

PHOTODIODE SENSOR ARRAY FOR MEASURING SETTLING SOLIDS

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ABSTRACT

At government nuclear waste sites, there is a need for monitoring the vertical density profile of underground radioactive waste tanks. Current monitoring systems require expensive hot cell analysis to determine vertical sludge concentrations; an automated system would make it easier and safer to monitor the sludge. A prototype monitor was built to measure solid-liquid interfaces and vertical concentration of solids in solution. This was done in order to determine the feasibility of implementing a full-scale monitor to measure a toxic sludge density profile while minimizing the need for hot-cell analysis.

Several alternative systems of emitters and receivers were evaluated for measuring sludge characteristics. Enclosed arrays of high intensity halogen lights and photodiode sensors were selected as emitters and detectors, respectively, based on design simplicity, component availability, and overall cost. A modular design approach was taken in hopes of simplifying full-scale implementation. In addition, a computer-controlled system was developed to automate control over lights and sensor selection based on a user-defined cycle and measurement duration.

Experimentation with the five-foot prototype showed that the system could detect solid-liquid concentration levels based on opacity differences. This system could prove to be a low cost method for measuring relative concentration changes in a dynamic environment where limited human contact is needed.

OBJECTIVE

The objective of this project is to develop a sensor array to measure the settling rate of aqueous slurry in a process vessel. The following measurements are required: 1) slurry density profile by measuring the vertical concentration of solids at one inch intervals; 2) solids/liquids interface level; and 3) settling rate (rate of density change). The process vessel contains various weight percents of solid particles of varying nature. The weight percent of solids varies from 0 to 30 percent, and particle size from 1-1000 microns.

PROBLEM SUMMARY

The current method for measuring depth of suspended solids is expensive and requires hot-cell analysis. A robust, in-tank monitor may reduce sampling cost. To be an effective alternative, an in-tank monitor must determine the relative density of the liquid phase, the elevation of the sludge-liquid interface level, and the clarity of the supernate. A sensor array will be built to determine the rate at which the solids settle by measuring the vertical concentration of solids as it varies from top to bottom as a function of time. The resolution of the sensor array should provide incremental measurements of solid concentrations per inch of vertical tank depth and the sensor array design should be adaptable to monitor a 20 to 30 foot vertical column of tank waste (the tank prototype will be a minimum of 5 feet high). The materials used in the sensor array must be compatible in highly radioactive tank waste with gamma radiation fields up to 1000 rad per hour. The material must also be able to withstand solution temperatures from 20-95 degrees Centigrade (ambient to near boiling), concentrations of caustic equivalent to 3M sodium

hydroxide, and heavily agitated solutions during the mixing and homogenization of the slurry (for the final sensor array design).

The prototype will be installed in a container that is 5 feet high and 1 foot in diameter. The sensor array will be installed after the material is stirred and will not be removed until completion of the process. Continuous data from the sensors will be kept throughout a test period of several days. The test slurry contains a mixture of 1.6 wt% kaolin, 15 wt% Min-U-Sil 30, water, and contains sugar and fine sand (that will pass through a Number 18 sieve).

ENGINEERING CONCEPT

The engineering concept for system design is that as light passes through the slurry, the light intensity decreases due to scattering and absorption in the slurry. The amount of light the materials absorb or scatter is exponentially related to both the distance between the light source and sensors and the opacity of the slurry^{3,4,5}. For a constant distance between the source and sensors, changes in light intensity can be attributed to an opacity change. By measuring these changes, one may determine the relative change in opacity of the material at any vertical position in the tank, as well as to determine solid-liquid interfaces. If the sensors cannot detect the light transmitted at a particular vertical position, it will be assumed that solid sludge has been detected, thus identifying the interface.

PROCESS DESIGN

Methodology

The design requirements were studied and several potential emitter-detector methods were considered. The basic design consists of a glass enclosed system of emitters that transmit a signal through the water-solid medium to a system of detectors that provide an output proportional to the signal received. After review of the many possibilities for the system design, a semi-focused halogen light source was selected because of its penetrating ability through the water-solid medium. The amplified photodiode integrated circuits were selected as detectors because of their variable sensitivity and voltage output representative of the light intensity. The following is an outline of emitter/detector possibilities reviewed:

Ultrasonic Transducers

Ultrasonic sound can propagate through both liquid and solid mediums. This propagation property made this method appealing. However, implementing ultrasonic transducers is too complex to implement in the time frame allowed (this was done as semester research project). The hardware would need to transmit an encoded signal through the medium, receive the signal, filter out background noise, and decode and analyze the resulting waveform. This method could well be a better method than the one chosen. However, an ultrasonic prototype was not investigated because of the time factor.

Infrared Transmission

Infrared transmission was attempted in the 940nm range, but it would not penetrate the glass enclosure with enough intensity to pass through dense solutions. Thus, this procedure was quickly dismissed.

Visible Light with Photodiode Amplifier

Visible light transmission through the medium became the most appealing option because of the variety and availability of visible light sources, the fact that transmission of visible light varies with the translucence of the medium, the availability of light sensors, low cost, and a

higher likelihood of creating a working prototype within the time frame. A photodiode sensor was selected as the light detector. Photodiode sensors¹ are practical because the output of the sensor is an easily measured voltage level and it has adjustable sensitivity. In addition, initial tests on the sensors indicated that they were easy to use and were sensitive enough to detect very low levels of light. The next decision was to choose an appropriate light source for the transmission of visible light. Intensity of light was the most important consideration since it was necessary to transmit light through translucent liquid. It was decided to focus resources on light sources that produce intense light. Visible light sources are available using white light (entire visible spectrum) or at specific wavelengths. Here are the light sources considered:

Laser Light: The intensity of laser light was very appealing for this project, knowing there would be very dark materials in the slurry. It was soon found that other light sources were just as intense as lasers; therefore, lasers would be impractical because they are more costly than any other light sources tested.

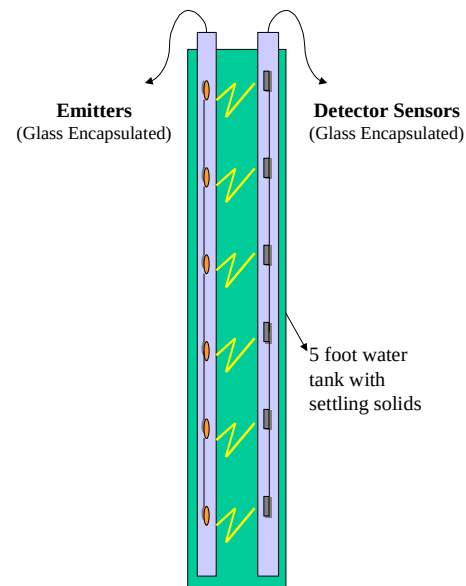
High Intensity Light Emitting Diodes: High intensity light emitting diodes (LED's) are the same cost as other light sources available. Although, they are not very bright compared to most of the lights tested, and therefore were not used.

Fluorescent Light: A fluorescent light source has some very appealing qualities. It produces white light that is easy to detect, can be directed to illuminate the medium with a single tube, and is inexpensive. Unfortunately, fluorescent lights produce "noise" since it is an AC device. They also operate at a higher voltage than desired and are not as intense as other sources.

Halogen Light: Halogen lights are an inexpensive, readily available source of very intense white light. Since halogen lights require relatively large power, the power supply could limit the supply current, thus limiting the number of lights that can be on at a time. In transmission tests using a halogen lamp with a current regulator, the light through the simulated media was found to be acceptable. It was further found that these lights are easy to control with the computer based control system. Controlling the lamp duty cycle (turning them on only when making a measurement) can reduce heat emission. Based upon the test data and analysis of all these sources, the halogen light source was considered the most promising and thus was selected.

Prototype Design Description

This design consists of glass encapsulated arrays of lights and sensors, submerged in the tank such that the liquid and solid medium is between the light array and the light detection sensors (see Figure 1). In order to have one-inch vertical resolution, 60 sensors and 30 halogen lights will be required for the actual system. When the density and concentration of the opaque solids change, the transmission of light to the sensor also changes. The light sensors output a voltage that represents the light intensity detected. The sensor circuitry is designed so that two levels of sensitivity can be selected, a low sensitivity for less



opaque medium, and high sensitivity for darker medium. The sensor output is sent to a computer for analysis and data storage. Each light and sensor pair is selected and sampled by the computer one at a time with the ability to sample the entire array every 3 minutes. The computer is programmed to turn on each lamp, then take 10-100 intensity measurements in 3 seconds. While the measurements are being made, the computer program textually and graphically displays the real-time data. The experimental process has been automated through the use of the computer interface input/output and control software.

Process Description

Setup, Initialization, and Calibration

Prior to attaching the sensors to the computer interface card, the interface card is precision calibrated so that it can accurately measure the sensor output voltages. To set up the measuring process, first submerge the encapsulated arrays into the medium, connect the appropriate cables to the computer and power supplies, and power up the computer. Next, the computer program will allow the user to set up options such as measurement duration, sensor sensitivity, light and sensor verification, and database selection. It will be necessary to calibrate the sensor array to ensure consistent intensity readings. Once all hardware is connected and software options are selected, the system is ready to begin measuring data. The user may then select the start button to begin the monitoring process.

Measurement

When the monitoring process is started, the computer software handles all the sensor and light selection processes (with the exception of user and safety overrides). Each sensor is analyzed individually and sampled at a maximum of 1KHz. For each sensor measurement, an ambient light measurement is taken first just before the light is turned on. Then an average light intensity measurement is taken when the light source is turned on. The ambient light reading is then subtracted from the average light intensity reading. This compensates the reading for the presence of stray light sources. Each sensor is measured in succession from top to bottom until the entire array is sampled. Sampling of the entire array is repeated for a user-selected duration. The software will graphically display the real-time data and sensor status so the user may see the current density profile of the settling slurry.

Analysis

Once the measurement process is complete, the user may select the following data presentations for analysis:

- Slurry-water interface changes per unit time (graphically representation and voltage readings),
- Graphical playback of events to view the overall changes that occurred over the course of the experiment.

DESIGN DESCRIPTION

The system is broken down into six basic blocks (see Figure 2). First, the computer uses graphical software to give the user control of the hardware system. Next, the light control system accepts computer input to turn lights on. The in-tank halogen light array is controlled by the light control system. The in-tank photodiode sensor array detects illumination intensity from the light sources. The sensor output selector then takes all the outputs of the sensor array and

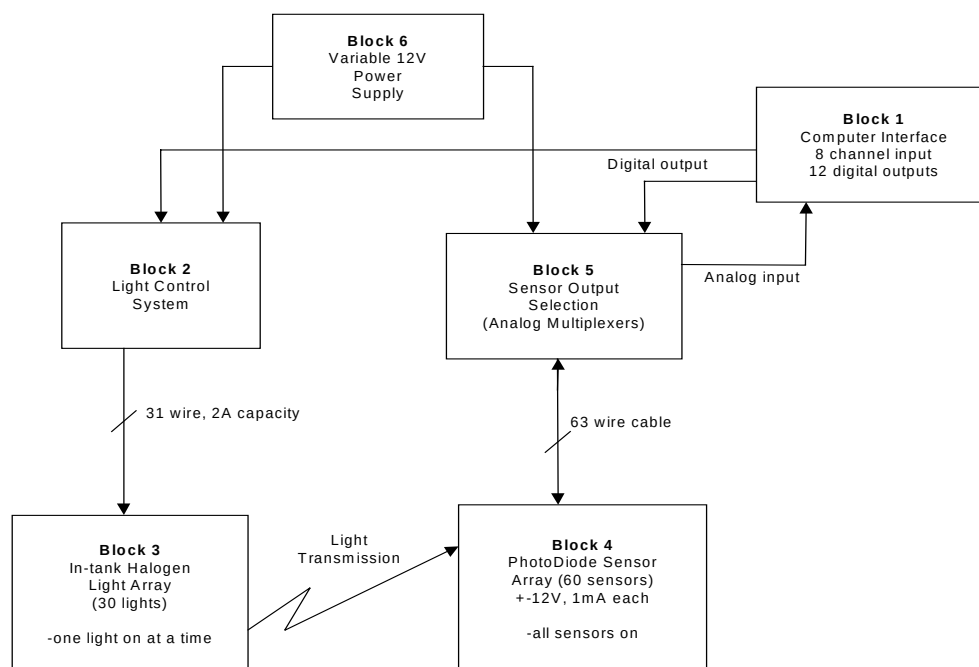


Figure 2. Process Block Diagram

supplies the computer with the two requested sensor outputs. Finally, the power supply module powers the entire hardware system.

The computer system is installed with software and a hardware interface card. The software has a graphical user interface that enables the user to set testing options, start an experiment, and analyze data. Once the user has set parameters, testing may be initiated. Then the software is put into a sampling loop until the experiment is over. The sampling loop activates specific lights and sensors, reads in data from the sensors, and then stores the data in a database. When sampling, the interface card sends information in 8 binary data bits. This information includes which lights to turn on as well as which sensors to read (using 5 bits). In addition, one bit tells the system to enable or disable the lights. Another bit changes the sensitivity of the sensors. Finally the last of the 8 bits is used to cut the power to the entire system. The interface card also reads in analog voltage levels in the range of 0 to 9.5 volts. This voltage level corresponds to the sensor output. Once the card reads the analog voltage, the software stores the data into a database. The database information may be displayed in real-time or used in post-test analysis.

The light control system is a system of multiplexers and high power switches that are used to select which lights to turn on based on the computer signal. When the multiplexer selects outputs based upon the computer binary signal, the high powered switches are triggered. The computer sends an 8 bit encoded binary signal, which contains information on the position of which light to turn on. This module has 30 output lines to the light array (one for every light). The computer signal is decoded to determine which output line to turn on. Since the computer output is only able to source low power devices, relays and other high powered switches are used in conjunction with the power supply to control the high power devices such as the halogen lights.

The light array controlled by the switches of the light control system. The halogen lights use reflectors to focus the light towards the sensors, and are approximately 2 inches in diameter. In addition, the halogen lights are mounted every two inches on printed circuit boards, for a total of 30 lights in the five-foot tank. The light is emitted through the slurry to the sensor array. The light array is encapsulated in glass to protect the electronics from the slurry-liquid material. The glass tubes for the light array and the sensor array are constructed to have flat vertical sides to reduce reflectance and to maximize transmission. Transparent surface coatings may be needed for the caustic environments of the intended commercial application.

The sensor array is also encapsulated in glass and is positioned in the tank opposite to the light array. All electronic components are mounted on a 2-inch wide by 10-inch long printed circuit board. A sensor is placed at every inch of the circuit board, for a total of 60 light sensors in the array. Every sensor converts the light intensity at its surface to a voltage level between 0 and 9.5 volts, this voltage is sent on 60 lines (one for every sensor) to block five. In addition, the circuit is designed to include a switching relay for every two sensors. This relay is for changing the sensitivity of the sensors. If the light is too bright (a reading of 9.5 volts), the computer can send a signal to switch this relay, which will change the amplification of the light reading. The same lines power all the sensors of the array so the computer can easily cut power to these lines to turn off the entire array.

The sensor output selector takes all the sensor array outputs and selects which sensor output to send to the computer. The selector is controlled from the computer digital output signal, which sends a binary sensor address from 1 to 30. The computer selection signal is sent to analog multiplexors, which select which sensor output to send to the analog inputs of the computer. Two sensor outputs are selected at the same time and correspond to the adjacent light that is turned on.

The general flow of the system is a loop. The computer sends signals to the light control system and specifies which light to turn on. The light control system deciphers which light to turn on and sends power to that light in the array. The sensors detect the light transmitted through the slurry. The sensors convert this light intensity to a voltage, and send this voltage level to the sensor output selector. Next, the sensor output selector receives the output of the sensors and sends the corresponding signal to the computer. This data is stored and the cycle is repeated until the test has timed out. It takes about 2 minutes to analyze the 5-foot prototype tank and about 12 minutes to analyze a 30-foot tank.

The overall design is based upon the theory that light absorption of a material and scattering by the suspended solids increases as slurry and solution opacity increases. From this concept, the design was developed using light generating sources and a method of light intensity detection. This unique design is not based upon any known existing design for measuring changes in liquid or slurry density.

POTENTIAL FULL SCALE IMPLEMENTATION PLAN

If our prototype were to be implemented in a commercial full-scale design, the scheduling would be broken down into three main phases: Research and Development, Full Scale Construction, and Maintenance. The estimated time to get the full-scale monitor built from start to final setup is about 2 years.

Research and Development

Phase one of the project has primarily been completed, although it is recommended that more research into other methods of monitoring slurry density changes be investigated (especially ultrasonic methods). It is estimated to take one year to fully research and develop a working prototype. The research and development of the 5-foot prototype has taken 5 months.

Full Scale Implementation

Full scale design, construction, mounting, and testing is estimated to take approximately one year to complete. Although the prototype is designed to be modular, construction and proper mounting in the full-scale tank may take more time to develop. The computer software will also require some modification to include more sensors and light controls.

Maintenance

Twice a year, the major in-tank components should be replaced since the parts are only rated for 2000 hours of continuous operation. This process should not take more than a couple of weeks to complete each year.

FULL SCALE MODIFICATIONS

One consideration of the full-scale design is the temperature of the large tanks. The temperature range, as stated in the problem statement, is between 20 and 95 degrees Celsius. There are a few choices to prevent temperature from effecting the measurements. Military grade electronic components will have to be used for any parts that are placed in the tank that are subject to high temperatures. Also, to keep the temperature in the glass containers within the operating range of the sensors, a cooling system can be implemented. When the temperature of the sensors reached a certain temperature, cold air would be pumped in the glass container to cool the electronic components in the tube. This cooling system would be fully automated, because the computer control can be set up to detect temperature changes to determine how to control a cooling system.

Construction of the sensor and light arrays will need considerable modification for the full-scale design. In the full-scale tank, internal support beams can be used to attach the glass sensor tubes. This will cost considerably more for labor and materials to construct and install the glass in the full-scale tanks (including crane rentals). The glass construction for the sensor tubes will also cost considerably more in order to achieve a 20 to 30 foot vertical sensor resolution.

The hardware and computer control systems will need to be upgraded to account for the additional quantity of lights to control and sensor data outputs to measure. This will include purchasing an interface card (or cards) that will handle the additional analog inputs and binary outputs. The controlling software will also have to be rewritten to handle the additional complexity. The light selection and sensor output selection hardware will have to be modified to account for additional sensor control bits and additional input/output signals.

Tank radiation will have a long term effect on electronic components^{2,7}. It will be necessary to implement a part replacement schedule to prevent breakdown. In addition, some of the operating hardware such as the computers can be located at a safe distance away from the tanks by using fiber optics to send and receive signals.

PROTOTYPE RESULTS

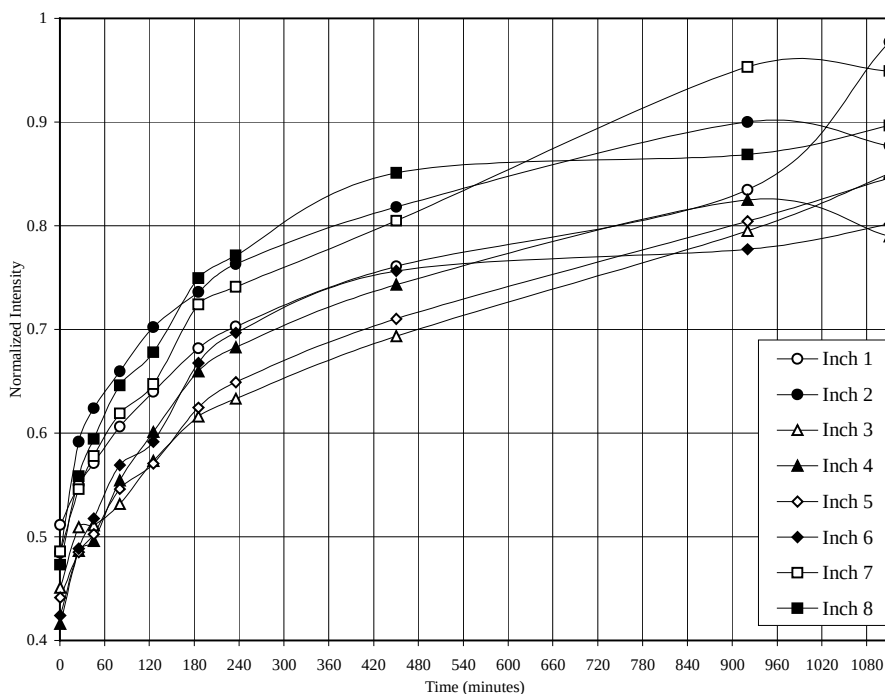
Prior to building the five-foot prototype, we constructed and tested an 8-inch pre-prototype. By building and testing a smaller prototype, it was possible to see what to expect when measuring intensity changes due to settling solids.

The experiment with the 8-inch prototype was conducted over a 16-hour period. First, a small tank was filled with water and baseline intensity measurements were taken. Next, sample solids of Min-u-Sil, Kaolin, and sand was added to the water and stirred. Intensity measurements were then taken at each vertical inch of the tank at increasing time intervals. Each intensity measurement of the slurry was normalized with the initial baseline intensity readings of water (see Table 1).

Table 1. Eight Inch Pre-prototype Test Results

Sensor Depth	Normalized Intensity (percentage)									
1"	51.14 %	55.01 %	57.12 %	60.63 %	63.97 %	68.19 %	70.30 %	76.10 %	83.48 %	97.72 %
2"	48.48 %	59.18 %	62.39 %	65.95 %	70.23 %	73.62 %	76.29 %	81.82 %	90.02 %	87.70 %
3"	45.09 %	50.95 %	51.12 %	53.18 %	57.31 %	61.62 %	63.34 %	69.36 %	79.52 %	85.03 %
4"	41.63 %	48.64 %	49.61 %	55.45 %	60.12 %	65.95 %	68.29 %	74.32 %	82.49 %	78.99 %
5"	44.15 %	48.52 %	50.26 %	54.62 %	57.07 %	62.48 %	64.92 %	71.03 %	80.45 %	84.64 %
6"	42.42 %	48.87 %	51.77 %	56.94 %	59.19 %	66.77 %	69.68 %	75.65 %	77.74 %	80.16 %
7"	48.59 %	54.60 %	57.79 %	61.91 %	64.73 %	72.42 %	74.11 %	80.49 %	95.31 %	94.93 %
8"	47.32 %	55.86 %	59.44 %	64.61 %	67.79 %	74.95 %	77.14 %	85.09 %	86.88 %	89.66 %
	0	25	45	80	125	185	235	450	920	1110
	Measurement Time (minutes)									

The data recorded was then plotted as shown in Figure 3. The chart shows that the light intensity increases over time as the solids settle. Initial tests of this pre-prototype showed that it would be able to detect changes in opacity of the slurry. By analyzing the intensity differences as opacity changes, the solid-liquid interface can be determined with respect to time.



After the encouraging results of the 8-inch prototype, the 5-foot prototype was constructed and tested. The prototype sensor probe was submerged in a tank of agitated sample solids including Min-u-Sil, Kaolin, sugar, and sand. The test lasted 31 hours and the entire tank was sampled every 5 minutes. External ambient light was minimized by covering the test tank with aluminum foil and black cardboard. In two instances, for about 7 hours, we experienced power loss, reflecting the sharp jumps in the data.

Each intensity measurement of the slurry was normalized with the initial baseline intensity readings from an averaged sample air measurement; this calibrates each sensor. Figure 4 shows the 5-point moving average light intensity data over tank depth at 10-minute intervals.

The graph shows a small deviation in intensity over the depth at the start of the experiment. As time progresses,

Figure 3. 8" Prototype Data for Normalized Intensity vs. Time

Five Foot Prototype Results

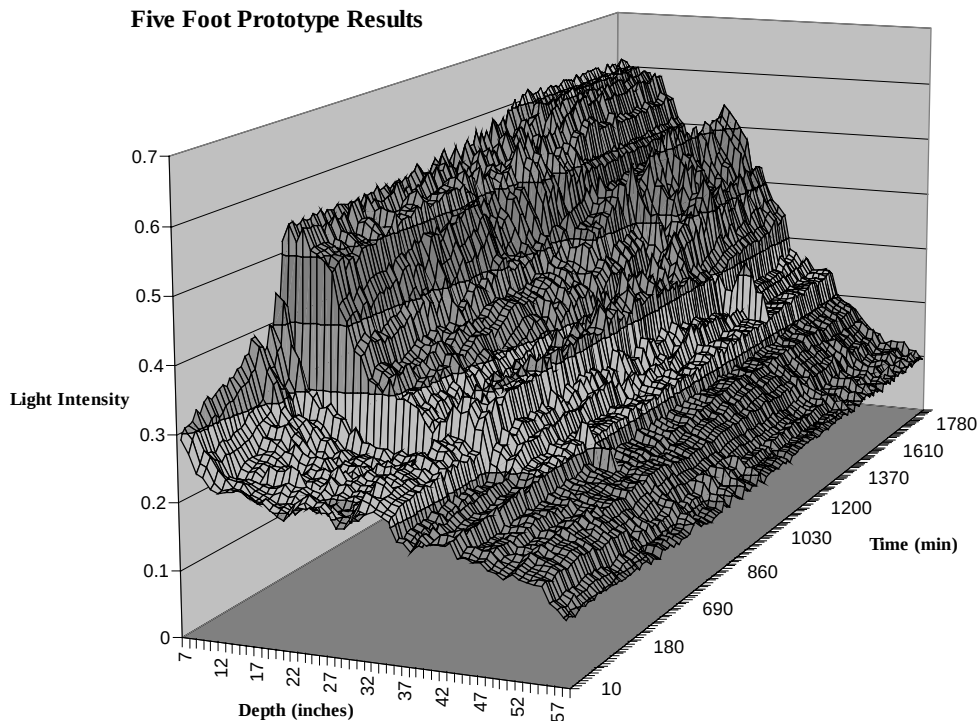


Figure 4. 5' Prototype Test Results Normalized Intensity vs. Time

intensity differences increase so that higher intensity light is detected through the solution at the top of the tank and almost no light is present at the bottom of the tank. This behavior corresponds to the settling of the suspended solids.

CONCLUSION

The general approach used to design the prototype was to transmit a signal through the slurry, receive the signal, and then decode the signal to give the output data. This would measure the transmittance of the material at every vertical inch of the tank. With this information, the opacity can be determined and the location of the solid liquid interfaces can be found. After experimenting with the one-foot prototype, the system was shown to be able to measure opacity changes in liquid relating to the settling of solids. Further experimentation with the five-foot prototype showed that the system could detect solid-liquid concentration levels based on opacity differences. This system could prove to be a low cost method for measuring relative concentration changes in a dynamic environment where limited human contact is needed. The design is modular so that the system can be scaled to any height needed and can handle multiple probe locations. In addition all electronic equipment is isolated from the solution being measured, and no moving parts are present.

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