



Ultrasonic emissions in snow
by William Francis St Lawrence

A thesis submitted to the Graduate Faculty in partial fulfillment of the requirements for the degree of
MASTER OF SCIENCE in Earth Science
Montana State University
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A detailed description of the acoustic emission monitoring system is provided and also a detailed circuit description of the signal conditioning unit.

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Date DECEMBER 21, 1972

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Abstract

Burst type acoustic signals have been monitored in snow subjected to various load and deformation histories over a wide range of frequencies. The pattern of the acoustic response is closely related to the particular load or deformation history applied. Examination of the emission pattern suggest a description of the deformation of snow in terms of a structural mechanism. The results of a number of experiments are given and interpreted in terms of their acoustic response.

A detailed description of the acoustic emission monitoring system is provided and also a detailed circuit description of the signal conditioning unit.

INTRODUCTION

A number of different types of acoustic signals which emanate from snow subjected to mechanical loadings have been detected. These signals can be broadly classified into two groups: audible and sub-audible. In terms of audible signals we can cite such examples as the squeaking which can often be heard when walking on snow on a cold day, or the sharp report which accompanies a rapidly propagating crack in the tensile region of a snow slope. Less familiar examples of audible sounds that can be detected in snow are the sound of a collapsing snow pack, and the sound of one layer of snow slipping over an adjacent layer.

The second category, subaudible noise, can be subdivided into frequency related classifications. In one instance the sound is in the audible spectrum, but is of such low intensity that it cannot be detected by the unaided ear. To date we have detected this type of signal only in snow samples subjected to deformation rates which induce a brittle response in the snow. The second type of noise is ultrasonic. This type of acoustic emission has been monitored in snow over a wide range of loadings. It is this kind of emission that will be dealt with in this thesis.

REVIEW OF RELATED LITERATURE

Until recently little attention has been given to second order effects associated with the deformation of materials. In general the production of heat, sound, and in some instances, electrons is either

ignored or only briefly considered. These quantities represent irreversible energy losses associated with material deformation, and in most instances, are not critical in describing a material's rheologic character. It is possible, however, that further consideration of these loss processes may yield a better understanding of the deformation mechanism and state of stress in materials.

Acoustic signals, which emanate from some materials subjected to mechanical or thermal loads, are presently the subject of intensive investigation. The first use of acoustic emissions from stressed materials was in the late 1930's*. At that time researches in the field of rock mechanics became interested in the acoustic activity associated with rockburst phenomena in mines. Acoustic emission techniques until the 1950's were utilized exclusively by researchers in the geologic sciences. In the early 1950's researchers in other fields of material science became interested in acoustic emission technology. In the field of fracture mechanics acoustic emission techniques were used in conjunction with more standard devices to study the initiation of failure. A number of attempts have also been made to characterize various materials in terms of their acoustic response. A major breakthrough was achieved when it was determined that many materials emit stress waves at frequencies in the range from 50KHz to 1.5MHz. A

* Although the study of seismic waves generated during earthquakes dates back 3,000 years this type of emission will not be considered here.

comprehensive survey and state of the art discussion of acoustic emission research can be found in papers by Hardy (1972) and Liptai et al. (1971). In reviewing the literature on acoustic emission technology it becomes clear that in its present state of development this science exists as an empirical form with little or no theoretical basis.

In his paper Liptai et al. (1971) considers a model of an idealized emission source in a polycrystalline material. The model is described by a single spherical grain of material sheared across its diameter, with each hemisphere vibrating at its fundamental frequency. Using this approximate analysis yields values for the expected frequency of an emission of 1MHz to 50MHz. More qualitative descriptions of the source mechanism of acoustic emissions in rock are given by Hardy (1972) and Goodman (1963). In the model they propose, a multiple source mechanism is considered which consists of: (1) the closing of microcracks, (2) relative motion between grains, and (3) twinning, splitting, shearing, and crushing within grains.

Related to the source mechanism of an acoustic event is the frequency spectra of the emission. A method for obtaining the frequency spectra of a typical acoustic event has been described by Liptai et al. (1971) but to date has not been implemented. The difficulty present in attempting to monitor, with good fidelity, an incoming acoustic event is presently limited by the resonant techniques now employed in acoustic emission monitoring systems. Since the acoustic event is of

extremely low amplitude the only way to detect it is by using sensitive transducers. The required sensitivity can be achieved with present day transducers only by using them at their resonant points.

In studying the noise generated in materials under stress it has become common practice to record only the occurrence of a burst of acoustic energy. Burst type emissions are generally recorded in terms of the rate at which they take place or their accumulation with time. These quantities generally show close correlation with load or deformation parameters such as stress, stress rate, strain, or strain rate. Other acoustic parameters which have been subjected to investigation, according to Hardy (1972), are event amplitude, event energy, accumulated energy, and energy rate. Although these parameters would appear to give a good indication of the process operating in the material, this is not the case. The reason for this is many fold, but the main reason for poor characterization in terms of energy parameters is due primarily to the monitoring system.

The energy parameters described are dependent not only on basic system sensitivity and signal to noise ratio, but also on the frequency response of the monitoring system. An emission originating at some point within the specimen and being monitored at its perimeter has a wide frequency band. This has been verified by the fact that emissions have been monitored in the same material at widely varying frequencies. This wide frequency spectrum may have a bandwidth of a

megahertz or more. Superimposed on the primary event signal will be specimen resonances. These resonances take the form of thickness reverberations, end to end reverberations, and spring mass phenomena. Egle and Tatro (1966) have investigated these phenomena in some detail. With these latter complications introduced and considering the frequency response of current monitoring systems, it will probably be some time before energy considerations can be properly examined. Liptai et al. (1971) have hypothesized that an ideal monitoring system should have adequate sensitivity and a flat frequency response over a bandwidth from zero to 100MHz.

Monitoring the occurrence of acoustic emissions in terms of event rate, total number of events, and event location is presently yielding the most meaningful data in applied acoustic emission research. The principles, which guide this data collection, are described by Tatro (1971). In this type of investigation it is of consequence to record only that an acoustic disturbance is taking place and the time of its occurrence.

In the field of snow and ice physics little information on acoustic emissions has been presented in the literature. Gold (1960) has considered the audible cracking associated with samples of polycrystalline ice subjected to various states of stress. In his experiments Gold found that the acoustic activity detected was associated with the formation of visible cracks in the ice. He determined that

in uniaxial compression a stress of 10^4 gm cm^{-2} produced little acoustic activity. When the stress was increased to $1.52 \times 10^4 \text{ gm cm}^{-2}$, the amount of acoustic activity was appreciable during primary creep. For ice subjected to stresses of $1.6 \times 10^4 \text{ gm cm}^{-2}$, the acoustic activity was found to increase with time over the duration of the experiment. In a more recent paper Gold (1966) expanded the scope of his original work to include temperature considerations in the cracking activity of ice.

In terms of field research, two papers reporting acoustic phenomena in ice have been published. Neave and Savage (1970) working on the Athabaska Glacier attempted to determine if slip faulting takes place at depth within a glacier. Using techniques along the lines of classical seismic investigations they found that no evidence of slip faulting could be detected. They did find that ice quakes originating from extensional faults near the surface could be detected. The transducers used in this study were geophones distributed in a three dimensional array. In a recent paper Milne (1972) has investigated tension cracking in sea ice as a source of underice noise. Using remote instrument packages placed on the sea floor, Milne was able to correlate underice noise and thermal cracking at the ice-air interface. He shows that under certain conditions where thermally induced cracks can exist that the underice noise rises in intensity exponentially with an increase of the thermal stress.

In a short note St. Lawrence et al. (1972), using low frequency techniques, determined that snow subjected to certain rates of deformation emitted low frequency burst emissions. It was determined that at rates of deformation which produced brittle failure in snow a definite and reproducible pattern of emissions is observed. The results reported are obtained at one temperature and for one density of snow. In discussing the source mechanism of these emissions it is proposed that the breaking of intercrystalline bonds is the most likely mechanism. This conclusion is based on information presented by Kinoshita (1966).

In reviewing the literature it is apparent that acoustic emission technology has not yet developed to its full potential. It is also apparent that although this science is still in its infancy, it represents a powerful technique when applied to many problems in material science. In the following pages possible applications in snow mechanics will be discussed.

EMISSION CHARACTERISTICS AND POSSIBLE SOURCES

To investigate the nature of ultrasonic emissions in snow, consideration must be given to the possible source of the acoustic event and to the system used for detecting it. Consideration of the acoustic emission monitoring system, and in particular the transducer, is important since information obtained in terms of frequency content, amplitude, and duration of an acoustic event in general reflect system

characteristics. The source disturbances probably bear little resemblance to the signal that is recorded. In defining ultrasonic emissions we are indicating that the transducer used is most sensitive to excitation in the ultrasonic region of the frequency spectrum.

Since the energy release associated with a burst emission is small (an estimate in the neighborhood of 10^{-13} Joules has been suggested by Liptai et al. (1971)), it is customary to monitor the transducer used to detect the acoustic signal in the vicinity of one of its resonance points. This method makes it possible to detect small amplitude signals, but provides little information about the form of the exciting signal. Using this technique limits the information obtained to establishing that a transient disturbance has taken place and that the disturbance has sufficient energy in the region of the transducers resonant frequency to excite the transducer to resonance. A definite advantage in working in the ultrasonic region of the frequency spectrum is that for frequencies above 30 KHz interference from extraneous noise is minimal.

Figure 1 is intended to illustrate the frequency dependence of the emission signal to the characteristics of the transducer. Figure 1a represents the calibration curve of the transducer over a frequency range from 30 KHz to 112 KHz. Note in this figure that the transducer shows a primary resonance peak at 55 KHz with a sensitivity at this frequency of -105 decibels (referenced to one volt per microbar).

A harmonic of this resonance point can also be observed at 110 KHz with the sensitivity at this point being reduced by 18 decibels.

Figure 1b represents a frequency analysis of an acoustic emission that was obtained with this transducer. Note that in general the wave analysis reflects the characteristics of the transducer with the exception of the amplitude at the 110 KHz point. This amplitude variance indicates that the acoustic signal has a higher energy component at the 110 KHz frequency. It should be noted that all other system components exhibited a flat frequency response over the frequency range in question.

As indicated it is difficult to describe in any detail or with any precision the form of the acoustic emission as it originates. The fact that acoustic signals are detected in snow indicates that when snow is subjected to mechanical loadings a non-conservative energy conversion takes place with part of this energy being dissipated in the form of noise.

It is probably correct to assume that acoustic energy represents only a small portion of the total energy dissipated. From oscilloscope and magnetic tape records we can establish that the emission of sound from snow occurs in burst of noise rather than continuously. These bursts take place at intermittent intervals depending on the particular loading applied.

To identify the sources of acoustic emissions in snow, we will

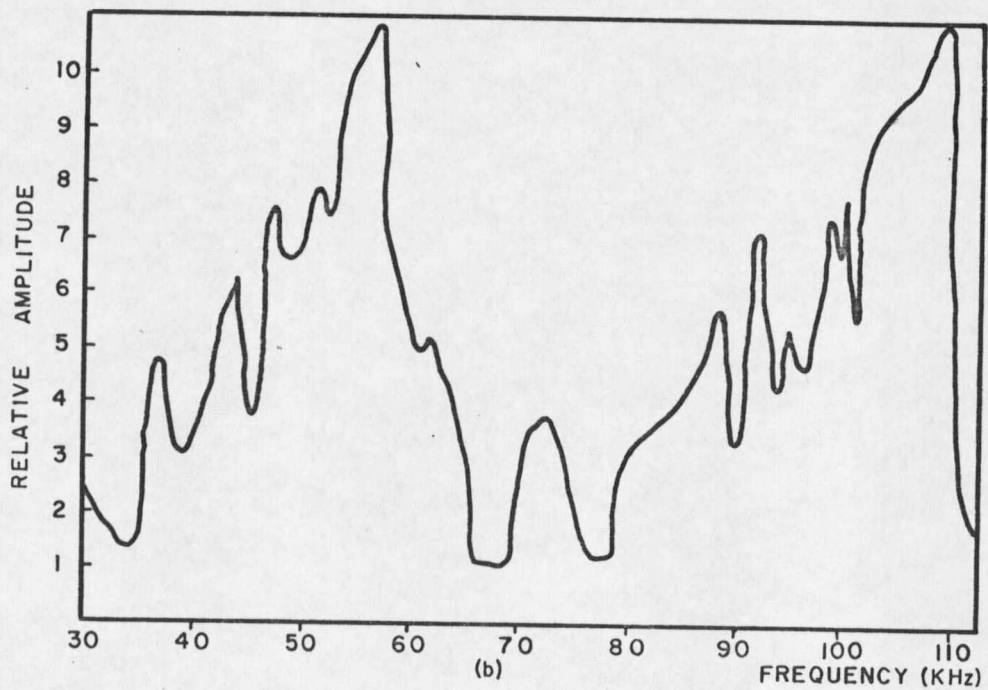
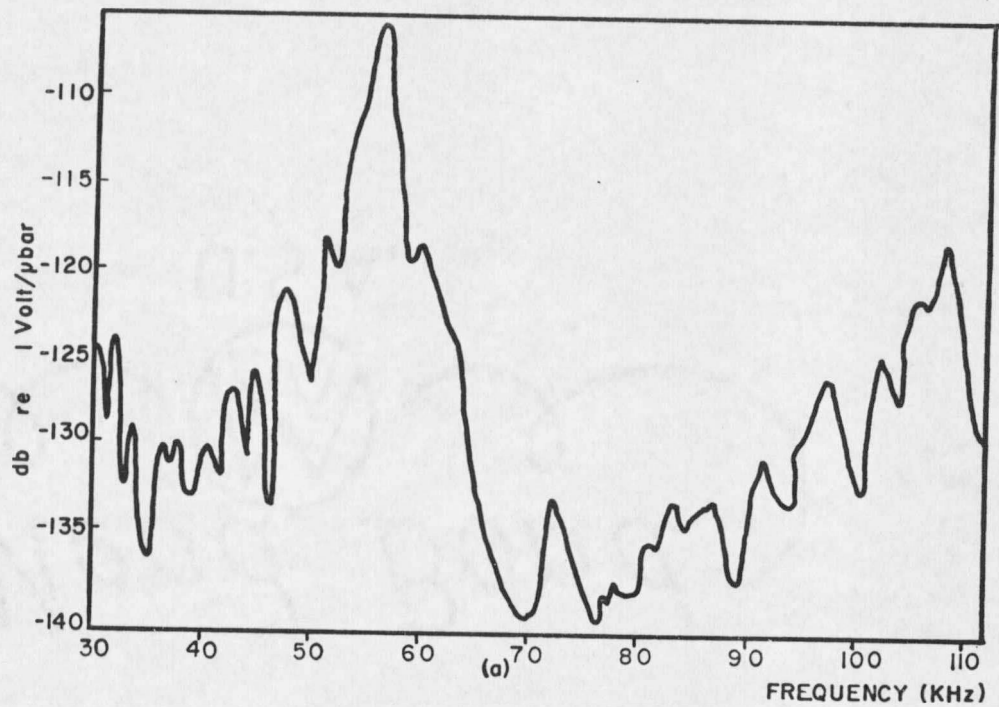


Figure No. 1. (a) Transducer calibration curve. (b) Wave analysis of an acoustic emission from snow.

rely on observations that have been made of the structural changes that take place in snow during the deformation process. From these observations we can tentatively identify possible emission sources. For deformation rates, which produce a brittle response in the snow, Kinoshita (1966) observes that failure is characterized by the breaking of bonds between ice crystals composing the snow matrix. For this type of deformation we detect both ultrasonic and audio signals emanating from the snow. Since Kinoshita indicates that intercrystalline fracture is the only means by which snow deforms at high rates, we are probably correct in assuming that for these rates some form of intergranular movement generates the acoustic signal observed.

For snow that is deformed at rates which produce a plastic response, acoustic emissions may be due to a number of mechanisms. Observations reported by Wakahama (1966) on the compression of snow at slow rates indicate that the structural changes, which take place in the snow matrix, are basal glide, slip at grain boundaries and separation of ice grains. It appears plausible that acoustic emissions can originate from the formation of slip planes in the ice grains and also from the separation of ice grains. In the case of the formation of the slip plane this takes place at a rapid rate in the ice grain. A number of these slip planes forming simultaneously in the ice crystal comprising the snow matrix might produce an acoustic signal at a level that can be detected. If the separation of ice grains takes place in

a rapid manner this may also represent an acoustic source. In the case of slipping at grain boundaries it would appear that this kind of process would not generate sufficient power to produce a detectable acoustic signal. Wakahama (1966) also reports that in addition to these primary mechanisms of grain fracture, void formation and grain boundary migrations are also observed. In considering these mechanisms as possible acoustic sources, it is probable that grain fracture and void formation within grains could generate transient acoustic signals. A number of experiments are now being planned which will attempt to look at each of the above mechanisms as possible emission sources. Brown (1972) is presently considering, on a theoretical basis, the form of the stress wave which might emanate from these mechanisms.

CONSIDERATION OF THE DEFORMATION PROCESS IN SNOW

In the previous section a number of possible sources of acoustic signals in snow were considered without being related in a particular manner to the deformation process. In this section we will examine more carefully observations that have been made of the structural changes that take place in snow undergoing deformation.

Since few investigators have reported in detail on the structural changes which take place in snow, we will rely to a great extent on the observations that have been reported by Yosida (1963). Yosida (1963) gives a detailed account of the structural changes that take

place in thin sections of snow undergoing uniaxial compression. Although he does not state specifically the strain rates at which these observations are made, he does indicate that the rates are in a range which produce a plastic response in the snow sample. An account of Yosida's observations are reviewed in detail here.

Yosida reports that during the initial rise of the force no changes in the ice matrix occur other than small displacements of the ice grains composing the snow. After the yield point is reached it is observed that slip lines are formed parallel to the basal planes of the ice crystals. As deformation continues phenomena such as slip at grain boundaries, separation of ice crystals, migration of grain boundaries, formation of cells in grains, recrystallization, formation of bend planes, cleavage fracture of grains, and nonhomogeneous lattice bending are observed. In studying this description of the deformation process it is of interest to note that two distinct mechanisms operate during the early stages of deformation. It seems that these two mechanisms operate in a sequential manner, the first mechanism being small displacements between ice grains and the second slip on the basal plane of the ice crystals. These two mechanisms are significant in terms of identifying the source of acoustic emissions. Salm (1971) has apparently used this description of the deformation process as the basis of his failure theory for snow.

Salm (1971) has considered the deformation of snow in terms of a three phase mechanism. In the first stage, immediately after loading begins, he considers the stress to be located on "primary elastic lines." In this phase the deformation is considered to be purely elastic with the deformation taking place between ice crystals. In the second stage of deformation Salm (1971) supposes the establishment of "secondary elastic lines." In this phase of the deformation part of the stress, energy is conserved and part of it is dissipated in the form of viscous flow. In the last stage he assumes that the deformation takes place due to purely viscous elements. In his analysis he indicates that for relatively high velocities elastic and visco-elastic elements operate, while at low velocities the deformation is due mainly to the operation of viscous elements. Salm quantifies his model by introducing a nonlinear Burger's body, this model consists of a linear Hookean element in series with a non-Newtonian fluid element, which in turn is connected to a non-Kelvin element. This non-Kelvin element is intended to replace the normal Kelvin element associated with the Burger's body. Salm's formulation is of interest since it represents a first attempt to characterize the mechanical behavior of snow while giving some consideration to the structural changes taking place.

Considering the load deformation character of snow in terms of the observations of Yosida (1963) and the analysis of Salm (1971) and

with information obtained in our own laboratory, it seems appropriate to make the following comments on the specific source of the acoustic activity in snow. It is probable that this phenomena is connected with the small displacements of the ice grains observed by Yosida (1963) during the early stages of deformation. As shown in Figure 2, the maximum rate of acoustic activity takes place during the rapid rise of the load curve. At the point where the stress varies from its initial linear rise (in relatively high rate experiments), we can observe that the emission rate begins to decline. This reduction in the emission rate coincides with the formation of slip bands in the ice crystals. Observation of the emission sequence appears to be consistent with a two phase mechanism during the early stages of deformation. If the motion between ice grains is the source of the acoustic activity in snow, we can hypothesize on the origin of the emission.

In a previous section evidence was presented which indicated that the acoustic activity detected is in the frequency range of 50 KHz to 110 KHz and possibly the primary frequency of the emission is much higher. To generate these frequencies, requires that the energy release takes place over an extremely small time interval; the time interval considered being on the order of microseconds. If the snow is deformed such that the stress between certain grains reaches a critical value, it is possible that the grain will fracture either at the necked portion of the grain or at the grain boundary. Accompanying fracture of

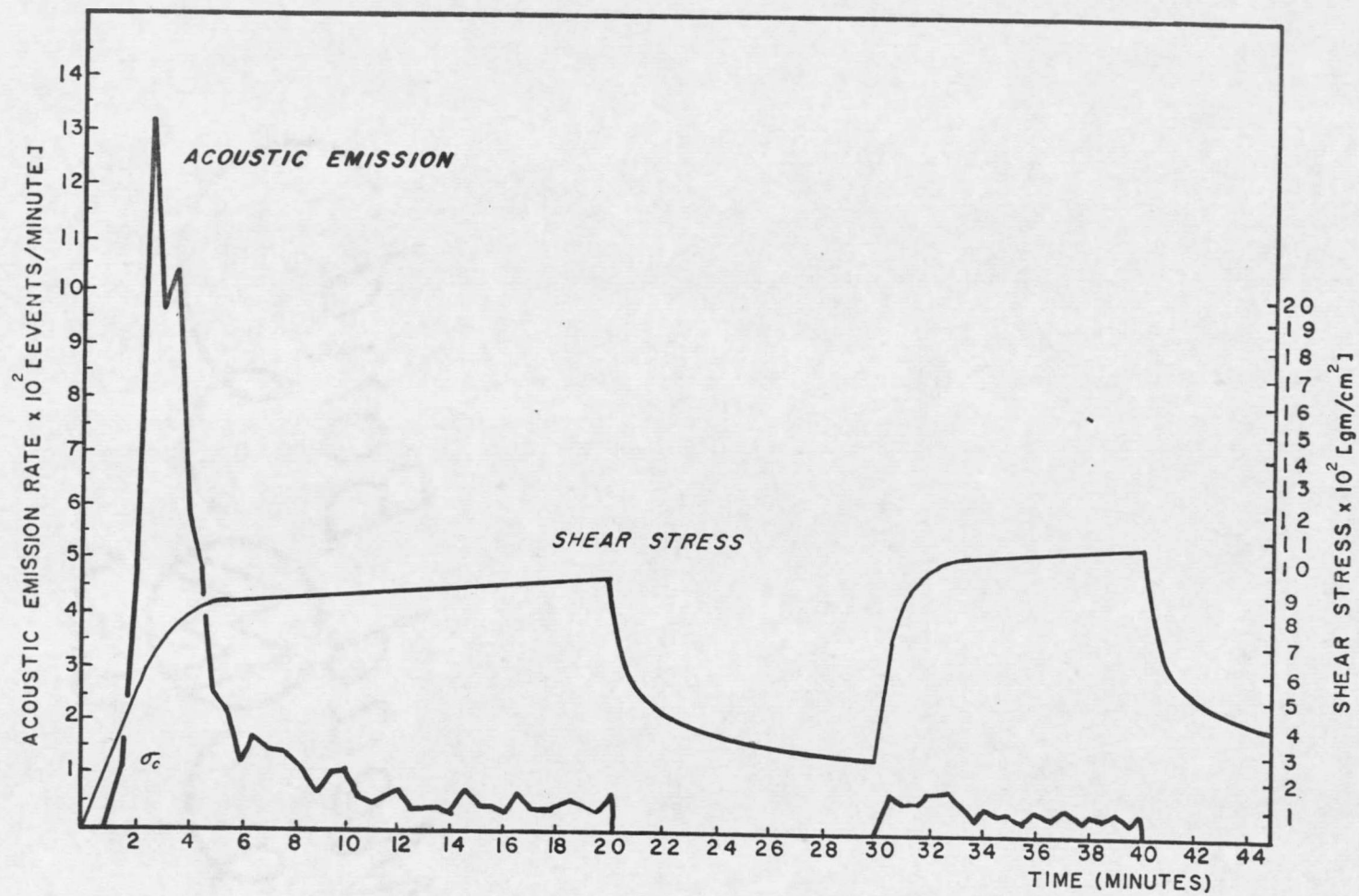


Figure No. 2. Acoustic emission rate response and stress deformation response for snow sample subjected to a constant angular rate of deformation.

the grain should be a rapid release of strain energy which might represent the acoustic source. The fracture process could also act as a means by which locally high stresses are relieved, so that the internal stress tends to approach in the mean the value of the applied stress. Although this is a purely conjectural argument, it fits well with our present understanding of the deformation of snow and the acoustic record.

Although it is not the intent of this thesis to deal specifically with the mechanical characterization of snow, it is felt that the following comments are in order. In dealing with snow we are considering an extremely complex material, which exhibits a varying material response depending on the mode in which it is loaded and also exhibits a high degree of nonlinearity for any given mode. It has been tacitly assumed that for low stress or strain rates that snow may be considered as a linear viscoelastic material. It is of some importance to note that to date no one has established the limits for which the assumptions of linearity are valid.

In establishing a comprehensive material theory for snow the following should be accounted for. When snow is deformed at constant deformation rates in compression, a definite work hardening effect is exhibited. This response has been observed by both Yosida (1963) and Salm (1971). Salm (1971) has determined that this response is a function of strain. For snow that is subjected to constant deformation

rates in uniaxial tension a yield drop is exhibited. Salm (1971) has noted the existence of this yield drop without extensive comment. A comprehensive theory for snow should take into account both of these phenomena.

Due to the difficulty in applying a nonlinear theory in stress analysis, once a comprehensive theory is developed, an attempt should be made to develop an equivalent linear theory for snow. Such a theory should set forth explicit guidelines in terms of the range of loads and deformations over which it applies. Such an equivalent theory has been proposed by Lang.*

EXPERIMENTAL ARRANGEMENT

Snow Specimens

The snow samples used for this research were prepared from naturally deposited snow. The snow was collected from the area of Greyling Pass, Montana, in March, 1972, and stored in a cold room at -10°C until it was used. Blocks of snow were sawed from the snowpack, sealed in large plastic bags, and placed in cardboard cartons for transportation and storage.

Immediately prior to the time of testing the snow was removed from the large containers and placed in a jig for specimen preparation. The jig consisted of a specially designed miter box from which

* Dr. Theodore Lang, Montana State University, Personal Communications

rectangular parallelepipeds were cut. To avoid applying high stress to the snow the blocks of snow were cut by means of a standard twelve tooth crosscut saw. For test in tension or compression the specimens were used in their rectangular form. These specimens were 7 x 7cm on each end and 20cm long. The specimens were cut such that their major axis was normal to the stratification of the snow.

To obtain right circular cylinders which are used for torsion experiments, a slightly different procedure was followed. Rectangular parallelepipeds 9cm on each minor axis were cut from the snow. Each specimen was then placed in a special holding fixture and a hollow steel cylinder was slid over the specimen. Using this method regular cylindrical specimens are obtained without subjecting the snow to high over-stress. The cylindrical specimens used are 6.75cm in diameter and 20cm long. After cutting, all samples are individually sealed in plastic bags until tested.

Mounting of Specimens

In all tests conducted the snow specimens are mounted to the load platens by freezing. For test in tension and torsion this was necessary for application of the load. In the compression mode it is found advisable to freeze the specimens to the load head to eliminate extraneous end noise that might take place due to motion between the snow and the end plates.

To freeze the snow sample to the load platens the following procedure was followed. Each end cap was removed from the test fixture and warmed to a few degrees above freezing and then replaced in the test machine. The snow sample was then placed in position and the end caps allowed to come in contact with the snow. This produced a certain amount of melting at the end of the specimens until the temperature of the end caps dropped below freezing. The melting of the snow sample produced a layer of solid ice approximately 0.6cm thick at each end of the sample.

An important modification that was made to the above procedure involved mounting each of the end caps so that the snow rested on top of them during the freezing process. This procedure was introduced when it was found that a certain amount of melt water percolated through the specimen from the top end cap.

Text Fixture

The experiments that were conducted consisted of uniaxial tension compression creep experiments and constant deformation rate tests in tension, compression, and torsion. To conduct these experiments a special test fixture was designed by Dr. R. L. Brown of the Civil Engineering and Engineering Mechanics Department. For creep experiments the fixture was loaded by means of a dead weight loading system. For constant deformation rate experiments, this fixture was mounted in an Instron Model TDL Universal Test Machine. When the fixture was used

in conjunction with the Instron machine, the load recording capabilities of the Instron was used. When the test fixture is used for creep experiments, crosshead deflection is measured using a linear variable differential transformer.

Acoustic Emission Monitoring System

The system used to monitor the acoustic response of the snow is shown schematically in Figure 3. This system is typical of acoustic emission monitoring systems currently in use and is generally well described in the literature (see Tatro (1971) and Dunegan and Harris (1969)). It is worth considering a special modification necessary when dealing with snow and also the method by which the acoustic signal is conditioned.

Since snow is a soft material, mounting the transducer to the snow poses two special problems. Care must be taken so that spurious stress fields are not set up by having the transducer come in direct contact with the snow. Also, many tests are conducted at relatively high rates and to a large deformation so that it is possible to generate pseudo emissions caused by the relative motion between the specimen and the transducer. Both of these problems are solved by applying a thick coating of silicon grease to the transducer so that it is not in direct contact with the snow sample. :

The acoustic emission system presently employed in our snow research presents the emission data in terms of the total number

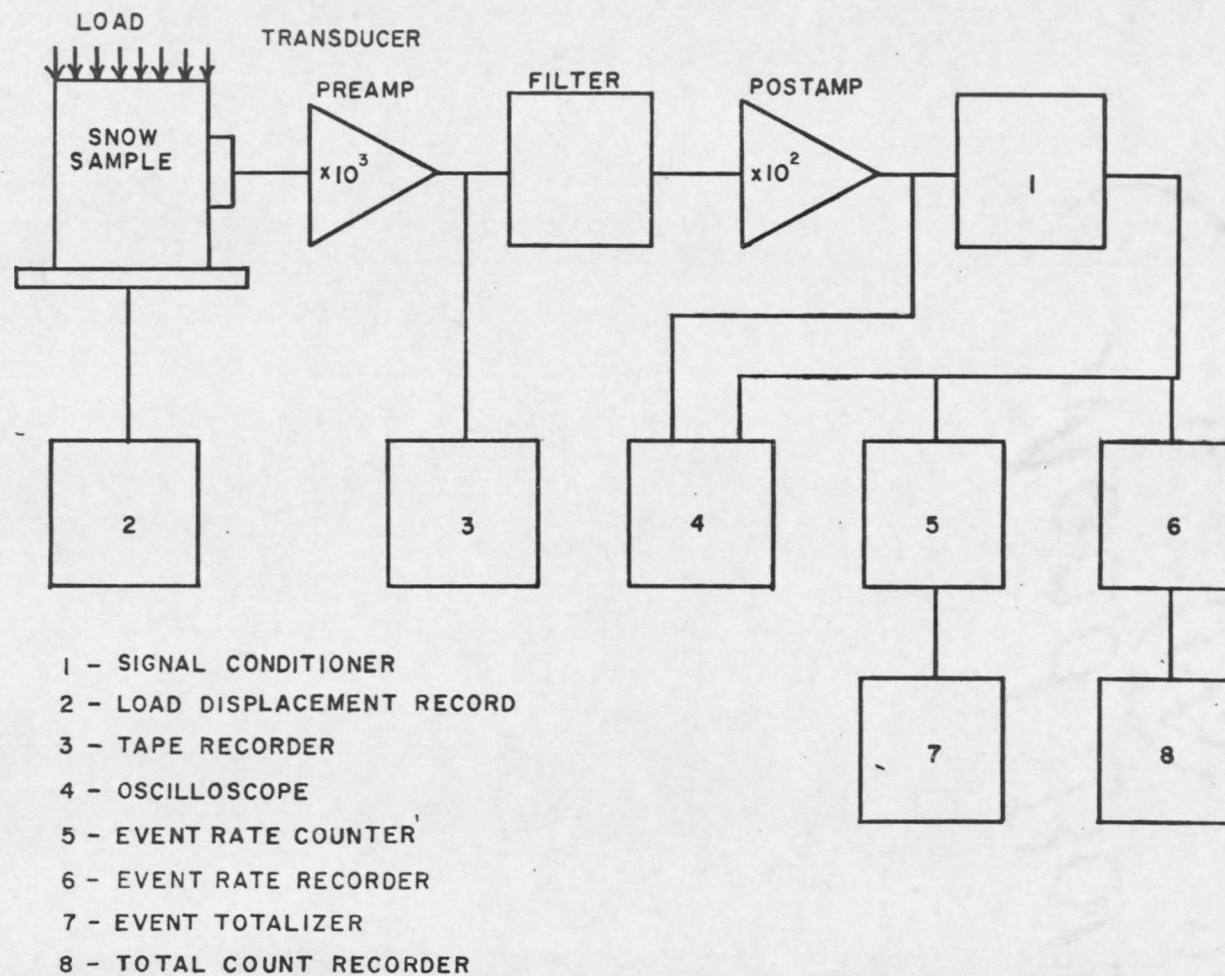


Figure No. 3. Acoustic emission monitoring system for snow.

of events that occur and the rate of occurrence with time. To obtain the data in this form requires a specialized electronic circuit. The function of this circuit is to allow each burst of acoustic energy with an amplitude above a specific level, to be represented in a digital form. The output of the digital counter undergoes a conversion to analogue form and a voltage output proportional to the number of emissions that have taken place is obtained. The circuit used to perform this function is shown in Figure 4. The means by which each burst is represented as one count is critical to the accuracy of the data and will be described in detail here.

As indicated earlier the acoustic emission is detected by means of a resonant technique. In this manner stress waves of extremely small amplitudes impinging on the transducer can be detected. To insure that the signals recorded represent the desired signal and not extraneous background noise a threshold limit is set below which no signal is recorded. Although this technique allows some low amplitude emissions to pass without detection it is necessary in terms of a method of discriminating against background noise. The threshold value that is used varies with the specific acoustic emission system employed and the background noise level. The detection level that is used for the present experimental work is 3.5 times the noise level.

The electronic response of the transducer to an acoustic burst may be represented as a damped oscillation with a complex frequency

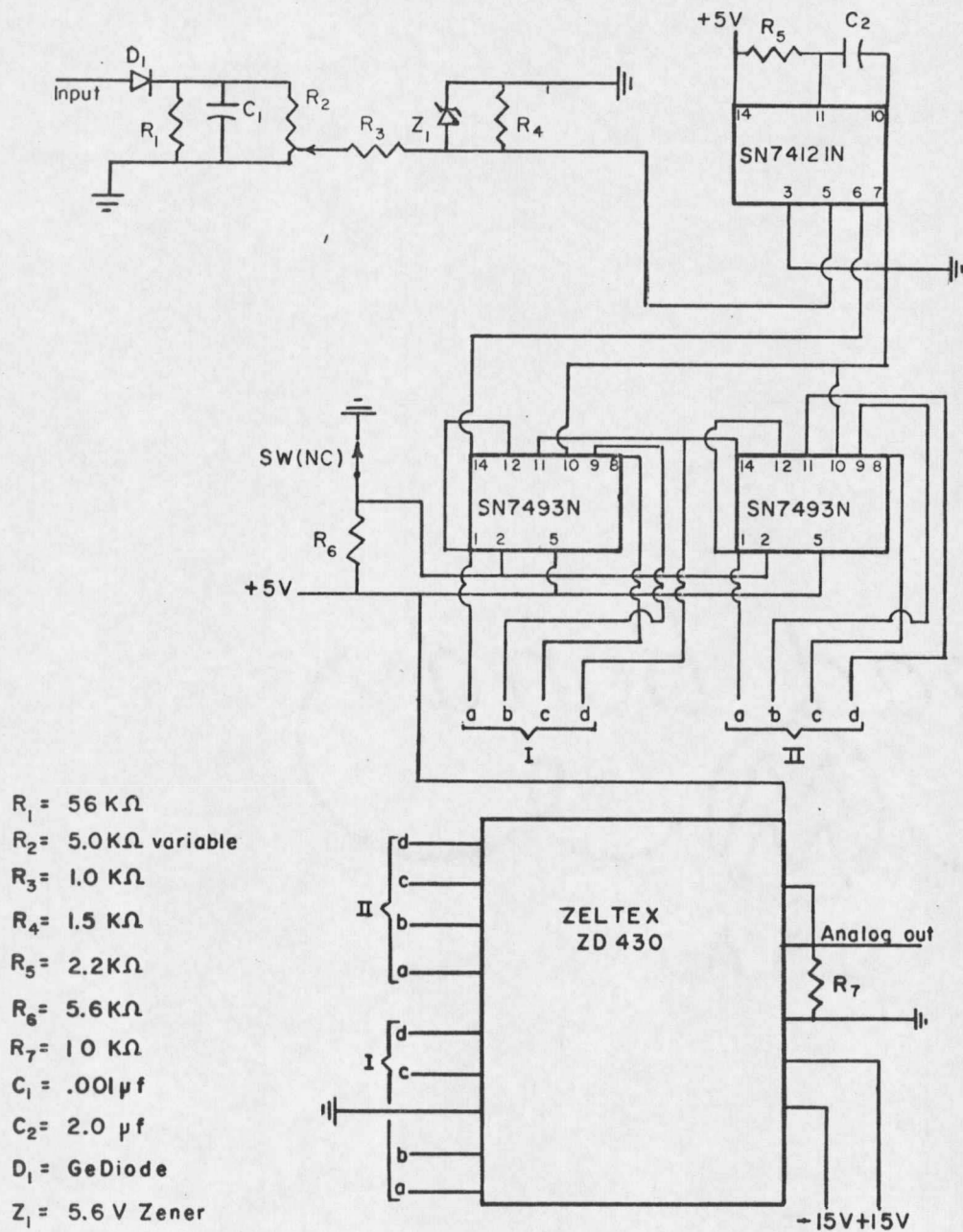


Figure No. 4. Schematic diagram of circuit for signal conditioning unit

distribution. The amplitude and duration of this signal dependent on the energy associated with the exciting stress wave. The incoming electronic pulse, if it is above the threshold detection level, is first rectified and the rectified electronic wave is then used to trigger a monostable multivibrator (one shot). This pulse is then used to trigger the counting circuit. This seemingly over-complex system is required to insure that an incoming emission is represented as only one count. Figure 5 is intended to illustrate the process for conditioning the acoustic emission.

EXPERIMENTAL RESULTS

In order to establish baseline data on acoustic emissions in snow, we conducted a series of experiments in which a number of load and deformations were applied. These experiments consisted of constant rate tests in tension, compression, and torsion and creep tests in tension and compression.

Figure 2 depicts a typical emission response curve (rate of emission vs. time) for a sample of snow subjected to a constant rate of deformation. The stress time curve for this test is also shown. The snow in this experiment was deformed at a constant angular rate of 2.2 degrees per minute (0.12 degrees per minute per centimeter of length) for 20 minutes and allowed to relax for ten minutes. At the end of the ten minute relaxation period the specimen was then reloaded at the same rate. The results obtained when the specimen was reloaded

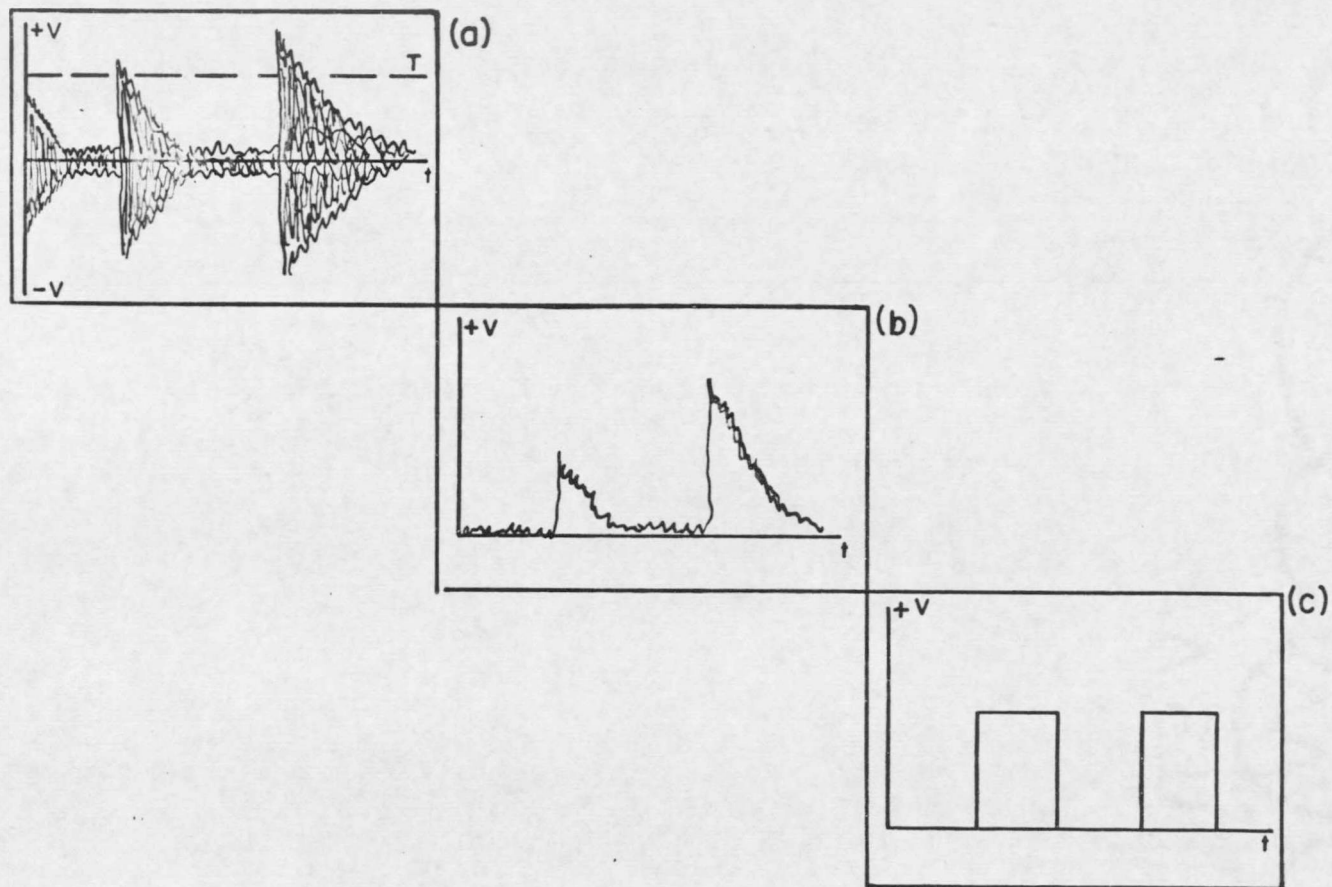


Figure No. 5. Illustrative diagram of steps used to condition the acoustic signal
 (a) Typical burst emission. (b) Discriminated and rectified signal. (c) Triggered pulse for counting.

are also shown. The stress response curve is for the shear stress calculated at the specimen's outer radius. The acoustic response depicted here is typical of the results obtained for snow subject to constant deformation rates, with variations being observed depending on the rate and mode of deformation (tension, compression or torsion). Figure 2 will serve to point out the salient features of the emission response for this type of load history.

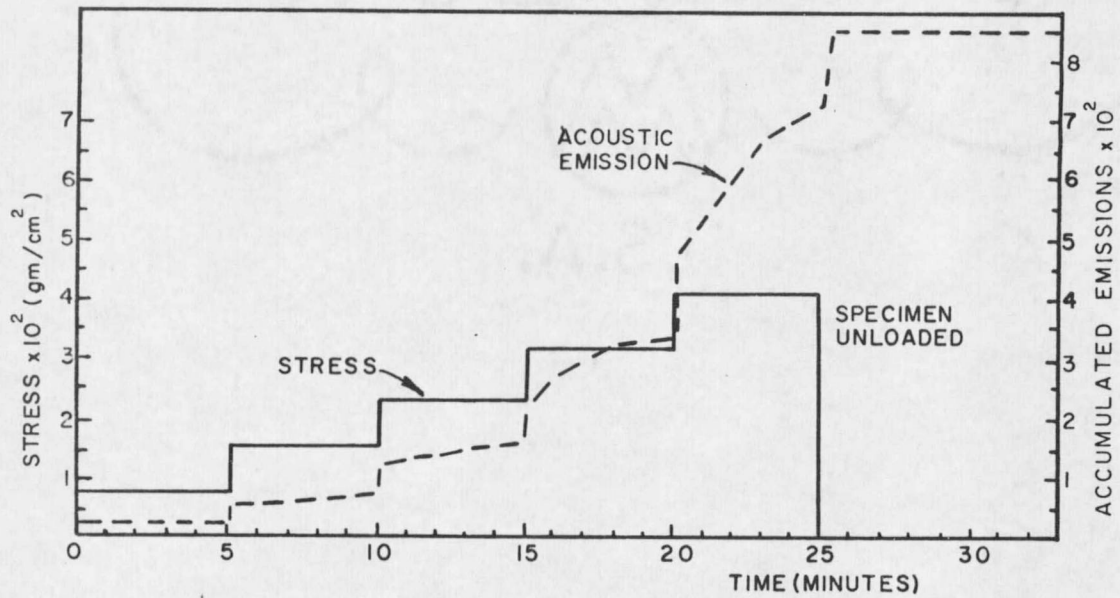
The snow used in these experiments was obtained from a collection area on relatively flat ground at a depth of about one meter. On this basis we will assume that the maximum stress that it had previously experienced was an overburden stress of 35 gm/cm^2 . This fact is significant since prior load history is an important parameter in terms of acoustic response. As shown in Figure 2, as loading is initiated, no acoustic response is observed until the stress reaches a certain level. This is depicted as σ_c in Figure 2. As the stress increases above this value, acoustic activity is initiated. The rate of acoustic activity then increases to a maximum which corresponds to the point in the stress deflection curve where the stress begins to fall off rapidly. With further deformation the rate of acoustic activity decreases steadily as the stress reaches a steady state response. If the deformation is stopped, the acoustic activity ceases and the stress relaxes. If after a period of relaxation the snow is again subjected to further deformation at the same rate, the acoustic activity resumes at a rate nearly

equal to what it was before deformation was terminated. This phenomena has been observed for relaxation periods of up to 15 hours, which is the longest time that we have allowed specimens to relax before reloading. As indicated earlier, the basic acoustic emission response is similar for the three modes of deformation studied.

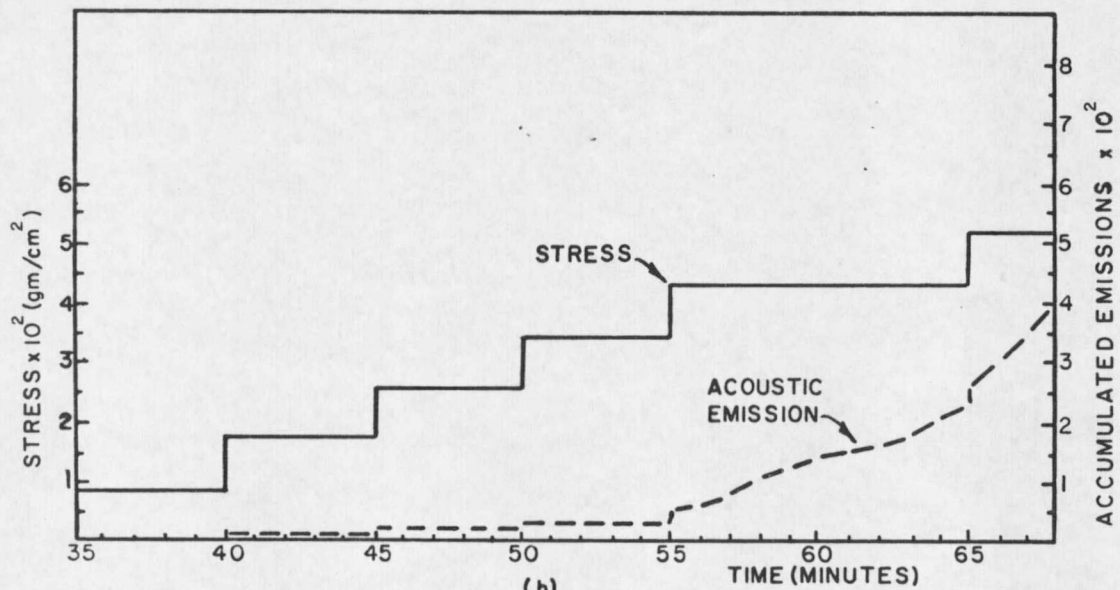
The acoustic emission response is very sensitive to the rate at which the snow is deformed. For relatively high rates of deformation (i.e., rates close to those which induce fracture in the snow), the rate of emission rises to its maximum value and then decreases rapidly with continued deformation. Figure 2 shows the typical emission response for a high deformation rate. For very low deformation rates the acoustic emission rate curve does not show this rapid rise and decay, the rapid rise and decay feature becoming increasingly pronounced as the rate of deformation is increased.

In addition to constant deformation rate experiments, a number of constant load tests in uniaxial compression and tension have been conducted and the acoustic response monitored. Figure 6a shows the acoustic response recorded for a snow sample subjected to a number of discreet load steps in uniaxial compression.

The acoustic response that is observed in creep experiments can be described as follows. For low stresses, below approximately 100 gm/cm², no emission activity is detected except for a few bursts when the load is initially applied. If the stress is increased an



(a)



(b)

Figure No. 6. Accumulated acoustic emission response for a specimen subjected to an incremental load history (a) Results of initial loading and unloading of snow sample. (b) Results obtained when snow specimen was reloaded.

incremental amount, to a level where activity is detected, acoustic emissions are observed throughout the region of primary creep. As the creep rate approaches a steady state, the rate of acoustic activity decreases to a near zero value. Again, it is important to emphasize that the snow used here was subjected to only overburden stresses prior to testing. Figure 6b shows the results of unloading the above specimen allowing it to relax and then reloading it. Note that little or no acoustic activity is observed until the stress applied to the specimen is equal to or greater than the maximum stress it had previously experienced. This interesting phenomena is known as the Kaiser Effect, and may have a possible application for measuring the state of stress in a snowslope.

Like the constant deformation rate the basic pattern of acoustic emission tends to be similar for both tension and compression at relatively low stresses. A number of tension creep tests have been conducted at relatively high stresses (stresses in the vicinity of 500 gm/cm²) with some interesting results being observed. The results of one such test is reported here.

A specimen was incrementally loaded over a 100 minute time interval to a stress of 500 gm/cm² and the acoustic response observed. Within a minute after the load was applied to produce this stress in the specimen the acoustic emission rate was 100 events per minute. Over the next 63 minutes the acoustic emission rate dropped to 25 per

minute. The emission rate then showed some sign of increasing for the next three minutes. It then increased in a monotonic manner for five minutes to a rate of 169 events per minute at which point the specimen failed catastrophically. This experiment was repeated with essentially the same result. The implication from this experiment is that for this type of load condition the onset of failure could be detected some minutes in advance.

DISCUSSION

This thesis has attempted to give a brief view of the acoustic emission phenomena in snow. We have considered some possible emission sources and also presented the results of a number of laboratory experiments. In observing the acoustic emission phenomena in snow, two possible applications in snow mechanics are suggested. As a purely empirical tool, it appears that a great deal of information about stress and strain in an avalanche slope may be gained by an acoustical monitoring system. Observations could be made both by placing transducers in an avalanche slope and making in situ observations and by removing samples and testing them in the laboratory. Using laboratory data as a basis, a comparative analysis could be made to interpret field data. One such test presently being investigated will utilize the Kaiser Effect to measure the state of stress over a period of time in a typical avalanche slope. If an oriented sample can be removed from the snowpack without introducing spurious overstress in the process,

it appears feasible that its in situ stress can be determined by controlled reloading in the laboratory.

A second possible research function of acoustic emissions would utilize this phenomenon, in conjunction with more standard techniques of experimental stress analysis, as an aid in the development of a constitutive relation for snow. At present the relation between acoustic emissions and the deformation mechanism in snow is not well understood. Consideration of the patterned acoustic response observed for various load and deformation histories indicates that it is related to the mechanical response. Since burst type emissions detected in snow originate from transient disturbances that take place in and between ice grains which compose the snow matrix, it appears reasonable to interpret the acoustic phenomena at the structural level.

SUGGESTIONS FOR FURTHER RESEARCH

After working on the development of this technique for research in snow mechanics it has become apparent that future application of this method in the field of snow and avalanche mechanics should yield a high return in terms of answering a number of pressing questions in this field. Listed here are some areas of research in snow mechanics for which the acoustic emission technique should prove an invaluable tool.

SNOW MECHANICS

- (1) Probably the most pressing problem in snow mechanics is the need for a comprehensive and physically satisfying theory to describe the deformation of snow. It is possible that the acoustic emission method might provide the necessary extra variable to develop such a comprehensive theory.
- (2) From all indications it appears that snow is a highly nonlinear material which should be accounted for in any comprehensive material theory. The problem of using such a nonlinear constitutive relation in applied analysis generally leads to the formulation of intractable problems. In light of this fact an effort should be made to develop a quasilinear law which can be applied within some established guidelines. In determining such guidelines delineating various ranges

of linearity might be determined using acoustic data.

- (3) Fracture of snow at rapid loading rates appears to correlate closely with observed emission rates. An investigation should be conducted to establish this relationship in a quantitative manner.

AVALANCHE MECHANICS

In field investigations application of the acoustic emission technique could prove a valuable tool for making in situ investigations of avalanche prone slopes. Below is a partial list of such applications.

- (1) By the methods described in the text this technique may have possible application in terms of determining the state of stress in unavalanched slopes.
- (2) With essentially the same method as used in (1) this technique could be used for making "post mortem" investigations in areas where the snow fractures.
- (3) By implantation of an acoustic emission system in an actual avalanche slope it is possible that changes in the state of stress could be detected as they occur. This implantation technique could also lead to monitoring possible pre-avalanche noise which might warn of an impending slope failure.

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