheep production per acre is another. The site has highway frontage along U.S. Highway 160, but so do thousands of acres of similar land for which there is little pressure for other than agricultural purposes. By using the aforementioned criteria, it is estimated that the land at and around the Tuba City site, which is primarily grazing land, is worth between $55 and $65/acre.

1.5 RECOVERY OF RESIDUAL VALUES

Only a few samples of tailings were obtained during this study. Consequently, calculations based on these samples would not be statistically representative. Estimates of the Tuba City tailings from AEC records show an average of 0.032% U_3O_8.

There are, however, five factors that can be employed to evaluate whether reprocessing Tuba City tailings to extract uranium and other mineral values would be practicable:

(a) The amount of tailings present

(b) Concentrations of residual values

(c) Projected recovery

(d) Current market price of recovered values

(e) Proximity to processing mills

Three principal alternatives for the reprocessing of the Tuba City tailings were examined:

(a) Heap leaching

(b) Treatment at an existing mill

(c) Reprocessing at a new conventional mill constructed for tailings reprocessing

Processing the Tuba City tailings by heap leach is not feasible because of the impermeability of the tailings to leach solution. The cost of the uranium recovered would be about $56/lb of U_3O_8 by conventional plant processes. The spot market price for uranium was $25/lb early in 1981. Therefore, reprocessing the tailings for uranium recovery appears to be uneconomical under present market conditions. However, if the market for U_3O_8 reaches levels which existed 2 yr ago, reprocessing might be economically attractive.

1.6 MILL TAILINGS STABILIZATION

Investigations of methods of stabilizing uranium mill tailings piles from wind and water erosion have indicated a variety of deficiencies among the methods. Chemical stabilization (treatment of the tailings surface) has been successful only for temporary applications and is thus viewed as inadequate for currently proposed disposal criteria. Volumetric chemical stabilization (solidifying the bulk of the tailings) techniques appear to be costly and of questionable permanence. Physical stabilization (emplacement of covers over the tailings) methods using soil, clay, or gravel have been demonstrated on a laboratory scale to be effective in stabilizing tailings. Artificial cover materials are attractive but have the disadvantage of being subject to degradation by natural and artificial forces. Vegetative stabilization (establishment of plant growth) methods are effective in limiting erosion. However, where annual precipitation is less than about 10 in., soil moisture content may be inadequate to ensure viability of the plant life.

Migration of contaminants into ground water systems must be limited under the NRC and EPA criteria. Control of water percolating through the tailings can be accomplished by stabilizing chemically, by physically compacting the cover material, and by contouring the drainage area and tailings cover surface. Isolation of the tailings from underlying ground water systems can be accomplished by lining a proposed disposal site with natural or artificial impermeable membranes.

Several materials have been identified which sufficiently retard radon migration so that the radon flux is substantially reduced, on a laboratory scale. Unfortunately, no large-scale application has been undertaken which would demonstrate that these materials satisfy all of the technical criteria in the EPA-proposed standards and the NRC regulations for licensing of uranium mills. However, extensive investigations of these questions continue in the Technology Development program of the Uranium Mill Tailings Remedial Actions Project Office in Albuquerque, New Mexico.

In view of findings from stabilization research, it appears that physical stabilization of tailings with 3 m of well-engineered cover material may be sufficient to appropriately stabilize tailings at their disposal site to meet NRC regulations.

1.7 OFF-SITE REMEDIAL ACTION

A mobile scanning unit, operated by the AEC under an interagency agreement with the EPA, performed a gamma radiation survey of the Tuba City area in 1972. Fourteen anomalies above the background criteria were discovered. In a subsequent field radiation survey, also performed in 1972, four locations were found with tailings more than 10 ft from a structure and tailings were found within 10 ft of two houses. These six locations are assumed to require remedial action based upon incomplete radiological measurements. A sum of $9,000 has been included in the various remedial action options to account for the cost of possible off-site remedial work for structures.

1.8 DISPOSAL SITE SELECTION

In this report, three of the alternative remedial action options include moving the Tuba City tailings to unspecified disposal sites at various distances from the tailings site.

In each disposal option, surface material would be removed, as appropriate, from the disposal area and stockpiled. A retaining dike and diversion ditches would be constructed if necessary. The tailings would be emplaced, contoured, and covered with 3 m of soil. The surface would be covered with 0.3 m of riprap for erosion control and the entire site fenced.

1.9 REMEDIAL ACTIONS AND COST-BENEFIT ANALYSES

1.9.1 Remedial Action Options

The remedial action options examined include stabilization of the tailings pile in its present location, and removal of all radioactive materials to an area where these materials could be isolated from the public. The options for which cost estimates were made include stabilization on the present site with 3 m of cover material and the removal of tailings to unspecified locations at three distances from the tailings pile. The options are summarized in Table 1-2. The basis for comparison, from which the cost effectiveness of remedial alternatives can be judged, is the present condition of the site with no remedial action.

Option I represents remedial action activities to stabilize the tailings more completely with the addition of 3 m of cover. Erosion of the tailings would be controlled more completely and radon exhalation would be reduced to not more than 2 pCi/m^2-s above background. The tailings site would have limited future use.

1.9.2 Cost-Benefit Analyses

As summarized in Table 9-1, the total costs for the four remedial action options vary from about $17,800,000 to about $23,100,000. Each of these options would have associated health and monetary benefits. The options are identified by number in Paragraph 1.1.

The number of cancer cases avoided per million dollars expended for each option is given in Figure 9-3. The curves in

Figure 9-3 indicate an increase in benefit-cost ratio with time due to the greater reduction in population exposure over longer periods of time as a result of remedial action. The potential cancer cases avoided for each option and the cost per potential cancer case avoided are given in Table 9-2.

TABLE 1-1

SUMMARY OF CONDITIONS NOTED AT TIME OF 1980 SITE VISITS

	Condition of Tailings[a]	Condition of Structures On Site[b]	Mill Housing[c]	Adequate Fencing, Posting, Security	Property Close to River or Stream	Houses or Industry within 0.5 Mi	Evidence of Wind or Water Erosion	Possible Water Contam- ination	Tailings Removed for Private Use	Other Hazards On Site
ARIZONA										
Monument Valley	U	R	N	No	No	Yes	Yes	No	Yes	No
Tuba City	U	PR-UO	E-P	No	No	Yes	Yes	No	No	Yes
COLORADO										
Durango	P	PR-UO	N	Yes	Yes	Yes	Yes	No	Yes	Yes
Grand Junction	S	PR-O	N	Yes	Yes	Yes	Yes	Yes	Yes	No
Gunnison	S	B-O	N	No	Yes	Yes	No	Yes	No	No
Maybell	S	R	N	Yes	No	No	Yes	No	No	No
Naturita	RMS	PR-O	N	Yes	Yes	Yes	Yes	Yes	No	No
New Rifle	P	M-O	N	Yes	Yes	Yes	Yes	Yes	No	No
Old Rifle	S	PR-UO	N	Yes	Yes	Yes	No	Yes	Yes	No
Slick Rock (NC)	S	R	N	Yes	Yes	Yes	Yes	Yes	No	No
Slick Rock (UCC)	S	R	E-P	Yes	Yes	Yes	No	Yes	No	No
IDAHO										
Lowman	U	R	N	No	Yes	Yes	Yes	Yes	Yes	No
NEW MEXICO										
Ambrosia Lake	U	PR-O	N	No	No	No	Yes	No	No	No
Shiprock	S	PR-O	N	Yes	Yes	Yes	No	Yes	Yes	No
NORTH DAKOTA										
Belfield	R	PR-O	N	No	No	Yes	No	No	No	No
Bowman	R	R	N	No	No	No	No	No	No	No
OREGON										
Lakeview	S	B-O	N	Yes	No	Yes	Yes	No	No	No

TABLE 1-1 (Cont)

	Condition of Tailings[a]	Condition of Structures On Site[b]	Mill Housing[c]	Adequate Fencing, Posting, Security	Property Close to River or Stream	Houses or Industry within 0.5 Mi	Evidence of Wind or Water Erosion	Possible Water Contam-ination	Tailings Removed for Private Use	Other Hazards On Site
PENNSYLVANIA										
Canonsburg	P	B-O	N	Yes	Yes	Yes	No	Yes	Yes	Yes
TEXAS										
Falls City	P	B-O	N	Yes	No	No	Yes	No	No	No
UTAH										
Green River	S	B-Y	N	Yes	Yes	Yes	Yes	Yes	No	No
Mexican Hat	U	PR-UO	E-O	No	No	Yes	Yes	Yes	No	No
Salt Lake City	U	R	N	No	Yes	Yes	Yes	Yes	Yes	Yes
WYOMING										
Converse County	U	R	N	Yes	No	No	No	No	No	No
Riverton	S	PR-O	N	No	No	Yes	No	No	No	No

[a]S - Stabilized but requires improvement

P - Partially stabilized

U - Unstabilized

RMS - Reprocessed, moved and stabilized - contamination remaining

R - Removed - contamination remaining

[b]M - Mill intact

B - Building(s) intact

R - Mill and/or buildings removed

PR - Mill and/or buildings partially removed

O - Occupied or used

UO - Unoccupied or unused

[c]N - None

E - Existing

O - Occupied

P - Partially occupied

TABLE 1-2

SUMMARY OF REMEDIAL ACTION OPTIONS AND EFFECTS

Option Number	Site Specific Cost ($000)	Description of Remedial Action	Benefits	Adverse Effects
I	17,800	The pile would be stabilized in place with 3 m of local earth cover. A riprap cover would be provided and on-site contaminated soil would be cleaned up.	A-D,F	P
II	22,600	The tailings, contaminated soil and rubble would be removed by truck to an unspecified disposal site, located about 5 mi from the tailings site. The tailings site would be decontaminated as in Option I and released for unlimited use.	B-F	--
III	22,600	Same as Option II, except tailings removed to an unspecified disposal site, located about 10 mi from the tailings site.	B-F	--
IV	23,100	Same as Option II, except tailings removed to an unspecified disposal site, located about 15 mi from the tailings site.	B-F	--

TABLE 1-2 (Cont)

Notes

1. All options include on- and off-site remedial action.

2. For Options II through IV, costs include removal of 3 ft of contaminated earth below the tailings.

Definition of Benefits

A. Access to the tailings site controlled by fencing and posting
B. Off-site windblown and water-eroded tailings cleaned up
C. Wind and water erosion controlled
D. Gamma radiation reduced
E. Unrestricted development possible on the tailings site
F. Radon gas exhalation greatly reduced or eliminated

Definition of Adverse Effects

P. Housing within close proximity of tailings pile

CHAPTER 1 REFERENCES

1. "Summary Report, Phase I Study of Inactive Mill Sites and Tailings Piles"; AEC; Grand Junction, Colorado; Oct 1974.

2. "Phase II - Title I Engineering Assessment of Inactive Uranium Mill Tailings, Tuba City Site, Tuba City, Arizona"; GJT-5; Ford, Bacon & Davis Utah Inc.; Mar 1977.

3. R.N. Snelling and S.D. Shearer, Jr.; "Environmental Survey of Uranium Mill Tailings Pile, Tuba City, Arizona"; Radiological Health and Data Reports; Nov 1969.

4. R.J. Countess; "^{222}Rn Flux Measurement with a Charcoal Canister"; Health Physics; Vol 31, p. 455; 1976.

5. F.F. Haywood, et al.; "Radiological Survey of the Inactive Uranium-Mill Tailings at Tuba City, Arizona"; ORNL-5450; Oak Ridge National Laboratory; Oak Ridge, Tennessee; Jan 1980.

6. J.M. Hans, Jr.; private communication of preliminary data; EPA-ORP-LVF; Las Vegas, Nevada.

7. Federal Register, Part II; EPA Interim Primary Drinking Water Regulations; EPA; July 9, 1976.

8. H.W. Kraner, G.L. Schroeder, and R.D. Evans; "Measurements of the Effects of Atmospheric Variables on Radon-222 Flux and Soil-Gas Concentrations"; The Natural Radiation Environment; J.A.S. Adams and W.M. Lowder, eds; University of Chicago Press; 1964.

9. Argonne National Laboratory and Ford, Bacon & Davis Utah Inc.; "Characterization of Uranium Tailings Cover Materials for Radon Flux Reduction"; NUREG/CR-1081 (FBDU-218-2); Mar 1980.

10. "The Effects on Populations of Exposure to Low Levels of Ionizing Radiation"; Report of Advisory Committee on Biological Effects of Ionizing Radiation; NAS, National Research Council; 1980.

11. B.L. Cohen; "The BEIR Report Relative Risk and Absolute Risk Models for Estimating Effects of Low Level Radiation"; Health Physics; Vol 37, p. 509; 1979.

12. H. Siegle; Navajo Area Indian Health Service; letter to Ford, Bacon & Davis Utah Inc.; Oct 14, 1976.

CHAPTER 2

SITE DESCRIPTION

CHAPTER 2

SITE DESCRIPTION

The purpose of this chapter is to describe the physical characteristics of the Tuba City site, its surroundings, and the characteristics of the tailings materials present on the site.

2.1 LOCATION

The Tuba City millsite is located approximately 85 mi north of Flagstaff and 5.5 mi east of Tuba City, Arizona, on the Navajo Reservation. The site is along the south side of U.S. Highway 160, which connects Tuba City and Kayenta, Arizona, as shown in Figure 2-1. More specifically, the site is in Sections 17 and 20, Township 32 North, Range 12 East, from Gila and Salt River Meridian, Coconino County, Arizona, at 36 deg 08 min 42 sec north latitude, 111 deg 08 min 02 sec west longitude. Figure 2-2 shows the relationship of the site to its surroundings. An ownership and site designation map of the tailings site adapted from the site description and ownership map prepared for DOE[1] is shown in Figure 2-3.

2.2 TOPOGRAPHY

The site is located in a gentle sloping area that drains south into the Moenkopi Wash. The uneven terrain of the area is characterized by gullies, washes, cliffs, and mesas and the sparse vegetation found in most areas of the Four Corners area. The land is used primarily for grazing sheep and cattle. The elevation of the site is about 5,000 ft above sea level. The tailings site is approximately 340 ft higher than the Moenkopi Wash.

The site consists of the mill, office, and ore storage area, which is south of the highway and east of the housing area (about 30 acres); the tailings area (about 22 acres); and the evaporation pond area (about 44 acres). The total area of the site is about 105 acres. The tailings area contains 800,000 tons of tailings at an average depth of about 16 ft.

The tailings pile is located on the flat area at an elevation of between 5,070 and 5,100 ft. The evaporation ponds are located on the border of the site at an average elevation of 5,060 ft. The drainage is to the south into Moenkopi Wash, the relatively steep slopes of which begin only 10 ft from the southern corner of the evaporation ponds. Figure 2-4 is a topographic map of the site area.

2.3 OWNERSHIP

The Rare Metals Corporation of America built the plant during 1955 and 1956 and operated it from 1956 until 1962. At that time, the corporation merged into the El Paso Natural Gas Company.

The mill was built on land leased from the Navajo Nation. Consequently, after the plant was shut down in September 1966 and the license to operate the plant was terminated by the Arizona Atomic Energy Commission in December 1968, control of the tailings and the site reverted to the Navajo Nation, the current owner.

2.4 HISTORY OF MILLING OPERATIONS AND PROCESSING

The Tuba City mill originally was designed to process uranium ores from the Cameron area southwest of Tuba City by a process based on acid leaching and resin-in-pulp ion exchange.[2,3] Ores were also received from Monument Valley on the Utah-Arizona border, from AEC stockpiles at the Cutter Buying Station near Globe, Arizona, from the Anderson or "Uraniumaire" mine near Congress Junction, Arizona, and from the Orphan Lode mine near the village of Grand Canyon, Arizona.

The first ore was processed in June 1956. The mill was in operation continually at a rate of 300 tons/day until April 1962, when it was shut down pending negotiations with the AEC for a contract to continue the production of U_3O_8 concentrate, and with Western Equities, Inc., owner of the Orphan Lode mine, for an ore supply. By 1962, the Orphan Lode had become the most important source of ore for the mill, and all of the other sources were becoming exhausted. A new contract was signed by the AEC and El Paso Natural Gas Company in November 1962. The plant then was converted from an acid leach to a carbonate leach process, which was more suitable for the Orphan Lode ore. In April 1963, the Tuba City mill resumed operations at a rate of 200 tons/day and continued until September 1966, when the last ore was fed to process. During its total operating life this mill processed 0.8 million tons of ore with an average grade of 0.33% U_3O_8 and produced 2,348 tons of U_3O_8 in concentrate.

2.5 PRESENT CONDITION OF THE SITE

A descriptive map of the site is shown in Figure 2-5 and a cross-section of the tailings pile in Figure 2-6.

Two of the original buildings, a main mill building, an office/entrance building, and a concrete pad remain on the millsite. They are located in the northern portion of the site. Both buildings have been severely cannibalized. All of the equipment, as well as some of the siding, has been removed from the mill building but the structural steel frame remains.

A residential area for mill workers was constructed by the Rare Metals Corporation. This consisted of 10 frame dwellings and a trailer park on the north side of U.S. Highway 160 and 16 frame dwellings and a trailer facility on the south side of the highway. Playground facilities for children were built, as was an asphalt tennis court. The playground facilities are not in use, and sparse vegetation has established itself. The recreational facilities exist intact, although they are in a state of disrepair.

There are 10 parking spaces provided for mobile homes in the trailer park north of U.S. Highway 160 and 6 spaces on the south. Only one was occupied at the time of the 1980 survey. Seven houses on the north and five on the south were also occupied at that time. Most of the houses are in poor condition with no electrical services to either the housing units or the trailer park spaces. The houses, however, do have water service.

Three evaporation ponds lie immediately adjacent to and southwest of the tailings. These pond areas contain few tailings. The tailings were piled to varying depths averaging 16 ft above the surrounding land in depressions formed by excavating the natural earth to obtain dike material. The pond southeast of the mill building was an emergency dump pit, but the type of material it received is not known.

After the plant was shut down in late 1966, the site was fenced and posted in accordance with State of Arizona regulations. The fence apparently was built on naturally migrating dune sand and not on tailings or subsoil. The site is fenced with barbed wire on the north, west, east, and half of the south of the mill area. The entrance to the mill area is restricted by the north fence adjacent to the highway. Portions of the fence northeast of the tailings pile are buried by windblown tailings; northwest of the evaporation pond there is only a small portion of a 4-strand barbed wire fence intact; the fences east, south, and west of the evaporation ponds are down. There are no secured gates or radiation warning signs on the perimeter of the site.

The open septic system that runs from the houses north of the site to a pond west of the remaining mill building is a potential hazard. The pond has recently been fenced with wire mesh fencing, and a sign warning of contaminated water has been posted.

In 1968, the El Paso Natural Gas Company in cooperation with the U.S. Bureau of Mines began application of chemical stabilizers to the pile. The commercial chemical applied has the trade name of DCA-70. This chemical was selected because of its expected effectiveness on the sandy and relatively steep dikes that are subject to severe water and wind erosion. Approximately 6.5 acres of dikes were sprinkled with the

DCA-70 water solution. The amount of chemical deposited per unit area varied from 0.045 to 0.068 gal/yd^2 in accordance with the susceptibility of the area to wind erosion.

Stabilization of this area was finished in September 1968, and an inspection in May 1969 indicated that the chemical binder had "maintained its integrity". By May of 1970 it was evident that the chemical stabilization was beginning to break down. In a May 1974 visit, a team composed of representatives from the AEC, the EPA, and the State of Arizona Atomic Energy Commission confirmed reports that the chemical stabilization had disintegrated extensively and had become ineffective. One of the main reasons for this deterioration was intrusion onto the surface of the tailings by livestock and persons. The summary of the survey team's findings recommended that an engineering assessment should be undertaken and directed to the further decontamination of the millsite and to the long-term stabilization of the tailings to prevent further wind and water erosion.

2.6 TAILINGS AND SOIL CHARACTERISTICS

Generally, the tailings are finely ground and have a high clay content that makes them relatively impermeable and difficult to dewater. Analyses of borings and samples indicate that the tailings were not deposited uniformly in the ponds. This nonuniformity can be attributed to a change in the refining process, the variety of ore sources, and the differential rates of deposit and migration of slimes from the discharge point. Assay results of composite uranium tailings samples are shown in Table 5-1. Except for a few small bushes on the fringes, there has been no vegetative growth on the pile.

The Tuba City site is underlain by a uniform subsoil of sand and clays, as indicated by soil borings taken at several locations on the tailings. Analyses of soil borings and radiometric measurements show that some radioactive elements have migrated a distance of 2 to 5 ft into the underlying undisturbed soil, as discussed in more detail in Paragraph 3.4.5.

Table 2-1 summarizes the types, volumes, and weights of materials at the Tuba City tailings site. Table 2-2 lists physical properties of the tailings; it also shows the pH of water samples obtained near the site to be slightly basic. Tailings pH varies since both acidic and carbonate leach processes were employed.

2.7 GEOLOGY, HYDROLOGY, AND METEOROLOGY

2.7.1 Geology[3]

The Tuba City site lies about 1.5 mi north of Moenkopi Wash, as shown in Figure 2-1. The tailings rest on loose sand derived from wind erosion of the underlying Navajo Sandstone.

This loose sand layer varies in thickness from less than 1 ft to 20 ft. The Navajo Sandstone is a weakly cemented, medium-grained, cross-bedded sandstone. It dips at a low angle (2 deg) away from the town of Tuba City toward the axis of the Tuba City syncline. This axis runs in a northwest-southeast direction about 1 mi east of the tailings site. The Navajo Sandstone is exposed south of the millsite along Moenkopi Wash. The Kayenta Formation (a series of silty mudstones with intertongues of sandstone) underlies the Navajo Sandstone.

2.7.2 Surface Water Hydrology

While no opportunity was provided for FB&DU to conduct field evaluations of site hydrology, existing information was examined to characterize general hydrologic conditions in the vicinity of the site. The results of this survey are contained in this and Paragraph 2.7.3. Apparently no further hydrologic characterization of the Tuba City tailings site is contemplated at this time.

Surface water contamination is unlikely since there are no surface waters of any consequence near the Tuba City millsite. Surface drainage runs to the Moenkopi Wash south of the site, as shown in Figure 2-7.[4] A study of the features in Figure 2-5 indicates that east-west U.S. Highway 160, about 0.25 mi north of the tailings, is located along the top of a low ridge. To the north of the highway, a large depression known as Greasewood Lake collects any surface runoff that may occur north of the highway. Surface drainage from the Greasewood Lake depression would drain to the west-southwest and would not cross the highway until well past the millsite. There is some drainage potential from precipitation falling in the area between the highway and the tailings pile. There is evidence of some sheet erosion of this steeply-sloping land due to thunderstorm runoff, but the amount of erosion has been small. Some erosion also has occurred along the northwest border of the tailings pile. This apparently has resulted from flow of water from the sewage disposal pond.

2.7.3 Ground Water Hydrology

The principal aquifer in the Tuba City-Moenkopi area is a multiple aquifer system consisting of Navajo Sandstone and some sandstone beds in the underlying Kayenta Formation.[5] Figure 2-8 shows a simplified stratigraphic cross-section. This aquifer is recharged by winter and spring precipitation in the Kaibito Plateau highlands some distance north of Tuba City, as shown in Figure 2-9. Water in the multiple aquifer system moves southward from the highlands; its principle discharge area is along Moenkopi Wash. Thus, the tailings are situated in the discharge rather than the recharge area of the aquifer system. Water in this multiple aquifer system is unconfined because the Navajo Sandstone is covered only by windblown sand over almost all of the areas of concern. Most of the water is produced by gravity flow where the water table intersects the land surface along Moenkopi Wash and its tributary gullies.

Springs and shallow wells in the vicinity of the site were checked in 1967 by the U.S. Public Health Service for radioactive contamination,[6] and results of this sampling showed no contamination in ground water from the mill tailings. However, it is possible that a small amount of the water cycled into the tailings ponds when the mill was in operation could have permeated into the underlying sand and in the future could be moved by ground water toward the Moenkopi Wash. The likelihood that such a water movement would occur is not great. There is a shallow well at a farm about 1.5 mi southeast of the site near Moenkopi Wash, but no new wells were found directly south of the site. Four wells that furnished water for the mill when it was in operation are located north of U.S. Highway 160. However, only one of these wells is connected to the water supply system while the other three are capped and not connected.[7]

The tailings are isolated effectively from inflow or outflow of surface water by high berms. The only water that can reach the tailings comes from precipitation directly onto the site. Because of the large moisture deficiency in the present tailings and the high rate of evaporation, any rain falling on the site would penetrate the tailings a few feet at most, then return to the surface as evaporation takes place, causing an upward soil moisture gradient. There is no potential danger of future infiltration of contaminants to the ground water of this area.

Periodic monitoring of nearby springs and wells is warranted during the next several years to determine if any movement of water that may have been contaminated during the active operation of the mill may have seeped into the underlying sand and sandstone. It is unlikely that any contamination from the tailings will ever affect the water supply at Tuba City.

Recent[8,9] and ongoing research by the Research Institute for Geochemical and Environmental Chemistry suggests that the presence of soluble sulfate salts in the tailings greatly modifies the hydrologic environment of the pile. The principal investigator[8] states that "the general trend of material transfer within the pile is from the interior to the surface where salts with the contaminants precipitate." It is not yet known how significant the observed migration of salts will be for tailings stabilization.

2.7.4 Meteorology

As reported by the U.S. Department of Commerce,[10] the average annual precipitation at Tuba City is 6.1 in. based on a 62-yr period of record. The maximum 24-hr precipitation recorded at Tuba City (over a 70-yr period of record) was 3.4 in. measured on September 27, 1926.[11] Measured against the 100-yr 24-hr precipitation estimated from these figures, the storm on September 27, 1926, exceeded the 100-yr projected amount by 0.27 in. The 24-hr precipitation would be expected to be at a rate of 1.3 in. once every 2 yr, with a "maximum observed" 24-hr storm at Tuba City of 4 in.

An analysis of the records at Tuba City over a 25-yr period indicates that the maximum daily precipitation usually occurs during the 3-mo period of August through October. This pattern is typical of much of the southwest desert area, being the time of most frequent thunderstorm activity.

There are no records of wind measurements at the Tuba City site or at any other nearby location. Since no wind direction measurements have been made, some method of estimating the direction of winds, as related to possible wind erosion of the tailings material, is necessary. Cooley and others state that strong winds are common throughout the Colorado Plateau[5] and postulate that the distribution and orientation of dunes and the directions of cross-beds in other eolian deposits indicate regional wind patterns during Quaternary and Tertiary ages. Figure 2-10 is a map showing that past and present wind directions prevail from southwest to northeast, as indicated by dune and cross-bed orientation.

Examination of the existing tailings pond dikes shows a number of locations where wind erosion of the dike material has taken place. These cuts in the dike, several feet deep in some instances, provide dramatic evidence of the strength of the winds in eroding the tailings materials. The cuts in the dikes and the windblown tailings that have been deposited outside of the eastern and northeastern boundary of the tailings substantiate the observation that the transport of materials by wind is mainly from the southwest toward the northeast. The amount of tailings that has been transported away by the wind is probably considerable, as the light-colored tailings material can be seen over an area up to 0.5 mi away from the existing tailings pile. The extensive wind erosion is due not only to the magnitude of the winds, but because of the fineness of the tailings resulting from the alkaline-leach process that was used. The material that has been transported from the tailings has been primarily in a northeastern direction, away from the residences along U.S. Highway 160 and away from Tuba City. There are no residences nearby in the path of the wind.

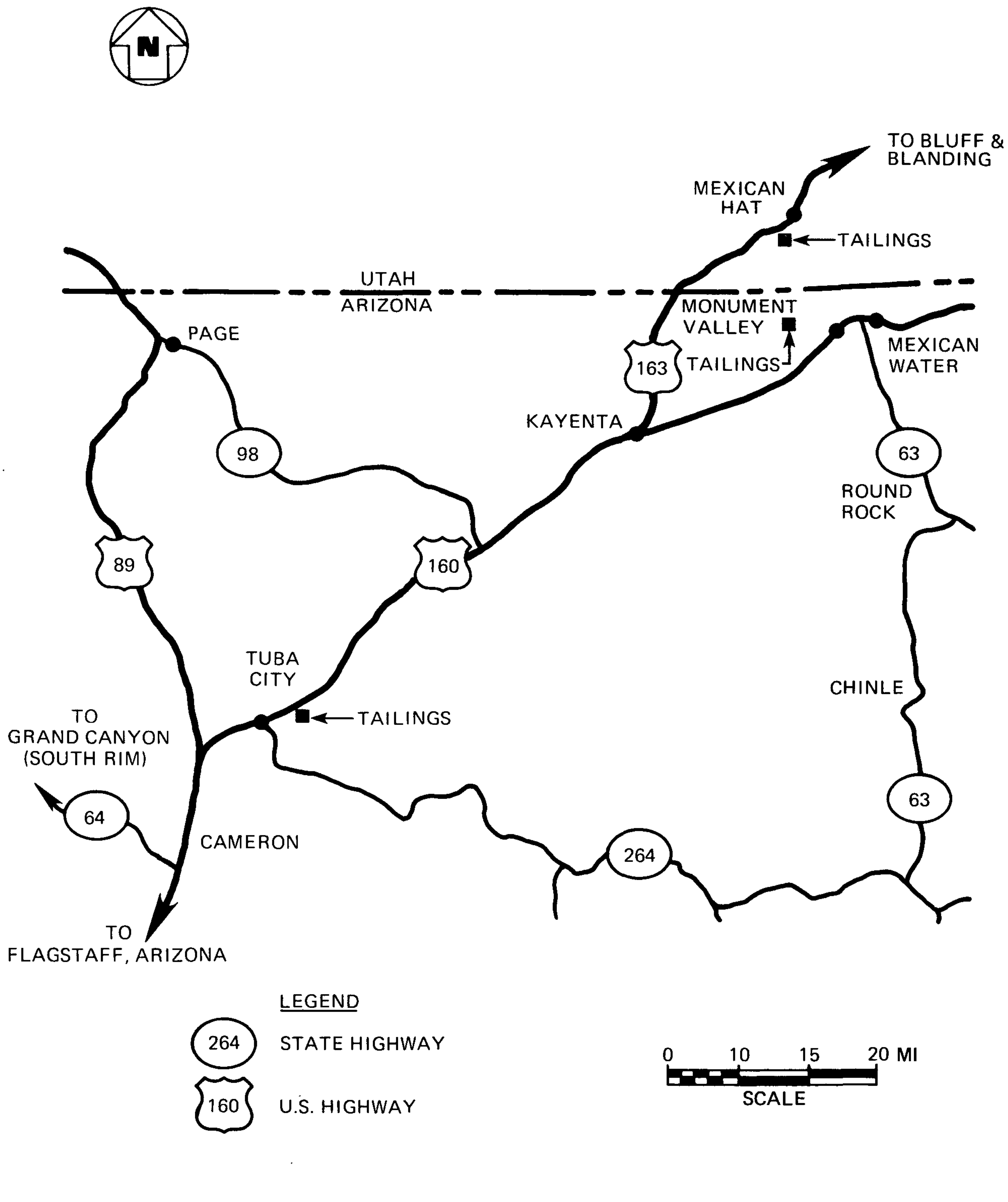


FIGURE 2-1. LOCATION OF SITE

360-05 1/81

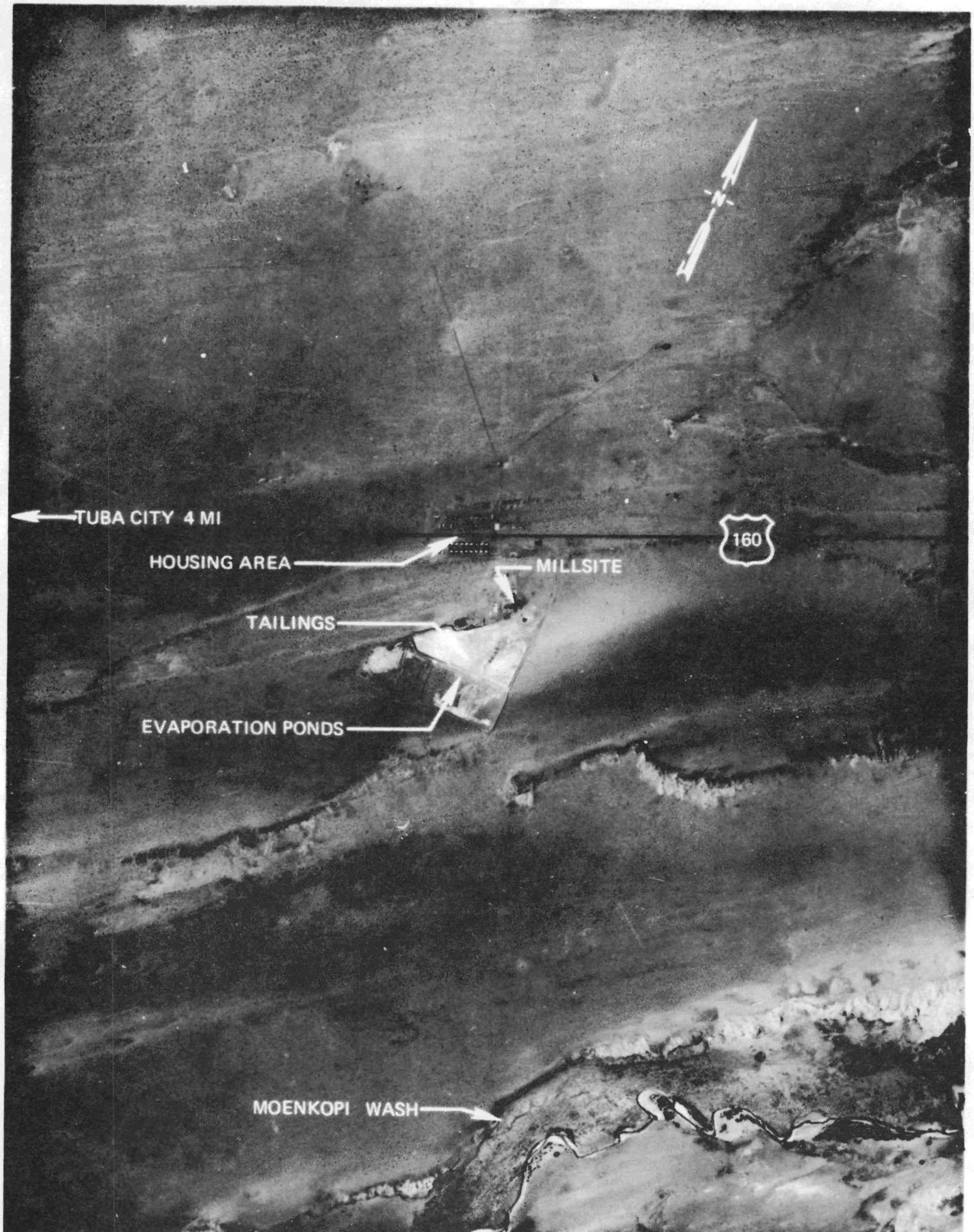
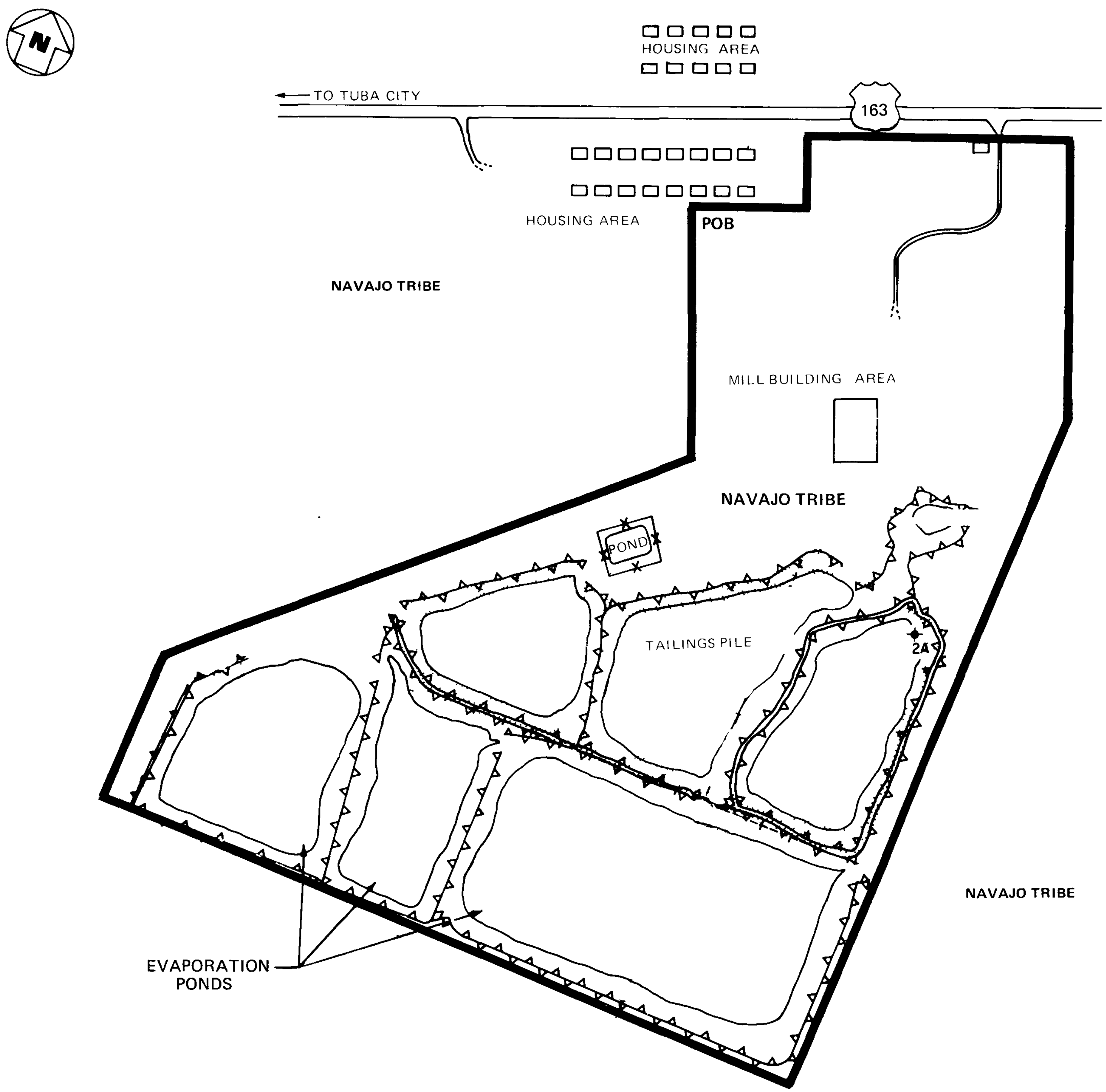


FIGURE 2-2. AERIAL PHOTOGRAPH OF SITE

360-05 3/77



TUBA CITY SITE

BEGINNING AT A POINT WHICH IS SOUTH 165.87 FT AND N 64°43'E 1395.76 FT FROM THE N.W. CORNER OF SECTION 20, T32N, R12E, SALT RIVER MERIDIAN, AND RUNNING THENCE N 64°43'E 372 FT, THENCE N 25°17'W 226 FT, (MORE OR LESS) TO THE SOUTHERLY R/W LINE OF U.S. HIGHWAY 163, THENCE N 64°43'E ALONG SAID R/W LINE 867.9 FT, THENCE S 24°15'27"E, 900 FT, THENCE SOUTH 2320 FT, THENCE WEST 2295.25 FT, THENCE NORTH 452.6 FT, THENCE N 44°36'39"E 1754.51 FT, THENCE N 25°17'W 800 FT, TO THE POINT OF BEGINNING.

CONTAINS 105 ACRES (MORE OR LESS)

NOTE: ADAPTED FROM REFERENCE 1

FIGURE 2-3. LAND OWNERSHIP AND SITE DESIGNATION MAP

360-05 1/81

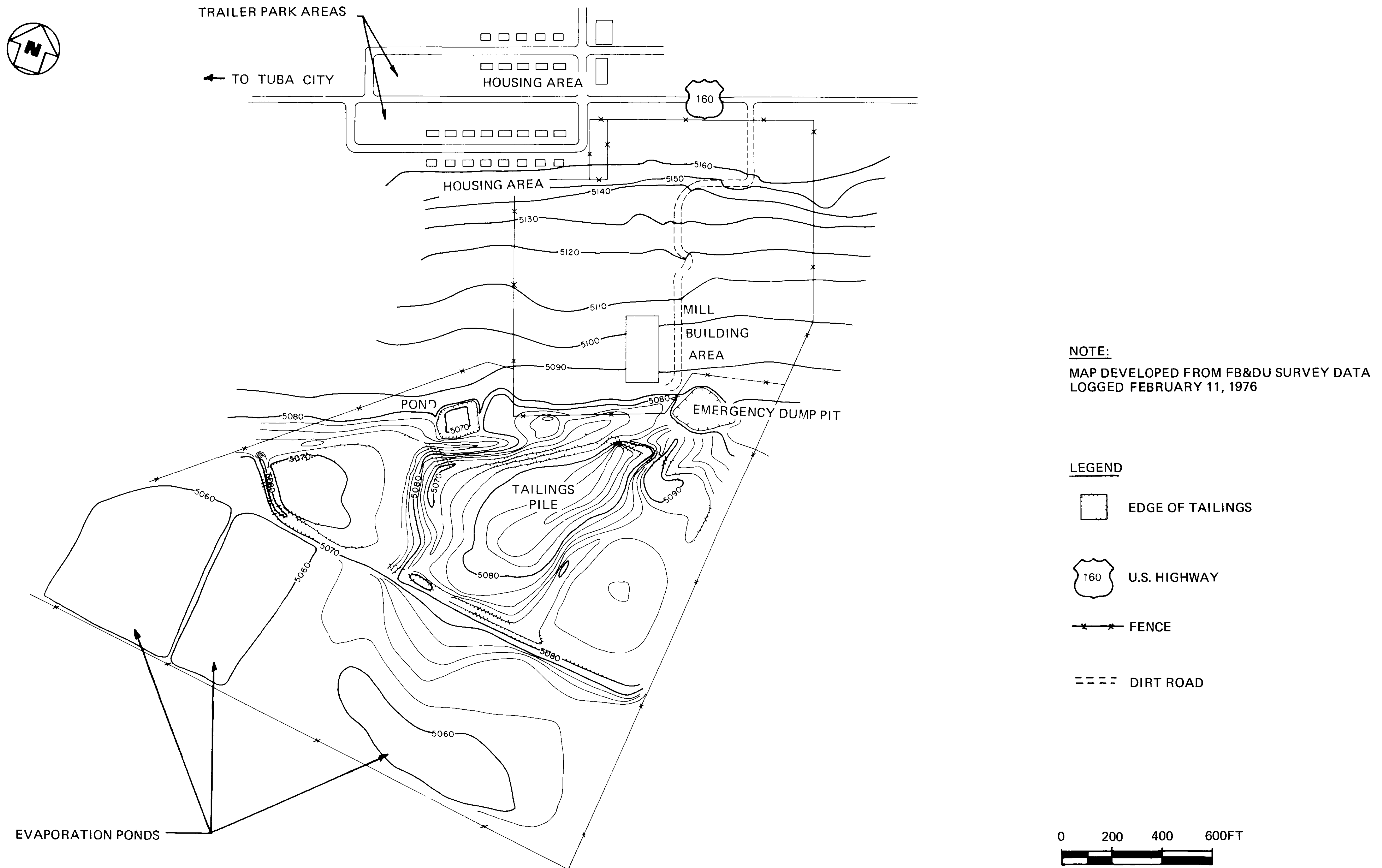


FIGURE 2-4. TOPOGRAPHIC MAP

360-05 3/77

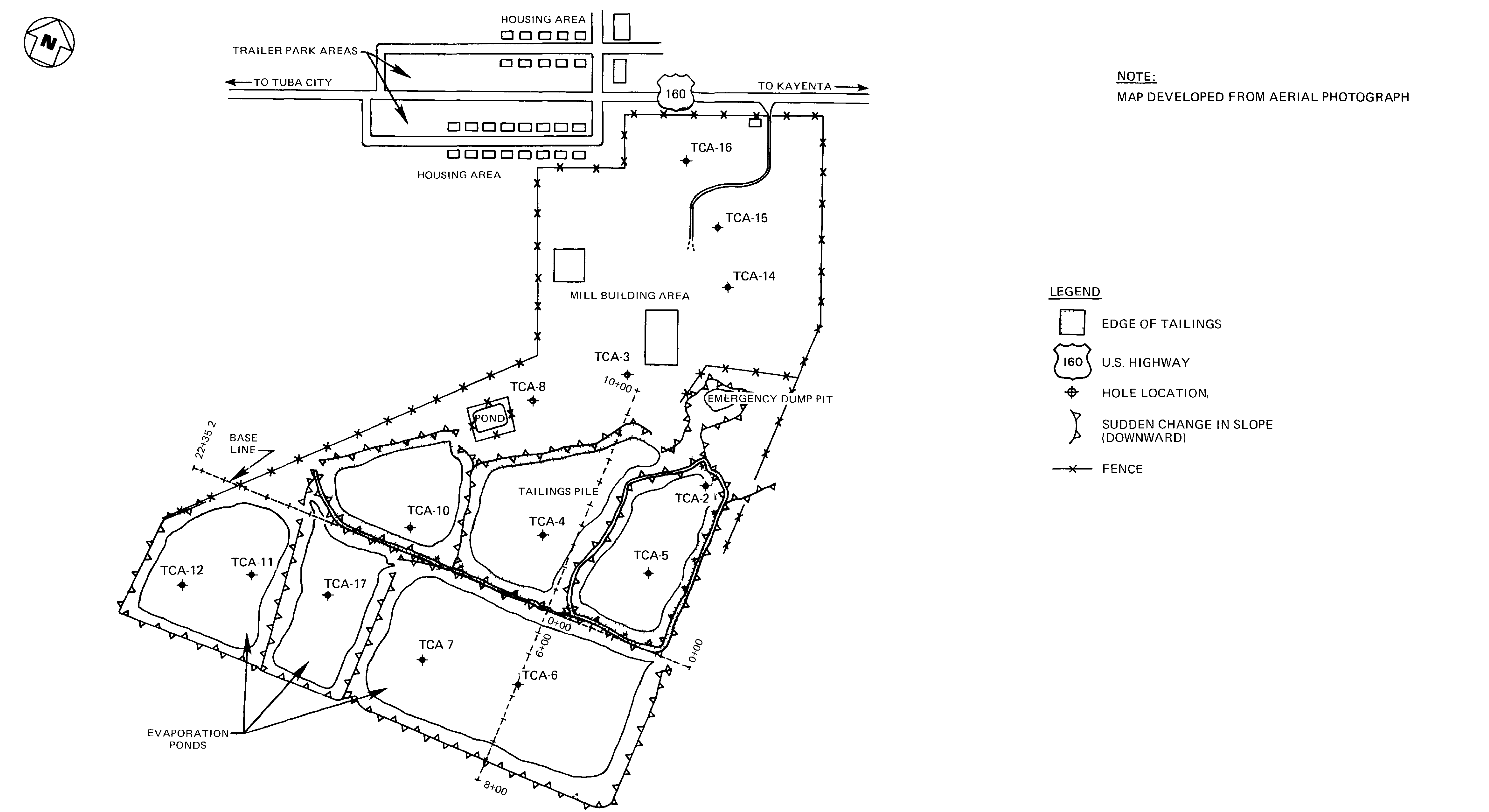


FIGURE 2-5. DESCRIPTIVE MAP

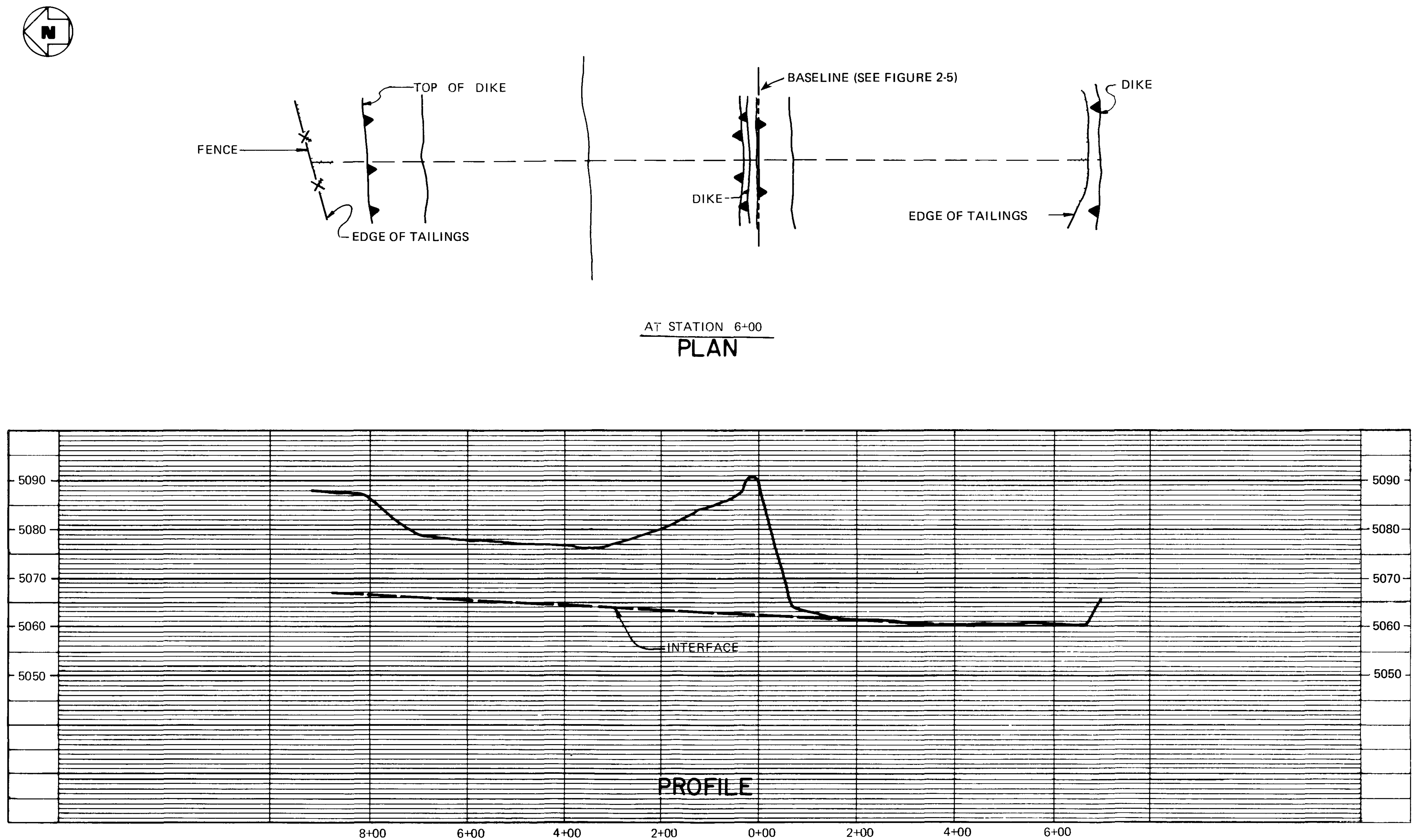
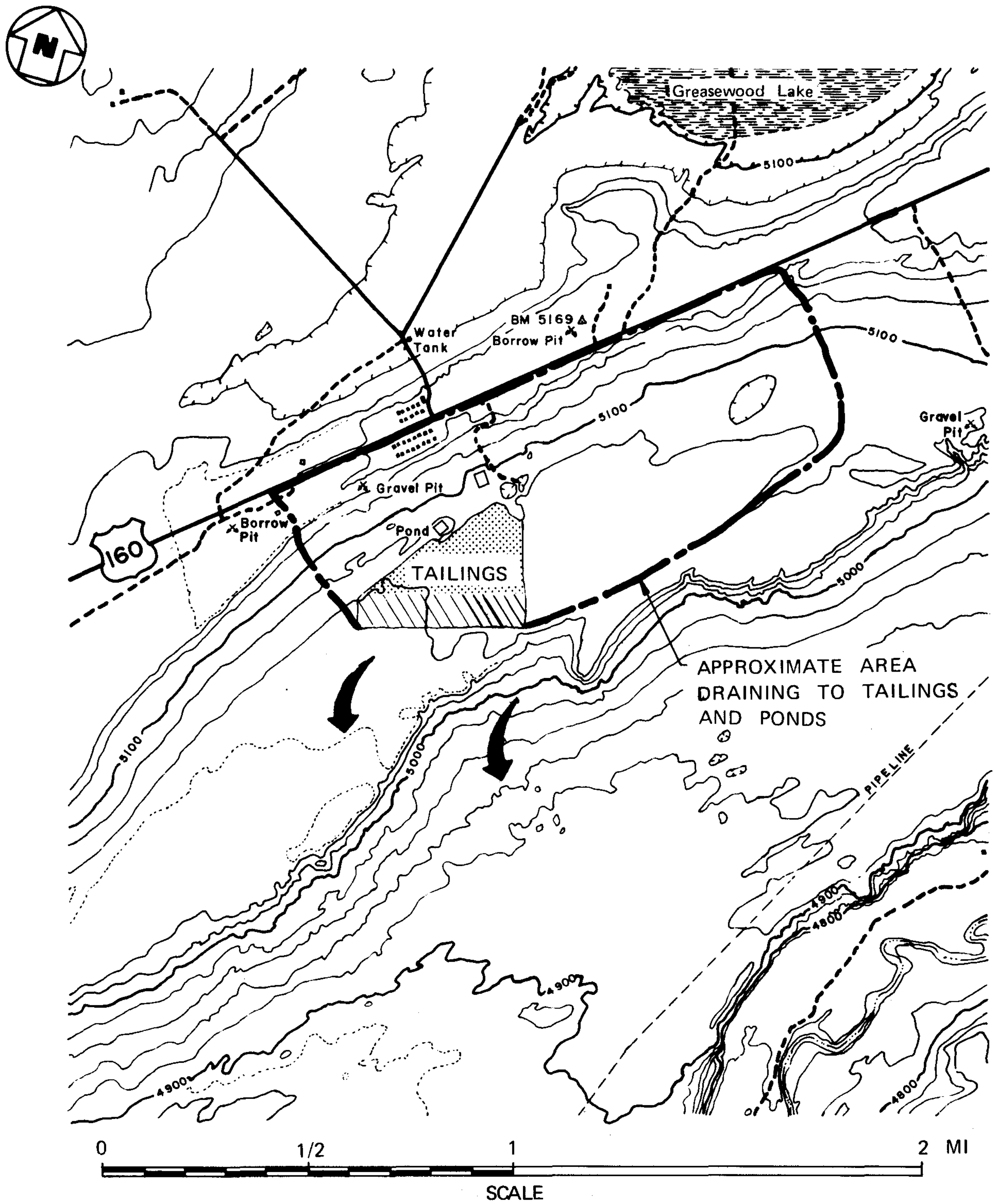


FIGURE 2-6. CROSS-SECTION AT STATION 6+00

360-05 3/77



(MAP TRACED FROM U.S. GEOLOGICAL SURVEY, TUBA CITY AND TUBA CITY NE QUADRANGLES.)

LEGEND

GENERAL DIRECTION OF SURFACE WATER MOVEMENT

160 U.S. HIGHWAY

FIGURE 2-7. SURFACE DRAINAGE PATTERNS

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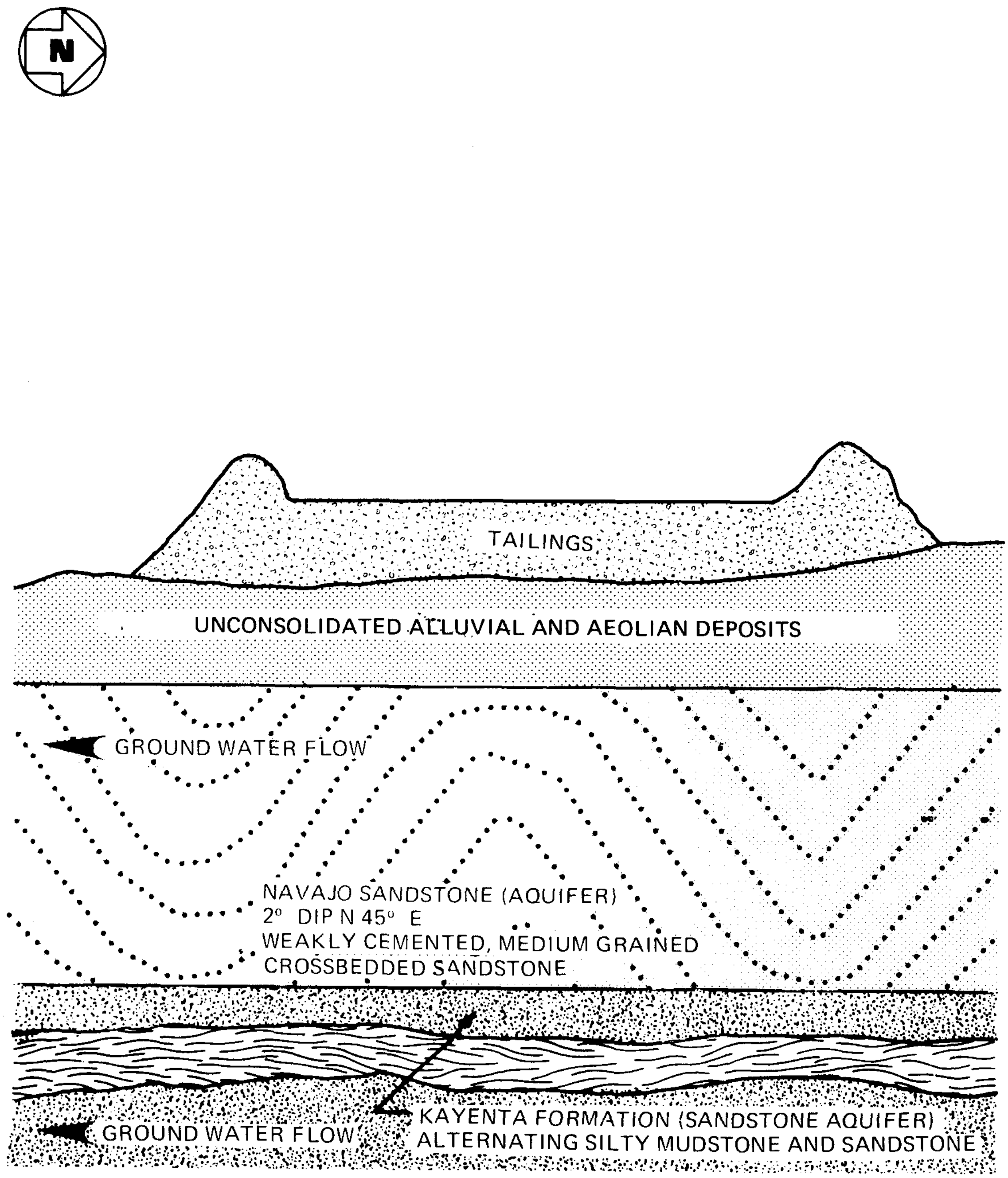
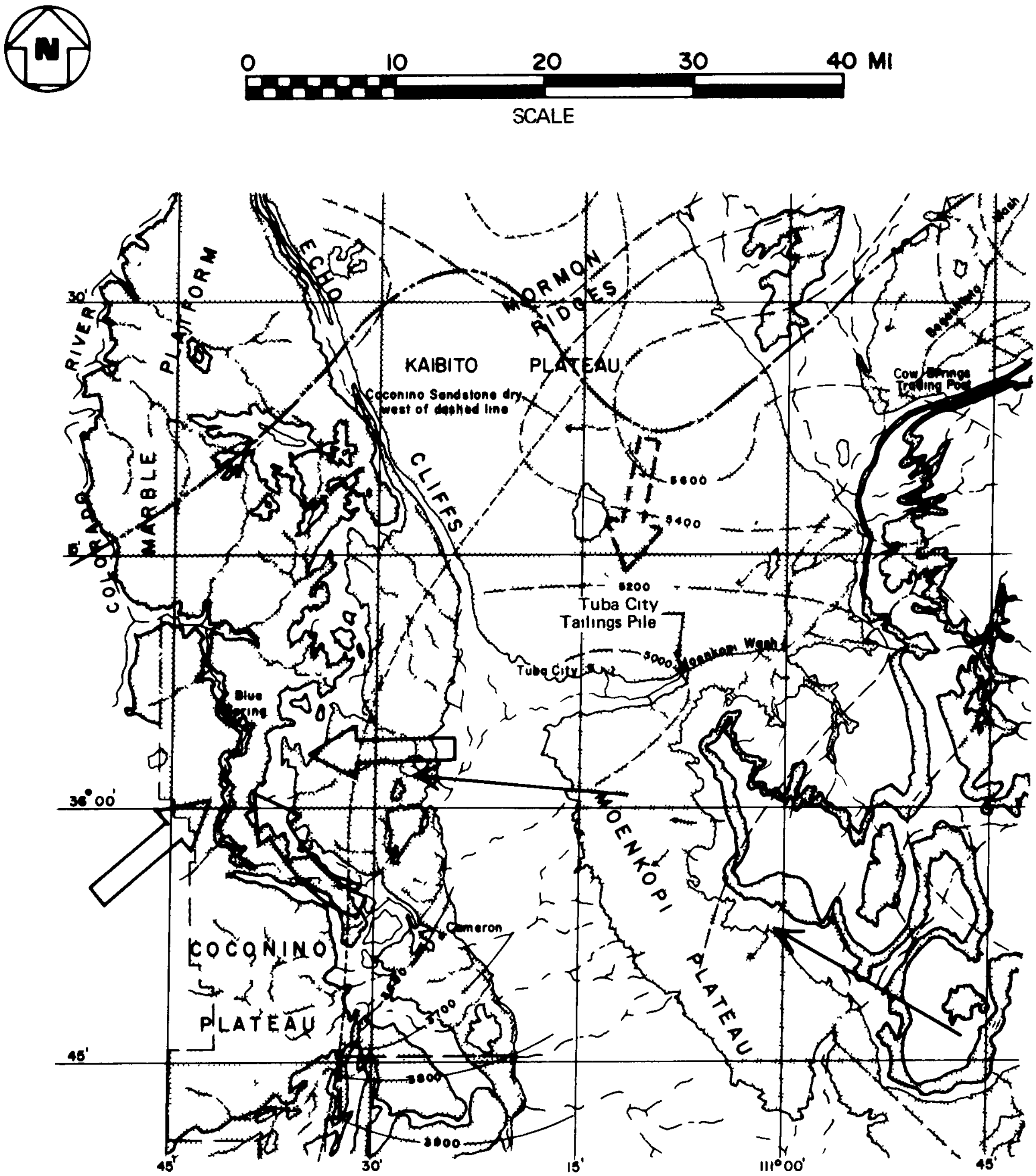


FIGURE 2-8. SIMPLIFIED STRATIGRAPHIC CROSS–SECTION

360-05 3/77



LEGEND

ROCKS RECEIVING RECHARGE

UNSHADED AREAS INDICATE AQUICLUDE (ROCKS RECEIVING LITTLE OR NO RECHARGE)

PROBABLE DIRECTION OF GROUND WATER FLOW

NOTE
FROM REFERENCE 5

FIGURE 2-9. PROBABLE DIRECTION OF GROUND WATER FLOW

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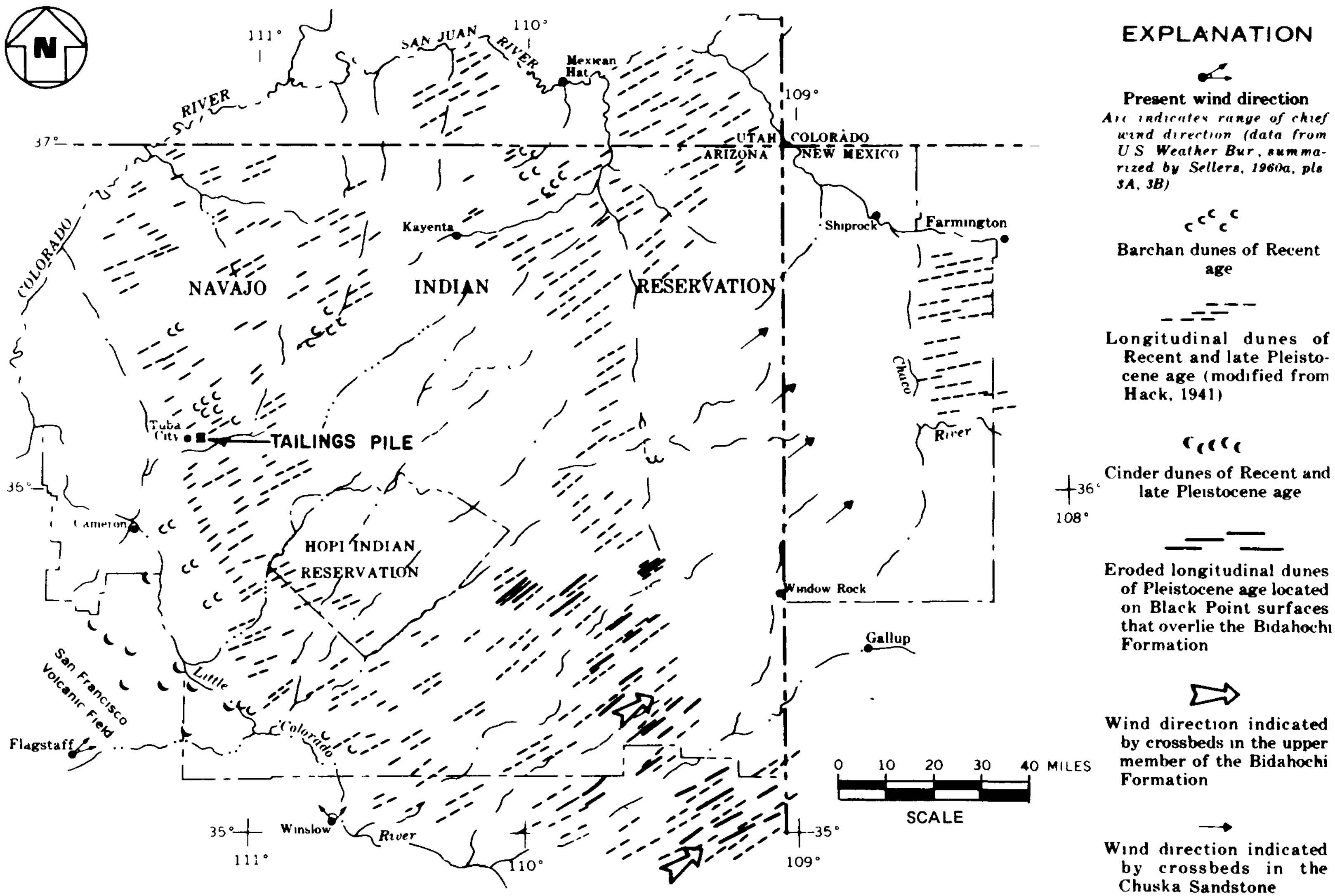

MAP SHOWING PAST AND PRESENT PREVAILING WIND DIRECTIONS

NOTE:
FROM REFERENCE 5

FIGURE 2-10. PREVAILING WIND MAP

TABLE 2-1

TAILINGS SITE MATERIALS

Material	Volume (yd^3)	Weight[a] (tons)
Tailings	761,000	800,000
Dikes and Pond Material	74,000	98,000
Contaminated Soil Under Tailings[b]	71,000	96,000
Contaminated Soil Under Ponds[c]	129,000	174,000
Millsite and Ore Storage Contaminated Material[d]	97,000	131,000
Windblown[e]	215,000	291,000
TOTAL	1,347,000	1,590,000

[a]Except for tailings, weight is based on average existing field densities, which include moisture.

[b]Based on 22 acres contaminated to an average depth of 2 ft.

[c]Based on 20 acres contaminated to an average depth of 4 ft.

[d]Based on 30 acres contaminated to an average depth of 2 ft.

[e]Based on 267 acres contaminated to an average depth of 6 in.

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TABLE 2-2

PHYSICAL PROPERTIES AND pH OF TAILINGS AND WATER SAMPLES

Soil Density

Sample Location[a]	Water (%)	Bulk Density (lb/ft^2)
TCA-10	8.13	73.1
TCA-5	3.18	77.2
TCA-4	1.59	83.5

pH of Water and Tailings

Sample Location	Water pH	Tailings pH (5% water by wt)
TCA-4	--	7.05
TCA-10	--	6.86
TCA-5	--	4.35
TCAWS No. A[b]	7.50	--
TCAWS No. B	7.20	--
TCAWS No. C	7.65	--
TCAWS No. D	7.60	--

[a]For locations see Figure 2-3.

[b]For locations see Figure 3-11.

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CHAPTER 2 REFERENCES

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3. D.K. Fuhriman and F. Hintze; "Hydrology and Geology of Uranium Tailings Site at Tuba City, Arizona"; Center for Health and Environmental Studies, Brigham Young University, Provo, Utah; 1976.

4. U.S. Geological Survey; Tuba City and Tuba City NE, Arizona, 7 Minute Quandrangle, Topographic Maps; 1969.

5. M.E. Cooley, J.W. Harshbarger, J.P. Akers, and W.F. Hardt; "Regional Hydrology of the Navajo and Hopi Indian Reservations, Arizona, New Mexico and Utah"; USGS Professional Paper 521-A; 1969.

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7. A.C. Damon, Jr.; Manager, Water and Sanitation Department; the Navajo Nation, Window Rock, Arizona; letter to R.D. Baird; Ford, Bacon & Davis Utah Inc.; dated Sep 15, 1980.

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11. A.H. Jennings; Maximum 24-Hour Precipitation in the United States; U.S. Weather Bureau Technical Paper No. 16; 1952.

CHAPTER 3

RADIOACTIVITY AND POLLUTANT IMPACT ON THE ENVIRONMENT

CHAPTER 3

RADIOACTIVITY AND POLLUTANT IMPACT ON THE ENVIRONMENT

The principal objective of the assessment in this chapter is to determine the magnitude and characteristics of the radiation emitted from the Tuba City uranium tailings pile and the resulting potential exposure to the population residing and working in the vicinity of Tuba City, Arizona. In addition, this chapter briefly describes the potential radioactive and chemical pollutants and their pathways in the environment. The notations and abbreviations used are given in Table 3-1.

A radiological survey of the site was conducted by Oak Ridge National Laboratory (ORNL),(1) concurrently with work performed by FB&DU in 1976. The principal results of that work are included in this engineering assessment.

3.1 RADIOACTIVE MATERIAL CHARACTERISTICS

Many elements spontaneously emit subatomic particles; therefore, these elements are radioactive. For example, when the most abundant uranium isotope, ^{238}U, undergoes radioactive decay, it emits a subatomic particle called an alpha particle; the ^{238}U after undergoing decay becomes ^{234}Th, which is also radioactive; and ^{234}Th subsequently emits a beta particle and becomes ^{234}Pa. As shown in Figure 3-1, this process continues with either alpha or beta particles being emitted, and the affected nucleus thereby evolves from one element into another. It is noted in Figure 3-1 that ^{230}Th decays to ^{226}Ra, which then decays to ^{222}Rn, an isotope of radon. Radon, a noble gas, does not react chemically. The final product in the chain is ^{206}Pb, a stable isotope that gradually accumulates in ores containing uranium. Uranium ore contains ^{226}Ra and the other daughter products of the uranium decay chain. One of the daughters of ^{226}Ra is the isotope ^{214}Bi, which emits a significant amount of electromagnetic radiation known as gamma radiation. Gamma rays are very similar to X-rays, only more penetrating. The ^{214}Bi is the principal contributor to the gamma radiation exposure in the uranium-radium decay chain.

Besides knowing the radioactive elements in the decay chain, it is also important to know the rate at which they decay. This decay rate, or activity, is expressed in curies (Ci) or picocuries (pCi), where 1 pCi equals 10^{-12} Ci or 3.7×10^{-2} disintegrations per second. The picocurie often is used as a unit of measure of the quantity of a radioactive element present in soil, air, and water.

Another important parameter used in characterizing radioactive decay is known as the "half life", $T_{1/2}$. This is the time that it takes for half of any initial quantity of the radioactive atoms to decay to a different isotope. For example, it takes 4.5 x 10^9 yr for half the ^{238}U atoms to decay to ^{234}Th. Similarly, half of a given number of ^{222}Rn atoms will decay in 3.8 days.

The activity and the total number of radioactive atoms of a particular type depend upon their creation rates as well as their half life for decay. If left undisturbed, the radioactive components of the decay chain shown in Figure 3-1 all reach the same level of activity, matching that of the longest-lived initiating isotope. This condition is known as secular equilibrium. When the uranium is removed in the milling process, ^{230}Th, which is not removed, becomes the controlling isotope. After processing the ore for uranium, the thorium, radium, and other members of the decay chain remain in the spent ore solids in the form of a waste slurry. The slurry is pumped to a tailings pond. The sands and slimes that remain constitute the tailings pile. Generally, the slimes constitute only 20% of solid waste material, but they may contain 80% of the radioactive elements of major concern: radium and its daughters.

3.2 RADIATION EFFECTS

The radioactive exposure encountered with uranium mill tailings occurs from the absorption within the body of the emitted alpha and beta particles, and gamma radiation. The range of alpha particles is very short; they mainly affect an individual when the alpha emitter is taken internally. Beta particles have a much lighter mass than alphas, and have a longer range; but they will cause damage mainly to the skin or internal tissues when taken internally. Gamma rays, however, are more penetrating than X-rays and can interact with all of the tissue of an individual near a gamma-emitting material.

The biological effects of radiation are related to the energy of the radiation; therefore, exposure to radiation is measured in terms of the energy deposited per unit mass of a given material. In the case of radon and its daughter products, the principal effect is from alpha particles emitted after the radon and its daughter products are inhaled.

The basic units of measurement for the alpha particles from short-lived radon daughters are the working level (WL) and the working level month (WLM). The working level is defined as any combination of the short-lived radon daughters in a liter of air that will result in the ultimate emission of 1.3 x 10^5 MeV of alpha energy. The working level is so defined because it is a single unit of measure, taking into account the relative concentrations of radon daughter products which vary according to factors such as ventilation. One WLM results from exposure to air containing a radon daughter concentration (RDC) of 1 WL for a duration of 170 hr.

The basic units of measurement for gamma radiation exposure and absorption are the roentgen (R) and the rad. One R is equal to an energy deposition of 88 ergs/g of dry air, and 1 rad is the dose that corresponds to the absorption of 100 ergs/g of material. The numerical difference between the magnitude of the two units is often less than the uncertainty of the measurements, so that exposure of 1 R is often assumed equivalent to an absorbed dose of 1 rad or a gamma dose of 1 rem. (Refer to Glossary at the end of the report.)

3.3 NATURAL BACKGROUND RADIATION

There are several sources of radiation that occur naturally in the environment. Natural soils contain trace amounts of uranium, thorium, and radium that give rise to radon gas and to alpha, beta, and gamma radiation. The average background value in six off-site soil samples for each member of the uranium decay chain, assuming equilibrium, was about 1.0 pCi/g.(1) The samples taken within an 80-mi radius of Tuba City and the corresponding ^{226}Ra concentrations are shown in Figure 3-2. No previous soil measurements are available for the area. Another natural source of radiation in the environment arises from the decay of ^{232}Th, the predominant thorium isotope. The half-life of ^{232}Th is 1.4×10^{10} yr. It is also the parent of a decay chain containing isotopes of radium and radon. The average background value in the same off-site samples for each member of the thorium decay chain, assuming equilibrium, is about 0.7 pCi/g of soil.(1) Table 3-2 lists the major background radioactive sources. It is noted that background values of the radium and thorium chains vary with locations by factors of 6 and 9, respectively. In addition, soils in the general area contain about 20 pCi/g of ^{40}K, a beta and gamma emitter.(2)

Background values of radon concentrations were measured at two locations, 0.5 and 3 mi from the Tuba City site as shown in Figure 3-3, using continuous radon monitors supplied by ERDA. An average outdoor value of 0.69 pCi/l was obtained from evaluation of the 24-hr samples. However, the range of the background measurements extends from about 0.7 to 1.2 pCi/l. A previous measurement taken in Tuba City during strong westerly wind conditions yielded a value of 0.1 pCi/l.(3)

Background gamma ray levels, as measured 3 ft above the ground, also were determined at several locations from 0.25 to 1 mi from the site by using a calibrated and energy-compensated Geiger Mueller detector and a sodium-iodide scintillometer. A value of 10 μR/hr was established as the average background level, but the values ranged from 6 to 13 μR/hr.(1) Previous measurements of background radiation(3) indicated an average background of 20 μR/hr in the area surrounding the site with a range from 20 to 40 μR/hr.

Cosmic rays contribute to background radiation levels. The contribution from cosmic rays is generally dependent upon the altitude and is approximately 5 μR/hr in the Tuba City area,[4] or approximately 50% of the average measured background value.

3.4 RADIATION EXPOSURE PATHWAYS AND CONTAMINATION MECHANISMS

As noted previously, the principal environmental radiological implications and associated health effects of uranium mill tailings are related to radionuclides of the ^{238}U decay chain: primarily ^{230}Th, ^{226}Ra, ^{222}Rn, and ^{222}Rn daughters. Although these radionuclides occur in nature, their concentrations in tailings material are several orders of magnitude greater than in average natural soils and rocks. The major potential routes of exposure to man are:

(a) Inhalation of the ^{222}Rn daughters, from decay of ^{222}Rn escaping from the pile; the principal exposure hazard is to the lungs.

(b) External whole-body gamma exposure directly from the radionuclides in the tailings pile (primarily from ^{214}Bi) and in surface contamination from tailings spread in the general vicinity of the pile.

(c) Inhalation of windblown tailings; the primary hazard relates to the alpha emitters ^{230}Th and ^{226}Ra, each of which causes exposure to the bones and the lungs.

(d) Ingestion by man of ground or surface water contaminated from either radioactivity (primarily from ^{226}Ra) leached from the tailings pile or from solids physically transported into surface water.

(e) Erosion and removal of tailings material from the pile by flood waters or heavy rainfall; this can create additional contaminated locations with the same problems as the original tailings pile.

(f) Physical removal from the tailings pile also provides a mechanism for contamination of other locations.

(g) Contamination of food through uptake and concentration of radioactive elements by plants and animals is another pathway that can occur; however, this pathway was not considered in this assessment.

The extent of radiation and pollution transport from the pile into the environment is discussed in the following paragraphs.

3.4.1 Radon Gas Diffusion and Transport

Field measurements of the radon exhalation flux from the tailings using the charcoal canister technique[5] are shown in Figure 3-4. The values range from 11 to more than 400 pCi/m^2-s on the tailings pile and evaporation pond areas. Radon flux depends principally on radium content of tailings. In general, reported values of radon flux vary considerably from time to time at a single sampling location. This variation is due, in part, to differing moisture, soil, and climatological factors, to major changes in pile configuration between different locations, and to the difficulty of performing such measurements.

Radon gas exhaling from the pile has been detected 0.2 mi north of the site. At this location, radon concentrations are at about background levels during the daytime, but at night the concentrations rise above the background level. The 24-hr average concentration was 1.2 pCi/l. This behavior during the study period was probably due to an inversion condition and reduced wind velocity, which minimized dispersion and allowed radon to accumulate at greater distances from the pile at night. The location and corresponding 24-hr average radon concentrations are illustrated in Figure 3-3. Even though the measurement time for each sample was only 24 hr, the values were obtained during atmospheric conditions normal at that time of year. Data were not recorded during rainstorms. The only other measurement known[3] indicated a background value of radon concentration (0.2 pCi/l) at a distance of 0.2 mi north of the tailings. The value was determined from a grab sample taken in the morning during unstable atmospheric measurements when the radon had been dispersed.

The variation of radon concentration during the measurement period and the existing weather conditions are shown in Figures 3-5 and 3-6. The sample location for Figure 3-5 is on top of the tailings pile and the sample location for Figure 3-6 is at the housing area north of the millsite. The increased radon concentration at night is evident in Figure 3-5 on the tailings but is barely discernible in Figure 3-6.

The measured radon concentrations are plotted in Figure 3-7 as a function of distance from the edge of the tailings pile. Also shown in this figure are predictions of the radon concentrations as a function of distance. The model considers radon transport by Gaussian diffusion[6] using dispersion coefficients for neutral stability conditions. As indicated in Figure 3-7, the measurements of radon around the Tuba City site area are about two to three times background from 0.25 to 0.5 mi. These predicted radon concentrations, shown in Figure 3-7, were used to calculate potential health effects resulting from radon diffusing from the Tuba City tailings.

3.4.2 Direct Gamma Radiation

The external gamma radiation (EGR) levels measured on the tailings with an energy compensated Geiger Mueller detector are shown in Figure 3-8.[1] The gamma levels measured in the area surrounding the pile are shown in Figure 3-9.

The highest gamma radiation (2,600 μR/hr) was measured on the tailings pile toward the west edge of the site. Gamma measurements in the mill and ore storage areas were less than 100 μR/hr, except for one small area near the tailings where readings reached 150 μR/hr.

The reduction of gamma radiation as a function of distance from the pile is shown in Figure 3-10. The gamma radiation decreases to background range at about 0.25 mi from the edges, except to the northeast where there are no inhabitants between the pile and the highway. In that direction, windblown tailings cause elevated gamma readings as far as 0.7 mi from the edge of the pile.

3.4.3 Windblown Contaminants

Another pathway through the environment is the result of windblown tailings deposited off the tailings site. Windblown tailings are apparent over a large area northeast of the tailings. Figure 3-11 indicates iso-exposure lines due to the residual windblown tailings as determined by the EPA.[7] If scattered tailings and ore are removed from inside the 10 μR/hr line (toward the pile), and if the pile is removed or covered to provide essentially complete gamma shielding, then the remaining tailings outside the line (away from the pile) would produce a new gamma exposure rate, 3 ft above ground, approximately equal to 10 μR/hr. A 40 μR/hr line also was determined by a similar method and is illustrated in Figure 3-11.

Surface soil samples were taken in the area surrounding the site. The sample locations and ^{226}Ra concentrations are shown in Figure 3-12. In the northeasterly direction, ^{226}Ra concentration is high as a result of the windblown tailings. Just south of U.S. Highway 160 and about 0.7 mi northeast of the tailings, the ^{226}Ra concentration is 20 times background concentration. At 1 mi, the concentration is about six times the average background value.[1]

Measurements and data analyses were performed in 1980 to establish the boundary of that region around the site that exceeds 5 pCi/g of ^{226}Ra concentration in the soil believed to be due to windblown contamination. A lead-shielded scintillometer, NaI(TL), was used. The scintillometer had one unshielded end directed toward the ground and was held about 1 in. above the ground surface. After obtaining an unshielded reading, a 0.5-in.-thick lead shield was placed over the unshielded end and a second reading was obtained. The difference, called "delta", between the unshielded and shielded readings represents the exposure at the surface at that location. A difference of about 400 counts/min between the unshielded and shielded count rates has been estimated to indicate an area with a soil concentration of about 5 pCi/g of ^{226}Ra with the meter used.

Nine traverses with the scintillometer were conducted across open lands adjacent to the tailings pile and were continued until a soil contamination of 5 pCi/g of ^{226}Ra was indicated. The traverses are shown in Figure 3-13 and the location of 5 pCi/g of ^{226}Ra is marked on each traverse. These points were connected to indicate the area surrounding the site that is contaminated in excess of 5 pCi/g of ^{226}Ra. The resulting boundary was found to be in good agreement with the background contour of the 1975 EPA gamma survey and also with the results of an aerial radiological survey carried out by EG&G in April 1977.(8)

Two soil samples collected in 1980 about 0.5 mi east and northeast of the site were found to have elevated levels of ^{226}Ra, 6.6 and 12.7 pCi/g, respectively. It may be that the higher concentrations of ^{226}Ra in these soil samples are due to windblown tailings.

The area of windblown contamination in excess of 5 pCi/g of ^{226}Ra outside the site boundaries was estimated to be about 250 acres. This estimate may differ from the actual area due to the coarseness of measurements on which the estimate is based.

Previous measurements(2) by the EPA-LV of airborne particulate concentrations in Tuba City are shown in Table 3-3. At the time of the measurements, the airborne concentrations of ^{226}Ra and ^{230}Th were well below the maximum permissible concentrations at the two locations. Other air sampling measurements in 1969(3) indicated that ^{226}Ra concentration was 0.0056 pCi/l or about 5 times the most restrictive concentration guideline at a station 200 ft east of the tailings. The ^{226}Ra concentration in air at the housing area was 1% of the recommended maximum value.(3)

3.4.4 Ground and Surface Water Contamination

Four water samples were taken around the tailings site,(1) as shown in Figure 3-12. Two samples were taken from the Moenkopi Wash, which runs southwest about 1 mi southeast of the tailings pile. These samples contained 1.24 and 0.37 pCi/l of ^{226}Ra, with the higher ^{226}Ra concentration taken upstream and closer to the pile. The sample taken from a spring 1 mi east of the tailings pile had a ^{226}Ra concentration of 0.46 pCi/l. The sample obtained from a well 2 mi northeast of the tailings pile contained 1.09 pCi/l. While the ^{226}Ra concentrations in all four samples were well below the EPA Interim Primary Drinking Water Regulations limit of 5 pCi/l of combined ^{226}Ra and ^{228}Ra, the ^{226}Ra concentration in the water in the vicinity of the tailings had apparently increased since the measurements were taken in 1967.(3) Consequently, the radon content in the ground water in the vicinity of the Tuba City tailings pile should be measured periodically to assure that the ground water continues to meet drinking water standards. No ground water was encountered in any drill holes on the tailings pile.

3.4.5 Soil Contamination

The amount of ^{226}Ra activity in the tailings and the extent of leaching of radium from the tailings into the soil were determined by drilling boreholes through the tailings and into the soil beneath both the tailings and evaporative ponds. The radioactivity profile was measured in these holes with a Geiger Mueller tube probe which collimates the radiation. Soil samples were taken with a Shelby tube sampler from selected holes for radiometric analysis.(1) Additional holes were drilled in the mill area. The locations of the boreholes are indicated in Figure 2-5.

Typical radium activity profiles in the Tuba City tailings and subsoil are shown in Figures 3-14 and 3-15. The variations in the radioactivity of the tailings noted in the profiles are due to variations in the grade of ore processed and the method of tailings deposition. Figure 3-14 presents the profile for hole TCA-10 on the west side of the tailings pile. Measurements indicated about 2 ft of contaminated soil beneath the pile. Figure 3-15 illustrates the ^{226}Ra activity in borehole TCA-5, drilled through the tailings pile on the eastern portion of the site. Five feet below the soil-tailings interface, the ^{226}Ra concentration reaches approximately twice the average background level. In other holes the ^{226}Ra concentrations in the tailings pile were measured as high as 1,900 pCi/g.

Subsoil contamination was measured in four shallow holes drilled in the mill area. In each case, the soil contamination decreased to the average background value within 2 to 3 ft. More extensive drilling was performed during an EPA survey to determine contours of subsurface contamination. Results were discussed in Appendix B of the 1977 engineering assessment.

Figure 3-16 shows that typically the radium concentration is about 5 pCi/g at 2 ft below the soil-tailings interface.

3.4.6 Off-Site Tailings Use

Uranium tailings have been located around occupied houses in the mill housing area and around the nearby playground. In all cases, the tailings appear to have been carried to these locations by wind. These locations have been identified by mobile and follow-up gamma surveys and are discussed in Chapter 7.

3.5 REMEDIAL ACTION CRITERIA

The criteria for remedial action which were adopted as a basis for the engineering assessments that preceded the enactment of PL 95-604, the Uranium Mill Tailings Radiation Control Act of 1978, applied to: (a) the cleanup of structures[9] where tailings are present, and (b) the cleanup of open land.

Prior to passage of PL 95-604, the criteria applied to structures were the guidelines established by the U.S. Surgeon General by letter of July 27, 1970, to the Director of the Colorado Department of Health for use in dwellings constructed with or on tailings. The guidelines were expressed in terms of external gamma radiation and radon daughter concentrations.

By letter of December 1974, the EPA provided radiological criteria for decontamination of inactive uranium millsites and associated contaminated land areas. These criteria were expressed in terms of the "as low as practicable" philosophy and required that after remedial action has been completed, the residual gamma radiation levels should not exceed 40 μR/hr above background in unusual circumstances and must be near background levels in most cases. Furthermore, these criteria required that cleanup of radium contamination should reduce the soil concentration of radium to less than twice background. The stabilized tailings area should be designated as a controlled area, restricted from human occupancy and fenced to limit access. However, open land areas where residual gamma levels were less than 10 μR/hr above background were allowed to be released for unrestricted use.

Title II, Section 206 of PL 95-604 required the EPA to promulgate standards for the protection of the public and the environment from radiological and nonradiological hazards associated with residual radioactivity (as defined in the Act) at inactive uranium mill tailings and depository sites. The EPA subsequently published both interim cleanup standards (45 FR 27366) and proposed disposal standards (46 FR 2556).

3.5.1 EPA Interim and Proposed Standards

The interim cleanup standards and the proposed disposal standards require that remedial actions be conducted to provide reasonable assurance that:

(a) For a period of at least 1,000 yr following disposal:

(1) Radon released from the disposal site to the atmosphere would not exceed 2 pCi/m^2-s;

(2) Substances released from the disposal site to underground sources of drinking water would not contaminate the water in excess of limits described in the tabulation below; and,

(3) Substances released from the disposal site to surface waters would not contribute to contamination otherwise existing in the water.

Substance	mg/l
Arsenic	0.05
Barium	1.0
Cadmium	0.01
Chromium	0.05
Lead	0.05
Mercury	0.002
Molybdenum	0.05
Nitrogen (in nitrate)	10.0
Selenium	0.01
Silver	0.05
	pCi/l
Combined ^{226}Ra and ^{228}Ra	5.0
Gross alpha particle activity (including ^{226}Ra but excluding radon and uranium)	15.0
Uranium	10.0

(b) The average concentration of ^{226}Ra attributable to residual radioactive material from any designated processing site in any 5-cm thickness of soils or other materials on open land within 1 ft of the surface, or in any 15-cm thickness below 1 ft, shall not exceed 5 pCi/g.

(c) The levels of radioactivity in any occupied or occupiable building shall not exceed either of the values specified in the listing below, because of residual radioactive materials from any designated processing site.

Average annual indoor radon decay product concentration--including background (WL)	0.015
Indoor gamma radiation--above background (mR/hr)	0.02

3.5.2 NRC Regulations on Uranium Mill Tailings

In the NRC's final regulations for uranium mill licensing requirements, amendments to 10 CFR Parts 40 and 150 incorporate licensing requirements for uranium and thorium mills including tailings and wastes into the Commission's regulations.

The amendments of Part 40, Section 40.2a, include the statement:

> Prior to the completion of the remedial action, the Commission will not require a license pursuant to this Part for possession of byproduct material as defined in this Part that is located at a site where milling operations are no longer active, if the site is designated a processing site covered by the remedial action program of Title I of the Uranium Mill Tailings Radiation Control Act of 1978. The Commission will exert its regulatory role in remedial actions, primarily through concurrence and consultation in the execution of the remedial action pursuant to Title I of the Uranium Mill Tailings Radiation Control Act of 1978.

In view of the foregoing and since under provisions of PL 95-604 a site on which tailings have been stabilized must be maintained under a license issued by the NRC, all uranium mill tailings disposal sites under PL 95-604 may eventually be subject to the criteria set out in Appendix A to Part 40. The criteria pertaining to tailings and waste disposal and stabilization that may apply in whole, or in part, to remedial action activities under PL 95-604 are summarized as follows:

<u>Criterion 1</u> - The disposal site selection process should be an optimization to the maximum extent reasonably achievable for long-term isolation of the tailings from man, considering such factors as remoteness, hydrologic and other natural characteristics, and the potential for minimizing erosion.

<u>Criterion 2</u> - To avoid proliferation of small waste disposal sites and thereby reduce perpetual surveillance obligations, with certain qualifications, byproduct material from in situ extraction operations and wastes from small remote above-ground extraction operations shall be disposed of at existing large mill tailings disposal sites.

Criterion 3 - The prime option for disposal of tailings is placement below grade. Where this is not practicable, it must be demonstrated that an above-grade disposal program will provide reasonably equivalent isolation of tailings from natural erosional forces.

Criterion 4 - If tailings are located above ground, stringent siting and design criteria should be adhered to. Factors to be considered include the following:

(a) Minimization of upstream catchment area

(b) Topographic features for wind protection

(c) Relatively flat embankment slopes

(d) Self-sustaining vegetative or riprap cover

(e) Earthquake impact avoidance

(f) Promotion of soil deposition

Criterion 5 - Steps shall be taken to reduce seepage of toxic materials into ground water to the maximum extent reasonably achievable.

Criterion 6 - Sufficient earth cover, but not less than 3 m, shall be placed over tailings or wastes at the end of milling operations to result in a calculated reduction in surface exhalation of radon from the tailings or wastes to less than 2 pCi/m^2-s above natural background levels. Direct gamma exposure from the tailings or wastes should be reduced to background levels.

Criterion 11 - Provisions are set out for eventual transfer of ownership of the tailings to the State or to the United States.

Criterion 12 - The final disposition of tailings or wastes at milling sites should be such that ongoing active maintenance is not necessary to preserve isolation. Annual inspections should be conducted by owners.

EPA proposed and interim environmental standards for uranium mill tailings stabilization are generally consistent with the NRC proposed criteria as given above. However, they add the important further condition that the stabilization should be designed to provide reasonable assurance of remaining effective for at least 1,000 yr.

3.6 POTENTIAL HEALTH IMPACT

An assessment has been made of the potential health impact of the tailings pile. The environmental pathways described in Paragraph 3.4 were evaluated. A summary of the evaluation of each pathway is presented below:

(a) Radon Diffusion - Inhalation of radon daughters from radon diffusion constitutes the most significant pathway and results in the largest estimated population dose.[1,10]

(b) External Gamma Radiation - Gamma radiation above background is measurable to distances up to 0.25 mi from the pile, an area containing no inhabited dwellings. Individuals on site will receive some gamma exposure until the pile is covered with sufficient material to reduce the gamma radiation to near background. Gamma radiation to the local population is a small fraction of the exposure from radon daughters.

(c) Airborne Activity - The limited, directional spread of significant quantities of windblown tailings toward inhabited areas indicates that direct inhalation or ingestion of tailings particles may be a minor component of the total population dose for the present population distribution. This is a general result also reported at other uranium tailings piles.[11,12] Stabilization of the Tuba City tailings against wind erosion will eliminate any gradual accumulation of tailings off the site.

(d) Water Contamination - The low ^{226}Ra activity in surface water away from the pile indicates little, if any, contamination from the tailings pile. Chemical analyses indicate that ground and surface water contain only selenium concentrations above the level of the EPA Interim Primary Drinking Water Regulations. The high selenium content was found to be indigenous to the Tuba City region.

(e) Subsoil Contamination - The limited extent of leaching of radioactive materials into the ground beneath the pile indicates this pathway results in negligible health effects.

(f) Physical Removal - Tailings that have been placed near a structure or used in its construction are sources of elevated gamma levels and radon daughter concentrations in the structure. Radiation exposure to individuals living or working in these structures can be significant. The off-site remedial action is described in Chapter 7.

Only the potential health effects from the inhalation of radon daughters (pathway a) are estimated quantitatively in this assessment because this pathway produces the most significant exposure.[9-11] Furthermore, the uncertainty in the estimates of the potential health effects from this pathway far exceeds the magnitude of the health effects from the other pathways.

It is extremely difficult to predict with any assurance that a specific health effect will be observed within a given time after chronic exposure to low doses of toxic material. Therefore, the usual approach to evaluation of the health impact of low-level radiation exposures is to make projections from observed effects of high exposures on the basis that the effects are linear, using the conservative assumption of no threshold for the effects. The resulting risk estimators also have associated uncertainties due to biological variability among individuals and to unknown contributions from other biological insults which may be present simultaneously with the insult of interest. No synergistic effects are considered explicitly in this analysis. For the purpose of this engineering study, lung cancer is the potential health effect considered for RDC. The health effects were estimated using the absolute risk model.

3.6.1 Assumptions and Uncertainties in Estimating Health Effects

Since radiation exposure from ^{222}Rn progeny is expressed in terms of working levels (WL) and working level months (WLM), total population exposures as well as health risk estimates are based upon these units; i.e., person-WLM. Exposures and resulting health effects are often expressed in terms of rems; however, estimates of the WLM-to-rem conversion factor for internal lung exposure to alpha particles from ^{222}Rn progeny are observed to vary by over an order of magnitude.[13] Presently, there are significant differences of opinion related to the choice of an appropriate conversion factor. Consequently, disagreements of calculated health effects from RDC occur when these effects are based on the rem.

The BEIR-III[14] risk estimator for lung cancer is based only on the absolute model since the relative risk model is not considered valid.[15]

The BEIR-III risk estimators for radon daughters are age-dependent, with the age specified as the age at the diagnosis of cancer. The minimal latent period following exposure is also age-dependent. The following values can be determined:

Age (yr)	Minimal Latent Period From Age at Exposure (yr)	Excess Risk at Age of Diagnosis (cancers per yr per 10^6 person WLM)
0-14	25	0
15-34	15	0
35-49	10	9
50-65	10	18
66-75	10	42

These risk values are expressed in terms of WLM using the BEIR-III recommended conversion factor of 6 rem per WLM. These risk estimators are based on combined estimates for uranium miners and fluorspar miners; no data exist that indicate whether these values may be used for groups irradiated in childhood. Nevertheless, in the treatment below they are conservatively assumed to apply to the population at large.

The BEIR-III report does not discuss plateau periods. However, some data presented in the report indicate cancers are still being detected as much as 50 yr after the period of exposure. Therefore, it is reasonable to assume that a lifetime plateau to age 75 may be applicable.

The age-dependent excess risks presented in the BEIR-III report must be adjusted, when applied to the population at large, to account for the fact that the breathing rate of miners on the job is about 1.9 times greater than that of the general population.(16) Since exposure is considered proportional to the breathing rate, the exposure (and hence the excess risk) of the general population would be smaller by this same factor.

The cumulative risk estimator is obtained from the BEIR-III data adjusted for breathing rate by determining specific cancer risks for each year following an exposure. These risks are summed for the years between age at exposure and age 75. The contribution to the cumulative risk estimator from each age group is weighted by the respective fractions of the U.S. population found in those age groups.(17) For the lifetime plateau to age 75, no cancers were assumed to occur in the years subsequent to age 75. The following cumulative risk estimator for the population at large is obtained using a lifetime plateau to age 75 and weighting by the age distribution of the U.S. population:

$$150 \text{ cancers per yr}/10^6 \text{ person - (WLM continuous)} \qquad (3\text{-}1)$$

Because of the many factors that contribute to natural biological variability and of the many differences in exposures among miners and among the population at large, this risk estimator is considered to have an uncertainty factor of about 3.

For the purpose of this assessment, equivalent working levels inside structures are determined from the radon concentration assuming a 50% equilibrium condition. This yields the following conversion factor:

$$1 \text{ pCi/l of } {}^{222}\text{Rn} = 0.005 \text{ WL} \qquad (3\text{-}2)$$

It is assumed that the component of indoor radon concentration due to radon originating from the pile is equal to the corresponding outdoor concentration component at that point. However, the total concentration of radon progeny is higher indoors owing to reduced ventilation, and to other sources such as building materials.

The exposure rate in terms of WLM/yr can be obtained from a continuous 0.005-WL concentration as follows:

$$(0.005 \text{ WL})(8766 \frac{\text{hr}}{\text{yr}})[\frac{1 \text{ WLM}}{(1 \text{ WL})(170 \text{ hr})}] = 0.25 \frac{\text{WLM}}{\text{yr}} \qquad (3\text{-}3)$$

The risk estimator used for continual exposure to gamma radiation is expressed as:(18)

$$72*\dot{D} + 0.8*\dot{D}^2 \text{ cancers per yr}/10^6 \text{ person rems/yr-continuous}$$

(3-4)

where $\dot{D}$ is the dose rate in rem/yr. In this assessment it is assumed that a gamma exposure of 1 R in air is equivalent to a dose of 1 rem in tissue.

3.6.2 Health Effects

The health effects due to radon transport from the Tuba City site in its present condition were calculated using a radon flux of 1,000 pCi/m^2-s for the tailings pile. This value was calculated using diffusion theory and the tailings physical properties. Even though the calculated value for radon flux appears much larger than the measured values, it is considered a more defensible estimate of the radon release rate since measurements of radon flux to date have been made only at a few points in time and give no suggestion of the magnitude of annual variations. In the absence of this information, the conservative estimate was chosen as the basis for health effect calculations.

The transport of radon from the tailings pile was modeled using a Gaussian plume model, meteorology characteristics of the Tuba City area, and the population distribution surrounding the tailings pile as a function of the radius and direction from the center of the site. The pile was modeled as a vertical cylinder with area and volume equivalent to the surface area and volume of the actual pile.

Total predicted outdoor ^{222}Rn concentration is shown in Figure 3-7, along with measured values, as a function of distance from the center of the pile in the north-northeast direction. The predicted ^{222}Rn concentration at 0.25 mi from the edge of the pile is about 3 times background levels but at 1 mi is only about 50% greater than background levels. The predicted radon concentration appears to be in general agreement with measured values.

The population distribution within 6 mi of the edge of the pile was developed using the best local statistics and other population information for the past decade. This distribution includes virtually all residents close enough to the pile to be exposed to any noticeable degree to radon emanating from the pile, as described in Chapter 4.

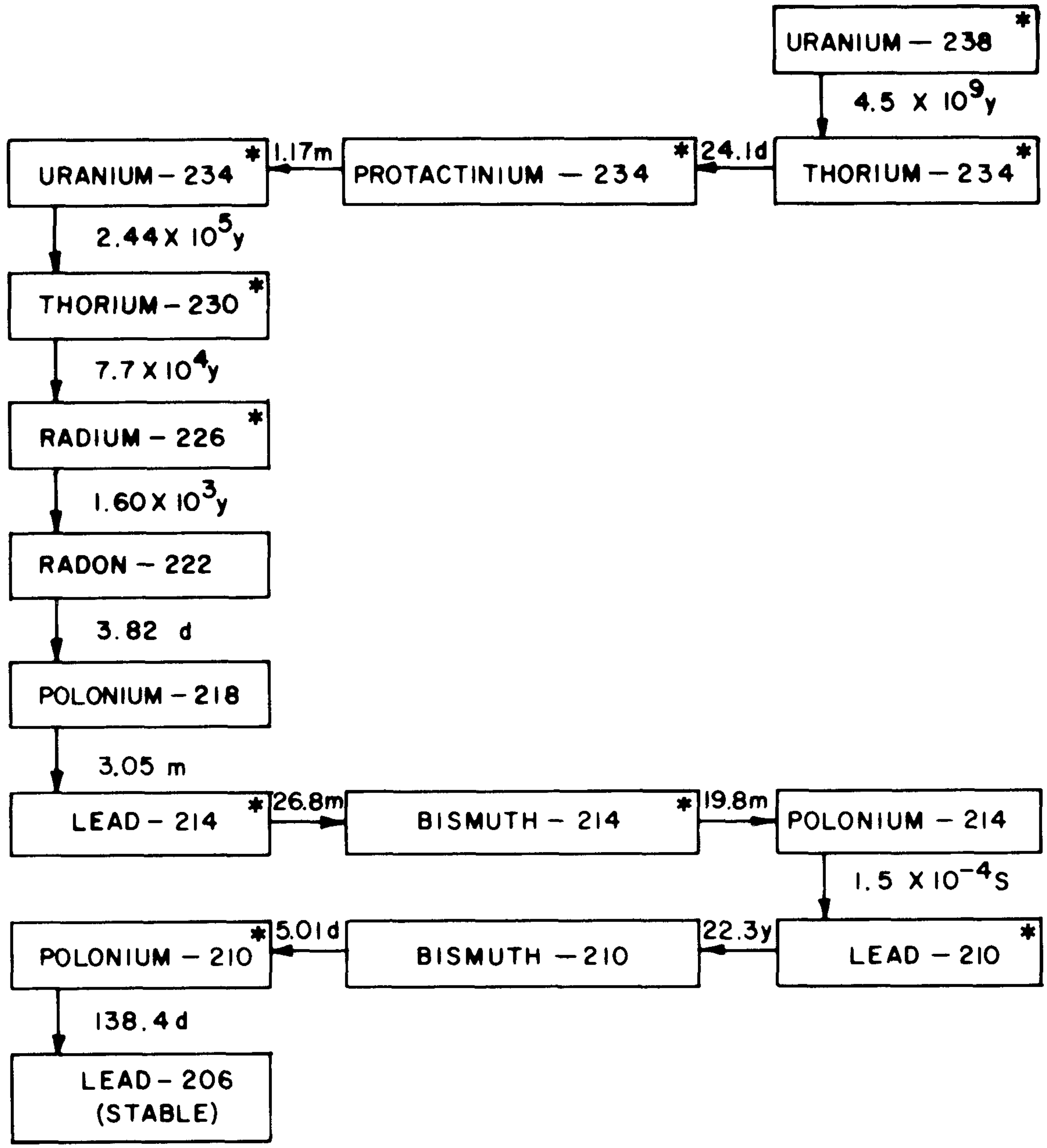
The three population projections used to estimate the cumulative health impacts attributable to the tailings pile are the 0.8% constant growth rate and the 4% and 6.4% declining growth rates, as discussed in Paragraph 4.2. All three growth projections assume that the population is distributed around the site in the same proportions as those reflected in Table 4-1.

Table 3-4 presents the estimated health impacts from the tailings pile for 0 to 6 mi from the edge of the pile, based on the estimated 1980 population distribution presented in Table 4-1. The cumulative health effects for the three growth scenarios considered for the Tuba City area are also included. In Table 3-4, the health effects from the pile radon are shown to be about 12% of those caused by background radon for the vicinity within 6 mi of the edge of the pile.

Figure 3-17 shows the lung cancer risk per year from continuous exposure to radon as a function of distance north-northeast of the edge of the tailings pile. The curve shows that the risk for developing lung cancer from radon emanating from the pile is about twice the natural occurrence from all causes at a distance of 0.25 mi from the edge of the site but declines to near the natural occurrence within 1 mi.

3.7 NONRADIOACTIVE POLLUTANTS

There are other potentially toxic materials in the tailings. Chemical analyses of tailings samples from drill holes in the Tuba City tailings showed arsenic, barium, and vanadium present in concentrations between 50 and 200 ppm. The highest selenium concentration was 12 ppm; the highest lead content was 1,050 ppm. The ground and surface water contained only selenium in concentrations above the level specified in the EPA Interim Primary Drinking Water Regulations (0.01 mg/l). The analyses of four water samples are presented in Table 3-5. The high selenium content was found in all water samples located in drainage areas above and below the tailings. This indicates a natural condition, which is a common occurrence on the Colorado Plateau[19] where high alkalinity and selenium occur together, but not attributable to the presence of the tailings.



NOTE:
VERTICAL DIRECTION REPRESENTS ALPHA DECAY, HORIZONTAL DIRECTION INDICATES BETA DECAY. TIMES SHOWN ARE HALF LIVES. ONLY THE DOMINANT DECAY MODE IS SHOWN.
* ALSO GAMMA EMITTERS

FIGURE 3-1. RADIOACTIVE DECAY CHAIN OF URANIUM-238

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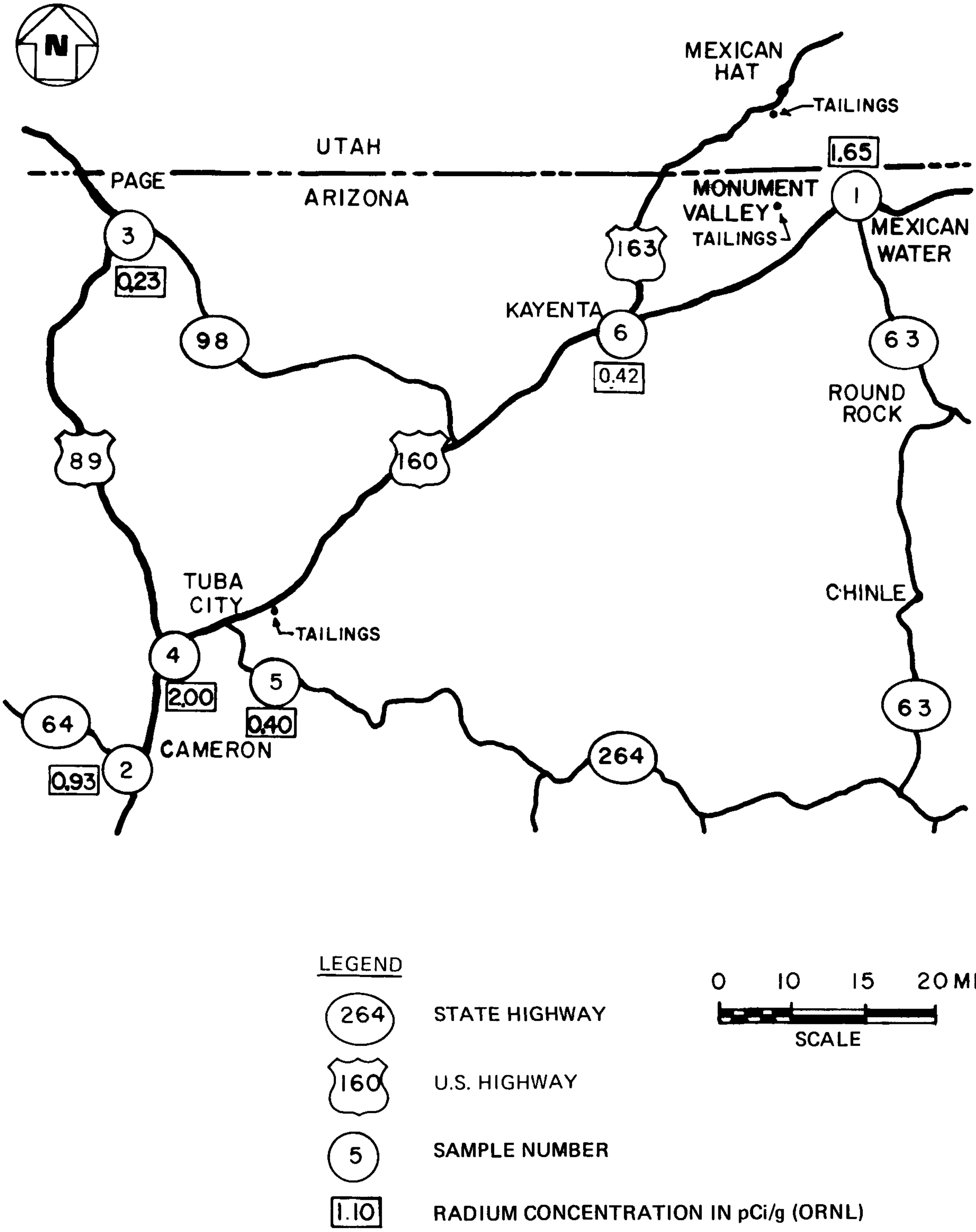
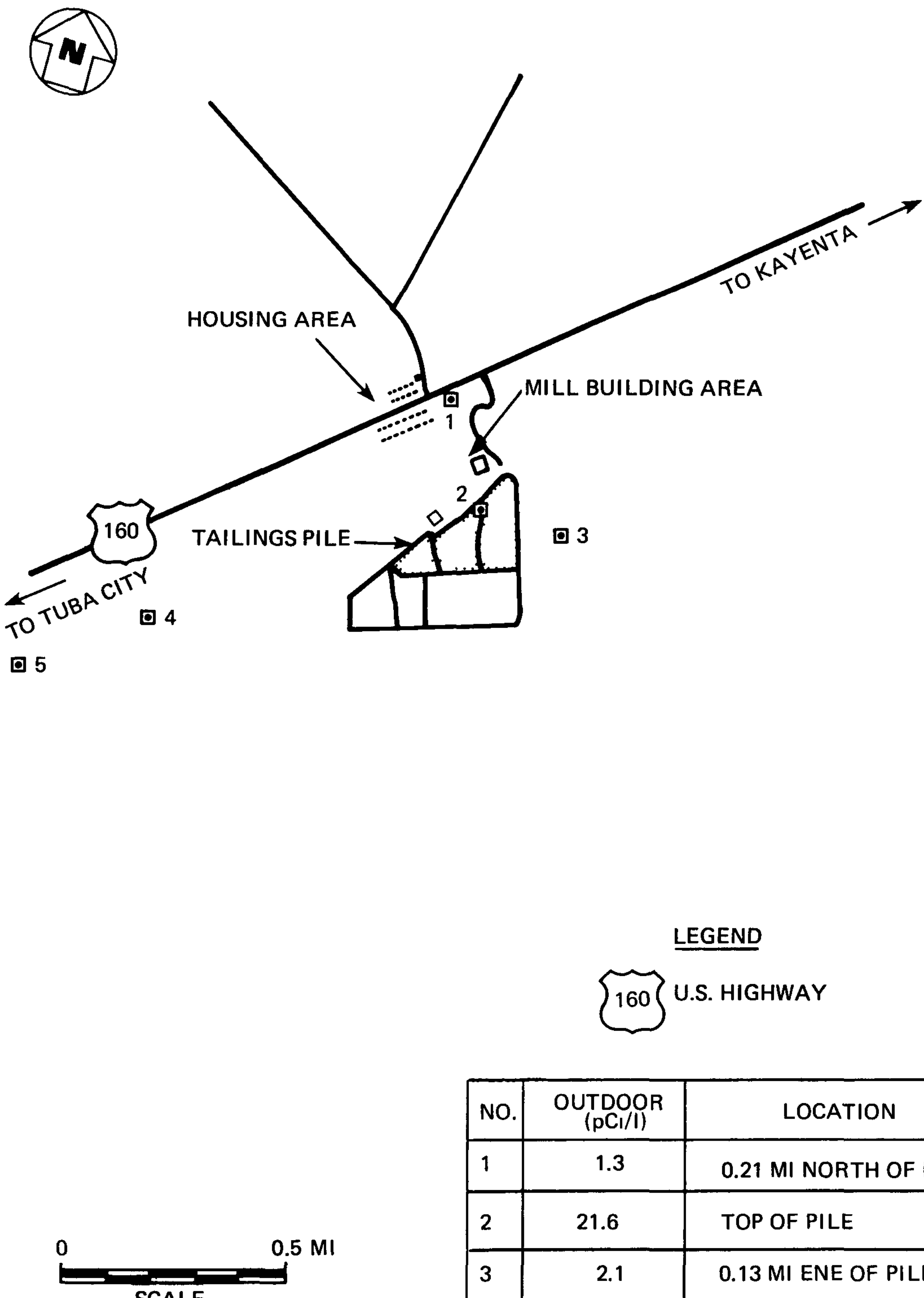


FIGURE 3-2. LOCATIONS FOR ^{226}Ra BACKGROUND SAMPLES

360-05 3/77



NO.	OUTDOOR (pCi/l)	LOCATION
1	1.3	0.21 MI NORTH OF PILE
2	21.6	TOP OF PILE
3	2.1	0.13 MI ENE OF PILE
4	1.2	0.5 MI WEST OF PILE
5	0.7	5.5 MI WEST OF PILE TUBA CITY COMMUNITY CENTER

FIGURE 3-3. RADON CONCENTRATION IN VICINITY OF PILE

360-05 3/77

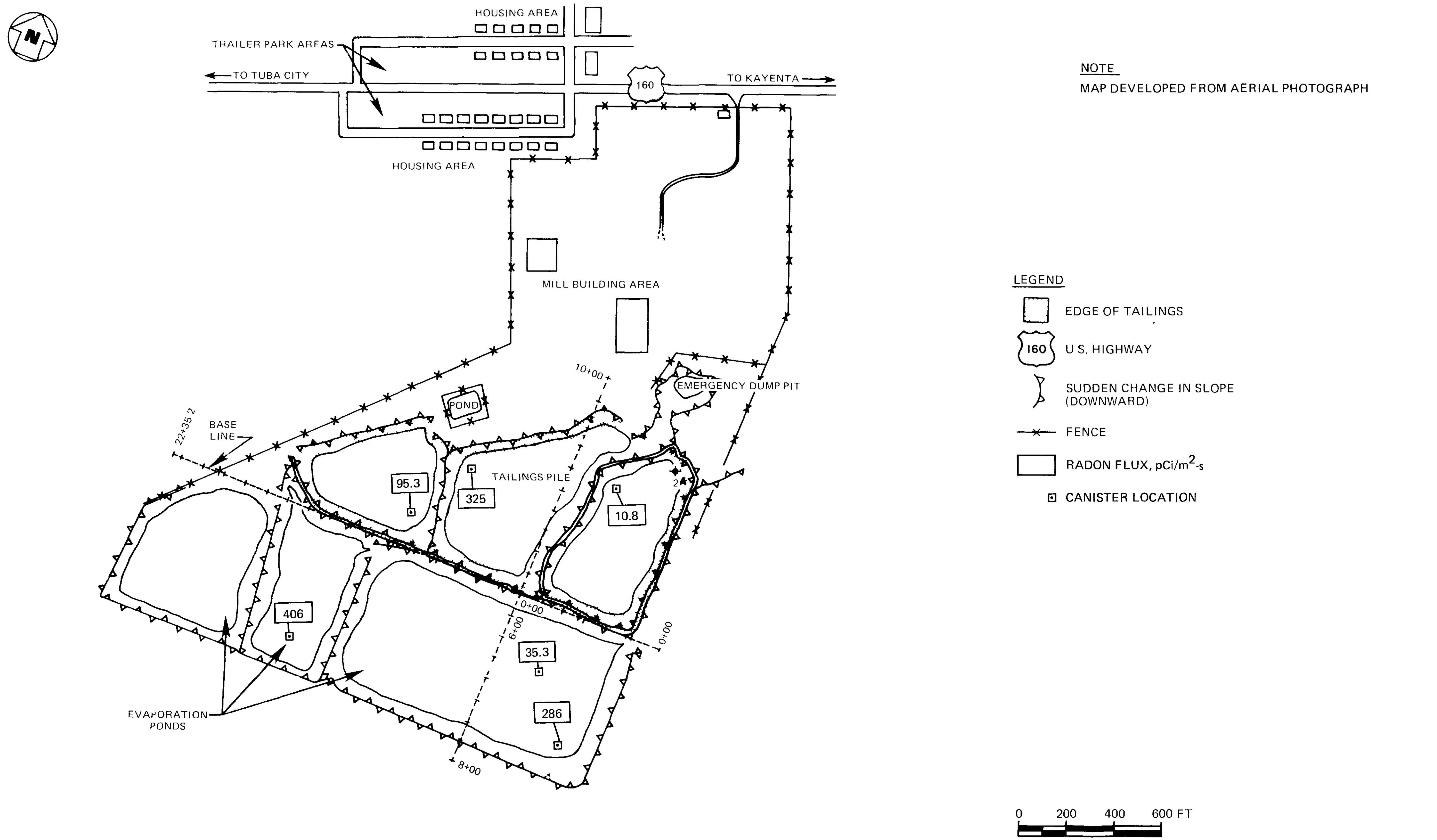


FIGURE 3-4. RADON CANISTER LOCATIONS AND FLUX VALUES

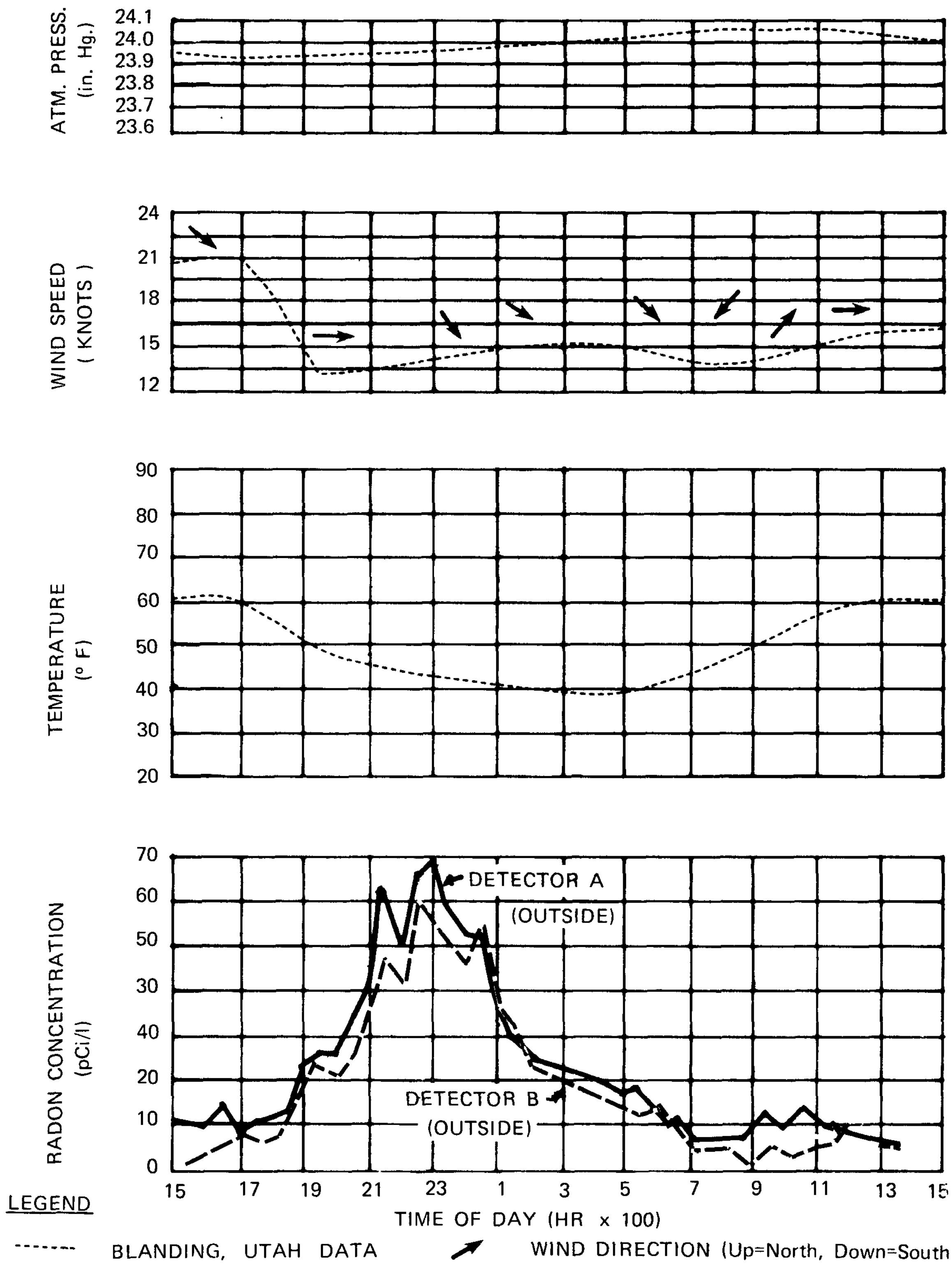


FIGURE 3-5. ^{222}Rn AND ATMOSPHERIC TRANSIENTS ON TOP OF PILE ON MARCH 23, 1976

360-05 3/77

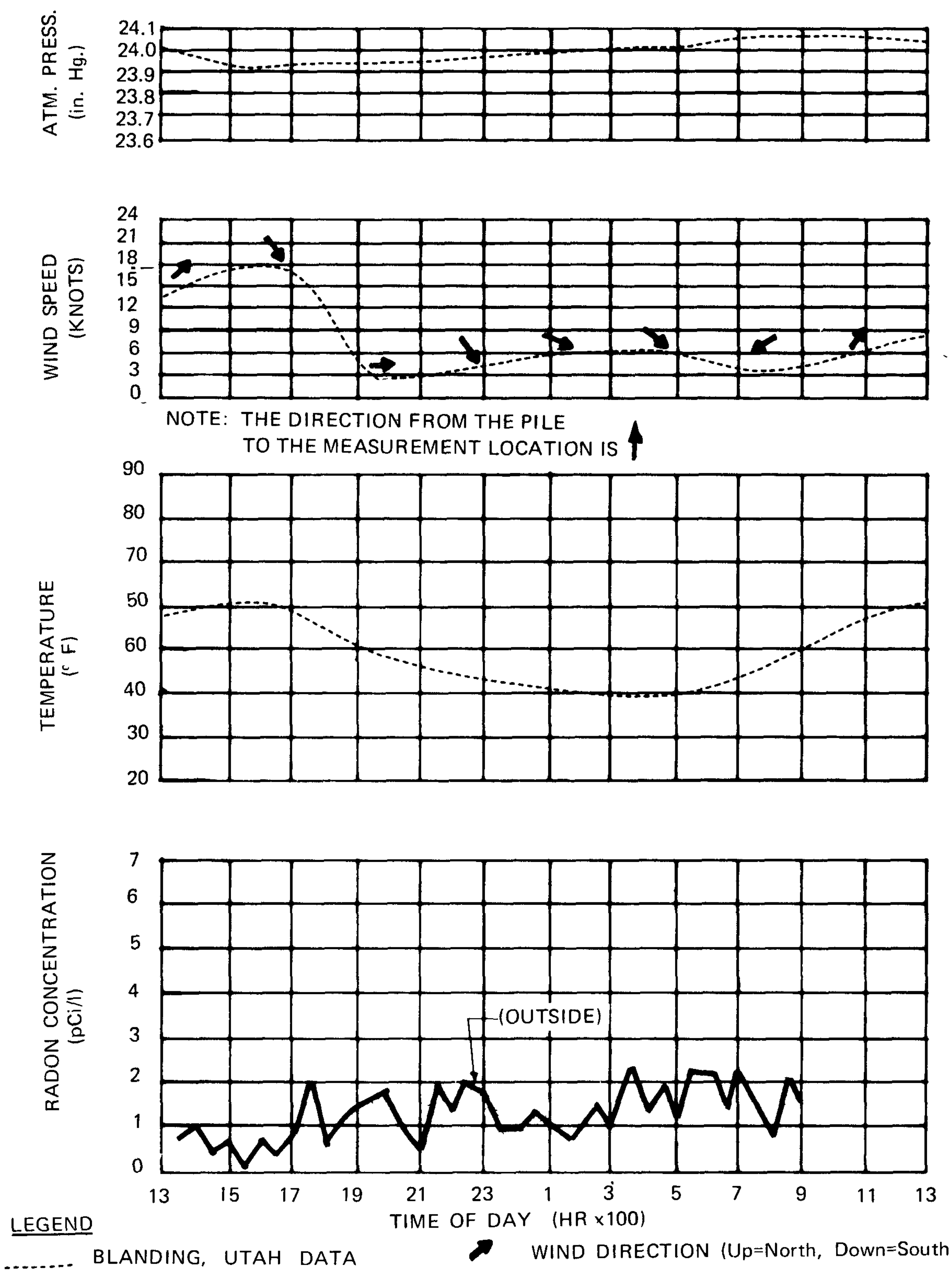


FIGURE 3-6. ^{222}Rn **AND ATMOSPHERIC TRANSIENTS AT HOUSING AREA, EAST END, ON MARCH 23, 1976**

360-05 3/77

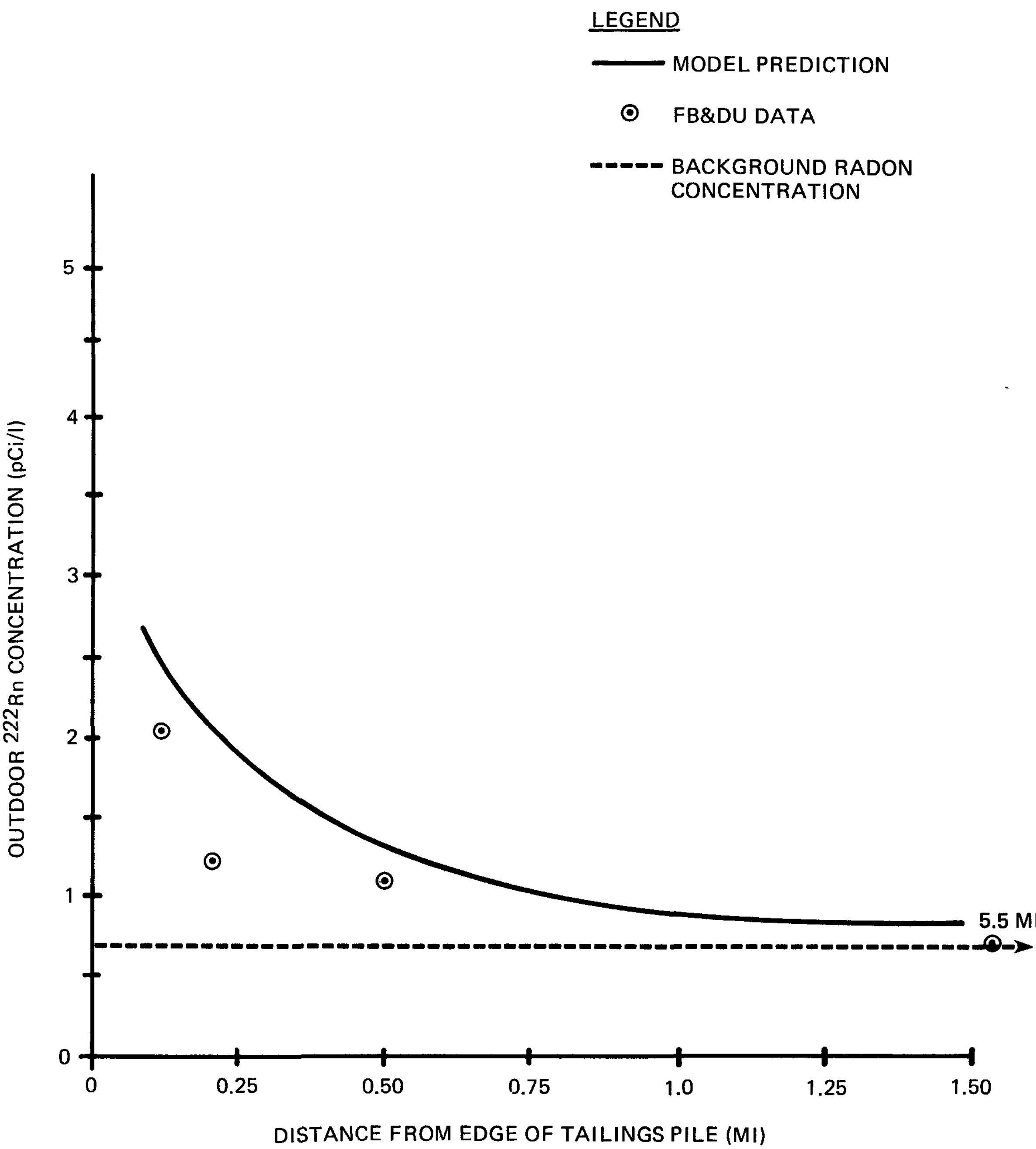
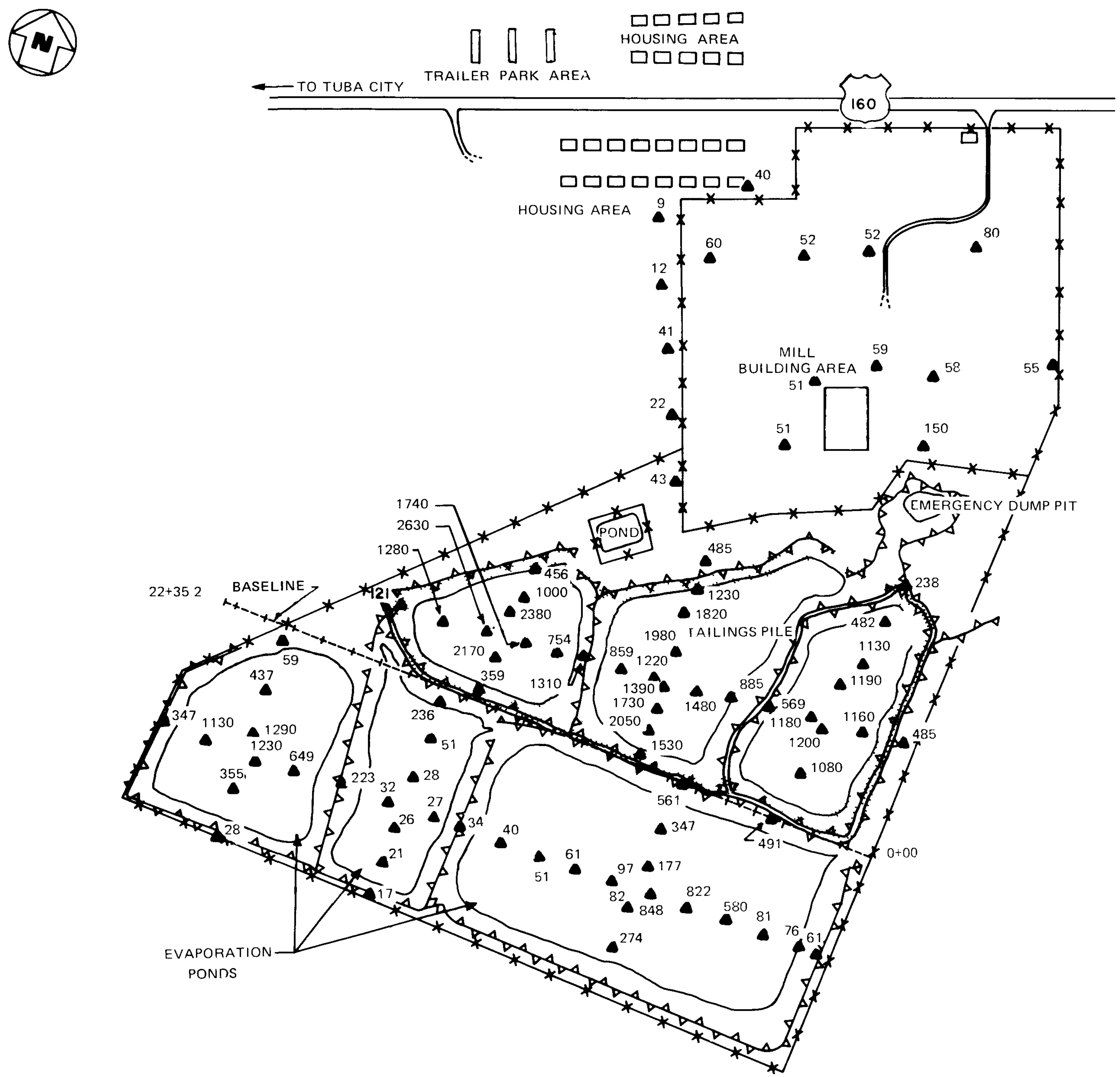


FIGURE 3-7. REDUCTION OF OUTDOOR ^{222}Rn CONCENTRATION WITH DISTANCE FROM THE TAILINGS PILE

360-05 REV 1/81



NOTE:

1. NUMBERS SHOWN ARE GAMMA LEVELS IN μR/hr (1)
2. MAP DEVELOPED FROM AERIAL PHOTOGRAPH

LEGEND

EDGE OF TAILINGS

0 200 400 600 FT
SCALE

FIGURE 3-8. GAMMA LEVELS 3 FT ABOVE GROUND

360-05 3/77

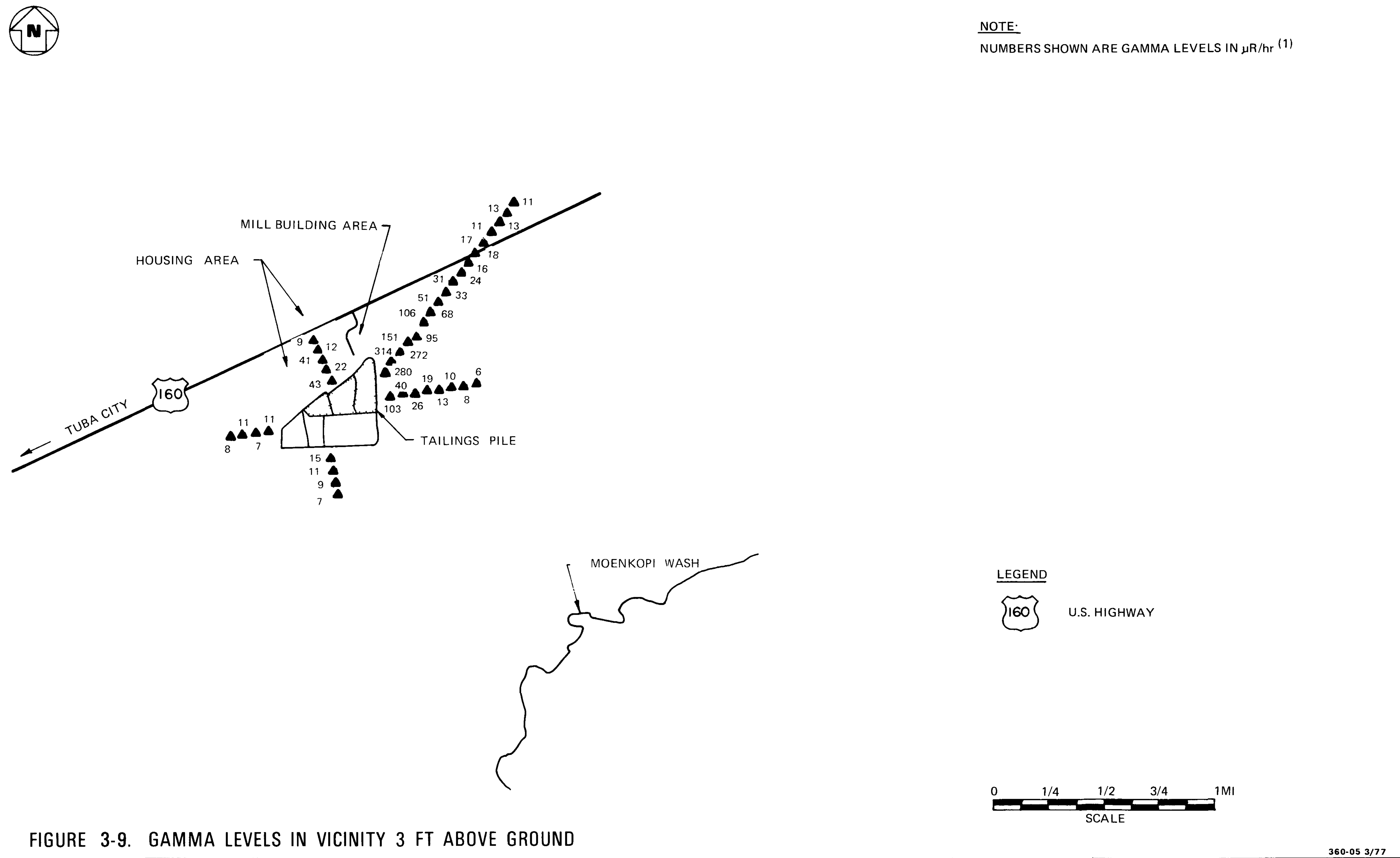


FIGURE 3-9. GAMMA LEVELS IN VICINITY 3 FT ABOVE GROUND

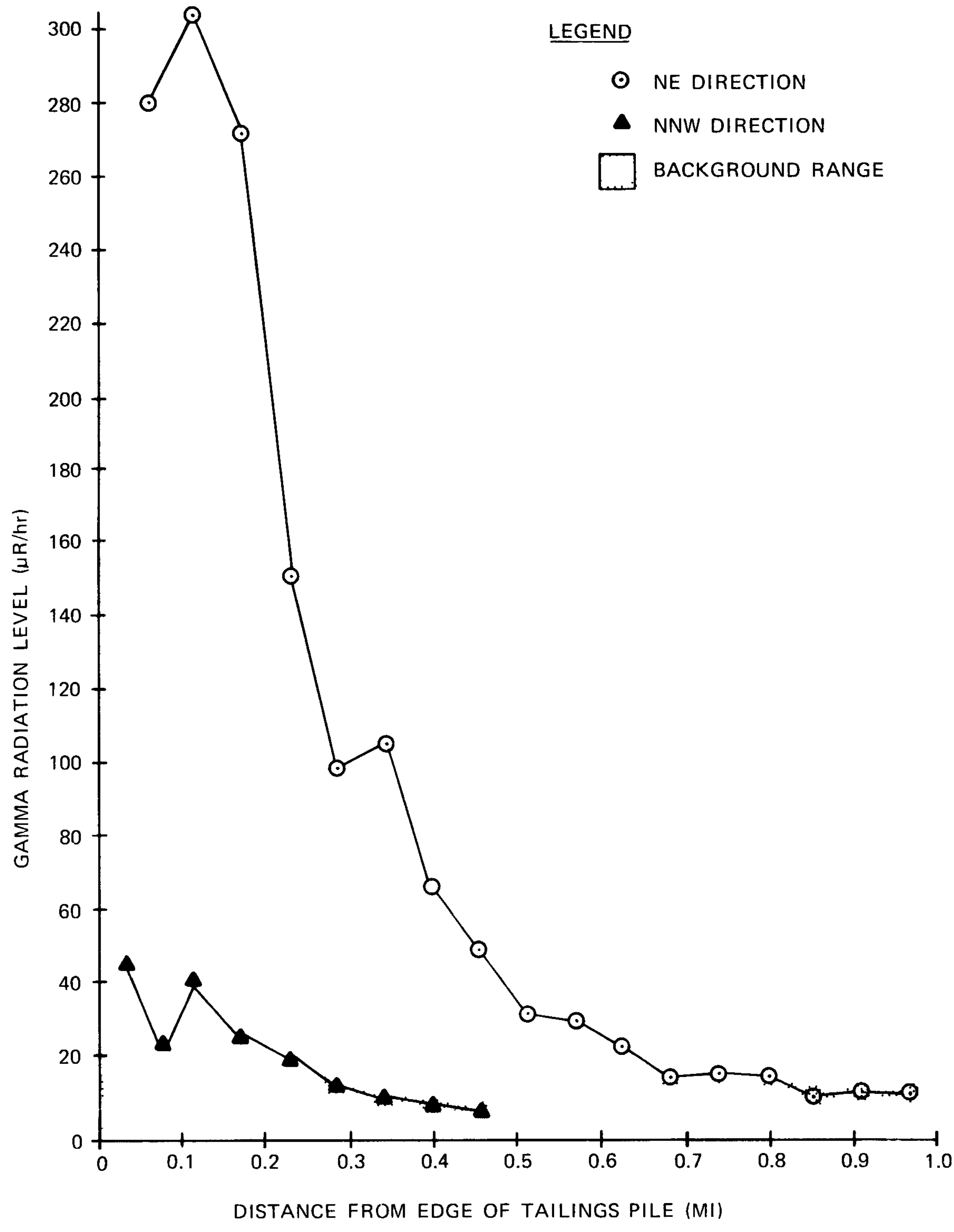


FIGURE 3-10. REDUCTION OF EXTERNAL GAMMA RADIATION LEVELS WITH DISTANCE FROM THE TAILINGS PILE

360-05 3/77

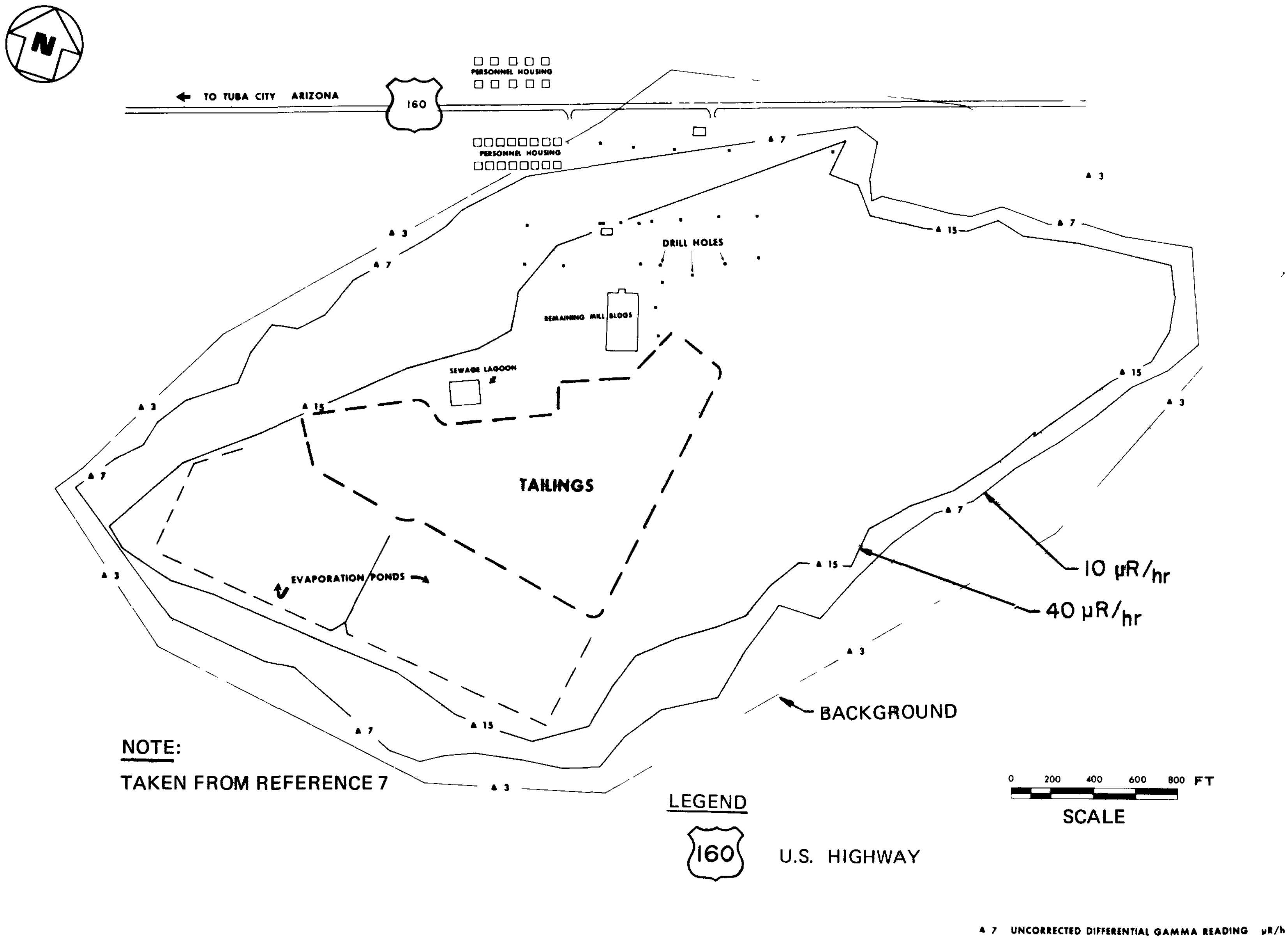


FIGURE 3-11. EPA GAMMA SURVEY SURROUNDING MILLSITE

360-05 3/77

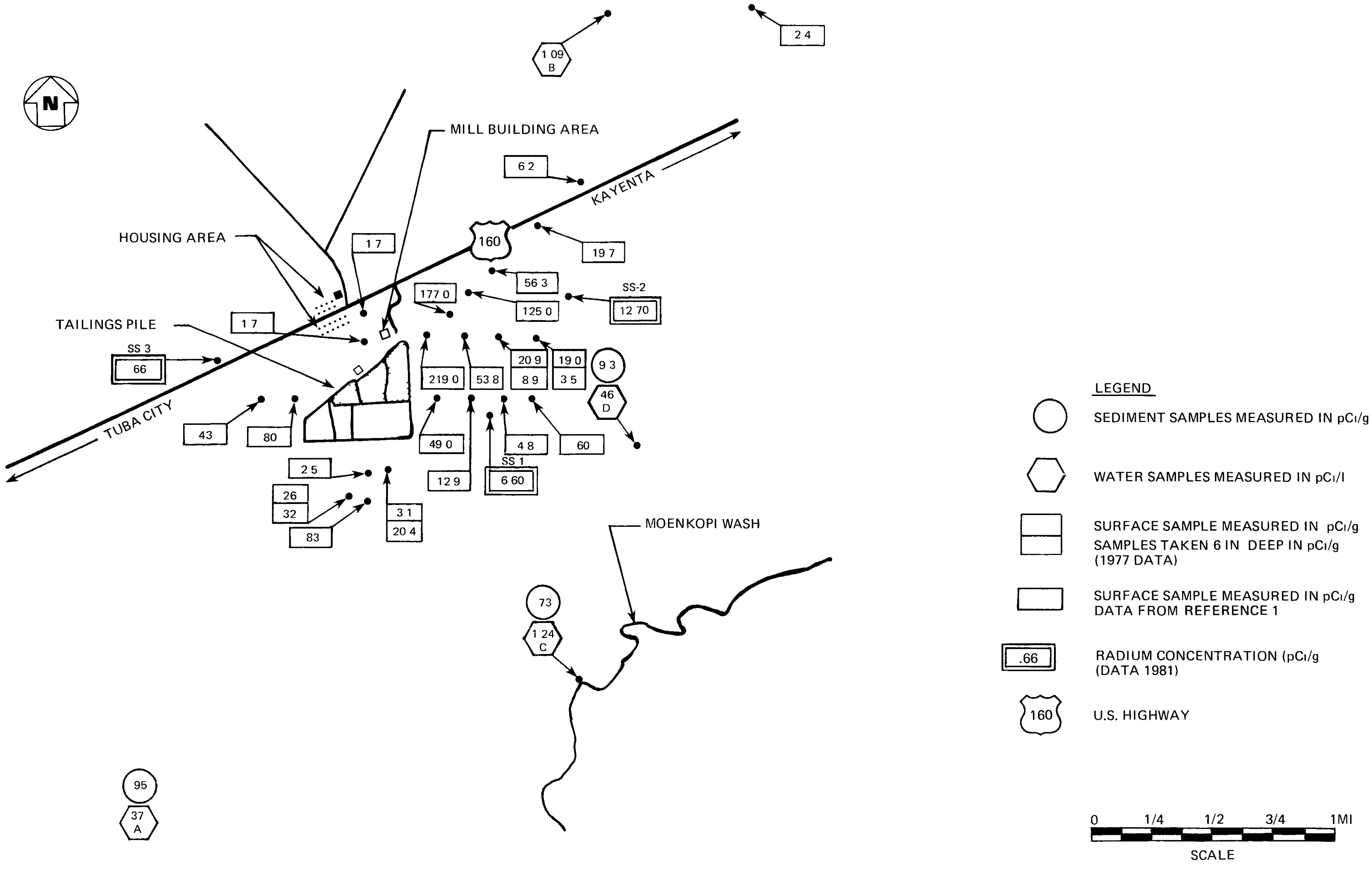


FIGURE 3-12. SURFACE AND SUBSURFACE RADIUM CONCENTRATIONS

360-05 REV 7/81

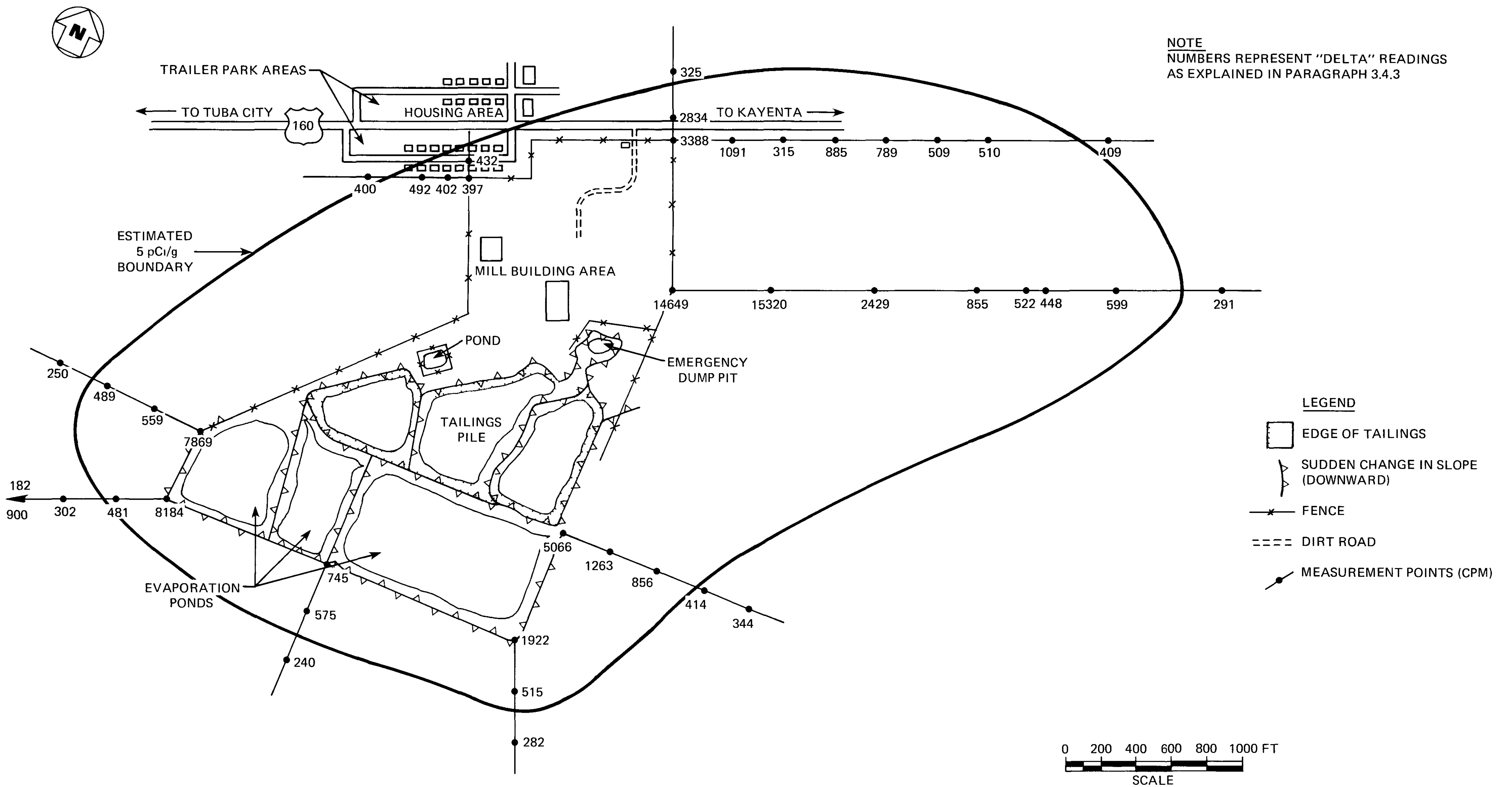


FIGURE 3-13. WINDBLOWN CONTAMINATION SURVEY

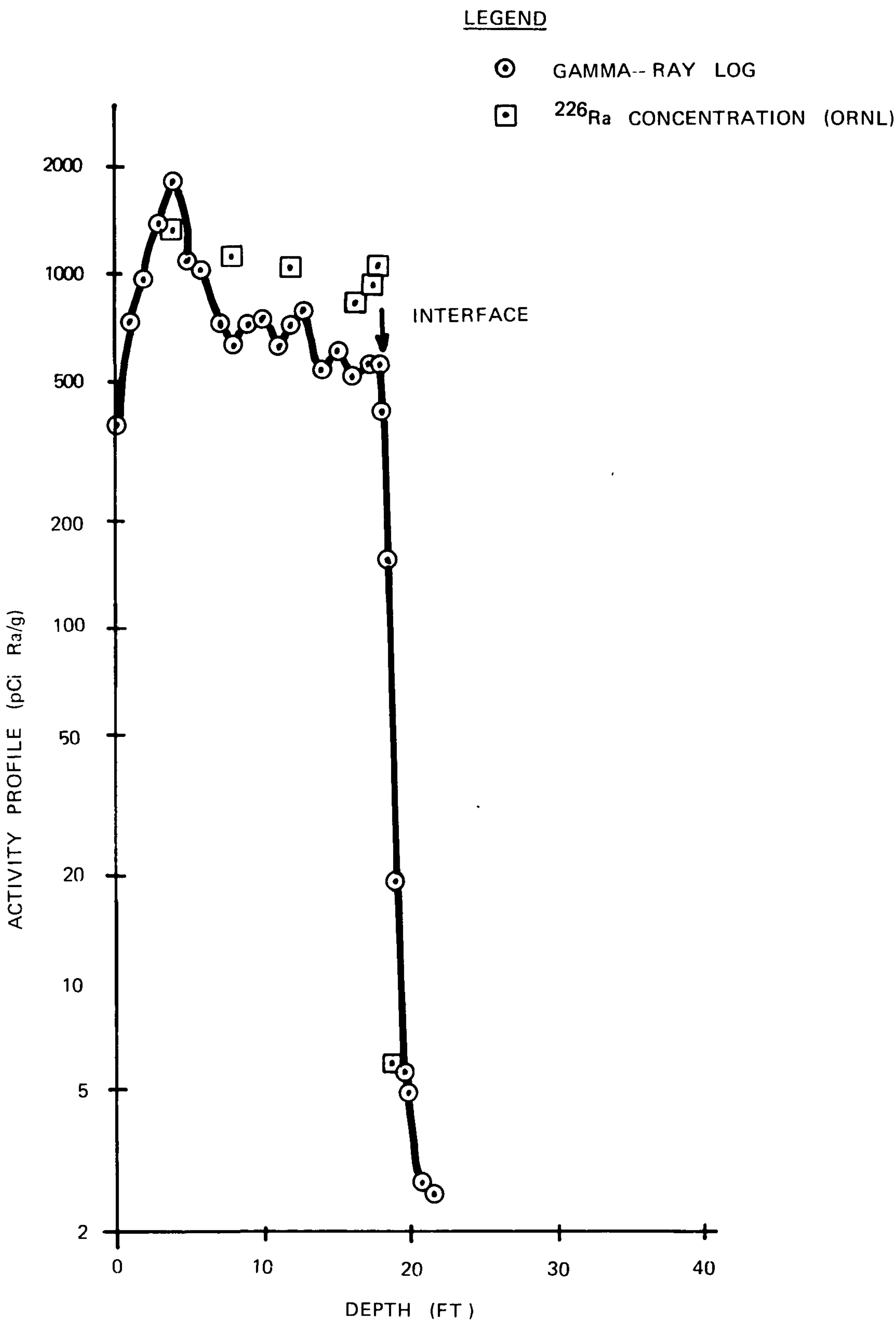


FIGURE 3-14. RADIOMETRIC PROFILE AT DRILL HOLE TCA-10

360-05 3/77

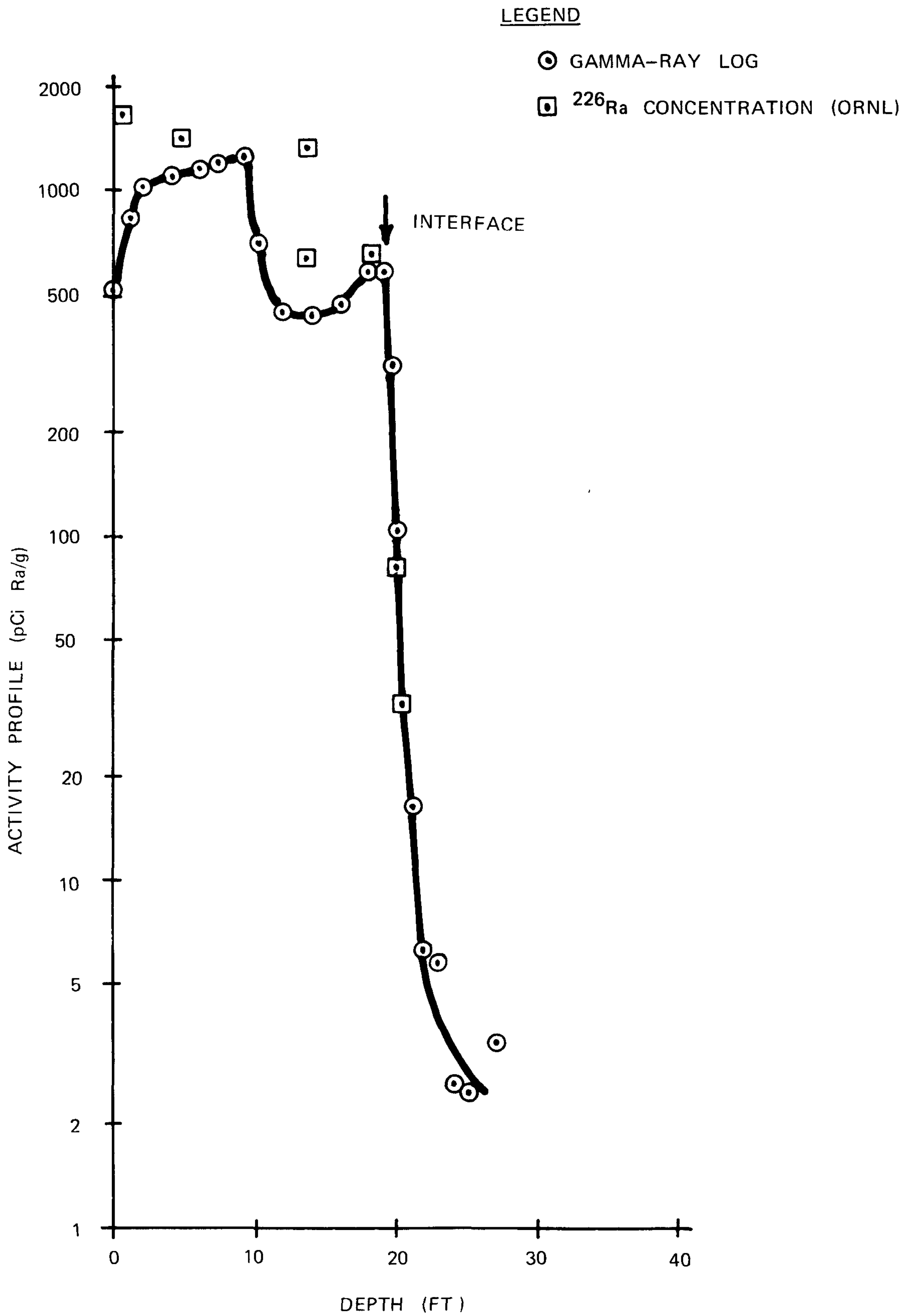


FIGURE 3-15. RADIOMETRIC PROFILE AT DRILL HOLE TCA-5

360-05 3/77

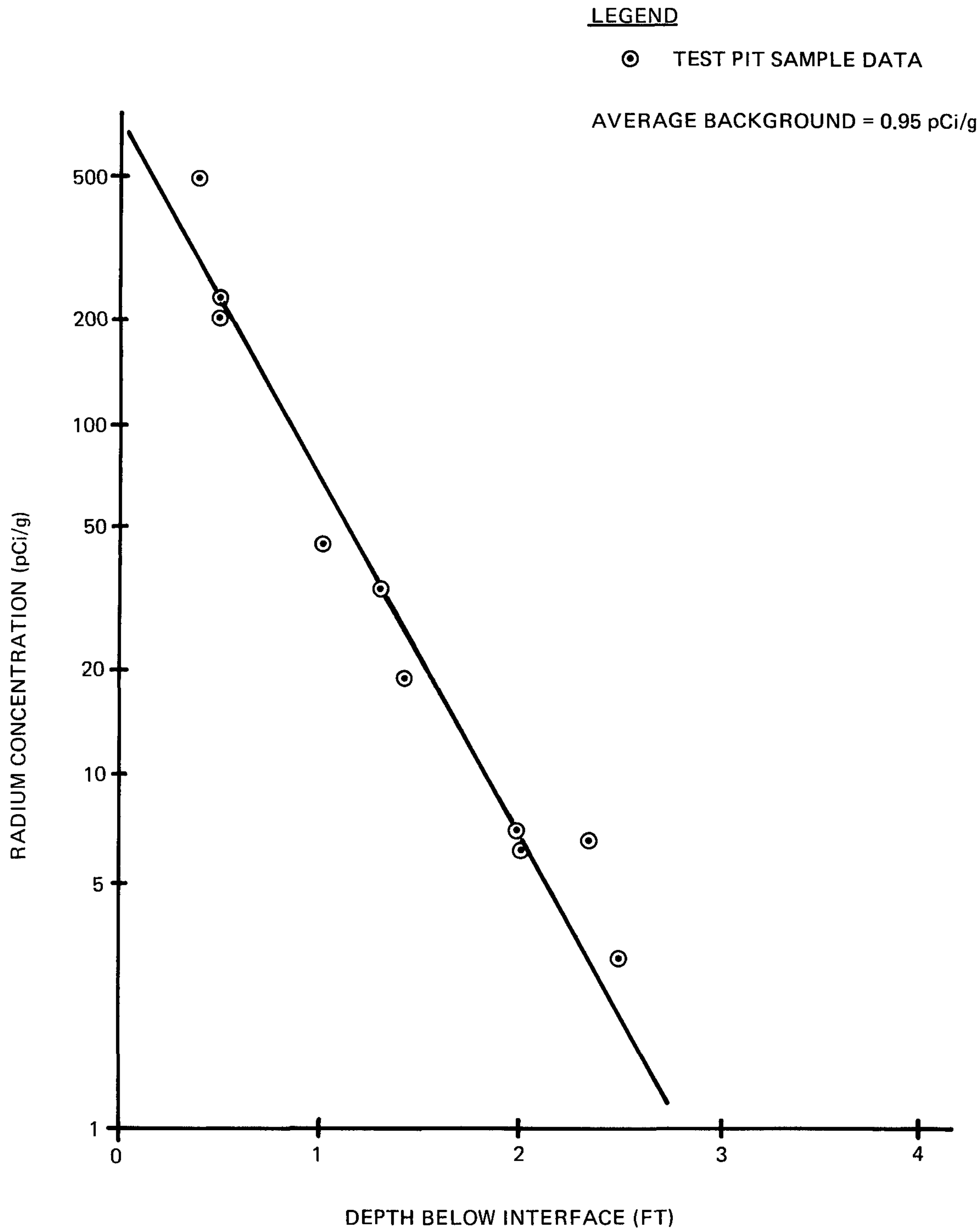


FIGURE 3-16. RADIUM ACTIVITY CONCENTRATION IN CONTAMINATED SUBSOIL

360-05 1/81

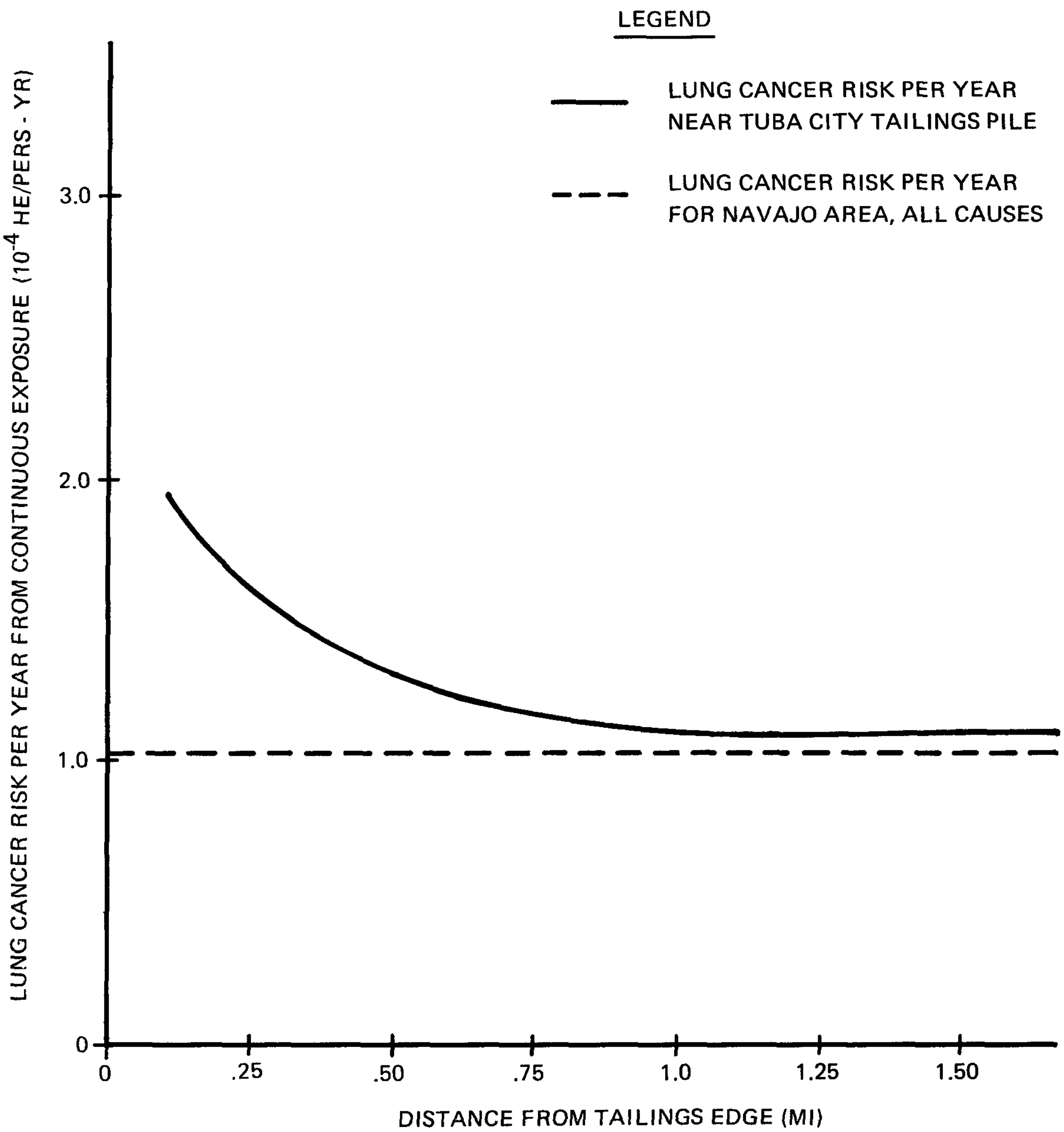


FIGURE 3-17. LUNG CANCER RISK FROM CONTINUOUS EXPOSURE TO RADON

360-5 REV 7/81

TABLE 3-1

NOTATIONS AND ABBREVIATIONS USED IN CHAPTER 3

Isotope - A particular type of element, differing by nuclear characteristics, identified by the atomic mass number given after the element name; e.g., Radium-226.

Isotope Abbreviations:

^{238}U = Uranium-238
^{234}Th = Thorium-234
^{232}Th = Thorium-232
^{234}Pa = Protactinium-234
^{226}Ra = Radium-226
^{222}Rn = Radon-222
^{218}Po = Polonium-218
^{214}Pb = Lead-214
^{214}Bi = Bismuth-214
^{40}K = Potassium-40

Radiations:

alpha particle	helium nucleus; easily stopped with thin layers of material, all energy deposited locally.
beta particle	electron; penetrates about 0.2 g/cm^2 of material.
gamma rays	electromagnetic radiation; similar to X-rays, and highly penetrating.
half-life ($T_{1/2}$)	time required for half the radioactive atoms to decay.
working level (WL)	measure of potential alpha energy per liter of air from any combination of short-lived radon daughters (1 WL = 1.3 x 10^5 MeV of alpha energy).
working level month (WLM)	exposure to air containing a RDC of 1 WL for a duration of 170 hr.

TABLE 3-1 (Cont)

roentgen (R)	that quantity of gamma radiation which yields a charge deposition of 2.58 x 10^{-4} coul/kg air. This is equal to the energy deposition of 88 ergs/g of dry air or 93 ergs/g of tissue.
μR/hr	10^{-6} roentgen/hr.
rad	energy deposition of 100 ergs/g of material.
picocurie (pCi)	unit of activity (1 pCi = 0.037 radioactive decays/sec or 2.2 min).
MeV	unit of energy; 1 MeV = 1.6 x 10^{-6} erg.
rem	unit of energy deposition in man; 1 rem = 1 rad x quality factor; the quality factor = 20 for alpha particles.

Note: Also see definitions of terms in Glossary.

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TABLE 3-2

BACKGROUND RADIATION SOURCES IN SOIL FROM NORTHEAST ARIZONA[1]

Isotope (Decay Chain)	Average Value (pCi/g)	Range (pCi/g)
^{226}Ra (^{238}U)	0.95 ± 0.73	0.23 - 2.00
^{232}Th (^{232}Th)	0.67 ± 0.46	0.20 - 1.29
^{40}K[2]	19.8	10.7 - 21.5

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TABLE 3-3

RADIOACTIVE AIRBORNE PARTICULATE CONCENTRATIONS NEAR THE SITE[2]

Isotope	Concentration (pCi/l)		
	Most Restrictive* Maximum Permissible	Tuba City Indian Hospital 4/16-20/74	Tuba City High-Rise Housing 4/16-20/74
^{238}U	3×10^{-3}	2.7×10^{-7}	5.4×10^{-7}
^{235}U	4×10^{-3}	$<2.5 \times 10^{-8}$	1.2×10^{-7}
^{234}U	4×10^{-3}	3.7×10^{-7}	6.9×10^{-7}
^{232}Th	1×10^{-3}	2.9×10^{-7}	1.8×10^{-7}
^{230}Th	8×10^{-5}	2.9×10^{-7}	6.6×10^{-6}
^{226}Ra	1×10^{-3}	5.6×10^{-7}	6.5×10^{-6}
^{210}Po	7×10^{-3}	7.9×10^{-6}	1.2×10^{-5}
^{210}Pb	4×10^{-3}	1.3×10^{-6}	2.6×10^{-5}

*From 10 CFR 20, maximum exposure to an individual in an unrestricted area

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TABLE 3-4

ESTIMATED HEALTH IMPACT FROM THE TUBA CITY TAILINGS
FOR AN AREA 0 TO 6 MILES FROM TAILINGS EDGE

Time Period	Population (Persons)	Total Pile-Induced RDC Health Effects/Yr	Background RDC Health Effects/Yr
1980	2,771	0.009	0.072
2005 (0.8% constant growth rate)	3,400	0.011	0.092
2005 (2.5% declining growth rate)*	3,800	0.013	0.100
2005 (4.0% declining growth rate)*	4,600	0.015	0.12

	25-Yr Cumulative RDC Health Effects	
Growth Projection	Pile-Induced	Background
0.8% constant growth rate	0.25	2.0
2.5% declining growth rate*	0.28	2.2
4.0% declining growth rate*	0.33	2.6

*Declines linearly from its initial value to zero in 25 yr and remains constant at zero thereafter.

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TABLE 3-5

CHEMICAL ANALYSES OF TUBA CITY WATER SAMPLES (mg/l)

Sample[a]	As	Se	Cr	Cd	Fe	Pb	Ba	V
A - Moenkopi Wash	0.009	0.043	<0.001	<0.001	0.156	<0.001	0.105	<0.001
B - Well (2 mi northeast)	0.005	0.083	<0.001	<0.001	0.182	<0.001	0.090	<0.001
C - Moenkopi Wash (nearest tailings)	0.004	0.184	<0.001	<0.001	0.463	0.047	0.019	<0.001
D - Spring (1 mi east)	0.006	0.073	<0.001	<0.001	0.109	0.005	0.065	<0.001
EPA Interim Primary Drinking Water Regulations[b]	0.05	0.01	0.05	0.01	0.3[c]	0.05	1.0	--

[a]See Figure 3-11 for locations.

[b]Federal Register, Dec 24, 1975.

[c]Recommended limit from Manual for Evaluating Public Drinking Water Supplies, U.S. Public Health Service, 1969.

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CHAPTER 4

SOCIOECONOMIC AND LAND USE IMPACTS

CHAPTER 4

SOCIOECONOMIC AND LAND USE IMPACTS

The Navajo Nation is divided into political divisions called "agencies" and subdivisions called "districts", which in turn are divided into "chapters", also known as "units". Tuba City is located within the Tuba City Agency, which is divided into five districts, as shown in Figure 4-1. The tailings and Tuba City are in the Tuba City Chapter (also known as Unit 2) of District 3.

4.1 SOCIOECONOMIC BACKGROUND

In several studies the social and economic conditions of Districts 1, 2, and 3 have been analyzed and compared to the reservation as a whole.[1,2] In the Overall Economic Development Plan, Tuba City is one of five communities designated as primary growth points in the Navajo Nation.[3] These communities have been singled out as having the greatest potential for various forms of development being planned and as centers for educational, health, and welfare services. Tuba City is the westernmost of these five communities and is an administrative center as well as the site of a major hospital; it also has educational facilities on the elementary and high school levels, and has a variety of other public services available. The districts around Tuba City are expected to receive large influxes of private and federal funds to develop economic alternatives for displaced residents of the disputed Navajo-Hopi lands.

According to the Office of Program Development, 17.2% of the Navajo labor force is located in the Tuba City Agency. The employed labor force is concentrated in government, crafts, agriculture, household services, and other categories. Over 90% of the people live in traditional housing, none live in government housing, and 7% live in mobile homes.

4.2 POPULATION ESTIMATES

The Navajo Research and Statistics Center of the Navajo Nation arrived at the following population estimates for 1978.[3] There is a total population of 27,597 individuals in the Western Agency, formerly the Tuba City Agency. Forty-three percent of this population is comprised of individuals under the age of 15 yr. District 3, including the chapters of Bodaway, Cameron, Coalmine Mesa, and Tuba City, is populated by 7,727 persons; 3,833 people reside in Tuba City Chapter itself.

Using a factor of 5.6 persons per an average Navajo family,[4] it is estimated that a potential of 235 people could reside in the housing units and trailer park adjacent to the site plus one additional family (6 people) within 0.8 mi of the site and 5 families (30 people) within 2 mi. Thus, a potential of 271 individuals are estimated to live within 2 mi of the site. Table 4-1 shows the 1980 estimated population distribution centered on the tailings pile out to 6 mi, and thus includes Tuba City.

As shown in Figure 4-2, population projections over the next 25 yr range from a constant 0.8% growth rate to a 4% declining growth rate.[5] The latter would cause the population to increase by 67% in 25 yr and would likely occur only if mineral and energy resources in the area were developed on a large scale. The most likely case is taken to be that of a 2.5% declining growth rate; this scenario would result in a maximum population of about 3,800, caused by a growth rate which decreases linearly from 2.5% to zero in 25 yr. An estimated population of 3,400 in the year 2005 results by using the 0.8% growth rate of the U.S. as a whole.

4.3 LAND USE

The land use of the area around the Tuba City uranium tailings site is dominated by Tuba City itself which is located 5.5 mi to the southwest. The buildings that still remain on the tailings site are unoccupied, and as of summer 1981, the site had been abandoned except for approximately 65 occupants in some of the 26 permanent houses located north of the tailings along both sides of U.S. Highway 160. The land surrounding the site is used for low-density grazing. An occasional dwelling is visible, as shown in Figure 4-3.

During the last several years, the east side of Tuba City has experienced considerable growth, including the construction of a high school and the development of three new subdivisions. However, even with the eastward growth, there is no reason to expect major changes in land use within a 1-mi radius of the tailings site. Tuba City probably will continue to grow toward the site with primarily residential developments, but the expectations for growth in the area do not suggest that the residential area will expand to within 1 mi of the tailings in the foreseeable future.

4.4 IMPACT OF THE TAILINGS ON LAND VALUES

In order to assess land values and the impact of the tailings on them, it is necessary to consider the Navajo system of land allocation and transfer.

All land is owned commonly by the Navajo Tribe. Individuals and families enjoy primary use rights to certain lands which have been established through historic grazing or other use. Such lands are called "assignments".[7]

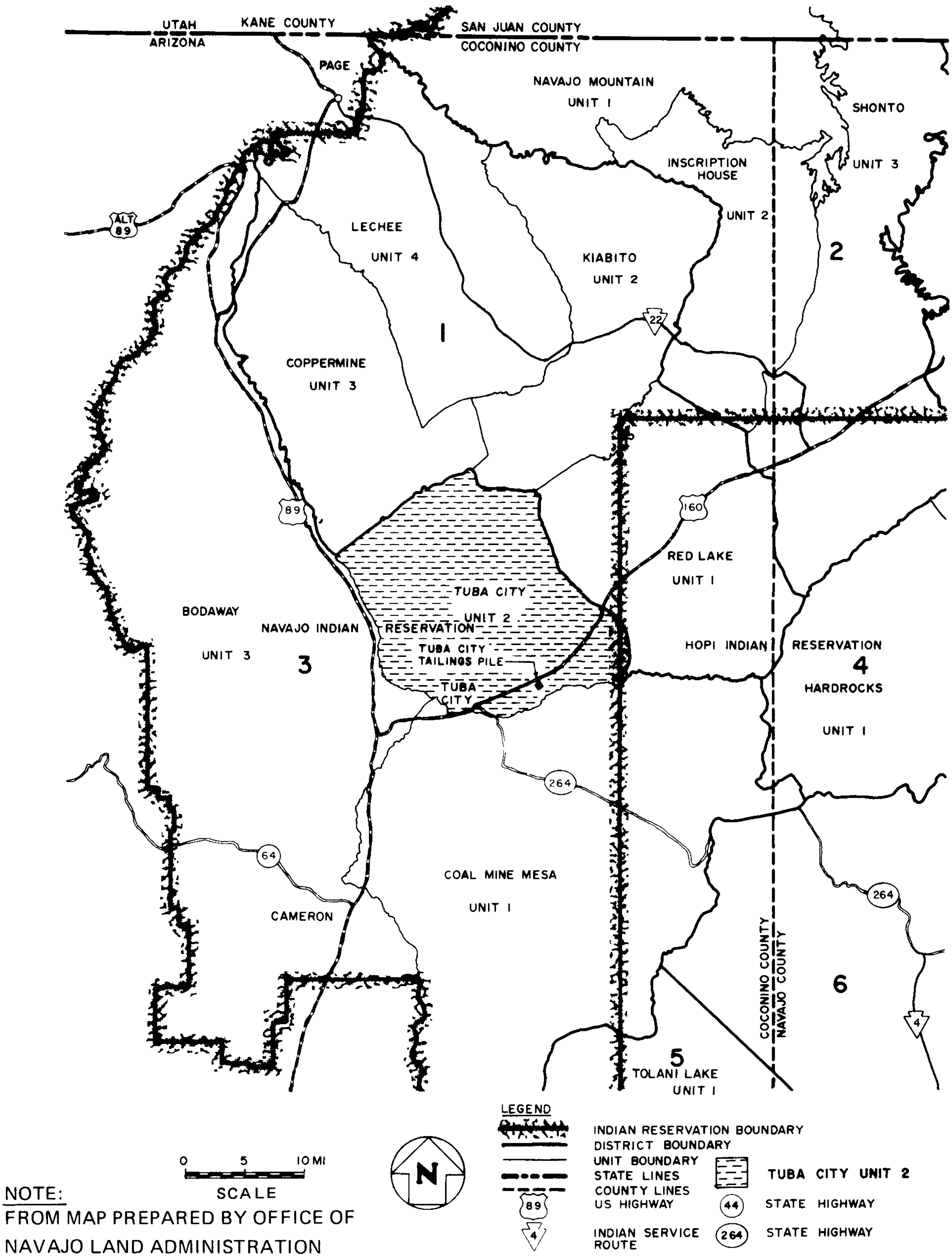
Only a few of the total assigned lands of the reservation have legally described boundaries, i.e., no specified boundary line has been agreed upon by adjoining neighbors and overlaps of grazing use are common. However, severe violations of the generally acknowledged boundaries are seldom tolerated.[8] Since no fee ownership exists within the reservation boundaries, assignees do not hold titles to the land that they use.[7]

There is currently an attempt to establish a buffer zone[6] around the tailings from which residences would be excluded and in which no development would be permitted. Should it be established, the buffer zone might affect land use immediately around the site since the affected land would continue to lie idle.

The lack of a traditional monetary market for land exchange on the Navajo Reservation makes it difficult to calculate the dollar value of the site and its environs. However, recent land exchanges by the Navajo Tribal Council whereby they received off-reservation land and exchanged it for tribal land are one indication. Another indication is the recent lease payments for Navajo lands, projected into land values. Comparisons with land values immediately outside the reservation also give an indication of the worth of the Tuba City site. By assigning a monetary value to sheep production per acre of land, and by translating this value into capital-valued land, another cash valuation may be determined.

At present, grazing land on the reservation is valued between \$55 and \$65/acre. However, the Navajo Nation is currently undertaking a minerals inventory for the purpose of assigning values to land that they may lease.[8] A lease on land where coal may be mined could range from \$350 to \$500/acre for a 10- to 15-yr lease. When land values are set they will be based on current land use and the presence of mineral deposits. However, it appears that there is no such potential for the Tuba City site.

The tailings pile may have an impact on land values if the buffer zone mentioned above is established, since the use of the site and the immediate vicinity would be restricted. Therefore, the presence of the tailings pile could have a negative impact on land value within the proposed buffer zone. However, it is unlikely that the worth of the land could be reduced below \$55/acre.



NOTE:
FROM MAP PREPARED BY OFFICE OF NAVAJO LAND ADMINISTRATION

FIGURE 4-1. MAP OF POLITICAL JURISDICTIONS

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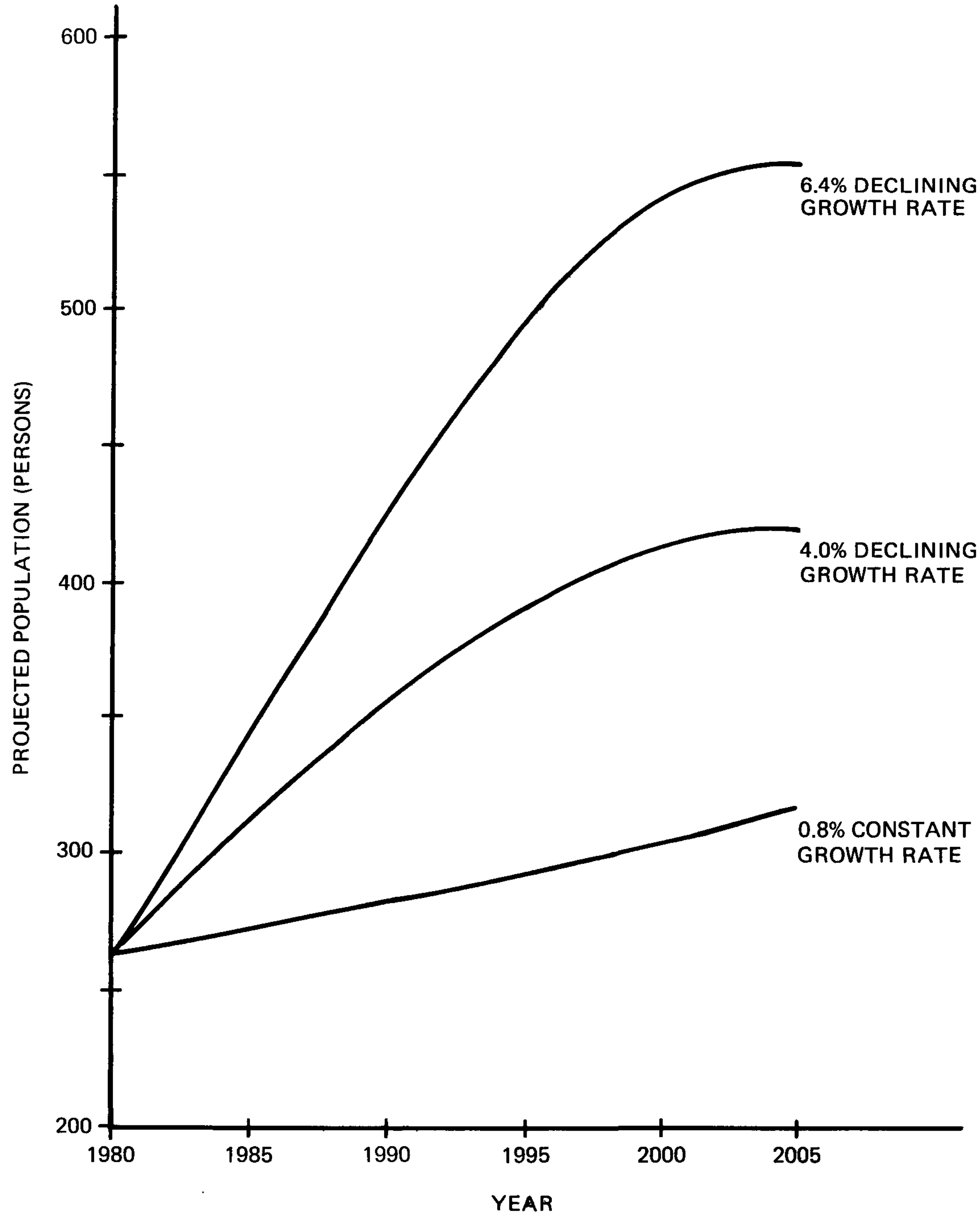

FIGURE 4-2. POPULATION PROJECTIONS

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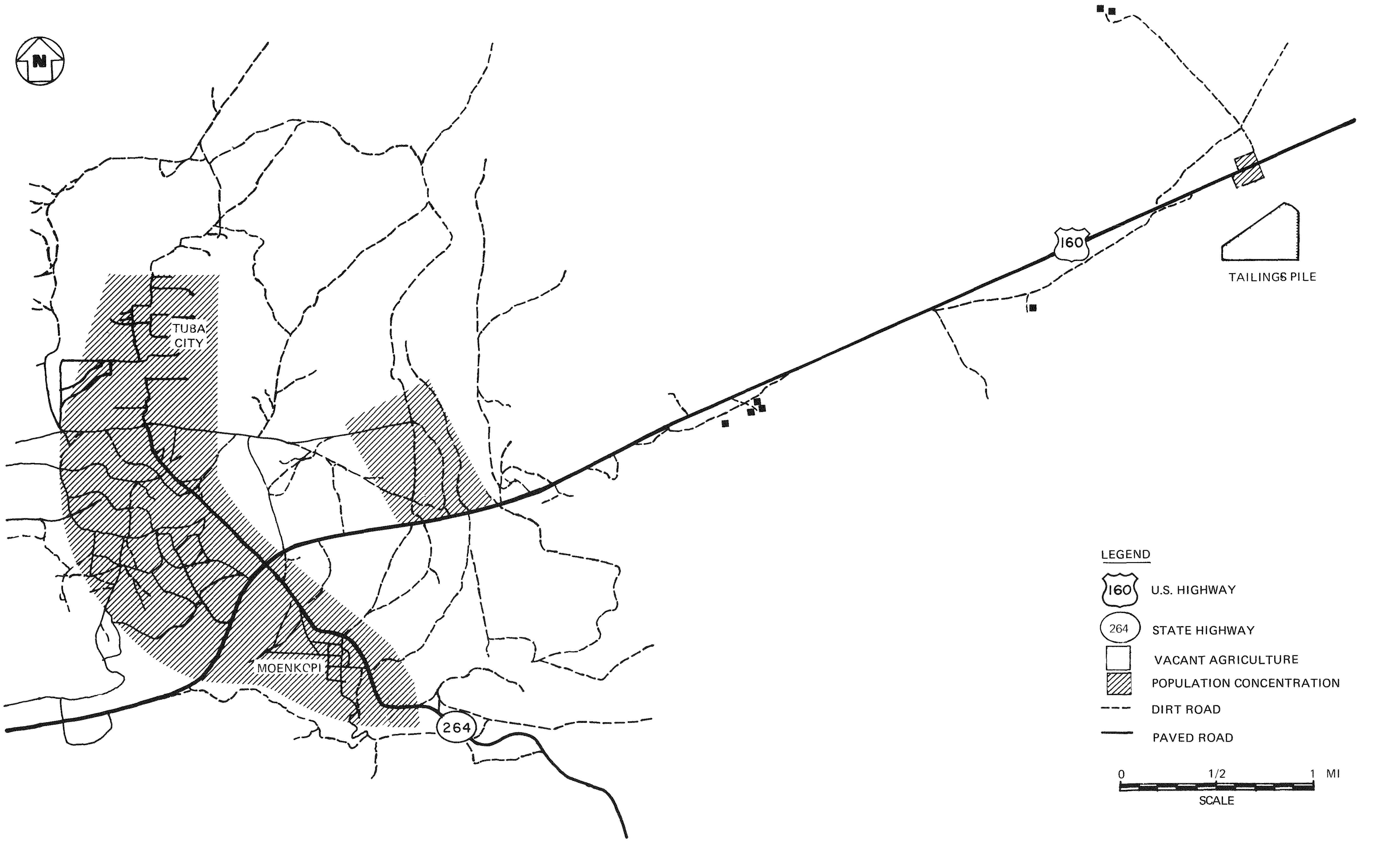

FIGURE 4-3. MAP OF POPULATION CENTERS AND LAND USE

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TABLE 4-1

ESTIMATED 1980 POPULATION DISTRIBUTION

Direction	Distance (mi)	Population (persons)
NNW	0.3	235*
NNE	0.8	6
WSW	1.0	6
ENE	1.5	12
NW	1.5	12
W	6.0	2,500
Total		2,771

*Estimated potential population of housing adjacent to the tailings site.

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CHAPTER 5

RECOVERY OF RESIDUAL VALUES

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RECOVERY OF RESIDUAL VALUES

The Tuba City tailings pile contains about 800,000 tons of tailings. The uranium content is 0.032% U_3O_8, based on AEC records of the plant operation. Table 5-1 gives the assay results obtained on a composite sample taken in 1976. The uranium content of this sample was 0.037%, which is in good agreement with the AEC records. The vanadium content of the composite sample was 0.062% V_2O_5, too low to be economically recoverable in a reprocessing operation. With the possible exception of copper, there are no other metals present in significant concentrations in the tailings.

No amenability testing has been performed by DOE to determine the recovery of uranium that could be achieved in a reprocessing operation. However, the uranium content of the tailings is high enough that at least one company has conducted sampling and amenability test work. The results of this test work indicated that the residual uranium in the tailings was readily leached, but that the high bentonitic clay content of the tailings prevented percolation of solution through the tailings in a heap leach operation. This was true even when the tailings were pelletized with leach reagents before being placed in piles for leaching. In the absence of evidence to the contrary, it must be concluded that the Tuba City tailings are not amenable to heap leaching by any known method, and probably can only be treated successfully by conventional processing methods such as acid leach, resin-in-pulp or carbonate leaching. These are the methods that were used in the Tuba City mill.

For the purpose of this chapter, it is assumed that the uranium content of 0.032% U_3O_8 indicated by AEC records is correct, and that recovery of uranium by a conventional process will be about 70%, or 0.45 lb/ton of tailings. This estimate of recovery is somewhat higher than would be indicated by the graph provided by the DOE Grand Junction Office, as shown in Figure 5-1. The higher uranium extraction is based on the test work and also on the experience of Rancher's Exploration and Development Corporation at Naturita. At October and November 1980 prices of $28/lb of U_3O_8, the total income from uranium recovery would be about $12.60/ton of tailings processed.

5.1 PROCESS ALTERNATIVES

There are three principal alternatives for the reprocessing of the Tuba City tailings:

(a) Heap leaching

(b) Treatment in an existing mill

(c) Reprocessing at a new conventional mill constructed for tailings reprocessing

5.1.1 Heap Leaching

The amenability test work done to date has indicated that due to the high clay content of the tailings, solutions do not percolate through a bed of tailings at a rate high enough to make reprocessing by heap leaching practicable. Therefore, heap leaching will not be discussed further in this chapter as a viable method.

5.1.2 Treating in an Existing Plant

For reprocessing in an existing conventional plant to be economically feasible, a mill with significant excess capacity must be located reasonably close to the present tailings site. The mill also must have a tailings disposal site with sufficient capacity to handle the additional tailings and to allow for adequate long-term stabilization. In addition to the 800,000 tons of tailings, there is a substantial quantity of contaminated waste at the Tuba City site, including contaminated soil resulting from tailings blown by the wind over a large area adjacent to the site.

The site has good access. Trucks could remove material from the site at a rate of at least 2,000 tons/day. At this rate, all tailings and contaminated materials could be removed from the site within 2 yr. However, the nearest operating mill is at Blanding, Utah, about 110 mi away. The transportation costs would far exceed the value of the uranium that could be recovered from the tailings.

5.1.3 Treating in a New Plant

Construction of a new mill to reprocess the tailings would permit: (a) plant design tailored for the material to be processed; (b) siting suitable for long-term tailings stabilization; and (c) optimum plant capacity and uranium recovery. The major disadvantage is in the high cost of new plant construction.

The Tuba City tailings would feed a 500 ton/day plant for about 5 yr. Normally, amortization of a plant is based on planned operation for 10 to 20 yr. While there is good potential for development of new reserves in the area which might be able to supply ore to feed such a plant, there are no production plans as yet.

5.2 TUBA CITY RECOVERY ECONOMICS

The parameters discussed in this section determine the economic viability of reprocessing uranium mill tailings to recover residual mineral values.

5.2.1 Market for Uranium

The demand and price for uranium from 1976 to 1980 have gone through a rapid rise and fall cycle. Spot prices for uranium as indicated by the exchange values reported by NUEXCO[2] rose from $30/lb of U_3O_8 in November 1975 to $43/lb in November 1977 and essentially held constant until the end of 1979. The price dropped precipitously to $28.50/lb of U_3O_8 by September 1980 and to $25/lb early in 1981. Prices in individual long-term uranium sales contracts have varied over a broad range.

A variety of factors has contributed to this pattern, including the Three Mile Island accident and the subsequent delays in nuclear plant licensing, rapidly escalating power plant costs, and the inflexibility of uranium production operations. Total uranium inventories held by U.S. companies as of January 1, 1979 were 44,700 tons equivalent U_3O_8, representing nearly 3 times the annual consumption rate at that time. Projected domestic uranium supply exceeds apparent buyer requirements each year through 1985.[3] Under these circumstances, no basis is evident for a turn-around in uranium prices for about 5 yr.[2] The supply and market for uranium as estimated by the DOE Assistant Secretary for Resource Applications are given in Table 5-2.

5.2.2 Escalation of Plant Construction Costs

The estimated construction cost of both heap leach plants and conventional mills without crushing and grinding facilities, as provided by the DOE Grand Junction, Colorado Office, were included as figures in the Phase II, Title I Engineering Assessment report.[1] The costs were adjusted to January 1977. Since then, relatively few plants have been built, and reported costs have been strongly influenced by new tailings control and stabilization requirements under NRC licenses. Recent estimates by R.B. Coleman of construction costs for conventional plants have been in the range of $13,000 to $30,000/ton of daily plant capacity.[4] In view of the many significant site-specific problems that can influence capital costs, for this report it was decided to apply suitable escalation factors to the 1977 Grand Junction Office estimates, which are based on construction costs of many plants.

The Engineering News Record[5] publishes reports quarterly on various construction cost indexes. The following data are derived from this source:

	Avg Index 1977	Latest Reported Date (1980)	Index	Percent Increase
Nelson Refinery Cost Index	223	Jan	276	23.8
Chemical Engineering Plant Cost	186	Apr	234	25.4
Engineering Construction Cost (20 Cities)	240	June	298	24.2

The Producer Price Index of Industrial Commodities[2] has increased as follows in the 1977-1980 period:

Period	Index	Total Percent Increase	Annual Percent Increase
Annual Average 1977	195.1	--	--
Annual Average 1978	209.4	7.3	7.3
Annual Average 1979	236.5	21.2	12.9
June 1980	273.0	39.9	15.4

From the above indexes, an increase in plant construction cost of 25% from January 1977 to mid-1980 has been applied as a conservative estimate. For a conventional mill of 500 ton/day capacity the cost, as indicated in Figure 5-3, would be about $6 million. If these capital costs were to be amortized on the Tuba City tailings only, the unit costs would be $7.50/ton, or about $16.70/lb of U_3O_8 recovered.

5.2.3 Escalation of Plant Operating Costs

The operating costs of uranium mills appear to have risen much more steeply than construction costs. In the March 1977 engineering assessment,[1] the direct operating costs of a 500 ton/day facility were estimated at $3.25 and $5.80/ton for heap leach and conventional acid leach mills, respectively. However, R.B. Coleman[4] reports that 1980 operating costs of conventional mills are in the range of $8.70 to $18.40/ton.

Ranchers Exploration and Development Corporation reported their operating costs for heap leaching at Naturita, approximately a 1,200 ton/day facility, at about $34/lb of U_3O_8 recovered, equivalent to $20.50/ton of tailings processed.

Costs of vanadium recovery were reported separately. In Figure 5-4, Grand Junction Office DOE 1977 estimates for heap leach plant operating costs are compared with Ranchers' 1978-1979 experience at Naturita. In Figure 5-5, conventional acid leach plant operating costs are compared with 1980 data reported by Coleman. The data indicate that conventional milling costs have risen by 250%, and the cost of heap leaching is higher by a factor of 400 to 500%. However, the slope of the 1977 heap-leach line is not confirmed by later information. Consequently, the dotted line in Figure 5-4 is considered more representative, and has been used as a basis of estimates.

Considering the differences in plant designs, it is estimated that average mill operating costs have increased by a factor of 2.5 from the January 1977 costs to mid-1980. This would result in operating costs for Tuba City tailings in a 500-ton/day conventional mill of about \$17.50/ton, or \$38.90/lb of U_3O_8 recovered (assuming 0.45 lb recovered/ton). In view of these operating costs, which exceed the current market price, no detailed analysis of optimum plant size is warranted. The 500 ton/day plant size is about the smallest that would be built today for an operation processing high-grade ore.

5.2.4 Competitive Market Factors

The average grade ore processed in conventional mills has decreased from 0.15% U_3O_8 in 1977 to 0.11% in 1979. The average recovery rate for the industry has been 91 ± 1% during this period.(6) However, since tailings have been processed previously, the recoveries in reprocessing are likely to be lower, as reflected in Figure 5-1. To produce a given quantity of uranium, nearly four times as much Tuba City tailings material would have to be processed as would when a mill is operating on ore of the average grade treated in 1979. Thus, the volume of tailings to be stabilized per unit of production is correspondingly greater. The fact that there are no mining costs for the tailings is a substantial off-setting advantage. However, it is not sufficient to compensate for the low grade and relatively small quantity of Tuba City tailings.

5.3 CONCLUSION

Based on the foregoing analysis, it is concluded that the processing of Tuba City tailings for the recovery of additional uranium in connection with the tailings stabilization operations is not feasible because of the impermeability of the tailings to leach solution. However, if a little more than 70% of the uranium could be recovered, and if prices return to the level of 2 yr ago, reprocessing could be economically attractive. For processing this material, assuming a plant of about 500-ton/day capacity, the cost of the uranium recovered would be about \$56/lb of U_3O_8, as shown below:

	Conventional Plant	
	$/ton	$/lb U_3O_8
Capital Cost	7.50	16.70
Operating Cost	17.50	38.90
Total	25.00	55.60

If another source of ore could be developed to provide additional feed, the capital cost per ton might be reduced. The cost is, of course, very sensitive to the percent recovery of metal values, which can be only roughly estimated in the absence of amenability tests on representative samples. Within a relatively short time, say 5 to 10 yr, supply and demand for uranium could change enough to make reprocessing the Tuba City tailings commercially attractive.

The spot market price for uranium in September 1980, when these economic analyses were prepared, was $28.50/lb of U_3O_8. Since that time, construction costs have continued to rise, while the spot market price for uranium has declined to about $25/lb of U_3O_8 early in 1981. These trends further reduce the economic attractiveness of tailings reprocessing.

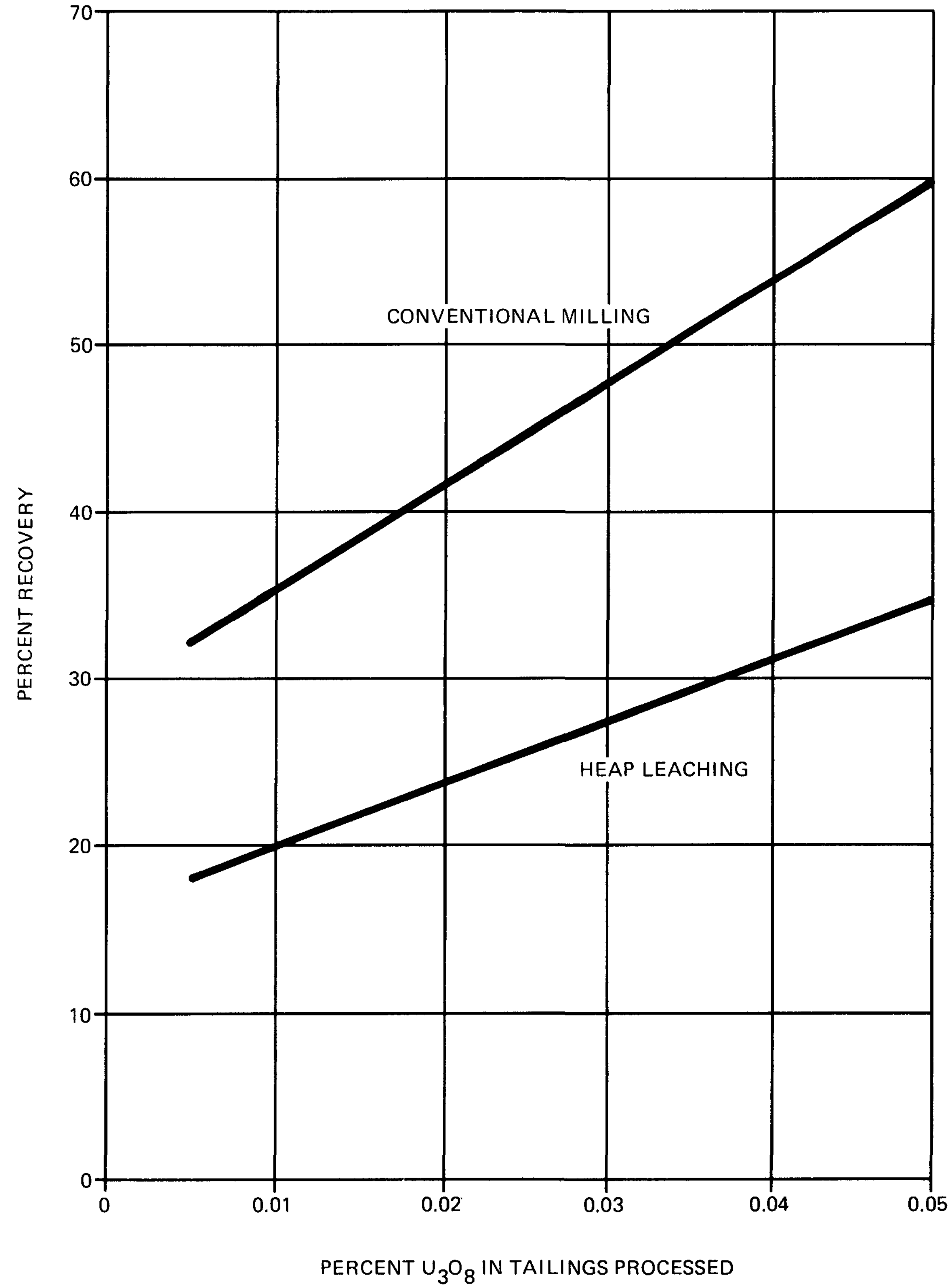

FIGURE 5-1. URANIUM RECOVERY FROM MILL TAILINGS AS A FUNCTION OF U_3O_8 CONTENT IN TAILINGS

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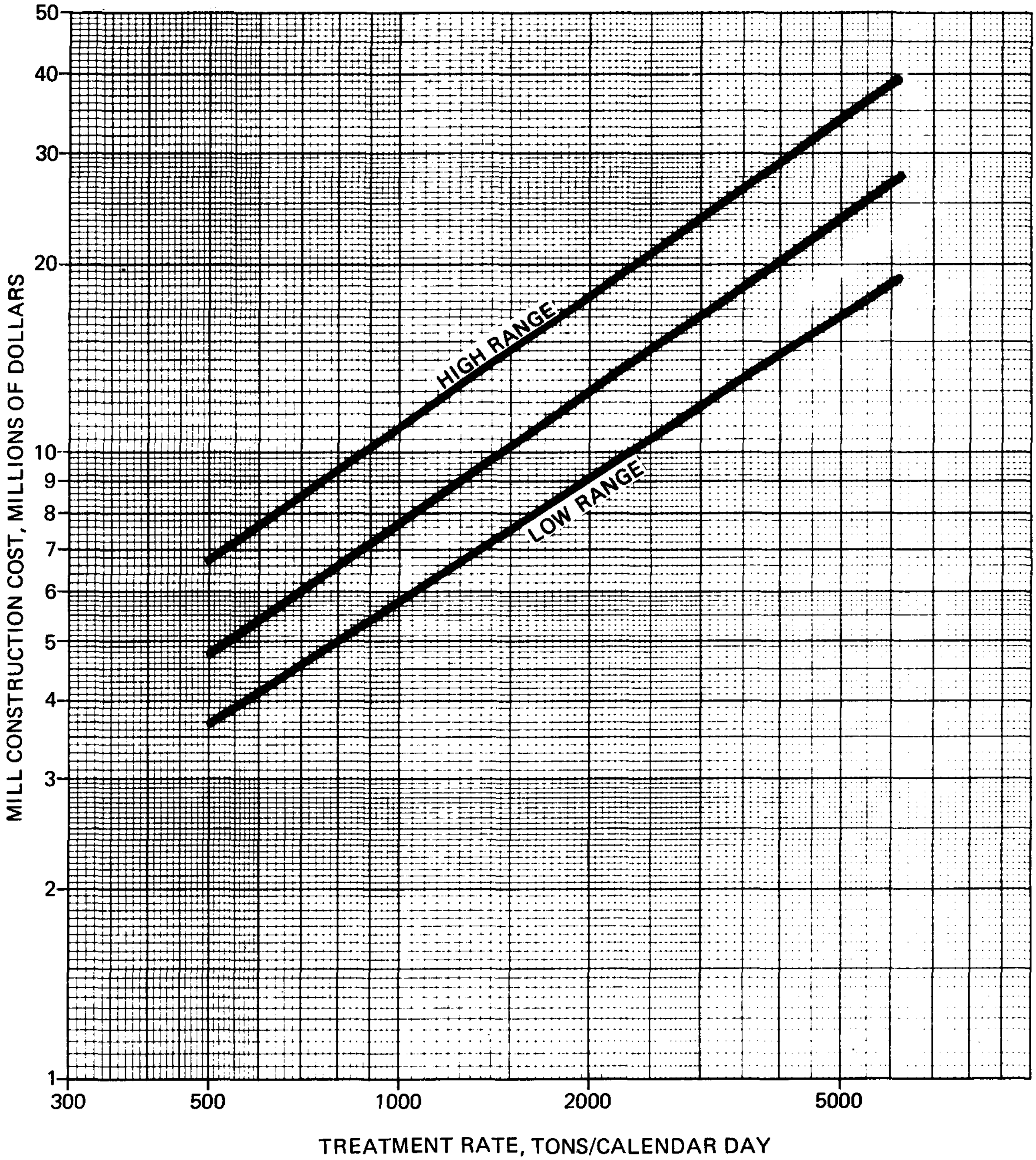

FIGURE 5-2. CONSTRUCTION COSTS OF HEAP LEACHING PLANT TO REPROCESS URANIUM MILL TAILINGS (COST ADJUSTED TO JULY 1980)

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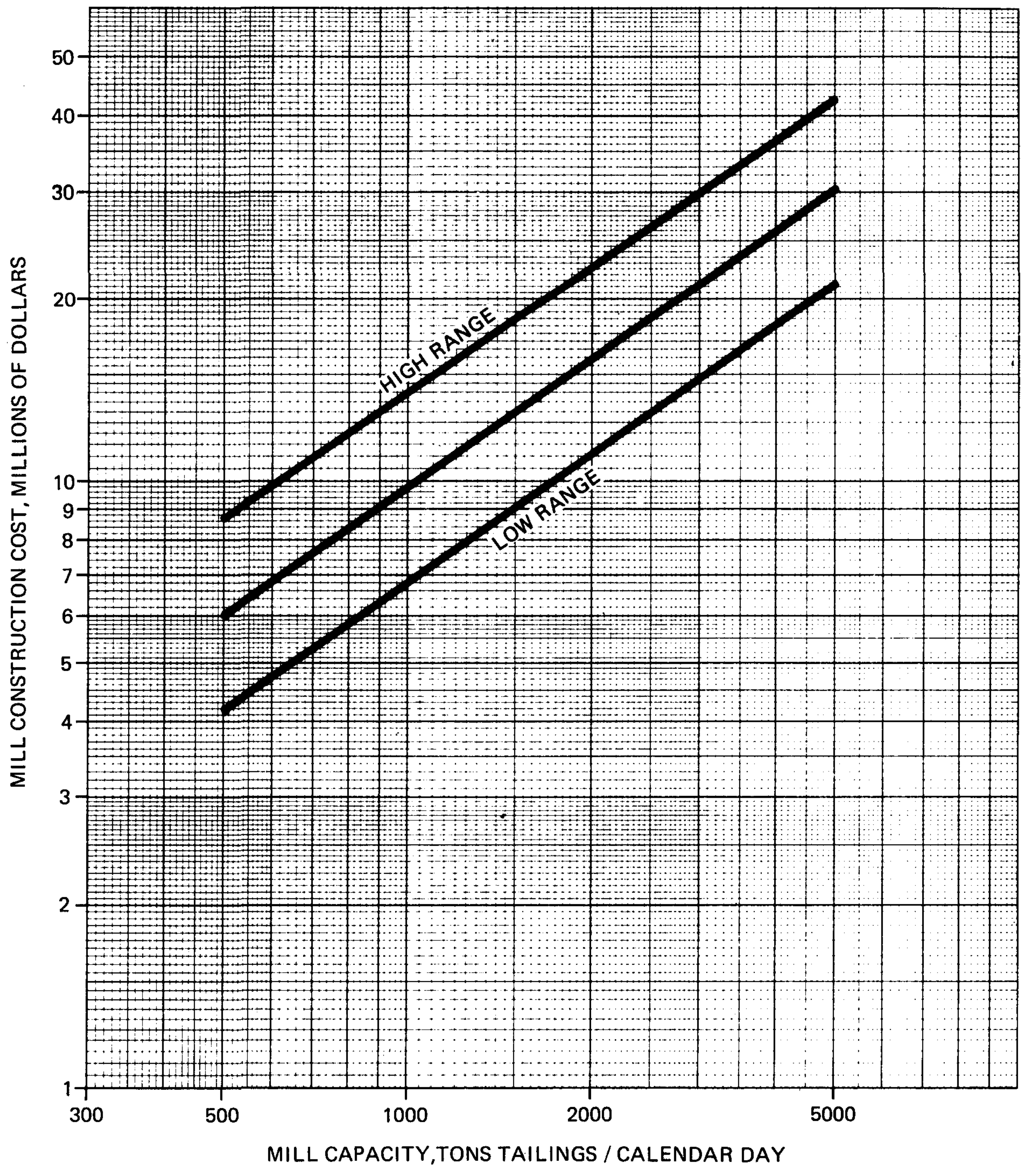

FIGURE 5-3. CONSTRUCTION COSTS OF A CONVENTIONAL URANIUM MILL TO REPROCESS TAILINGS W/O CRUSHING AND GRINDING FACILITIES OR TAILINGS STABILIZATION COSTS (COST ADJUSTED TO JULY 1980)

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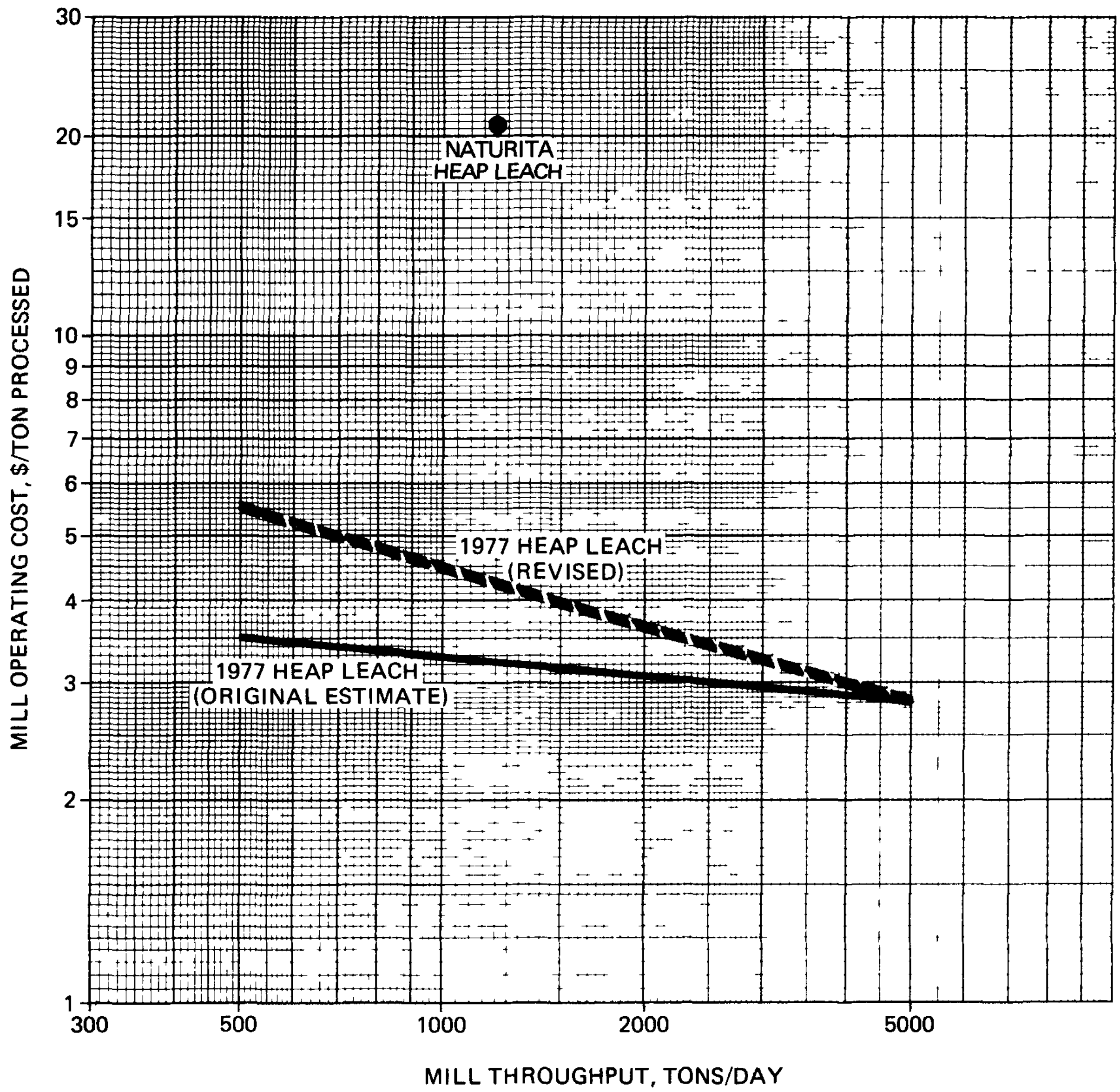

FIGURE 5-4. OPERATING COSTS OF HEAP LEACHING OF URANIUM MILL TAILINGS

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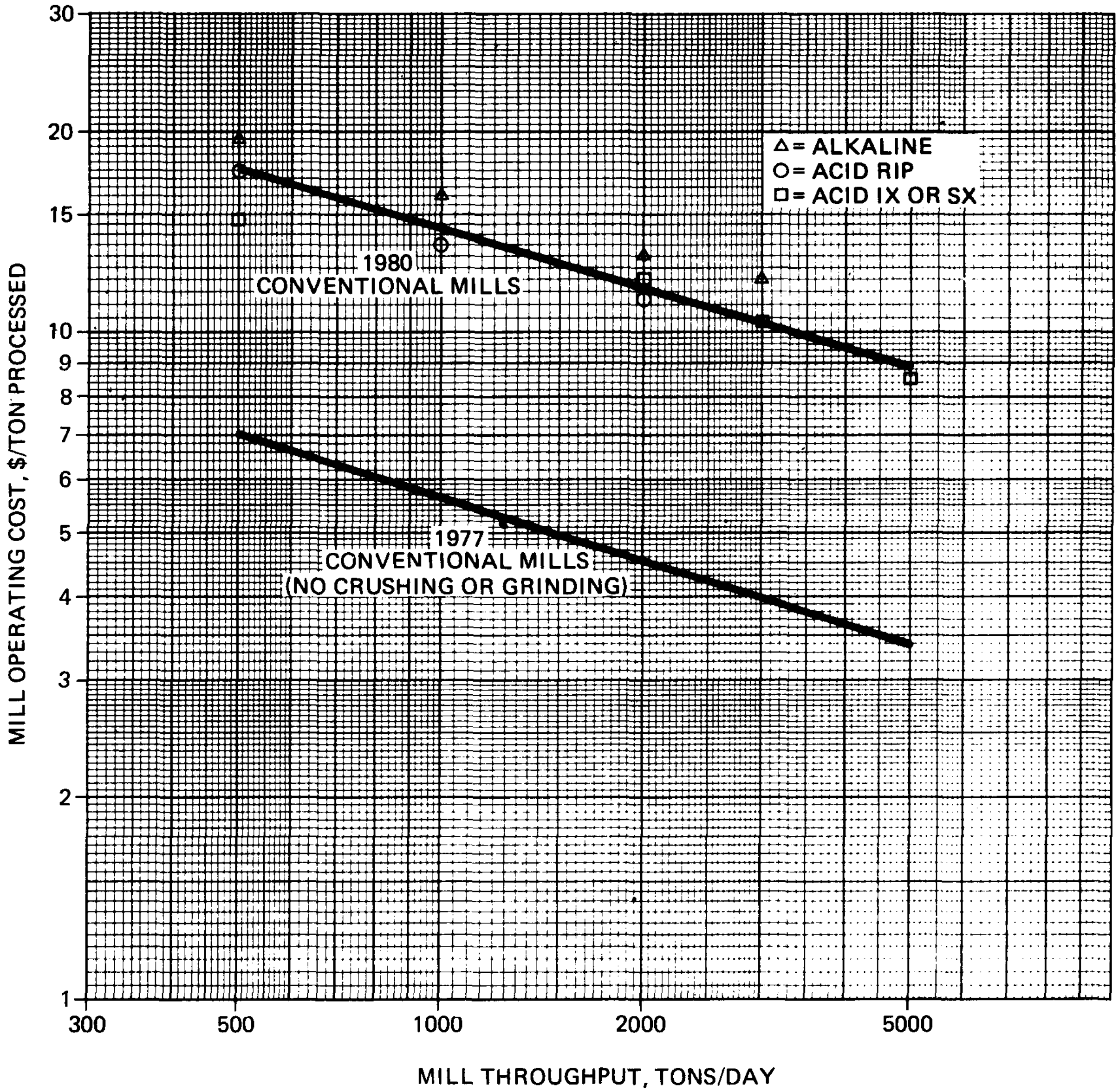

FIGURE 5-5. OPERATING COSTS OF CONVENTIONAL MILLING W/O CRUSHING AND GRINDING FACILITIES TO REPROCESS TAILINGS (COST ADJUSTED TO JULY 1980)

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TABLE 5-1

ASSAY RESULTS OF COMPOSITE TAILINGS AND BACKGROUND SAMPLES

Percentage by Weight (unless noted)

Element	Atomic Absorption	Spectrographic	Chemical	Background (ppm)	Delta	AEC* Estimate
Aluminum	--	1.0-0.01	--	--	--	--
Arsenic	0.0082	--	--	1.321	0.0081	--
Barium	0.0086	--	--	--	--	--
Boron	--	<0.01	--	--	--	--
Cadmium	0.0004	--	--	--	--	--
Calcium	--	1.0-0.01	--	--	--	--
Chromium	0.0006	--	--	--	--	--
Cobalt	0.0182	--	--	--	--	--
Copper	0.1160	--	--	--	--	--
Cyanide	<0.000001	--	--	--	--	--
Gallium	--	<0.01	--	--	--	--
Iron	0.7230	--	--	--	--	--
Lead	0.0812	--	--	--	--	--
Magnesium	--	1.0-0.01	--	--	--	--
Manganese	--	1.0-0.01	--	--	--	--
Mercury	<0.0000001	--	--	--	--	--
Molybdenum	--	<0.01	--	--	--	--
Nickel	--	<0.01	--	--	--	--
Potassium	--	<0.01	--	--	--	--
Selenium	0.0010	--	--	0.032	0.0010	--
Silicon	--	>1.0	--	--	--	--
Silver	0.0006	--	--	--	--	--
Titanium	--	<0.01	--	--	--	--
Uranium (U_3O_8)	--	--	0.037	<0.001	0.037	0.032
Vanadium (V_2O_5)	--	--	0.062	14.198	0.061	--
Zinc	0.0249	--	--	--	--	--

*Calculated tailings assay based on plant operation(2)

TABLE 5-2

U.S. URANIUM SUPPLY AND MARKET SUMMARY

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	Sales Commitments		Est. U_3O_8	Procure-		Total	Total	Apparent
Year	To Domestic Buyers	To Foreign Buyers	To Be Available For Sale	ment of Foreign Uranium	Reported Unfilled Requirement	Domestic Production Potential (1+2+3)	Domestic Supply (1+3+4)	Buyer Requirements (1+4+5)
1980	21,500	2,000	2,600	1,800	400	26,100	25,900	23,700
1981	20,000	1,000	3,100	2,700	800	24,100	25,800	23,500
1982	19,400	1,000	4,300	2,800	1,300	24,700	26,500	23,500
1983	17,400	900	7,100	2,500	1,800	25,400	27,000	21,700
1984	16,000	500	7,800	2,500	4,000	24,300	26,300	22,500
1985	13,900	500	8,800	2,400	4,300	23,200	25,100	20,600
1986	11,200	300		1,000	9,900			22,100
1987	11,400	300		1,000	11,700			24,100
1988	10,500	300		1,000	12,000			23,500
1989	9,500	100		1,000	15,100			25,600
1990	7,300	100		1,000	14,400			22,700

Source: DOE/RA-0053
Survey of United States Uranium Marketing Activity, July 1980 (p. 17)

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CHAPTER 6

MILL TAILINGS STABILIZATION

CHAPTER 6

MILL TAILINGS STABILIZATION

In all alternative remedial actions considered in this study, the stabilization of mill tailings is required. Stabilization, as used here, means implementation of efforts to prevent the introduction of potentially harmful materials into the biosphere from the tailings. Government agencies and private industry have conducted and are conducting research to develop economical and environmentally suitable methods of stabilizing uranium mill tailings. The methods, technology, and data on stabilization that are presently available were reviewed and are described in this chapter. This information includes results from previous investigations, as well as findings of current and continuing research.

The objective of stabilizing the uranium mill tailings is to eliminate the pathways to the environment for the radioactive and other toxic particles which are described in Chapter 3. Alternatively, conditioning tailings might significantly reduce the rate at which potentially hazardous substances are released to the environment. Ideally, complete stabilization of radioactive tailings should permanently eliminate the possibilities of:

(a) Wind and water erosion

(b) Leaching of radioactive materials and other chemicals

(c) Radon exhalation from the tailings

(d) Gamma radiation emitted from the tailings

Implicit in these objectives is the additional goal of ensuring long-term stability and isolation of the tailings without the need for continued active maintenance. These objectives are consistent with those of the proposed EPA standards for inactive uranium mill tailings disposal.[1]

6.1 PREVENTION OF WIND AND WATER EROSION

Wind and water erosion could be prevented by treating the tailings surface (surface stabilization), solidifying the bulk of the tailings (volumetric stabilization), by emplacing covers over the tailings (physical stabilization), or by establishing plant growth over the tailings (vegetative stabilization). Each of these is discussed in the following paragraphs.

6.1.1 Surface Stabilization

Surface stabilization involves applying chemicals to the surface of the tailings to form a water- and wind-resistant crust. Surface stabilizers have been used successfully as a temporary protection on portions of dikes and tailings ponds which have dried and become dusty, and in areas where water shortage or chemical imbalance in the tailings prevents the use of cover vegetation. Surface stabilizers, however, are susceptible to physical breakup and gradual degradation and may not meet the long-term requirements for permanent stabilization of uranium mill tailings.

Other complications also can arise in achieving satisfactory surface stabilization. For example, the surfaces of tailings piles seldom are homogeneous, and variables such as particle size, acidity, and moisture content affect the bonding characteristics and stability of the surface stabilizers.[2,3] Studies are currently being conducted to assess the possibilities of conditioning uranium mill tailings to minimize their impact if they were to migrate to the biosphere.[4] It is possible that some conditioning techniques may change the characteristics of the tailings such that degradation of surface stabilizers by the tailings would be minimized.

Among the substances used to form crusts on mill tailings surfaces and thus reduce their susceptibility to wind erosion are: resinous adhesives; lignosulfonates; elastomeric polymers; milk of lime; mixtures of wax, tar, and pitch; potassium and sodium silicates; and neoprene emulsions.

Tests were conducted by the Bureau of Mines[2] using certain chemicals (e.g., Compound Sp-400 Soil Gard, and DCA-70 elastomeric polymers) on both acidic and alkaline uranium tailings. Subsequently, the chemicals DCA-70 and calcium lignosulfonate were applied to the surfaces of the inactive uranium tailings ponds and dikes at Tuba City, Arizona, in May 1968, because low moisture conditions and high costs prohibited vegetative or physical stabilization. After 4 yr, approximately 40% of the dike surface showed disruption while the crust in pond areas was affected to a lesser extent. The major disruptions were attributed to initial penetration of the stabilizer by physical means such as vehicles, people, or animals crossing the tailings surface.

In 1969, a portion of the Vitro tailings at Salt Lake City, Utah, was sprayed with tarlike material as a Bureau of Mines experiment[5,6] to achieve surface stabilization and to reduce wind erosion. The material decomposed and exposed the tailings within 2 to 3 yr after application.

"Cut-back" asphalt and asphalt-in-water emulsions also have been tested for use in protecting soils against wind and water erosion.[7] Both were shown to be effective for short periods of time when applied as a fine spray on sandy soils. On clay soils, the film disintegrated within a few weeks of application, apparently because of expansion and contraction of the clays during cycles of wetting and drying. The film was porous, allowed infiltration of water, and did not interfere with germination of wheat, grass, or legume seeds. The film is damaged by insects and rodents, and respraying may be necessary. Three to five years after application of the asphalt treatment, the amount of dry erodible surface area in the tested soils had increased, suggesting that asphalt treatments may not be desirable under all conditions.

More recent experiments performed for DOE are attempting to establish that surface stabilizers are useful in the long term.[3,8,9,10,11] Although some asphaltic emulsions applied on tailings surfaces have degraded in less than 1 yr, covering the surface stabilizer with soil after application can extend its useful life. Nevertheless, additional data must be obtained to demonstrate long-term effectiveness of surface stabilizers.

Asphalt emulsions might be useful if mixed with a sufficient thickness of tailings or overburden material (admixing) to form a volumetric seal, as opposed to a thin coating on the tailings surface.[12] Admixing depths would have to be sufficient to minimize the potential for breakup of the volumetric seal. Recent studies have suggested that asphalt emulsion seals for uranium mill tailings may be stable for long-term applications.[11] Results of tests to determine the effects of temperature cycling (freeze-thaw), aqueous leaching, oxidation, exposure to brine solutions, and microbal attack indicate satisfactory stability of asphalt emulsions.

6.1.2 Volumetric Stabilization

Volumetric stabilization, which has been used in other mineral industry operations, involves the mixing of chemicals in sufficient quantities with tailings to produce a solidified, leach-resistant mass, much like mixing cement with sand and gravel to form concrete. The chemicals could be added in two ways: to a tailings slurry in a pipeline, or to the tailings in-situ. The in-situ method of stabilization is relatively new and research is being conducted to determine desirable materials to be added to tailings and the best techniques of application.[10,11]

One of the features claimed for this stabilization method is that all pollutant chemicals are locked in the solidified mass so they cannot be leached from the solid. Recent studies have indicated that volumetric stabilization may suffer from eventual degradation, and requires careful matching of environmental conditions, tailings, and solidifying chemicals in order to be effective.[9]

A cover material, such as soil, might be required to protect the solidified mass from wind and water erosion, depending on the substances added to the tailings. Shallow rooted vegetation can be established after soil cover has been placed over the solidified mass. However, the long-term effect of plant root penetration into the stabilized tailings is unknown but probably would be a function of the specific chemical makeup of the solidified mass. Continued research to identify the conditions under which vegetation could thrive without affecting the integrity of volumetric stabilizers is required.

6.1.3 Physical Stabilization

Physical stabilization consists of isolating the contained material from wind and water erosion by covering the tailings with some type of resistant material (e.g., rock, soil, smelter slag, broken concrete, asphalt, polymeric film, etc.).

Covers of gravel or crushed rock have been shown to be effective in preventing wind erosion and allow infiltration of water without permitting substantial erosion.(13) Riprap, a cover of substantial rocks, armors the surface against erosion and may enhance growth of vegetation.(14,15) Clays or clayey soils would be self-healing if the tailings settled, would hold moisture, and could be a key component of a stabilizing cover.

Artificial covers, such as a layer of asphalt or a synthetic membrane, could be placed over the tailings to reduce wind and water erosion. However, synthetic membrane materials containing plasticizers, e.g., polyvinyl chloride (PVC), are not suitable for exposed surface application because they are susceptible to damage by ultraviolet radiation. However, a thin synthetic sheet, although protected by soil from direct exposure, would have questionable mechanical strength and might not be able to maintain integrity in the long term.

In some arid regions, where the potential for successful vegetative stabilization is slight, physical stabilization may be the preferred alternative. In such areas, combinations of pit-run sand and gravel, soil, and riprap have been placed over the tailings and have been successful in preventing wind and water erosion.

An important component of physical stabilization is the proper treatment of the finished surface by such means as contour-grading and terracing. Broad range surface runoff control channels and grading are also imperative to assure that the tailings site is protected from erosion by rainstorms and floods. Such treatments can greatly reduce long-term maintenance requirements and costs.

Both root growth and animal burrowing may provide pathways from the stabilized tailings to the environment and are therefore of concern. Research is currently under way to evaluate various chemical biobarriers for uranium mill tailings.[11] Herbicides in the form of polymeric sheets and pellets are being tested to determine their long-term ability to prohibit root growth into the tailings through the stabilizing cover material. Apparently, polymeric sheets containing herbicide are more costly than pellets, and pellets are substantially more convenient to use.

Burrowing habits of rodents and potential methods to limit burrowing are being investigated. It is believed that mechanical barriers will be more effective and less costly than chemical barriers in excluding burrowing animals from disposed tailings.

6.1.4 Vegetative Stabilization

Vegetative stabilization involves the establishment of plant growth on the tailings or on a growing medium placed over the tailings on the premise that the root system will tend to hold the soil in place.

Criteria for plant selection provide that the plants will:[11]

(a) Be tolerant of local environmental conditions.

(b) Have properties that will aid in erosion control.

(c) Have propagules that are readily available.

(d) Be relatively easy to establish.

(e) Be perennials, or annuals with good reproductive capabilities.

(f) Have minimal rooting depth requirements.

(g) Be of low food value and/or palatability.

(h) Have low value as habitat for wildlife.

Many species of plants require little or no maintenance after growth becomes established, an essential aspect of vegetative stabilization. Vegetation may be able to survive provided that:

(a) Evapotranspiration is not excessive.

(b) Landscapes are properly shaped.

(c) Nontoxic soil media capable of holding moisture are provided.

(d) Irrigation and fertilization appropriate to the area are applied to initiate growth.

Growth of vegetation at sites receiving less than 10 in. of annual precipitation and with high evapotranspiration rates requires initial irrigation and fertilization. At Tuba City, precipitation averages about 6 in. annually.

A principal disadvantage of vegetative stabilization is the possibility of uptake of radioactive elements by the plants. However, if the plants are properly selected, and if there is a sufficient depth of soil cover over the tailings, this uptake will be minimal. Barriers to root penetration are currently being evaluated.

6.2 PREVENTION OF LEACHING

Leaching into underground aquifers is one of the pathways that chemicals and radioactive materials might follow to the environment. The techniques that could be employed to control leaching from tailings piles include the following:

(a) Employ surface, volumetric, or physical stabilization to minimize infiltration of water, which would prevent leaching of hazardous elements into underground aquifers.

(b) Physically compact the tailings to reduce the percolation of water through the materials.

(c) Contour the drainage area and tailings surface to minimize the potential for water to penetrate into the tailings.

(d) For a new site, line the disposal area with a low-permeability membrane.

(e) Condition tailings to reduce leachability or contaminant content.

Current research of various liner systems has identified eight liner materials for continued laboratory study:

(a) Natural soil amended with sodium-saturated montmorillonite (Volclay*)

(b) Typical local clay with an asphalt emulsion radon-suppression cover

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*Registered trademark.

(c) Typical local clay with a multibarrier radon-suppression cover

(d) Rubberized asphalt membrane

(e) Hydraulic asphalt concrete

(f) Chlorosulfonated polyethylene (Hypalon*) or high-density polyethylene

(g) Bentonite, sand and gravel mixture

(h) Catalytic airblown asphalt membrane

Of these materials, the rubberized and hydraulic asphalts are judged to be the two most viable candidates at this time.[11]

Other studies[4] are addressing the possibility of conditioning the tailings such that if they were to leach, there would be minimal adverse impact.

6.3 REDUCTION OF RADON EXHALATION

Continuing research is directed toward reduction of radon exhalation from tailings piles.[3,8,9,16,17] While there are materials that can seal or contain the gas on a laboratory scale, their use for permanent coverage of large areas is presently being studied.

From simplified diffusion theory estimates, it can be shown that about 13 ft of dry soil[18,19] are needed to reduce radon flux by 95%, but only a few feet of soil are needed if a high moisture content in the cover material is maintained. Figure 6-1 depicts the dependence on moisture content of the effective diffusion coefficient for radon in soil. The dramatic decrease of the magnitude of the effective diffusion coefficient as the moisture content increases is responsible for the resulting reduction of radon flux.[20]

The reduction of radon exhalation flux for three soil types versus depth of cover is presented in Figure 6-2 and is based upon the theory and diffusion coefficients presented in the references cited earlier. Further research is currently under way to explore more precisely the problems associated with reducing and eliminating the exhalation of radon from radioactive tailings material. The effects of applying various surface stabilizers and varying thicknesses of stabilizing earth covers and combinations of materials are being investigated. The results may have an important impact in planning radon

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*Registered trademark.

exhalation control. However, proposed NRC standards for stabilizing inactive mill tailings require a minimum of 3 m of cover over the tailings.[1] The 3-m cover was assumed to be sufficient to meet proposed radon release requirements in remedial action cost estimates presented in this report.

Investigations described in Paragraph 6.1 have shown that cationic asphalt emulsions can be effective in large-scale applications in reducing radon fluxes to required levels.[11]

Studies of multilayer physical stabilization systems presently in progress are directed at identifying cost effective cover systems to satisfy proposed EPA standards for disposal.[1] These studies have indicated that, under a given set of conditions, a single-material cover would have to be up to about 24 ft (7.2 m) thick to reduce radon flux to the required 2 pCi/m^2-s. In contrast, a well designed multilayer cover system of less than 8.5 ft (2.6 m) thickness under the same conditions could satisfy the radon flux requirement.

6.4 REDUCTION OF GAMMA RADIATION

A few feet of cover material have been shown to be sufficient to reduce gamma radiation to background levels.

The reduction of gamma exposure rates resulting from a packed earth covering is given in Figure 6-3.[8,21] Two feet of cover reduce the gamma levels by about two orders of magnitude. Therefore, an average cover thickness of 3 m should reduce gamma levels from the tailings to background. Multilayer and asphalt cover systems currently under investigation have been shown to effectively attenuate gamma levels to acceptable ranges.

6.5 ASSESSMENT OF APPLICABILITY

Available data indicate that the methods previously used at the inactive sites in attempts to stabilize uranium tailings have not been totally satisfactory and that long-term solutions to uranium tailings site radiation problems have yet to be clearly demonstrated. Consequently, new or combination methods of stabilization are being evaluated. The present remedial action options include physical stabilization of the tailings with at least 3 m of well designed soil cover and 0.3 m of riprap. This action will reduce gamma radiation and wind and water erosion, substantially reduce radon exhalation, minimize infiltration, and allow reestablishment of native vegetation.

If remedial actions are taken, combinations of the methods described in this chapter for preventing erosion, leaching to ground water, radon exhalation, and gamma radiation will be implemented based on climatic, hydrogeological, economic, and demographic factors. The method of stabilizing uranium mill tailings whereby 3 m of well-engineered cover is placed on the pile is apparently the primary method currently available that satisfies both U.S.[1] and Canadian[22] regulatory requirements.

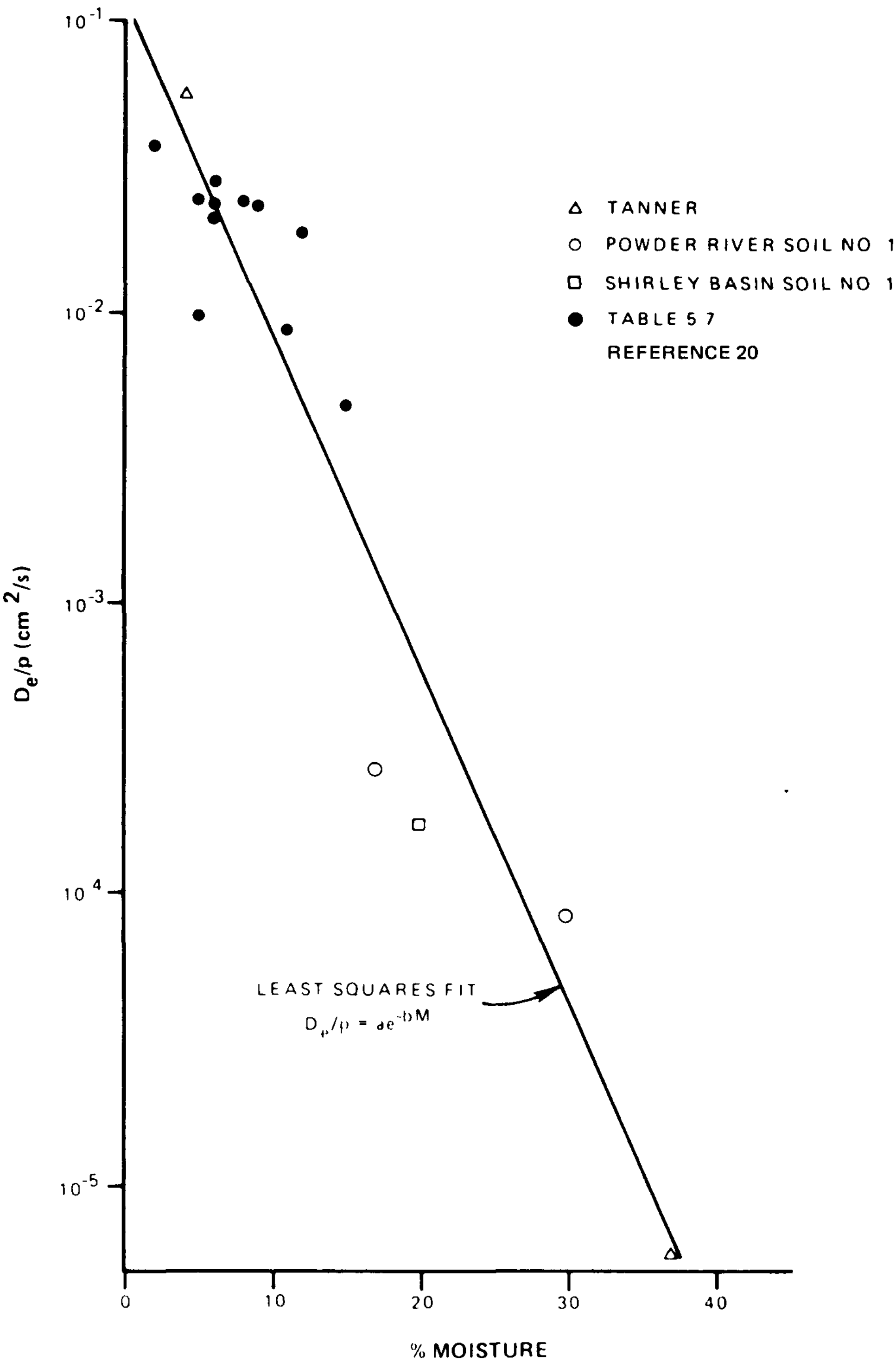

FIGURE 6-1. EXPONENTIAL MOISTURE DEPENDENCE OF THE DIFFUSION COEFFICIENT

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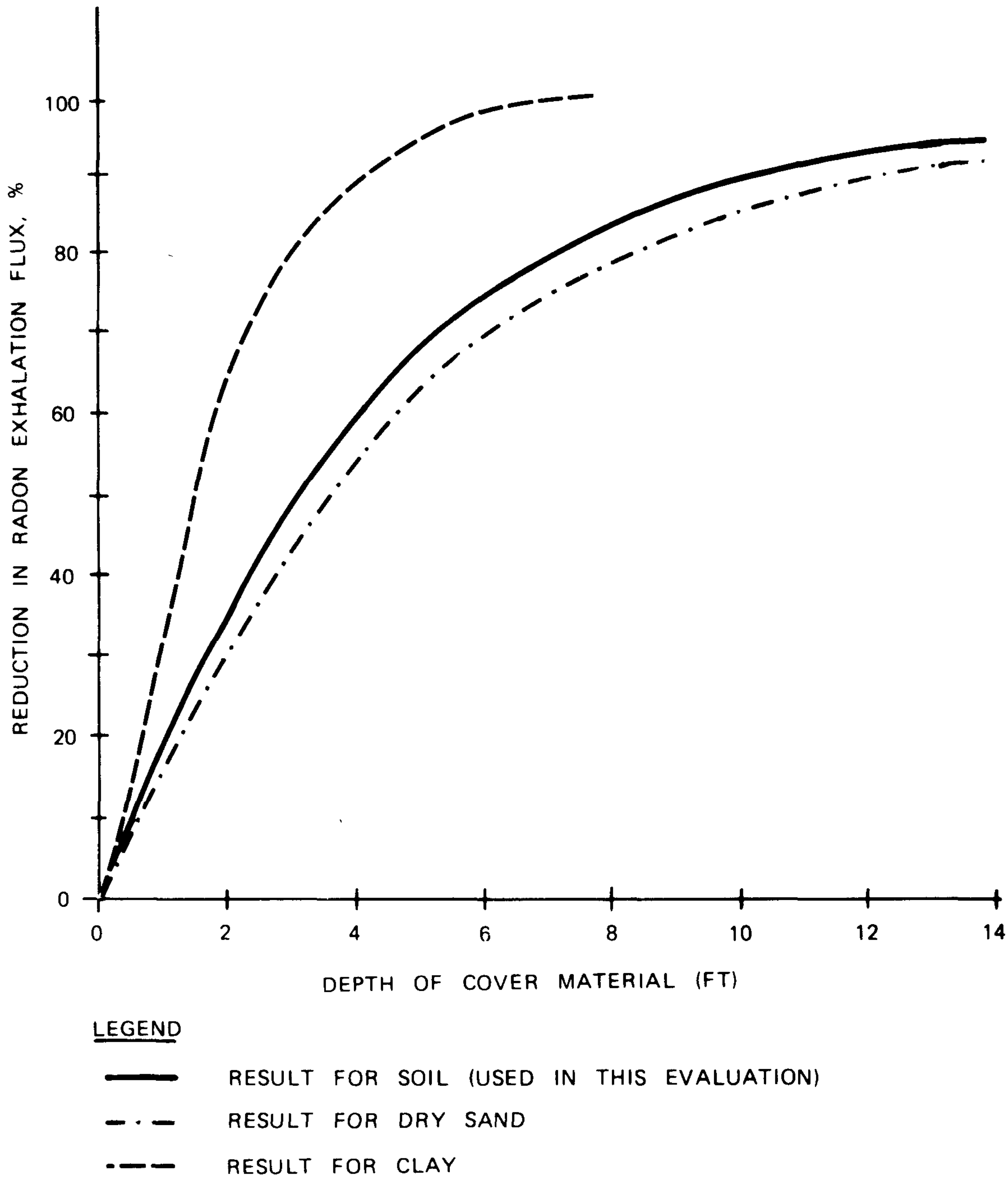

FIGURE 6-2. REDUCTION OF RADON EXHALATION FLUX WITH DEPTH OF COVER

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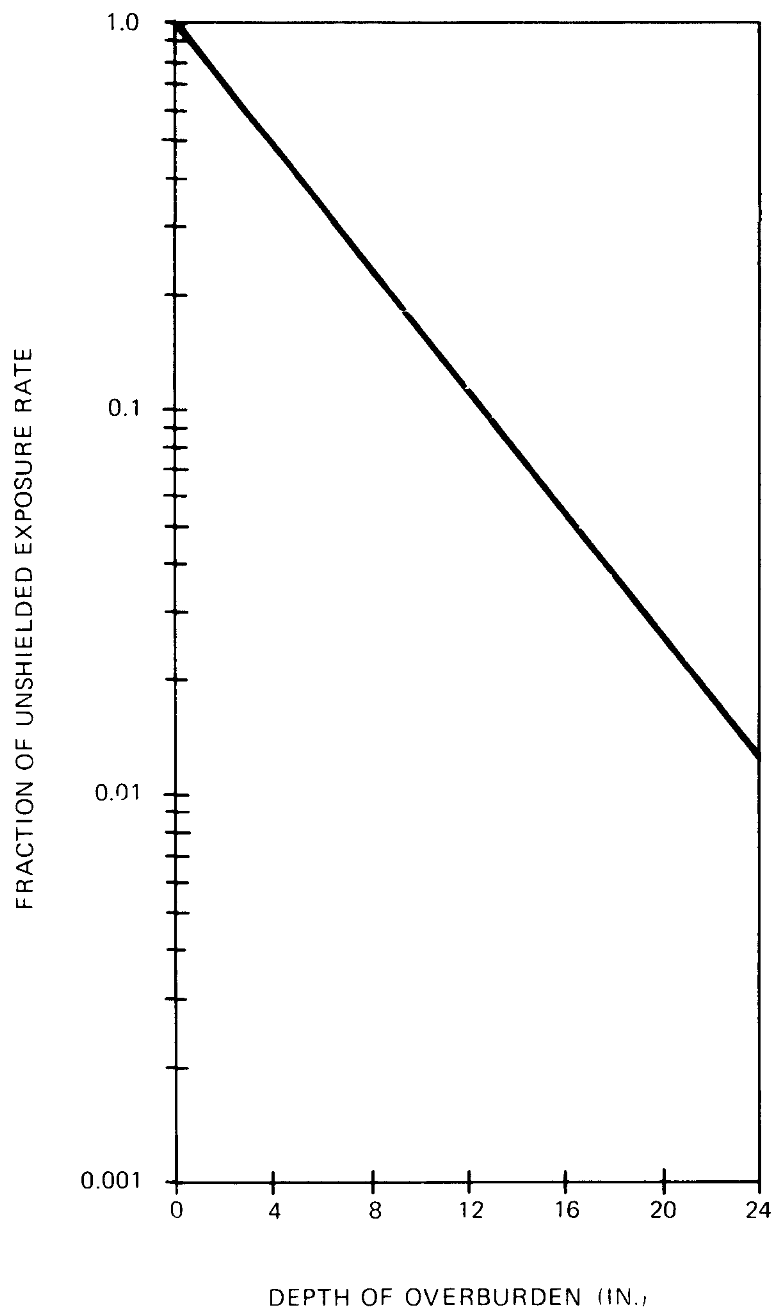

FIGURE 6-3. REDUCTION OF GAMMA EXPOSURE RATE RESULTING FROM PACKED EARTH SHIELDING

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CHAPTER 7

OFF-SITE REMEDIAL ACTION

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OFF-SITE REMEDIAL ACTION

An important objective of this engineering assessment is to estimate the cost of appropriate remedial action for those off-site properties contaminated with tailings.

Those locations where tailings have been transported off site are discussed in this chapter. Such off-site locations are classified as off-site windblown properties and off-site properties other than windblown. Costs associated with the cleanup of on-site contaminated areas, i.e., windblown, tailings pile, millsite, and ore storage, are considered in Chapter 9.

7.1 DATA SOURCES

A mobile scanning unit, operated by the AEC under an interagency agreement with the EPA, performed a gamma radiation survey of the Tuba City area in 1972. Of the 427 structures scanned, 13 anomalies were discovered. A joint team from the EPA Office of Radiation Programs, Las Vegas, Nevada, (EPA-ORP-LV) and the Arizona Atomic Energy Commission performed individual gamma surveys of locations to determine the source of the anomalies and, if tailings, how they had been used.[1] High and low inside and outside gamma readings were recorded. A gamma map was drawn of areas where gamma readings inside the structures exceeded 20 μR/hr.

The gamma survey and ^{226}Ra 5-pCi/g boundary mentioned in Paragraph 3.4.3 were the data sources for consideration of remedial action for windblown areas.

7.2 REMEDIAL ACTION FOR OFF-SITE PROPERTIES OTHER THAN WINDBLOWN

A follow-up survey of the anomalies[1] indicated six locations where tailings had been used. In the other seven cases no source of the anomaly could be found. Additional tailings use locations may be identified during future work.

The Navajo Environmental Protection Commission conducted an exhaustive series of gamma measurements in and around the buildings of the Tuba City site housing area in August 1980.[2] Radiation levels were found to be appreciably in excess of background at only 5 or 6 locations out of a total of 228 locations where gamma readings were obtained.

Costs for remedial action at off-site properties, other than windblown, have been estimated to be $100,000, exclusive of engineering and contingency allowances, based on available information and adjusted Grand Junction off-site remedial action costs. These costs include cleanup, backfill, restoration, and health physics and monitoring services. The estimated cost includes remedial action for the six locations where tailings use has been confirmed. An allowance for remedial action at some of the seven possible tailings locations also has been included.

7.3 REMEDIAL ACTION FOR OFF-SITE WINDBLOWN PROPERTIES

The extent of windblown tailings is indicated by the 5-pCi/g line in Figure 3-13. Decontamination of the area containing windblown tailings consists of removing 6 in. of soil and replacing it with clean fill. The result of this action is assumed to satisfy remedial action criteria as discussed in Paragraph 3.5.

The costs for cleanup and restoration of approximately 248 acres of off-site land due to windblown contamination are estimated to be $2,800,000, exclusive of engineering and contingency allowances.

It may be found expedient and acceptable to excavate windblown areas only, without returning clean material, since there is substantial movement of sandy soil as a result of wind erosion in this area. Were the area to be backfilled, the fill material could conceivably soon be blown away. Conversely, it is reasonable to expect that migrating sands would fill the area naturally within a few years. In any event, the final grade of the area is not crucial and a far more important consideration is probably stabilization of the disturbed area in this harsh environment.

CHAPTER 7 REFERENCES

1. "State Summary Report for Radiation Surveys: Tuba City, Arizona"; EPA, Office of Radiation Programs, Las Vegas, Nevada; Dec 1972.

2. T.R. Begay; Navajo Environmental Protection Commission; Window Rock, Arizona; Aug 1980.

CHAPTER 8

DISPOSAL SITE SELECTION

CHAPTER 8

DISPOSAL SITE SELECTION

Several of the remedial action options considered in this engineering assessment would involve moving the Tuba City tailings to a disposal site. Three unspecified disposal sites, at distances from 5 to 15 mi, are postulated. With the presently proposed regulations requiring at least 3 m of cover for the disposal of tailings, potential sources for these large amounts of cover material have been examined. The relative locations of actual sources of cover material to the various disposal sites will impact the costs.

8.1 CRITERIA FOR DISPOSAL

While disposal of the tailings at an alternative disposal site is not considered a necessary option, it is included in this report to provide a means of comparison between the cost of stabilizing the tailings in place and that of moving them to an unspecified disposal site, as well as to facilitate comparisons between this report and similar reports for other mill tailings sites.

Presently proposed regulations require 3 m of cover for the disposal of tailings. The relative locations of sources of cover material to actual disposal sites will impact the costs.

The return of tailings to the mines from which the ores were obtained is impractical since the ores processed at the plant came from many mines scattered over a wide area.

8.2 DESCRIPTIONS OF UNSPECIFIED DISPOSAL SITES CONSIDERED AS OPTIONS

A general description of unspecified disposal sites located 5, 10, and 15 mi from the Tuba City tailings pile is included in Paragraphs 8.2.1 through 8.2.3. All sites are demographically remote, and all are on the Navajo Indian Reservation within the Tuba City Chapter.

Although the vast areas of the Navajo Reservation seem to offer unlimited locations for disposal sites, consideration of the criteria limits the number of practical locations. Continued isolation on most possible sites seems very probable. Physical stabilization would be accomplished with sand, gravel, and soil coverings obtained from the vicinity of the disposal areas or from more distant borrow areas. A 0.3-m-thick cover of riprap would be placed to limit erosion.

The existing vegetation cover in the Tuba City area is 40% or less, and the average annual rainfall at Tuba City is approximately 6 in. Where dirt roads would be traversed by trucks carrying tailings, the cost estimates include the construction of gravel-based surfaces sufficient to handle the heavy loads and traffic. Transportation, site preparation, and maintenance costs are discussed more fully in Chapter 9. A general description of each of the disposal possibilities considered is outlined below.

8.2.1 Unspecified Disposal Site 5 Miles from the Tuba City Tailings Site

An unspecified disposal site at a distance of about 5 mi from the tailings site would be constrained to lie to the east, on U.S. Highway 160. Moving the tailings to the west would place them closer to Tuba City and moving them north would increase haul distances for cover material. The topography of the area renders a move to the south difficult.

In areas surrounding the Tuba City site, locations in the vicinity of the outcrops of the Petrified Forest Member of the Chinle Formation and of the Mancos Shale were found to yield potentially good cover materials where residual soils were present. The Petrified Forest Member of the Chinle Formation outcrops along most of the length of U.S. Highway 89. Good residually weathered outcrops of this formation are present from Cameron north to Cedar Ridge. North of Cedar Ridge to Bitter Springs the formation is in a valley and is, therefore, covered with alluvial deposits. North of the Bitter Springs Fault, the Chinle Formation is uplifted and begins to outcrop on the Echo Cliffs. This makes access to the formation more difficult, and because the residually weathered deposits are thinner, a larger surface area would be involved in obtaining the desired amounts of clay. Several areas underlain by the Mancos Formation were also examined; suitable samples were found in two other locations northeast of Tuba City, 24 and 54 road miles from the tailings site, respectively.

Moving the tailings to a disposal site about 5 mi east of their present location would situate them closer to the sources of clays, while still placing them in a similar hydrologic position on the Navajo Formation.

8.2.2 Unspecified Disposal Site 10 Miles from the Tuba City Tailings Site

An unspecified move of 10 mi to the east, south, or west would bring the pile closer to sources of fine-grained cover. If the move were to the west, the pile could be placed on the Kayenta Formation, on an aquiclude. Disposal at a distance of 10 mi on presently existing roads to the south or east would leave the tailings on Navajo Sandstone.

8.2.3 Unspecified Disposal Site 15 Miles from the Tuba City Tailings Site

Moving the tailings a distance of 15 mi either east or west along existing roads could place them, in each case, on an aquiclude. To the east the tailings would be placed on the Mancos Formation. Fine-grained soils should be readily available from the surrounding area. To the west the tailings could be placed either on the Kayenta Formation or on certain members of the Chinle Formation. Here too, clay sources should be readily available from the surrounding area. However, moving the tailings more than 5 mi to the west of their present location would place them upwind of the population center of Tuba City.

CHAPTER 9

REMEDIAL ACTIONS AND COST-BENEFIT ANALYSES

CHAPTER 9

REMEDIAL ACTIONS AND COST-BENEFIT ANALYSES

Various remedial action options for the tailings on the Tuba City site were identified and investigated. The remedial actions presented are those considered to be the most realistic and practical when evaluated with regard to the present remedial action criteria, technology, and information available. Costs and benefits have been estimated and evaluated for each option considered.

The procedures for decontaminating inactive mill tailings sites have not been well established. Although remedial action criteria have been established tentatively, the methodology of satisfying such standards is still in a state of change. The position has been taken that radiological and industrial safety should be pursued to the extent necessary to satisfy remedial action criteria and to provide assurance to the public and to workers. The public should feel comfortable with the methodologies used.

Remedial actions designed to meet the EPA interim remedial action criteria were investigated. Three unspecified disposal sites, identified in Chapter 8, were evaluated in terms of the cost of disposal. Although each alternative disposal site has specific and unique characteristics that were considered in estimating costs, great care must be exercised in the use of these site-specific cost estimates. The unspecified disposal sites have been characterized in typical terms for the purpose of estimating site development costs.

The process of obtaining the necessary permits and the associated costs were considered to be included in the various agency budgets and are not included in this report. Similarly, the tailings sites and the proposed disposal sites have been treated as lands belonging to the Navajo Nation with no acquisition costs included.

Costs for future maintenance and radiological monitoring at the location of the tailings are not included in this estimate. Funding for such future costs is assumed to come from separate contracts administered by the Federal Government.

The options for disposal at the sites would provide for the relocation of all debris and contaminated materials from the tailings pile and off-site locations. Thus, in all of the disposal options, the entire site and off-site areas would be left free of any tailings or contaminated materials in excess of the allowed 5 pCi/g of ^{226}Ra above background. The area to be decontaminated at the Tuba City site is shown in Figure 9-1.

A discussion of the concepts involved in tailings stabilization and their applicability to the Tuba City site has been detailed in Chapter 6. It is assumed that a riprap or gravel cap of 0.3 m on top of a 3-m depth of cover material for all options will suffice for erosion control.

9.1 STABILIZATION OF THE TAILINGS ON SITE WITH A 3-METER COVER (OPTION I)

In this section, the conceptual design of the option to stabilize the Tuba City tailings pile is discussed, and the estimated cost of the corresponding remedial actions presented.

9.1.1 Conceptual Design

Stabilization of the Tuba City tailings on the present site is a viable option because of the relatively isolated location of the present tailings pile. In preparing the cost estimate for this option, the possible problem of migration of contamination via unconfined ground water was not considered and the cost does not include the placement of a clay or synthetic liner under the tailings. The cost of this option would increase significantly if the liner were required.

Under this option the tailings would remain on site. Contaminated materials from all windblown areas, off-site properties, evaporation ponds, millsite, and ore storage areas would be consolidated at the tailings pile. For purposes of cost estimates, it was assumed that all areas would be backfilled to natural grade, although this cost may be avoided since the final grade is not a crucial concern at this site. This savings is expected to be on the order of $1 million, without contingency or other allowances.

The tailings would be leveled, graded, and stabilized with 3 m of cover material, which has been shown to be adequate under certain conditions to reduce flux to less than 2 pCi/m^2-s. Clay for cover material can be obtained at distances varying from about 25 mi to about 65 mi from the tailings site. Since clay is not required as cover material, it is possible to use a greater thickness of locally available, but more permeable, material to satisfy the requirement on radon flux from the stabilized pile. In such a case, the total savings might be as high as $5 million, including allowances for contingency and design.

If the Tuba City site were stabilized in place, the area where the tailings are located would have limited future use.

9.1.2 Costs

As shown in Table 9-1, the cost for stabilization at the Tuba City site is estimated to be $17,800,000. Costs include cleaning up of off-site locations, windblown tailings, evaporation ponds, millsite, ore storage areas, and covering all contaminated materials with 3 m of cover, contouring the surface, and reclaiming all areas.

9.2 REMOVAL OF TAILINGS AND ALL CONTAMINATED MATERIALS FROM THE SITE (OPTIONS II THROUGH IV)

Options II through IV would provide for the complete removal of all tailings, contaminated soil, buildings, materials, and rubble from the tailings site and off-site areas to unspecified disposal sites. The amount of soil to be removed depends on the depth of contamination. Removal to averages of 2 ft of subsoil beneath the tailings pile, 4 ft of subsoil at evaporation ponds, 2 ft at the millsite and ore storage area, and 6 in. of soil at windblown areas would reduce apparent residual radium concentration to less than the allowed 5 pCi/g above background levels. Finally, the site would be backfilled to natural grade and released for unrestricted use.

9.2.1 Excavation and Loading of Tailings and Soils

The tailings pile poses no major excavation problems. Different methods of excavation are possible, with a single bench open-pit method being the most feasible for the tailings pile. Suitable equipment would have to be used to excavate windblown and shallow contaminated areas.

To eliminate further tailings dispersion during loading and transportation operations, dust control equipment and washdown facilities would be provided.

The Tuba City site would be backfilled to natural grade. Local materials, all of which must be hauled onto the site, would be used as backfill. No special treatments of the final surface other than establishing native grass cover at the decontaminated tailings site are considered in this assessment.

9.2.2 Transportation of the Materials

Railroad transportation is not considered feasible for tailings transport since there are no rail facilities in the vicinity of the tailings or disposal sites.

Slurry pipeline transportation was not considered feasible due to the lack of water in the area.

The use of conveyors in transporting the tailings and contaminated materials has been investigated briefly to assess its viability. While any conclusive statement is very dependent upon the site- and route-specific parameters, some generalizations can be made about the viability of conveyors in this application:

(a) The longer the life of the project, the more attractive the use of conveyors becomes.

(b) The greater the mass to be moved, the more attractive the use of conveyors becomes.

(c) Conveyors can be more attractive in difficult terrain.

However, there are many complications involved in the use of conveyors, many of which are difficult to quantify. Public acceptance, acquisition of rights-of-way and permits within a reasonable time frame, and environmental impact are considerations that cloud the evaluation of conveyors.

With all of the factors considered, the quantity of material to be moved does not appear to warrant the use of conveyors, making transportation by truck preferable. At such time as a specific site is chosen, a detailed evaluation would disclose whether this generalization holds true for the selected site and routes.

If trucks could move the materials at the rate of about 4,800 tons/day, working 5 days/wk, all contaminated materials could be removed in less than 1.3 yr. This method assumes the use of conventional truck-trailer dump trucks. Dust control measures, such as covers and washdown facilities for the trucks, are included as capital costs associated with transportation.

Transportation costs for trucking include all costs associated with tailings, necessary cover material, and riprap material. No costs are included for repair and maintenance of public roads. Capital costs include development of access roads and maintenance thereof whenever such roads are required.

9.2.3 Disposal at Alternative Sites

A discussion of proposed unspecified disposal sites is given in Chapter 8. Each disposal site has different physical, geological, and hydrological characteristics. However, because the Federal Government, with input from the State and Tribe, as appropriate, is ultimately responsible for the selection of disposal sites, there is no assurance that any of the disposal sites considered in this report will be selected. Nevertheless, an effort was made to quantify these differences based on what limited data was available for each site and to show the approximate costs that would result if the contaminated materials were actually disposed of at the sites, as discussed in Chapter 8.

Unspecified disposal sites are located within 15 mi of the tailings pile. Vegetation covers 40% or less in the vicinity of Tuba City, and the average annual rainfall at all disposal areas is about 6 in. Where existing dirt roads are to be traveled by trucks carrying tailings, the cost estimates include the construction of a gravel-based surface sufficient to handle the heavy loads. Improvement of 3 mi of haul road was assumed for each option.

The disposal sites may be isolated from drainage basins naturally or by dikes and drainage ditches. In general, disposal of the tailings will be above ground, requiring transportation of cover material from a source located 24 mi northeast of the site. Extensive diking and contouring for erosion control might be necessary in such situations. Figure 9-2 is a schematic representation of how these disposal sites might be developed.

Disposal site costs consist of preparation of the site, placement of tailings and cover material, diking and contouring, and necessary reclamation of surface areas.

The unspecified disposal sites evaluated are described in Chapter 8. The estimated costs for the disposal options are shown in Table 9-1 and range from about $21,600,000 for Options II and III to about $23,100,000 for Option IV.

The range in cost is due to differences among costs associated with transportation. Consequently, the overall cost estimate is largely dependent on the distance from the tailings site to the disposal site and the availability of cover material to the site.

Costs for health physics and radiological monitoring are included in individual component costs (lines 1 through 5, Table 9-1). Such costs reflect approximately 19% of the total cleanup costs (line 6).

In Options II through IV the estimated costs include cleanup of off-site locations and tailings pile; backfilling the former tailings site; establishing vegetative cover at and around the tailings site; covering all tailings and contaminated materials at the disposal site with 3 m of cover material; and contouring the stabilized disposal site and placing 0.3 m of riprap for erosion control.

9.3 ANALYSES OF COSTS AND BENEFITS

9.3.1 Health Benefits

Each of the remedial action alternatives considered in this chapter has an associated health benefit that would be experienced as a result of the remedial action. This health benefit is the reduction of the health effects (number of lung cancer cases) resulting from the remedial action. In Chapter 3, the estimated number of health effects was determined for the Tuba City tailings pile in its present condition. In order to estimate the number of health benefits attributable to particular remedial actions, the effects of those remedial actions on radon exhalation from the pile must be determined, because the health effects calculated in Chapter 3 were associated with radon daughters. While there are some benefits associated with actions such as fencing, these have not been quantified in this assessment of health benefits.

In this evaluation, the health benefit of each option is calculated from the reduction in radon exhalation that is expected for that option. In accordance with proposed requirements for stabilization of uranium mill tailings, radon fluxes were assumed to be reduced from their predicted values under present conditions (as conservatively calculated in Paragraph 3.6.2) to the required flux of 2 pCi/m^2-s for Option I. In all other options, radon flux was assumed to be reduced to zero by the removal of the tailings. Since health effects are proportional to radon flux, the present health effects rate was estimated to be reduced by more than 99% with stabilization in-place and by 100% with tailings removal.

The potential cancer cases avoided (health benefits) for each option are given as a function of time in part A of Table 9-2. The cost per potential cancer case avoided for each option is included as part B in Table 9-2.

As an alternative to the presentation in Table 9-2, the number of potential cancer cases avoided per million dollars expended were calculated and plotted in Figure 9-3. Option I yields the maximum health benefit per unit cost, whereas Option IV yields the minimum benefit per unit cost.

9.3.2 Land Value Benefits

Because all reservation land is owned in common by the Navajo Tribe, there is no conventional valuation for Navajo properties. There are ways, however, that dollar values of land on the Navajo Reservation can be approximated, as discussed in Chapter 4. At present, grazing land on the reservation is valued at \$55 to \$65/acre. A 10- to 15-yr lease to land where coal may be mined could range between \$350 and \$500/acre. Should the Tuba City tailings be removed to a remote disposal location, the value of the site might increase over the \$55 to \$65 figure, but the exact increase would be related to the land demands involved.

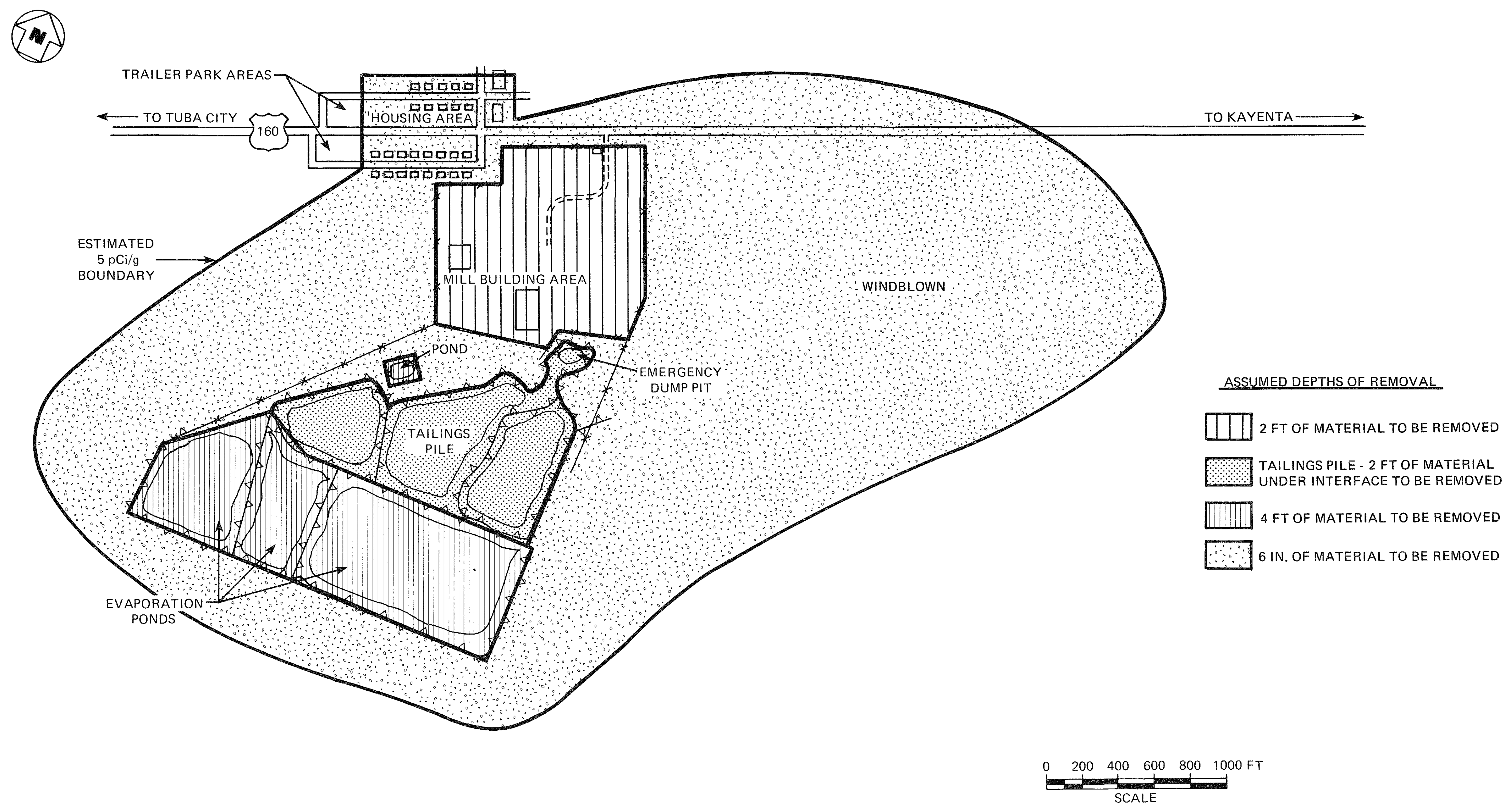

FIGURE 9-1. AREA DECONTAMINATION PLAN

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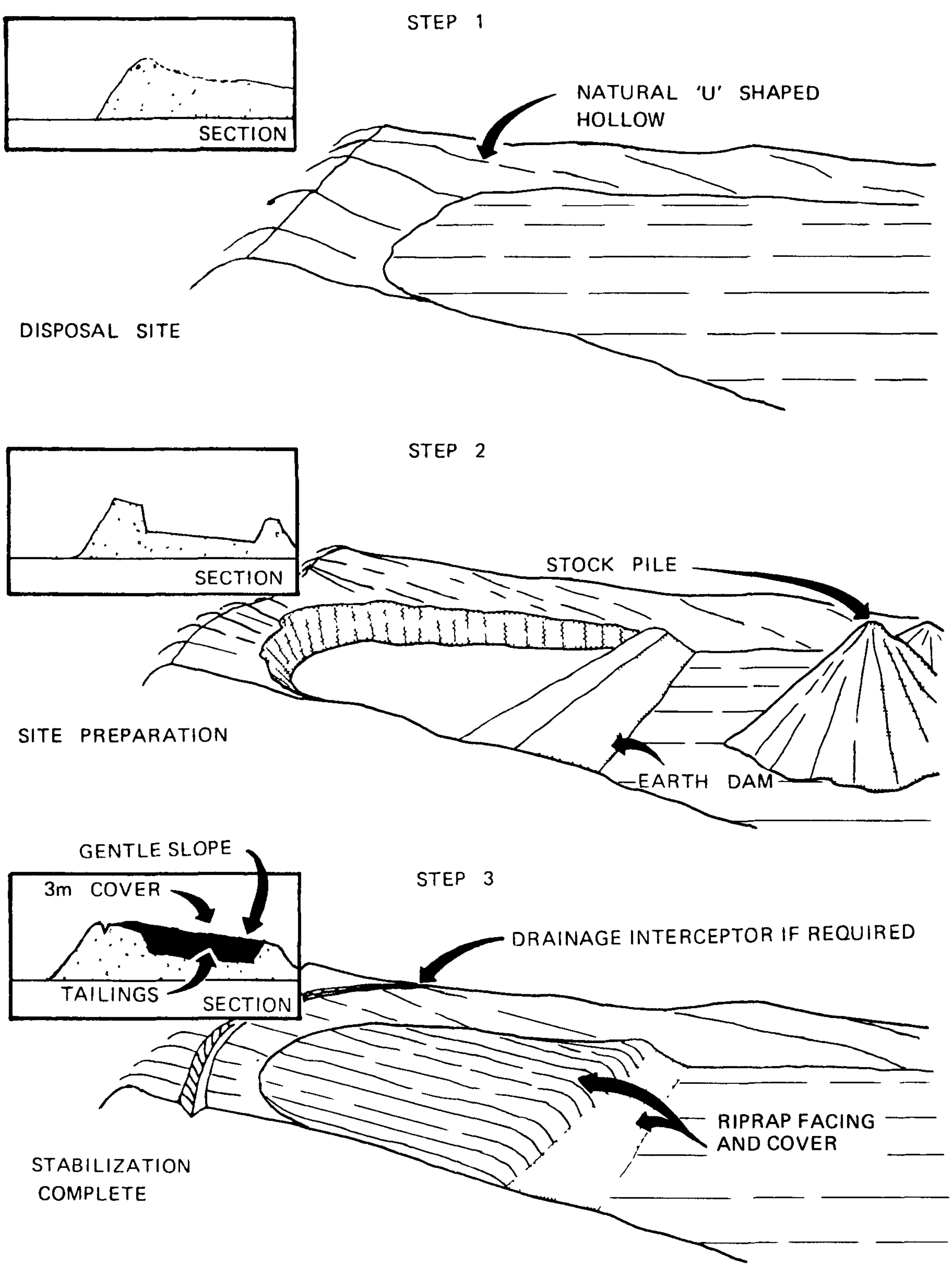

FIGURE 9-2. SCHEMATIC OF TYPICAL TAILINGS DISPOSAL SITE

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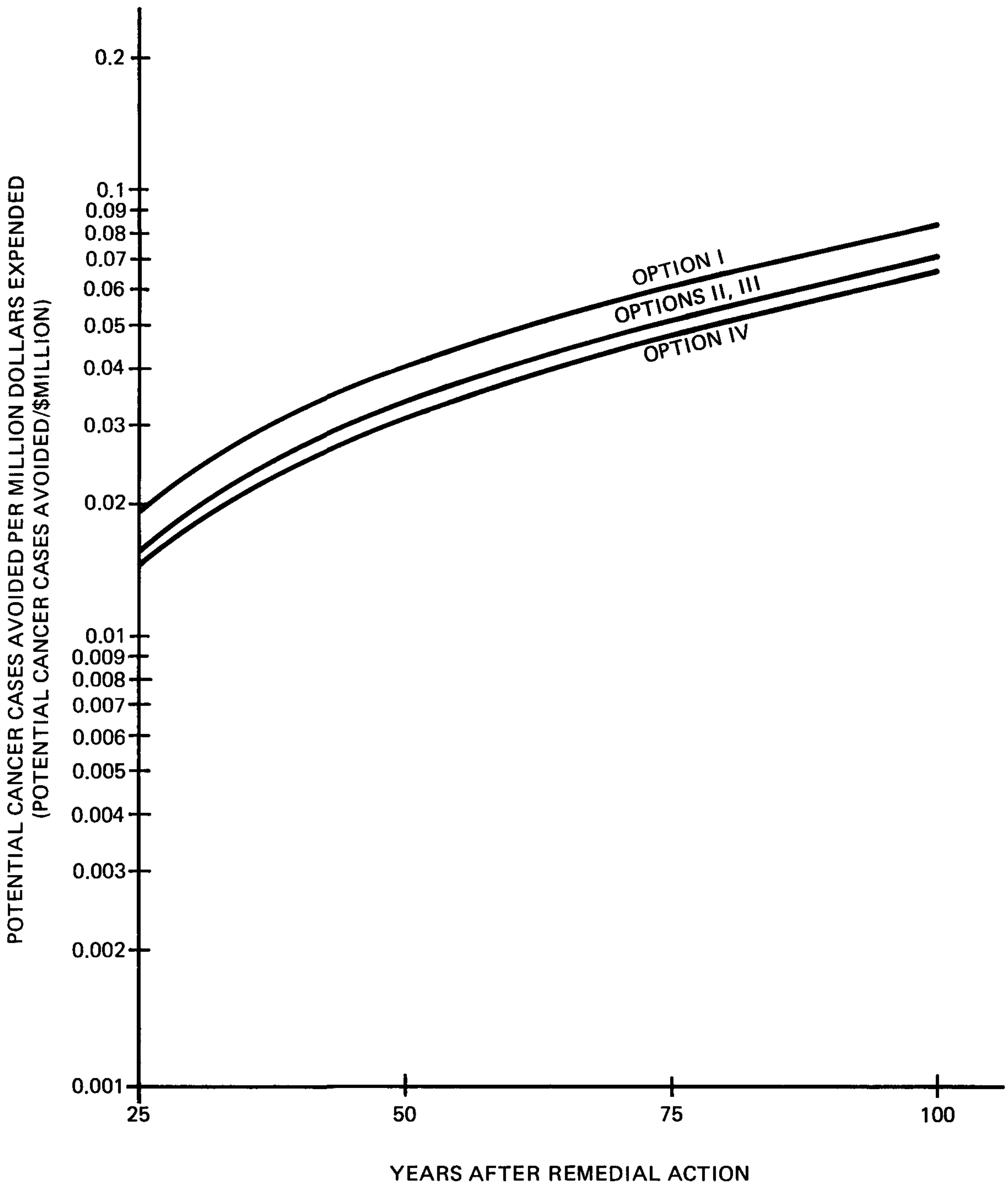

FIGURE 9-3. POTENTIAL CANCER CASES AVOIDED PER MILLION DOLLARS EXPENDED

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TABLE 9-1

SUMMARY OF STABILIZATION AND DISPOSAL COSTS[a]

		Options			
		I	II	III	IV
1.	Tailings Site	7.6	3.2	3.2	3.2
2.	Off-Site Other than Windblown	0.1	0.1	0.1	0.1
3.	Off-Site Windblown[b]	2.8	2.8	2.8	2.8
4.	Transportation				
	a. Capital Costs	--	0.2	0.2	0.2
	b. Haul Costs[c]	--	4.5	5.4	5.6
5.	Disposal Site	--	3.0	3.0	3.0
6.	Total Cleanup[d] (sum of lines 1 through 5)	10.5	13.8	14.4	15.0
7.	Engineering Design and Construction Management (30% of the difference between lines 6 and 4b)	3.2	2.8	2.8	2.8
8.	Total[d] (sum of lines 6 and 7)	13.7	16.6	17.2	17.7
9.	Contingency (30% of line 8)	4.1	5.0	5.2	5.3
10.	GRAND TOTAL[d] (sum of lines 8 and 9)	17.8	21.6	22.3	23.1

TABLE 9-1 (Cont)

[a] Costs are in millions of 1980 dollars.

[b] A savings of about $1 million, without engineering and contingency allowances, might be realized, if backfilling decontaminated areas can be dispensed with.

[c] If locally available sandy soil were used to cover the tailings pile, a savings of about $3 million, without engineering and contingency allowances, might be realized.

[d] Totals may differ from the sum of component costs because of round-off.

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TABLE 9-2

POTENTIAL CANCER CASES AVOIDED
AND COST PER POTENTIAL CASE AVOIDED

A. Number of Potential Cancer Cases Avoided

Options:	I	II	III	IV
Option Cost (million $)	17.8	21.6	22.3	23.1
Years After Remedial Action				
25	<0.28	0.28	0.28	0.28
50	<0.61	0.61	0.61	0.61
75	<0.93	0.93	0.93	0.93
100	<1.3	1.3	1.3	1.3

B. Cost Per Potential Cancer Case Avoided (Million $)

Options:	I	II	III	IV
Option Cost (million $)	17.8	21.6	22.3	23.1
Years After Remedial Action				
25	>64	77	80	83
50	>29	35	37	38
75	>19	23	24	25
100	>14	17	18	18

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TABLE 9-2

POTENTIAL CANCER CASES AVOIDED
AND COST PER POTENTIAL CASE AVOIDED

A. Number of Potential Cancer Cases Avoided

Options:	I	II	III	IV
Option Cost (million $)	17.8	21.6	22.3	23.1
Years After Remedial Action				
25	<0.34	0.34	0.34	0.34
50	<0.72	0.72	0.72	0.72
75	<1.1	1.1	1.1	1.1
100	<1.5	1.5	1.5	1.5

B. Cost Per Potential Cancer Case Avoided (million $)

Options:	I	II	III	IV
Option Cost (million $)	17.8	21.6	22.3	23.1
Years After Remedial Action				
25	>52	64	66	68
50	>25	30	31	32
75	>16	20	20	21
100	>12	14	15	15

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GLOSSARY

GLOSSARY

Terms/Abbreviations	Definitions
absorbed dose	Radiation energy absorbed per unit mass.
A-E	Architect-Engineer.
AEC	Atomic Energy Commission.
alpha particle (α)	A positively charged particle emitted from certain radioactive materials. It consists of two protons and two neutrons, hence is identical with the nucleus of the helium atom. It is the least penetrating of the common radiations (α, β, γ), hence is not dangerous unless alpha-emitting substances have entered the body.
amenability	The relative ease with which a mineral can be removed from an ore by a particular process.
anomaly (mobile gamma survey)	Any location detected by the mobile gamma survey where the recorded counts per second (c/s) from the large gamma-ray detector exceed the determined background for that area by 50 or more c/s.
aquifer	A water-bearing formation below the surface of the earth; the source of wells. A confined aquifer is overlain by relatively impermeable rock. An unconfined aquifer is one associated with the water table.
atmospheric pressure	Pressure exerted on the earth by the mass of the atmosphere surrounding the earth; expressed in inches of mercury (at sea level and $0^{\circ}C$, standard pressure is 29.921 in. Hg).

background radiation	Naturally occurring low-level radiation to which all life is exposed. Background radiation levels vary from place to place on the earth.
beta particle (β)	A particle emitted from some atoms undergoing radioactive decay. A negatively charged beta particle is identical to an electron. A positively charged beta particle is called a positron. Beta radiation can cause skin burns and beta emitters are harmful if they enter the body.
BEIR	Biological Effects of Ionizing Radiation.
BOM (USBOM)	Bureau of Mines.
CHES	Center for Health and Environmental Studies, Brigham Young University, Provo, Utah.
Curie (Ci)	The unit of radioactivity of any nuclide, defined as precisely equal to 3.7×10^{10} disintegrations/second.
daughter product	The nuclide remaining after a radioactive decay. A daughter atom may itself be radioactive, producing further daughter products.
diurnal	Daily, cyclic (happening each day or during the day).
dose equivalent	A term used to express the amount of effective radiation when modifying factors have been considered (the numerical product of absorbed dose and quality factor).
EPA (USEPA)	Environmental Protection Agency.
ERDA (USERDA)	Energy Research and Development Administration.

ERDA-GJO	Energy Research and Development Administration-Grand Junction Office.
erg	A basic unit of work or energy in the centimeter-gram-second system (1 erg = 7.4 x 10^{-8} ft-lb, or 10^{-7} joule).
external gamma radiation (EGR)	Gamma radiation emitted from a source(s) external to the body, as opposed to internal gamma radiation emitted from ingested or inhaled sources.
exposure	Related to electrical charge produced in air by ionizing radiation per unit mass of air.
exhalation	Emission of radon from earth (usually thought of as coming from a uranium tailings pile, but actually from any location).
FB&DU	Ford, Bacon & Davis Utah Inc.
fixed alpha	Particulate alpha emitting isotopes which have become imbedded in otherwise non-radioactive surfaces and which cannot be removed by standard decontamination techniques.
gamma background	Natural gamma ray activity everywhere present, originating from two sources: (1) cosmic radiation, bombarding the earth's atmosphere continually, and (2) terrestrial radiation. Whole body absorbed dose equivalent in the U.S. due to natural gamma background ranges from about 60 to about 125 mrem/yr.
gamma ray (γ)	High energy electromagnetic radiation emitted from the nucleus of a radioactive atom, with specific energies for the atoms of different elements and having high penetrating power.
GJO	Grand Junction Office.

ground water	Subsurface water in the zone of full saturation which supplies wells and springs.
health effect	Adverse physiological response from tailings (in this report, one health effect is defined as one case of cancer from exposure to radioactivity).
heap leaching	A process for removing uranium from ore, tailings, or other material wherein the material is placed on an impermeable pad and wetted with appropriate reagents. The uranium solution is collected for further processing.
HEW (USHEW)	Department of Health, Education, and Welfare.
insult	Negative impact on the environment or the health of individuals.
Interim Primary Drinking Water Regulations	Title No. 40 of the Code of Federal Regulations, Chapter 1, Part 141, dated Dec 24, 1975 and effective June 24, 1977.
iso-exposure line	A line drawn on a map to connect a set of points having the same exposure rate.
isotope	One of two or more species of atoms with the same atomic numbers (the same chemical element) but with different atomic weights. Isotopes usually have very nearly the same chemical properties, but somewhat different physical properties.
JCAE	Joint Committee on Atomic Energy.
knot	A unit of velocity, approximately equal to 1.15 mi/hr.
man-rem (person-rem)	A unit used in health physics to compare the effects of different amounts of radiation on groups

	of people. It is obtained by summing individual dose equivalent values for all people in the population.
μR/hr	Microroentgen per hour (10^{-6} R/hr).
mR/hr	Milliroentgen per hour (10^{-3} R/hr).
MeV	Million electron volts.
maximum permissible concentration (MPC)	The highest concentration in air or water of a particular radionuclide permissible for occupational or general exposure without taking steps to reduce exposure.
NAS	National Academy of Sciences.
NIOSH	National Institute for Occupational Safety and Health.
noble gas	One of the gases, such as helium, neon, radon, etc., with completely filled electron shells, which is therefore chemically inert.
NRC	Nuclear Regulatory Commission.
nuclide	A general term applicable to all atomic forms of the elements; nuclides comprise all the isotopic forms of all the elements. Nuclides are distinguished by their atomic number, atomic mass, and energy state.
ORNL	Oak Ridge National Laboratory.
ORP-LVF (EPA)	Office of Radiation Programs, Las Vegas Facility (Environmental Protection Agency).
pCi/l	Picocurie per liter (10^{-12} Ci/l)
pCi/g	Picocurie per gram (10^{-12} Ci/g)
pCi/m^2-s	Picocurie per square meter per second (10^{-12} Ci/m^2-s)

PHS (USPHS)	Public Health Service.
quality factor (QF)	An assigned factor that denotes the modification of the effectiveness of a given absorbed dose by the linear energy transfer.
rad	The basic unit of absorbed dose of ionizing radiation. A dose of 1 rad means the absorption of 100 ergs of radiation energy per gram of absorbing material.
radioactivity	The spontaneous decay or disintegration of an unstable atomic nucleus, usually accompanied by the emission of ionizing radiation.
radioactive decay chain	A succession of nuclides, each of which transforms by radioactive disintegration into the next until a stable nuclide results. The first member is called the parent, the intermediate members are called daughters, and the final stable member is called the end product.
radium	A radioactive element, chemically similar to barium, formed as a daughter product of uranium (^{238}U). The most common isotope of radium, ^{226}Ra, has a half-life of 1,620 yr. Radium is present in all uranium-bearing ores. Trace quantities of both uranium and radium are found in all areas, contributing to the background radiation.
radon	A radioactive, chemically inert gas. The nuclide ^{222}Rn has a half-life of 3.8 days and is formed as a daughter product of radium (^{226}Ra).
radon background	Low levels of radon gas found in air resulting from the decay of naturally occurring radium in the soil.

radon concentration	The amount of radon per unit volume. In this assessment, the average value for a 24-hr period of atmospheric radon concentrations, determined by collecting data for each 30-min period of a 24-hr day and averaging these values.
radon daughter	One of several short-lived radioactive daughter products of radon (several of the daughters emit alpha particles).
radon daughter concentration (RDC)	The concentration in air of short-lived radon daughters, expressed either in pCi/l or in terms of working level (WL).
radon flux	The quantity of radon emitted from a surface in a unit time per unit area (typical units are in pCi/m^2-s).
raffinate	The liquid part remaining after a product has been extracted in a solvent extraction process.
recharge	The processes by which water is absorbed and added to the zone of saturation of an aquifer, either directly into the formation or indirectly by way of another formation.
rem (roentgen equivalent man)	The unit of dose equivalent of any ionizing radiation which produces the same biological effect as a unit of absorbed dose of ordinary X-rays, numerically equal to the absorbed dose in rads multiplied by the appropriate quality factor for the type of radiation. The rem is the basic recorded unit of accumulated dose to personnel.
residual value	The value of minerals in tailings material.

riprap	An irregular protective layer of broken rock.
roentgen (R)	A unit of exposure to ionizing radiation. It is that amount of gamma or X-rays required to produce ions carrying 1 electrostatic unit of electrical charge, either positive or negative, in 1 cubic centimeter of dry air under standard conditions, numerically equal to 2.58×10^{-4} coulombs/kg of air.
sands	Relatively coarse-grained materials produced along with the slimes as waste products of ore processing in uranium mills (see tailings). These sands normally contain a lower concentration of radioactive material than the slimes.
scintillometer	A gamma-ray detection instrument normally utilizing a NaI crystal.
slimes	Extremely fine-grained materials mixed with small amounts of water, produced along with the sands as waste products of ore processing in uranium mills (see tailings). The highest concentration of radioactive material remaining in tailings is found in the slimes.
tailings	The remaining portion of a metal-bearing ore after the desired metal, such as uranium, has been extracted. Tailings also may contain other minerals or metals not extracted in the process (e.g., radium).
UMTRA	Uranium Mill Tailings Remedial Action
working level (WL)	A unit of radon daughter exposure, equal to any combination of short-lived radon daughters in 1 liter of air that will result in the ultimate

emission of 1.3 x 10^5 MeV of potential alpha energy. This level is equivalent to the energy produced in the decay of the daughter products RaA, RaB, RaC, and RaC' that are present under equilibrium conditions in a liter of air containing 100 pCi of Rn-222. It does not include decay of RaD (22-yr half-life) and subsequent daughter products.

working level month (WLM) — One WLM is equal to the exposure received from 170 WL-hours.