DEVELOPMENT OF A CHAIR FOR MONITORING MICTURITION OF SMALL FEMALE CHILDREN

by

Arthur R. Giaquinta and John R. Glover

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E R R A T A

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Page	Paragraph	Line	Correction
Abstract		7	Change "instrumentating" to "instrumentation"
1	1	13	Change "frequency" to "frequently"
2	2	2	Change "technuqies" to "techniques"
2	2	5	Change "suprepubic" to "suprapubic"
2	3	3	Change "boilet" to "toilet"

ABSTRACT

A monitoring chair has been designed to permit recording of the voiding patterns of young female children in a natural and uninhibiting environment. The chair utilizes a standard bathroom toilet in order to present a familiar image to the patient. Patients void whenever they have a natural desire to do so and there is no external filling of the bladder. The data are obtained in the form of recordings of urinary outflow volume and volume flow rate, both as functions of time; and because there is no instrumentating of the patient, preoperative and postoperative studies may be made in addition to studying healthy children to obtain normal micturition patterns. Detailed descriptions and results of dynamic testing of the detection and electronic systems are presented.

Introduction

Recurrent urinary tract infections in small children, particularly females, are recognized as one of the present leading problems in urology. The gravity of the attendent problems is discussed at length by Leadbetter [1]. Some of the factors which may play a role in producing these infections are (1) congenital and acquired urethral narrowings, (2) redundant urethral mucosa, and (3) poor emptying of the periurethral glands. The primary cause of urinary tract infections is unknown; but persistence of these infections can cause irreparable damage to the upper and lower urinary tracts and can result in severe complications and even renal failure in middle age. There are some indirect indications that these infections result from abnormal voiding patterns, such as incomplete emptying of the bladder or urethra, which can result in non-sterile urine. The retrograde movement in the ureter frequency noted in these children might also be explainable in terms of the hydrodynamics of the voiding process. However, pursuit of a fluid dynamic explanation of chronic lower urinary tract infections has been severely limited by the absence of data on voiding patterns in healthy children, and of reliable data on children with these problems.

A number of urological studies have been made on young females in recent years, but the data obtained from these studies are unreliable for several reasons. Scott, *et al* [2,3] tried to apply to the human urethra the same physical principles that were used in earlier experiments on flexible tube models. Regardless of the validity of the models and the accuracy of the instrumentation, the recordings presented as voiding patterns of female children are questionable for two main reasons: (1) the psychological effect of forced voidings in an unnatural environment; and (2) the presence of a catheter in the urethra. To be more explicit, the patient was forced to void, by filling the bladder externally through a urethral catheter, while sitting in an unnatural position on a strange "commode" in the presence of many instruments, recorders, motors, etc., — hardly the private, homelike atmosphere which would be conducive to normal voiding. In addition to adverse psychological effects, the presence of a catheter in the urethra most likely interfered with the normal voiding process, particularly in this case since the catheter was slowly withdrawn during micturition [4].

Whitaker and Johnston [5] have designed an interesting device utilizing the momentum of the urine stream to obtain information about urinary outflow resistance. They also recorded bladder pressure and volume voided as functions of time. As in the work described above, the validity of the theory of the measurements and the reliability of the instrumentation are not being questioned. However, the technique used in monitoring a micturition, as illustrated in Figure 1, can only give questionable information related to the normal voiding process. As seen in the figure, the patient was standing, a needle was inserted into the bladder suprepubically, and the patient was again in the presence of various instruments, machines, and recorders. It should also be mentioned that the method used for recording the volume of the urine flow versus time introduced artifacts which would negate the validity of the volume-time tracing.

There are many other papers which report studies of voiding patterns of young females [6,7], but because of the technuqies employed to stimulate and record voiding (external filling of the bladder, presence of catheters in the urethra during micturition, unnatural position of the patient during voiding, anal catheterization, suprepubic needles, etc.) the techniques cannot be applied in studies of healthy children to establish normal voiding patterns. Hence, the object of the present work was to improve the techniques for studying the voiding process of young female children in a natural and uninhibiting environment. An additional advantage provided by the system developed in the present study is that voiding patterns in patients may be studied both preoperatively and postoperatively without inconvenience or harmful side effects.

The monitoring chair was designed to permit recording of the voiding patterns without instrumenting the patient, and utilizes a chair that presents to the patient a familiar image: a standard bathroom boilet. The data are obtained in the form of recordings of urinary outflow volume and volume flow rate, both as functions of time. Patients void whenever they have a natural desire to do so, and there is no external filling of the bladder.

Design of the Voiding Chair

As indicated some of the information relevant to the voiding process which can be obtained without instrumenting the patient is the time variation of urinary volume outflow and volume flow rate. This information can be determined by using the simple principle of hydrostatics,

$$p = \gamma z \tag{1}$$

where p is the pressure on a horizontal plane located at a distance z below the free surface of a body of a homogeneous fluid at rest having a specific weight of γ. If a certain amount of fluid is added to a container with constant cross-sectional area, A, the rise of the free surface, h, will be sensed as an increase in the pressure, p. The quantity p, which can be sensed by a transducer, is then directly proportional to the volume inflow, V.

$$\Delta V = (A/\gamma)\ \Delta p \tag{2}$$

The instantaneous volume flow rate, Q, can then be determined by differentiating the volume inflow with respect to time,

$$Q = dV/dt = (A/\gamma)\ dp/dt \tag{3}$$

This differentiation can be performed electronically and recorded together with the undifferentiated pressure transducer output to obtain the information desired. These same principles were used in 1957 by von Garrelts [8] to obtain voiding patterns from male patients. However, the design of von Garrelts' system cannot be used for voiding studies of young females.

To be effective in eliminating any adverse psychological effects which may disturb the normal voiding process, it was decided that the voiding chair should be designed around a standard bathroom toilet with all of the electronic and hydraulic appurtenances completely out of the sight of the patient (Figure 2). The toilet which was chosen for the construction of the chair was a Champlain Model, number K-3390-EBA, manufactured by the Kohler Company of Kohler, Wisconsin. This model is the so-called "low silhouette" model, and was chosen because of the manner in which the pressure transducer could be mounted in the water closet. The chair was mounted on an 8-inch high wooden platform with casters to facilitate movement.

The major revision which was made to the toilet was the addition of a cylindrical receptacle, approximately 3 inches in diameter and 4 inches high, for storing the urine during voiding (Figure 3), and a large, steep funnel which directed the urine into the cylinder (Figures 4 and 5). Four equally spaced pressure taps were mounted in the vertical wall of the cylindrical vessel close to the bottom. The four pressure taps were connected to a manifold located in the water closet (Figure 6) by means of 3/16-inch I.D. Tygon tubing, and the manifold was connected to a Statham Model PM5TC ± 0.15 psid transducer. The tubing used for this latter connection was nylon with a 0.055-inch I.D. This arrangement was chosen in order to smooth the effects of the fluid surface fluctuations in the cylinder — the manifold averaging the pressure and the small nylon tubing providing viscous damping. The cylinder, which had a bottom attached to it, was seated inside the toilet bowl directly over the drain and was firmly cemented to the porcelain by a silicone rubber bathtub caulk manufactured by the Dow Corning Corporation.

Proper operation of the pressure measuring system depends on the complete elimination of all the air from the cavity of the transducer, the manifold, and all of the tubing between the pressure taps in the cylinder and the transducer. To accomplish this the small reservoir connected to the transducer is filled with distilled water, and a cap which has a suction line connected to it is tightly placed over the cylinder. Lowering the pressure in the cylinder by this means creates a pressure gradient from the transducer reservoir through the transducer, manifold, and lines to the cylinder. This pressure gradient causes the distilled water to flow through the system and thereby eliminates the possibility of urine coming in contact with the pressure transducer. To facilitate removal of the air bubbles, a drop of Kodak Photo-Flo is added to the water in the small reservoir. When the air is removed, the suction is stopped and the cap is removed from the cylinder. Before replacing the funnel, its surface is wiped with Lustre-Creme hair shampoo to reduce surface tension effects.

Electronics

Extremely reliable DC amplification, the type associated with chopper-stabilized DC amplifiers, of the pressure cell output is not required because the flow rate, Q , is obtained by differentiating the amplified pressure cell signal, and because the total time interval for recording volume is of the order of a few seconds. Hence, the Burr-Brown Model 3090/25 was selected for amplifying the pressure cell signal, and its gain is adjusted to give five volts, which corresponds to full-scale meter deflection, when full-scale pressure (±0.15 psi) is applied to the pressure transducer.

Following amplification the signal is conditioned by a third-order low-pass Butterworth filter. This suppresses the higher frequency fluctuations to an acceptable level for differentiation. The 3 db frequency is 2 Hz and the gain of the filter in the pass band is -1. The filtered signal corresponding to volume voided is connected to an output jack, a metering network, and the differentiating network for obtaining the volume rate of flow. The differentiating network consists of an operational-amplifier differentiator with a time constant of 0.4 seconds. An integrating capacitor is incorporated into the feedback network to prevent differentiation of the high-frequency components of pressure-transducer signal. The time constant of the integrating network is 5 milliseconds. Recording of these signals is accomplished by a Beckman Instruments, Incorporated, Type RS Dynograph.

The operational amplifiers used for both the differentiating circuit and the active filter network are Philbrick/Nexus Model SA-2. Figure 7 is a block diagram of the system and Figures 8, 9, and 10 are schematics of the individual networks.

Dynamic Response Characteristics

Dynamic limitations were purposely imposed by the low-frequency active filter conditioning the pressure cell output signal in order to reduce the effects of free-surface disturbances on the recorded signal. However, normal frequency response information concerning the spectrum of the filter is of little value for evaluating the transient response capabilities of the system because of the form of a micturition flow curve. A rise-time specification in conjunction with percentage overshoot indicates the response to a step change in input, but again this is of little value because it does not give continuous dynamic behavior information for a wide range of changing flow rates.

To determine how quickly the system responds to a change in flow, an "unsteady flow simulator" was designed which would produce a continuously rising water surface. The rising water surface was achieved by submerging a solid cone at a constant velocity into the partially filled storage cylinder. The unsteady rise of the free surface in the cylinder, sensed and recorded in the usual manner, generated a variable flow for determining the dynamic characteristics of the measuring system. Figure 11 shows the cone and the mechanism used for driving it. The sudden transition from a conical to a cylindrical shape of the same diameter was a useful feature because the rate of surface rise became constant and remained so during the submergence of the cylindrical portion of the device.

Since the geometry of the system and the speed of cone advance into the cylinder were known, the exact rate of surface-level rise, and hence the simulated volume flow rate, could be calculated. A relationship yielding simulated volume flow rate as a function of time was derived and plotted. The cone and driving mechanism were mounted on the seat of the voiding chair over the cylinder, and the output from the pressure transducer was recorded as the cone was submerged. The driving apparatus was operated at three different speeds: 0.55, 0.75, and 1.65 cm/sec. Typical records of surface rise versus time for each of these cases are illustrated in Figures 12 and 13. These data were then plotted for comparison with the exact relationship derived below. A static type of calibration was also made by advancing the cone known distances and measuring the surface level rise with a standard point gage.

Derivation of the Simulated Flow-Rate Equation

The equation yielding the simulated rate of flow as a function of time during submergence of the cone was derived in the following manner using terminology defined in Figure 14.

The cylinder was partially filled with water such that the initial free-surface level was at the position indicated before the cone was submerged. When the cone was submerged a distance y below the original free surface, the volume displaced by the cone, V_A, caused the free surface to rise to a new location as indicated in the figure. The rise of the free surface, h, can be determined by equating volumes V_A and V_B. The displaced volume, V_A, is given by

$$V_A = \pi r_0^2 \, y/3 \qquad (4)$$

where r_0 = the radius of the base of the cone which is submerged a distance y beneath the original level of the free surface.

Volume V_A must be displaced into volume V_B which is given by the difference of the cylindrical volume of radius R and depth h and the volume of the truncated cone of height h having bases of radii r and r_0,

$$V_B = \pi R^2 h - (\pi r^2(y + h) - \pi r_0^2 y)/3 \qquad (5)$$

Equating V_A and V_B gives

$$R^2 h = r^2(y + h)/3$$

From the geometry of the cone, r is related to the altitude y + h by K,

$$r = K(y + h) \qquad (7)$$

where K is a known constant calculated from the cone dimensions. Substitution of Eq. (7) into Eq. (6) results in a cubic expression for h, the surface-level rise,

$$h^3 + 3yh^2 + (3y^2 - 3R^2/K^2)h + y^3 = 0 \qquad (8)$$

The rate of the surface-level rise which is related to the simulated volume flow rate can be obtained by differentiating Eq. (8) with respect to time. Solving for dh/dt, one obtains

$$\frac{dh}{dt} = (y + h)^2 \frac{dy}{dt} / [R^2/K^2 - (y + h)^2] \qquad (9)$$

The rate of vertical displacement of the cone was controlled by the driving mechanism and was set at one of the three values mentioned above. The depth of submergence of the cone below the original free surface is

$$y = Ct \qquad (10)$$

where the time t is measured from the instant that the vertex of the cone touches the free surface. The submergence speed can also be expressed as

$$C = dy/dt \qquad (11)$$

Substitution of Eqs. (10) and (11) into Eq. (9) gives

$$\frac{dh}{dt} = C(Ct + h)^2 / [R^2/K^2 - (Ct + h)^2] \qquad (12)$$

Equation (12) describes the rate of the surface level rise as a function of the known constants C, R, and K and the variables h and t. Equation (8) can be rewritten in terms of these constants and the independent variable,

t, and can be used for establishing h as a function of t.

$$h^3 + 3Cth^2 + (3C^2t^2 - 3R/K)h + C^3t^3 = 0 \qquad (13)$$

The surface-level rise, h, can be determined at any time by finding the roots of the polynomial expressed in Eq. (13). The real roots of the polynomial (only one being significant) were determined by the Secant Method [9] with the aid of a digital computer. The value of h thus found and the corresponding time were substituted into Eq. (12) to obtain the rate of the surface-level rise. The simulated flow rate, Q_s, was then calculated simply by multiplying by the cross-sectional area of the cylinder,

$$Q_s = \pi R^2 \, (dh/dt) \qquad (14)$$

The variation of Q_s with time is plotted in Figure 15 as a solid line for three values of the cone submergence speed, C. The plotted points represent values determined from the recorded output of the actual experiments with the cone, as seen in Figures 12 and 13. Since the time when the cone first touched the water surface was difficult to determine, the points were plotted by choosing a reference value of Q_s, matching the theoretical and experimental values at that point, and then plotting the simulated flow rate versus time as measured from the reference point. For each value of C, two different output curves were plotted for the comparison.

The agreement between the measured values and the theoretical curves indicates that the dynamic response of the electro-hydraulic system is quite adequate in the range tested. That is, with respect to an arbitrarily chosen reference point, the recorded output is seen to be a valid representation of the actual flow rate as a function of time.

A more important consideration is, however, the ability of the system to respond to rapid changes of the flow rate. The slope of the Q_s versus t curve gives a measure of this variable.

Results and Conclusions

After the voiding chair was built and tested at the Institute of Hydraulic Research, it was transferred to the Department of Urology at the University Hospital for clinical work. The chair was installed in the Medical Research Facility of the Department of Urology in a small room with the toilet secluded by a fabric curtain to provide complete privacy. For each recording the equipment was turned on and the patient was left alone in the room. On occasion very young children were accompanied by a nurse during the micturition.

Since installation of the chair in the Department of Urology, more than 100 voiding patterns (see Figure 16 for several samples) have been obtained from hospital patients having either normal or abnormal lower urinary tracts. Some of these patterns were obtained preoperatively and others postoperatively. Presently, the only quantitative information which is being added to the patient's permanent history is the total volume voided and maximum flow rate, although techniques for obtaining additional information by digital processing are being considered. Figure 17 shows digital plots of the examples a and b in Figure 16 for confirming correct digitizing of the data. These records were recorded at the time of micturition on a portable magnetic-tape recording system. The reproduced records were digitized and punched onto cards in standard IBM format using an IBM 1801 Data Acquisition and Control System located at the Institute. Plotting was done by an 1816 printer included with the system.

The question as to whether the system is adequate in responding to changes in flow rate is, as yet, unanswered. The results of the simulated flow test indicate that it is capable of responding to a rate of change in flow rate of 30 cc per second per second. To date no recorded patterns have approached that limit, which may be because of funnel storage. To be sure, there are many other questions concerning performance capabilities but until an intensive study utilizing the monitoring chair is conducted there can only be much speculation. It is felt, however, that the design has satisfied the original objectives and will provide useful information on the urination processes while also suggesting better methods for monitoring micturition.

Acknowledgments

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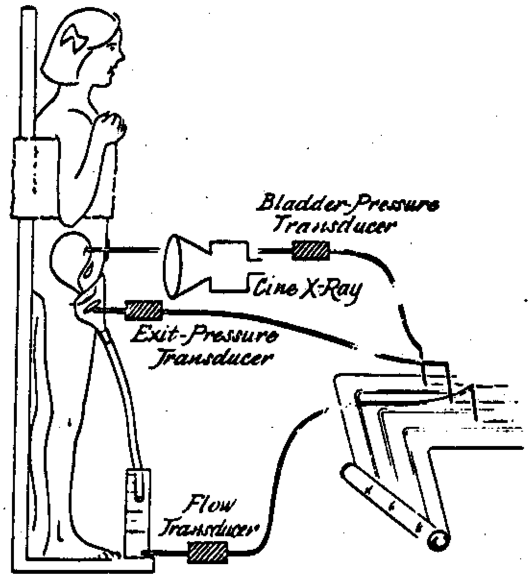


Fig. 1. Technique used by Whitaker and Johnston [Ref. 5].

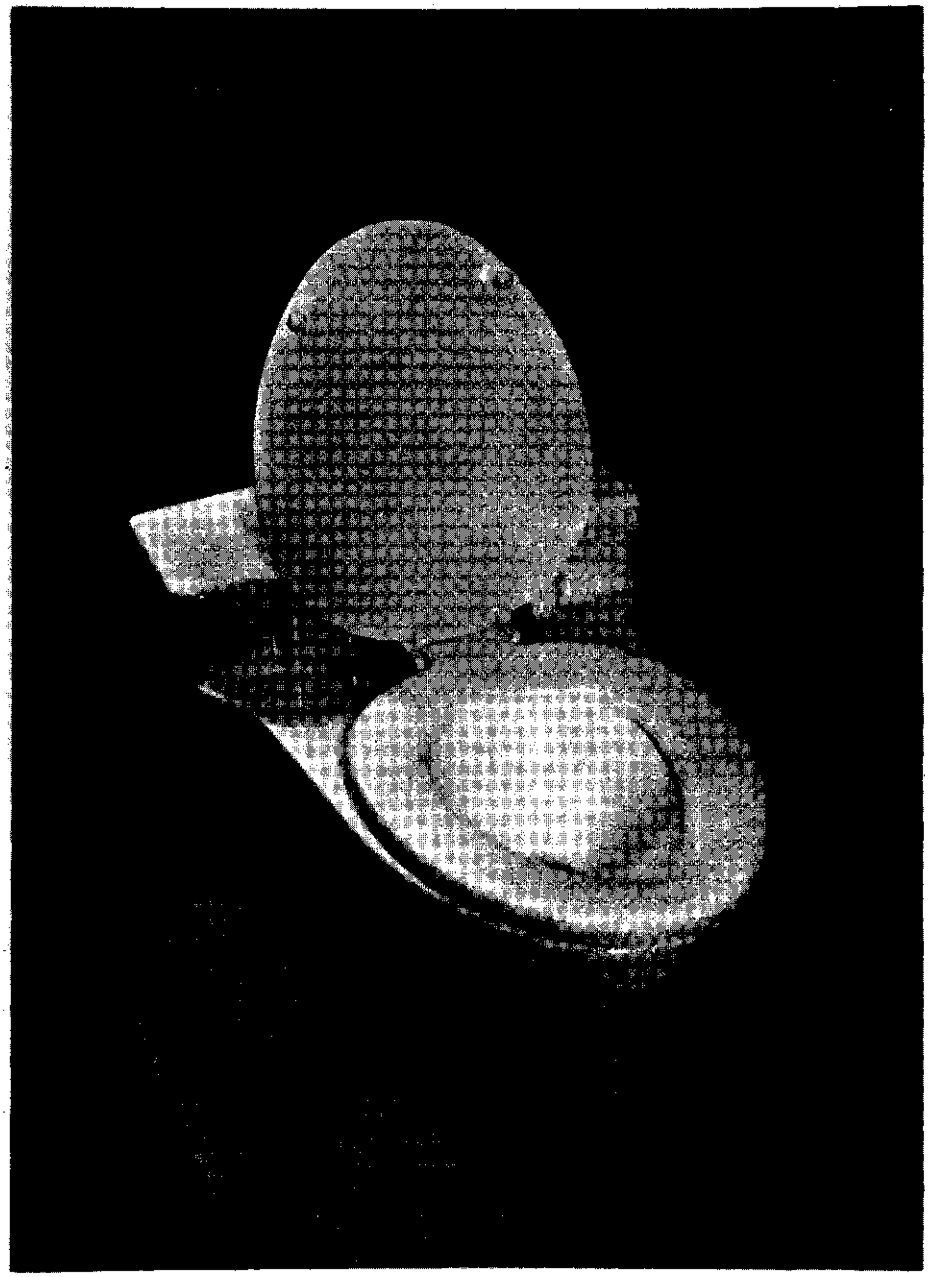


Fig. 2. Voiding chair.

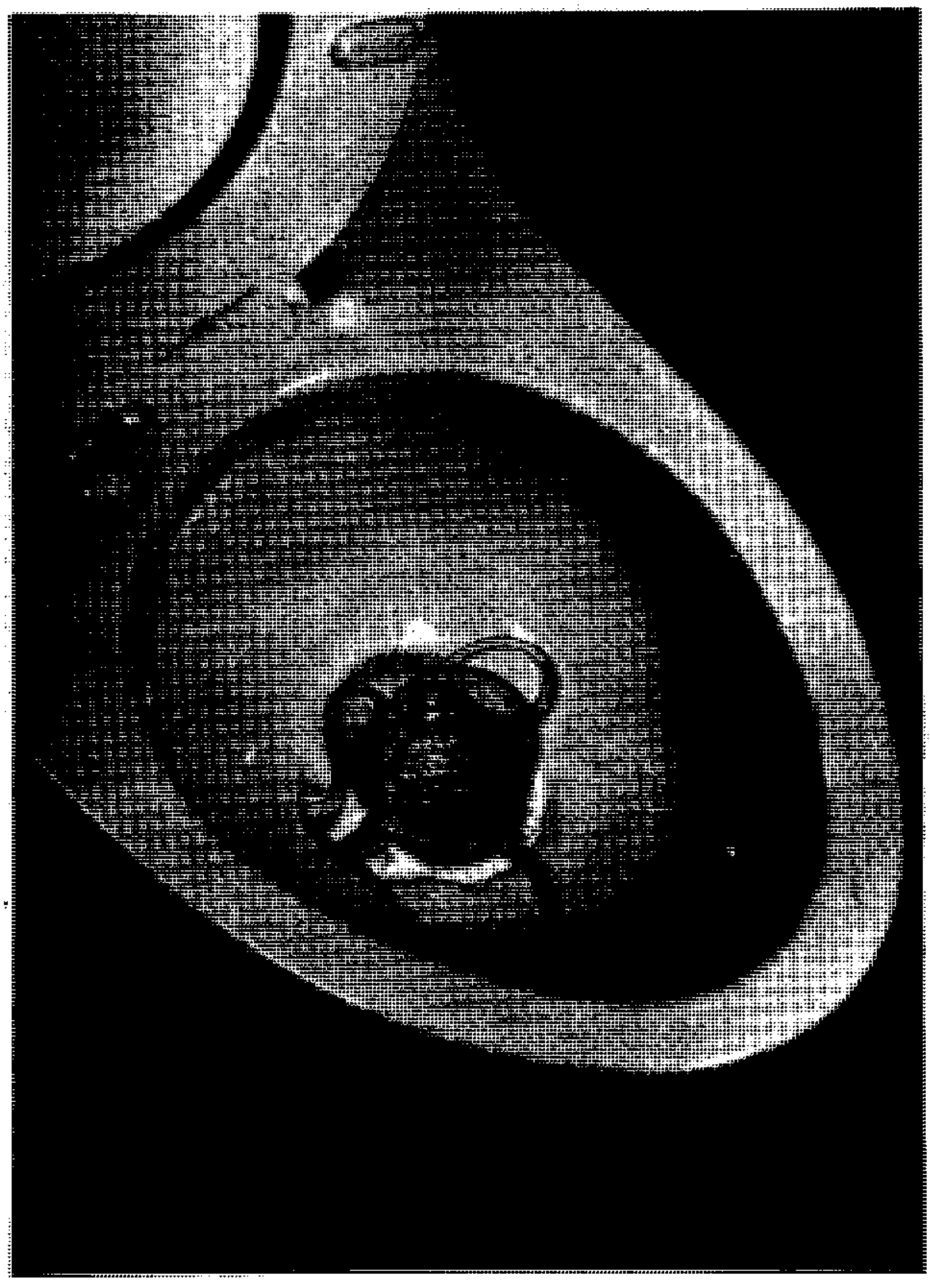


Fig. 3. Urine storage receptacle.

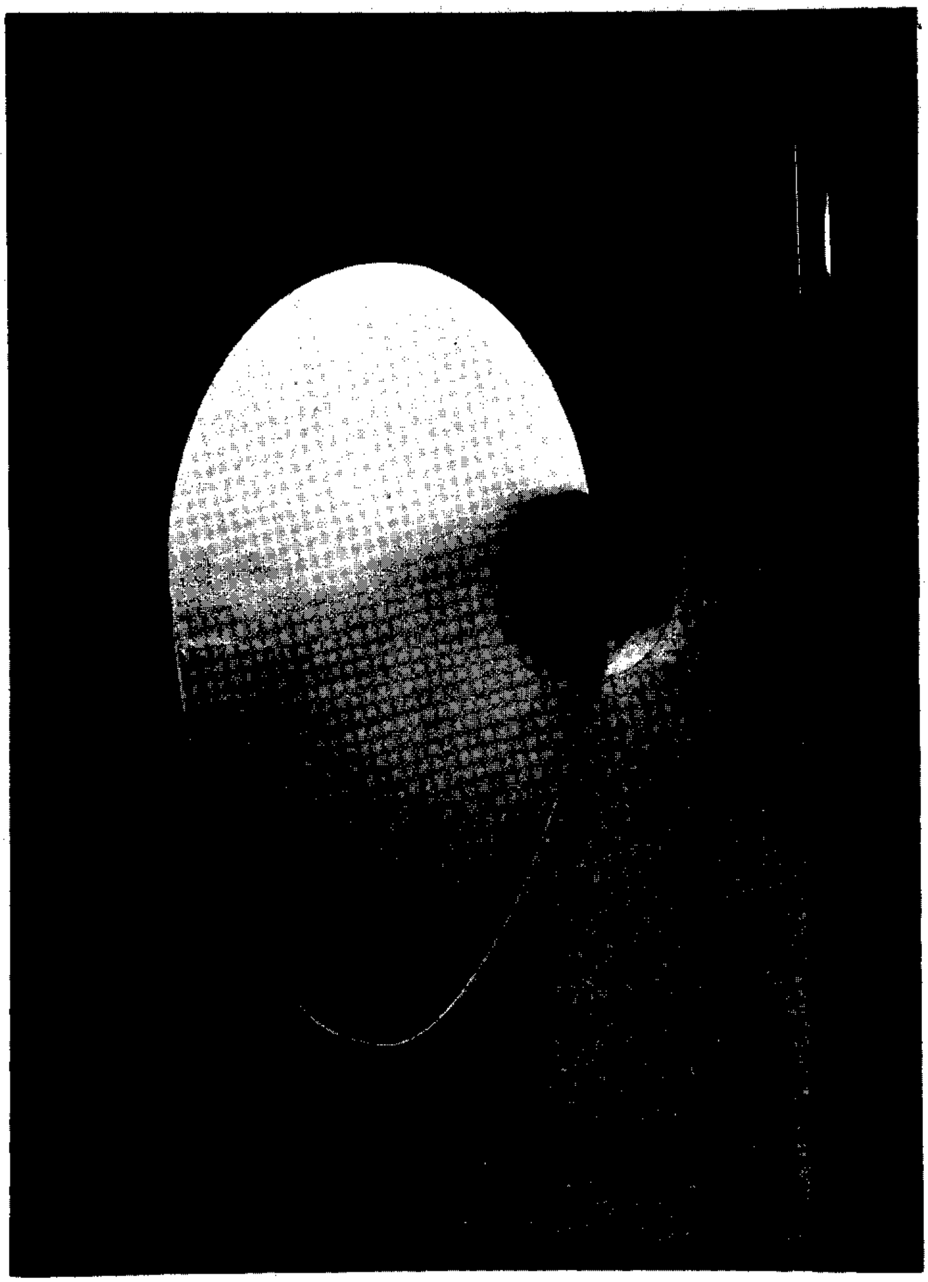


Fig. 4. Funnel.

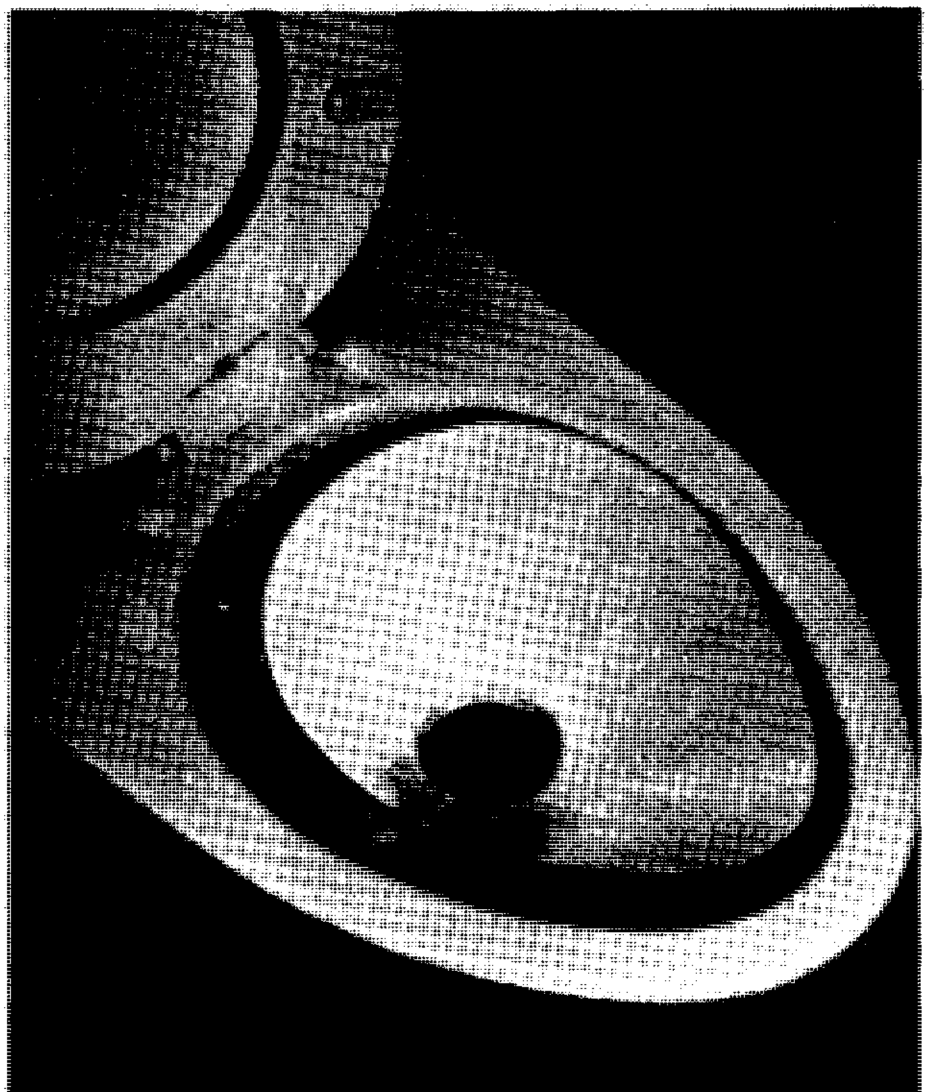


Fig. 5. Funnel in place on storage receptacle.

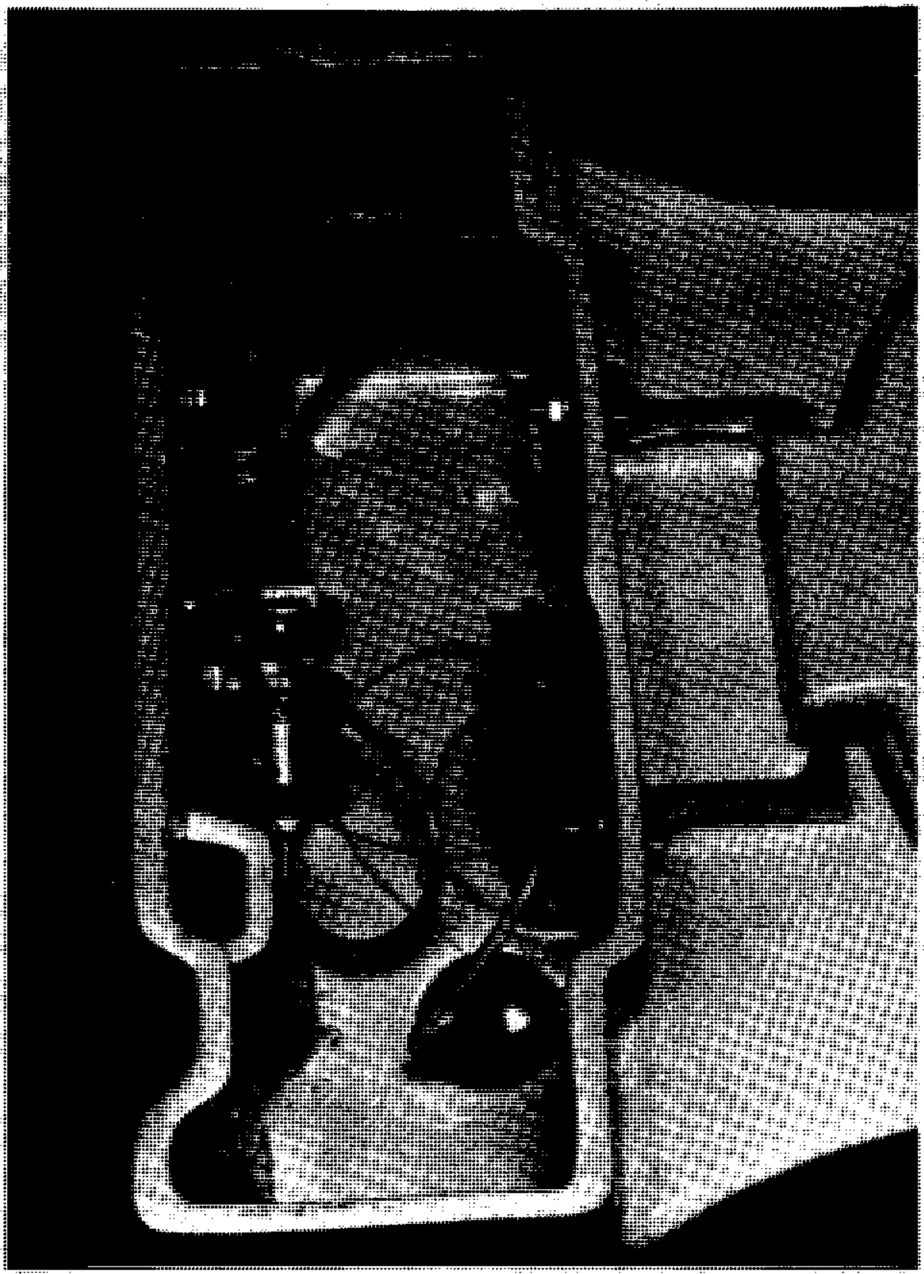


Fig. 6. Instrument arrangement in water closet.

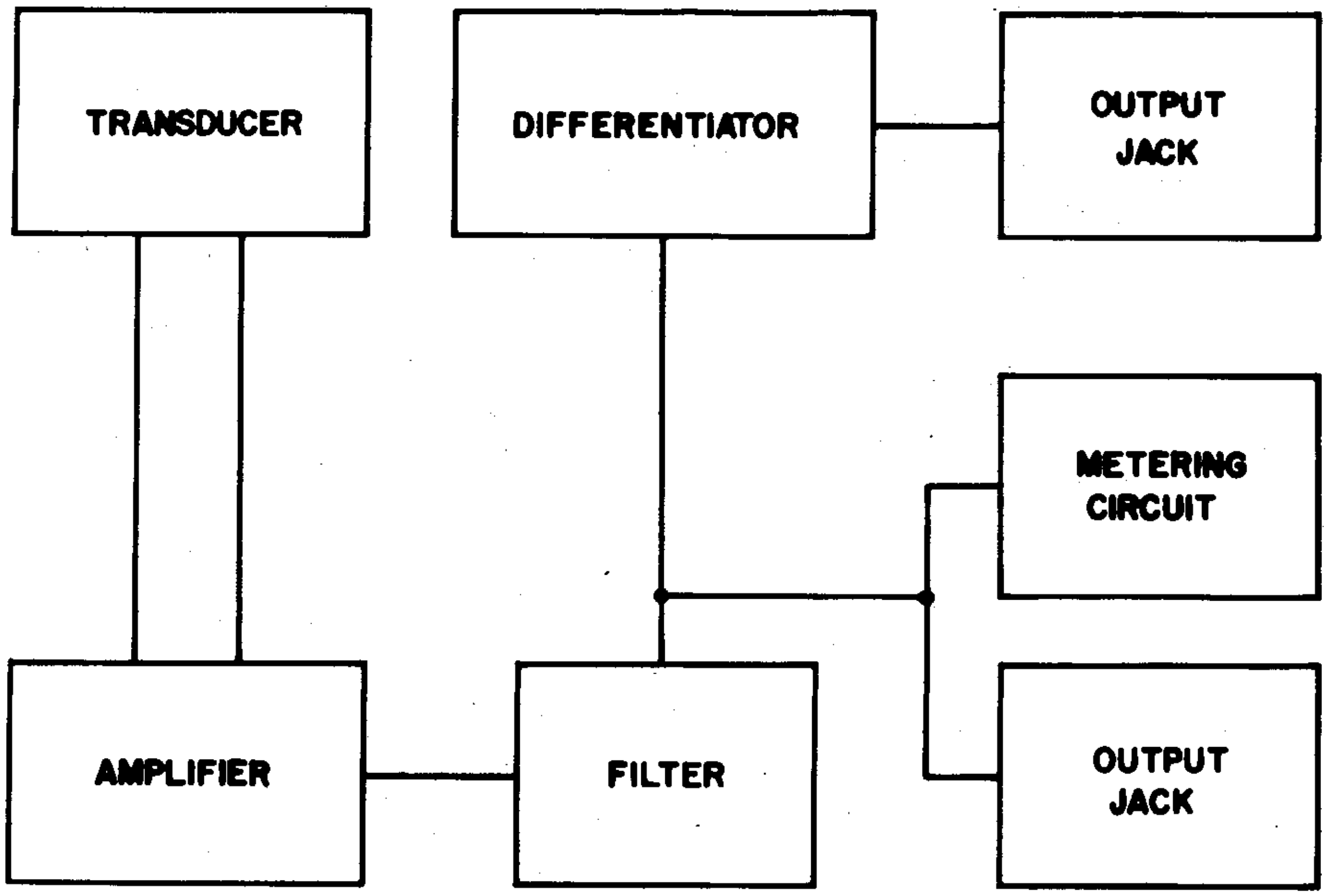


Fig. 7. Block Diagram of Electronic System.

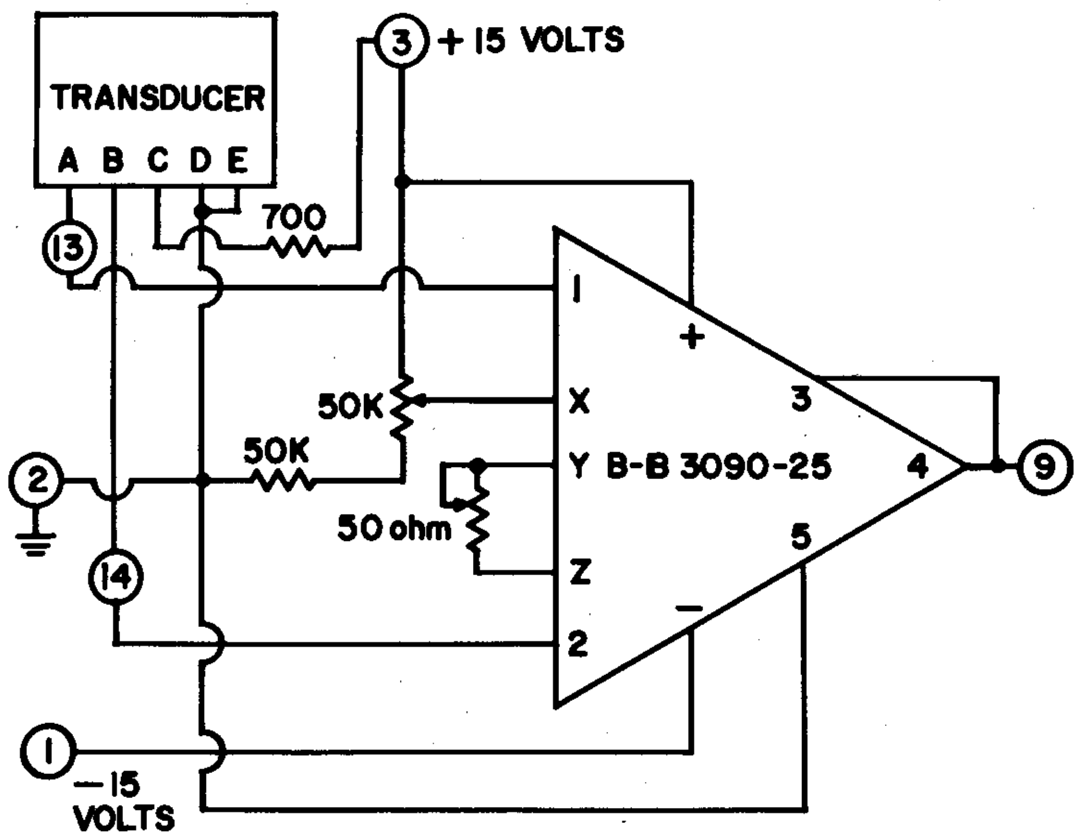


Fig. 8. Transducer and Amplifier Circuit.

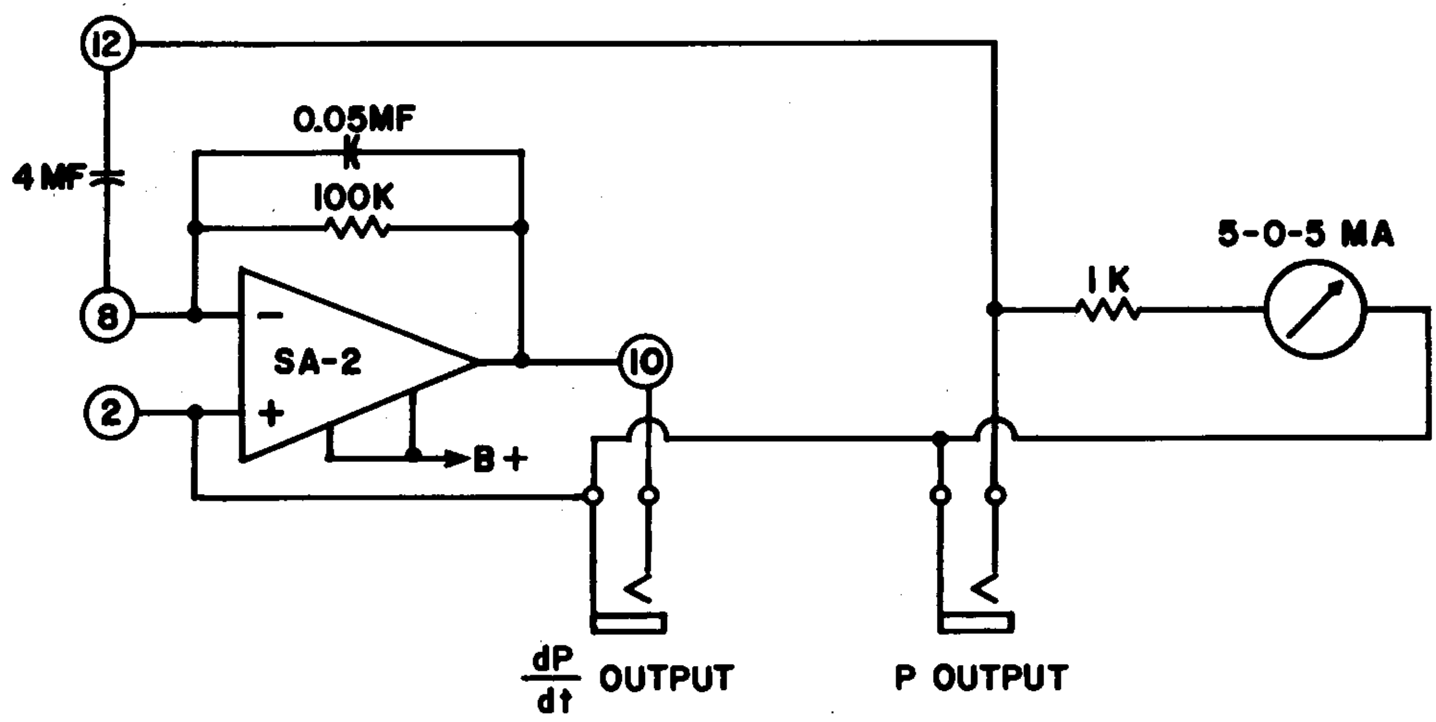


Fig. 9. Differentiating Circuit and Output Terminals.

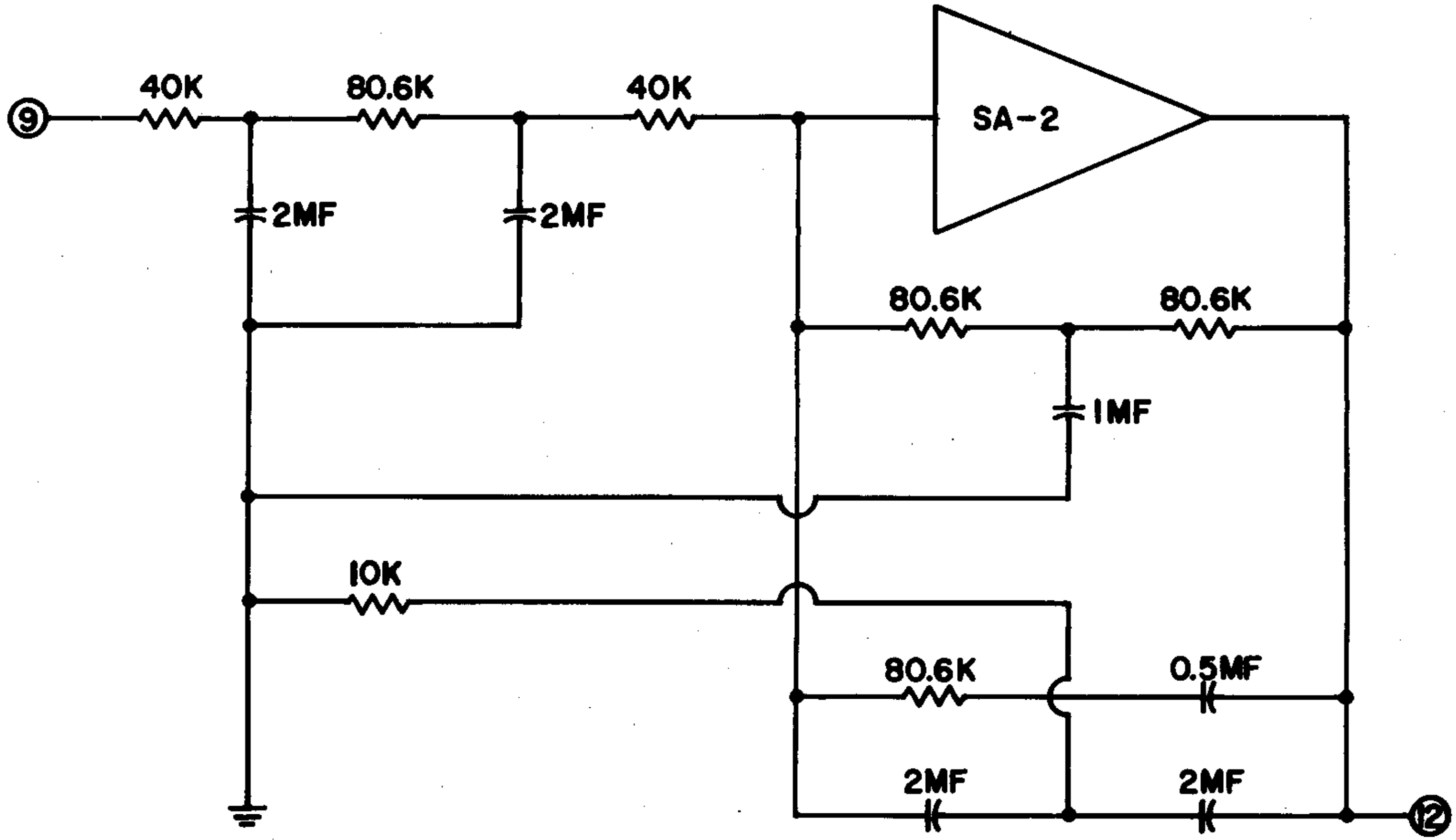


Fig. 10. Third-Order Low-Pass Butterworth Filter.

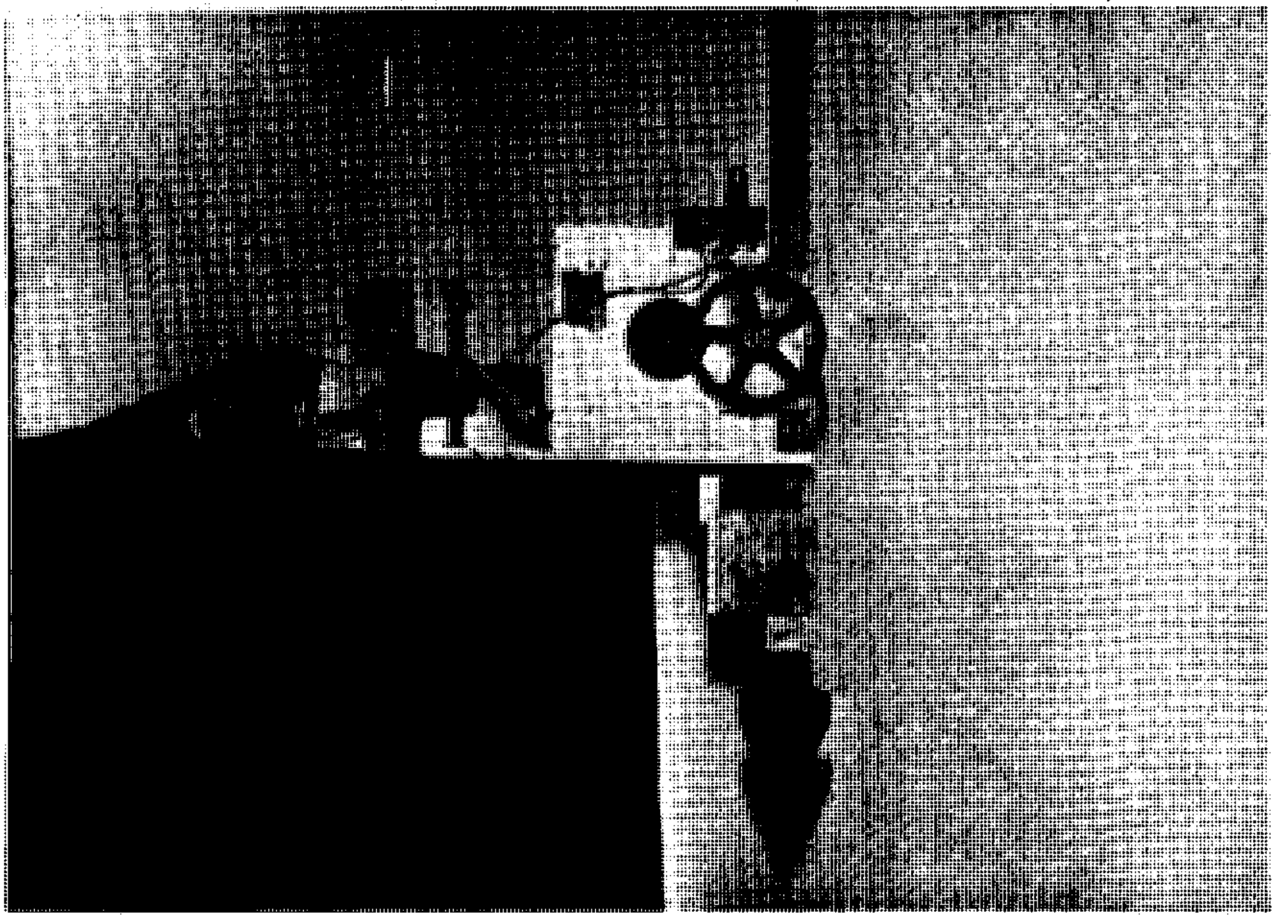


Fig. 11. Device used for dynamic response testing.

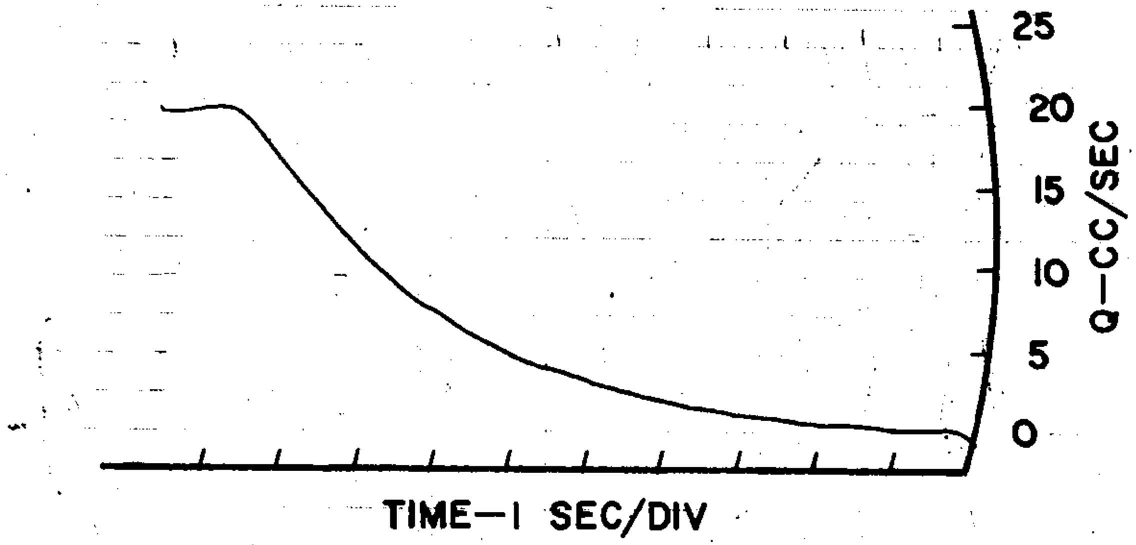
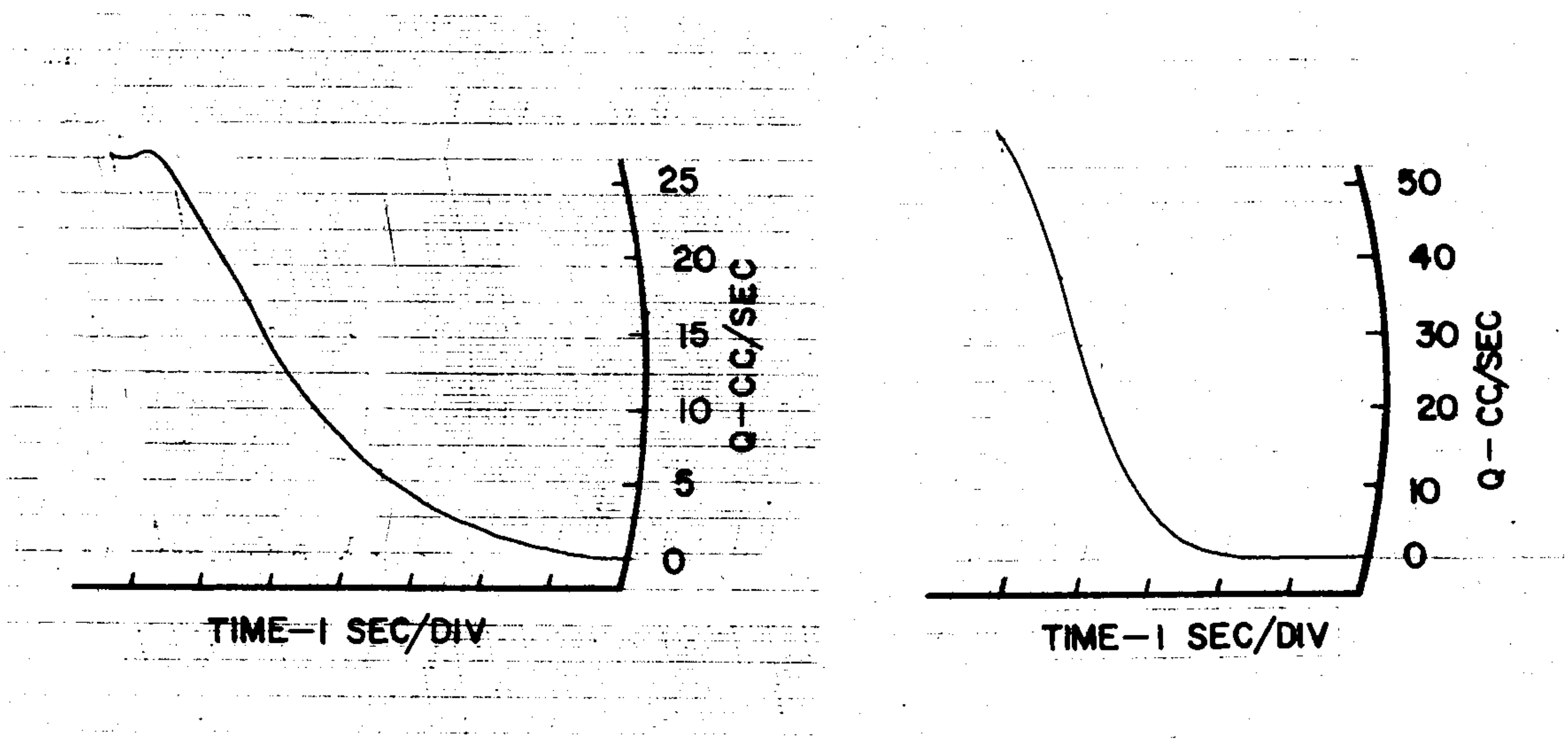


Fig. 12. Simulated discharge for cone velocity of 0.55 cm/sec.



(a) (b)

Fig. 13. Simulated discharge for cone velocity of 0.75 cm/sec (a) and 1.65 cm/sec (b).

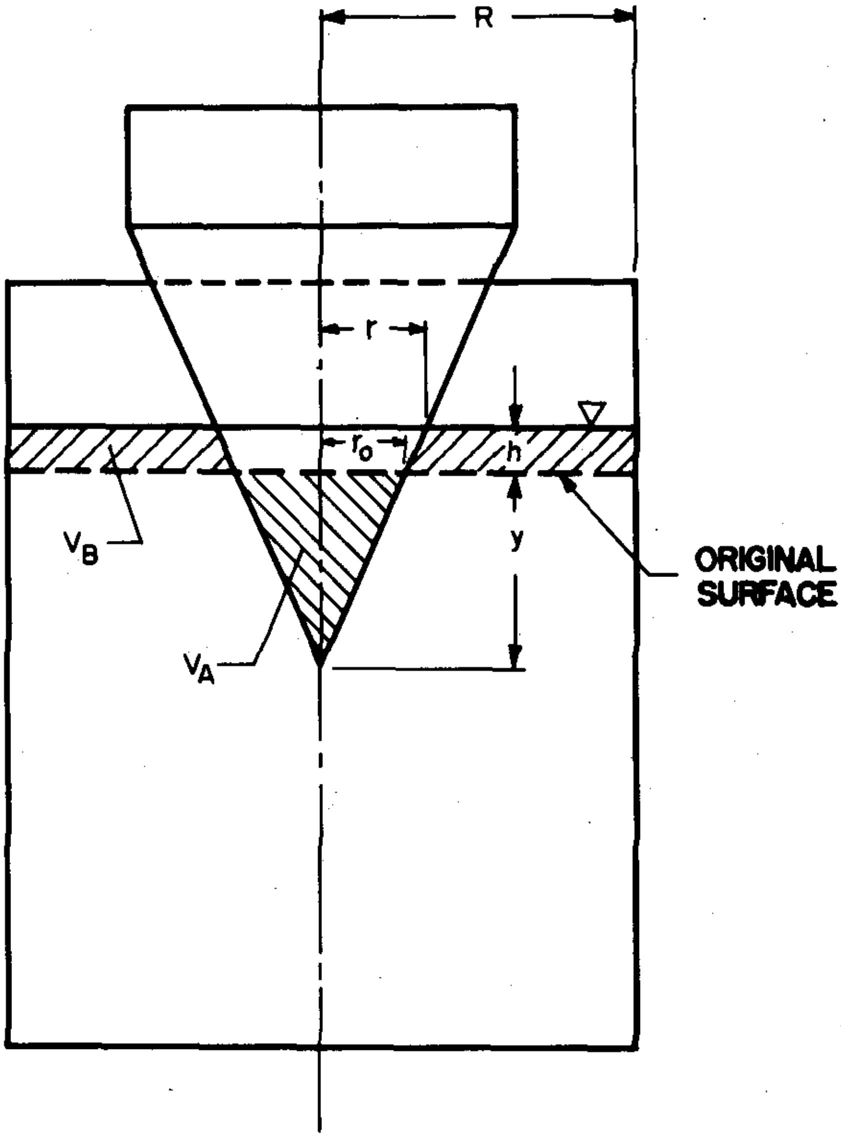
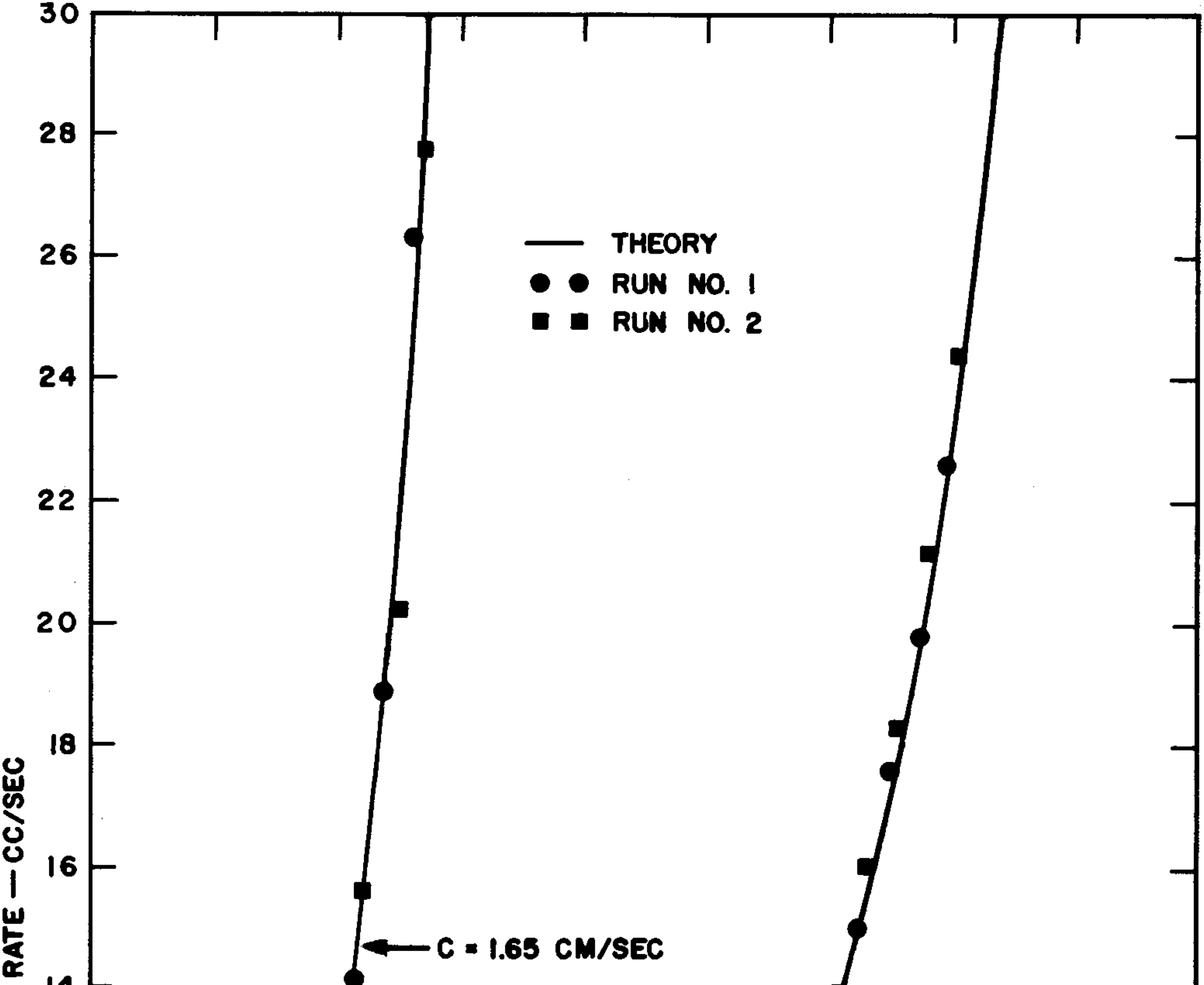


Fig. 14. Definition Diagram for Simulated Flow-Rate Equation.



30
28
26
24
22
20
18
16
14
THEORY
RUN NO. 1
RUN NO. 2
C = 1.65 CM/SEC
RATE — CC/SEC

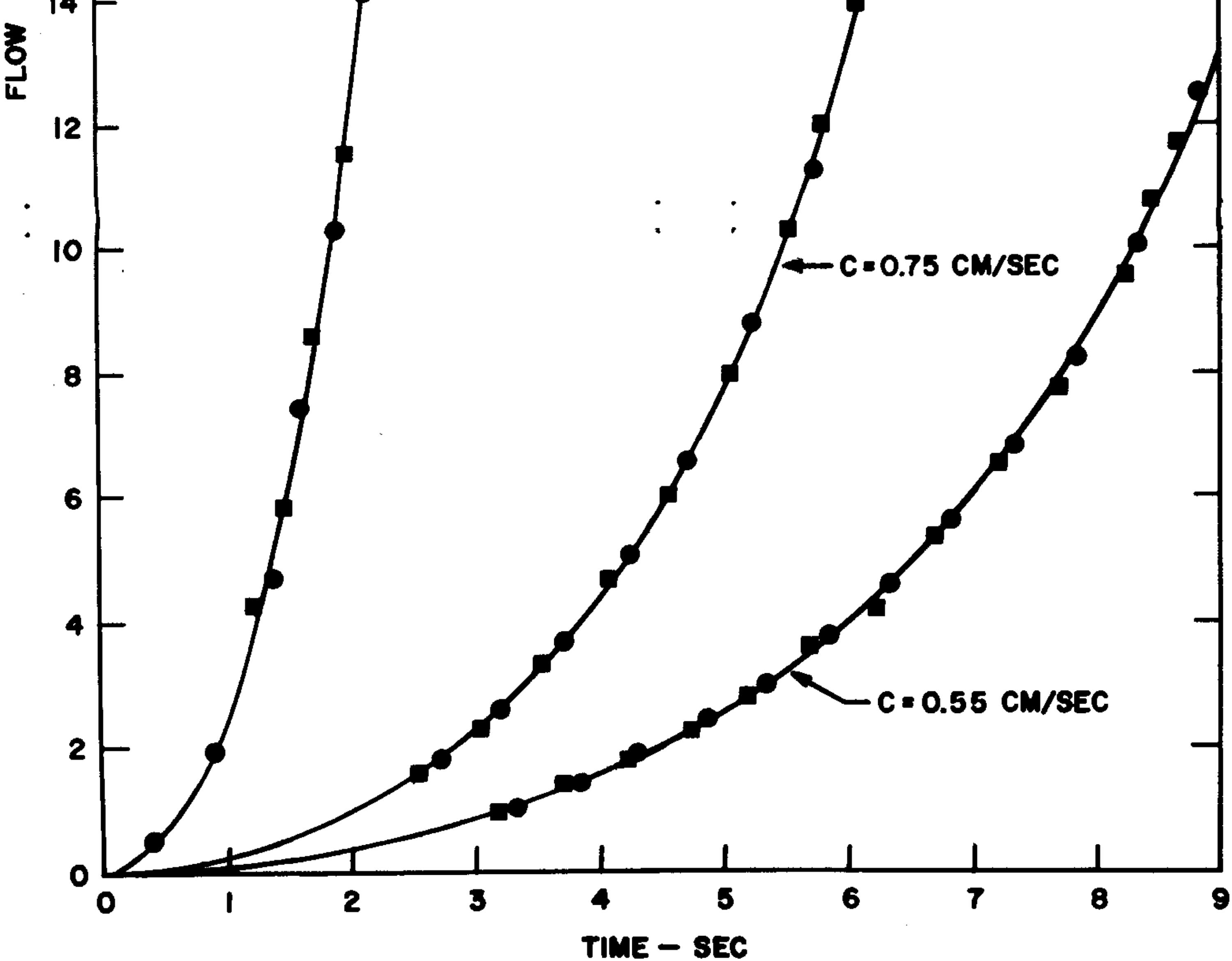


Fig. 15. Dynamic Response Characteristics of the Monitoring System.

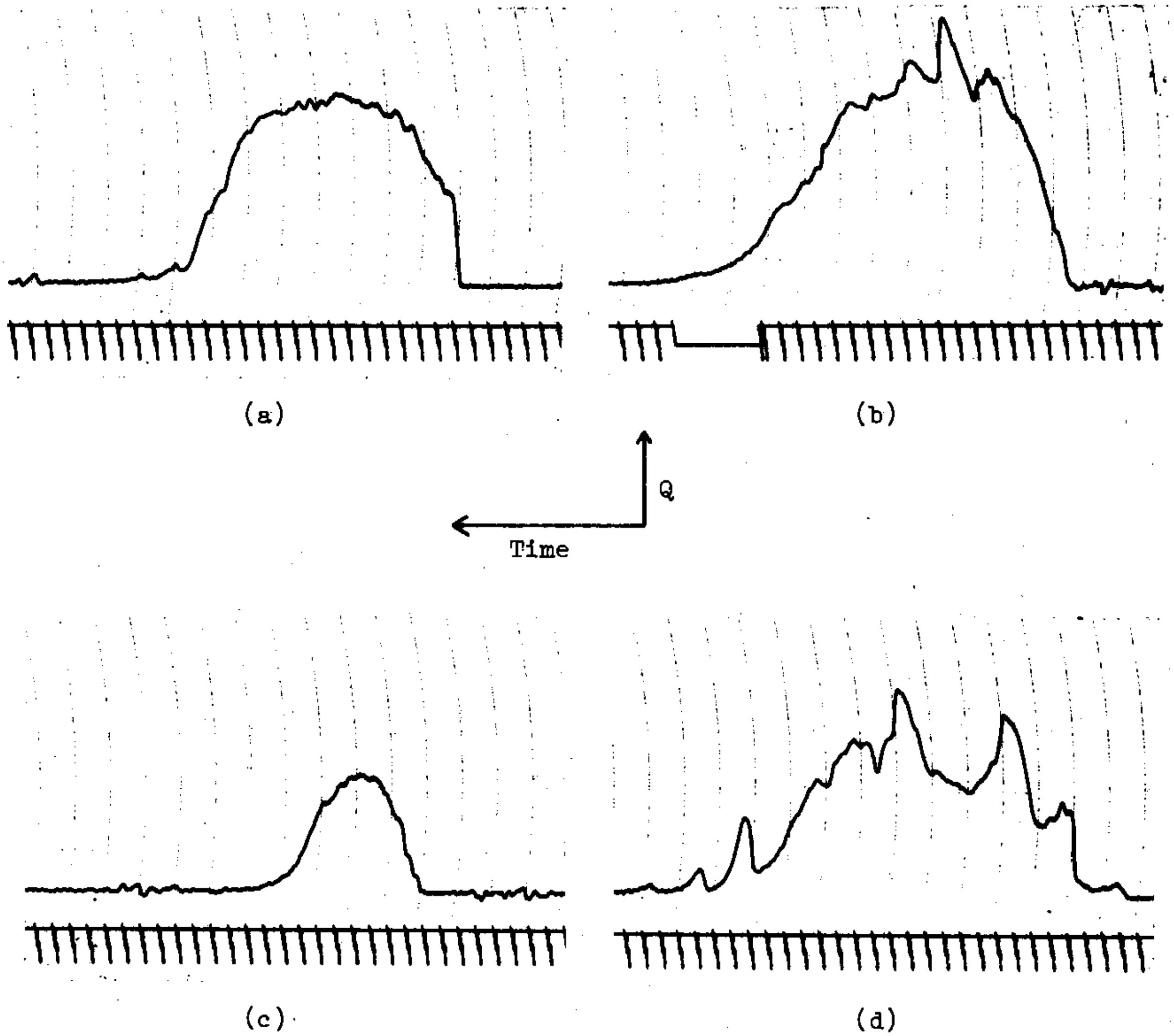


Fig. 16. Recorded micturition patterns of young female children.

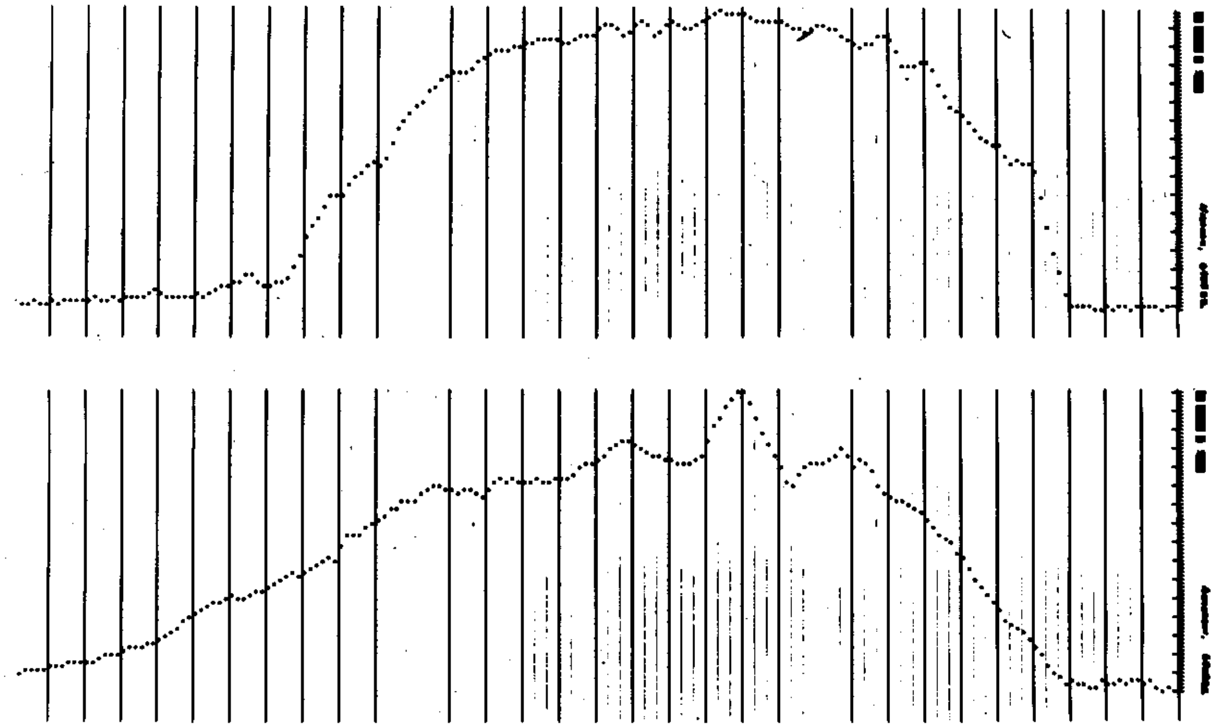


Fig. 17. Digital plots of micturition patterns.