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Electronic Refinements for Improved Operation of Portable Industrial Hygiene Air Sampling Systems

ELECTRONIC REFINEMENTS FOR IMPROVED OPERATION OF PORTABLE INDUSTRIAL HYGIENE AIR SAMPLING SYSTEMS

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PREFACE

This report is intended to serve as a recommendation developed by the technical staff of the Engineering Branch, Division of Laboratories and Criteria Development, NIOSH, for some specific improvements in the performance of commercially available industrial hygiene instrumentation. As such, this document should be used as a reference in the development of future sampling and analytical criteria, especially where the performance of portable field instrumentation is under serious consideration. Designers of the appropriate instruments may also find the information contained in this report helpful for some aspects of the design process.

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A B S T R A C T

The operation, reliability, and cost effectiveness of portable air sampling systems used for industrial hygiene monitoring can be improved by the utilization of the two electronic circuit developments presented in this paper. The developments result from recent advances in electronic components and systems technology. The presentation is made in an effort to advance the state of the art in portable instrumentation, thus improving the accuracy with which certain health hazards in man's environment can be measured.

The first development consists of a motor speed controller which has application to any air moving system involving a positive displacement pump where a unique linear relationship exists between motor speed and air flow rate. This controller senses motor speed and can maintain constant motor speed by transferring whatever power is necessary to do so from the battery pack to the motor. An inexpensive realization of the new design is described, along with the presentation of pertinent test data. Other design ideas for this type of system are presented in the interest of developing a generalized design procedure for motor controllers used in this application.

The second development involves the utilization of rapid charge batteries in the design of power packs for portable instruments, in general. The realization of portable instrument designs utilizing these new batteries should result in virtually continuous instrument availability for sampling operations, as opposed to present situations where instruments spend most of their time in recharging mode. This section of the paper also presents preliminary design and cost data for the implementation of such systems.

The conclusions of this paper present recommendations as to how the technology described can be transferred to realization in field monitoring systems, where applicable, in order to achieve the desired improvements.

INTRODUCTION

The National Institute for Occupational Safety and Health (NIOSH) is responsible for designing, developing, and improving portable instruments which assist in the detection and quantification of health hazards in the workplace. In carrying out this responsibility, NIOSH conducts studies which result in the improvement of existing instruments,[1] often through the promulgation of the appropriate regulations.[2] The Institute also encourages the development of new instruments and techniques by funding the design and construction of engineering prototypes for subsequent laboratory and field evaluation.[3,4] Finally, through programs of testing, certification, and project oriented evaluations, NIOSH works to insure that devices and instruments used for the determination of occupational hazards meet the minimum performance requirements necessary to protect the worker's health and safety.[5,6,7,8]

In the context of this study, the laboratory and field performance of various prototype and commercially available portable industrial hygiene instruments were review, vis a vis the legal requirements and the overall intent of the sampling and analytical methods involved. Perspective for the review was also gained by considering some of the more practical aspects of the day-to-day use of these instruments in the workplace. Although the review was centered largely on particulate air sampling instruments, some of the following results refer to portable instruments in general:

1. Air sampling instruments presently used in sampling schemes which involve only gravimetric analytical methods are, in general, acceptable suited to the application, at least as far as performance is concerned.

2. It is apparent that some air sampling schemes and analytical methods require larger and more accurately measured volumes of air to be sampled than is presently possible for commercially available instruments. This, in turn, implies that greater flow rates and running times must be more accurately controlled.

3. Many practical considerations in the workplace hinder the proper adjustment and operation of instruments as they are used. This includes the flow rate adjustments and running time determinations for personal sampling instruments referred to in 30CFT 74,[9] both of which are usually left to the discretion of the worker who is being studied. It is not reasonable to expect flow rates to be adjusted, without fail, twice or more during each eight-hour shift. Also, a ten-minute error in running time during an eight hour sampling interval implies at least a 2.1% error in sampled air volume.

4. The increasing complexity and unit costs associated with some portable instruments imply that careful scheduling of their use is imperative. This scheduling process is often hindered by the fourteen-hour recharging period necessary for these instruments, during which they cannot be used for sampling.

5. Presently available technology can be utilized to substantially improve the design and operation of most commercially available portable instruments as well as some that are now in the advanced prototype design stages.

In the spirit of the above results, this paper is concerned with a treatment of two common problem areas in the design and performance of presently available portable instruments. These problems are apparently present in most existing instruments:

1. The air flow rates and running times for many air sampling instruments cannot be maintained to a suitable accuracy level, especially in the case of intermediate volume air sampling systems (e.g., flow rates of 5 to 75 liters per minute) and in the light of recent improvements in some analytical methods. As a function of operating time and sampling train loadings, present air sampling instruments simply do not provide adequate automatic flow rate and running time control for many applications.

2. In general, portable instruments spend two thirds of their useful lives in recharging mode. This is a significant problem for the user who conducts sampling activities continuously or during multiple eight-hour shifts in single twenty-four hour periods.

In the following sections, present day electronics technology will be utilized to implement some solutions for the above problems. The performance, cost, and operational convenience tradeoffs will be discussed for each theoretical design approach and documented by test data for the designs which have been realized in the laboratory. Recommendations for the implementation of the appropriate designs in workplace monitoring and compliance determination systems will be made in the Conclusions section.

MOTOR CONTROLLERS

Three basic flow rate control methods are presently being used in motorized portable industrial hygiene air sampling systems. In this section these methods will be reviewed and some new approaches will be discussed. The design, construction, and testing involved with one new method will be described in detail. The design aspects for variations on this method as well as a totally different approach will also be treated.

The fact that a lineal relationship exists between motor speed and sampled air volume for a positive displacement air pump can be used to control flow rate and measure the total volume of air sampled. For a given negative internal pressure drop and elevation above sea level, there is a unique linear relationship between motor rpm and flow rate. For many practical application, where altitude and pressure drop errors do not play a significant role in the total sampling error, it can be said that a single linear relationship exists between rpm and flow rate for positive displacement pumps, regardless of reasonable pressure drops and altitude differences.

A listing of flow rate error percentages for fixed motor rpm as a function of elevation above sea level and internal pressure drop is presented in Table I. The pump whose performance is portrayed in the table is necessarily a "perfect" one in that it is calibrated against a specific rpm versus flow rate line at 0" internal pressure drop at any altitude and no other error in flow rate is included. The talbe has been constructed only to indicate the direction and magnitude of the errors involved. Note that the figures represent decreases in flow rate as altitude and sampling train loading increase and that the most significant error is -3.58% at 10,000 feet and 10" of water pressure drop. Thus, even at the extreme end of the table, errors in a "unique rpm versus flow rate" assumption are insignificant in practical situations which involve much greater errors in the sampling and analytical methods.

One of the worst practical situations is, of course, sampling for particulates or fibers and utilizing gravimetric or human fiber counting methods for analysis. It should be pointed out, however, that the sensitivities of some sampling and analytical methods may require the application of the correction procedures implied by the table. Since most air sampling systems utilize positive displacement pumps, the advantages of this approach will be assumed for the remainder of this section.

The first and perhaps the most prevalent means of flow rate control in present use is known as "manual control". This method, as reflected in the performance requirements,[9] involves the use of reasonably stable pump motors and the assumption that increasing sampling train loadings and decreasing battery pack voltages will result in flow rate drifts which can be maintained to within $\pm 5\%$ by two manual adjustments during an 8 hour operating cycle. This method of flow rate control, therefore, assumes that

TABLE I

Percent flow rate error for a constant rpm positive displacement pump as a function of elevation above sea level and internal pressure drop.

Elevation: (ft.)	(mm of Hg)	Pump internal pressure drop (inches of water): 0	1	2	3	4	5	6	7	8	9	10
0	(760)		.25	.49	.74	.98	1.23	1.48	1.72	1.97	2.21	2.46
1000	(734)		.25	.51	.76	1.0	1.27	1.53	1.78	2.04	2.29	2.55
2000	(708)		.26	.53	.79	1.1	1.32	1.58	1.85	2.11	2.38	2.64
3000	(682)		.27	.55	.82	1.1	1.37	1.65	1.92	2.19	2.47	2.74
4000	(657)		.28	.57	.85	1.1	1.42	1.71	1.99	2.28	2.56	2.85
5000	(631)		.30	.59	.89	1.2	1.48	1.78	2.07	2.37	2.67	2.96
6000	(605)		.31	.62	.93	1.2	1.55	1.85	2.16	2.47	2.78	3.09
7000	(584)		.32	.64	.96	1.3	1.60	1.92	2.24	2.56	2.88	3.20
8000	(558)		.34	.67	1.0	1.3	1.68	2.01	2.34	2.68	3.02	3.35
9000	(543)		.34	.69	1.0	1.4	1.72	2.07	2.41	2.76	3.10	3.44
10000	(522)		.36	.72	1.1	1.4	1.79	2.15	2.51	2.87	3.22	3.58

Notes:

1. Figures in parentheses represent absolute pressure in mm of mercury. Charted figures assume that the sampling device is calibrated for its nominal flow rate at 0" pressure drop at any elevation.

2. To derive other figures: Flow error % = $(-\Delta P / (P-\Delta P))(100)$, where P is absolute ambient pressure and ΔP is pump internal pressure drop. (In. of water x 1.87 = mm of mercury)

3. To calculate rpm correction necessary for the charted flow rate error figures: $P_2 = -P_1 / (1+P_1)$, where P_1 is charted flow rate error percent, and P_2 is the necessary rpm correction percent.

the wearer of these personal samplers is conscientious in carrying out the necessary readjustment procedures and maintaining the proper running times. If these assumptions are true, it can be said that this method of flow control is acceptable in situations of particulate and fibrous dust sampling where gravimetric or similar analytical methods prevail.

A second method of flow rate control is used in some gas and vapor sampling systems and intermediate volume particulate air sampler prototypes. The need for this approach is justified by the increased sensitivity and accuracy in many sampling and analytical schemes, as well as the need to free the user from flow rate adjustments during the sampling process. Furthermore, in the case of intermediate volume particulate samplers, operating above 20 lpm, the previous assumptions of constant motor speed under conditions of varying sampling train loadings and battery pack voltages are much less valid.

This second method of flow rate control is illustrated schematically in Figure 1. The design involves a constant voltage regulated power supply consisting of three additional electronic components over the approach previously discussed: A non-recharageable reference battery, a flow rate adjustment potentiometer, and a Darlington pair transistor. The total unit costs for the additional parts is typically less than $5.00. The circuit will maintain a relatively constant voltage across the motor, as determined by the reference voltage applied to the base of the transistor. It will supply whatever current is required by the motor, up to the practical limit of the batteries, in order to maintain the voltage required for the desired flow rate.

This method of automatic control is fully acceptable for low flow rate devices and for motor loads that do not vary appreciably. However, the following problems exist with this approach:

1. When the main battery is fully discharged, the reference battery will soon become depleted also, if the sampler is left on.

2. The mere presence of a non-recharageable reference battery (usually a small mercury cell) inside the sampler unit is bothersome. The normal lifetime of such a cell used in this application ranges from 3 months to 5 years. This battery is the most expensive of the additional system components, and flow rate recalibration is required with each battery replacement. In some cases, however, the reference battery has been replaced by a zener diode with little loss of flow rate operating range and control.

3. Samplers using this circuit will maintain constant flow rates for a relatively narrow band of sampling train loadings, especially at flow rates greater than 10 lpm.

The laboratory performance of one prototype intermediate volume personal sampler[3] utilizing a constant voltage controller is summarized in Table II. The sampler was developed under a NIOSH contract with the objectives of low power drains and nominal flow rates adjustable over the range of 25 to 75 lpm. The motor controller in the sampler is a

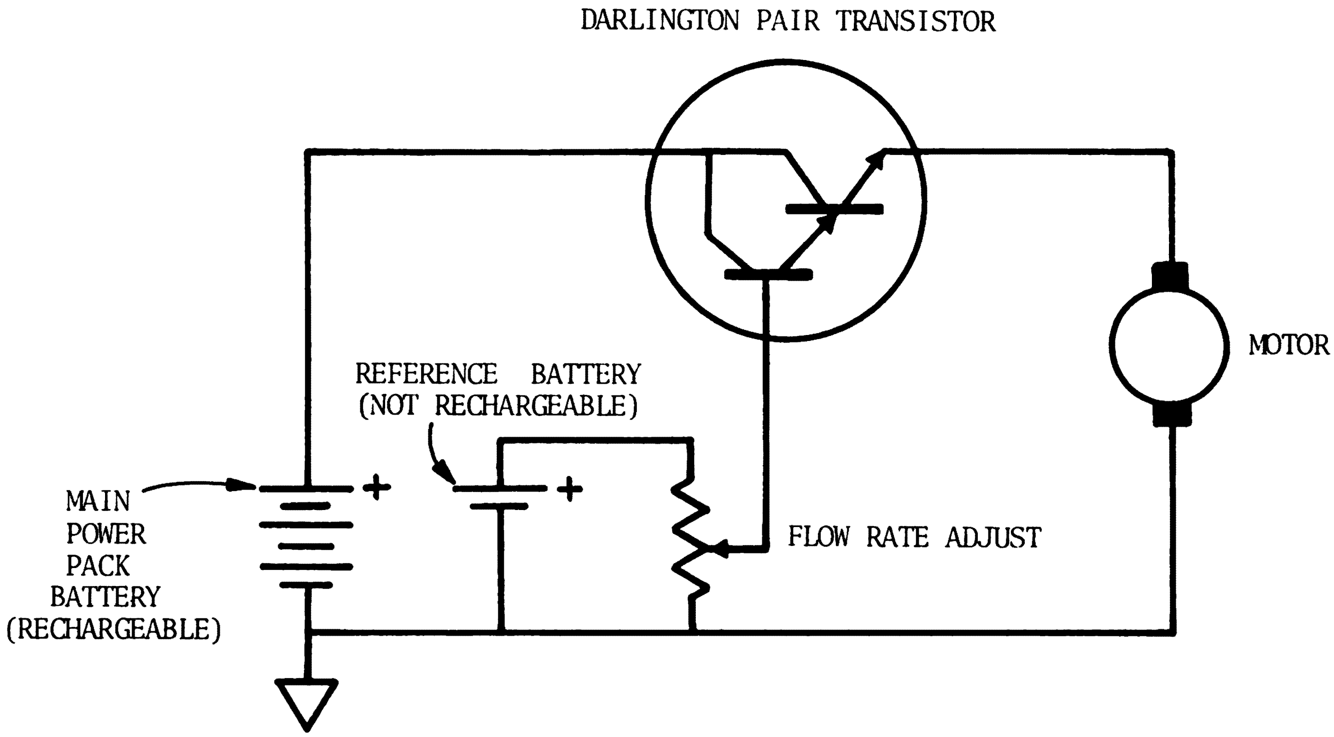

FIGURE 1. Constant voltage regulator circuit as used presently in some air sampling units.

TABLE II

Performance of constant voltage regulator in intermediate volume personal sampler operating at 25 lpm

Pressure drop:[1] (inches of H_2O)	Error in rpm:[2] (%)	Motor Current:[3] (mA)
0.75	0.0	100
0.85	0.0	105
1.00	-2.7	115
1.50	-10.8	140
2.00	-15.4	156
2.50	-23.9	180
3.00	-32.6	205
3.50	-35.3	235
4.00	-45.6	275
4.50	(inoperative)	290
5.00	(inoperative)	305

Notes:

1. Static pressure measured in inches of water, between inside of pump and atmosphere. Pump inlet was closed off by a valve to simulate filter and sampling train loading.

2. For the magnitude of these variations, rpm error percent is equivalent to flow rate error percent, without using Table I.

3. Constant voltage regulator maintains a steady 3.62 volts, supplying only increasing current for an increasing load.

realization of Figure 1 and is capable of maintaining ±5% accuracy at a 25 to 75 lpm nominal flow rate, against ±0.5" of water internal pressure drop, as long as the total pressure drop is less than 2" of water. The performance was considered adequate for the purposes of laboratory prototype testing and light field use. However, it would probably not suffice in many field applications in that extreme sampling train loading variations would probably be present and a direct flow rate measurement capability would not be practical in a field instrument operating at such high flow rates. Without the minimum performance offered by the constant voltage controller, at least, this intermediate volume sampler would be totally useless in any situation.

The third flow rate controlling approach presently in use is more closely connected with the accurate measurement of total sampled air volume rather than the precise control of flow rate, per se. Unlike the particulate air samplers combined with size classifiers and whose size separation characteristics depend on a specific flow rate, flow rate control is not as important as the measurement of total sampled air volume in gas and vapor sampling systems. Therefore, the approach of combining either of the first two flow rate control methods previously discussed with the mechanical counting of total number of pump strokes during a measurement period is quite adequate for gas and vapor samplers. A mechanical stroke counter has been shown to be practical only in samplers which operate at flow rates less than 1.0 lpm and whose motor speeds are less than about 500 rpm. It should be noted that automatic pump stroke counting during a sampling run is a desirable feature in any air sampler, since the calculation of total sampled air volume would thus be independent of errors in running time.

The implicit need for an improved motor controller in intermediate volume particulate air samplers and the need for more accurate total sampled air volume measurements, as well as the inherent shortcomings of the existing flow and running time control methods has resulted in the development of some new approaches in the course of this study. The following features in the performance of an improved system would be desirable:

1. A controller design which automatically supplies variable current <u>and</u> voltage to the motor would result in a constant motor speed over a much broader band of pressure loadings. Such a controller would be called a "power regulator".

2. A feedback control system would maintain tighter control of motor speed with the added advantage of employing amplification techniques to provide the overcorrections implied in Table I. The inputs to such a controller would be a signal indicating the actual speed of the motor and an adjustable reference signal.

3. An electronic means of counting the total number of pump strokes and / or the automatic control of sampler running time during a measurement period would be helpful.

4. Total power consumption for all control circuitry would be less than 10% of the total power consumption of the sampler.

5. Recalibration of sampler flow rate should be simple, direct, and required at very infrequent intervals.

6. Cost should be minimized subject to the constraint that component quality reflects stable performance in environmental extremes and in the absence of any flow measurement devices in the field.

One direct method of sensing motor speed has been described in the computer hardware literature,[10] and is shown in Figure 2. This circuit consists of three resistors and an operational amplifier. The voltage across resistor R (IR_m) is subtracted from the motor voltage ($IR_m + E_b$) to produce an output voltage which is directly proportional to the back emf (E_b) of the motor. Since the magnitude of E_b is linearly proportional to motor speed, the amplifier output voltage is also directly proportional to motor speed. The range of the output voltage is determined by the operational amplifier gain, A, i.e. the ratio of R_f to the equivalent input resistance to the amplifier. For this circuit, speed sensing resistor, R should be about equal to the D.C. motor resistance, R_m, and the other values are not critical. Component quality is not critical here so the use of a temperature compensated Fairchild μA741 operational amplifier will result in acceptable operation and a total parts cost of less than $2.00 for this circuit.

The next step in the development of the power regulator design is the use of the motor speed sensing concept described above to provide an input signal to a feedback control circuit for maintaining constant motor speed and sampler flow rate. A basic circuit to accomplish this is shown in Figure 3. In this circuit, a signal proportional to the motor speed is compared to a reference voltage at the positive and inverting inputs of a power operational amplifier. The reference voltage is derived from a constant voltage source and is adjusted by a potentiometer to produce the proper sampler flow rate. The operational amplifier drives the motor, R_m, directly, supplying whatever power is necessary to minimize the difference between the positive and inverting amplifier inputs, thus maintaining constant motor speed. To minimize wasted power, speed sensing resistor, R, is made as small as possible....on the order of one tenth of the D.C. motor resistance. Resistor R and the op amp must be rated to handle the anticipated maximum power levels that will be directly applied to the pump motor during operation. Resistors R_i and R_r are selected such that they place an insignificant load on the constant voltage source. The ratio of R_f to R_i determines the gain applied to the speed adjust reference voltage and should be set to provide the proper flow rate adjustment range for R_r. The magnitude of R_f is somewhat critical. Significantly above a critical value, determined by the specific circuit parameters of the situation involved, the controller can become quite unstable due to the value of R_f. Slightly above the critical value, stability is assured and the controller overcorrects slightly with increasing motor loads,

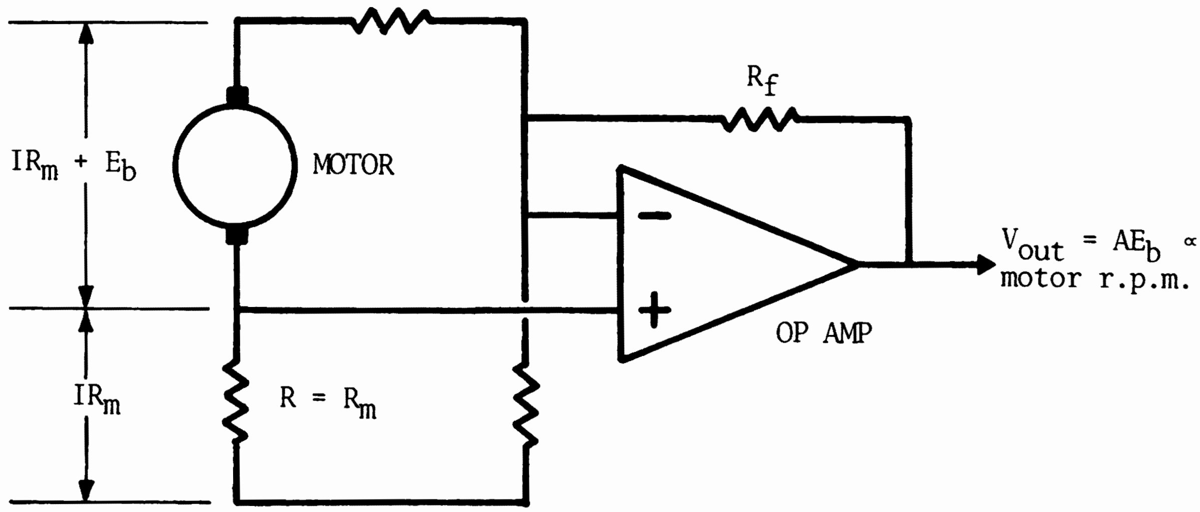

FIGURE 2. Sensing motor speed

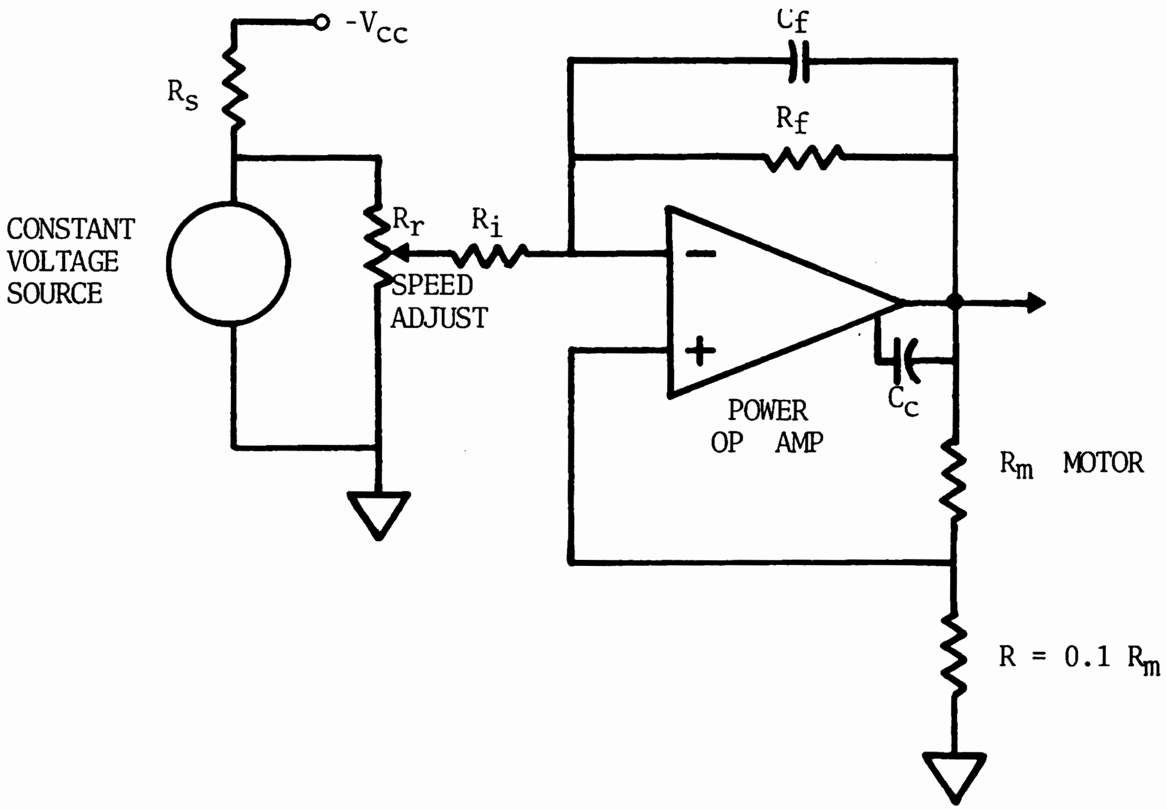

FIGURE 3. Controlling motor speed with a power regulator

accounting for the speed corrections required in Table I, at the optimum value for R_f. For a value of R_f equal to the critical value, i.e. within ±5% of it, the controller will maintain a very constant motor speed for widely varying loads, to the power limit of the battery pack. For values significantly below the critical value, the controller will undercorrect and the flow rate will gradually drift downward as loading is increased. The time constant of C_f R_f (that is, the product of the two values measured in farads and ohms) should be adjusted to a value between 50 and 200 milliseconds, in order to insure stable operation and even flow rate control. Compensating capacitor, C_c is picked to provide the rolloff in frequency response required in the manufacturer's application notes for the amplifier.

In order to realize the power regulator design, the circuit shown in Figure 4 was constructed for the intermediate volume particulate sampler discussed earlier.[3] The circuit in the figure drives the 10 ohm D.C. motor directly and was installed in place of the existing constant voltage regulator whose performance was described earlier. Two additional 1.25 volt NiCad cells were required in the power pack to supply the necessary +5.0 and -2.5 volts. The original battery charger circuit (not shown) required no modifications. The operational amplifier is a one amp National Semiconductor LH0021CK unit,[11] chosen for its power handling capability and adaptability to this design. The component values shown in the figure were arrived at by following the basic design procedure indicated in the preceding paragraph. In this circuit, a value of 190k ohms for R_f comprises the "critical value", which results in neither undercorrection nor overcorrection of the flow rate as the sampling train loading is varied between 1" and 4" of water. For a value of 100k ohms, the degree of overcorrection is commensurate with Table I for the altitude of this laboratory. The performance results are tabulated in Table III. With a slightly more careful adjustment of R_f in the neighborhood of 100k ohms, the flow rate can be controlled to within ± 1% in the range of 25 to 50 liters per minute nominal flow for sampling train loadings ranging from 0.75" to 7.0" of water, either with or without the corrections indicated in Table I. This performance continues throughout an eight hour sampling period at temperatures ranging from 35° to 105° F and for vibration treatments which more than simulate field abuse of the instrument. During the remainder of the laboratory evaluation of the circuit, component or parameter drift was not noted and no recalibration was necessary as the instrument was subjected to a fairly rigorous simulation of field conditions. The following notes are also pertinent to this particular realization:

1. The constant voltage reference is based on the voltage versus current relationship for a light emitting diode, the Texas Instrument type TIL209. The diode is operated at about 20 mA of forward current, supplying both the constant voltage (about 1.65 volts) and the visual indication to the operator that the sampler is operating properly.

2. The circuit, as shown, is believed to be "minimal", in that the

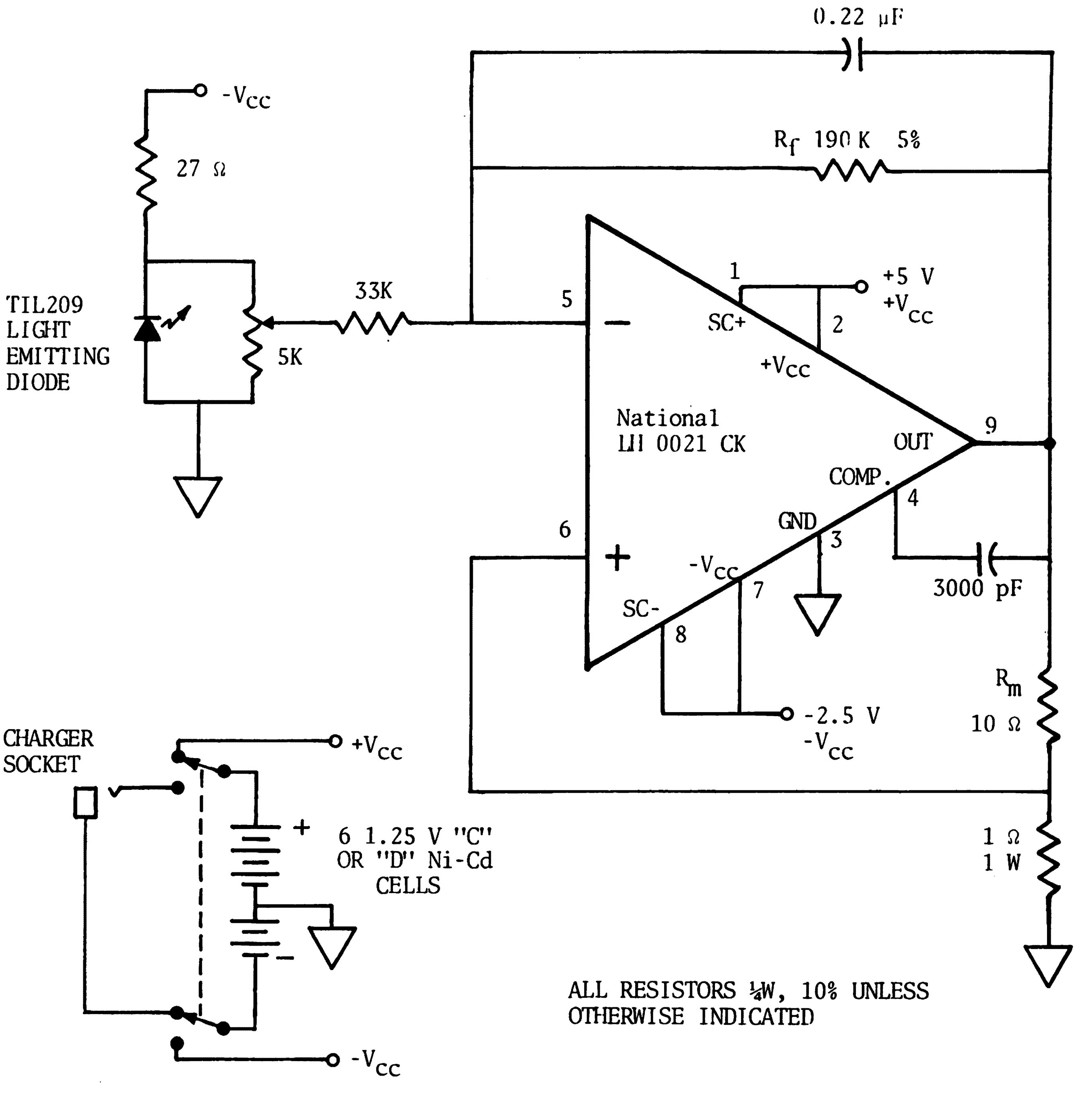

FIGURE 4. Realization for 25 lpm intermediate volume personal sampling pump

TABLE III

Performance of constant rpm variable power regulator in the intermediate volume personal sampler operating at 25 lpm.

Pressure Drop:[1] (inches H_2O)	Error in rpm:[2] (%)	Motor current, voltage, power:[3] (mA)	(Volt)	(Watt)
0.75	0.0	100	3.30	0.33
0.85	+0.2	110	3.34	0.37
1.00	+0.3	120	3.37	0.40
1.50	+0.4	145	3.43	0.49
2.00	+0.6	169	3.49	0.59
2.50	+0.7	194	3.56	0.69
3.00	+0.8	212	3.64	0.77
3.50	+0.9	231	3.72	0.86
4.00	+0.9	255	3.80	0.97
4.50	+1.0	274	3.87	1.06
5.00	+0.8	300	3.95	1.18
5.50	+0.5	310	4.02	1.25
6.00	+0.2	321	4.09	1.31
6.50	-0.6	334	4.16	1.39
7.00	-2.0	340	4.19	1.42
7.50	-5.2	390	4.19	1.64
----	----	(limit of power pack)		

Notes:

1. Inches of water; same as Table II.

2. Apply Table I to obtain new flow rate error. Overcorrections in these figures are intended in the design in order to cancel the effects of Table I data and minimize net flow rate error.

3. Power regulator supplies increasing power (voltage and current), to the limits of the power pack, to maintain constant rpm with increasing load.

reduction of component count would most certainly degrade the performance of the circuit.

3. Referring to Figures 5a and 5b, the laboratory test setup included the sampler, a pressure gauge, a valve to simulate sampling train loading, a strobe light to count and adjust motor speed (through the transparent pump cylinder wall), and a stopwatch to measure sampling intervals. The strobe light was calibrated by a precision electronic frequency counter (not shown).

4. Total parts cost for the power regulator circuit is about $20.00, due mostly to the $16.50 cost of the power operational amplifier. In a production version of an intermediate volume sampler, a design with a lower power op amp, driving a power transistor output circuit would work just as well as this laboratory version, with the total cost for unit quantities of less than $5.00. The power transistor output circuit will be presented in a later design in this section.

5. Calibration of a field version of this design should be a two level process. First, the flow rate vs rpm curve should be checked annually by the direct measurement of both flow rate and rpm. Second, weekly checks of the motor voltage should be made under a given loading condition, such as a clean filter and sampling head. Flow rate measurements and readjustments should not be necessary at other times, especially during sampling operations.

6. The total current drawn by this circuit, not including the motor, is 30 milliamps, 25 of which is due to the light emitting diode, and 5 for the rest of the circuit. Currents, voltages, and powers for the motor, itself, are tabulated in Table 3, given the various loadings. Note that the motor of this 25 lpm sampler draws less power than most 2.0 lpm samplers that are presently commercially available.

The new design that has just been described introduces a level of precision and dependability in automatic flow rate control that should be more than adequate for any air sampling situation. The applications need not be limited to portable instruments, nor to systems with small motors, but rather applied wherever precise flow rate control via constant motor speed is required. Of course, the technical necessity and economic desirability of such precision should always be balanced, especially in the light of consideration of an analytical method involved and careful assessment of the applicability of the design to the situation.

The design developed above has no provision for the control of total sampler running time or the measurement of total sampled air volume. Accordingly, an alternate approach will now be presented, as illustrated in Figure 6. A slotted opaque disc, fastened to the pump motor shaft interrupts

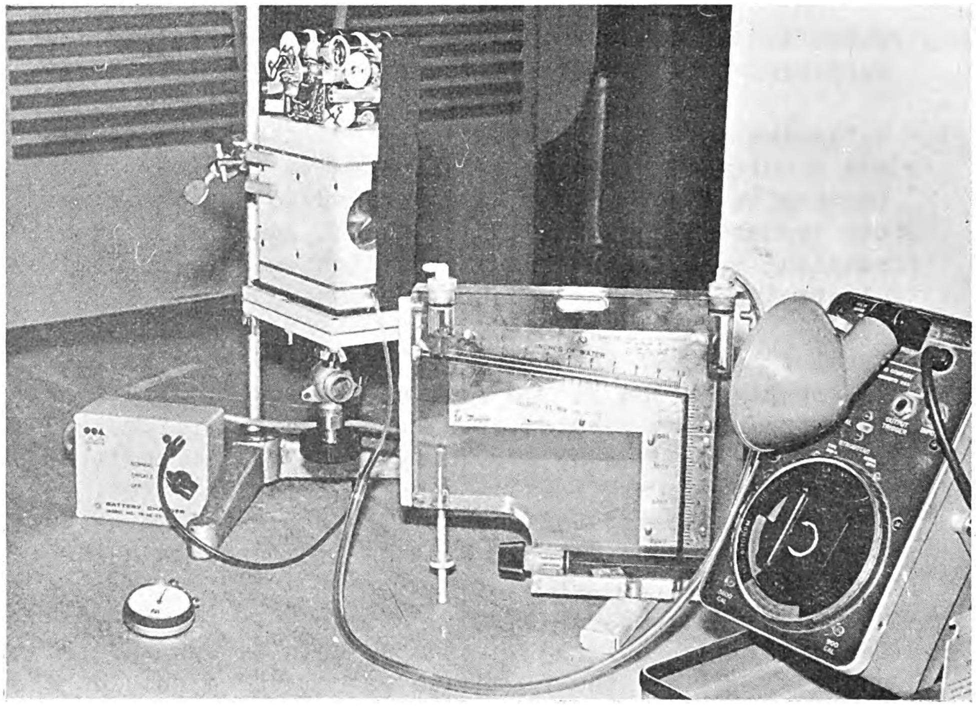

FIGURE 5a. Test setup for power regulator and intermediate volume personal sampler.

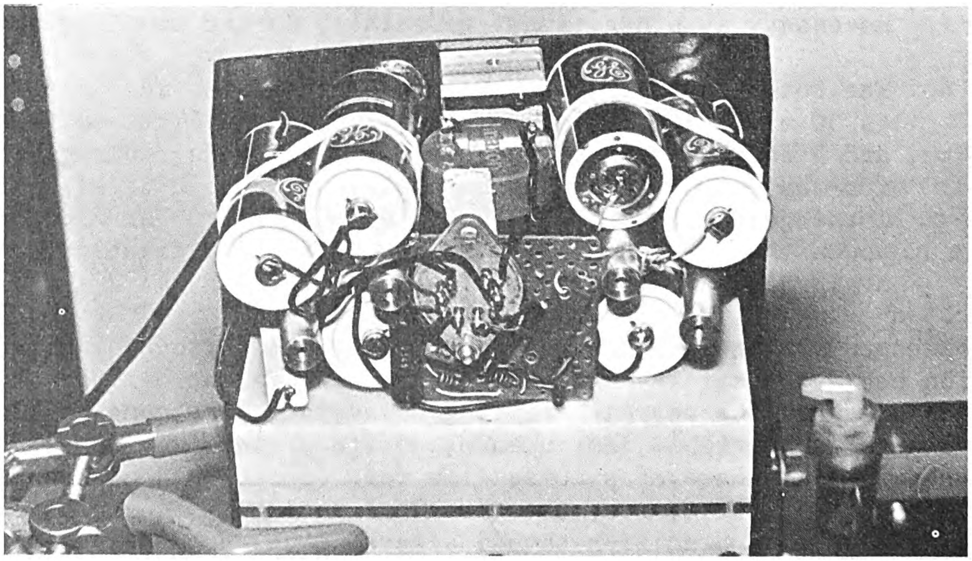

FIGURE 5b. Closeup of motor controller and power supply section of 25 lpm intermediate volume personal sampler.

a light beam, causing the beam to pulsate with a frequency proportional to the motor speed. A phototransistor converts the beam into electrical pulses which are fed to a phase locked loop (PLL) integrated circuit. The PLL is used in a feedback loop which holds the motor speed constant by adjusting the motor voltage to compensate for changes in the light beam pulsation frequency. The pulses from the disc can be fed to a counter which can be used to monitor the number of revolutions the pump motor has made during a given period of time, thus determining the total sampled air volume. Very simple control circuitry can also be added to shut the pump off and/or sound an alarm when a given volume has been sampled or a given time has passed.

Detailing the operation of this circuit, reference is made to Figure 7. Light generated by a light emitting diode (LED) is picked up by a phototransistor except when interrupted by opaque sections of the slotted disc. The phototransistor and LED can be incorporated in a single opto-interruptor module or they can be separate components. The generated signal is fed to a phase locked loop. The PLL produces a DC voltage proportional to the difference between the input frequency and the reference frequency generated in the PLL. This voltage is amplified and fed to the pump motor. Any change in motor speed causes a change in the frequency created by the rotating disc. This is detected, amplified, and fed to the motor as an error signal. The result is a control unit that holds the frequency and motor speed extremely constant. The PLL in the figure is an Exar type XR-215 phase locked loop.[12] A single 5 to 6 volt supply, corresponding to 4 or 5 NiCad cells, is used. Since the controller uses frequencies for speed sensing and control, it is relatively insensitive to varying power supply voltages. The XR-215 was chosen because it will run with a supply as low as 5.0 volts.

The circuit is designed for a 920 rpm motor (25 lpm for the intermediate volume personal sampler discussed previously) with a six slot disc, giving a 92 Hz signal from the phototransistor when the speed is correct. The PLL's reference oscillator is set to this frequency by R_x and C_0, according to the equation:

$$f_0 = \frac{200}{C_0} \left\{ 1 + \frac{0.6}{R_x} \right\} \quad \text{Hz},$$

where C_0 is in microfarads, R_x is in kilohms, and f_0 is in Hz. The pump speed control adjusts this frequency to a value between 87 and 97 Hz, and is calibrated by measuring the frequency at pin 15 of the XR-215 with pin 6 grounded or with the slotted wheel stopped. If another frequency is desired, C_0 and/or R_x should be changed accordingly. Large changes in f_0 may require C_1 to be changed also. The approximate value of C_1 is given by:

$$f_0 = 500/C_1 ,$$

where f_o is in Hz and C_1 is in microfarads. This is only an approximation. If C_1 is too large, response to variations in loading will be sluggish. If C_1 is too small, perturbations in loading will cause pulsations in motor speed.

The GAIN control adjusts the gain of the amplifier that feeds the output transistor. If the gain is set too high (large R_f), the system may overshoot the desired speed before settling down. If too low, R_f will cause the speed to lock in too slowly. Proper adjustment allows a small degree of overshoot. Production versions of this circuit would use a fixed resistor of the proper value. R_b biases the output transistor on and it may or may not be necessary in the realization of this design. If the controller has difficulty maintaining full motor speed at maximum load, R_b should be added, and the use of a Darlington pair transistor in place of Q_2 may be necessary. Pump motors which require more than about 500 ma of drive current will also require a larger output transistor. Incidentally, the Q_2 output stage shown here could also form the basis for the output stage for a low power op amp in the previous controller design. This would save the cost of the high power op amp, as alluded to earlier.

The following miscellaneous notes are also pertinent to this design:

1. Other phase locked loop integrated circuits can be used in this design, including the Signetics 560 series and the Motorola PLL group. Both of these families share the advantages of lower cost, but the tradeoffs of performance, convenience of power supply voltages, etc., are also involved. For more information, see the manufacturer's data sheets and the other pertinent references [13-15].

2. This design was not implemented in the laboratory and it would therefore be necessary to breadboard and debug it somewhat.

3. The total unit quantity parts cost for this design would be on the order of $25.00.

4. If the level of sophistication of the flow controlling aspects of this circuit are not required, the interrupted light beam concept can be utilized just to drive a stroke counter to determine the total sampled volume or to control running time. The advantages of this approach over the mechanical pump stroke counters now being used are that moving parts would be kept to a minimum and that the stroke counting approach could be used on higher volume samplers than before. Parts costs for such an approach would be below $25.00, and the design is quite straightforward.

5. A Signetics NE555 Timer integrated circuit could be incorporated into any of these designs, resulting in the ability to automatically set the running time of the sampler. The wearer of the sampler would then push a single "start" button at the beginning of the sampling interval, and the unit would automatically stop at the end.

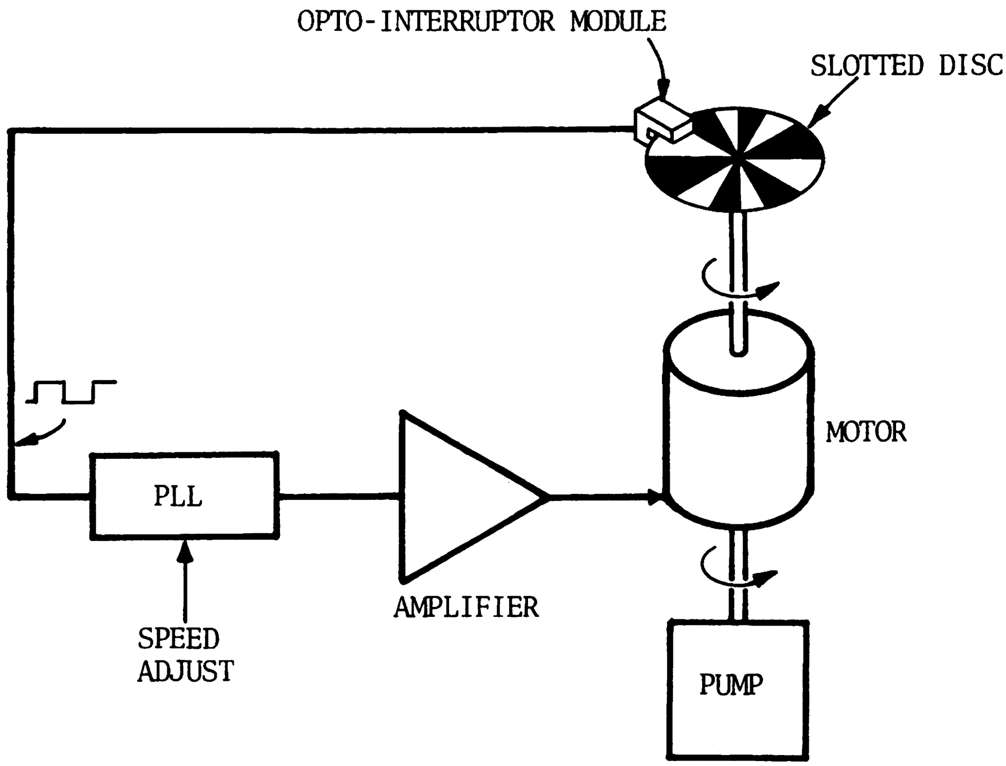

FIGURE 6. Photoelectric speed control block diagram

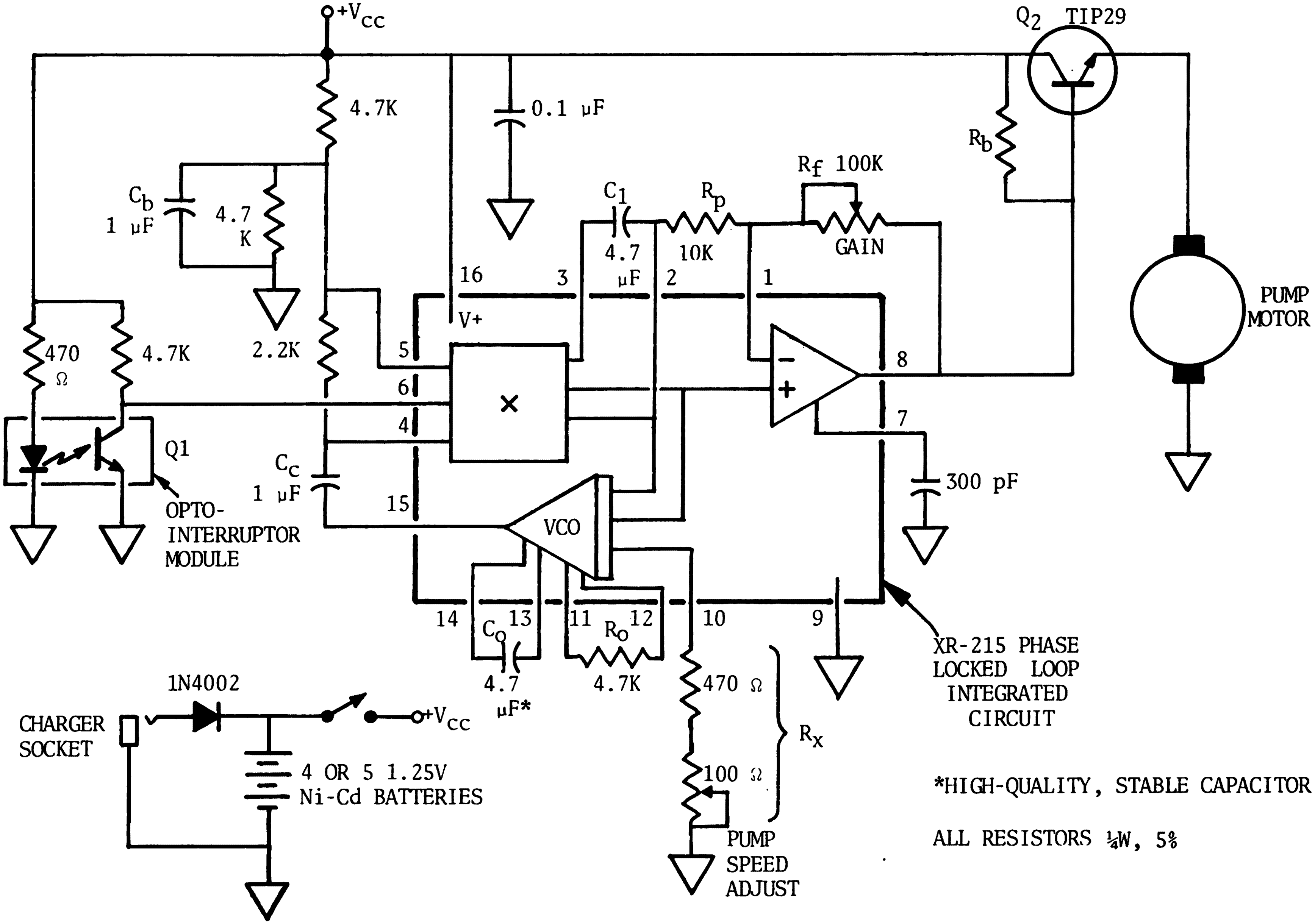

FIGURE 7. Photoelectric speed control circuit

RECHARGEABLE BATTERIES

Rechargeable or "secondary" batteries are electrochemical devices which are widely used to supply energy for portable industrial hygiene instrumentation. Since the time of the design efforts to which we owe the present state of the art in portable instruments, the following improvements in rechargeable battery technology have occurred:

1. High temperature batteries -- up to 65° C continuous operation

2. Quick charge batteries -- reach full charge in 3 to 4 hours

3. Fast charge batteries -- reach full charge in less than 1 hour

4. Standby power batteries -- years of extended operation and rough treatment

In this section, the technological improvements listed above will be used to suggest methods by which the performance and cost effectiveness of portable industrial hygiene instrumentation, in general, can be substantially upgraded. Specific design realizations will not be given but sufficient guidelines and references will be provided in an attempt to motivate the implementation of these improvements in portable systems which should become available within the next two years.

Anyone who has had to purchase, inventory, or replace batteries for presently available portable instruments is aware of the rapid acceptance of Nickel-Cadmium rechargeable batteries for many applications. Among the most significant features of "NiCads" which lead to their choice as the preferred power source are the following:

1. NiCads have a very long operating life, measured either by number of charge/discharge cycles or by years of useful life. Most NiCads will operate for more than 1000 charge/discharge cycles, or for many years in ready-to-serve standby function.

2. The NiCad battery is designed to accommodate extended overcharge current, at very low charge rates, with no noticeable effect on performance or life. If satisfied with slow charging rates, the designer can use very simple and relatively inexpensive chargers.

3. NiCads can deliver energy at very rapid rates; achievable without degrading cell performance or life.

4. Sealed NiCad cells can be operated in any position, without electrolyte spillage.

5. With proper charger and battery design, as will later be discussed, NiCads can be charged very quickly.

6. The NiCad cell can be stored for many years, with no degradation of cell performance.

7. NiCad cells are maintenance free.

8. The NiCad cell delivers a nearly constant voltage throughout most of the discharge period.

The sealed Nickel-Cadmium cell is an electrochemical system in which the electrodes containing the active materials undergo changes in oxidation state without any change in physical state. These active materials are highly insoluble in alkaline electrolyte. They remain as solids and do not dissolve while undergoing changes in oxidation state. Because of this, the electrodes are long lived, since no chemical mechanism which would cause the loss of active materials exists. In the NiCad cell, nickel oxide hydroxide is the active material in the positive plate. During discharge, the nickel oxide hydroxide, NiOOH, goes to a lower valence state, $Ni(OH)_2$, by accepting electrons from the external circuit. Cadmium metal is the active material in the negative plate. During discharge, it is oxidized to cadmium hydroxide and releases electrons to the external circuit. During charging, these reactions are reversed. The net overall reactions occur in KOH electrolyte and can be expressed as follows:

Discharge: $$Cd + 2H_2O + 2NiOOH \rightarrow 2Ni(OH)_2 + Cd(OH)_2$$

Charge: $$2Ni(OH)_2 + Cd(OH)_2 \rightarrow Cd + 2H_2O + 2NiOOH$$

Most sealed cells contain a pressure relief safety vent which opens only if the internal pressure of the cell reaches a predetermined level. Normally, the cell pressure will never reach such a high value because sealed cells are designed to operate under normal conditions at low gas pressures. Since these gases are usually retained within the sealed cell, the cell is designed to limit internal pressures on charge or recharge. Within the cell, oxygen acts as sort of a chemical short circuit, enabling the sealed cell to be continuously overcharged without an excessive increase in internal pressure. Thus, sealed cells can be kept on slow overcharge current for long periods of time without noticeable loss of performance.

TABLE IV

Definitions of rates for charging and discharging of Batteries

Method of Charging:	Nickname:	Current Rate:*	Hour Rate:**
Standby	"Trickle"	C/100	100 hr.
		C/50	50 hr.
		C/30	30 hr.
Slow	"Overnight"	C/15	15 hr.
		C/10	10 hr.
Quick	"Hustler"[a]	C/5	5 hr
	"Goldtops"[b]	C/4	4 hr.
		C/3	3 hr.
		C/2	2 hr.
Fast	"Powerup-15"[b]	C	1 hr.
		2C	30 min.
		4C	15 min.

Notes:

*The notation which includes the letter "C" is used to describe current rates in terms of a fraction of the nominal capacity rating of the battery. A comparison of cells from different manufacturers requires rationalization to a common standard for nominal capacity rating at the same discharge rate.

**The hour rates, associated with both discharging and charging the battery, are in terms of discharge time at the nominal capacity rating of the battery. Of course, the charge input must always be more than the discharged output.

[a] Trademark, Union Carbide Corp.

[b] Trademark, General Electric Corp.

Two important electrical characteristics of the NiCad cell are the battery charge and discharge rates. These rates are expressed in multiples of the "C" rate. A cell discharging at the "C" rate will expend its nominal rated capacity in one hour. Likewise, a cell charging at the "C" rate will be fully charged in one hour. At the 0.25 C rate, the rated capacity will be delivered in four hours. Table IV describes the normally used charging current rates for presently made NiCad batteries. Note that only "standby" and "slow" charging levels are permitted in <u>all</u> rechargeable portable instruments presently available for industrial hygiene use.

There are at least three characteristics of sealed NiCad cells that are important to the battery system designer since they determine the permissible charging rate. First, the charge voltage, or the voltage that the cell develops under charge, must be slightly higher than the rated discharge voltage, ranging from 1.4 to 1.6 volts for each cell whose normal discharge voltage is 1.25 volts. During charging and over-charging, the internal cell pressure is an important consideration, since it increases due to the generation of oxygen. Thirdly, the cell temperature is important in that it increases during overcharging due to the heat generated by the recombination of oxygen on the negative plate as well as the reduction of cadmium hydroxide to cadmium metal. During rest in the charged state as well as during normal discharging, NiCad cells normally exhibit no difficulties in maintaining the proper voltage, pressure, and temperature relationships. The importance of these parameters during charging, however, is often critical, as reflected in Table IV. The permissible charging rates are directly a function of the manner in which these three parameters are handled within the cell.

For many years, users of NiCad cells had to be content with a 16 to 24 hour recharge time to bring a discharged battery back to full capacity. This is still true, unfortunately, for users of <u>all</u> presently available rechargeable portable industrial hygiene instrumentation. This means, for example, that the user of an instrument such as the GCA RDM-101 respirable dust monitor,[7] is allowed to use his rather expensive instrument for sampling in the workplace for only 3 hours before setting it aside for 14 hours in order for it to become fully recharged. Further examples of potentially wasted resources are evident throughout the spectrum of portable rechargeable instrumentation presently on the marketplace and in the advanced prototy!e stages of development. As Table IV indicates, however, two new types of batteries are now commercially available, namely: The "quick-charging" battery and the "fast-charging" battery.

The "quick" charge rate is defined in the NiCad battery industry as one that will recharge a discharged battery to full capacity in 3 to 5 hours. At least two manufacturers offer quick-charge batteries as part of their regular product lines,[17,18] at a unit quantity cost which ranges from 10% to 15% higher than regular NiCads. The fact that quick-charge batteries can be charged at the 0.3C to 0.5C rates means that a partially discharged battery can be returned to full capacity in an hour or two. The ability of these cells to withstand and control elevated pressures and temperatures in normal operation is attributable to numerous improvements in cell design and construction.[17,18] Thus, the following advantages are available to the designer and user of systems using quick-charge batteries:

1. On the average, recharging time can be cut from 14 to 3 hours, a savings of 80%.

2. In discharging mode, there is no difference between quick charge cells and those that are currently being used. Therefore, no modifications are required in the instrument in which these batteries supply power. The user simply replaces the present cells with the equivalent type of quick-charge units.

3. Except in charging mode, no problems exist with regard to the performance of these cells in explosive environments, approval for intrinsic safety, etc., that do not exist with presently used equivalent cells. In other words, the terminal characteristics of the two cell types are virtually identical.

4. When charging in non explosive atmospheres, the only requirement for the new cells is a charger which supplies current at the increased rate. No automatic sensing or control of charging that doesn't exist with presently used cells is required. Therefore, the cost for the charger is as low or lower than for those presently used and, in fact, it is possible to make minor modifications to some of the present charging units to operate satisfactorily with the new cells.[17,18]

5. These cells can withstand significantly higher ambient and internal temperatures during all phases of operation than presently used cells. Both manufacturers indicate strong evidence for an increased life expectancy for the new cells as a function of environmental abuses, over the presently used units.

6. The cost effectiveness of this approach can be very high for the frequent user of expensive portable instruments.

The second approach to rapid charging is the more comprehensive system implied by the "fast" charge battery system concept. The definition of this system includes any battery capable of charging at the 1 hour rate or faster, without suffering permanent damage. Typically, such batteries are capable of reaching 90% of their rated charge in less than 15 minutes with unit battery costs on the order of 25% higher than equivalent cells of the present types used in portable instruments. The benefits of having such a battery/charger system in a cordless electrical product are:

1. Ability to use the full capacity of the battery several times each day.

2. Products can be designed with smaller, lighter weight batteries in place of large, bulky batteries, thus providing mobility and flexibility.

3. The capability exists to recharge fast enough to permit use of the produce without hours of advance planning.

4. Products can be continuously operated with two sets of batteries, one on charge while the other is in use.

A number of considerations in the design of fast-charge battery systems are in order, specifically for the charging operation, since the standby and discharging modes are, again, identical to those of all other NiCad cells. First, a temperature or pressure transducer must be designed into the charger unit to detect full charge conditions and effect a termination of the extremely high charging rate before the overcharging region of operation is begun. Usually, the heat generated by the cells provides a means by which the full charge conditions can be detected, either by a thermostat or a thermistor. In some cells, thermistors or bimetallic thermostats are integrated into the cell, itself.[18] In other situations, special heat conductive canisters are constructed to house the batteries during charging and are fitted with heat sensitive solid state devices. Obviously, the design and manufacturing costs associated with the more sophisticated charger required for this type of cell are higher than with any other approach. The design procedures, diagrams, charts, cost estimates, and the like are very well documented by the manufacturers of these cells.[17,18,19] Summarizing, the basic advantages of the "fast" charge battery systems are as follows:

1. Other than the charging system and the charging process, the terminal characteristics of these cells are such that direct replacement of equivalent cell types is possible for any cordless instrument designed for NiCad cells, in just the same manner as the quick-charge types.

2. The design of the charging system and the carrying out of the charging process is very straightforward. Except where atmospheres may be explosive, ambient conditions have very little effect on the charging operation and it could thus be carried out virtually anywhere.

3. As a general statement, the implementation of fast-charge batteries seems highly advisable for portable cordless instruments that, in themselves, have unit costs greater than $2,000. Where one charger can be used for more than one instrument, the break even point is, of course, quite lower, since the battery costs are only about 25% higher than for most "slow" charge cells.

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

In summary, the rationale for some improvements in portable industrial hygiene instrumentation has been presented. The general areas in which these improvements can and should be realized have been indicated from both the technical and economic standpoints. The technological, economic, and practical feasibility of improving the state of the art in certain types of air sampling instruments has been illustrated with performance requirements, designs, laboratory realizations, test results, and preliminary cost data. The manner in which the performance and cost effectiveness of existing rechargeable portable instruments may be improved by the implementation of "quick" and "fast" charging batteries has been demonstrated. Ample evidence has been provided to indicate the existence of similar innovations in other fields of endeavor. The existence of competitive and stable markets for the procurement of the necessary hardware to realize these improvements in the industrial hygiene field has been assured. Throughout the development, the appropriate reference materials have been cited for future work in these areas.

As a result of this study, the authors have arrived at the following conclusions:

1. Regarding personal particulate air sampling systems using low flow rates and gravimetric analytical methods: It is not technically or economically feasible to implement the improvements described in this report, other than the possibility of using quick charge batteries as replacements for present units. The feasibility of these battery replacements would be highly justified for situations in which samplers would be used continuously on a 24 hour basis.

2. Intermediate volume (5 to 75 lpm) air sampler performance and cost effectiveness would improve substantially with the implementation of either new motor controller design and either of the two rapid charge battery approaches. For this specific type of air sampling instrument, these refinements make the difference between unreliable and highly reliable operation for varying loads and environmental conditions encountered in the field.

3. Any air sampler which is used as part of one of the more sensitive and selective sampling and analytical schemes should employ a flow rate controller and/or pump stroke counter with performance and cost features commensurate with the improvements presented here.

4. The photoelectric pump stroke counter portion of one of the motor controller designs can be used to provide total sampled air volume measurements for all instruments in which mechanical stroke counters would be too expensive and/or physically impossible to implement.

The running time could thus be either accurately controlled and measured or totally neglected in the appropriate contaminant concentration calculation. This includes all types of air sampling instruments.

5. The applications of motor controllers are not limited to air sampling systems. For example, a motorized portable breathing apparatus can be modified to include a motor controller which can supply fresh air to the respirator as it is required by the user.[20]

6. The use of rapid charge batteries in all cordless industrial hygiene instruments becomes more cost effective, efficient, and technically desirable as the acquisition and operating costs of these instruments increases...especially for instruments that are used continuously or for extended periods of time.

As a primary recommendation, the authors strongly suggest that the technologies described in this report be implemented through development of commercially available industrial hygiene instruments, as indicated in the conclusions above. One way in which this can be accomplished is to motivate further technical innovation in the development and market availability of improved instruments, as appropriate. Instrument performance regulations and procurement specifications should be upgraded to reflect the technical improvements which have occurred in the past four years in the electronic components industry. Many prospective buyers of sophisticated cordless instruments should demand rapid charge battery systems as options for their applications, thus optimizing the cost effectiveness of their purchases. Many existing instruments are not subject to most of the improvements suggested here. However, some of the more recent analytical methods and sampling criteria are in need of significant improvements in the performance of the appropriate sampling hardware in order for the overall sampling and analytical approach to be valid.

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