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Automation of the Continuous Coagulation Monitor

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A CONTINUOUS COAGULATION EFFICIENCY MONITOR FOR WATER AND WASTE SYSTEMS

By

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Water Resources Research Center

UNIVERSITY OF ARKANSAS

Fayetteville, Arkansas

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1. INTRODUCTION

The development of automation in the past 50 years has paralleled the accelerating growth of today's vast technological society. Automatic control systems are indispensable extensions of man's brain that enable him to monitor and regulate his complex environment. The principles of automatic control have a wide range of applications and interests in virtually every scientific field.

The need for automatic control systems in vital applications of environmental engineering is both real and urgent. Extensive pollution has resulted in unavoidable water re-use and in the inevitable establishment of stringent effluent standards. Both water and wastewater treatment processes have necessarily become more advanced and complicated. Automation can reliably provide the critical, sophisticated control required to maintain adequate treatment. In his pollution abatement or water quality program, the environmental engineer can employ automatic control systems to continuously and accurately monitor contaminant levels or the removal efficiencies of treatment processes and to effect rapid responses when treatment adjustment becomes necessary by automatically adjusting processes.

2. OBJECTIVE

This research project was the final phase in the laboratory development of the continuous coagulation monitor. The broad scope of this work entailed limited automation of the device, whose ability to control the chemical coagulation process had been demonstrated in both water and wastewater treatment applications.

This automatic control system provided continuous, cyclic sampling of the effluents of the six separate flow channels of the monitor through a continuous flow turbidimeter. Control instrumentation provided continuous indication of the chemical treatment producing the lowest turbidity. Reliable performance of the control system was demonstrated by its incorporation in the actual continuous operation of the monitor under controlled laboratory conditions.

3. LITERATURE REVIEW

Most water and wastewater treatment systems are designed for continuous operation employing several unit processes. Relatively few of these are well suited to automatic control because of a notable lack of continuous analyzers sufficiently reliable to measure all the necessary parameters of water quality. A discussion of means to control the coagulation-flocculation-sedimentation process for water clarification is conspicuously absent. This process is, for the most part, an art, not a science, still requiring some human judgment to determine chemical application rates and process control parameters (1).

3.1 DEVELOPMENT OF THE CONTINUOUS COAGULATION MONITOR

Weir (2) initiated research directed toward development of a device that would continuously monitor the water clarification process, provide reliable feedback of one or more control parameters, and automatically make necessary adjustments in chemical feed rates. Weir designed and constructed the first working model, which he succinctly labeled the "continuous coagulation monitor". The original apparatus consisted of four separate flow channels, flocculation chambers, and high-rate shallow tube settlers. The selected coagulant was alum with sodium hydroxide added to buffer the alkalinity. Two peristaltic pumps fed separate solutions of the chemicals into the split flow lines at a point ahead of the flocculation chambers so that rapid mixing would occur. The alum range and sodium hydroxide dosage were determined by a jar test analysis of the influent raw water. The monitor was first tested under continuous operation at a working water treatment plant, the municipal waterworks in Charleston, Arkansas; it was then moved back into the laboratory for test runs under controlled conditions. Batch samples of each tube-settler effluent were manually collected for analysis. Turbidity was chosen as the primary process control parameter, but pH, alkalinity, and color were also monitored.

Weir's original monitor was essentially a continuous-flow jar test, which, however, better represented actual plant operating conditions and considerably shortened the time lag between sample collection and production of interpretative results. In the actual plant operation, the alum and lime feeders were adjusted according to the results of the monitor; consequently, water clarification was enhanced and tedious trial-and-error adjustment was eliminated. Thus, the feasibility of the monitor to efficiently control the coagulation process was successfully established.

3.2 APPLICATION OF MONITOR IN WATER TREATMENT

McLaughlin (3) increased the number of independent flow channels to six and enclosed the apparatus in a portable iron-frame housing. Another major mechanical modification included installation of a jet water spray system to wash down the tube settlers when they were being drained to remove sludge build-up. The spray and drainage systems were coupled by a simple automatic control system that incorporated a time clock and time delay relays. McLaughlin conducted further similar testing of the monitor at both the Lowell (Beaver Water District) and Fayetteville water treatment plants.

3.3 APPLICATION OF MONITOR IN TERTIARY TREATMENT

Additional modifications were made by Reed (4) in order to improve the flow-through characteristics of the monitor. He then applied the monitor to the effluent of the Fayetteville wastewater treatment plant and obtained preliminary data on the effectiveness of chemical precipitation in tertiary treatment.

Bishop (5) followed up Reed's preliminary investigation with a more extensive study in which the continuous coagulation monitor itself again provided pilot-scale tertiary wastewater treatment. Test results indicated residual turbidity to be a reliable control parameter in the chemical precipitation process. Bishop reported that phosphate removal positively correlated with turbidity removal. He recommended the use of continuous flow turbidimeters in future applications of the monitor to control tertiary wastewater treatment processes employing chemical precipitation for phosphate removal.

3.4 SUMMARY OF LITERATURE REVIEW

The continuous coagulation monitor has been developed as a result of coordinated graduate research conducted over the past few years. The function of the monitor is to provide a positive means of controlling the coagulation operation, a unit chemical treatment operation employed in both water and wastewater treatment processes. The original monitor, a crude laboratory bench model, surpassed the standard jar test. The continuous flow monitor better simulated actual plant operation and provided usable results in a shorter time. A successive series of research projects demonstrated the capability of the monitor to control the coagulation operation. Water clarification was noticeably improved at a working water treatment plant when results of the monitor were interpreted to adjust chemical feed rates. The monitor has also been used as a research tool in wastewater treatment. The monitor provided pilot-scale treatment in an investigation of chemical precipitation as a tertiary treatment process.

4. CONTROL SYSTEM DESCRIPTION

4.1 DESCRIPTION OF CONTINUOUS COAGULATION MONITOR

The continuous coagulation monitor is a device developed to control the chemical coagulation process, a unit process employed extensively in both water and wastewater treatment. The monitor consists of six separate treatment systems, as sketched in Figure 1. Raw water flows from a constant-head reservoir and is split into six equal flows. Peristaltic pumps feed different concentrations of the coagulation chemicals into the split flow lines at a point ahead of the flocculation chambers so that rapid mixing can occur. After flocculation, sedimentation of the floc is achieved in high-rate tube settlers. The settled effluents can be sampled for analysis of the selected process control parameter in order to determine the treatment system providing the optimal chemical treatment. In all applications of the monitor prior to the development of the automatic control system described in this report, sampling of the effluents and analysis of the process control parameter were accomplished manually.

4.2 DESCRIPTION OF AUTOMATIC CONTROL SYSTEM

The automatic control system (Figure 2) consisted of the following components listed in functional sequence: (1) effluent solenoid-valve control circuit; (2) continuous-flow turbidimeter; (3) analog-to-digital conversion circuit; (4) comparison circuit; and (5) numerical readout circuit.

The control system was developed to provide continuous, automatic sampling and analysis of the effluents of the six treatment systems comprising the coagulation monitor. A solenoid valve was placed in each effluent line. Control instrumentation regulated opening and closing of the six valves in

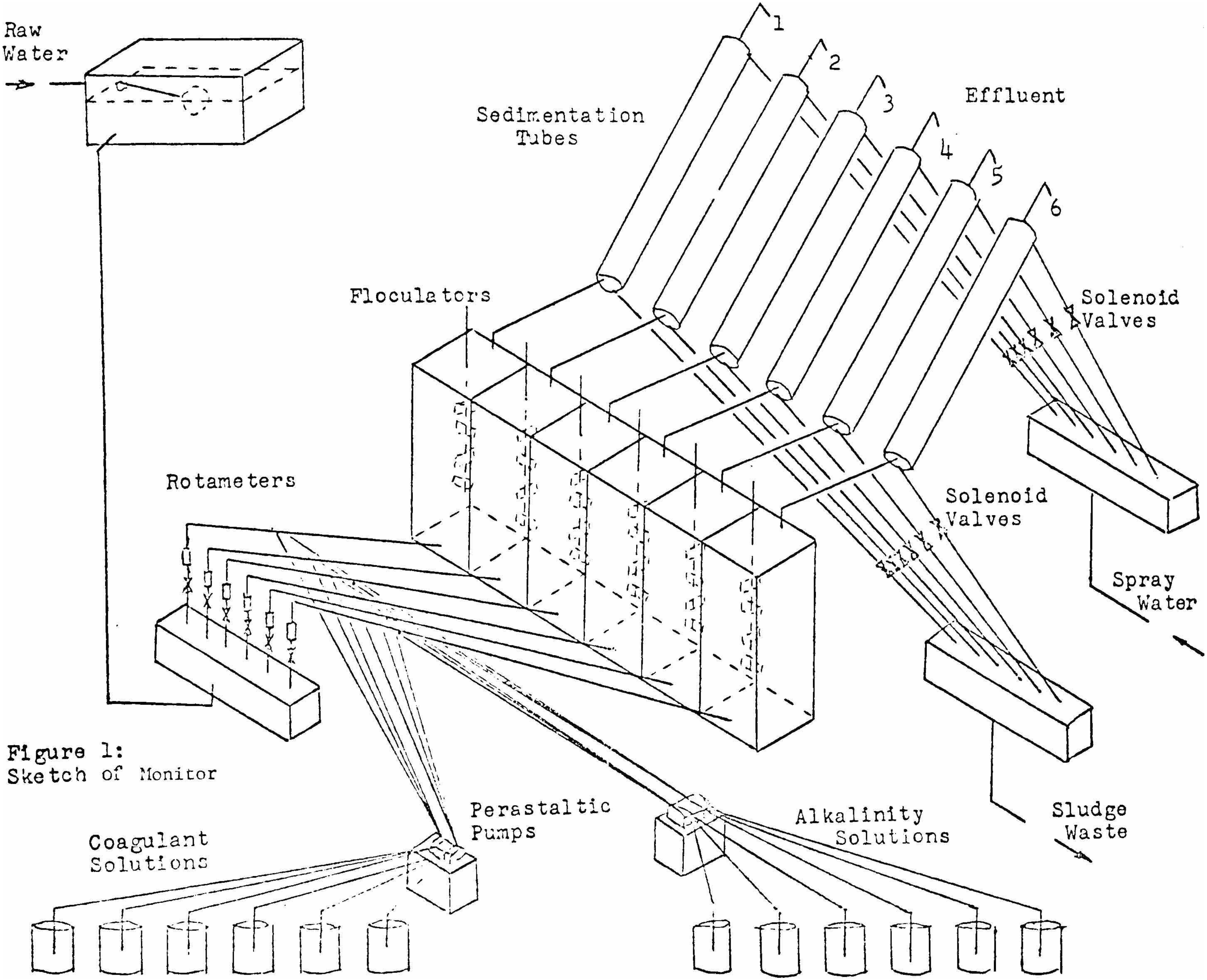

Figure 1: Sketch of Monitor

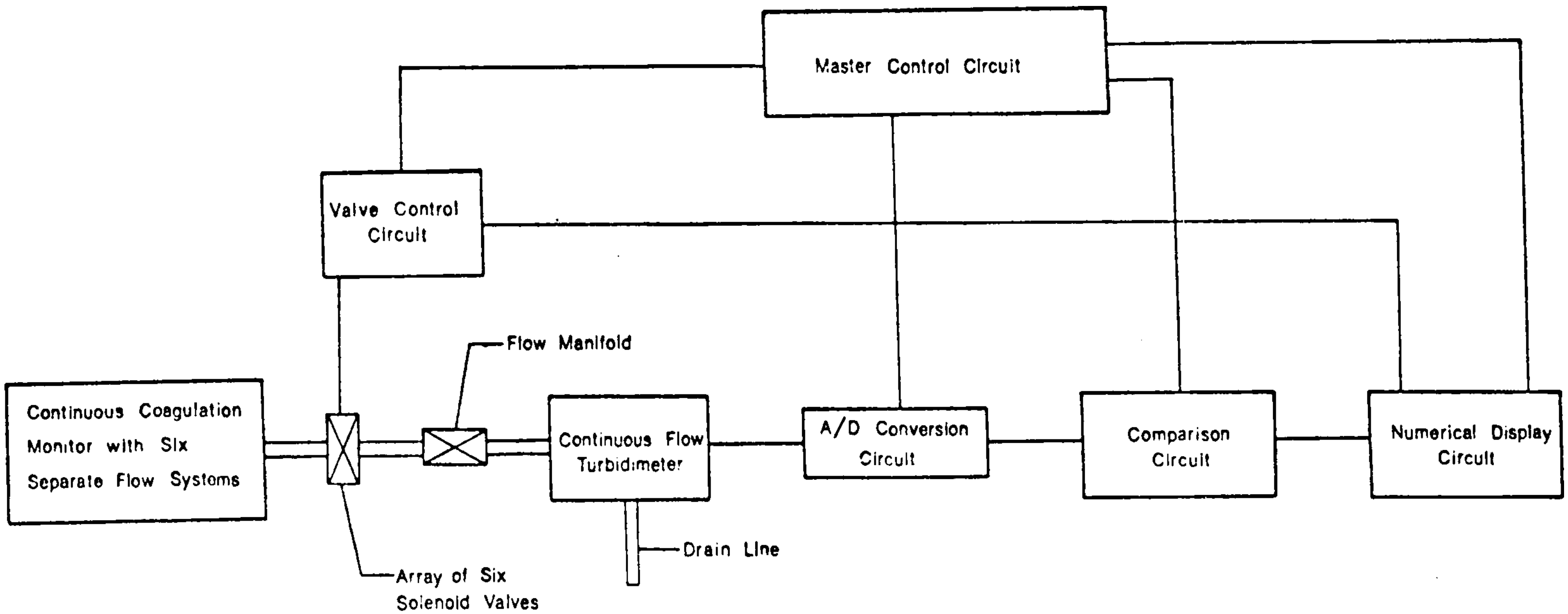

FIGURE 2. BLOCK DIAGRAM OF AUTOMATIC CONTROL SYSTEM FOR CONTINUOUS COAGULATION MONITOR

sequence. One valve was opened at a time, and the effluent of that treatment system was sampled through a continuous-flow turbidimeter. The residual turbidity was measured, and the corresponding electrical output signal of the turbidimeter was stored in electronic binary "memory" circuits. The valve was then closed, and the next valve in sequence was opened to sample the effluent of the second treatment system through the turbidimeter. The electrical signal corresponding to the second turbidity measurement was then compared by means of logic circuitry with the previously stored signal. The lower digital voltage signal corresponded to the lower turbidity value. The lower signal was retained in the binary storage elements of the comparison circuitry and would be compared with the next turbidity measurement. Another logic circuit, called the display circuit, converted the stored signal to a digital readout which indicated the treatment system providing the highest turbidity removal.

In summary, the designed control instrumentation performed the following functions in sequence:

(1) Provided continuous, automatic sampling of the effluents of the six treatment systems of the monitor through a continuous-flow turbidimeter.

(2) Determined which treatment system provided optimal treatment by comparing turbidity measurements, which had been converted to digital voltage signals.

(3) Provided a continuous numerical readout which indicated the optimal treatment system.

4.3 DESCRIPTION OF FLOW SYSTEM

The first step toward implementation of the proposed automatic control system entailed improvisation of a continuous flow turbidimeter. Commercial models are available, but their high cost or sample flow-rate requirements ruled out their application in this particular project. The Hach Model 2100A Laboratory Turbidimeter was purchased, and this instrument was converted to a continuous analyzer by substitution of its batch sample cell with a specially designed continuous flow-through cell. An aluminum foil-lined cardboard cover was fabricated for use with the flow-through cell in order to exclude ambient light.

Automatic control instrumentation provided continuous, cyclic sampling of the six settled effluents of the coagulation monitor. Individual channel flow was controlled by a solenoid valve placed in each tygon-tubing effluent line. When its valve was opened, each effluent line fed separately into a manifold whose outlet was connected through latex tubing to the inlet of the flow-through sample cell of the turbidimeter. When channel flow was checked by closing of the solenoid valve, it was wasted to a floor drain through a pyrex glass tee inserted into the flow line. The outlet of the turbidimeter sample cell also drained to this point.

5. CIRCUIT DESIGN PROCEDURE AND TESTING METHODS

The design of the proposed automatic control instrumentation proceeded in a functional sequence, as listed previously in Section 4.2. Each component circuit in the control sequence was designed separately, constructed and thoroughly tested before it was interlocked with the other component circuits to form the complete circuitry. The Digi-Key integrated-circuit testing module was used extensively in order to develop the desired performance of each component circuit. The testing module is equipped with an integrated-circuit socket breadboard, built-in 5-volt power supply and terminals, chassis ground terminals, two clock pulsers and four monitoring lamps. Four logic switches and two pushbutton pulsers can provide either high (1's) or low (0's) input signals. Output signals could be monitored by means of the lamps. A 5-volt integrated-circuit testing probe with an indicator light was used in conjunction with the testing module.

Overall performance of the complete control instrumentation was established by actual operation of the coagulation monitor under controlled laboratory conditions. Raw water turbidity and coagulant dosages were process variables that were manipulated in order to change conditions such that a different channel provided the best treatment. A concurrent jar test analysis of the six channel effluents was conducted to provide a check of the results indicated by control instrumentation.

6. CONTROL INSTRUMENTATION

The automatic control system was essentially a sequential logic system, comprised of several sequentially operating logic currents. For description purposes, the control instrumentation can be broken down into the following five basic component circuits: (1) master control circuit; (2) valve control circuit; (3) analog-to-digital conversion circuit; (4) comparison circuit; and (5) numerical display circuit. The function and operation of each component circuit will be fully described in succeeding separate sections.

The flip-flop is the basic building block in sequential logic systems, in which the order of occurring signals or events is important and must be recognized. A flip-flop can be described as an electronic binary storage element that is directly controlled by binary logic signals (10). A flip-flop has two outputs, called Q and $\overline{Q}$, which are complements of each other. The most important property of the flip-flop is that it can exist in one of two stable states, either Q=1 ($\overline{Q}$=0), called the 1 state, or Q=0 ($\overline{Q}$=1), referred to as the 0 state. In clocked flip-flops, the transition of Q from one state to the other may occur only with the application of a clocking signal. The output or state is determined by the logic values of the control inputs at the triggering instant, which usually occurs at the trailing or negative-going edge of the clocking signal.

Sequential circuits are logic circuits that contain memories, and the outputs depend also on the earlier values of the input variables. They are contrasted with combinational logic circuits, whose outputs depend only on the present values of input variables. Logic gates are combinational circuits. Flip-flops are elementary sequential circuits since they are storage elements intended for the "remembering" of binary signals. Flip-flops and logic gates can be interconnected to implement more complicated sequential circuits. This fundamental concept was generally employed in the design of the automatic control system for the coagulation monitor.

6.1 MASTER CONTROL CIRCUIT

The automatic control system was a sequential system, consisting of sequentially operating logic circuits. The order of operation was important and was controlled by a master circuit, which activated the operation of component logic circuits in the required sequence. The control sequence activated by the master control circuit consisted of the following component operations:

(1) A solenoid valve was opened and the settled effluent of a treatment system flowed through the turbidimeter.

(2) After a time delay of about two minutes, so that the previously sampled effluent would be flushed from the turbidimeter sample cell, the turbidity was measured and the corresponding electrical output signal was converted to a digital voltage signal.

(3) The new turbidity measurement was compared with an old measurement stored in the comparison circuit. The stored value was the lower value of the previous comparison operation.

(4) The lower value of the comparison operation was retained in the storage elements of the comparison circuit and would be compared with the next turbidity measurement.

(5) The result of the comparison operation was sent to the display circuit for readout.

(6) The valve was closed and the next valve was opened to repeat the sequence.

The master control circuit (Figure 3) consisted basically of a self-starting eight-step ring counter and two timing circuits. Eight clocked J-K flip-flops were interconnected to form the ring counter. The J-K designation refers to the two control inputs, J and K, of the flip-flop. The outputs of one flip-flop were connected directly or through gating to the inputs of the next flip-flop or stage. Such a ring counter is analagous to a stepping switch, where each triggering pulse causes an advance of the switch by one step (11). Succeeding clocking signals transferred the state 1 progressively around the ring. One or both of the outputs of each flip-flop comprising the master ring counter was connected to an input in another component circuit. When the state of the flip-flop changed from 0 to 1, the successive logic operation in the control sequence was activated. Connection of the NOR gate enabled the master ring counter to automatically re-start its stepping operation. A NOR gate is a combinational logic circuit in which the output is a 0 (off) if one or more inputs are 1 (on). Conversely, if the inputs are all 0 (off), the output is a 1 (on).

A timing circuit, operating in the astable mode, supplied the clocking signals that stepped the ring counter. The astable timer (Figure 4) triggered itself and ran free as a multivibrator. Its timing interval, or pulse period, was set at 7.2 microseconds, which was more than sufficient, as sequential logic circuits performed in the order of nanoseconds.

In order to flush the preceding channel flow from the flow system before the next turbidity measurement was taken, it was necessary to incorporate a second timing circuit into the master control circuit. This timer (Figure 5), operating in the monostable mode, functioned as a one-shot. When the TIMER-SET flip-flop (FF no. 2) was changed to the 1 state, its low-voltage output $\overline{Q}$ activated the monostable timer. The timing interval was set at 110 seconds.

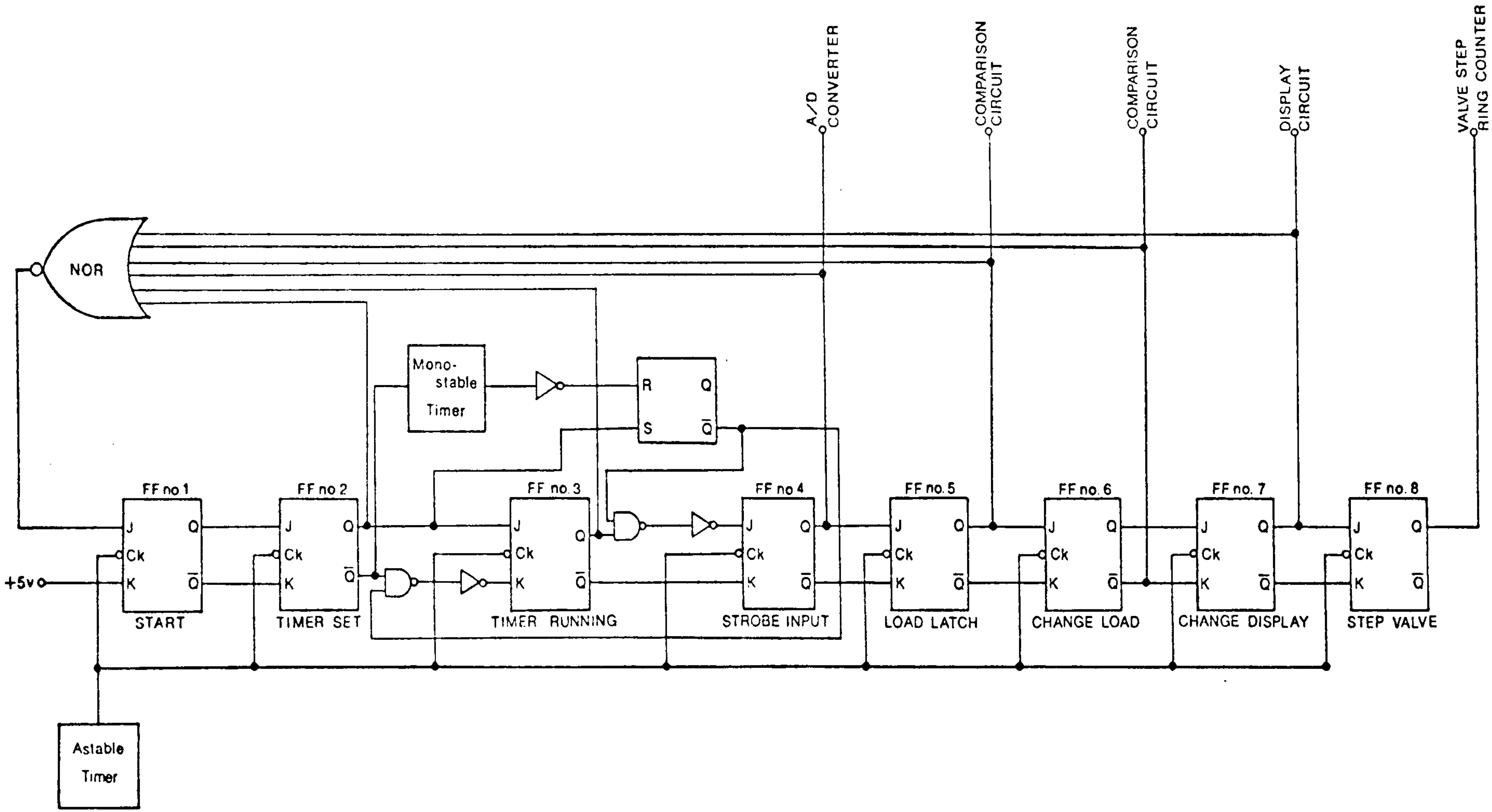

FIGURE 3. MASTER CONTROL CIRCUIT

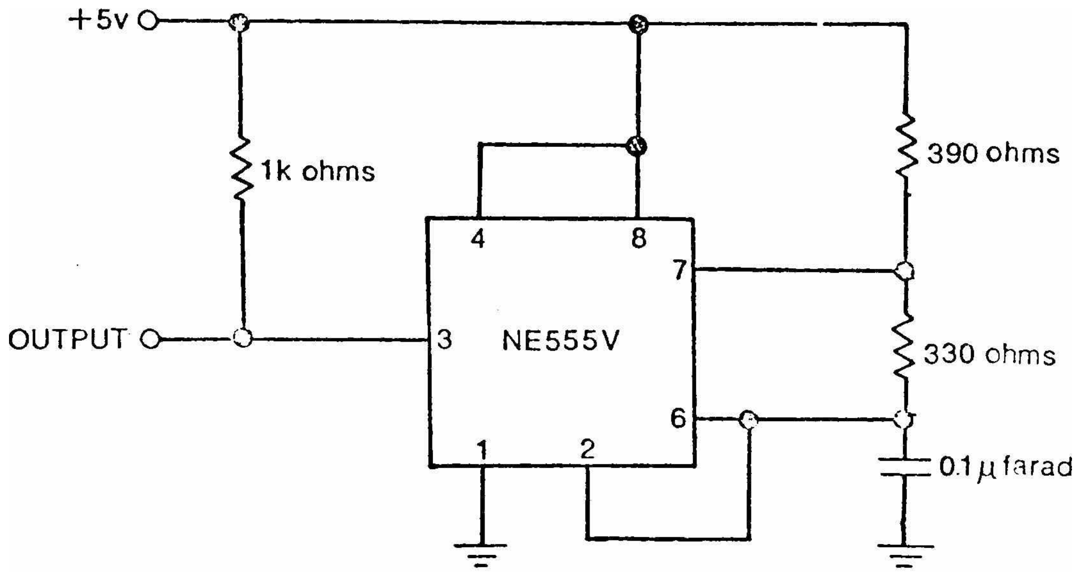

FIGURE 4. ASTABLE TIMER

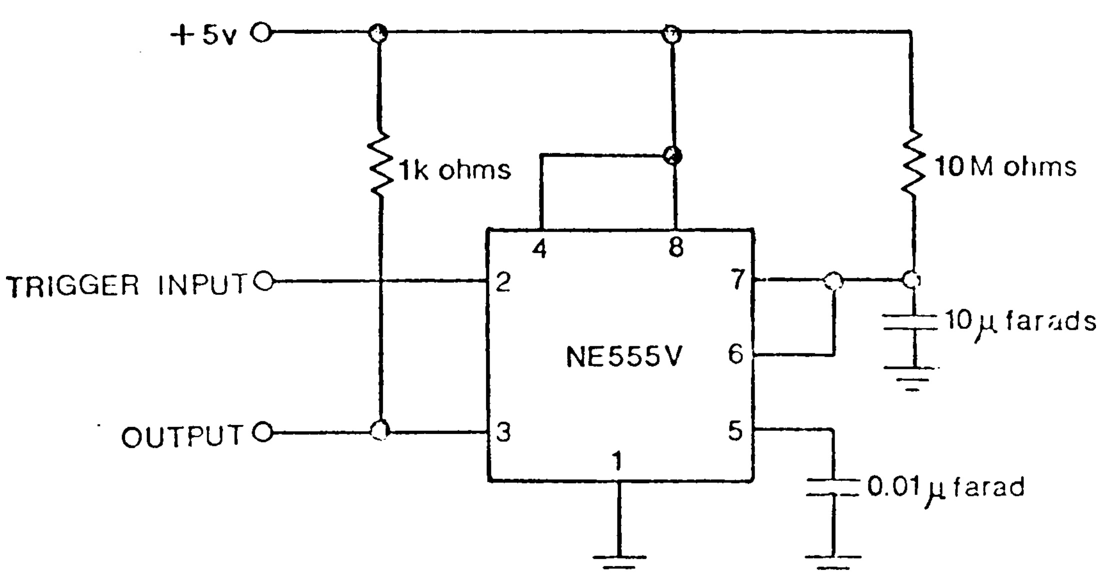

FIGURE 5. MONOSTABLE TIMER

While the monostable timer was running, the stepping of the ring counter was "arrested" by the connection of the R-S flip-flop and the gating. When the set interval of the timer had elapsed, the stepping operation continued.

6.2 VALVE CONTROL CIRCUIT

Continuous, cyclic sampling of the six flow channels was provided by the valve control circuit (Figure 6). Opening and closing of the six solenoid valves in sequence was implemented by this circuit, which itself was activated by the master control circuit. Opening the valve was the first operation in the over-all control sequence. The main element in this circuit was a six-step ring counter (Figure 7) similar to the ring counter in the master control circuit. The STEP-VALVE flip-flop (FF no. 8) in the master ring counter supplied the clocking signals to step or advance the valve ring counter.

Each Q input of the six flip-flops comprising the valve ring counter was connected through a "driving" circuit to a 24-volt relay coil. The relays were the sealed midget plug-in type (about 2 cu. in. in volume) with a two-pole, double-throw (2 PDT) contact assembly. The "driving" circuit consisted of a 4.7k-ohm resistor and an n-p-n silicon transistor connected in the common-emitter configuration. The transistor circuit amplified the output of the flip-flop so that it would "drive", or trip, the relay. When the Q output of the flip-flop changed from 0 to 1 in response to a clocking signal sent from the master control circuit, the relay closed and the solenoid valve was energized to open. When the flip-flop returned to the 0 state, the relay opened and the solenoid valve was de-energized to close.

The monostable timer in the master control circuit was set to provide a 110-second interval in which the valve was open. This period was necessary

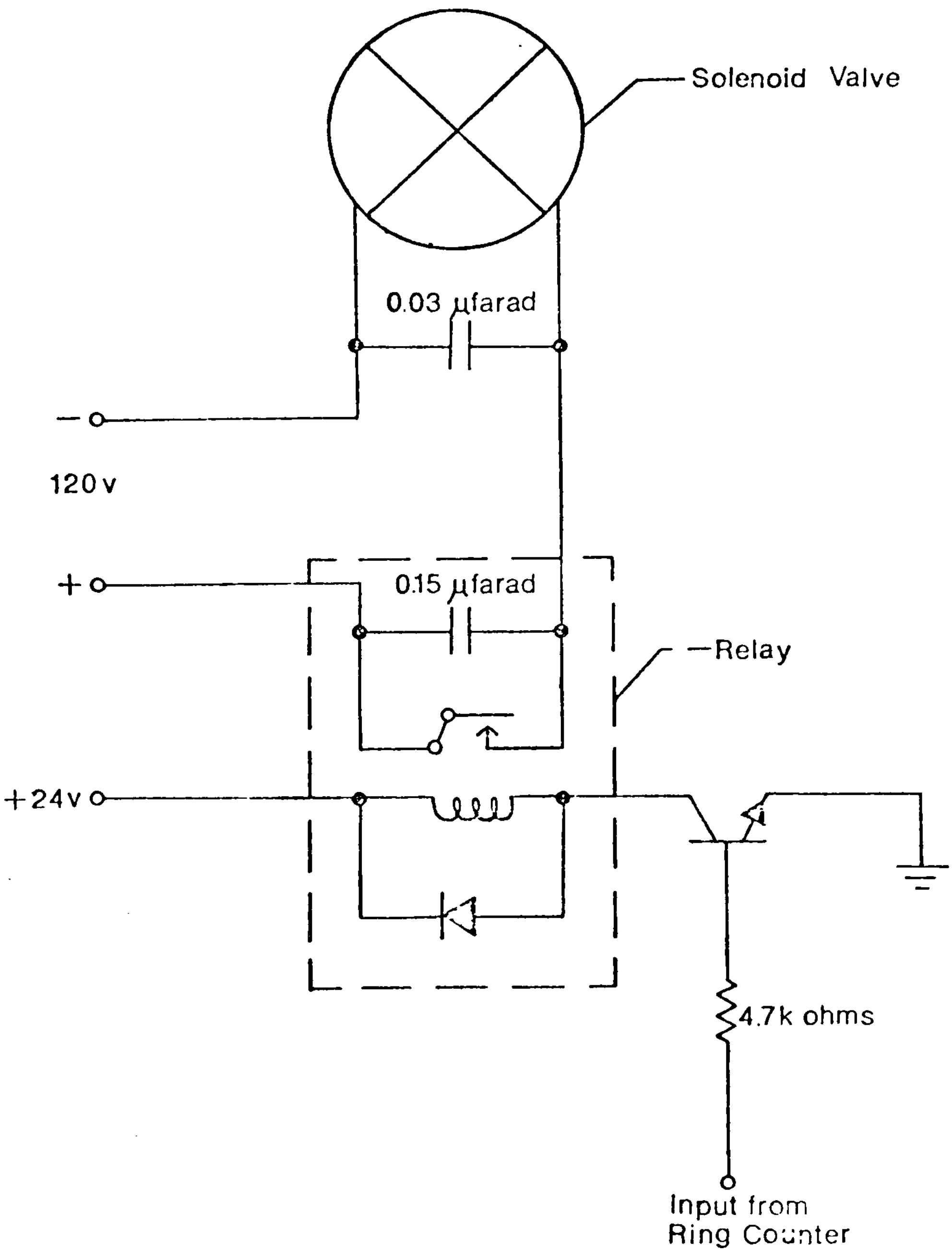

FIGURE 6. INDIVIDUAL VALVE CONTROL CIRCUIT

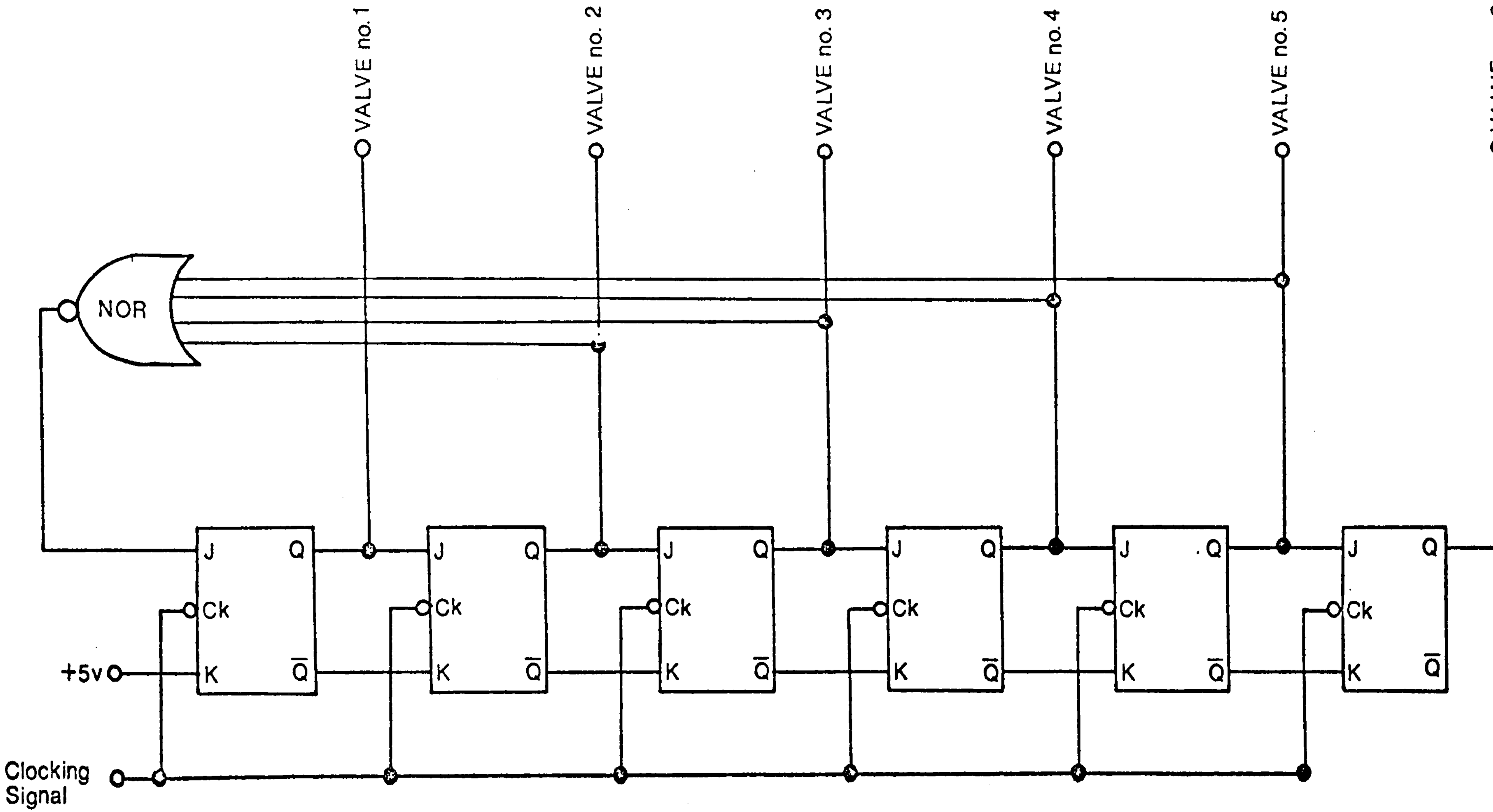

FIGURE 7. SIX-STEP RING COUNTER
IN VALVE CONTROL CIRCUIT

in order to flush the previously sampled channel flow from the manifold and the turbidimeter sample cell.

The six relays were plugged into octagonal amphenol sockets and centrally mounted on an aluminum chassis. A diode was connected across each relay coil to suppress transients, and a capacitor was connected between the relay contacts to minimize arcing.

6.3 ANALOG-TO-DIGITAL CONVERSION CIRCUIT

The analog-to-digital conversion circuit changed the electrical output signal of the turbidimeter from the analog to the digital mode. This conversion enabled the next operation in the control sequence, the important comparison operation, to be performed. The comparison operation was carried out by logic circuitry, which required digital inputs.

The electrical output of the turbidimeter was a current signal from the photomultiplier tube. An operational amplifier circuit was used to convert the current signal to a proportional output voltage. A parallel resistance-capacitance component in the operational amplifier circuit reduced high-frequency noise and stabilized the voltage signal.

Conversion of the voltage signal from the analog to the digital mode was implemented by an analog-to-digital (A/D) converter using the successive approximation method. This method repeatedly approximates the input voltage by successively dividing the voltage range in half. The number of approximations depends on the degree of bit reduction. For example, in order to resolve an 8-bit digital number, eight approximations are made. A bit is a binary digit (a 1 or a 0), and a group of bits having a significance comprises a binary number or word. The selected degree of resolution in the analog-to-digital conversion of the turbidimeter output signal was 8 bits.

Resetting of the A/D converter and the initiation of conversion was controlled by the strobe input, which was supplied by the Q output of the STROBE-INPUT flip-flop (FF no. 4) in the master ring counter. When the flip-flop was changed to the 1 state, the A/D converter was reset. Conversion began when the flip-flop returned to the 0 state.

6.4 COMPARISON CIRCUIT

The crux of the control instrumentation was the comparison circuit (Figure 8). The comparison of two turbidimeter output signals, which had been converted to the digital mode, was performed by this vital circuit. The results of the comparison were sent to the display circuit. The comparison operation can be further broken down into two unit operations, the LOAD-LATCH and the CHANGE-LOAD operations, which were activated in the appropriate sequence by the master control circuit.

Two cascaded 4-bit magnitude comparators performed the critical comparison operation. Three fully decoded decisions about two 8-bit words, designated A and B, were made and were externally available at three outputs. The comparator determined whether the binary number A was greater than, equal to, or less than the other number B.

One of two 8-bit banks of bistable latches received the digital voltage output of the analog-to-digital converter. The two sets of latches, also designated as A and B, served as temporary storage for the binary information between comparison determinations.

During initialization of control instrumentation, two preparatory operations were necessary to establish the proper initial conditions in the comparison circuit. All 1's were loaded into the B set of latches, and the J-K flip-flop was enabled to load the incoming digital voltage signal into the A latches. Both operations were implemented by toggling ($0 \rightarrow 1 \rightarrow 0$) two "debounced" SPDT switches (Figure 9).

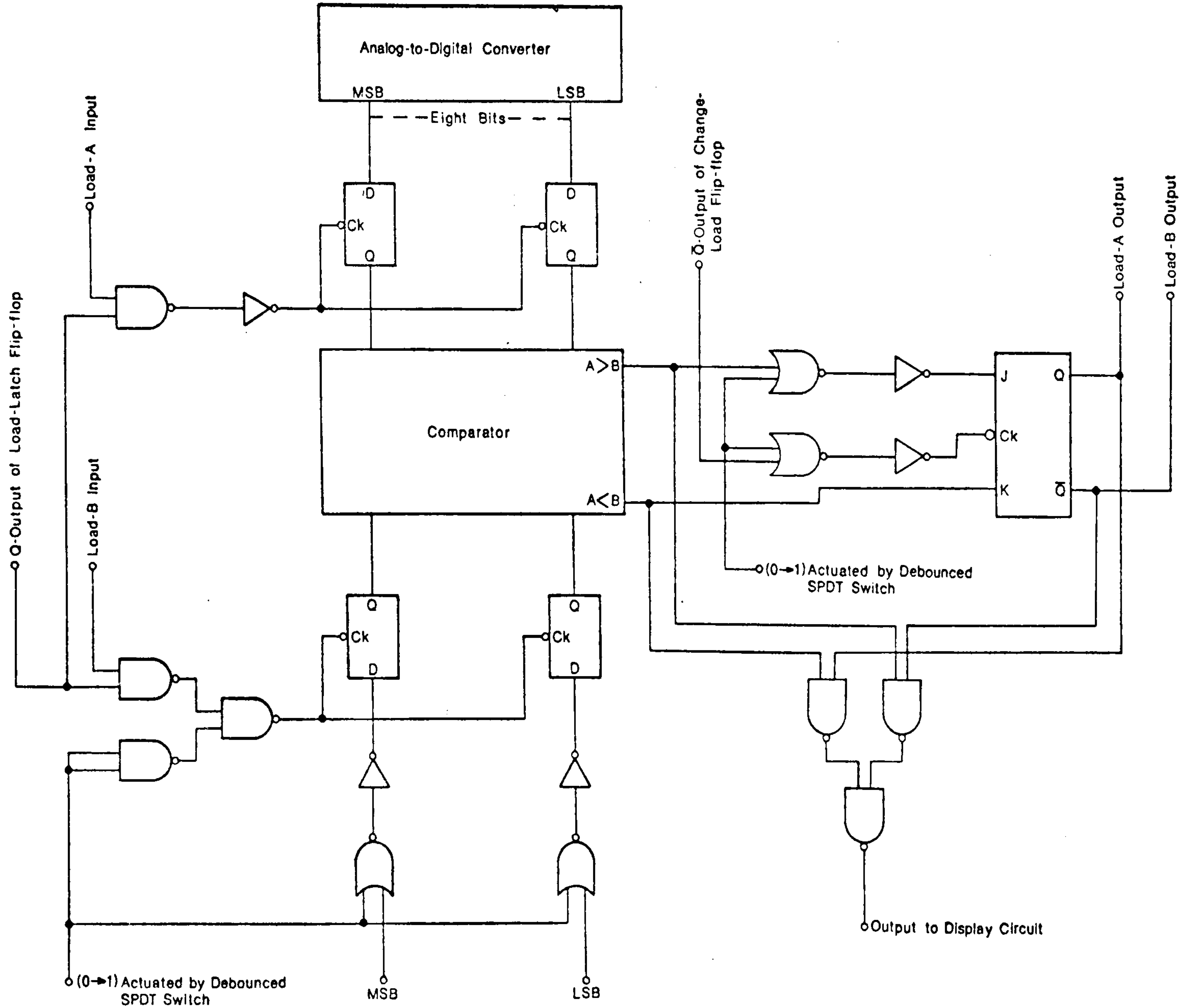

FIGURE 8. COMPARISON CIRCUIT

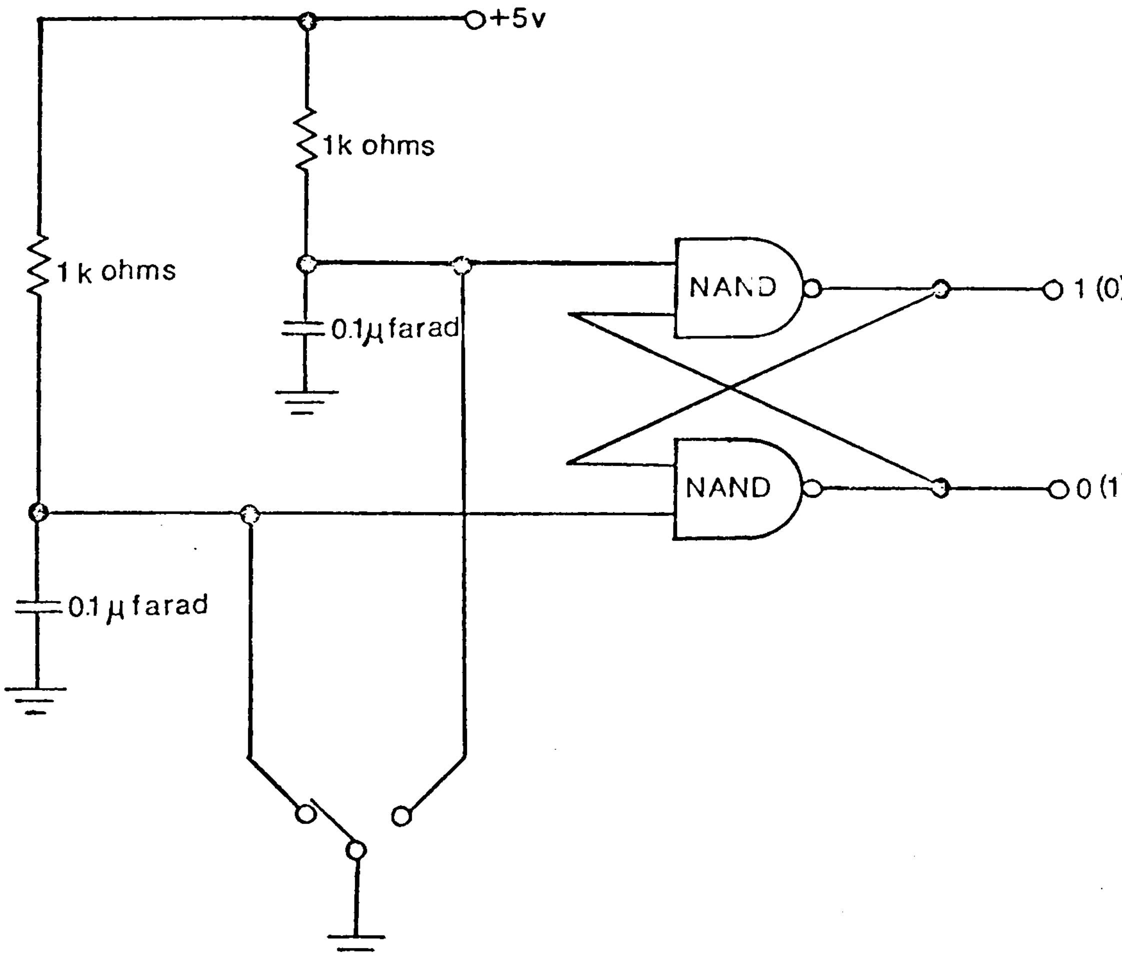

FIGURE 9. DEBOUNCED SPDT SWITCH USED TO INITIALIZE COMPARISON CIRCUIT

The function of the J-K flip-flop was to indicate which set (A or B) of latches would receive the new binary information from the analog-to-digital converter. This depended on the result of the previous comparison. If A>B, the flip-flop was in the 1 state, and the next 8-bit word would be loaded into the A latches; if A<B, the flip-flop was in the 0 state, and the new information would be stored in the B latches. In other words, the lower turbidity value, as determined by the comparison operation, was retained as a binary number in one set of the bistable latches. The second set of latches was empty and would receive the new turbidity measurement from the analog-to-digital converter. On command from the master control circuit, the turbidity measurements in the two sets of latches would be fed into the comparator to determine the lower value.

Sequential operation of the comparison circuit proceeded as follows. The digital voltage output of the analog-to-digital converter was presented at the data (D) inputs of both the A and B latches. When the LOAD-LATCH flip-flop (FF no. 5) in the master ring counter changed to the 1 state, its Q output triggered one set of the latches, as determined by the state of the flip-flop following the comparator, and the information present at the data inputs was transferred to the Q outputs of the latches. This new binary number was compared with the old number previously stored in the other set of latches, and the results fed to the J and K inputs of the following flip-flop. When the CHANGE-LOAD flip-flop (FF no. 6) in the master ring counter changed to the 1 state, its $\overline{Q}$ output enabled the comparison flip-flop to load the next piece of binary information into the appropriate set of latches.

6.5 NUMERICAL DISPLAY CIRCUIT

The final operation in the control sequence was performed by the numerical display circuit (Figure 10). The function of the display circuit was to indicate which flow channel was producing the effluent with the lowest residual turbidity. Essentially, the display circuit received the result of the comparison operation in the form of a binary-coded-decimal (BCD) signal and converted this logic signal to a visible numerical display corresponding to the flow channel providing optimal turbidity removal. A readout tube, driven by a BCD-to-seven segment decoder/driver, provided a digital fluorescent display. Numbers were displayed by excitation of phosphor-screened segments, which were energized by electrons emitted by a directly heated cathode.

Initial input signals to the display circuit came from the valve-control and comparison circuits. These inputs were gated to a set of six J-K flip-flops, the triggering of which was controlled by the CHANGE-DISPLAY flip-flop (FF no. 7) in the master ring counter. When FF no. 7 was triggered by the astable timer, its Q output in turn triggered one of the six flip-flops in the display circuit. The particular flip-flop corresponded to the optimum flow channel. For example, if FF no. 4 in the display circuit was triggered, this meant that flow channel no. 4 was now producing the effluent with the lowest residual turbidity. The $\overline{Q}$ outputs were gated through NAND's to the inputs of the decoder/driver. The output of a NAND gate is 0 (off) only if all inputs are 1's (on); conversely, the output is a 1 (on) if one or more inputs are 0 (off). If FF no. 4 had been triggered, the decoder/driver activated the tube to provide a bright, sharp display of the numeral 4.

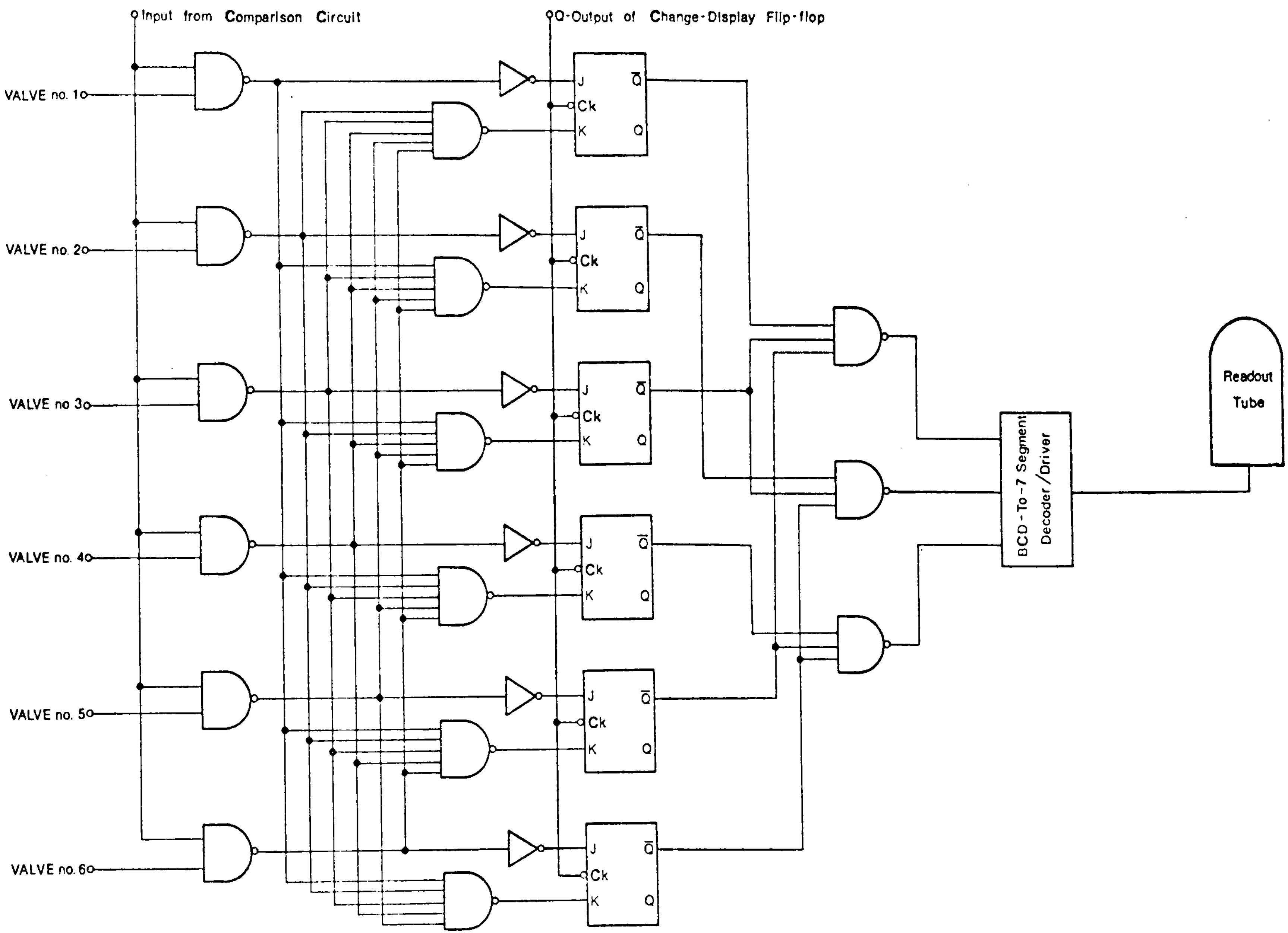

FIGURE 10. NUMERICAL DISPLAY CIRCUIT

7. SUMMARY

The work reported herein entailed the design of a control system to automate the operation of a coagulation monitoring device. The developed automatic control system is essentially a sequential logic system, comprised of several sequentially operating logic circuits. The basic functions of the control instrumentation are synopsized below:

(1) A relay-valve system, controlled by logic circuitry, implemented continuous, cyclic sampling of the six flow channels through a continuous flow turbidimeter.

(2) The logic circuitry made a comparison of two turbidity signals, which had been converted to digital voltage outputs, and reported the results to a display circuit.

(3) Logic circuitry provided a visible numerical display that corresponded to the flow channel producing the lowest residual turbidity.

8. FUTURE WORK RECOMMENDATIONS

1. A commercial continuous flow turbidimeter, such as the Hach Model 1720, should be used in future development or applications of the coagulation monitor. The commercial instrument would provide a direct recorder output, i.e., an analog signal which would probably be more stable and consequently more amenable to digital conversion. However, the use of such a continuous analyzer may necessitate other modifications of the monitor. For example, the flow rate through the monitor would have to be increased in order to meet sample requirements of the Hach Model 1720.

2. A digital voltmeter with true root-mean-square (rms) capability should be placed between the electrical circuit of the turbidimeter and the analog-to-digital converter. The rms circuit would stabilize the turbidimeter signal input to the adc.

3. All circuitry should be solid-state. This includes all required power supplies. Component circuits should be mounted on shielded printed-circuit cards and centrally housed in order to minimize voltage leakage and noise interference. A solid, common circuit ground should also be provided.

4. After each monitoring cycle the numerical comparison circuit should be reset to zero in order to reflect possible changes in raw water quality.

5. Research should be undertaken to determine the applicability of other water quality indices as control parameters in the coagulation process. Feedforward control of raw water quality parameters -- such as turbidity, pH, and alkalinity -- in conjunction with feedback control of residual turbidity should be studied. Analysis or interpretation of several control parameters could be implemented by a computer, which could also control

chemical feed rates in order to determine the optimum coagulant dosage and maximize the efficiency of the coagulation process.

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