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EDITORIAL

by

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School of Engineering

"The time has come to speak of many things, of shoes and ships and sealing wax and cabbages and Kings." The start of a delightful conversation as reported many years ago by an expert in his field. I wish I were that expert, that skilled, that entertaining, but the words are just as important to the success of the engineering endeavor as those older lines were to their cause.

For some time now, the profession of engineering has been trying to be many things and as such has attempted to follow at least two of the more senior professions, law and medicine. In the attempts, I fear that it has followed the most senior profession and engineering is ill equipped to succeed in this area.

One of the most important considerations is that of recognition of support staff. We often are so involved in the technical aspects of our profession that we ignore the critical items of contributions to the quality of our output, the work done by others. This is especially true in a school such as this, where there are so many pressures on the learned members of the profession that there is a tendency to think that they are the only contributors to the game. For one member let me try to set my house in order.

This magazine is the product of two very capable young ladies, Cindy Owen and Stephanie Faussett. They spend many hours arranging the articles, material, mailing lists without recognition. Yet it is their artistry, skill in handling over wrought authors, cajoling printers that produce this product. They have learned a complex computer system to provide this magazine at a price that we can continue to publish. They have displayed a sensitivity to appropriateness of material that far transcends their backgrounds.

The same is true for the rest of the staff in all parts of this endeavor. From secretary to executive officer to financial clerk to electronic technician to video coordinator to machinist to all the unsung staff, we owe more than we can describe. With your permission I would like to publicly take this opportunity to introduce you to the real reason this school is successful, our staff:

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Duane Cook	*Electronic Technician*
Bonnie Crandall	*Fiscal Analyst*
Susan Earp	*Video Coordinator*
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The research investigations being conducted by the School of Engineering are those studies in support of the people of Alaska, to create a better quality of life, an improved economy, and a more progressive use of our assets while maintaining the overall pristine character of Alaska. The role all of you play in this, is the continued support of ENGINEERING and the staff and faculty who are working for you.

THE **NORTHERN ENGINEER**

The School of Engineering
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COVER

The cover photo was taken by Dr. Donald Lynch during a trip to Norway, see *Notes on Norwegian Road Construction*, page 26.

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.

ANCHORAGE - FAIRBANKS INTERCONNECTED POWER SYSTEM STUDY

by

Laurie J. Oppel, George A. Mulligan, P.E. and John D. Aspnes, P.E.

INTRODUCTION

The Alaska Intertie, a radial 138 kilovolt (kV) transmission line connecting the Anchorage and Fairbanks power systems, was placed in commercial operation May 1, 1986. The interconnection was constructed to provide the benefits of improved electric service reliability, exchanging lowest cost generation between the two areas, and providing power to intermediate communities previously unserved by any utility. A research project to study power system operation and the interconnected system's ability to survive major disturbances has been performed by electrical engineering department personnel through the University of Alaska's Institute of Northern Engineering. The Intertie Operating Committee, which consists of representatives from seven Railbelt electric utilities, funded the research effort. The project has led to results that are very useful to improving the performance and reliability of the interconnected power system. The focus of this paper is to describe results of this research project and benefits from this industry-sponsored university research effort.

DESCRIPTION OF THE RAILBELT POWER SYSTEM

The Railbelt power system consists of seven electric utilities: Fairbanks Municipal Utilities System (FMUS) and Golden Valley Electric Association (GVEA) at the northern end, and Anchorage Municipal Light and Power (AML&P), Chugach Electric Association (CEA), Homer Electric Association (HEA), Matanuska Electric Association (MEA), and Seward Electric System (SES) at the southern end.

The Railbelt system supplies a 1987-88 winter peak load of 615 megawatts (MW), of which approximately 117 MW is supplied by the northern end companies, and 498 MW is supplied by the southern end companies. The total installed generation capacity is 1164 MW, which is comprised of four hydroelectric, seven steam turbine, fourteen diesel, and thirty gas turbine generators. The system has 1020 miles of transmission lines operated between 69 kV and 230 kV.[1]

The Alaska Power Authority (APA) owns the Alaska Intertie connecting Anchorage and Fairbanks. Figure 1 is a map showing the Intertie.[2] The Intertie is a 170 mile transmission line connecting the Douglas (near Willow, Alaska) and Healy 138 kV substations. The Intertie is presently operating at 138 kV, but was built to 345 kV specifications to provide maximum flexibility for future needs. The 138 kV lines from Healy to Gold Hill (near Fairbanks) and from Douglas to Teeland and the 230 kV line from Teeland to Point Mackenzie (near Anchorage) complete the interconnection from Anchorage to Fairbanks. The 138 kV lines existed prior to the construction of the Intertie

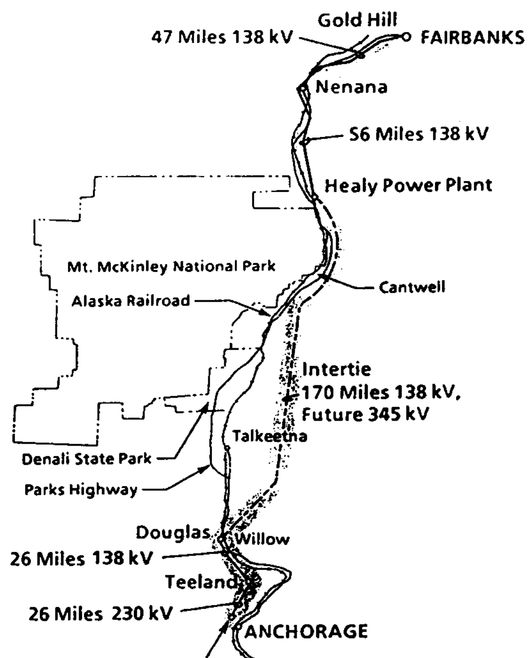

Figure 1: Semi-graphic Map of the Alaska Intertie

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and presently limit the maximum transferable power to 70 MW. Future operation of the Intertie at 345 kV or larger power transfers will require upgrades on the Healy to Gold Hill and Douglas to Point Mackenzie lines.

With the present configuration, the Intertie is capable of transferring a maximum of 70 MW between Anchorage and Fairbanks in either direction. This relatively modest amount of power, combined with the extremely long distance of 325 miles between the two major load and generation centers and the relatively low transmission voltage of 138 kV, chosen for economic reasons, created major engineering challenges. Some of the electric power system challenges that required solution included maintaining acceptable voltage levels along the interconnection and maintaining the stability of the system both during normal steady-state conditions and following transient disturbances, such as short circuits or loss of a major generator.[2]

Voltage control along an interconnection is normally provided by the installation of shunt compensation consisting of switchable capacitor banks and/or inductive reactors at suitable locations. When an interconnection is lightly loaded, shunt reactors are required to absorb the line's natural capacitive current and to reduce voltages to their design level. As the line loading increases, the line's inductive voltage drop increases and shunt capacitors are required to raise system voltages back to design levels.

The shunt capacitors and reactors need to be switched on or off during the day as interconnection loading changes. This can be done by mechanical means using circuit breakers. Mechanical switching is adequate for maintaining acceptable voltage levels during normal steady-state conditions, but more rapid switching is required to maintain voltages and system stability following major disturbances. Rapid switching of shunt compensation can now be accomplished by means of modern power electronic devices called thyristors or silicon controlled rectifiers (SCRs). Shunt compensation equipment utilizing thyristors are called static var compensators (SVC) and are dynamic or continuously adjustable reactive power devices. SVC units are capable of maintaining substantially constant voltages at their locations, and of rapidly, as fast as two cycles or 0.03 seconds, varying their reactive outputs to respond to the system's needs following a disturbance.

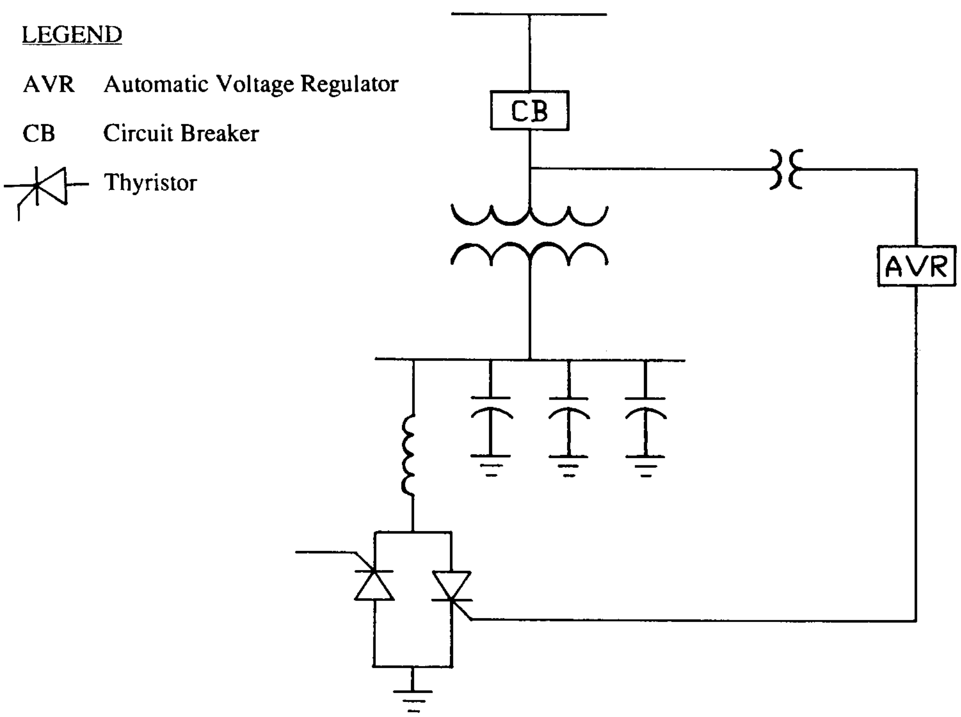

Figure 2: Thyristor Controlled Reactor, Fixed Capacitor Static Var Compensator Configuration

The Alaska Intertie has SVC units, manufactured by General Electric Company, installed at the Teeland, Healy, and Gold Hill substations. The units are the thyristor controlled reactor, fixed capacitor (TCR-FC) type, whose reactive power output is varied by the thyristor assembly in response to a voltage regulator feedback control loop. The basic TCR-FC configuration is shown in Figure 2. The controlling element is the thyristor controller, shown as two oppositely poled thyristors which conduct on alternate half-cycles of the supply frequency. If the thyristors are gated into conduction at the peaks of the supply voltage, full conduction

Intertie SVC Ratings	
Substation	MVAr Range
Gold Hill	-5 to +33
Healy	-33 to +22
Teeland	-22 to +22

results in the reactor. If the gating is delayed by equal amounts on both thyristors, varied amounts of reactive power can be generated. The sensing and gating equipment are so fast that it is possible to change the level of current flow through the thyristors every half cycle, if necessary.

The voltage-current characteristic of a TCR-FC static var compensator is given in Figure 3. For small bus voltage changes about the SVC controller setpoint, V_o, SVC output is regulated within the linear control range to provide inductive compensation for voltage rises and capacitive compensation for voltage droops. Point 2 on Figure 3 represents a low system voltage such as might occur under peak load conditions without SVC units. As shown, an SVC unit would respond to this condition by drawing capacitive current, I_4, and would thereby raise the system voltage to point 4. Point 4 is determined by the intersection of the SVC characteristic and the system reactive load line passing through point 2. Conversely, for light load conditions, the system voltage may rise to point 1 if SVCs are not operational. However by drawing inductive current, I_3, the SVC is able to hold the system bus voltage at point 3. The slope of the control characteristic within the linear range is dependent on the gain of the SVC controller, and is usually 2% to 5%.

Static var compensators are located at three substations along the Intertie to provide voltage support. The static var compensator ratings for each substation are given in the following table, where positive reactive megavolt-amperes (MVArs) are capacitive and negative MVArs are inductive.

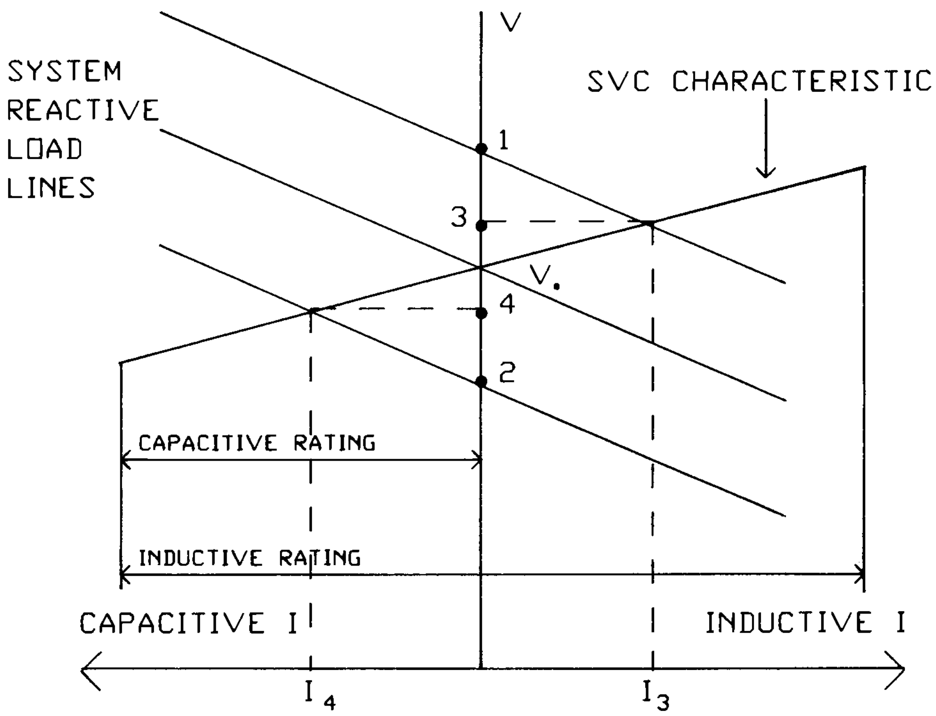

Figure 3: Voltage-Current Characteristic of TCR-FC Static Var Compensator

METHOD OF INVESTIGATION

The dynamic performance of a power system is determined through load flow and transient stability computer simulations. Load flow calculations provide bus voltages and line flows, including current and real and reactive power flow, under steady-state conditions. This is used to evaluate the ability of the power network to supply its required load and interchange within specified voltage limits with the reactive power compensation available and without overloading the transmission facilities. Load flow results are also used as initial conditions for stability studies. The interconnected power system was evaluated for various load levels, including peak (100%), medium (70% of peak), and light (40% of peak) load conditions, and Intertie transfer levels of 0, 20, 40, and 70 MW. Transient stability analyses, simulations lasting less than five seconds, were also conducted for the Alaska Railbelt power grid. A major concern in the stability of power transmission systems is whether the system will recover normal operation following major disturbances such as three phase short circuits (also called faults), loss of major transmission lines, and loss of major generation. Stability analyses also evaluate the adequacy of system relaying schemes and critical fault clearing times.

The effectiveness of the installed static var compensators to aid the stability of the Intertie was also investigated. Through this type of simulation, it is possible to determine weaknesses in power system operation and suggest areas for improvement without physically short circuiting the system or using other deliberate tests that could endanger system operation.

To perform the necessary load flow and transient stability analyses, the Electric Power Research Institute's (EPRI) Transient-Midterm Stability RP-745 code and, more recently, the Electrocon Power System Analysis software package were utilized. These are state-of-the-art programs which contain load flow, stability, and plotting algorithms. They are installed on the University of Alaska Computer Network's (UACN) Digital Equipment Corporation's Vax 8800 computer residing on the University of Alaska Fairbanks (UAF) campus.

RESULTS

One of the largest power outages in Alaska history occurred on April 1, 1987. According to the Associated Press, about 400,000 residents from Fairbanks to Homer were without power for up to several hours.[6] The blackout was initiated by a short circuit occurring on one of the two 230 kV lines extending from the Chugach Electric Association's Beluga power plant to the Point Mackenzie substation near Anchorage. At the time of the blackout the International Brotherhood of Electrical Workers (IBEW) were striking CEA and sabotage was suspected as the cause of the short circuit due to the discovery of fishing line and copper wire draped over the line about four miles from the Beluga plant.

A fault on the transmission line is detected by protective relays of the impedance type which are located at both ends of the line. The relays send a trip signal to their associated circuit breakers to disconnect the faulted line. The relaying scheme tripped the circuit breaker at the Beluga end in three cycles or 50 milliseconds, but tripping at the Point Mackenzie end occurred in the relatively slow time of 27 cycles or 0.45 seconds. This scenario is illustrated in Figure 4.

Slow clearing occurs for faults near either end of the line, and is necessary to allow proper time coordination with relays at adjacent substations. Generally, an impedance relay will provide 3 cycle clearing for the first 80% of line length, and slower clearing for the remaining 20% of line length. Impedance relays will, therefore, trip both ends of a line in 3 cycles for faults occurring in the middle 60% of the line. Conversely, for faults occurring in the 40% of the line nearest the ends, the end of the line furthest from the fault will be opened in 27 cycles.

This disturbance was studied by a transient stability computer simulation. A three phase fault was placed at the Beluga end of one of the Beluga to Point Mackenzie 230 kV lines. The line was opened at the Beluga end in 3 cycles. The fault remains on the system being fed from the Point Mackenzie end of the line, until that end is opened 27 cycles after the disturbance occurs, thereby removing the short circuit from the system. The case was run for 3.0 seconds, but the system went unstable at 58 cycles or 0.97 seconds indicating a Railbelt-wide blackout would have occurred.

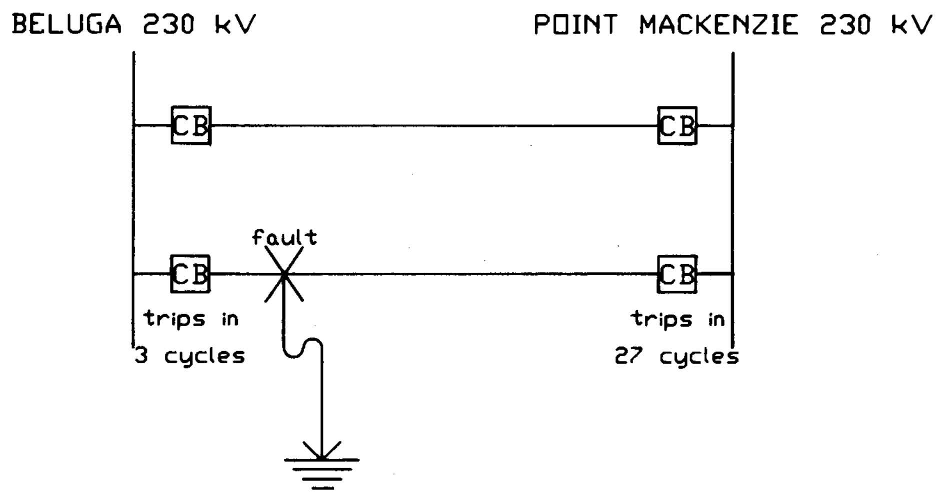

Figure 4: Fault Near Beluga 230 kV Bus on Beluga - Point Mackenzie 230 kV Line

The plot of rotor angles of several generators versus time, shown in Figure 5, shows the system is unstable. The generators have lost synchronism. Machine 6 is Chugach Electric Association's Beluga Power Plant 68 MW unit 6 generator; Machine 53 is Municipal Light and Power's Plant 2 86 MW unit 8 generator; Machine 94 is Homer Electric Association's 45 MW Soldotna generator; Machine 106 is Golden Valley Electric Association's Healy 25 MW generator; and Machine 128 is one of Golden Valley Electric Association's North Pole 60 MW generators. The North Pole generator decelerates and reaches an angle less than -335°. The Anchorage area generators accelerate with the Soldotna unit reaching an angle of 25°. After synchronism is lost, some generators will be tripped off line by overspeed relays to prevent damage to the units. The case was automatically stopped at 58 cycles or 0.97 seconds by a program feature that considers a case to be unstable when any two generators are more than 360° apart.

This case confirms that a fault on a Beluga to Point Mackenzie 230 kV line with the standard impedance relay scheme results in the system going unstable which will very likely lead to a widespread blackout as occurred on April 1, 1987.

Means of preventing system instability were then sought. Particular emphasis was placed on the effect of faster relaying schemes. Relaying schemes known as transfer trip or pilot relaying can be used which will send information gathered by one relay to the relay at the other end of the line. In a transfer trip scheme, the relay closest to the fault will trip its circuit breaker in 3 cycles and will send information to the remote relay that the fault indeed exists on the line. This information then frees the remote relay to also trip its circuit breaker in 3 cycles, rather than delaying until 27 cycles for relay coordination purposes.

Results of the stability case with 3 cycle clearing at both ends of the line are shown in Figure 6. The generators remain in synchronism with each other and the rotor angle swings are relatively small, indicating that the system is very stable for this fault with fast 3 cycle clearing. Figure 7 is a plot of voltage versus time at various locations in the system and shows that the voltages return to about the desired value of 1.0 per unit (100% of rated voltage) shortly after the fault is cleared. In Figure 7, Bus 43 is Teeland 138 kV; Bus 55 is MLP Plant 2 230 kV; Bus 93 is Soldotna 115 kV; Bus 105 is Healy 138 kV; Bus 110 is Gold Hill 138 kV; and Bus 138 is Fort Wainwright 69 kV. The three SVC units along the interconnection rapidly vary their reactive power output (MVArs) as can be seen in Figure 8, to aid in maintaining the voltage profile.[3] Compensator 1 is the

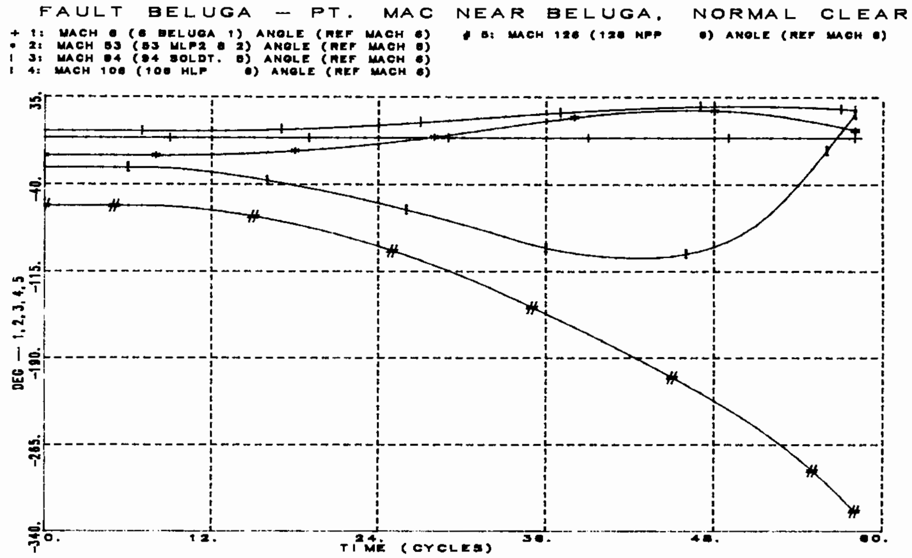

Figure 5: Generator Rotor Angles for 3 Cycle and 27 Cycle Clearing

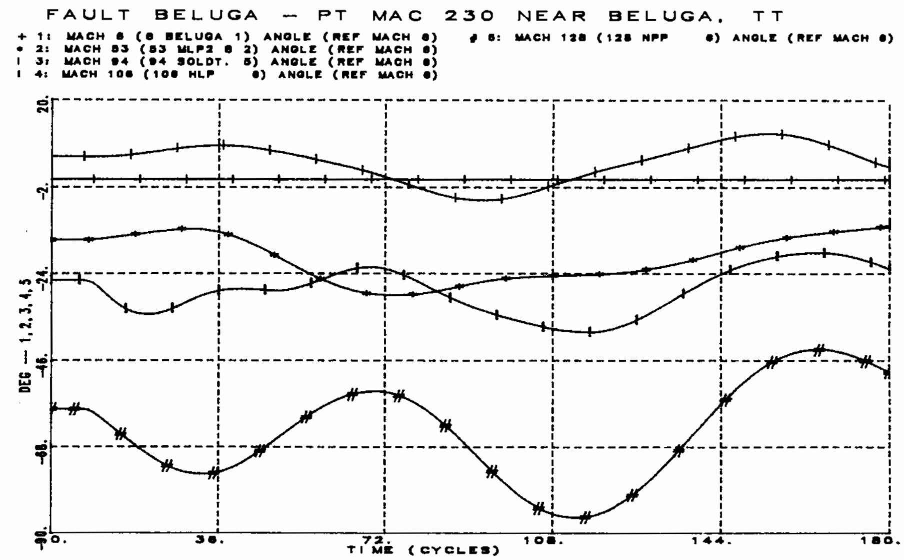

Figure 6: Generator Rotor Angles for Simultaneous 3 Cycle Clearing

Teeland SVC; Compensator 2 is the Healy SVC; and Compensator 3 is the Gold Hill SVC.

Comparison of the results of the two stability cases shows the vast improvement in system integrity that may be realized by utilization of a high speed transfer trip relay scheme.

The same impedance type relay scheme was found to exist on the Point Mackenzie to MLP2 230 kV line. This is also an important 230 kV line as AML&P's major power plant is connected into the system at the MLP2 230 kV substation. The same result was found to occur for a three phase fault on this line. The system was highly unstable with the 27 cycle clearing provided by the existing impedance type relay scheme, and a system blackout would likely result. Again a 3 cycle transfer trip relay scheme was found to vastly improve the stability of the power system.[3]

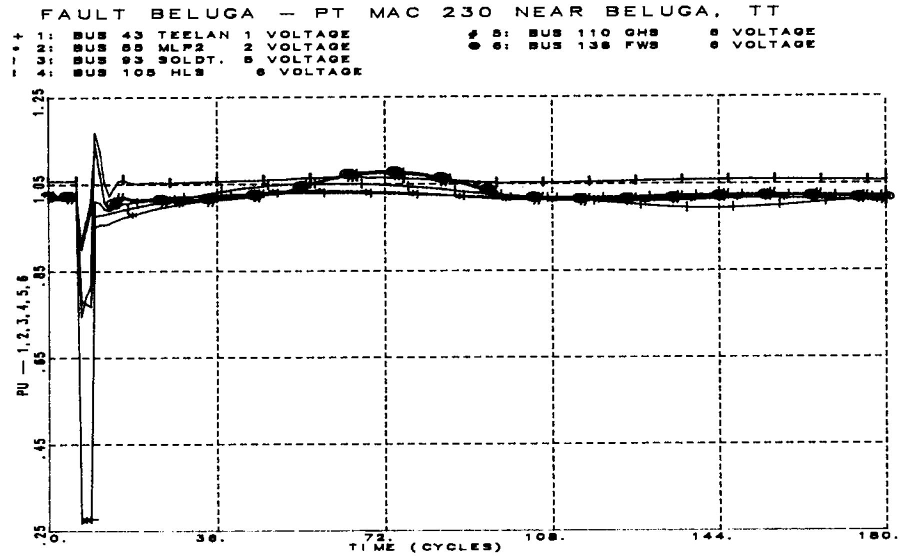

Figure 7: AC Bus Voltages for Simultaneous 3 Cycle Clearing

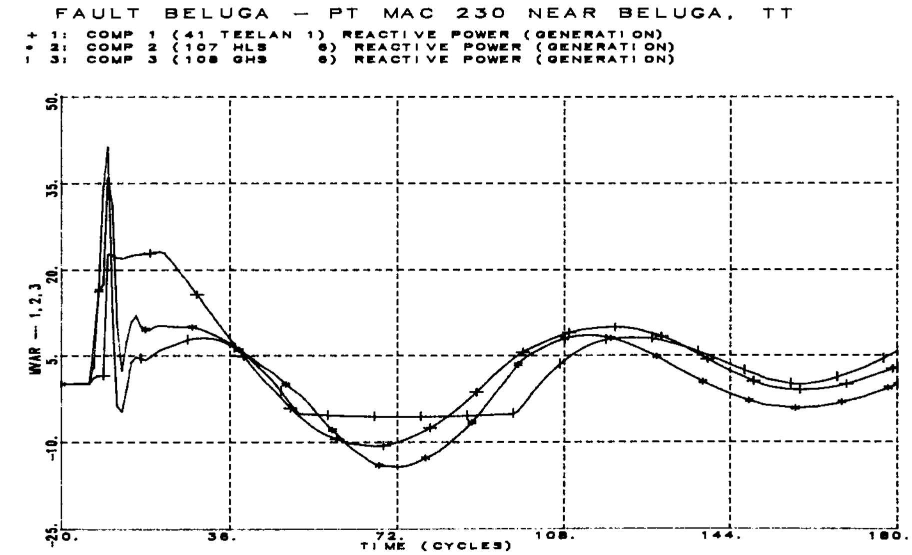

Figure 8: Static Var Compensator Output (MVArs) for Simultaneous 3 Cycle Clearing

TRANSFER TRIP SCHEMES

A variety of relaying schemes are available and widely used for providing high-speed simultaneous detection of line faults and tripping of circuit breakers. These schemes are usually applied to transmission lines of 69 kV and above, particularly where rapid clearing of faults is necessary for system stability reasons.[4] "Directional comparison" is a method in which the direction of current at both ends of a line are compared. For a fault anywhere on the protected line, the directional relays see current entering the line from both ends. This information, when communicated over a pilot channel, confirms that a fault is indeed on the protected line.[5]

Various communication channels are used for transmitting this information. They include pilot wires, leased telephone lines, power line carriers in which radio frequencies between 30 and 300 kilohertz (kHz) are superimposed on the power line conductors, microwave, and most recently, fiber optic cable.[4] The particular scheme to be used is largely one of personal preference and economics. The choice must be made after study by the owner utility.

BENEFITS OF RESEARCH PROJECT

The work that has been performed has resulted from a very successful and cooperative effort between the University of Alaska Fairbanks and the sponsoring Railbelt utilities. This effort has provided many benefits to both the utilities and the University. A partial listing of the benefits would include:

- A load flow and stability data base for the Alaska interconnected system is kept current by annual updating. The base cases are stored on the University of Alaska Computer Network (UACN) and are available to all seven participating utilities and APA.
- Load flow and transient stability case studies can be made that accurately model the Alaska Railbelt system. The studies can include all load levels and all possible power transfer levels. All studies to date have been of the existing system. Studies could be extended to include proposed alternate future systems.
- Acquisition of state-of-the-art software packages. The Electrocon Power System Analysis package was purchased in May 1987 and includes power flow, transient stability, short circuit, one-line diagrams, and optimal power flow computer programs. A prior acquisition was the EPRI software package. These programs may be accessed by the participating utilities and APA through UACN.
- The Electrocon software is being used in the undergraduate and graduate electric power courses offered by UAF. Use of this software improves the quality of the electric power engineering education that UAF provides.
- The project has supported and provided educational experience to four masters' degree students. A fifth masters' degree student has recently started to work on the project.

This paper has described some results of the project studies that can lead to improved performance of the Alaska Railbelt power system and are therefore of significant benefit to the sponsoring utilities and ultimately to the electric energy consumers served by those utilities. In summary, the project has been a model of successful industry-sponsored university research and of the benefits that can accrue to each of the participants.

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[3]Laurie Jean Oppel, "A Load Flow and Transient Stability Analysis of the Anchorage-Fairbanks Interconnected Power System," Masters Thesis, University of Alaska Fairbanks, May 1987.

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5William D. Stevenson, Elements of Power System Analysis, fourth edition, New York: McGraw-Hill, 1982, p. 336.

[6]"Power officials say sabotage cause of outage," Fairbanks Daily News Miner, April 2, 1987, p. 2, col. 1.

BIOLOGICAL BENIFICATION OF AN ALASKAN ORE

by

Seongho Hong, Huan V. Luong, David R. Maneval, and Edward J. Brown

INTRODUCTION

The application of microbiological technology is being revitalized for the leaching of metals from metal-bearing ores, recovery of metals from wastes and desulfurization of coal.

Conventional mining and ore concentration in remote areas requires large developmental costs for transportation and processing facilities. United States and Canadian environmental regulations essentially prohibit constructing new pyrometallurgical processing facilities in pristine areas. Thus biohydrometallurgical processing in remote areas such as Alaska is extremely desirable. However, detailed evaluations of ore types, microorganisms and biohydrometallurgical processes have not been studied for application in remote areas as they have in other parts of the world where transport and/or processing facilities already exist.

Ehrlich (1964) reported that a pure culture of *Thiobacillus* sp. would oxidize arsenopyrite. Recently, there has been renewed interest in using thiobacilli to pretreat gold ores containing arsenopyrite (Bruynesteyn et al., 1986). While accurate numbers are difficult to obtain, it is estimated that 25-30 million ounces of lode gold are associated with placer gold deposits in Alaska. Many of the known gold deposits, including several in Alaska, are associated with arsenopyrite. Arsenopyrite is a particularly strong inhibitor of gold extraction by cyanide leaching. Removal of arsenopyrite from gold bearing material by microorganisms increases gold recovery in some ores from 60% before removal to 94% after removal (Bruynesteyn, 1982). Experiments have shown that *T. ferrooxidans* can dissolve arsenic from both low sulfide gold mine material (Brown et al., 1983, Luong et al., 1985) and arsenopyrite concentrates (Groudev, 1981).

Boyle and Jonasson (1973) provide a simplified expression of the oxidation of arsenopyrite, the most common of the arsenic minerals.

$$4FeAsS + 13O_2 + 6H_2O \rightarrow 4Fe^{2+} + 4SO_4^{2-} + 4AsO_4^{3-} + 12H^+ \qquad (1)$$

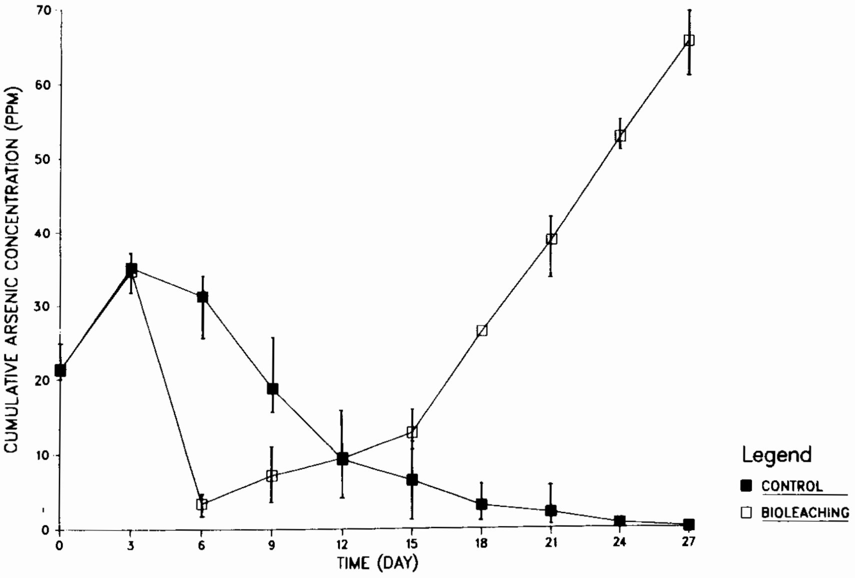

Figure 1. Time vs. Cumulative Arsenic Concentration of Fresh Sample.

Similar equations can be written for other arsenic-containing minerals (Boyle and Jonasson, 1973). Equation (1) is analogous to the initiation phase of microbially mediated oxidation of metal sulfide ores in general. Ultimately, microbial oxidation of metals from sulfide ores can lead to production of mobile forms of the metal and high concentrations of acid (acid mine drainage). As with pyrite oxidation, arsenopyrite oxidation may proceed beyond equation (1) in the following sequence of reactions known as the propagation cycle (Singer and Stumm, 1970).

$$4FeSO_4 + O_2 + 2H_2SO_4 \rightarrow 2Fe_2(SO_4)_3 + 2H_2O \qquad (2)$$

and

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$$2FeSAs + 14Fe^{3+} + 3O_2 + 10H_2O \rightarrow$$
$$16Fe^{2+} + 2SO_4^{2-} + 2AsO_4^{3-} + 20\,H^{+} \qquad (3)$$

As Fe^{2+} is released in the initiator reaction (1), (either by microbial activity or by chemical oxidation) a cycle is established in which Fe^{2+} is oxidized to Fe^{3+} (2) and subsequently reduced by arsenopyrite generating additional Fe^{2+}, As^{5+} and acidity (3). Singer and Stumm (1970) have shown that the rate-limiting reaction of pyrite oxidation at pH 3 is equation (2) because Fe^{3+} is a much better oxidant of pyrite than oxygen. Further, they have shown that microbial activity can increase the reaction rate of equation (2) at pH 3 by a factor of 10^6.

In this study, we used biochemical benification to remove arsenic from a sulfide ore and ore concentrate obtained from a gold and silver mine near Fairbanks, Alaska.

MATERIALS AND METHODS

Gold Mine Material

Ore material was provided by the Wackwitz mine located in the Pedro Dome-Cleary Summit area of Fairbanks district, Alaska.

A complete description of the mineralogy of the mine has been done (Lin, 1984) and minerals such as jamesonite, arsenopyrite, galena, albite, tetrahedrite-tennantite and sphalerite occur. We analyzed the handpicked sample used for these studies by ore microscopy and X-ray diffraction and found arsenopyrite, galena, boulangerite, covellite, chalcopyrite, stibnite and quartz. The elemental composition of the sample as determined by atomic absorption spectrophotometry and inductively coupled plasma spectrophotometry is shown in Table 1. Details of sample preparation and operating procedures for the X-ray, microscopic, atomic absorption and inductively coupled plasma analyses are found in Hong (1988).

Microorganisms and growth medium

Isolates of *T. ferrooxidans* from 14 locations in Alaska and Canada were obtained and maintained in liquid medium containing $FeSO_4 \bullet 7H_2O$ (30 g/L), $MgSO_4 \bullet H_2O$ (0.4 g/L), $(NH_4)_2SO_4$ (0.4 g/L) and KH_2PO_4 (0.1 g/L). Sulfuric acid (10N) was added directly to dry ferrous sulfate (2.5 ml/30 g $FeSo_4 \bullet H_2O$). The resulting acid-iron paste was autoclaved separately from salt solution and mixed with the salt solution upon cooling (Braddock et al. 1984). Isolate AK1 from Eva creek near Fairbanks, Alaska was used in all experiments because of its resistance to arsenic (Luong et al. 1985). The organism was further adapted to the leaching environment by growing in the presence of in-

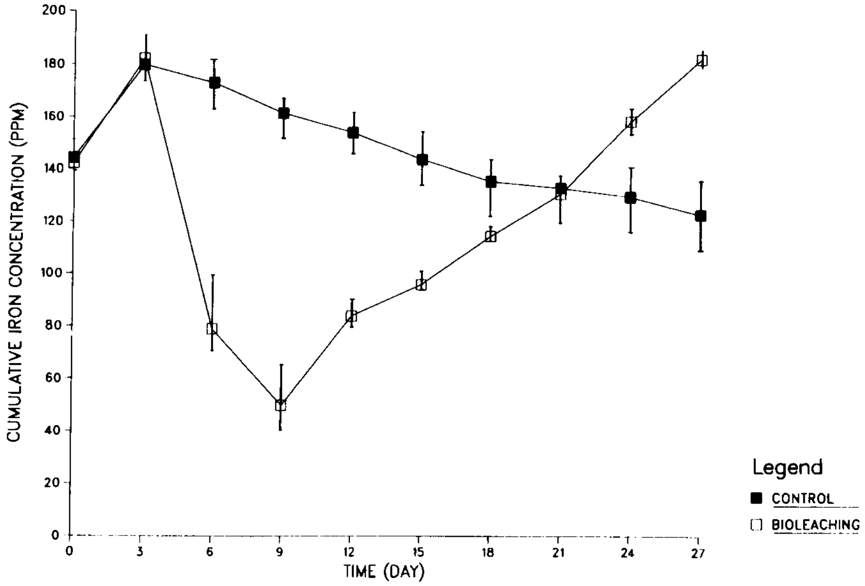

Figure 2. Time vs. Cumulative Iron Concentration of Fresh Sample.

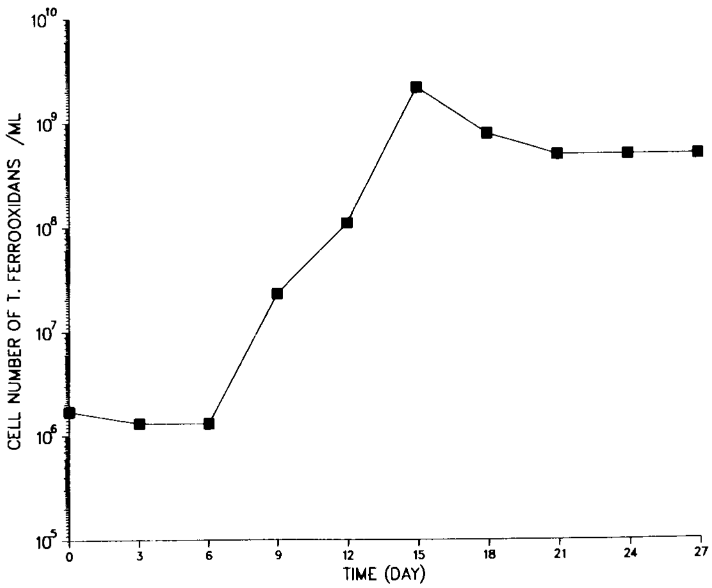

Figure 3. Time vs. Cell Number of Fresh Sample.

Table 1.						
Elemental Composition of the Sample						
Au(*ppm*)	Ag (%)	Cu (%)	Zn (%)	Pb (%)	Fe (%)	As (%)
1.0	0.1	0.1	0.035	10.0	5.7	5.8

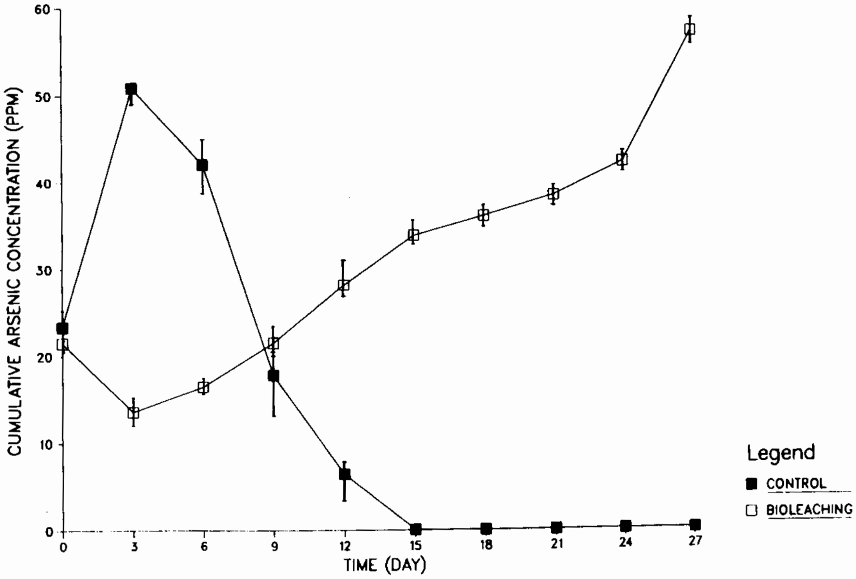

Figure 4. Time vs. Cumulative Arsenic Concentration of Flotation Concentrate Sample.

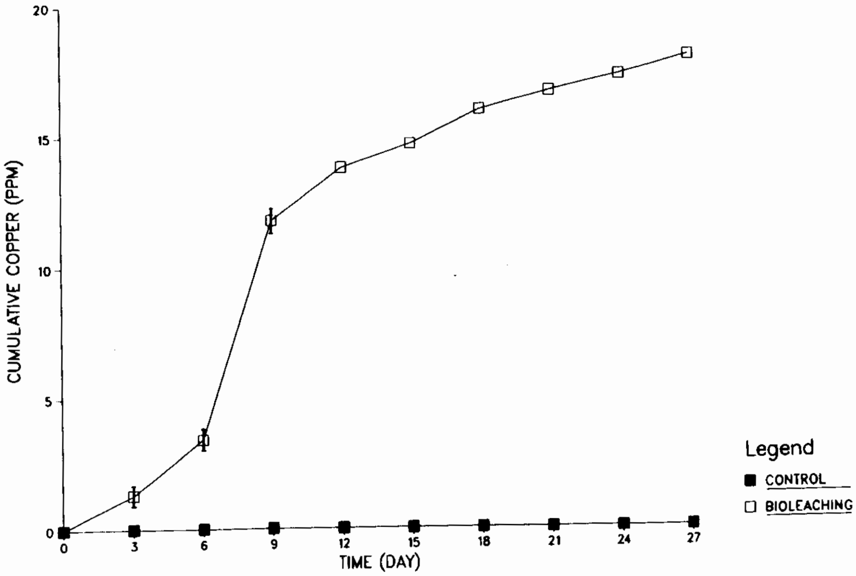

Figure 5. Time vs. Cumulative Copper Concentration of Fresh Sample.

creasing concentrations of the ore material.

Froth Flotation

A Denver Sub-A laboratory flotation cell was used to prepare ore concentrate. Pulp density of the ore was 25% solids (by weight). Samples were ground -65 mesh in a disc pulverizer. All other reagents added to the flotation cell were in liquid form and their concentrations, pH and contact time were optimized by trial and error (Hong, 1988). The frother used was Dowfrother-65 while the collector was Aeroxanthate-350 (Dow Chemical Co.)

Bioleaching Experiments

Batch-type leaching experiments were conducted as described by Luong et al. (1985). Both untreated ore material and froth flotation concentrate were used and each experiment was done in triplicate.

All leaching flasks contained 10 g of ore material (or concentrate) and were autoclaved for 20 minutes at 15 psi prior to the addition of 300 ml of autoclaved salt solution (growth medium without iron). Bioleaching flasks were then inoculated with 5 ml of 10-day-old culture of growing *T. ferrooxidans*. The control flasks were inoculated with 5 ml of sterile salt solution. All flasks were incubated at 25°C on a rotary shaker at 150 rpm.

RESULTS AND DISCUSSION

Figure 1 shows that arsenic is leached from the ore material in the presence of *T. ferrooxidans.* The control flasks show a decline in dissolved arsenic while the bioleaching flasks show a steady increase of dissolved arsenic after an initial decline. The initial decline in the bioleaching flasks and continued decline in the control flasks is probably due to coprecipitation with iron (Fig. 2). The first six days is characterized by the removal from solution of both arsenic and iron. Arsenic dissolution occurs only in the bioleaching flasks after the initial precipitation and the appearance coincides with bacterial growth (Fig. 3).

Figure 4 shows that arsenic can also be leached from the froth flotation concentrate. However, the flotation reagents do inhibit the growth of *T. ferrooxidans* (Hong, 1988) and thus these reagents must be rinsed from the concentrate before bioleaching can occur.

In addition to arsenic, copper can be leached by *T. ferrooxidans* from this ore and concentrate (Figs. 5 and 6). Copper does not inhibit the cyanidization process for gold but can be recovered from the leachate as a side-product of the bioleaching process.

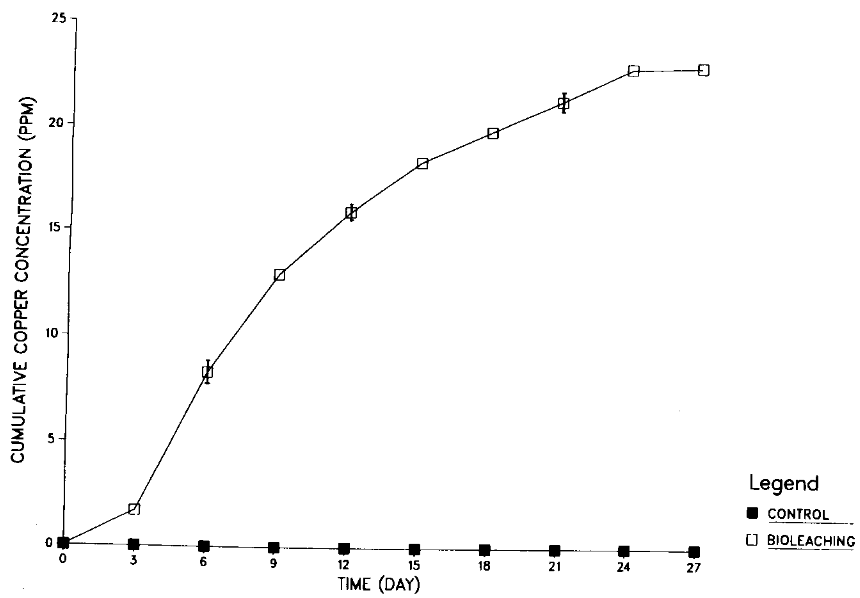

Figure 6. Time vs. Cumulative Copper Concentration of Flotation Concentrate Sample.

The state government of Alaska is actively encouraging development of mines throughout Alaska. In order to be economically feasible, mines in remote areas with little or no on-site processing facilities must be limited to high-grade deposits and be able to concentrate for transport only high-grade materials.

Since biochemical benification of sulfide ores and float concentrates is kinetically slow, even under ideal conditions compared to conventional benification processes, its use must be evaluated on a case-by-case basis in comparison to conventional techniques and newer hydrometallurgical processing techniques. However, since benification of sulfide minerals is only beginning in Alaska, the advantages of biochemical benification should be considered and evaluated as an alternative to development of conventional benification processes that generally tax heavily energy and the quality and quantity of air and/or water resources. The time has come for bioleaching of refractory gold ores for Giant Yellowknife Mines, Ltd. Salmita Mine in Canada's Northwest Territories (International Bioleach, Inc., information brochure, 1988). The results of this study support consideration of biohydrometallurgy for use in development of sulfide ore deposits in Alaska

ACKNOWLEDGEMENTS

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SOME ANALYTICAL METHODS FOR CONDUCTION HEAT TRANSFER WITH FREEZING/THAWING

by

V.J. Lunardini

ABSTRACT

One of the most difficult and yet most interesting areas of heat transfer is conduction (or convection) with freezing or thawing. The inherent non-linearity of the problem along with the unknown moving interface precludes exact solutions for most practical cases. This has spurred great effort to devise approximate solution methods which are accurate and of general application. Many of the known exact solutions are listed here along with a brief discussion of two approximate methods: the quasi-static and the heat balance integral. Space limitations rule out the inclusions of such useful variational methods as that of Biot or of a treatment in more detail.

INTRODUCTION

Phase change occurs quite regularly in engineering problems dealing with permafrost and seasonally frozen ground, thermal storage systems for solar energy, the freezing of food or biological material, and the solidification or melting of metals.

Ideally, exact solutions of engineering problems of freezing and thawing are sought. However, due to the non-linearity of the phase change system, there are very few exact solutions. Thus, approximate methods are sought for those problems which have not been solved exactly. Several approximate methods have been widely used including quasi-steady methods, the heat balance integral concept, and variational methods. A discussion of these methods will follow the presentation of some exact solutions.

Basic Equations

During a melting or freezing process, the system is divided into regions separated by a phase change interface, or a phase change region, which is usually at the phase change (fusion) temperature. In general, the thermal properties of the frozen and unfrozen region are different, but are not strong functions of temperature for each individual phase.

The transient temperature, boundary heat fluxes, and location of the phase change interface are of particular interest. The concepts of solid and liquid relate to the thermodynamic state of the water (or other liquid) contained in the voids of a porous system.

A porous material may consist of a framework or skeleton of solid material enclosing numerous voids filled, or partially filled, with fluids or other solids. An important example is a soil system consisting of a mineral skeleton whose voids may contain air, water, water-vapor, ice, hydrocarbons, or various solute solutions.

When porous systems are to be considered the basic equations for a continuum will be considered valid with the average properties of the porous material used.

Using fundamental laws, it is possible to write a general equation for the temperature of a continuum at any point and time, (Lunardini 1981a)

$$\mathrm{div}\,(\overline{\overline{k}}\ \mathrm{grad}\ T) + q_r + q_g = \rho c_p \frac{DT}{Dt} - T\beta \frac{Dp}{Dt} - \mu\phi_f \qquad (1)$$

For flow of a liquid through permeable materials, such as soils, the viscous dissipation is often negligible. If the material is isotropic and orthotropic, with constant thermal conductivity, then Eq. (1) can be written

$$\nabla^2 T + \frac{q_g}{k} = \frac{1}{\alpha}\left[\frac{\partial T}{\partial t} + \underline{s} \cdot \nabla T\right] \qquad (2)$$

where ∇^2 is the usual Laplacian operator and $\alpha = k/\rho c$ is the thermal diffusivity.

For pure conduction the simplified energy equation is

$$\nabla^2 T + \frac{q_g}{k} = \frac{1}{\alpha}\frac{\partial T}{\partial t} \qquad (3)$$

For the porous medium assume that conduction and enthalpy flows are the energy flux terms. The energy equation is, (Luikov 1964, 1975)

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$$\frac{\partial \sum_{i=0}^{4} \rho_o \psi_i h_i}{\partial t} = -\mathrm{div}\,(q + \sum_{1}^{4} j_i h_i) \quad (4)$$

Where q equals conduction heat transfer and h_i is the enthalpy of each component.

The mass ratio of each bound constituent is

$$\psi_i = \frac{m_i}{m_o} \quad (5)$$

where m_o is the mass of the solids and the solid density is defined as $\rho_o = m_o/V$.

The mass fluxes in a soil are made up of liquid water and vapor, and can be expressed (De Vries 1958) (Cary 1966) as

$$\frac{j_1}{\rho_w} = -D_{\psi V} \nabla\psi - D_{TV} \nabla T \quad (6)$$

$$\frac{j_2}{\rho_w} = -D_{\psi L} \nabla\psi - D_{TL} \nabla T - K_L \nabla z \quad (7)$$

where ψ is the sum of the total water in the soil.

It has been known for many years that, notwithstanding the mass and heat flux relations shown, pure conduction may be an excellent assumption for porous media such as soils, Porkhayev (1959), Martynov (1959).

Consider the total heat flux that might occur in a porous medium

$$q_{TOT} = (k + \rho_w h_v D_{TV} + \rho_w h_L D_{TL} + h_c + h_r) \nabla T - (\rho_w h_v D_{\psi V} + \rho_w h_L D_{\psi L}) \nabla\psi \quad (8)$$

where h_c, h_r are convective and radiative coefficients. An effective thermal conductivity can be defined to account for that part of the non-conduction heat flux which is expressed in terms of the temperature gradient

$$k_e = k + \rho_w h_v D_{TV} + \rho_w h_L D_{TL} + h_c + h_r \quad (9)$$

If the second term on the right hand side of Eq. (8) is negligible then pure conduction is an excellent assumption, with the thermal conductivity and other properties of the medium altered to account for the convection, radiation, and moisture effects, as given by Eq. (9).

For many applications, it is a very reasonable assumption to treat a soil system as a continuum and to evaluate the temperature field on the basis of conduction only. The effects of moisture can be incorporated into the soil properties.

Energy Balance at the Phase Change Interface

At the interface between the phases, energy will be released or absorbed as the material changes phase, Patel (1968). The conservation of energy applied to the mass which undergoes phase change is

$$-k_1 \frac{\partial T_1}{\partial x} + k_2 \frac{\partial T_2}{\partial x} = \pm \rho L \frac{dX}{dt}; \quad x = X \quad (10)$$

Where the upper sign is for melting and the lower sign is for freezing.

Eq. (10) is also valid for cylindrical and spherical coordinates if x is replaced by r.

Non-linearity of Solidification Problems

Phase change introduces a basic non-linearity into the boundary conditions of the problem. The temperature at the phase change interface can be combined with equations (3) and (10) to obtain a boundary condition in the form

$$-k_1 \left(\frac{\partial T_2}{\partial x}\right)^2 + k_2 \left(\frac{\partial T_2}{\partial x}\right) \frac{\partial T_1}{\partial x} = \pm \rho L \alpha_1 \frac{\partial^2 T_1}{\partial x^2}; \quad x = X \quad (11)$$

The non-linear nature of the problem is quite obvious in this form. The non-linearity can also be explicitly expressed in the differential equation for the energy. This inherent non-linearity, along with the unknown motion of the phase change interface, has limited the exact solutions of phase change problems to a mere handful of cases with particularly simple geometries and boundary and initial conditions.

Exact Solutions

The relatively few exact solutions available for phase change problems (also called free boundary or Stefan problems) will be reviewed briefly.

Neumann Problem and Solutions for Plane Geometries

Systems with plane interfaces occur frequently in engineering design. The first and still the most comprehensive exact solution method is due to Neumann (c 1860), generalized in Carslaw and Jaeger (1959).

Initially, a semi-infinite region is at a constant temperature, T_o, and the temperature of the surface is suddenly dropped to T_s and held constant (step change at surface). It is assumed here that initially the medium is in a liquid state, i.e. $T_o > T_f$.

A similarity solution leads to

$$T_1 = T_s + \frac{(T_f - T_s)}{\text{erf}\gamma} \ \text{erf} \ \frac{x}{2\sqrt{\alpha_1 t}} \tag{12a}$$

$$T_2 = T_o - \frac{T_o - T_f}{\text{erfc}\,(\gamma\sqrt{\alpha_{12}})} \text{erfc} \ \frac{x}{2\sqrt{\alpha_2 t}} \tag{12b}$$

$$X = 2\,\gamma\sqrt{\alpha_1 t} \tag{13}$$

$$\frac{\exp(-\gamma^2)}{\text{erf}\ \gamma} - \frac{k_{21}\sqrt{\alpha_{12}}\ \phi\ e^{-\alpha_{12}\gamma^2}}{\text{erfc}\ (\gamma\sqrt{\alpha_{12}})} = \frac{\gamma\sqrt{\pi}}{S_T} \tag{14}$$

The Stefan number, S_T, is a commonly used dimensionless parameter which is the ratio of the sensible heat to the latent heat. The latent heat dominates if the Stefan number is small.

If the medium is initially at the phase change temperature only one phase will be present. This special case of the Neumann problem is also often referred to as the Stefan solution, following the original work on sea ice of Stefan (1891), who obtained a solution when the Stefan number is small. The phase change depth simplifies to

$$X = \sqrt{2\,S_T\,\alpha t} \tag{15}$$

The Neumann solution is widely used for soil freezing estimates but special names have been given to it which can be confusing. Berggren (1943) was apparently the first to actually apply the Neumann solution to soil phase change problems. Aldrich and Paynter (1953) later used the Stefan form of the phase change solution to arrive at the modified Berggren equation which is actually the Neumann solution in a different form.

Exact solutions are available for the case of a constant heat flux at the phase change interface, Stefan (1891), Rubinsky and Shitzer (1978).

If the density of the solid and liquid phases differ, a solution can again be found using similarity techniques, Crank (1975), Carslaw and Jaeger (1959). This problem actually involves convection in the frozen phase, due to the motion of the solid, but it can be formulated and solved as a pure conduction problem.

Cho and Sunderland (1974) have extended the Neumann problem when the thermal conductivity varies linearly with temperature and a further extension of the similarity method was used by Tao (1978) to obtain an exact solution for arbitrary surface and initial conditions.

Cho and Sunderland (1969) evaluated an exact solution for the phase of a binary eutectic mixture if melting occurs over a temperature range. For soils, if the unfrozen water content varies linearly with temperature then an exact solution may be found (Lunardini 1985).

A problem of some practical interest relates to the freezing of a liquid initially below its fusion temperature, in a metastable state where phase change results in the release of latent heat which warms the liquid to its normal fusion point. The solid phase remains at the freezing temperature. This can be related physically to the formation of frazil ice in water which supercools due to turbulence. The solution is detailed by Lunardini (1987).

The freezing of liquid in contact with a cold wall is of importance in casting metals and in the intrusion of magmas during geological processes, there a semi-infinite liquid is brought into contact with a semi-infinite cold wall. The exact solution is shown by Carslaw and Jaeger (1959).

An interesting problem arises due to the fact that some porous media, such as soils, can become more compact after thawing. A certain amount of the water in the frozen soil is forced out as the solid particles settle and the thawed soil becomes denser. The situation is similar to the variable density problem, with a solution by Lunardini (1987a).

Lozano and Reemsten (1981) present an exact solution, to a single phase problem for the case of surface convective heat flow. Westphal (1967) obtained an exact solution using infinite series for the freezing of a semi-infinite medium with convection, letting the ambient temperature be a function of time.

Tao (1979) has derived an exact solution to the freeze problem for a liquid, initially at a temperature that is a function of position and that has a transient heat flux imposed upon its free surface. Evans et al. (1950) also presented an exact solution for this problem by assuming Taylor Series expansions for the phase change depth. A further exact solution form is given by Lozano and Reemsten (1981). All three solutions are exact, although they all appear distinctly different, and they reduce to the identical series for the phase change interface, Lunardini (1987).

Cylindrical Geometry

In contrast to the Neumann problem, there are no general, exact solutions for practical phase change problems in cylindrical coordinates which have the same applicability as does the Neumann solution.

Carslaw and Jaeger (1959) give an exact solution for the case of a subcooled liquid which freezes while the solidified region remains at the fusion temperature.

Carslaw and Jaeger (1959) present the freezing solution for a line source which extracts energy along the origin. Ozisik and Uzzell (1979) considered an extension of the method for the case of a material with an extended fusion temperature range. Boles and Ozisik (1983) obtained an exact solution for freezing about a line sink with moisture flow in the surrounding medium. A simple system which has an exact solution requires that the temperature gradient at the phase change interface be a constant (Kreith and Romie 1955).

Spherical Geometry

An exact solution is available for the continuous extraction of energy at the origin, (Lunardini 1987).

An exact solution has been published for the problem with a solid region for r < R and a subcooled liquid for r > R (Frank 1950).

Rubinsky and Shitzer (1978) solved an inverse Stefan problem to obtain the temperature as a function of the interface velocity and heat flux.

The Neumann problem has shown that the similarity method and error functions can lead to an exact solution, suitable for certain boundary conditions. However, the method cannot be applied in general. The similarity solution required that the differential equation and all of the initial and boundary conditions could be expressed with a single independent variable. Similarity solutions will not exist for finite domains, two phases present initially, non-uniform initial temperatures, and boundary temperatures which are arbitrary functions of time.

Since there are so few exact solutions existing, there is considerable interest in approximate methods that can yield solutions acceptable for engineering design. Aside from the usual numerical procedures, several analytical methods have been of great value including: the quasi-static approximation, the heat balance integral method, and variational methods.

PERTURBATION AND QUASI-STATIC APPROXIMATIONS

If the phase change interface moves relatively slowly, then it can be assumed that the moving interface will not exert a major influence upon the temperature field during short time periods. This observation is the basis of the quasi-static method. Two approximations have been used.

The quasi-stationary assumption neglects the moving interface in evaluating the temperature field and consequently the diffusive flux anywhere in the volume of interest. The assumption can handle initial conditions but is not generally valid for all times if the temperature ahead of the interface is non-uniform or is changing due to the interface motion. The problem is reduced to one of transient conduction with no phase change. The actual phase change is then introduced through the interface boundary condition.

The quasi-steady approximation further simplifies the quasi-stationary problem by dropping the transient term in the energy equation. The justification for the method is somewhat tenuous since it cannot satisfy the initial conditions, however the problem is mathematically so simple that the idea has been widely used.

Quasi-Stationary Approximation

The melting system will be examined, for a Neumann problem with variable density, in order to illustrate the quasi-stationary idea.

The equations are (Lunardini, 1987)

$$\frac{\partial^2\theta}{\partial x_1^2} = \frac{\partial\theta}{\partial\tau} + \left(\frac{\rho_2}{\rho} - 1\right) S_T \frac{\partial\theta}{\partial x_1} \left(\frac{\partial\theta}{\partial x_1}\right)_\xi \qquad (16)$$

$$\theta(x_1, 0) = 0$$
$$\theta(o, \tau) = \phi_s$$
$$\theta(\xi, \tau) = \phi$$

$$\frac{d\xi}{d\tau} = -S_T \left(\frac{\partial\theta}{\partial x_1}\right)_\xi \qquad (16a)$$

$$\theta(\xi, \tau) = \phi$$

The quasi-stationary approximation, which tends to be valid if $S_T << 1$, is

$$\frac{\partial^2\theta}{\partial x_1^2} = \frac{\partial\theta}{\partial\tau} \tag{17}$$

$$\theta(x_1, 0) = 0$$
$$\theta(0. t) = \phi_s$$
$$\theta(\xi, \tau) = \phi$$

After solving Eq. (17), the interface location is evaluated with Eq. (16a).

Duda and Vrentas (1969) showed that the quasi-stationary solution is the first term of an asymptotic series. The temperature and interface position are expanded, with the Stefan number as the perturbation parameter

$$\theta = \theta_o + S_T\,\theta_1 + S^2_T\,\theta_2 + S^3_T\,\theta_3 + ... \tag{18}$$

$$\xi = 1 + S_T\,\xi_1 + S^2_T\,\xi_2 + S^3_T\,\xi_3 + ... \tag{19}$$

The temperature relations at the interface position can be expanded by Taylor Series, about the initial interface location, $\xi_o(0) = 1.0$.

The procedure is called a surface-volume perturbation since the differential equation and the boundary conditions both contain non-linearities. See Van Dyke (1964) and Cole (1968) for further details on regular perturbation methods. Applying Eqs. (18, 19) to Eq. (16) leads to the following system of equations up to order one:

$$\frac{\partial^2\theta_i}{\partial x^2_1} = \frac{\partial\theta_i}{\partial\tau} \tag{20}$$

$$\theta_i(x_i, 0) = 0$$

$$\theta_i(0, \tau) = \begin{cases} \phi_s & i = 0 \\ 0 & i = 1 \end{cases}$$

$$\theta_i(1, \tau) = \begin{cases} \phi & i = 0 \\ -\xi_i\,(\frac{\partial\theta_o}{\partial x_1})_i & i = 1 \end{cases}$$

$$-\frac{d\xi_i}{d\tau} / (\frac{\partial\theta_o}{\partial x_1})_1 = \begin{cases} S_T & i = 0 \\ 1 & i = 1 \end{cases}$$

It is clear that the zeroth order system, Eq. (20 with i = 1.0), is the quasi-stationary approximation.

A regular perturbation (volume) can also be used, if the non-linearities are concentrated in the differential equation by immobilizing the interface with a Landau transformation

$$\eta = \frac{x_1}{\xi}.$$

__Quasi-Steady Approximation__

The quasi-stationary method can be further simplified if the unsteady terms in the diffusion equation are also neglected. To justify this a new characteristic time will be used.

$$\tau_1 = \frac{\alpha\tau}{X^2_o} S_T \tag{21}$$

The characteristic time is now long compared to the diffusion time X_{o2}/α, if ST < 1.0. The new time domain is ideally suited to the later stages of the interface movement. Jiji and Weinbaum (1978) used two time domains, the quasi-stationary for initial growth and the quasi-steady for later growth with the two times joined at an intermediate position.

The non-dimensional equations are

$$\frac{\partial^2\theta}{\partial x_1^2} = S_T\frac{\partial\theta}{\partial\tau_1} - (\rho_2/\rho - 1)\,S_T\,\frac{d\xi}{d\tau_1}\,\frac{\partial\theta}{\partial x_1} \tag{22}$$

$$\theta(x_1, 0) = 0$$
$$\theta(0, \tau_1) = \phi_s$$
$$\theta(\xi, \tau_1) = \phi$$

$$\frac{d\xi}{d\tau_1} = -(\frac{\partial\theta}{\partial x_1})\,\xi$$

It is now obvious that for small Stefan numbers the diffusion equation reduces to

$$\frac{\partial^2\theta}{\partial x_1^2} = 0 \tag{23}$$

Thus, no transient term need be considered and the solution is extremely simple. Solutions are easy to obtain compared to the quasi-stationary equations, but the utility of the solution is limited since the initial conditions cannot be met and the sensible heat is not accounted for. Nevertheless, this concept is very widely used for freezing and thawing problems. The quasi-steady method can also be examined from the viewpoint of perturbation solutions. The following system of equations are generated using Eqs. (18) and (19):

$$\frac{\partial^2\theta_i}{\partial x_1^2} = \begin{cases} 0 & i=0 \\ \left(\frac{\partial\theta_{i-1}}{\partial x_1}\right)\xi_o & i=1 \end{cases} \tag{24}$$

$$\theta_i(0,\tau_1) = \begin{cases} \phi_s & i=0 \\ 0 & i=1 \end{cases}$$

$$\theta_i(\xi_o,\tau_1) = \begin{cases} \phi & i=0 \\ -\xi_i\left(\frac{\partial\theta_{i-1}}{\partial x_1}\right)\xi_o & i=1 \end{cases}$$

$$\frac{-d\xi_i}{d\tau_1} = \begin{cases} \left(\frac{\partial\theta_i}{\partial x_1}\right)\xi_o & i=0 \\ \xi_i\left(\frac{\partial^2\theta_{i-1}}{\partial\xi_1^2}\right)\xi_o + \left(\frac{\partial\theta_i}{\partial\xi_1}\right)\xi_o & i=1 \end{cases}$$

$$\xi_i(0) = \begin{cases} 1 & i=0 \\ 0 & i=1 \end{cases}$$

The zeroth solution is the quasi-steady approximation. Pedroso and Domoto (1973a) also demonstrated this for a spherical system.

Huang and Shih (1975), introduced a useful concept for perturbation methods. They replaced the time variable τ by $\xi(\tau)$, the phase change interface position. This transformation is acceptable if ξ is a monotonic function of τ, a common relation for many practical problems.

An advantage of this procedure is that it is no longer necessary to expand the unknown functions about ξ_o when considering the conditions at the change interface. This greatly simplifies the formulation of the equations but the solutions are not necessarily simpler.

The Stefan Problem

As an example of the quasi-steady method consider the Stefan problem. The solution mentioned earlier, Eq. (15), was based on the assumption that the Stefan number is small which is equivalent to the quasi-steady approximation. The quasi-steady freezing problem reduces to

$$\frac{\partial^2 T_1}{\partial x^2} = 0 \tag{25}$$

$$T_1(0,t) = T_s$$

$$T_1(X,t) = T_f$$

$$k_1\frac{\partial T_1(X,t)}{\partial x} = \rho_1 L\frac{dX}{dt}$$

The solution to this system is

$$T_1 = (T_f - T_s)\frac{x}{X} + T_s \tag{26}$$

$$X = \sqrt{\frac{2k_1}{\rho_1 L}\int_o^t [t_f - t_s(t')]\,dt'} \tag{27}$$

The phase change depth X given by Eq. (27) is identical to that of Stefan (1891) who seems to have been the first to use the quasi-steady method.

A major limitation of the quasi-steady approximation is the failure to account for the sensible heat during the phase change. The total surface energy flow, during the time that a layer of thickness X freezes, is simply the latent heat. The method does not take into account any sensible heat although the temperature of the frozen layer does decrease with time. This is in contrast to the Neumann Solution where it can be shown that the heat removed equals the latent heat plus the sensible heat involved in lowering the temperature of the frozen layer. This limitation is directly associated with the assumption of a Stefan number of zero.

The quasi-static and perturbation methods have been used for plane systems by Pedroso and Domoto (1973), Seeniraj and Bose (1982), Lock (1969), Seban (1971), Huang and Shih (1975), London and Seban (1943), Foss and Fan (1974, 1972), Lunardini (1978, 1978a), Gutman (1986), and Citron (1960, 1962).

Cylindrical and spherical geometries have been considered by Carslaw and Jaeger (1959), Khakimov (1957), Hwang (1977), Lunardini (1983, 1981c), Seshradi and Krishnayya (1980), Thornton (1976), Riley et al. (1974a), Asfar (1979), Jiji and Weinbaum (1978), Pedroso and Domoto (1973), Hill and Kucera (1983), Gupta (1973), and London and Seban (1943).

THE HEAT BALANCE INTEGRAL METHOD

An approximate method which has been used with good results for phase change problems involves the concept of the temperature penetration depth. The integral method, introduced by Goodman (1958), is based on the same concepts as the boundary layer momentum integral method in fluid mechanics (Pohlhausen 1921), (von Karman 1921). Consider a semi-infinite solid. At a time t, after the surface temperature has dropped to T_s, the temperature in the solid will be disturbed to a depth $\delta(t)$. Beyond this depth, the temperature of the solid remains at the initial temperature T_o and no energy is transferred. The penetration distance δ is analogous to the boundary layer thickness in fluid mechanics nd the basic equations are satisfied on average over the volume of thickness $\delta(t)$, rather than at each point.

Phase Change Integral Equations

Examine the case of phase change where the properties of the frozen region differ from those of the thawed region. There will then be two integral equations as follows, Lunardini (1981a)

$$\frac{d}{dt}\int_o^X T_1\ (x,t)\,dx - T_f\frac{dX}{dt} - \alpha_1\left[\frac{\partial T_1\ (X,t)}{\partial x} - \frac{\partial T_1\ (0,t)}{\partial x}\right] = 0 \qquad (28)$$

$$\frac{d}{dt}\int_X^\delta T_2\ (x,t)dx - T_o\frac{d\delta}{dt} + T_f\frac{dX}{dt} + \alpha_2\frac{\partial T_2\ (X,t)}{\partial x} = 0 \qquad (29)$$

The solution of a general problem with superheat or subcooling (the initial temperature not at the freezing temperature) will involve two coupled parameters X and δ. The derivation of the method and some applications have been described by Goodman (1958, 1964).

The Stefan Problem

As an example, the Stefan problem will again be examined. The heat balance integral reduces to only one equation since a single phase is present

$$\frac{d}{dt}\int_o^X T_1\,dx = \alpha_1\left[\frac{\partial T_1\ (X,t)}{\partial x} - \frac{\partial T_1\ (0,t)}{\partial x}\right] + T_f\frac{dX}{dt} \qquad (30)$$

The boundary conditions are

$$T_1(X,t) = T_f$$
$$T_1(0,t) = T_s$$

$$k_1\frac{\partial T_1(X,t)}{\partial x} = \rho_1 L\frac{dX}{dt}$$

If T_1 is assumed to be a quadratic function of x then the equation for X is

$$X\frac{dX}{dt}6\alpha_1\left(\frac{1-\sqrt{1+2\,S_T}+2\,S_T}{5+2\,S_T+\sqrt{1+2\,S_T}}\right) \qquad (31)$$

The solution is then

$$X = \sqrt{3}\left(\frac{1-\sqrt{1+2\,S_T}+2\,S_T}{5+2\,S_T+\sqrt{1+2\,S_T}}\right)^{1/2} 2\sqrt{\alpha_1 t} \qquad (32)$$

The solution is in the same form as the exact solution for the Neumann problem. The Stefan solution, Eq. (15), can also be put into this form

$$X = 1/2\ \sqrt{2S_T}\ \ 2\sqrt{\alpha_1 t} \qquad (33)$$

The exact, quasi-steady, and heat balance integral solutions can be compared for a specific case. For $T_f - T_s = 5°C$, using the properties of ice, $S_T = .0292$ and

Value of	Exact	Quasi-Static	Integral Method
γ	.124	.1208	.1207

The integral solution is virtually identical to the much simpler quasi-steady solution but the integral solution is not limited to small Stefan numbers.

In general, the accuracy of the approximate, heat balance integral solution can be improved by using higher order temperature profiles, however, the algebraic work also increases. Unfortunately the accuracy may decrease when a polynomial above a certain order is chosen. The convergence of the method for a given situation is unpredictable, as has been discussed by Langford (1973).

Extension of Heat Balance Integral Method

The problem of the proper approximation to use for the assumed temperature profile can be eased with a refinement to the heat balance integral method suggested by Noble (1975) and carried out by Bell (1978). Instead of following only the phase change and initial temperature penetration depths, any number of isotherms can be followed by writing the heat balance integral for an arbitrary number of regions.

Bell (1978) showed that the error can be reduced for two sub-divisions and Bell (1979, 1982) also noted that calculations suggested that the approximate solution asymptotically approached the exact solution as the number of intervals increased. The refinement described here can reduce the errors on the heat balance integral method, but it also tends to negate the simplicity of the method. For more than two sub-divisions or for more complicated boundary conditions it is likely that numerical solution of the set of simultaneous differential equation will be required.

Bell and Abbas (1985) used a sub-division of the penetration depth and solved for the temperatures at each sub-division. They proved that the solution converges to the exact value, at least for a simple problem (without phase change).

The usual heat balance integral equations for two-phase problems, equations (28, 29) are coupled and the solution can be difficult. A slight variation of the heat balance integral method can be used to find an explicit functional relation between δ and X following Lunardini (1983a). This will uncouple the equations and simplify the solution.

The overall energy balance for the entire volume of interest is

$$\frac{d}{dt}\Big[\rho_1 c12 \int_0^X T_1 dx + \rho_2 c_2 \int_X^\delta T_2\, dx + \rho_1 LX + (\rho_2 c_2 - \rho_1 c_1)\, T_f X - \rho_2 c_2 T_o(X+\delta)\Big] = -k_1 \frac{\partial T_1(0,t)}{dx} \qquad (34)$$

The heat balance integral method has been applied to plane geometries by Lunardini and Varotta (1981), Lunardini (1981, 1981a, 1982, 1983, 1983a, 1985), Cho and Sunderland (1969, 1981), Yuen (1980), Goodman (1958), Altman (1961), and Tien and Geiger (1967).

Cylindrical and spherical systems have been treated by Bell (1979), Goodling and Khadar (1975), Poots (1962), and Lunardini (1980, 1981, 1981b).

NOMENCLATURE

A .... area
c_p, c_v .... specific heat at constant pressure, constant volume
C .... heat capacity per unit volume
D .... dissipation (thermal) function
$D_{\psi v}$, $D_{\psi L}$, D_{Tv}, D_{TL}
.... diffusion coefficients
h_r.................. radiation coefficient
h_c .... coefficient of convection
h_i.................. specific enthalpy of ith component in porous body
I .... source/sink of component in porous body
j_i.................. mass flux rate of ith component of porous body
k.................. thermal conductivity
$\bar{\bar{k}}$.................. thermal conductivity tensor
K_L................ hydraulic conductivity
L .... latent heat of fusion
m_i................. mass per unit volume of ith component of porous system
p.................. pressure
q.................. heat transfer rate
q_g, q_f, q_r...... generated, frictional, and radiant energy per unit volume, per unit time
r .... radial coordinate
$\underline{s}$ .... velocity relative to x, u, z frame
$S_T = \frac{c}{L}(T_s - T_f)$
.... Stefan number
t.................... time
T .... temperature
T_o, T_f, T_s ..... initial, fusion, and surface temperatures
x, y, z .... cartesian coordinates
x_1.................. x/X_o
X .... phase change depth
α .... thermal diffusivity
β.................. coefficient of thermal expansion - $1/\rho(\partial\rho/\partial T)p$
γ.................. Neumann parameter

δ..................thermal disturbance depth or radius

η..................x/X

$\theta - \dfrac{T - T_o}{T_s - T_f}$ .. Temperature

$\xi = X/X_o$

μ..................viscosity

ρ..................density

$\tau = \alpha t/X_o^2$

$\tau_1 = \dfrac{\alpha t S_T}{X^2_o}$

$\phi = \dfrac{T_f - T_o}{T_s - T_f}$

ϕ_f..................frictional dissipation function

$\phi_s = \dfrac{T_s - T_o}{T_s - T_f}$

ψ..................moisture content

ψ_i..................bound component

Subscripts

L..................liquid

v..................vapor

w..................water

1,2................thawed and frozen regions

0, 1, 2, 3, 4... solid, vapor, liquid, ice, air components in porous medium

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NOTES ON NORWEGIAN ARCTIC ROAD CONSTRUCTION TECHNIQUES

by

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INTRODUCTION

Development in the Arctic or Subarctic, or anywhere else for that matter, must include some sort of transportation system. We are familiar with the route to the Klondike, the trails to the Interior of Alaska and riverboat traffic on the Yukon and Tanana. Road construction in the North is faced with special problems. Not only does the annual spring break-up cause grief, but there are additional problems when a road encounters perennially frozen ground, permafrost.

Permafrost was both a help and a hindrance to the early placer miners. The presence of frozen ground made drift mining of deep placer deposits possible, while in some areas surface disturbance could turn the foundation for access roads or railroads into bottomless bogs. Historical photographs showing these conditions are available through the Alaska and Polar Regions Department, Elmer E. Rasmuson Library, University of Alaska Fairbanks.

NORWAY AND SVALBARD

Norway is usually considered to be south of the true permafrost regions. Sporadic permafrost is present in Alpine regions and in parts of the interior of North Norway. On trips to this region, I have observed both patterned ground and palsas. Under certain circumstances, ice created during the winter may not totally melt the following summer. This was a problem at the Bidjovagge Copper Mine in Finnmark. The water in the mill tailings pond froze during the winter and all of the ice did not melt during the short summer giving rise to a tailings disposal problem.

True or continuous permafrost conditions are found on the Norwegian Arctic Archipelago, Svalbard, also called Spitsbergen. The island group lies north of Norway and covers the area from about 76° to 81° N and between 10° and 30° E. The islands have an area of 62,700 km^2 and form 16 percent of Norway's total territory. Norway proper lies in about the same latitudes as Alaska, but is one fifth the size.

Mine #1 Longyearbyen. Built by John Longyear

Dr. Nils Johansen, Associate Professor of Geological Engineering, University of Alaska Fairbanks, is a registered professional engineer in Indiana and Alaska. Dr. Donald F. Lynch, Professor of Geography, University of Alaska Fairbanks, has travelled with Dr. Johansen to Northern Scandinavia to study resource development. Dr. Mritunjoy Sengupta, Associate Professor of Mining Engineering at the University of Alaska Fairbanks, is a registered professional engineer in Alaska, Colorado, Idaho, and New Mexico and is involved in research on Arctic mining operations. Photocredits: Dr. Donald F. Lynch.

Whalers used the islands in the 18 and 19th centuries, but because of harsh climates, they established no permanent settlements. This picture changed in the 20th century when coal-mining became a reality. The island of West Spitsbergen has large Mesozoic coal deposits. These were originally explored by Mr. John Longyear, an American, and also by Swedish, Norwegian, Dutch and Russian interests. Mr. Longyear's mining activities in Advent Valley eventually lead to a permanent settlement there, Longyearbyen. Soviet mining activities support permanent settlements at Barentsburg and Pyramiden. Today, the Norwegian mining company, Store Norske Spitsbergen Kulkompani A/S, and government offices are located in Longyearbyen. The airport was completed in 1974. The city is served by air year round. Earlier the only connection with the outside world was by ship, and, because of ice conditions, shipping was not feasible for part of the winter.

Tourism is a small, but potentially growing facet of the development of Svalbard. At the present time some 800-1200 people visit the islands annually. There are no accommodations on land. Tourists come either off the cruise ships and return or they have to pack their own provisions. A ban on snow machine operations is being considered because of wildlife disturbance as well as general environmental degradation. The Norwegian government publishes separate regulations for Svalbard in the effort to protect this Arctic wilderness.

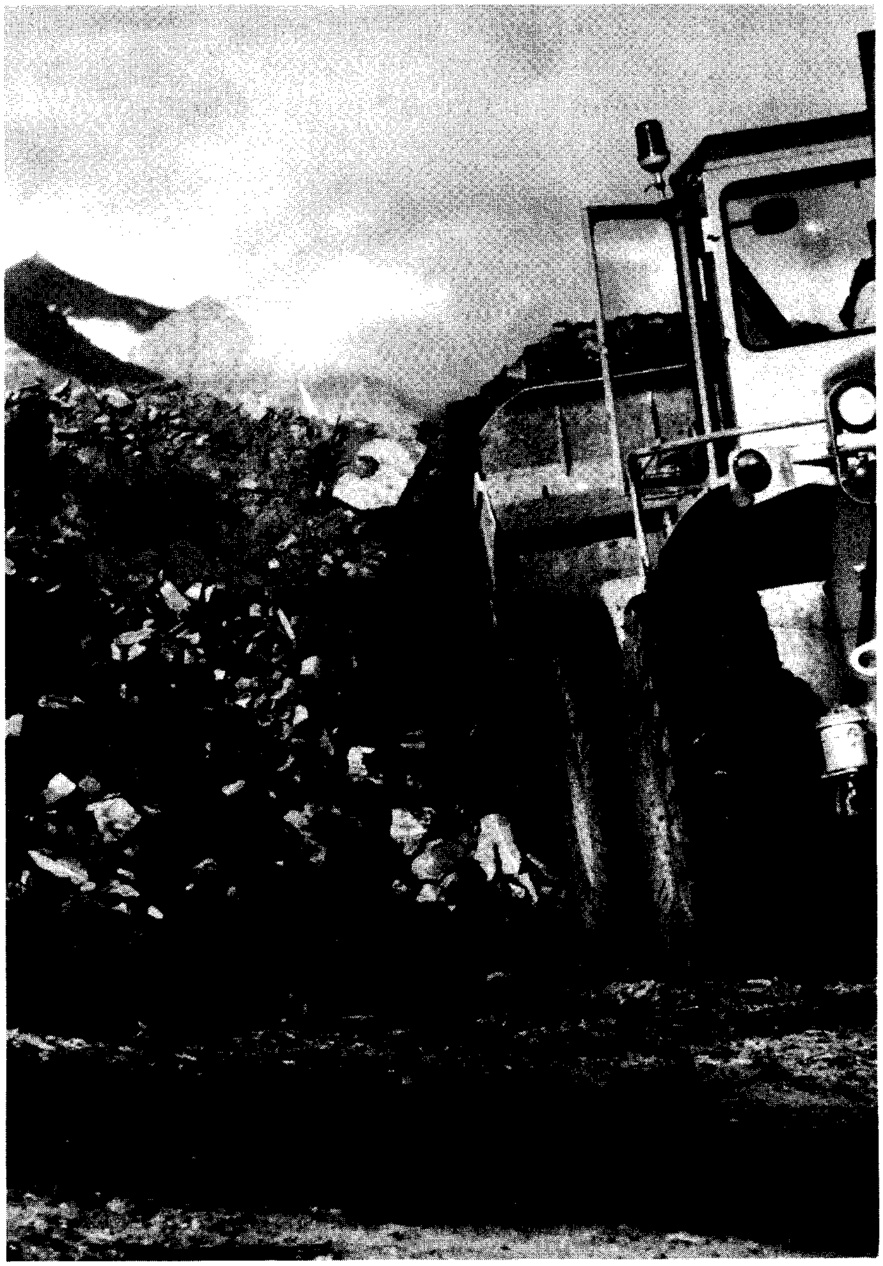
Stakes showing design height for road fill in Svea built on permafrost

SVALBARD ROAD DESIGN CRITERIA

Settlements on Svalbard have historically been linked to the sea. Ships served the communities, whether these were temporary or reasonably permanent. Essentially no effort was made to develop overland connections between the settlements. In Advent Valley a road system has been built to serve the mines. Similar developments have taken place in Barentsburg and in Svea. In Svea a water reservoir has been constructed along with an access road from the fjord to the mine. The mine has the potential of being a major coal producer; however, the coal chemistry has created marketing problems. In 1988 the project is again dormant. A harbor (loading facility) in this area has been designed and the design criteria were discussed by Gregersen (1987). Construction however will have to await the commencement of the mining operations.

The overland distance from Svea to Longyearbyen is short. Plans have been made for a 66 km road connecting the two mining operations, but with the Svea operations suspended, the road is a low priority item. The road was projected to cost Nkr. 13 million in 1978 (about U.S. $1.625 million or $39,600 per mile) and includes a 2 km tunnel, 2 bridges and necessary culverts. If the cost estimates are correct, they indeed reflect a low-cost road. In talking with Norwegian engineers familiar with Svalbard, there was a recurring theme that road construction is actually cheaper on Svalbard than in Norway. The reasons may be found in examining the road design criteria used on Svalbard. Road design on Svalbard is discussed by Mellerud (1980) and tunneling by Sondbø and Orheim (1987).

The typical cross section of the road consists of a gravel fill within a minimum thickness of 1.20 m (about 4 ft) supporting a 20 cm+ base and pavement structure. The roads are placed directly on the ground without use of insulation. This design will actually raise the permafrost table to within the fill itself thus creating a stable foundation for the road. The elevation of the roadbed will also assure that it is kept free from drifting snow (at least in theory) and thus reduce the need for snow removal. Exposing the bare windswept road surface to the winter climate will also contribute to a deeper freeze in the winter and a stable (frozen) subgrade in the summer. Gravel is abundant in the area and is readily removed and placed in the embankment. This contributes to the relatively low cost. In North Norway, similar gravel sources may not be available, and the construction costs are for this reason higher.



Svea gravel removal from thawed permafrost

Culverts for cross drainage are placed where needed and may be covered up to keep snow from entering during the winter and then uncovered and thawed in the spring as part of routine maintenance. This also avoids the build-up of melt water on the uphill side of the road embankment if the culvert remains filled with ice. The presence of standing water also accelerates melting and may create additional stability problems from an increase in pore pressure.

ROAD INSULATION AND SOFT SOIL

The Norwegian Road Research Laboratory has created a method constructing road fills out of expanded polystyrene plastic for use in soft soil conditions. Norwegians discovered that frost insulation in roads did not deform under normal traffic load, and considered laying down a 3 foot, rather than 3 inch, layer of insulation. In so doing, they developed a successful way to cross soft soil. The weight of the road has been greatly reduced, but the pavement structure can still tolerate the heavy axle loads encountered in normal traffic. The concept was the subject of a one day meeting in 1985 and the development was summarized by Frydenlund (1985). This construction method has proved effective and Norwegian highway engineers have been using it for over ten years. The method is not cheap, but is often cheaper than many alternatives in crossing soft soils. The thick insulation is an added bonus in discontinuous permafrost.

Today's roads in the Arctic regions typically have layers of insulation incorporated in the fill. A road construction sequence for a road in the high Arctic would typically consist of scalping or leveling of the tundra during the wintertime to maintain frozen conditions followed by the placement of insulation and then a layer of gravel making up the roadbed. The insulation thickness and gravel thickness depend on the climatic conditions and the axle load anticipated on the road. The system is quite effective. The permafrost is not allowed to melt under the road, insulation keeps the soil cold, and the roadbed has a solid foundation. A similar construction method is used elsewhere in the north, south of the permafrost regions, but the purpose of insulation is now to keep the soil warm under the road so ice lens development during the winter and subsequent spring break-up problems are greatly reduced or eliminated.

It would, however, be premature to state that we have reached the end in arctic road design. Problems that still need to be addressed include a better method for construction in the arctic during the summer season. In flat areas, and Alaska's North Slope is a good example, present day road construction methods create what amounts to low dams across the tundra. Low water crossings help, but a possibly better solution could be to develop a permeable road bed that would permit cross drainage, be suitable for summer construction, support heavy (more than 10 ton) axle loads and maintain the underlying permafrost.

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Mellerud, Ole Th. Juni 1980. "Permafrost og byggearbeider pa Svalbard." Frost i jord. pp. 39-43.

Frydenlund, Tor Erik. June 25, 1985. "Plastic Foam in Road Embankments" Proceedings. Plastic Foam in Road Embankment. Oslo, Norway.

Gregersen, Odd. Des 1987. "Foundation design on Permafrost." Frost i jord. pp.33-42, Nr. 26.

Sondbø, Lasse and Orheim, Alv. Des 1987. "Experiences from tunneling in Svalbard." Frost i jord. pp.43-49, Nr. 26.

NOTE ON THE REFERENCES

Veglaboratoriet, The Norwegian Road Research Laboratory in Oslo, Norway publishes bulletins, many of which are in English. The publication Frost i jord is published by the Norwegian Committee on Permafrost and is available through the Norwegian Geotechnical Institute in Oslo or through the Road Research Laboratory, Postboks 6390 Etterstad, N-0604 Oslo 6, Norway.

BOOK REVIEW

• PIPELINES AND PERMAFROST
by Peter J. Williams
Carleton University Press, 1986

When one starts to talk about pipelines in the North, one is immediately overwhelmed by the cost, environmental concerns and technical problems. Professor Williams, in 1979, tried to address these issues in the first printing of Pipelines and Permafrost. Seven years later, he has republished this book, with a sprinkling of new material here and there plus one completely new chapter.

The original book started with an introductory chapter on why our society needs pipelines and a cursory overview of early pipelines as they grew in size. This blends into a discussion of cold regions and special terrain problems. Chapter two expands the topic of terrain in cold regions. Included are a few informative pictures and the material presented is not that technical. The following chapter presents a brief summary of engineering geotechnical practices in the North from before World War II until the present; a discussion of scientific contributions is also presented. This is followed by a case study of the trans-Alaska oil pipeline. The next three chapters deal with gas pipelines and the engineering problem of frost heave, the Alaska Highway pipeline, Russian pipelines, and the Norman Wells pipeline. Special emphasis is given to the problem of frost heave, including a heave test on a buried pipeline in France. The final chapter is a look into the future of pipelines in cold regions and scientific problems of frozen soils.

While there are many technological needs in cold regions, the resources to attack these problems are only made available when large projects like pipelines come along. Professor Williams highlights the geotechnical problems associated with warm and chilled pipelines. While it is evident that hydrocarbon resources exist in large qualities in the North, the transportation of these resources to the market is precluded by economics. Both the remoteness from the marketplace and the increased cost associated with geotechnical obstacles are responsible for the shelving of many proposed pipelines.

Professor Williams has tried to make a case for the need for long-term scientific research in the North, research not necessarily driven by present needs, and research done by unbiased institutions where it will be published in a timely manner. He has reflected back on the history of existing, as well as proposed pipelines, to add credence to his arguments in regards to geotechnical problems of freezing and thawing soils.

Pipelines and Permafrost is an excellent introductory book on the interaction of pipelines, society and science (the science being exclusively geotechnical). Students, engineers and scientists who have limited experience with frozen soils, and decision makers from both the public and private sectors should find this book very enlightening.

• by Douglas L. Kane
Professor of Water Resources and Civil Engineering University of Alaska Fairbanks

BACK OF THE BOOK

MEETINGS

10th Canadian Waste Management Conference ~ Winnipeg, Manitoba ~ October 25 - 27, 1988

This national conference provides an annual forum for the exchange of scientific and technical information on the management of solid and hazardous wastes. Papers will address topics related to: Legislation and Regulations; Municipal Waste Incineration; Waste Management Options; Waste Minimization; International Perspectives; and Identification of Residues and Clean-up.

For More Information Contact:
Stephanie Hunt; Seminar Coordinator; Technology Development and Technical Services Branch; Conservation and Protection; Environment Canada; Hull, Quebec K1A 0H3; (819) 953-5363.

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Second Biannual Conference on Optimizing Concrete Mixtures to Satisfy Modern Engineering, Construction, Durability and Economics Needs ~ Dallas/Ft. Worth, Texas ~ December 12 &13, 1988

The conference, sponsored by the concrete consulting firm of Shilstone & Associates, Inc., Dallas, TX, will address new approaches to concrete mix selection and management during construction.

For More Information Contact:
Shilstone & Associates, Inc.; 8577 Manderville Lane; Dallas, TX 75231; (214) 361-9681.

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12th Energy-sources Technology Conference & Exhibition ~ Houston, Texas ~ January 22 - 25, 1989

This ASME sponsored conference will contain symposiums on: Drilling & Production; Offshore & Arctic Operations; Hydrocarbon Processing; Ocean Engineering; Internal Combustion Engines; Pipeline Engineering; Synfuels & Coal Energy; Wind Energy; Fracture Manufacturing; and Management of Energy Projects.

For More Information Contact:
Frank Demarest; ASME; P.O. Box 59489; Dallas, TX 75243; (214) 437-0094.

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International Conference on Municipal Waste Combustion ~ Hollywood, Florida ~ April 11 - 14, 1989

This technology transfer conference, which is being jointly organized by Environment Canada and the U.S. Environmental Protection Agency, will address topics related to municipal waste incineration, highlighting the results of the National Incinerator Testing and Evaluation Program. Sessions will include: Ash Residue Management; Air pollution Control Technologies; Sampling and Analysis; Health Risk Assessment; Regulatory Trends; and Combustion Technologies.

For More Information Contact:
Stephanie Hunt; Seminar Coordinator; Technology Development and Technical Services Branch; Conservation and Protection; Environment Canada; Hull, Quebec K1A 0H3; (819) 953-5363.

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CALL FOR PAPERS ~ **12th Annual Conference on Modeling and Simulation** ~ Pittsburgh, Pennsylvania ~ May 4 & 5, 1989

Emphasis for the 1989 Modeling and Simulation Conference will be Computer Science: artificial intelligence, expert systems, robotics, microprocessors, and personal computer applications and software.

For More Information Contact:
William Vogt or Marlin Mickle; Modeling and Simulation Conference; 348 Benedun Engineering Hall; University of Pittsburgh; Pittsburgh, PA 15261.

NOTED

An index of nearly 1,000 southcentral Alaskan lakes lists historical and current limnological references in a new report published by the U.S. Geological Survey, Dept. of the Interior.

The report, *Index to Limnological Data for Southcentral Lakes*, by Mary A. Maurer and Paul F. Woods, is published as U.S.G.S. Open-File Report 87-529. It can be purchased from the U.S.G.S. Books and Open-File Reports Section; Box 25425; Federal Center; Denver, CO 80225.

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The U.S. District Court for Alaska, in a June 29, 1988 ruling, has declared that the Hooper Bay Agreement of 1984 and the 1985 Yukon-Kuskokwim Delta Goose Management Plan were invalid agreements.

This appears to be the final action in a long-standing legal contest over the U.S. Fish and Wildlife Service enforcement policies relating to subsistence hunting of migratory birds in Alaska, said Walt Stieglitz, Fish and Wildlife Service Regional Director. "I am pleased at long last, to see a resolution of legal questions regarding application of the Migratory Bird Treaty Act to subsistence hunting of migratory birds," he said. "This provides an opportunity for all involved parties to begin working together to more effectively manage the birds about which we are all concerned."

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Dozens of wildfires have scorched more than a quarter of a million acres so far this year in the Yukon Flat National Wildlife Refuge, 100 miles north of Fairbanks, Alaska. And wildlife biologists are glad.

Though the fires may produce occasional smoke problems and sometimes threaten private property, they often benefit wildlife.

"Our research shows that most wildlife moves away from fire, so they aren't usually threatened by it," said Fred Deines, Fire Management Officer for the Yukon Flats Refuge. "Ultimately, the refuge has better habitat to support the wildlife when the fire burns out."

"It takes a lot of planning and coordination, and lots of consultation with other agencies," says Bill Larned, Fire Management Officer for the Kenai National Wildlife Refuge. "With the wrong conditions, a fire can get out of control fast." "Fires can be extremely dangerous," he adds, " so controlled fires take hours of planning and coordination by experts." Although fires on refuges are helping improve conditions for the wildlife residents, officials must keep a close watch to insure that they burn safely and stay in control.

PUBLICATIONS

Engineers, contractors and suppliers who are called upon to evaluate concrete mixture proportions will find the recently announced **seeMIX Jr** IBM PC compatible software to be a comprehensive, state-of-the-art tool which introduces new approaches to an old task. **seeMIX Jr** provides the first quantifiable method to evaluate the performance of concrete mixtures before they are batched.

For More Information Contact:
Shilstone Software Co.; 8577 Manderville Lane; Dallas, TX 75231; (214)361-9681.

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Welch Allyn, Inc. has introduced two new longer length articulation VideoProbes that represent an entirely new technology for articulation in remote visual inspection, Developed for use in Welch Allyn Video-Probe 2000 systems, the new probes extend the benefits of four-way articulation to 1/2" diameter probes up to 100' and allow full articulation range, even when coiled.

The new longer length articulating Video-Probes offer solutions to a range of inspection applications in the power generation, aviation/aerospace, and process industries.

For More Information Contact:
Welch Allyn, Inc.; Video Division; 4341

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