HYDRAULICS DIVISION

TECHNICAL NOTE

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TITLE: An Engineering Proposal For a Frazil Ice Recorder

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REASON FOR REPORT: This note opens the first phase of planning for a frazil ice recorder system that is requested by J.G. LOCKHART, Program Manager of the Canada-New Brunswick Flood Damage Reduction program.

The note makes a proposal on how to proceed in the development phase.

CORRESPONDENCE FILE NO. Study 82-377

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INTRODUCTION

Some Canadian rivers are prone to flooding caused by ice jams. Frazil ice may initiate the jams by forming a hanging dam under the ice cover. It can also impede the river flow generally because it clings to itself and other things readily. An overview given by Pratte (1976) describes the types of river flow resistance and mentions the effects of frazil ice.

The Flood Forecasting Centre of the Environment New Brunswick requires a system for the detection and recording of the concentration of frazil ice in fast flowing sections of a river. The system must remain unattended for long periods and since parts of the system cannot be retrieved during the ice up period, the system must be simple and reliable.

This proposal defines three methods of detecting frazil ice concentration and are given in the order of the author's perception of the likelihood to succeed.

Statement of Requirements

The original request, by J.G. Lockart (1981), and the minutes by B.C. Burrell (1981) give the essential statement of requirements. These are:

1. The device must record the amount of frazil ice in a water course.
2. The device must withstand the environment of a hydrometric station shed.
3. The device should be adaptable to other ice-troubled areas in Canada.
4. Shallow and deep river installations are to be possible.
5. Cost of the instrument must be minimal in capital costs, maintenance costs and manpower.
6. The device must be easy to operate, test, calibrate, and repair.
7. Accuracy of measurement must be within 20% of the true value.

Further requirements that were evident from a field trip include:

8. False alarms must be avoided through secondary diagnostic subsystems.
9. The parts installed in the river bed must be expendable therefore inexpensive.
10. Telemetry of an alarm at the onset of the formation of frazil ice is a long -term requirement.
11. The flow cross-section of the sensing head must be small and the head robust enough to withstand blows from trash ice.
12. Ice formation on the sensing head must be avoided.
13. Plugging of the sensor's active volume(s) with ice must be avoided.
14. Power consumption must be reasonable (about 1 kW maximum).
15. Public safety must be maintained at the site.
16. The attraction of vandals and the effects of them must be minimized.

Discussion on the Requirements

It is evident that the Frazil Ice Recorder must be either based on a straightforward physical principle which makes it easy to understand, operate and repair or it has to be based on a principle that has a very low probability of failure or both.

There can be no second chances for the sensing device because it is installed in a fast flowing river during its low period. Access to the head is highly unlikely once the river rises again.

Therefore, the key to success is simplicity, ruggedness, and reliability even at the expense of accuracy.

The following two descriptions outline approaches which may be taken to avoid complications arising from more sophisticated approaches such as conductivity (G. Tsang, 1977).

Calorimetric Pump Method

If a constant flow of water or water with frazil is drawn down a sufficiently long tube while it is being heated, a temperature gradient along the tube is formed. The shape of the gradient changes signficantly between the frazil-free water and the frazil-ladened water cases.

This can be expressed theoretically in the following way.

In a tube of radius R metres let there be a disc of water of incremental length, dx metres, with a volume $R^2 \pi dx$ cubic metres, and a surface in contact with the tube of area, $dA = 2 \pi Rdx$ square metres. Let there be a heat flow into the water through the wall, FdA watts. For pure water with a volumetric heat capacity of c joules per cubic metre-degree celsius, the temperature rise with time is

$$\frac{dT}{dt} = \frac{FdA}{cdV} \qquad (1)$$

If the water is travelling at $v = dx/dt$ the temperature gradient along the tube is

$$\frac{dT}{dx} = \frac{FdA}{vcdV} \qquad (2)$$

By subsituting for dA and dV the equation becomes

$$\frac{dT}{dx} = \frac{2F}{vcR} \qquad (3)$$

Since R and c are constants and if F and v are held steady the mean temperature gradient is constant. If two or more temperature measuring devices are spaced down the tube and the water is well mixed, the difference of the readings is constant regardless of the initial water temperature.

However, if ice is present in the water, the specific heat of ice will suppress the gradient until the ice is melted. The initial temperature will be held to zero until the ice is melted. The distance that the mixture travels before melting is complete is computed as follows.

The rate of change of heat content dH is equal to the rate of heat input and the rate of conversion of ice to water.

$$dH = FdAdt = sndV \tag{4}$$

where
F = the heat flow, W/m^2
dA = the incremental wall area of dV, m^2
dV = the incremental volume of the mixture, m^2
dt = the incremental time, seconds
S = the heat equivalent of fusion per volume of ice, J/m^3
n = the fractional volume of ice to water.

Substituting for dA and dV in terms of dx and R the equation becomes

$$2Fdt = SnR \tag{5}$$

Integrating for time and substituting distance and velocity for time the results are

$$x = SnRv/2F \tag{6}$$

This means that the heat does not increase the temperature of the water until it has travelled x metres down the tube. The resulting delay of the gradient will decrease the difference in temperature at the second locations down the tube. Temperature differences become a measure of the frazil ice through the following logic. See Figure 1.

If T_2 is the downstream temperature at a distance ℓ from the upstream temperature and T_1 is the upstream temperature at the origin. The distance back from the T_2 location where the ice is completely melted is

$$x' = \frac{T_2-T_1}{\frac{dT}{dx}} = \frac{(T_2-T_1)\ vcR}{2F} \tag{7}$$

The distance travelled before the ice was melted is $\ell - x' = x$. From substituting equation (6)

$$n = \frac{2F\ell}{sRv} - (T_2-T_1)\frac{c}{s} \qquad (8)$$

By dividing both sides by 100, the percent frazil ice content by volume is derived.

If ℓ, F, R, v are correctly chosen, the frazil ice will be melted between the two measuring locations and a reading will always be available for a given range of n.

Physical Realizations of the Method

Five other considerations must be included in the design to produce a working system.

1. The intake of ice and water must not be biased or upset by the different rates of water flow in the rivers. Therefore a tube with a sufficiently high length to diameter ratio must be used according to Lau (1979) and a positive displacement pump must be used.
2. The water and ice should be sufficiently mixed as it travels down the tube to avoid non-uniform heating affects.
3. The melting of frazil ice ahead of the upstream sensor should be minimized.
4. The heating must be uniform along the measuring section.
5. More than one temperature difference measurement would be a good diagnostic indicator.

With this under consideration the system is as follows:

The sensing device (Fig. 2) is a tube of an optimum length to diameter ratio to avoid biasing the results yet allowing a reasonable sensitivity. At the outflow end of the tube is a pump. The most suitable is the progressive cavity type such as offered by Moyno. This pump can pass solid objects such as pebbles without damage yet it has a positive displacement operation. Along the length of the tube, from the intake lip onward, a heater applies heat uniformly. The best heater for this is the sheet type. The outside jacket of the tube is well insulated to minimize losses from the heater tape and the influences of outside temperatures. The tube is coated with teflon to avoid clumps sticking at the intake and clogging the tube. A mechanical stirring device may be necessary to keep the water mixed and to break up ice clogs in the intake (not shown in Fig. 2).

For early models, four thermistor sensors will be used to measure the temperature differences. Two at the intake lip will measure the initial temperature and two more spaced down the pipe will take difference readings. These difference readings will be used for cross-checking the frazil ice readings and the difference of the intake pair will check for correct operation of the system.

Other diagnostic measurements will include the pump motor current, the heater current and a tilt switch for the sensor.

The signals and power are carried to and from the metering shed by a multiconductor cable that is buried in the river bed and bank for safety.

The metering shed will shelter an electronics rack (see Fig. 3) which will have the hydro power controls, the electronics signalling distribution panel, the regulated power supply and a multipoint chart recorder. The recorder will record at least four signals, two temperature differences, the motor current and the heater current. Preset alarms will help identify suspect readings.

An initial design example is given where the variables have been set for the tube size, pump rate and heater output.

Tube diamter (2R)	0.02 m
Working length between thermistors (ℓ)	0.3 m
Power (total) into heater tape (W)	200 W
Speed of water down the tube (v)	0.028 m/s

Constants for water and ice are:

Volumetric heat capacity of water (c)	$4.217 \times 10^6 J/m^3\ °C$
Volumetric heat of fusion of ice (s)	$3.337 \times 10^8 J/m^3$.

If frazil ice concentrations were 3% (30 ppt) by volume, equation (8) predicts a temperature difference over the 0.3 metre length to be 3.02°C. If no frazil were present ($n = 0$) the temperature difference will rise to 5.39°C. To measure frazil ice within a resolution of 1 ppt, the temperature differences along the tube would have to be measured to within 0.079°C which is within the capability of simple electronics thermometry.

The length to diameter ratio is well in excess of the requirement for minimum disturbance down the tube.

The accuracies of the instrument constants are expected to be

$$\ell = o \pm 10\% \text{ (turbulence along the tube)}$$
$$(T_2-T_1) = (T_2-T_1)_o \pm 1\% \text{ (thermocouple pairs)}$$
$$W = W_o \pm 1\% \text{ (regulated power supplies)}$$
$$R = R_o \pm 0.1\% \text{ (tube diameters)}$$
$$v = v_o \pm 3\% \text{ (pump stiffness and constancy)}$$
$$s = s_o \pm 0.01\% \text{ (pure ice)}$$
$$c = c_o \pm 1\% \text{ (aeriated water)}$$

The total error (worst cast) in the frazil reading is expected to be

$$n = n_o \pm 16.11\ \%.$$

In summary, the submerged part of the system will involve a progressive cavity pump drawing water into a heated tube. The temperature differences will be recorded on shore on a chart recorder. A set of diagnostic signals will be included to flag any period of suspect malfunction. These will include out of bounds temperature differences, heater currents, motor currents and a tilt switch to detect gross displacement of the submerged sub-system.

Preliminary Specifications

Power consumption (total	350 watts
Mass of submerged system (less stand)	20 kg

Power and signal lines (5 of #10, 7 of #16)	12
Chart Recorder (multipoint), print rate	1 scan/minute
Alarm set points	4
Regulated heater power supply	50 W ± 1%
Pump rate (syncronous motor)	132 L/min. ± 3%
Frazil ice measurement accuracy	± 3 ppt (ice to water)
Frazil ice measurement resolution	± 1 ppt (ice to water)
Cost of submerged system	$800 to $1000

Dielectric Measurement Method

The relaxation time of ice molecules exposed to an oscillating electric field is sufficiently long that the dielectric constant of ice drops significantly at high frequencies whereas water molecules maintian their high dielectric characteristics (Eisenberg and Kanzmann, 1969). When the oscillations of the electric field are raised above sixty kilohertz, the dielectric constant of ice drops to about 4 whereas water maintains a constant of about 80 even beyond a megahertz (Dorsey, 1940). This implies that the electric field would be influenced by ice. If an automatic capacitance meter were operated at about one megahertz, the change in the frazil ice content would be detectable.

Ideally, if a parallel plate capacitor is operated at 60 kHz or above, the capacitance is $C = \varepsilon A/4\pi d$, (I.T. and T., 1961) where

C = capacitance, pF
A = area of the plate (one of two), cm^2
d = the thickness of the dielectric, cm
ε = the dielectric constant relative to air, cm

When all parameters are held constant and the dielectric constant varies from 80 for water to 77.7 for water containing 3% frazil ice, the capacitance changes by about 2.9%. The temperature coefficient is close to 5 ppt per degree celsius (Dorsey,. 1940).

In a practical situation, the following considerations must be made.

1. The resistivity of the water changes with the frazil content therefore the impedance meter must be automatic to balance the real component of the impedance continously.
2. The reactive component of the circuit includes the transmission line between the impedance meter and the location of the sensor. This line must be very stable or very predictable in its characteristic impedance.
3. Commercial impedance meters are likely unable to make the measurement without some modification. The reason is that the shunt resistance across the sensor's capacitance is much lower than the normal range. A modified Hewlett-Packard 4271, B Digital LCR meter would be a likely candidate to generate the reading.

Before a firm prediction can be made on the success of this technique, further research will have to be done. Work done by van Beek, et al, (1976) will be quite relevant to the dielectric measurement method.

In summary, the dielectric method makes use of an electrically insulated rod-like antenna and a coax cable to the shore. An accurate thermometer is incorporated to compensate for the temperature coefficient of the dielectric constant of water.

In the metering shed, is an auto-reading impedance meter. The output is compensated for the temperature and recorded on a multipoint recorder.

For a self-diagnosing system, a dummy cable and load would be switched in periodically to ensure that the impedance instrument is functioning within bounds.

Conductivity Measurement Method

The third method is the conductivity method described by Tsang (1977). The method is analogous to the dielectric method but the electrodes must be in electrical contact with the water to make the measurement.

The method will not be described further in this proposal except to point out that care must be taken to account for the effects of temperature changes on conductivity because the conductivity would change with temperature to the equivalent of 100 ppt frazil per degree celsius, (Ford et al, 1981). Because the change in the natural conductivity of water can be confused with frazil ice, a compensating parallel-plate cell is suggested by Tsang. This cell is screened off to prevent frazil ice from entering the active volume.

Kristinsson (1970) describes a simpler probe shape for the conductivity method and he also points out the problems of compensating for natural changes in the river water's conductivity.

Discussion on Preferences

In terms of the statement of requirements, the colorimetric method ranks high in requirements 1, 2, 3, 4, 5, 6, 7, 8, 10, 15. 16. A lower rating is given to 9 because a moderate amount of capital ($1,000 estimated) is exposed to the dangers of the river ice. Requirements 11 to 14 all involve ice plugging and fouling which could be a problem even though the intake is a heated tube.

The dielectric measuring method ranks high in requirements 1, 3, 4, 7, 9, 10, 11, 12, 13, 14, 15 and 16. The weakness in the method is the high capital cost of the instruments in the metering shed, the complexity of the impedance meter which offers few clues to when it is malfunctioning. However, the absolute simplicity and low cost of the riverbed installation is a major feature. Another feature is that there are no moving parts in the system.

The conductivity measuring method is considered to be too difficult to control for unattended operation mainly because of the chances of the screens becoming plugged or damaged and causing de-icing or temperature effect problems.

Proposal

With the approval of the Subcommittee on River Ice, New Brunswick, the plan is to proceed on the calorimetric method by building a prototype and testing it in the NWRI cold chamber and ice flume.

As well, further investigation should be done on the dielectric method as a backup, should the clogging problems for the calorimetric method be excessive.

If successful and resources available, both methods should operate in tandem to check each other and for a comparison of reliability and ease of application.

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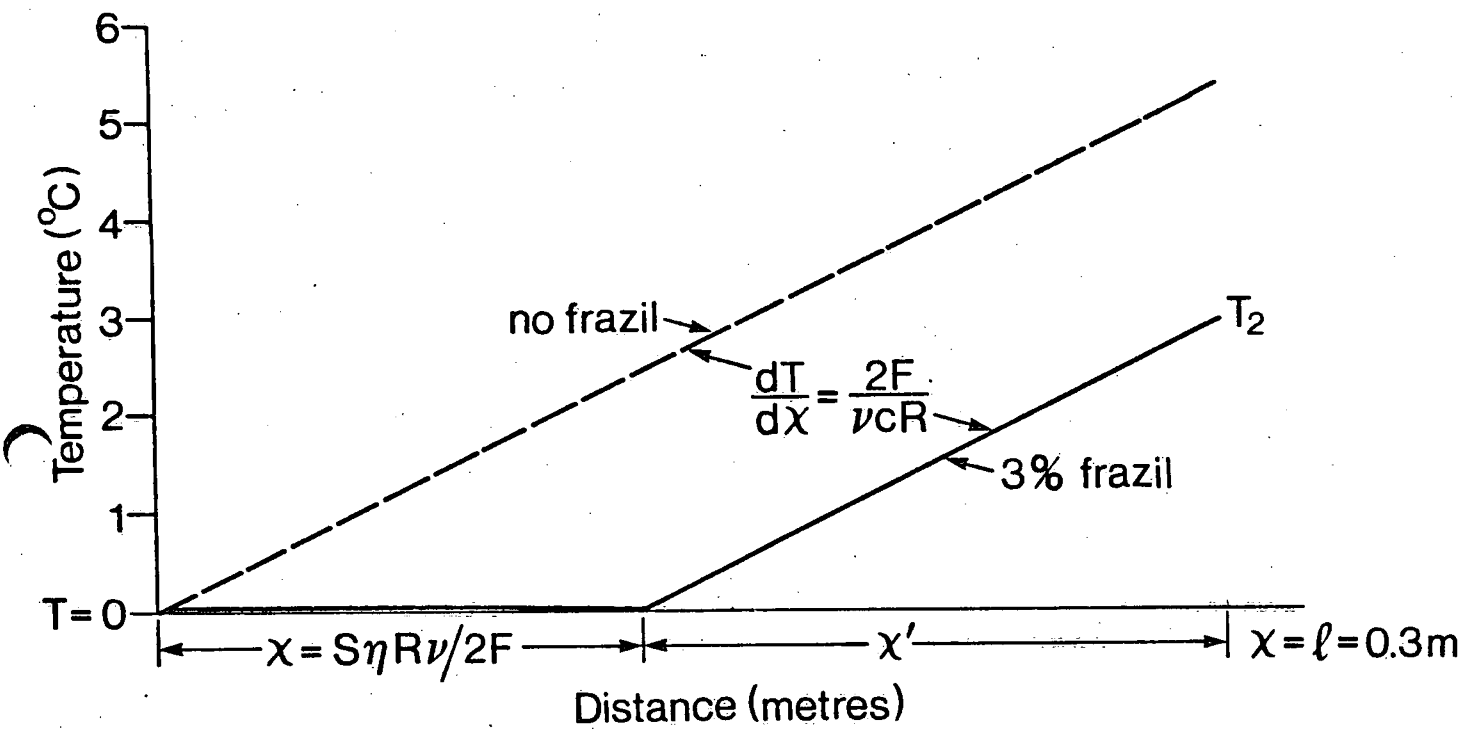

Figure 1 Temperature Gradient Diagram

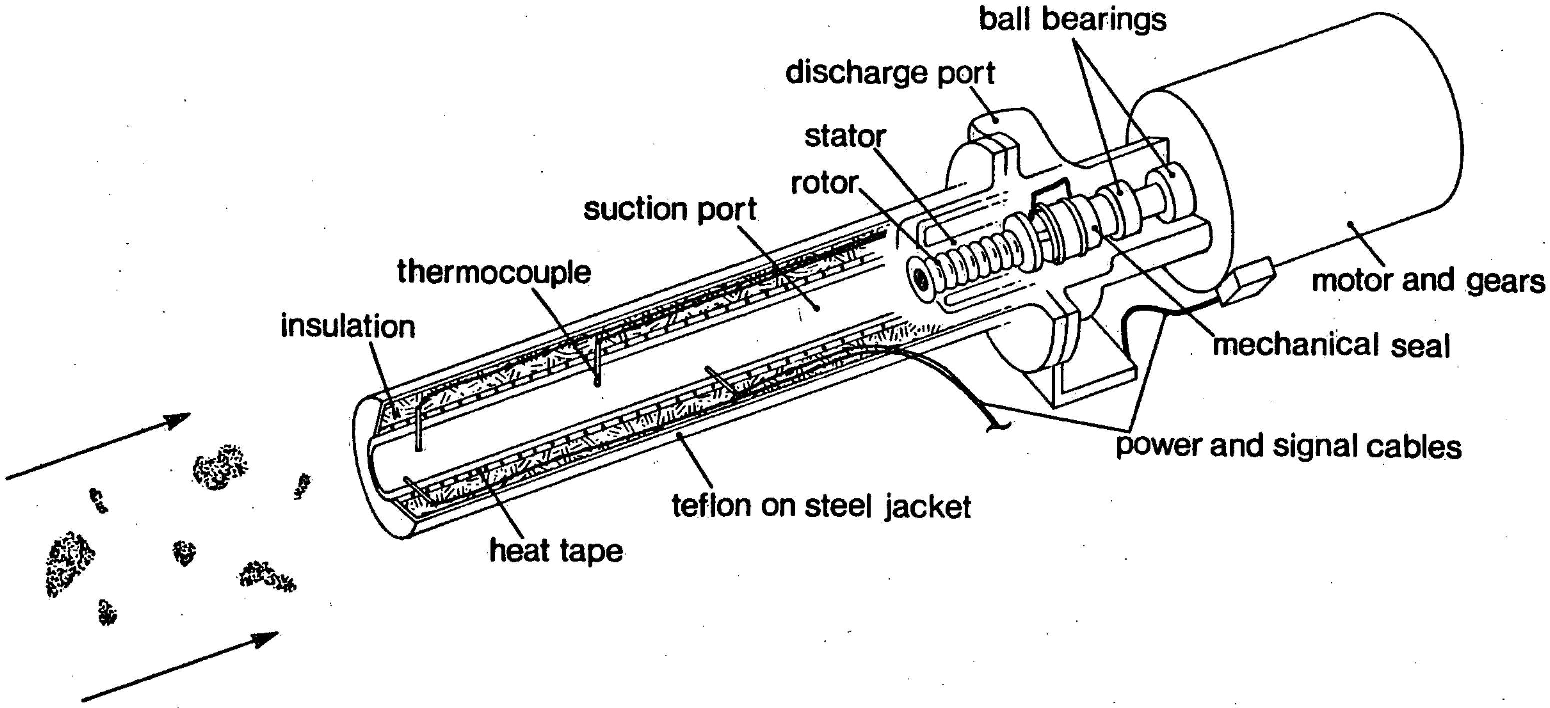

Figure 2 Concept Sketch of Frazil Ice Sensor

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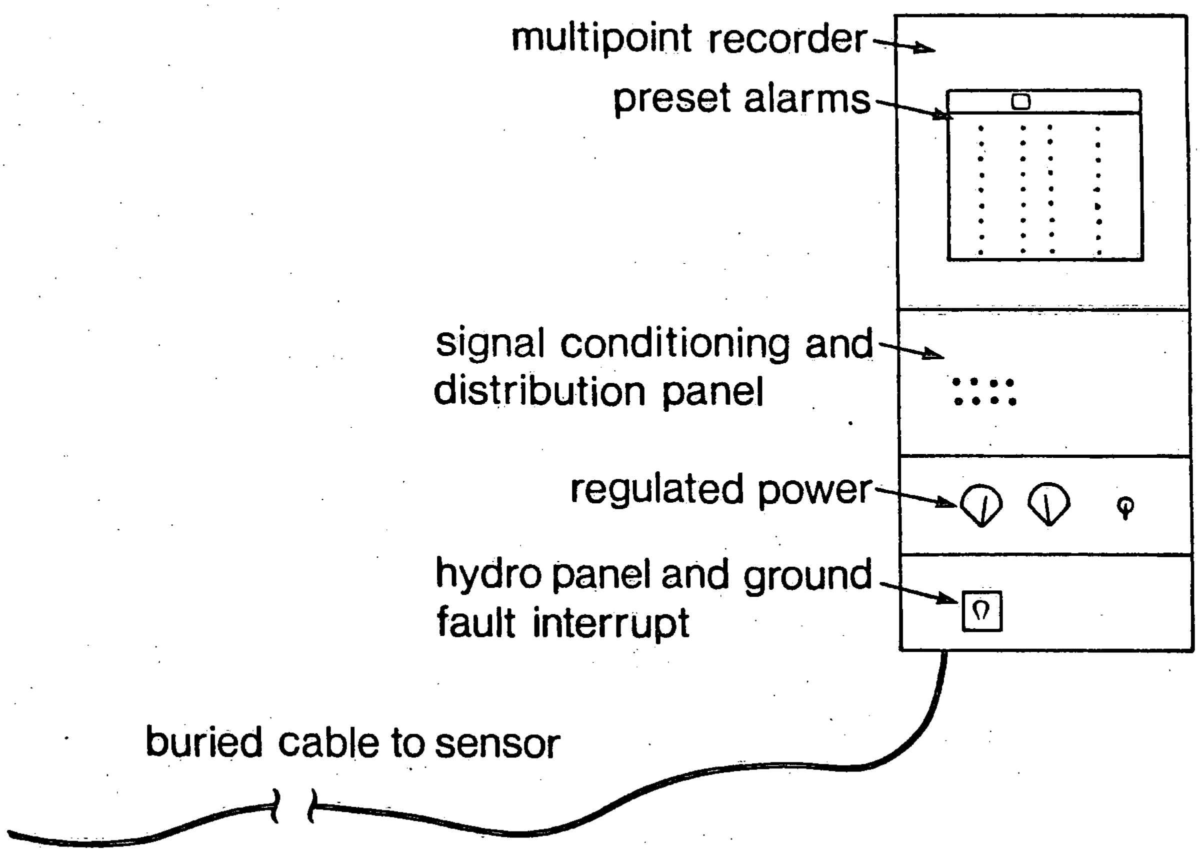

Figure 3 Concept Sketch of Recorder Subsystem