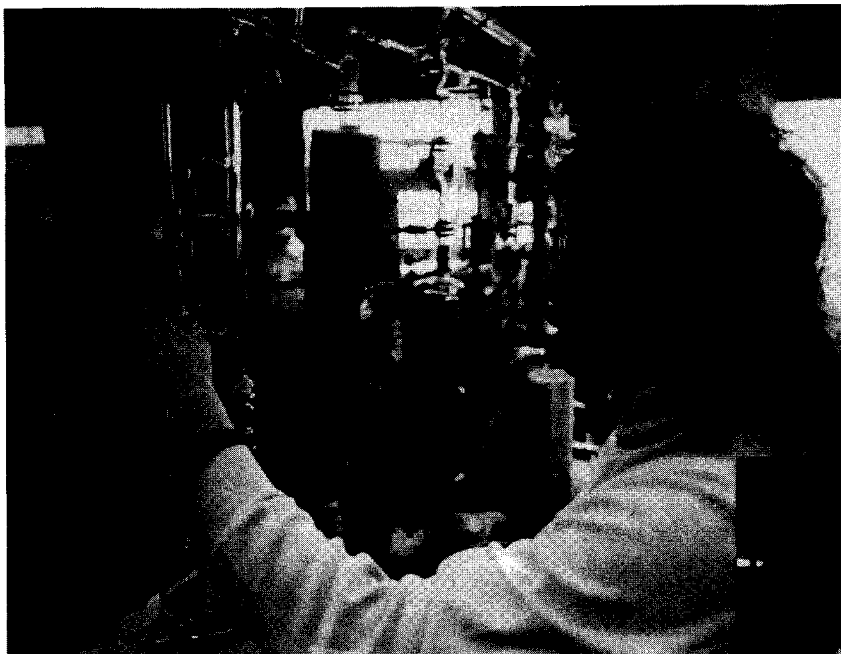
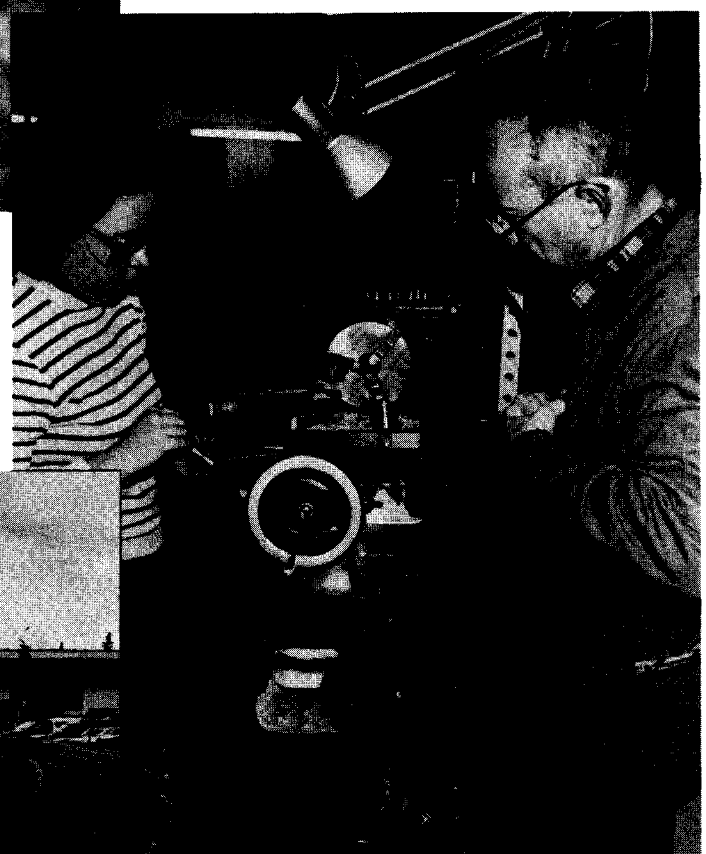
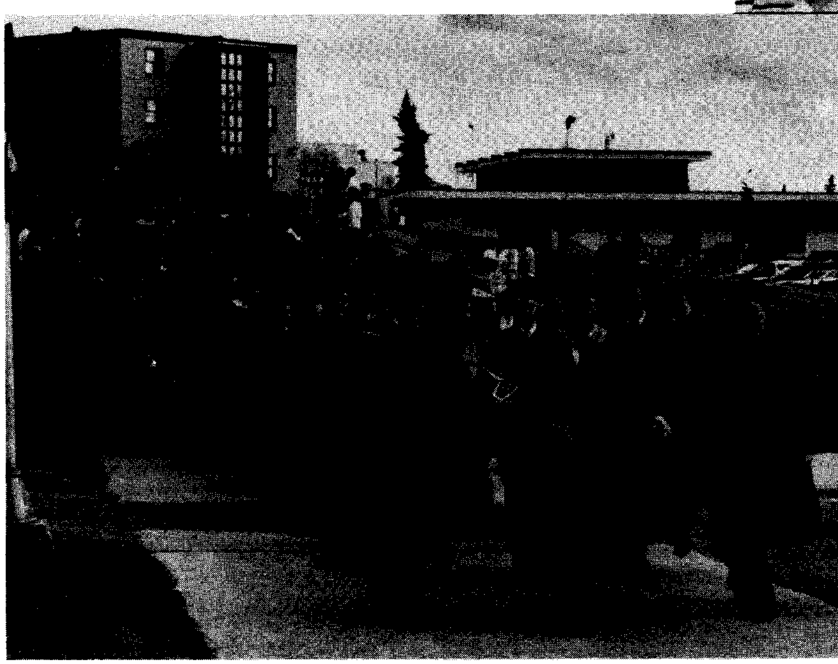
# THE NORTHERN ENGINEER







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Summer 1987

# OPINION

## *Professional Assets* *by Stuart G. Walesh, Dean, Valparaiso University*

*Last October's "Black Monday" affected most of us as our retirement accounts, mutual funds, and other investments plummeted in value. Suddenly our personal wealth was less. We feared the negative effect on the material well-being of our family and others who depend on us. Many of us vowed to be more careful where we invest and to be more watchful of our investments. After all, prudence requires careful management of our financial assets.*

*But what about the status of and the attention to our professional assets? By virtue of individual talents, education and experience, each engineering practitioner and educator has significant value to society. In contrast with one's financial assets, which can be measured to the penny, the value of one's professional assets defies quantification. In a narrow sense, individual professional assets might be valued as the present worth of the projected stream of future earnings. In a broader and more accurate sense, one's professional assets are measured by the actual good accomplished and by all the good a person has the potential to accomplish through conscientious use of his or her talents, education and experience.*

*Although the true value of our individual professional assets defies quantification, it nevertheless is very real. Furthermore, the value of professional assets, even if narrowly defined, far exceeds the value of one's financial assets except perhaps for those few who are independently wealthy. Like our financial assets, our professional assets can appreciate, remain level, or decline.*

*We should appraise our professional assets at least once a year, perhaps as part of a resume update exercise. What new areas of technology have we mastered? What new management techniques have we used? What new concepts, ideas or principles have we studied? What new skills have we acquired? What new challenges and responsibilities have we accepted? What new opportunities have we seized and new risks have we taken? What knowledge have we shared with our professional colleagues? What new contributions have we made? In what ways have we been "good and faithful servants" with our God-given talents?*

*If an annual accounting of our professional assets reveals a loss or no increase in value, we've experienced a personally devastating "Black Monday." We've lost a year of growth and increased contribution, neither of which can ever be regained. As a result of mismanagement of our professional assets, we've failed ourselves, our family, our employer, our client, our students, our profession, and society.*

*Each of us is gifted with a unique combination of talents. The challenge in our professional life is to discover and develop through reflection, education and experience, our special set of talents and then to dedicate and direct those talents to meaningful professional work and service. Let's commit now to manage our professional assets at least as well as we manage our financial assets.*

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This "Opinion" article came to us by way of a newsletter called "Venture", published by the College of Engineering at Valparaiso University in Valparaiso, Indiana. We felt it to be a compelling piece, something to contemplate as we put the whole of our lives in perspective. We thank Dean Walesh for his permission to reprint his "Opinion" in TNE.

THE **NORTHERN ENGINEER**

The School of Engineering
University of Alaska Fairbanks

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## IN THIS ISSUE . . .



## COVER

This issue is dedicated to the students of the University of Alaska Fairbanks, School of Engineering. The magazine cover depicts students and faculty at UAF. Photos courtesy of Sam Winch, University Relations and Alan Paulson, Institute of Northern Engineering.

*The Northern Engineer* (ISSN 0029-3083) is a quarterly publication of the School of Engineering, University of Alaska-Fairbanks. The magazine focuses on engineering practice and technological developments in cold regions, but in the broadest sense, including articles stemming from the physical, biological, and behavioral sciences. It also includes views and comments having a social or political thrust, so long as the viewpoint relates to technical problems of northern habitation, commerce, development or the environment. Opinions in the letters, reviews, and articles are those of the authors and not necessarily those of the University of Alaska, the School of Engineering, or *The Northern Engineer* staff and board. Address all correspondence to THE EDITOR, THE NORTHERN ENGINEER, SCHOOL OF ENGINEERING, UNIVERSITY OF ALASKA FAIRBANKS, FAIRBANKS, ALASKA 99775-1760, U.S.A. The University of Alaska is an EO/AA employer and educational institution.

# APPLICATION OF STABLE NITROGEN ISOTOPE TECHNIQUES TO DISCERN SOURCES OF GROUNDWATER NITRATE IN THE FAIRBANKS, ALASKA AREA

by

Rebecca Johnson-McNichols

## INTRODUCTION

### HISTORY OF NITRATE CONTAMINATION IN THE FAIRBANKS AREA

The occurrence of high concentrations of nitrate in the groundwater of the hills surrounding Fairbanks, Alaska has been recognized for nearly 40 years. The sources or trends over time of this contaminant, however, have never been conclusively determined. In 1982, water from the newly-constructed Pearl Creek Elementary School yielded nitrate concentrations of 14 ppm (40% higher than the maximum contaminant level of 10 ppm set in 1977 by the EPA), necessitating the installation of a second system for potable water. This finding provided impetus for this study on nitrogen cycling and an attempt to ascertain if the anthropogenic inputs of nitrogen to groundwater could be separated from nitrogen arising from natural processes through the use of natural isotope abundances.

### STABLE NITROGEN ISOTOPES

The two naturally occurring, stable (non-radioactive) isotopes of nitrogen, $^{14}N$ and $^{15}N$, differ only by one additional neutron in the $^{15}N$ nucleus. Atmospheric nitrogen gas is composed of 99.632% $^{14}N$ and 0.368% $^{15}N$ (Junk and Svec, 1958). Other nitrogen-containing compounds, however, may have $^{15}N$ abundances greater or less than that in air.

The equilibrium or kinetic characteristics of one isotopic species usually differ from those of another by only a few percent, and the variations in isotopic abundances imposed by those differences are small. Highly precise analytical techniques are required, and it has been found convenient to compare samples using isotopic ratios rather than to attempt absolute measurements of isotopic abundances.

The differences in stable isotope ratios in a sample relative to those in a standard are expressed as del$^{15}$N in parts per thousand (ppt):

$$\text{del}^{15}\text{N} = \frac{^{15}\text{N}/^{14}\text{N (sample)} - ^{15}\text{N}/^{14}\text{N (atmos.)}}{^{15}\text{N}/^{14}\text{N (atmos.)}} \times 1000$$

Atmospheric nitrogen is the standard employed for nitrogen isotope ratio measurements and has a del$^{15}$N = 0. Substances with an $^{15}N$ content higher than air are said to be "heavy" or "enriched" (del$^{15}$N > 0), and those that have an $^{15}N$ content lower than air are "light" or "depleted" (del$^{15}$N < 0). Del values of naturally occurring substances generally range between -20 to +20 (Wolterink et al., 1979).

The isotope ratio of a nitrogen compound is the result of the kinetic and equilibria reactions of physical and chemical processes on the original isotopic composition of the material from which the compound was formed. Therefore, the study of nitrogen isotopes provides a method of monitoring the transformation of nitrogenous compounds in biogeochemical cycles. As nitrogen compounds are altered chemically within a system, the stable isotopes ($^{14}N$ and $^{15}N$) may undergo isotopic fractionation, resulting in a del$^{15}$N value different than the source from which they came. If such fractionations are unique, then nitrogen isotopes can be used as tracers to determine major sources and pathways of nitrate in the ecosystem.

### CYCLING

The mechanisms by which nitrogen is transferred from one reservoir to another in the global nitrogen cycle are very complex, involving a large number of pathways and numerous compounds. The situation is complicated by such factors as the recycling of nitrogen in the biosphere, the complex photochemical reactions involving nitrogen oxides in the atmosphere, and the influence of man's activities.

This study was concerned with those pathways of the nitrogen cycle which lead to the presence of nitrate in soils and groundwaters. Initially, the major input of nitrogen to this soil-water-biomass subsystem of the nitrogen cycle is the biological or industrial fixation of atmospheric $N_2$. The inorganic nitrogen eventually produced with recycling can be utilized within the root zone of plants, but once transported beyond this depth it is biologically inactive.

## TOXICITY

The presence of excessive nitrate in drinking water supplies is a well-recognized public health hazard. The most familiar problem arising from nitrate consumption is methemoglobinemia, a cyanosis which is brought about by the bacterial reduction of nitrate ($NO_3$-) to nitrite ($NO_2$-) in the digestive tract, followed by absorption of the nitrite in the bloodstream. There, the nitrite oxidizes the ferrous ion ($Fe^{++}$) in hemoglobin to ferric ion ($Fe^{+++}$), converting the hemoglobin to methemoglobin (or ferrihemoglobin) and preventing the transport of oxygen.

At high concentrations this results in a gradual cell asphyxiation, primarily in infants whose digestive systems are less acidic and provide a more favorable environment for the nitrate-reducing bacteria.

A positive correlation has also been made between nitrate and cancer in laboratory studies. Nitrite can react with secondary amines in the mammalian stomach to form nitrosamines, many of which are carcinogenic.

## USE OF STABLE NITROGEN ISOTOPES IN NITRATE CONTAMINATION STUDIES

Kreitler and Jones (1975) were the first to employ stable isotope ratio techniques to determine the source of nitrate in contaminated groundwater. They were able to show that the high concentrations of nitrate in Runnels County, Texas, groundwater derived from agricultural leachates and not from animal wastes. Nitrogen isotope abundances were sufficiently different in natural soil organic nitrogen released upon cultivation versus those from animal wastes to yield an unambiguous difference in the nitrate resulting from each source. Kreitler et al. (1978) used $^{15}N/^{14}N$ abundances in Long Island, New York, aquifers to demonstrate that the nitrate burden was entering the groundwater from several sources and that regional source importance could be clearly distinguished. The differences in isotopic signals between animal waste, nitrogen arising from cultivation, and fertilizer nitrogen were similarly useful in assigning importance to each source in Lockhart and Taylor counties in Texas (Kreitler, 1979), in Nebraska (Gormly and Spalding, 1979) and Washington (Spalding et al., 1982), as well as in African and European countries (Heaton, 1984; Mariotti, 1982).

This project attempted to utilize the stable isotope techniques outlined in earlier groundwater studies to trace the formation of nitrate and ammonia in well waters of the Musk Ox Subdivision northwest of Fairbanks.

## STUDY AREA

The Musk Ox Subdivision is located on a permafrost-free, south-facing slope at an average 750 foot elevation. The region is characterized by a typical subarctic continental climate (Hartman and Johnson, 1984) with an average annual precipitation of 13.5 inches at an elevation of 750 feet.

The study area is covered by vegetation typical of early successional sequence of south-facing slopes around Fairbanks. The dominant tree species on these well-drained soils are paper birch (Betula papyrifera), white spruce (Picea glauca), and quaking aspen (Populus tremuloides). The green alder (Alnus crispa) is a common shrub in disturbed or lower-lying areas. A variety of herbaceous plants, leguminous and non-leguminous, comprise the understory. Litter from these plants accumulates in a thin organic soil layer on the surface of the forest floor. A thicker layer of mineral silt loam soil underlies this and covers a schist bedrock. The aquifer system in the uplands surrounding Fairbanks is contained in highly-conductive fractures in the bedrock, and residents in these areas obtain water for domestic use only if their well intersects one of these water-bearing fractures.

# METHODS

## FIELD SAMPLING

Four well sites in the Musk Ox Subdivision (Figure 1) were sampled each month from September 1985 through August 1987 in order to determine seasonal concentration and isotope ratio trends. These specific wells were chosen on the basis of their high nitrate concentrations (10 to 65 mg/l) determined in a preliminary survey. The samples were collected in polyethylene containers and immediately frozen. Water from three control sites—Fox Spring, a spring at 4.7 mile Murphy Dome Road, and a spring at 6.8 mile Murphy Dome Road (Figure 1)—was also collected in the same manner. These Goldstream valley springs, particularly the latter, provided information on natural water unimpacted by human development.

Samples of all possible sources of nitrogen in the study area were also sampled: precipitation (snow and rain), organic and inorganic soil layers, fertilizers, and septic effluent. Specimens of local vegetation were also collected to provide information on plant accessible nitrogenous nutrients. Mass balance calcula-

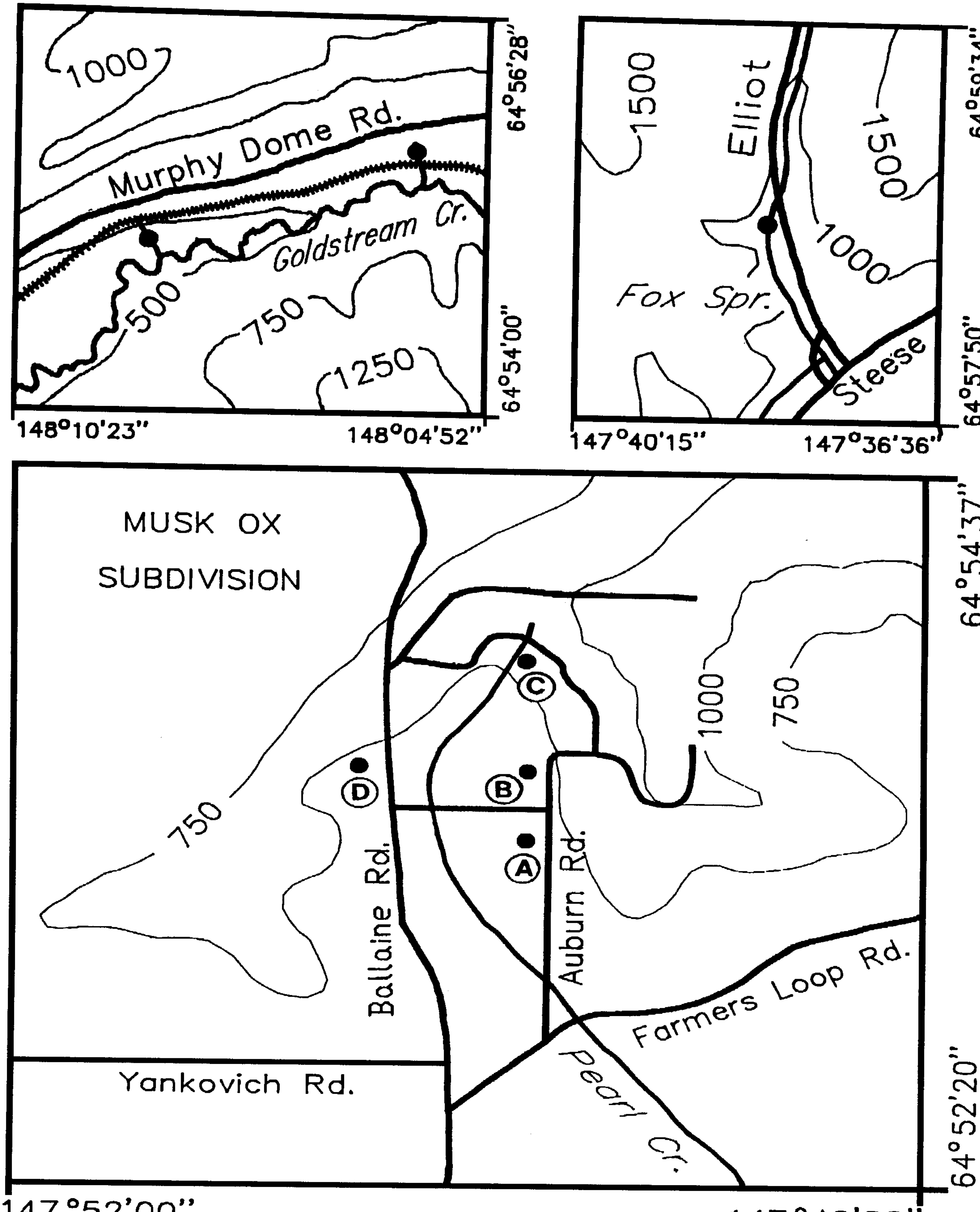



***Figure 1. Study area and control sites***

tions indicate, however, that precipitation and fertilizer imputs are minimal. Therefore, the nitrate in well waters is probably derived either from natural soil processes or septic tank leachate, or a combination of both.

### LABORATORY PROCEDURES

**Concentration Determinations**—The nitrate and ammonia concentrations of all water samples collected were determined on a Technicon Autoanalyzer II (Technicon methods, 1973 and 1978). A method to determine organic nitrogen content by ultraviolet oxidation (Strickland and Parsons, 1977) was modified for freshwater use. By exposing oxygenated water to short wavelength (<200 nm) high intensity UV radiation, most organic molecules containing nitrogen will be photo-oxidized to ammonia, and then a nitrate-nitrite mixture which can be easily measured again on the Autoanalyzer.

Nitrate-N, ammonia-N, and dissolved organic nitrogen (DON) concentration determinations were performed on standard potassium chloride extracts of the organic and mineral soils (Page et al., 1982).

**Isolation of N**—Isotope analyses required the isolation of approximately one milligram (mg) of the particular nitrogen species of interest from the water sample. The nitrate in well and spring waters (representing >95% of the nitrogen present) could be isolated by raising the pH of the water (>9) and evaporating the sample containing approximately one mg of nitrate-N to a fraction of a milliliter. The water containing the concentration of nitrate ions could then be adsorbed onto a glass fiber filter and dried overnight at 120°C.

An experimental ammonium-selective molecular sieve product (Ionsiv W-85 from Union Carbide) was used to recover ammonium from samples with a high ammonium content and negligible nitrate (i.e. septic effluent). A solution of filtered septate containing approximately one mg of $NH_4$-N was allowed to filter through 300 mg of the seive on a glass fiber filter. The filter and sieve containing adsorbed ammonium ions were dried overnight at 120°C.

**Combustion of N**—The glass fiber filters with adsorbed nitrate or ammonium (with or without the sieve) are ground with CuO and metallic Cu, combusted in a double quartz tube at 870°C for thirty minutes and allowed to cool to 700°C over several hours. Organic or reduced forms of nitrogen are oxidized to $N_2$ gas with CuO at elevated temperatures. Copper metal is used to reduce the oxidized $NO_2$--N and/or $NO_3$--N to N2.

Organic soil or plant tissue samples containing one mg of N (previously determined on a Perkin-Elmer 240C CHN analyzer) were ground with CuO and prepared for isotope ratio analyses as described above.

**Purification and Analysis of N gas**—The nitrogen gas produced from all samples was liberated into a vacuum manifold using a tube cracker (Des Marais and Hayes, 1976), and purified by cryogenic cleaning. The pure nitrogen was then Toeppler pumped into a glass tube and sealed. These tubes were opened on the mass spectrometer (VG Isogas SIRA-9) automated sample inlet manifold, and the isotope ratio was determined against a secondary standard of cylinder nitrogen gas.

## RESULTS AND DISCUSSION

### GROUNDWATER NITROGEN CONCENTRATIONS AND ISOTOPE RATIOS

Average nitrate, ammonia, and DON concentrations, as well as isotope ratios for the $NO_3$-N are listed in Table 1.

**Table 1.** Average values of nitrogen constituents in study wells and springs.

| Sample | $NO_3$-N, ppm | $NH_3$-N, ppm | DON, ppm | del $^{15}N$ |
|---|---|---|---|---|
| Well A | 17.0 | 0.065 | ND | +7.8 |
| Well B | 11.5 | 0.094 | ND | +7.9 |
| Well C | 12.6 | 0.132 | ND | +9.6 |
| Well D | 51.7 | 0.425 | ND | +4.9 |
| 4.6 Mi. Spr. | 3.2 | 0.005 | 0.099 | +7.6 |
| 6.8 Mi. Spr. | 1.6 | 0.014 | 0.072 | +5.6 |
| Fox Spr | 0.2 | 0.010 | 0.044 | |

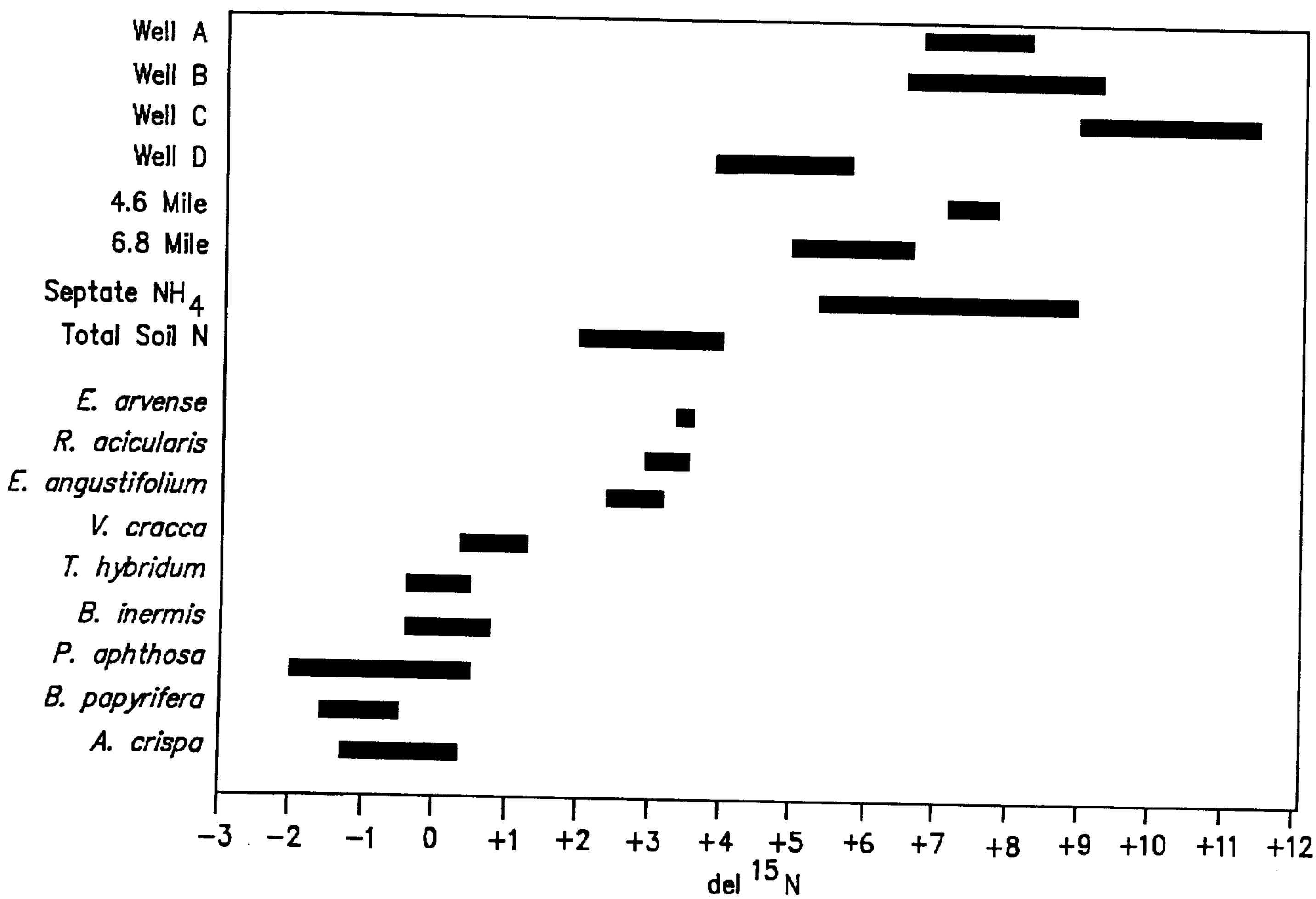
The isotope ratios of well and spring waters showed no apparent seasonal trends over the two-year sampling period. Nitrate-N concentrations in most of the groundwaters remained nearly constant, suggesting little or no temporal change in either the sources or their magnitudes of contamination. The high concentrations of nitrate found in these Musk Ox well waters may be a function of the local hydrologic cycle. A water balance and potential groundwater recharge estimates can be calculated from meteorological data using a modification of the groundwater recharge equation from Dunne and Leopold, 1978. By subtracting evapotranspiration, runoff, and soil moisture demands from incoming precipitation and moisture held in the soil from the previous fall rains, a groundwater recharge potential can be approximated. In 1986, the potential groundwater recharge for the Musk Ox watershed was zero inches.

Although 64% of the moisture in the Fairbanks area falls as rain, the most substantial recharge to groundwater occurs in permafrost-free areas during snowmelt when evapotranspiration rates are lowest and the soil still holds moisture from the previous fall (Kane and Stein, 1983). Rains that occur in August and September rarely replenish the deficit in soil moisture storage and satisfy evapotranspiration losses. A continued trend in dry years and resulting water table minimums may be reflected in increased concentration trends of dissolved ions. Therefore, an apparent rise of dissolved ion concentrations (including nitrate) in well waters over a short period (one or two years) may merely be reflecting a temporary condition. Whether the high concentrations found in these wells is the result of a concentration effect produced by successive dry years with little or no recharge, or of anthropogenic inputs, is unclear. Further investigations into the change in concentration and del$^{15}$N over time in newly developed areas may provide insight into this phenomenon.

## COMPARISON OF DEL$^{15}$N VALUES

By comparing the del$^{15}$N values of the well and spring waters to the del$^{15}$N of the possible source inputs, a stepwise enrichment from recently fixed N in plants to the organic soil N to the spring and well water $NO_3$-N was evident (Figure 2). However, the del$^{15}$N of septic effluent ammonium was also reflected in the water samples. Therefore, a clear source-to-product relationship cannot be derived from the isotopic values alone.

**Soil/Plant Interactions**—Total nitrogen del$^{15}$N of the organic soil layer can be predicted from the del$^{15}$N values of the non-fixing plants that live on it. The non-leguminous plants in this area range from -1.4 to +3.6 ppt and the organic soil is +2.0 to +4.1 ppt. The range in plant del$^{15}$N values depends on the nitrogen species utilized, the degree of fractionation it has undergone in the soil before being absorbed, and fractionation processes within the plant. The oxidative respiration and depolymerization of complex detrital components in soil organic matter results in preferential loss of $^{14}$N and leaving the residual plant remains enriched in $^{15}$N. The del$^{15}$N of the total



to +4.1 ppt. The range in plant del$^{15}$N values depends on the nitrogen species utilized, the degree of fractionation it has undergone in the soil before being absorbed, and fractionation processes within the plant. The oxidative respiration and depolymerization of complex detrital components in soil organic matter results in preferential loss of $^{14}$N and leaving the residual plant remains enriched in $^{15}$N. The del$^{15}$N of the total soil N will show a slight enrichment over the average plant values growing on it, and an increase of $^{15}$N with depth.

**Soil Nitrogen**—The isotopic ratios of nitrate-N found in the study wells, with del values from +4 to +11, may be the result of one or more processes originating in the soil organic layer with a del$^{15}$N of +2 to +4 ppt (Figure 2). Ammonium is generally preferred to nitrate by non-leguminous plants (Rice and Pancholy, 1972), and is retained as an exchangeable cation in the soil. The dry nature of the deep loess soils on lower slopes allows oxygen to penetrate deeply into the soil profile allowing nitrifying bacteria to oxidize reduced forms of nitrogen. Nitrate produced may leach and migrate past the shallow root zone and descend towards the ground water supply. Unfortunately, quantitative information on the leachate is unknown.

In contrast, periodic saturation of the soils during heavy fall rains and during snowmelt may temporarily create anoxic conditions. As oxygen concentrations are depleted, and if a carbon source is readily available, denitrifying bacteria (generally Pseudomonas or Bacillus species) will utilize the nitrate as an electron acceptor. If denitrification is incomplete, the lighter nitrogen isotope will be preferentially lost from the aqueous system. Thus the initial losses of $^{14}$N during recycling in the soil system coupled with partial denitrification deeper in the soil column will result in an $^{15}$N enrichment in the remaining nitrate. Exposure to further reducing conditions will leave no nitrate, but some ammonia resulting from heterotrophy. If, however, a source of oxygen becomes available, the ammonia will be oxidized, and if the reaction is carried to completion, the resulting nitrate will have a del$^{15}$N typical of the source ammonia. Since several mixes and repeats of this process can occur at sites within an aquifer, varied del$^{15}$N-$NO_3$ in wells may result.

The evidence for nitrate input derived from natural sources is supported by observing the isotope ratios of nitrate in the spring waters, which are devoid of anthropogenic input. The spring water values range from +5 to +7 ppt and fit in the midst of the well water values, suggesting a common natural source of nitrogen. The nitrate produced from soil fractionation processes is therefore enriched by approximately three ppt over the source organic N if the values from the Murphy Dome Springs are indicative of the net processing in uncontaminated systems.

**Septate Ammonium**—Assignment of a del$^{15}$N value to the $NO_3$-N produced from septic effluent and transported through the vadose zone is difficult. Within the leach field alone nitrate may be produced and subjected to subsequent anoxic events in response to intermittent additions of household wastewater. This, in turn, may cause isotopic fractionation through partial denitrification of the nitrate. Additional loss of $^{14}$N due to ammonia volatilization and cation exchange of ammonia within the soil will cause an increased isotopic discrimination. Further fractionation in deeper soils will be a function of Eh, moisture, organic matter availability, and continued cation exchange of ammonium. If bacterial mineralization of septate organic nitrogen in the soil column was followed by recycling and isotopic discrimination similar in extent to that of soil organic matter, the anticipated $^{15}$N abundances in end-product nitrate would be more enriched than that observed in springs by about three ppt. However, if the inputs to the soil column occur below the root zone, and very little biological uptake and recycling occurs, the end product nitrate may show a lesser fractionation and more nearly match the values found in well water. Thus the allocation of source from nitrogen isotope abundances of the nitrate concentrations in Musk Ox well waters presents an ambiguous problem until the fractionation of ammonium oxidation is understood.

## WELL WATER NITRATE DEL$^{15}$N VERSUS CONCENTRATION

A plot of nitrate concentrations vs. del$^{15}$N for the study wells and two wells outside of the study area yields an inverse hyperbolic relationship (Figure 3). This is the same curve found in Nebraska groundwaters by Gormly and Spalding (1979) which they attributed to isotopic fractionation of the source N by denitrification. Mariotti (1982) found these curves in a variety of nitrate contaminated environments around the world, but interpreted the trends as nonlinear mixing curves from one source with a high del$^{15}$N signal (low concentration) and one of lower del$^{15}$N (high concentration). He felt that denitrification could not possibly explain the pattern because the data points did not fall along a curve fit for the "most probable" fractionation factor of -20 ppt (determined in laboratory studies; Mariotti, 1982). It is unclear which, if either, of these explanations is correct for the data obtained from the Musk Ox wells until a better understanding of fractionation processes is acquired.

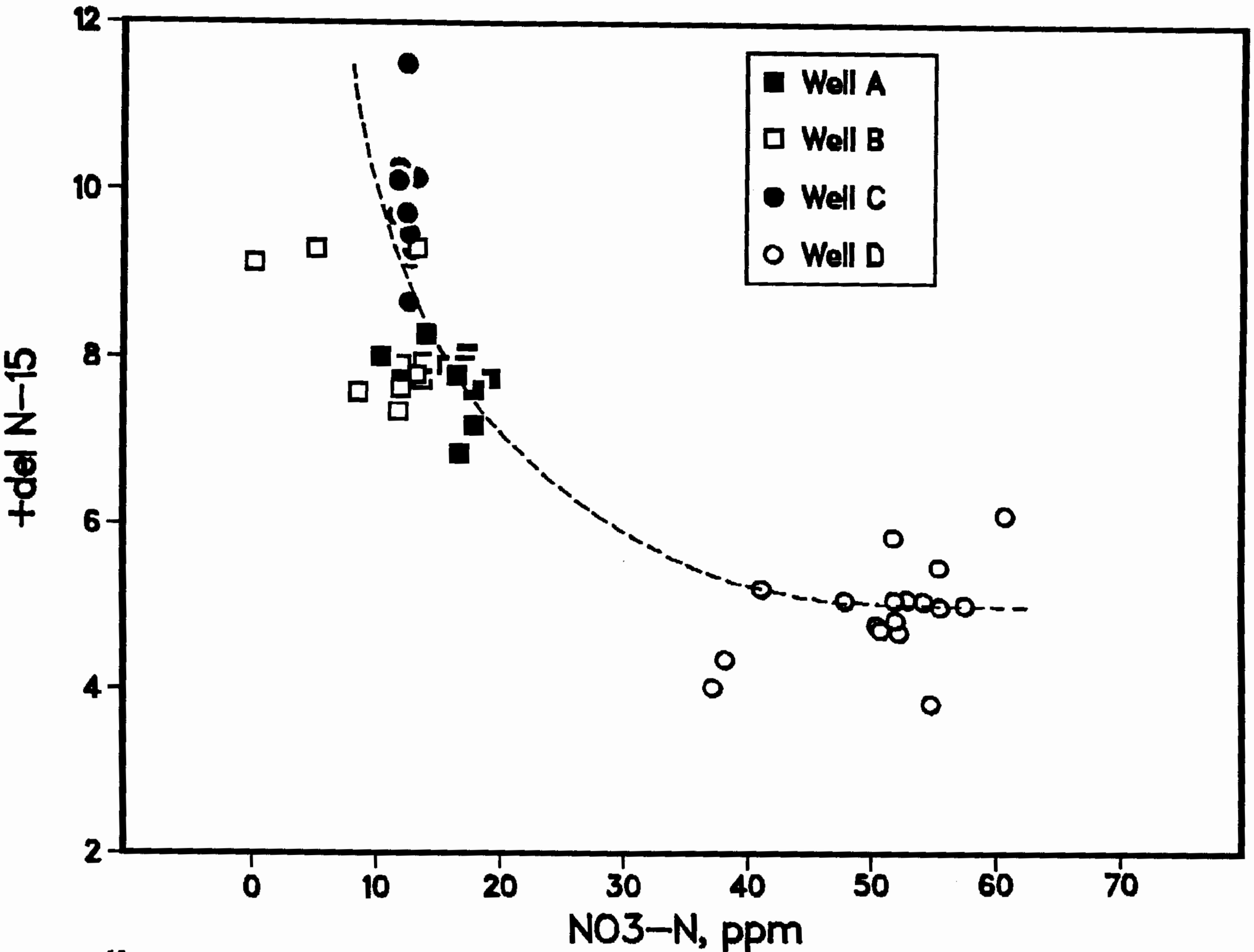



***Figure 3.*** ***Del$^{15}$N versus NO3-N concentrations in well waters***

## CONCLUSIONS

This project has provided the first database on nitrogen isotope abundances in a subarctic upland ecosystem and associated groundwater nitrate. In progressing from recently fixed nitrogen in vegetation (-6 to +4 ppt) to soil organic nitrogen (+2 to +4 ppt) and finally to groundwater nitrate (+4 to +12 ppt) in the Musk Ox subdivision northwest of Fairbanks, a marked enrichment in $^{15}$N occurs. This fractionation and loss of the lighter isotope provides a strong indication that nitrification and denitrification processes are closely coupled and active in subarctic soils.

In this watershed, mass balance calculations indicate that soil microbial processes and possibly septic effluent input govern the fractionations leading to groundwater nitrate del$^{15}$N. However, because of the similarity of isotopic signals among the well and spring water nitrate, total soil nitrogen, and septic effluent ammonium (+5 to +9 ppt), a clear source to product determination of high nitrate levels cannot be made. An inverse relationship between del$^{15}$N and nitrate-N concentrations in groundwater was found which may be due to nonlinear mixing from the two sources, or denitrification of the lighter soil organic nitrogen.

Local nitrate contamination in well waters results from a complex system wherein biological, chemical, and physical processes interact to simultaneously alter concentrations and nitrogen isotope ratios. Continued research into the occurrence and importance of these formation pathways may aid in understanding the high nitrate concentrations in the Fairbanks aquifer.

Simplistic models which attempt to directly link sources and specific del$^{15}$N values in well water nitrate may alone be inadequate in this system, but can be used in conjunction with hydrological and biological fractionation data to gain a more complete understanding of nitrogen cycling in this subarctic watershed.

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# COLD SET CONCRETE

by
Rufus Bunch

## INTRODUCTION

Cold set concrete is defined as concrete composed of portland cement, water, coarse and fine mineral aggregates, and admixtures that will develop a usable compressive strength and durability when placed in forms and cured at a temperature below freezing (32°F). The compressive strength of cold set concrete increases with time after casting and this process will continue even if the concrete temperature falls below freezing before the initial or final set occurs.[1] Initial set is the time required for the concrete mass to stiffen appreciably, and final set is the time required to attain a hardness predetermined by different testing organizations such as ASTM.[2]

When concrete is mixed, the portland cement and water combine into a cement paste that coats and lubricates the aggregate particles. As the cement paste cures, a hydration process takes place in which the cement and water react to form a "binder" for the aggregate particles. Concrete that is being placed and cured at temperatures below freezing becomes troublesome because the water tends to become ice. The crystallizing of the water removes the water from the hydration process, and the expansion caused by the crystal formation causes a physical disruption of the concrete matrix. The chemical reaction of the hydration process releases a substantial amount of heat which helps prevent the freezing of the curing mixture. This heat of hydration especially prevents the freezing of the center of large masses of curing concrete. Cold set concrete can use one of three strategies: lowering the freezing point of the mixing water, suppressing the formation of ice crystals, and manipulating the heat of hydration.

## HISTORY OF THE PROBLEM

Up until the end of World War II, construction in northern climates more or less shut down during the winter months for two reasons. It was possible to satisfy the demand for new structures with an 8 or 9 month building season, and workers experienced a great deal of climatic discomfort that significantly lowered their productivity. At the end of World War II, Europe's tremendous need for new buildings developed the need for year–round construction. It was found that, if the need were great enough, the workers could withstand severe winter conditions, but the use of concrete was limited unless elaborate heating mechanisms were used to prevent the freezing of the curing concrete.[3]

As a result of this problem, an international symposium was organized and held in Copenhagen in 1956. The RILEM Symposium was the first attempt to bring together those involved in building research from different countries around the world. The symposium resulted in the collection of a large volume of data concerning the effects of subfreezing temperatures on the curing of concrete. RILEM is an acronym for Reunion Internationale des Laboratoires d'Essais et de Recherches sur les Materiaux et les Constructions.

## SOLVING THE PROBLEM

Type III portland cement is composed of the same ingredients as type I cement, except that the ingredients are in different proportions. Portland cement is made up of four main compounds: tricalcium silicate ($Ca_3S$), dicalcium silicate ($Ca_2S$), tricalcium aluminate ($Ca_3Al$), and tetracalcium aluminoferrite ($Ca_4AlFe$). Type I consists of 45% $Ca_3S$, 27% $Ca_2S$, 7% $Ca_3Al$, and 11% $Ca_4AlFe$, whereas type III consists of 60% $Ca_3S$, 15% $Ca_2S$, 7% $Ca_3Al$, and 11% $Ca_4AlFe$.[4] There are variations of these percentages among different cement producers.

Ernst Gruenwald, in association with the Lone Star Cement Corporation of New York, carried out extensive testing of the use of type III portland cement in concrete subjected to below–freezing temperatures during the curing period. His testing procedure consisted of mixing the ingredients of the concrete at 70°F and then subjecting the curing concrete to different temperatures with or without precuring exposure at 70°F. The temperatures used were 70°F, 55°F, 40°F, 25°F and 10°F, and the precuring times were 0, 0.25, 1, 2 and 28 days for 55°F and 40°F. The precuring times were 0.25, 1, 2, 3 and 28 days for 25°F, and 1, 2, 3 and 28 days for 10°F. The exposure to the lower temperatures continued for 28 days and then the specimens were transported to a fog room with a temperature of 70°F and a relative humidity of 100%.[5] This procedure assumed that the concrete would be exposed to temperate climates at some time after casting. The problem with arctic conditions is that concrete is sometimes placed in permafrost, which is frozen year round.

Gruenwald found that type III cement produced concrete with greater compressive strength at all ages and under all temperatures than did type I cement. He found that even type III cement required some heating prior to exposure to subfreezing temperatures to attain usable compressive strengths. The heating time required for type III was one-third the time required for type I cement. If the concrete was to be exposed to below-freezing temperatures and if it could be heated until reaching a compressive strength of 1,000 psi, there would be no noticeable decrease in the ultimate compressive strength.[6]

A more recent study by B.J. Houston and G.C. Hoff of the Cold Regions Research and Engineering Laboratory (CRREL) in 1975 found that concrete froze and never attained initial set if type III cement was used in concrete that was mixed at above-freezing temperatures and immediately placed in a 15°F environment.[7] This confirmed Gruenwald's conclusion that some protection is necessary for type III cement.

## USE OF ADMIXTURES

An admixture is defined as any "material other than water, aggregate or hydraulic cement that is used as an ingredient of concrete and is added to concrete (before or during its mixing) to modify its properties."[8]

The use of entrained air and calcium chloride was studied by Lewis H. Tuthill of the Bureau of Reclamation in the early 1950s. Tuthill found that, if 1% calcium chloride and 4% air entrainment were added to a concrete mixture using Type II cement, the time required for protection against freezing was reduced from 14 days to 3 days with no loss of 28 day compressive strength. Tuthill also found that specimens subjected to daily freezing and thawing cycles after an initial protected curing time of three days showed retardation in attaining compressive strength. The 28 day compressive strength showed a loss of 30%, but the 180 day compressive strength showed only a loss of 10%.[9]

Another experimental admixture used the addition of alcohol to the mixing water. Though the results were somewhat inconclusive, it was suggested that for certain rapid setting cements there was an increase in the 91 day compressive strength. This was found only in one set of mortar cubes and was not evident in the type I portland cement nor in the super-rapid cement mortar cubes. The research procedure was based on repeated freeze-thaw cycles of 19 hours thaw at 18°C and 5 hours at -10°C.[10] This procedure again does not address the conditions found when placing concrete in permanently frozen ground.

The Arctic Alaska Testing Laboratories recently carried out research on the use of commercially available admixture to achieve cold set concretes. Though this research was aimed at exploring "the mechanism which exists, to allow hydration and curing at temperatures below 0°C (32°F), to determine if this reaction may be enhanced, and to develop practical means to apply it to Portland cement concrete utilization in cold regions",[11] the actual compressive strengths were not reported in the document. The procedure used concrete placed in permanently frozen ground. The ingredients were at room temperature, and mixing was carried out at room temperature. The specimens were placed at a temperature of 14°F within 10 minutes of completed mixing and allowed to cure at this temperature for 14 days.[12]

Thermocouples were placed in the center of the concrete mass to measure temperature decrease. The study concluded that hydration does take place and that usable compressive strengths can be attained using type III portland cement and admixtures, as long as the concrete is not cooled so rapidly that ice crystals begin to form. While some admixtures could depress the freezing point of the mix water to about 27.4°F, it was an admixture's ability to prevent or retard the formation of ice crystals that determined its suitability for producing concrete with cold set characteristics. The following commercial admixtures were tested: Master Builders AE-10 (Air Engraining Agent), Microair Admixtures, Master Builders Pozzolith 322N, Master Builders Pozzolith 400N, Master Builders Pozzolith 500A, Master Builders Pozzolith 555A, Master Builders Pozzolith 122HE, Anhydrous Calcium Chloride, Anhydrous "Activated Alumina", Anhydrous Drierite (VWR Scientific Cat. No. 22890-284), Disodium Ethylenedinitrilotetraacetate, and Magnesium Fluosilicate. The test results showed that the following admixtures could favorably retard the formation of ice crystals: Pozzolith 122HE, AE-10, Microair admixtures, Pozzolith 400N, Pozzolith 500A, Pozzolith 555A, and 2% calcium chloride[13]

Finally, the researcher found that care must be exercised when preparing the mix and placing the mix because the plastic form of the concrete can set rather rapidly. Super plastizers are recommended to further reduce the amount of water used.[14]

## USE OF REGULATED-SET CEMENT

Regulated-set cement was developed by the Portland Cement Association about 1975. This was neither a mixture of cements nor an admixture, but a portland cement in which new ingredients were blended in the kiln. The new ingredient was calcium fluoraluminate, which provides a relatively high early strength when compared to type III cement. The development of the high early strength is associated with a large amount of liberated heat, which is chiefly caused by the water-cement reaction and the acceleration of this reaction by the calcium fluoroaluminate. The liberated heat from the water-cement reaction is concentrated within the first four days of curing, while type III cement liberates heat over the first year of curing. Concrete made with regulated-set cement will develop a compressive strength of 1,000 psi within one and a half hours when cured at 73°F. The rate of increasing compressive strength is directly proportional to the amount of calcium fluoroaluminate in the cement.[15]

The research carried out by the Cold Regions Research and Engineering Laboratory (CRREL) was conducted in two phases: one testing mortar and another testing concrete. In the mortar phase, 41 different mortar mixes were made and cured under different conditions to determine the most promising mixture for phase two. The mixing conditions were varied by changing the initial temperature of the ingredients prior to mixing, and by using different mold materials to cast the cubes. Also varied was the water-cement ratio and whether or not admixtures were added (and, if added, the amounts used). Six cubes were cast for each moisture, and compressive strength was tested on groups of two at different times after casting.[16]

The concrete phase consisted of mixing concrete with 3/4" maximum size aggregate and limestone sand. Ten 6" x 6" x 36" beams were cast. Two of the beams were exposed to 70°F and 90% relative humidity immediately after casting; two beams were exposed to 15°F immediately after casting; two beams were exposed to 15°F one hour after casting; two beams were exposed to 15°F three hours after casting; and two beams were exposed to 15°F twenty-four hours after casting. The beams were cut into 6" x 6" x 6" cubes at the time of testing. Two cubes from each of the five exposures were tested in compression to failure after curing 3, 7 and 28 days. Those cubes stored in the 15°F environment were thawed for two hours before testing. Also cast were four 20" by 20" slabs of different thicknesses—one slab was 3" thick, two slabs were 6" thick, and one slab was 12" thick. One of the 6" slabs was cured at 70° and 90% relative humidity; the other three slabs were placed in a 15°F environment immediately after casting. Those slabs placed in the 15°F room had a sand base in which thermocouples were placed to record the change in temperature of the sand as curing took place. At testing time, the 3" slab was cut into 3" x 3" cubes, the 6" slabs were cut into 6" x 6" cubes, and the 12" slab was first cut horizontally into two 6" slabs, and then into 6" x 6" cubes.[17]

The results of the mortar phase of this research showed that, for the three type III cement mortar cube sets that were cast, the one set placed immediately into the 15°F room failed to achieve an initial set. The other two cube sets in which the water-cement ratios were 0.5 and 0.6 (all ingredients were initially at 40°F and the curing process took place at 40°F) developed a 7 day compressive strength of 3,670 psi and 3,155 psi respectively. These same two mixes developed a 28 day compressive strength of 6,540 psi and 5,325 psi respectively. Some of the remarkable cube sets using regulated-set cement follow: Mix #14 (which had a water-cement ratio of 0.4, an initial cement temperature of 73°F, an initial sand temperature of 40°, an initial water temperature of 100°F, a mixing temperature of 73°F and a curing temperature of 15°F) developed a 7 day compressive strength of 3,940 psi. Mix #15 (which was identical to mix #14 except that the initial sand temperature was 15°F and 7 $cm^3$ of water was added to reduce the admixture) developed a 7 day compressive strength of 3,405 psi. Mix #29 (which had a water-cement ratio of 0.45, an initial cement temperature of 73°F, an initial sand temperature of 15°F, an initial water temperature of 100°F, a mixing temperature of 73° and a curing temperature of 15°F) developed a 7 day compressive strength of 3,335 psi. Finally, Mix #39 (which had 3.5 $cm^3$ of water reducing admixture added, a water-cement ratio of 0.5, an initial cement temperature of 40°F, an initial sand temperature of 15°F, an initial water temperature of 140°F, a mixing temperature of 40°F and a curing temperature of 15°F) developed a 7 day compressive strength of 2,350 psi.[18]

Other general results from the mortar phase show that the effect of water-cement ratios on compressive strength is more pronounced when the curing is done at below–freezing temperatures, because higher water-cement ratios make more water available for freezing. Generally, the regulated-set cement developed substantially more compressive strength when exposed to 15°F curing temperatures than type III portland cement. The use of water–reducing admixtures seemed to be more effective in producing compressive strength than air–entraining admixtures. The type of mold that provided the most insulation produced greater compressive strengths due to reduced heat loss and sustained hydration reaction. The lower curing temperatures resulted in low compressive strengths, as would be expected.[19]

The mix chosen for the concrete phase (phase II) was Mix #39 which had an initial water temperature of 140°, an initial sand temperature of 15°F, an initial cement temperature of 40°F, a water-cement ratio of 0.5, and 3.5 $cm^3$ of water reducing admixture. Phase II of this research showed that the 3 day compressive strength was slightly less than 1,000 psi and concrete continued to gain strength while curing at 15°F when the concrete ingredients were initially at 35 to 40°F, the mixing and casting were done at 73°F and the specimens were immediately placed in a 15°F environment after mixing. The 28 day compressive strength was directly related to the length of time the mix was left at a temperature above freezing. Those beams exposed to 73°F for 24 hours before going into the 15°F room developed an equal compressive strength to the beams exposed to 73°F and 90% relative humidity for the full 28 days. Those beams exposed to 73°F for three hours before being placed in the 15°F room had 97.3% of the 28 day compressive strength of the control beams. The beams that were placed in the 15°F environment 1 hour after mixing developed 96.7% of the 28 day compressive strength of the control beams. The beams that were placed immediately into the 15°F room after casting developed 58.7% of the 28 day compressive strength of the control beams.[20]

## CONCLUSIONS

These studies showed that commercially available hydraulic cements can be safely used for cold weather concreting. The use of type III portland cement with admixtures (which would lower the freezing point to 27.4°F) would enable it to be used in areas where the average ground temperature is slightly below freezing, with only a slight thawing effect to the surrounding ground. The use of the regulated-set cement would induce short–term thawing and could be used in temperatures as low as 15°F with good results.

It appears that warming the ingredients (especially the water) would enhance the use of the regulated-set cement. The use of insulated forms would provide a slower dissipation of hydration heat and would further protect the surrounding frozen ground.

One problem not addressed in these studies is that much of the concrete that is placed in normal construction practice is extremely massive, which would cause very high internal temperatures when regulated-set cement is used. Some type of heat dissipation or redistribution system would have to be incorporated to protect the pour.

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# Thermal Modeling for Freezeback Disposal of Drilling Wastes on Alaska's North Slope

by

Richard Cormack

## INTRODUCTION

Regulations pertaining to solid waste disposal have recently undergone major revision by the Alaska Department of Environmental Conservation (ADEC) and now include special provisions especially relevant to the disposal of drilling wastes. Among the various options now available to a permittee, the new regulations allow that freezeback containment is an acceptable and perhaps preferable means of disposal in certain permafrost soils. Maximum thaw depth prediction in order to ensure that wastes are buried sufficiently deep to remain frozen is felt to be important. The purpose of this paper is to examine thermal analysis methods which are currently being used, or which might be used to predict thaw depths associated with such disposal sites.

One factor that simplifies arriving at a starting point for critique of thermal analysis models in the subject context is that virtually all oil company proposals to date for freezeback disposal of drilling wastes have been accompanied by the modified Berggren equation as an analytical tool of choice for evaluating thaw depths. An interesting aspect of these submittals has been the widely ranging values of thaw depth arrived at for what would otherwise appear to be similar soils in similar circumstances. Other than to make the forgoing statement based on privileged information gained by the author as an employee of ADEC, it is not the intent of this paper to critique the oil company submittals. Rather it is the intent to examine variables that may lead to the differing interpretations, and to touch on additional options for thermal analysis models.

## THE MODIFIED BERGGREN EQUATION

Analytical solutions can generally be classified as Stephan or Neumann solutions. The Neumann equation is cited by Lunardini (1981) as being the only complete analytic solution for conduction problems with phase change. It involves the tedious solution of transcendental equations, however it can easily be estimated graphically with the modified Berggren equation and associated nomographs (Cameron, 1975).

The modified Berggren equation can also be solved easily using a public domain computer program called "Berg," available from the Alaska Department of Transportation (Braley, 1984). The menu-driven program works on an IBM PC, is adept at handling multi-layer soils, and even includes Prudhoe Bay as an option for regional default values.

The modified Berggren equation was originally developed by Aldrich and Paynter in 1953 but most recent references point to the U.S. Army (1966) as giving a definitive statement on use of the equation and explanation of its factors. As used for thaw depth prediction, the equation is typically expressed as follows (Berg, 1973):

$$X = \lambda\sqrt{48k_a\, nI/L}$$

Where:

- $X$ = depth of thaw (ft)
- $\lambda$ = coefficient which considers the effect of temperature changes within the soil mass (dimensionless)
- $k_a$ = average thermal conductivity (Btu/ft hr degree F)
- $I$ = air thawing index (degree F days)
- $n$ = an empirical constant relating air and surface thawing indexes (dimensionless)
- $L$ = latent heat (Btu/ft$^3$)

These factors are discussed in detail as follows:

**A. Depth of thaw, "X"**

The solution to the modified Berggren equation is an estimate of the depth in a soil profile where the 32° isotherm lies at maximum thaw. Normally this would also be considered to indicate the depth to the top of permanently frozen ground. This may be an inaccurate assumption if freezepoint suppression due to the nature of the wastes is not accounted for (Pita, 1986). Hydrocarbons and salinity have been cited as the first and second most frequent contaminants found in abandoned reserve pits (Smith, 1986). Both contaminants are capable of lowering the freezing point of the wastes, although if hydrocarbons are present only in solution, and not as a separate phase, it is not expected to be a significant depression. Uncontaminated freshwater drilling muds will likely have a freezing point near 32°F;

however, the nature of materials brought up from down-hole during drilling could also be a factor. Rose (1986) has reported a freeze point of 32°F for a typical Milne Point/North Slope freshwater drilling mud.

### B. Thermal Conductivity, "k"

Thermal conductivity is defined as the quantity of heat flow in a unit time through a unit area of a substance, caused by a unit thermal gradient. It is dependent upon a number of factors: density; moisture content; particle shape; temperature; solid, liquid, and vapor constituents; and the state of the pore water, whether frozen or unfrozen. For soil systems, the thermal conductivity of the solids will not vary significantly as phase change occurs, so the ratio of the frozen and unfrozen conductivity will be related to the thermal conductivity of ice and water (U.S. Army, 1966).

### C. Thawing Index, "I"

The thawing index is based on ambient air temperature and is expressed as degree days above freezing. Areas with small thawing indexes in relation to freezing indexes (degree days below freezing) are usually areas of continuous permafrost (Johnston, 1981). The thawing index for the Prudhoe Bay area has been calculated by Hartman and Johnson (1984) to be 500 degree days (in Farenheit), based on air temperature data current through 1967. A freezing index for the same period of record has been given as 8500 degrees. Hartman and Johnson also provide a "design thawing index" of 900 degrees. This index is normally based on the three warmest summers of a 30 year period, or, in the absence of such a record, the highest thawing index in the most recent 10-year period.

The weather record at Prudhoe is based on National Weather Service data taken at the ARCO airstrip near the ARCO Operations Center. Santana and Kinney (1984) show graphically how annual average temperatures from the Prudhoe Bay airstrip have varied from 1974 to 1983 (Figure 1); and how the annual thawing index has varied for those same years (Figure 2). The average annual temperature during this period ranged from about 0°F in 1974 to about 14°F in 1981, while the thawing index ranged from

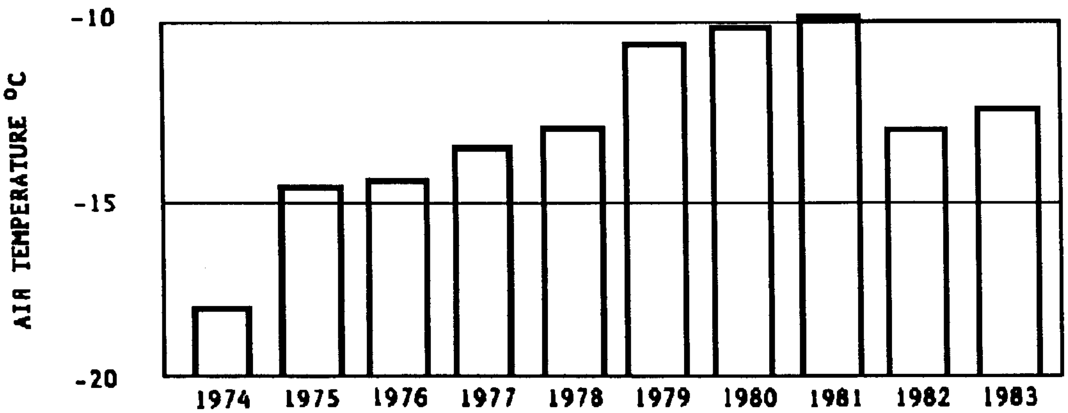


*Figure 1. Average annual air temperature, Prudhoe Bay airstrip (ARCO)*

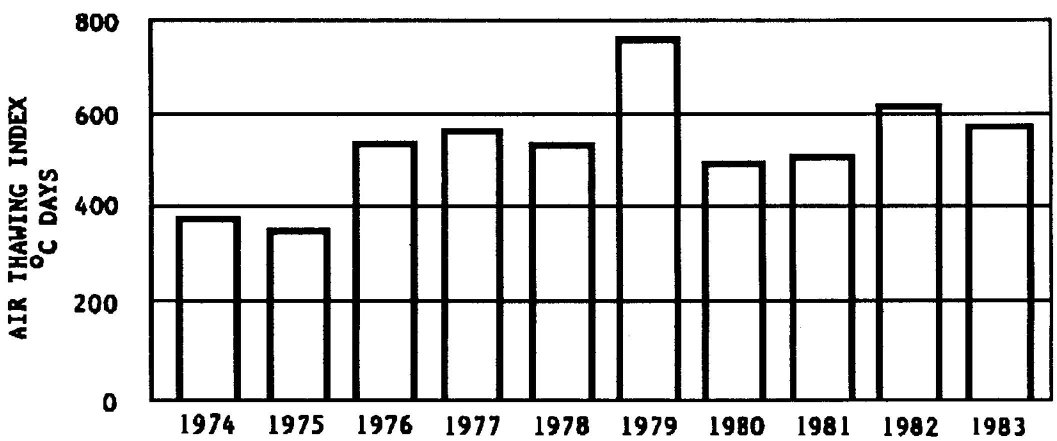


*Figure 2. Average annual thawing index, Prudhoe Bay airstrip (ARCO)*

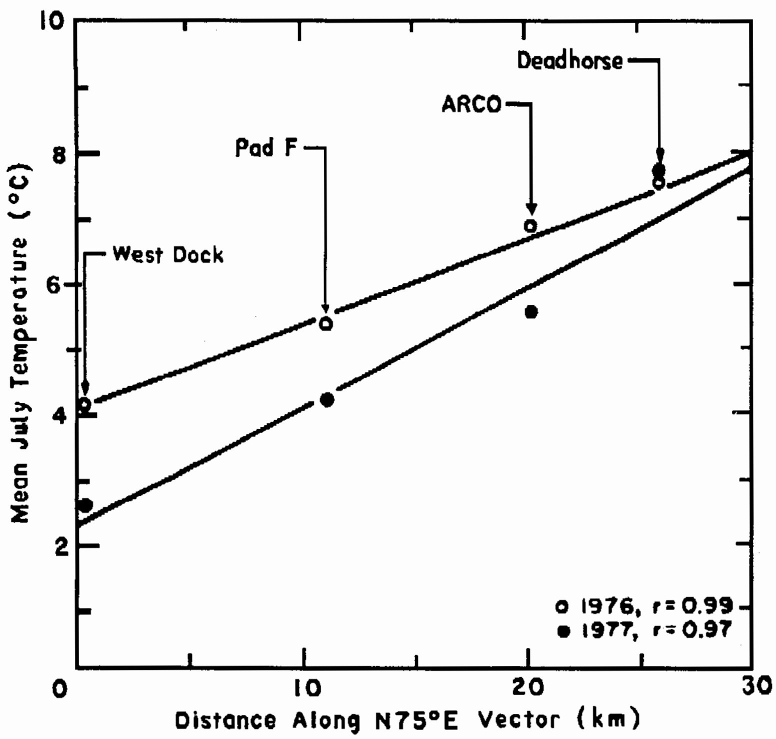


***Figure 3. Mean July air temperatures along a transect inland from the coast within the Prudhoe Bay region for 1976 and 1977 (U.S.Army, 1980)***

about 630 degree days in 1975 to about 1350 degree days in 1979.

Santana and Kinney (1984) found that average annual temperatures at the Central Gas Injection Facility at Prudhoe Bay were from 1.6° to 8°F warmer than at the airstrip. The U.S. Army (1980) has also observed that air temperatures vary significantly by location at a given time during the summer at Prudhoe Bay, and are most closely related to the distance to the Beaufort Sea, measured in the direction of the primary summer wind vector (N75°E). The summertime gradient is steepest near the coast where the July mean air temperature is about 39° F, while the 43°F isotherm lies just a few kilometers inland, in the vicinity of the ARCO camp. In 1977, the degree thawing-day accumulation at West Dock was only 572 while at the ARCO station it was 1157. The gradient was found to be more gradual inland from ARCO. Figure 3 depicts the temperature gradient from West Dock to Deadhorse for 1976 and 1977.

Haas (1984) has pointed out that the common engineering practice of calculating freezing indexes from monthly average temperatures instead of daily temperatures involves an error associated with the change-over months. The average temperatures for the change-over months may be within a few degrees of freezing, and may be either above freezing or below. If the average monthly temperature is above freezing, zero freezing degree-days would be attributed to that month. Assumably, the same could be said for a thawing degree day index based on monthly averages. For freezing index Haas found the error amounted to as much as 175 degree days at Grand Rapids, Michigan.

### D. The "n" factor

Probably the most difficult variable to standardize in the modified Berggren equation is the n factor necessary to convert air thawing degree days, I, to meaningful ground surface temperatures. The n factor is an empirically derived ratio defined as the ground surface freezing or thawing index divided by the corresponding air temperature index. Both the numerator and denominator are determined by field measurements. Johnston (1981) has stated that uncertainty owing to the n factor alone may contribute to an uncertainty in the frost or thaw penetration of about 25–30%.

n factors are situation specific because they lump the effects of many parameters into a single factor. Heuer et al. (1985) noted the many different heat transfer mechanisms associated with the n factor that come into play at the ground surface, including forced and natural air convection, longwave and shortwave radiation, evaporation, and conduction through snow or organic layers. It was further noted that changes in these heat transfer mechanisms can be caused by: (1) changes in surface roughness, absorptivity, and emissivity, (2) changes in surface elevation which can in turn cause ponding and changes in snow accumulation patterns, (3) changes in the type of vegetation, and (4) changes in the organic layer thickness. The U.S. Army (1980) found that ground surface temperatures on sunny days at Prudhoe Bay were as much as 18°F higher than ambient air temperature one meter above the surface.

Lunardini (1981) pointed out that, for arctic and subarctic regions, the thaw n factor decreases with increasing wind speed. Table 1 shows the variation of n factors with wind speed for an asphalt surface near Fairbanks. The n factor for a given site may also vary with time, from month to month and from year to year (Lunardini, 1981). Table 2 shows variation of monthly n factor at Chitina in 1972. Most experimental studies of n factors have been for paved surfaces, which are the most interesting from the viewpoint of engineers. Asphalt thaw n factors have been found to vary from 1.39 to 2.28 for the same location (Lunardini,

**Table 1.** n factor variation with wind speed (Lunardini, 1981)

| wind speed (mph) | thaw n factor (dimensionless) |
|---|---|
| 2 | 1.96 |
| 6 | 1.34 |
| 10 | 1.21 |
| 16 | 1.13 |

**Table 2.** n factor variance by month (Lunardini, 1981)

| surface | May | June | July | Aug | Sept |
|---|---|---|---|---|---|
| asphalt | 2.0 | 2.05 | 1.55 | 1.69 | 2.04 |
| gravel | -- | 1.53 | 1.20 | 1.52 | 1.40 |

1981). Table 3 gives some examples of n factors for other surfaces.

**E. Latent Heat of Fusion, "L"**

The factor L in the modified Berggren equation is an expression of latent heat of fusion of ice within the soil matrix (Lunardini, 1981). As such, it is also a function of how much water is present, or in some instances, the salinity of the water. As moisture content in soil increases, the latent heat becomes dominant in thermal calculations.

The Army (1966) gives a good example of the significance of latent heat of fusion. A typical soil with 15% moisture content requires the same quantity of heat to accomplish phase change and remain at 32°F as would be required to heat the same soil from 32°F to 76.4°F, when a phase change is not involved.

**Table 3.** Some example n factors (Phukan, 1985)

| Surface | Thawing Factor $n_t$ | Freezing Factor, $n_f$ |
|---|---|---|
| Snow | -- | 1.0 |
| Pavement free of snow and ice | -- | 0.9 |
| Sand and gravel | 1-2 | 0.9 |
| Turf | 1.0 | 0.5 |
| Spruce | 0.35-0.53 | 0.55-0.9 |
| Spruce trees, brush | 0.37-0.41 | 0.28 |
| Willows | 0.82 | -- |
| Weeds | 0.86 | -- |
| Gravel fill slope | 1.38 | 0.7 |
| Gravel road | 1.99 | -- |
| Concrete road | 2.03 | 0.8 |
| Asphalt road | 1.96-1.25 | 0.8 |

Typical soils on the North Slope would appear to be quite high in moisture content. LaVielle et al. (1983) found that natural soils profiled at one construction site on the North Slope tended to display high ice contents and low dry unit weights. Moisture contents of the tundra ranged from 41% to 237% and averaged 172%. Moisture values for an underlying silt unit ranged from 46% to 368% and averaged 127%, and moisture values for a sand unit underlying the silt ranged from 19% to 188% and averaged 42.5% by weight. Dry unit weights averaged 19.3 lb/ft$^3$ 39.8 lb/ft$^3$, and 87.6 lb/ft$^3$ for the tundra, silt and sand units respectively. Figure 4 depicts a generalized near–surface soil profile in the Prudhoe region.

Johnston (1981) has criticized the modified Berggren equation, as well as the Stephan and Neumann equations, because

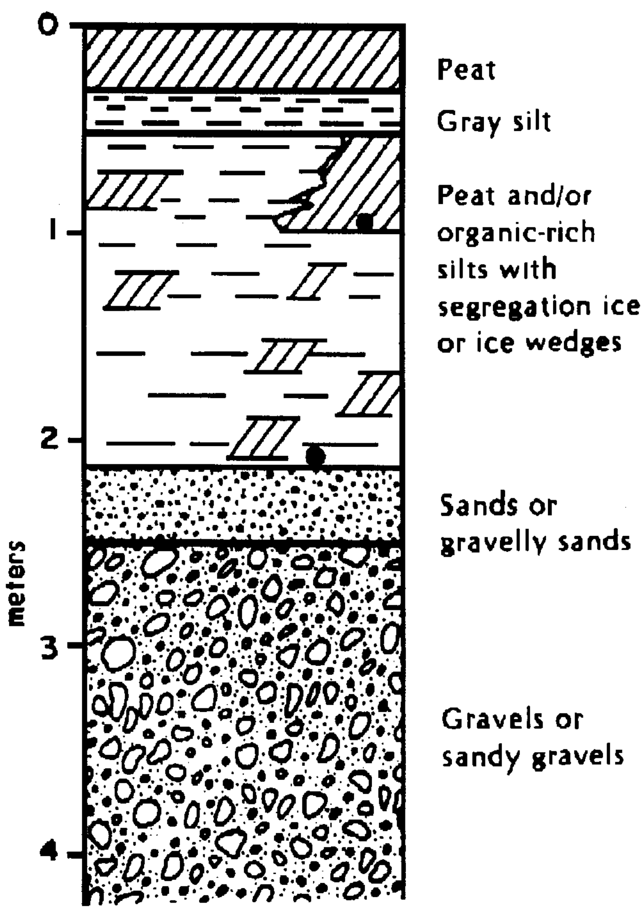


*Figure 4. Generalized stratigraphic section of the near-surface deposits in the Prudhoe Bay region*

they assume that phase change occurs at a single temperature, when in fact latent heat is released over a temperature range which may amount to several degrees in the case of fine grained soils. Differences of as much as 25% for typical cases were noted when comparisons were made with and without a freezing range.

**F. The λ factor**

λ is a coefficient which considers the effect of temperature changes within the soil mass. It is a function of the thawing (or freezing) index, the mean annual temperature and the thermal properties of the soil (Berg, 1973). The λ factor can also be thought of as accounting for sensible heat, as opposed to latent heat of fusion (Johnston, 1981). Sensible heat is defined as that which, when removed or added, results in a temperature change (Lunardini 1981).

Values for λ involve complex transcendental mathematical solutions as a legacy of the Neumann solution. More commonly, they are obtained by interpolation using nomographs. It can be seen from these nomographs that the value of λ is always less than one and approaches one as the heat transfer due to sensible heat becomes insignificant. Lunardini (1980) gives an excellent treatment of the several variables inherent in λ.

## THE STEPHAN EQUATION

The Stephan equation is the same as the modified Berggren equation except that λ, which accounts for sensible heat, is absent. The Stephan equation was originally developed for calculating the thickness of ice on a calm body of water (Berg, 1973). The fact that it neglects sensible heat does not lead to great error in soils with high moisture content according to Johnston (1981). Lunardini (1981) has also stated that taking sensible heat effects as negligible may be a good assumption if soils have a high water content.

Johnston (1981) suggested that more elaborate calculations do not necessarily lead to more reliable results, and that the simple Stephan formula might even be preferred for design purposes since it overestimates frost or thaw penetration depth and is therefore conservative. In the Stephan formula, both the heat capacity of the frozen layer and heat flow from the underlying thawed zone are neglected. Since both quantities act to retard penetration of the freezing or thawing plane, the Stephan equation will overestimate frost or thaw-penetration depths. Frost or thaw penetration depths calculated using the simpler Stephan formula in examples given by Johnston would be, even in the worst case, about 20% greater than those obtained from the modified Berggren. Johnston concluded that the simple Stephan equation is adequate except for the driest soil conditions.

## NUMERICAL MODELS

Berg (1973) noted that numerical procedures are normally more accurate in transient heat flow problems than the analytical techniques available with the aforementioned equations.

Numerical models are based on discretization of the differential equations which describe the continuum that make up a region of heat transfer. Finite difference and finite element methods are the most commonly used. Both lead to a set of N equations with N unknowns that can be solved by the method of relaxation, normally using a digital computer. The finite element method is generally preferred because it is able to handle complex geometries whereas the finite difference method is stymied by all but rectangular geometries (Freeze and Cherry, 1979).

Hromadka et al. (1983) have had very good luck using a "nodal domain integration" model which yielded a system matrix similar to a finite element scheme. This method and a method known as "boundary integral method" were compared to one another and to actual field data at the Deadhorse runway embankment. It was concluded that both models can accurately predict the thermal regime of embankments, provided thermal boundary condition and domain solution initial condition information is available.

Thomas and Hart (1984) cited several proprietary numerical solution computer programs in current use for heat transfer problems, but advocated the use of a public domain finite element program entitled "Determination of Temperature." A citation for obtaining the program in Fortran IV was given in their paper. They have suggested that results using this numerical model may be superior to those obtained using analytical means, such as the modified Berggren equation. Advantages cited for the finite element model stem from the 2-dimensional nature of the model and include the ability to handle arbitrary geometries and non-uniform initial ground temperatures.

Heuer et al. (1985), felt that numerical surface heat balance models can account for all the significant parameters but felt that the greater complexity compared to n factors does not guarantee better accuracy, since there may be several correlations offered in the literature. It was found that potential correlation errors of 25% are not unusual. Cameron (1975) also noted that numerical solutions, like any other mathematical equation, are limited by quantity and reliability of input data and internal mathematical approximations.

## FIELD VALIDATION

The ADEC solid waste regulations now require that, where freezeback is the mode of containment for drilling wastes, thermal monitoring of a site after closeout must be conducted for a period in order to ensure the thermal integrity of a cap. An added benefit of such monitoring will be the ability to validate thermal models.

Miller (1985) has observed that thermistors have become the temperature measuring sensor of choice. He noted that thermocouples have fallen into disfavor because of their limited accuracy (about 1.0°C) and the need for ice baths and specialized readout equipment. A thermistor is a thermally sensitive resistor whose primary function is to exhibit a change in electrical resistance with a change of temperature. As temperature increases, the resistance of a thermistor decreases. The change in resistance is generally nonlinear but is quite large for small temperature changes, resulting in high sensitivity to temperature changes. With individual calibration, the accuracy of a thermistor can be better than 0.01°C. Miller noted that cost (1985 dollars) for multiconductor thermistor strings was about $15 to $20 per thermistor plus $1 to $2.50 per foot of wire. Ohm-meters with 4.5 digit accuracy can be purchased for about $400. Additional costs include multi-pin connectors and switches, protective pipe, and the time for installation, readings, and data reduction and presentation.

Klein et al. (1986) examined various methods of installing thermistor strings in test borings and concluded that the most economical method was to install the strings in 3/4-inch diameter casings. Field evidence showed that the strings deployed in this fashion avoided convective heat loss due to the small diameter of the casing, and rapidly achieved equilibrium temperatures as evidenced by comparison with strings buried on the outside of the casings and in closer contact with the soil.

## SUMMARY AND CONCLUSIONS

Given the uncertainty associated with input parameters for the modified Berggren equation as noted by Johnston and others, it may be that use of the Stephan equation is justified as being preferable due to the added conservatism it provides by not accounting for sensible heat. For very high moisture contents, such as appear to be normal in the Prudhoe Region, sensible heat does not appear to be important in any case.

It is clear that a considerable amount of slop is possible with the n factor, and that it cannot necessarily be chosen from tabulated data. An additional complicating factor may be surface disturbance. The Alaska Department of Transportation (1983) found that simply stripping and exposing soil surface to sunlight greatly increased the maximum summer thaw depth near Fairbanks. Insolation values from Fairbanks are obviously not transferable to the North Slope but a lower magnitude effect may be important nonetheless, and should be accounted for. Validation of thermal models with field data will help refine accurate values for the intended purpose over time.

The nature of encapsulated drilling wastes in terms of potential freeze-suppression can be an important consideration and should be accounted for in design.

It may be appropriate to update the design thawing index based on the more recent annual high thawing index of 1350 degree days reported by Santana and Kinney (1984). This appears to be the high value in the literature for the last 10 years, which meets the criteria for arriving at the design thawing index. It may also be appropriate to factor the thawing index to account for position in the Prudhoe area in relation to the established temperature gradient found by the U.S. Army (1980).

It would be useful to determine if there is an important error in the thawing index for Prudhoe owing to the use of average monthly temperatures instead of average daily temperatures.

Numerical models would appear to have merit over analytical models where complex geometries are involved. Capped reserve pits do present some interesting questions related to geometry. For instance, what are the insulative effects of snow drifted on the downward side of the cap, or what are the effects of sun on one side of the cap and shade on the other? It is conceivable that analytical modeling could take these considerations into account by profiling the individual points of concern. An example of an outcome of this might be an n factor value for the sunny side of a cap that is very much different than one on the shady side, or one on top of the mounded cap.

As a closing note, a thought is offered which really has little to do with the subject paper, and yet it seems appropriate to at least mention here. Esch (1984) has suggested that all permafrost engineers should look at current projections for climatic warming trends expected as a result of increases in atmospheric carbon dioxide. In support of his concerns, he cites a 1983 EPA document entitled "Can we delay a greenhouse warming?", in which mid-range temperature projections are for a global 1°C rise in the next 25 years with a 2°C rise by 2040 and a 5°C rise by 2100. It was also projected that a 3°C global increase would result in a more pronounced increase at the poles, with perhaps a 6° to 8°C increase for Alaska and northern Canada. The impact of such events on thermal modeling are obvious. Structures with a design life of 25 years might weather such changes better than wastes intended to be freeze-encapsulated in perpetuity.

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# BACK OF THE BOOK

## MEETINGS

The ASME International Pipeline Seminar is scheduled for October 20-21, 1988 at the Ramada Inn Galleria West in Houston Texas. This seminar is sponsored by the Petroleum Division of the American Society of Mechanical Engineers and focuses on pipeline safety and leak detection. For more information contact *Frank Demarest at ASME, P. O. Box 59489, Dallas TX 75229; (214) 437-0094.*

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The Third National Conference on Drinking Water "Small System Alternatives" will be held June 12, 13 & 14, 1988 at the Radisson Plaza Hotel & Convention Centre in St. John's Newfoundland, Canada. The objective of the conference is to bring together practitioners, regulatory personnel and researchers concerned with all aspects of design, construction and operation of small systems for the provision and treatment of drinking water. Information on existing and emerging technologies will be presented. *Contact Mr. Ken Dominie at (709) 576-2556 or Mr. Art Cheeseman at (709) 576-8248 for more information.*

## NOTED

George Nelson, president of Alyeska Pipeline Service Company, has announced the appointment of Tom Brennan, a long-time Alaska public relations professional and former newspaper reporter, as Associate Manager of Public Affairs effective April 18. Brennan is a 20-year Alaska resident and will be primarily responsible for increased communication with the news media. He also announced the recent appointment of Beverly Michaels, well known Alaska television producer, as Senior Public Affairs Specialist. Ms. Michaels joined Alyeska last December and is responsible for company publications and photography, including production of a quarterly videotape news report for employees.

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In late January, the U.S. Army Environmental Hygiene Agency published the results of its June 1987 tests on Boiler Number 6 at Fort Wainwright, Alaska. The purpose of the tests was to determine whether particulate emission rates exceeded federal and state air quality standards while burning mixtures of coal and wood chips. Waste oil and coal were tested in a separate procedure during the same test period.

The Fort Wainwright power plant has six 200 MBtu/hr boilers with a maximum rated steam capacity of 150,000 pounds per hour. Boilers are typically operated at 125,000 pounds per hour at 425 psig. The boilers are mechanically fired by spreader stokers with traveling grates and are equipped with fly ash reinjection systems.

The test goal was to assess the boiler at Btu replacement percentages of 10% and 20% for both green and dried wood. Actual percentages, however, fell short of the goal.

The final report showed that wood chips can be burned with coal, without exceeding applicable particulate emission standards. Testers recommended, however, limiting wood chip concentrations to 20% by weight. This would allow the mixture to stay within the operational capabilities of the stoker system and assist in keeping steam loads at satisfactory levels. *(From Bioenergy News, Alaska Power Authority, No. 13, March 1988.)*

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The U.S. Fish and Wildlife Service has joined other U.S. Government agencies in making their telephone lines accessible to people with hearing impairments. The numbers to call for TTY access telephones at the U.S. Fish and Wildlife Service in Anchorage are 786-3328 or call toll free 1-800-478-3501 from other areas.

## PUBLICATIONS

The Alaska Department of Community and Regional Affairs has published a guide to assist Alaskan communities with economic development planning and projects. The Economic Development Resource Guide provides information on federal, state and private non-profit programs that provide funds or other assistance for community development. The Guide will also assist those planning bioenergy projects in Alaska. For further information on this publication, please contact: *Joanne Erskine, Administrative Assistant, Department of Community and Regional Affairs, Rural Development Division, P. O. Box BC, Juneau, Alaska 99811; telephone (907) 465-4890.*

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The Bonneville Power Administration released its February 1987 Yearbook for the Pacific Northwest and Alaska Bioenergy program. The Yearbook outlines program objectives and provides an overview of current and future bioenergy projects. Washington, Oregon, Idaho, Montana and Alaska participate in the program. The Yearbook also includes descriptions of projects that promote development of biomass as an energy fuel. Projects demonstrating biomass technology applications are also described in the Yearbook. These include harvesting and collection systems for forest residues and a review of woody biomass harvesting, transportation and storage economics. Alaskan readers may receive a free copy of the Yearbook from *Pat Woodell, Alaska Power Authority, P. O. Box 198869, Anchorage, AK 99519;* out of state readers may contact *Gary Insley, RMG, Bonneville Power Administration, P. O. Box 3621, Portland, OR 97208.*

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Gulf Publishing Company's new 1988 Software Catalog features information on 49 science, engineering and business programs for the IBM-PC/XT/AT and compatibles as well as descriptions of programs for hand-held calculators and interactive videotape/software training. To receive your free 1988 Software Catalog, write to *Gulf Publishing Company, Software Division, Dept. G9, P. O. Box 2608, Houston, TX 77252-2608, or call (713) 520-4444.*

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Cutter Information Corp. has just released *Practical Radon Control for Homes*, a hands-on guidebook to controlling and preventing radon hazards in houses. This new report is designed to help builders, designers, educators, homeowners and others assess the design of a house to determine risks and select the most effective mitigation technique. *Practical Radon Control for Homes* is available for $40 from *Cutter Information Corp., 1100 Massachusetts Avenue, Arlington, MA 02174; (617) 648-8700.*

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By popular demand, Gulf Publishing Company has released the all-new second edition of Pipe Line Rules of Thumb Handbook. The handbook is loaded with useful tips on conversion factors, pipeline construction and design, gas engineering, oil products, corrosion, economics and much more. This edition has been extensively expanded and reorganized. Pipe Line Rules of Thumb is available from *Gulf Publishing Company, Book Division, Dept. X8, P. O. Box 2608, Houston, TX 77252-2608; (713) 520-4444.* Include purchase price of $45.00 plus $4.50 each shipping and handling.

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Newly updated with the latest research findings, Metals Handbook, Ninth Edition, Volume 13--Corrosion is the most extensive collection of information on corrosion anywhere. This new handbook is published by ASM International and distributed by Gulf Publishing Company and features 1400 pages of information, more than 1000 detailed photos and illustrations, and contributions from more than 500 corrosion experts on every facet of corrosion buildup, prevention and treatment For your copy, send $104 plus $7.50 shipping & handling to *Gulf Publishing Company, Book Division, Dept. N8, P. O. Box 2608, Houston, TX 77252-2608; (713) 520-4444.*

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