UNITED STATES
DEPARTMENT OF THE INTERIOR
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# INSTRUMENTATION FOR MEASURING AND RECORDING STREAMFLOW DATA AT RIVER-CONTROL STRUCTURES

By The Instrument Development Laboratory

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# INSTRUMENTATION FOR MEASURING AND RECORDING STREAMFLOW DATA AT RIVER-CONTROL STRUCTURES

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## ABSTRACT

The instrumentation described in this report was developed in the mid to late 60's to resolve the dilemma of intolerably high percentages of missing streamflow records on certain large and highly-controlled streams in industrialized parts of the United States. Analysis of the field situation at specific problem sites quickly suggested that conventional stream-gaging techniques should be supplanted by new instruments, designed to measure key hydraulic data at the nearest stream-control structures. The key data were found universally to include some combination of a length measurement to specify the vertical height of a gate opening in a dam; measurement of pressure-head differential in a turbine; a count of lockages; and precise measurement of time, to give one master reference scale to which all measurements could be keyed.

The instruments designed to collect such key data are the shaft position digitizer, the shaft output follower, the STACOM manometer, the lock pressure switch, and the digital data collection console. Although their design was prompted by the need to collect data at river-control structures their potential for field use is not that restrictive. Several of these instruments have already found widespread use in the hydrologic data-collection program at large.

In the 12-1/2 year period from June 1968 to December 1980 nineteen different river-control structures were instrumented. The general experience to date has been a marked improvement in completeness of record, with the average performance somewhere in the 80percentile range. Performance percentiles at individual sites have ranged from the mid 90's to about 70. Maintenance records show the instruments to be virtually trouble-free, except for the unpredictable acts of nature and man.

# INTRODUCTION

Work on the design and the establishment of a network of flow measuring stations on streams throughout the United States can be traced back at least to 1888 when the U.S. Geological Survey began its formal assessment of the Nation's surface-water supply. One tangible product in this assessment has been and continues to be a series of periodic reports in which the streamflow data for each station for a specified period are assembled.

For a given station on a given stream the struggle for completeness of record is unrelenting, as a number of factors usually conspire to frustrate attainment of perfection. One such factor suddenly grew in importance in the early 1960's when the cumulative effects of industrialization and development along certain large rivers in the United States invoked demands for continuous streamflow records, especially during periods of low flow. The particular missing-record factor related to difficulties in gaging the sluggish low flows in streams highly controlled by multiple dams, locks, power structures, and reservoirs. Symptomatic of this problem is the example cited by Wires (1971) that for 7 key gaging stations on the Ohio River, 40 percent of the daily discharge records were not determined in 1962 and 1963.

With the normal streamflow measurement techniques -- using appropriately-sloped open (uncontrolled) reaches of river -- ruled out, the only recourse, at the growing list of key stations plagued with missing low-flow record, was to examine the measurement prospects at the nearest control structures. This led to the development of the instrumentation and measuring techniques summarized in this report. The first successful prototype installation was in June 1968 at Greenup Locks and Dam on the Ohio River near Greenup, Ky. By the end of 1980 the number of such Survey installations had risen to nineteen.

## Acknowledgments

A number of individuals in or associated with the Instrument Development Laboratory shared in preparing this report. The principal writing effort was accomplished by Russell H. Brown and Francis C. Koopman. Much of the source material was provided by Samuel E. Rickly, with key support from James I. Rorabaugh and William L. Rapp.

## THE FLOW-MEASUREMENT PROBLEM

A survey of the variety of control structures built on certain large rivers in industrialized parts of the United States reveals that the problem of making an accurate stream-discharge measurement at any given structure can be overcome by deciding how best to measure five principal types of flow. By paraphrasing from Wires (1971) these types are identified as:

1. Flow through controlled gates
2. Flow through locks
3. Flow through turbines
4. Flow over dams and spillways
5. Flow as leakage through the cited structures.

The measurement task for each type of flow is analyzed by drawing upon well established fundamentals of hydraulics, which then enables the complete specification of a stream-discharge-measurement procedure for any combination of control structures.

### Parameters to be Measured

Each of the cited five principal types of flow through river control structures has been rigorously analyzed and the appropriate mathematical expression developed to describe, in quantitative terms, the flow regime. Results of this analytical work are presented in careful detail in two important papers by Wires (1971) and Collins (1977). These provide the necessary foundation for deciding just exactly what parameters must be measured to define each flow type.

### Flow Through Controlled Gates

On dam structures one of the largest and most commonly encountered flow-control devices is the Tainter gate (fig. 1) which rotates about a horizontal steel axis whose two ends bear in steel trunnions on concrete or steel support structures downstream from the spillway crest. In its closed position the full weight of the gate forces the lower edge into a longitudinal seal that spans the entire width of gate sill or spillway opening, thereby minimizing the leakage and limiting it primarily to the two gate ends. In operation the radial movement of the Tainter gate permits an infinite number of settings between the closed and wide-open positions. Thus a key parameter to be measured for any setting is the gate opening (fig. 1) which means the clear vertical distance from gate sill (spillway crest) to lower edge of gate. Although this cannot usually be measured directly it can be determined indirectly through the fixed geometry and dimensions of the gate, and observations on an arbitrarily selected visible reference point (R.P.) thereon. Corollary parameters that must be measured are headwater and tailwater elevations, respectively, (fig. 1) referenced to a convenient common datum such as the gate sill. All of the foregoing measurements must be keyed to a common and precise time scale.

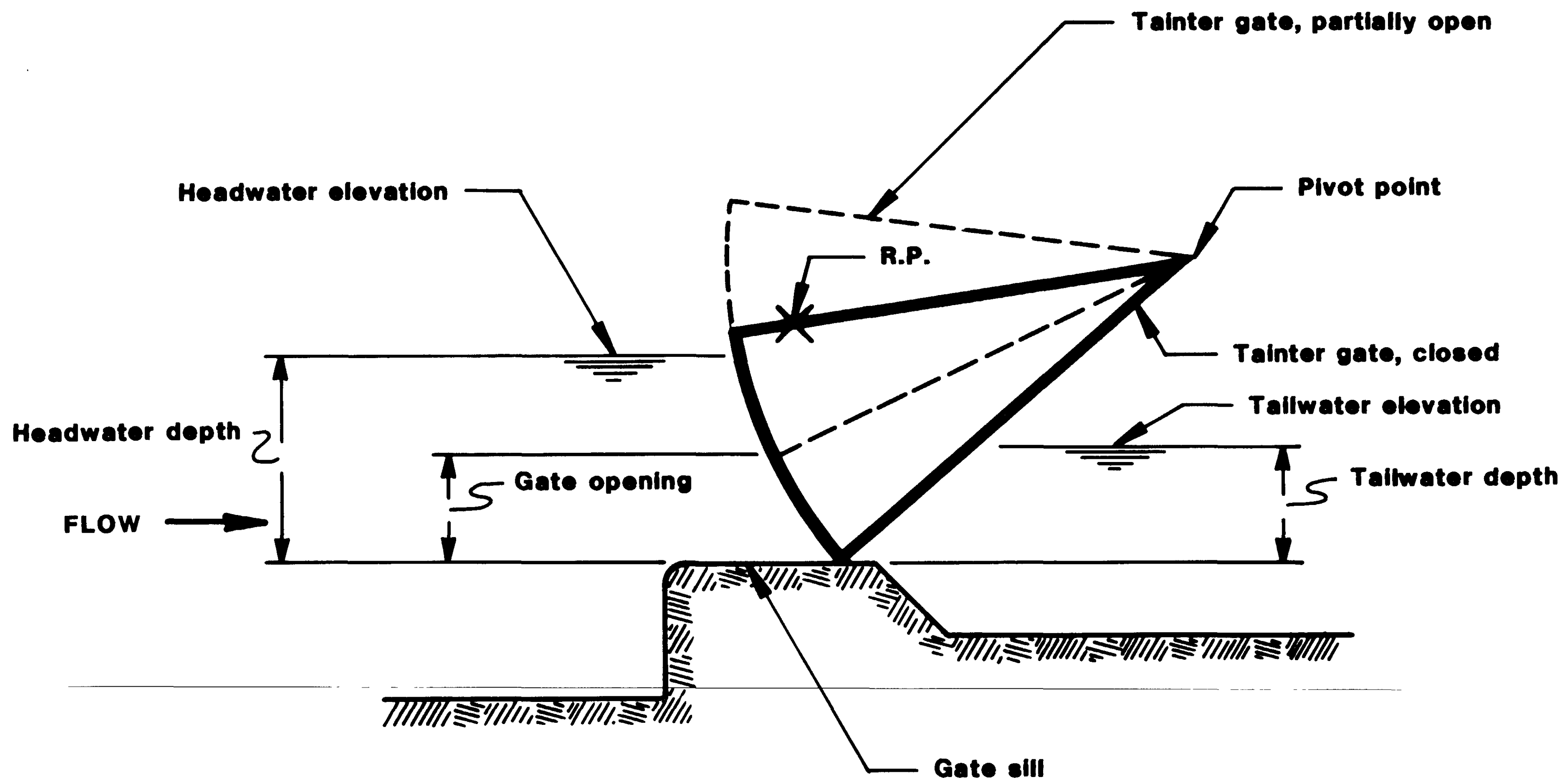



Figure 1.-- Cross section showing generalized Tainter gate geometry

Despite a variety of other gate types, each one of which may exhibit some unique feature(s), the flow measurement task generally devolves, as noted for the Tainter gate, into the precise determination of parameters involving heads of water at specified points, gate size and geometry, and elapsed time. The only factor omitted in the discussion thus far is the numerical coefficient in the appropriate mathematical equation that allows correct computation of the volumetric rate of flow through the gate opening. This coefficient is really a "calibration" factor and although some theoretical definition can usually be given to its makeup, its final and precise determination rests upon volumetric flow measurements over a range of flow conditions at the particular gate.

## Flow Through Locks

The operation of a set of locks is a mechanical exercise analogous to emptying and filling a container whose dimensions (and hence volume) can be specified. The critical dimensions are obviously the plan area of the lock and the difference -- whenever a lockage occurs -- between headwater and tailwater elevations, referenced to a convenient common datum such as the lock sill. The key parameters to be measured, therefore, for any given lock, are the headwater and tailwater elevations keyed to a precise time scale, and the number of lockages keyed to arbitrary intervals (say, one- or two-hour periods) on the same time scale. Out of these measured data, combined with the known lock plan area, the total volume of flow during the entire recording interval can be computed and converted into average flow rates for any desired time periods.

## Flow Through Turbines

In the United States the use of hydropower to produce mechanical energy dates back to the simple "wheels" used in streams or estuaries by the earliest mills in the Colonies. Out of these humble beginnings evolved the sophisticated designs for the modern hydraulic turbines which, coupled with electrical generators, now serve very efficiently to convert hydropower into much needed electrical energy. In its simplest conceptual form a turbine is just another device for controlling the descent of water from a higher to a lower elevation. The turbine form of control is exercised by requiring the water to move through smooth precisely-built steel passageways that have no abrupt changes in cross-sectional area. Mechanical energy is extracted from the mass of descending water as it moves through the turbine propellor or runner at the lower end of the cited passageways. Maximum overall efficiency is achieved by minimizing head losses due to friction or turbulence.

The technique adopted by the Survey for measuring the volumetric rate of flow through a turbine capitalizes on the foregoing controlled flow environment and the fundamental hydraulics theory (see Winter, 1934) available for its analysis. As with other control devices, head parameters are found to be the key items to be measured.

Where the precise shape and dimensions of the enclosed water passageway can be defined (given by the turbine manufacturer) it is only necessary to measure the pressure head at two convenient points along the flow path. The head differential thus observed, keyed to a precise time scale, is a quantitative indicator of the flow magnitude which is then computed through use of the appropriate mathematical equation.

The choice of suitable points for the pressure-head measurements is commonly taken on the turbine spiral or scroll steel case where the venturi effect along the flow path, as the passageway cross-sectional area steadily shrinks, produces clear-cut head differentials.

Again, as in the discussion on gates, the equation for computing the flow contains a numerical coefficient that is really a "calibration" factor for the particular turbine. Although it is given by the turbine manufacturer it is verified through currentmeter measurements at a downstream cross section, for a range of flow conditions at the dam site.

## Flow over Dams and Spillways

From countless worldwide hydraulic experiments on laboratory models and field prototypes there exists today in the hydraulics literature a wealth of mathematical equations that quantitatively describe the volumetric rates of flow of water over weirs and dams of all shapes and sizes under almost any conceivable set of flow conditions. For the range of field conditions envisioned in developing the instrumentation described in this report the pertinent flow equations may be generalized in a single relatively simple form. This, as might be surmised, requires the measurement of only two key parameters -- namely, headwater and tailwater elevations referenced to the elevation of the dam or spillway crest -- that are keyed to a common and precise time scale. As a matter of fact the tailwater elevation does not enter into the equation unless the dam becomes "submerged," and by definition this occurs only if the tailwater rises above the dam or spillway crest.

In common with the previously described flow situations the mathematical equation contains a numerical coefficient that allows correct computation of the volumetric rate of flow. Although this coefficient may be closely determined by matching the physical characteristics of the given dam or spillway with reference data in the hydraulics literature, its final and precise determination is a field "calibration" exercise based on current-meter measurements over a range of flow conditions.

## Flow as Leakage

As intimated in the preceding sections leakage can occur, under certain flow conditions, through most river-control structures. The challenge in measuring this type of flow usually relates uniquely to the particular combination of control structures at a given river site. The measuring challenge does generally devolve, however, into a field calibration or rating exercise, whether it be for the entire combination of structures or for individual components (such as a single gate). No new parameters need to be measured inasmuch as the rating exercise yields leakage flow expressed in terms of those parameters already described, the principal ones being headwater and tailwater elevations and gate openings.

## DEVELOPMENT OF THE INSTRUMENTATION

In confronting the design task for instrumenting river-control structures, so that they could become a useful part of the streamgaging station network, the developmental plans required a conscious decision on the particular scientific avenue to be explored. Several avenues were available, in the mid-1960's when the work began, but the one chosen involved the use of electromechanical devices linked to the physical movement of gates and water surfaces.

From the discussion of "Parameters to be Measured" it becomes obvious that the overall task can be generalized as involving only four basic types of measurement, namely:

1. Monitoring gate openings or settings.
2. Monitoring fluctuations of water-level elevation.
3. Monitoring (counting) lockages.
4. Monitoring fluctuations of pressure-head differentials.

Implicit in "monitoring" is the requirement for all observations to be keyed precisely to a common time scale.

The need to monitor gate openings led to the practical realization that through the physical linkage of the gate-hoisting mechanism it would only be necessary to monitor, say, the rotation of a suitable shaft in that mechanism. This in turn led to the conception, design, prototype fabrication, and successful field installation of the shaft position digitizer (SPD) instrument.

The need to monitor water-level fluctuations at control-structure sites where conventional gage-house stilling wells often were not feasible or cost effective led to the conception, design, prototype fabrication, and successful field installation of the shaft output follower (SOF) instrument.

The need to count lockages led to the very simple and direct solution of mounting on the lock wall or cavity, at the approximate midway or mean water-level position (midway between average headwater and tailwater elevations), an electrical switch that closes to register one count when the water pressure dissipates as the lock empties. Such a lock pressure switch can actually be rigged, as the need arises, to register a count when a lock either empties or fills or both.

The need to monitor pressure-head differentials could have been approached by using commercially available recording manometer devices. However, special problems of maintenance and calibration arise through the Survey requirements for overall precision in computing the streamflow data, and for minimizing missing-record periods even though the instrument site may be unattended much of the time. This led, therefore, to the conception, design, prototype fabrication, and successful field installation of the stabilized and temperature compensated manometer, now termed the "STACOM" manometer. This particular instrument is now widely used at many stream-gaging stations throughout the United States, and in this application it simply monitors how the stream stage (water level) changes with time. When used in this manner the STACOM manometer is functioning as an alternate for the SOF unit.

Finally, it was recognized that at any given river-control-structure site the eventual stream-discharge computations would entail appropriate use of each of the foregoing individual suites of measurement data peculiar to that site. Those computations would be expedited if the mix of data suites unique to the site was combined in one neat and compact record. This need led, therefore, to the conception, design, prototype fabrication, and successful field installation of a conveniently located console unit, termed a digital data collection console, which could be programmed to interrogate, in a specified sequence and time interval, the individual data collection points in use at the site.

Although the foregoing instruments were developed specifically in response to needs at river control structures, and were first used to satisfy those needs, they obviously have potentials for a much broader range in use. This is exactly what has occurred already with the STACOM manometer, which is now being used at a modest variety of stations throughout the Survey network and is therefore stocked at the Hydrologic Instrumentation Facility (HIF) warehouse as a standard item of Survey equipment. For the other instruments detailed drawings and specifications are on file at the HIF to anticipate future requests for the information needed to commission suitable commercial fabrication and supply.

## Shaft Position Digitizer (SPD)

This electromagnetic device is the brainchild of two Survey employees, Harold O. Wires (dec.) and Samuel E. Rickly (ret.). It is described and illustrated in great detail under U.S. Patent No. 4,010,464 dated March 1, 1977. Only limited explanation and illustration are therefore deemed appropriate in this report.

The shaft position digitizer (SPD) is housed in a sturdy rectangular metal case (see fig. 2) about 10 in. long, 6 in. wide, and 4-1/2 in. deep, which is fitted with a rubber-gasketed removable cover. A 2-inch-diameter window in the cover allows direct reading of a 4-place mechanical counter. The only feature external to the case is a chain sprocket mounted on the protruding end of an input shaft which is journaled in the two sides of the case. This permits linkup, via chain drive, to a similar chain sprocket on the main shaft of the gate hoisting machinery. Weight of the SPD unit is 7-1/2 lbs.

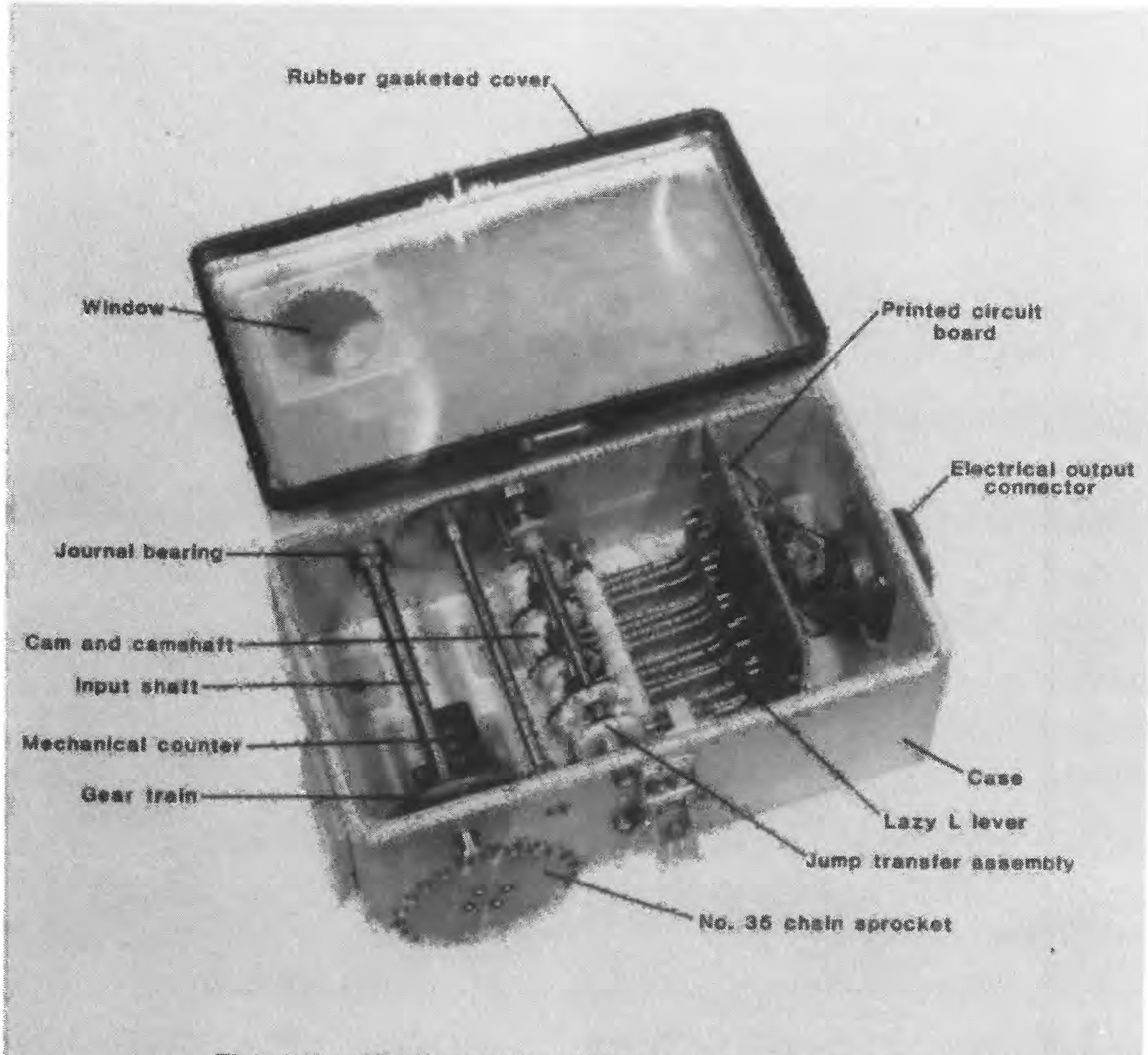



Figure 2.--Shaft position digitizer and nomenclature.

Operation of the SPD unit is logically described in a step-bystep sequential manner, from the chain drive of the input shaft to the electrical digital output (binary coded decimal, that is, BCD) which is delivered when the unit is electrically interrogated. The description should be read and interpreted in conjunction with the labeled perspective view of the SPD unit (fig. 2).

Through a suitable gear train arrangement the rotation, in either direction, of the input shaft drives a conventional 4-place mechanical counter. A count of "one" in the first or units decade of the counter is equivalent to linear movement of 0.01 ft in the chain drive.

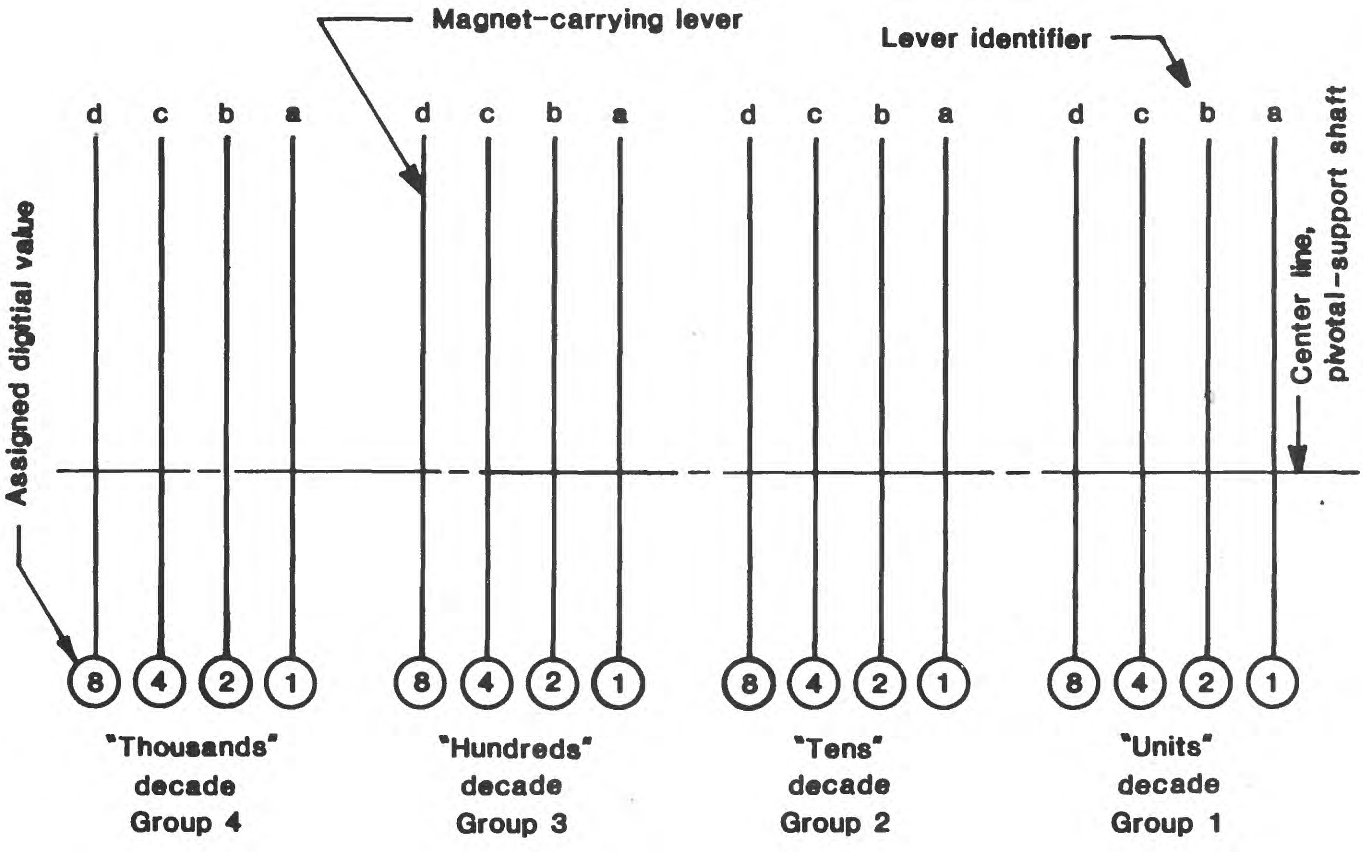
The input shaft also drives, through the cited gear train, a shaft on which are mounted 16 freely rotatable cams. These comprise the input side of an electro-mechanical assemblage (a counting digiizer) which accumulates and yields--when electrically interrogated-the same shaft-rotation "count" (in BCD format) as that displayed by the mechanical counter. The shape of each cam is designed to engage, at the proper movement, the near-horizontal end of a "lazy L" shaped lever. The horizontal (long) leg of each lever is pivoted on a supporting shaft at a point significantly displaced toward the cam shaft from the weight-balance point. This means that when the cam is not engaged the unbalanced weight of the upstanding (short) leg causes limited rotation of the lever. The upstanding leg carries a small magnet which aids the unbalanced weight in making contact with and thereby closing a reed switch, mounted on a printed circuit board which is secured in a vertical position on the base of the SPD case. The circuit board contains suitable buffer circuitry components for producing an electrical BCD output via the particular lead that links the closed switch to a designated pin in a multi-pin electrical output connector. The SPD unit is in a continuous standby mode with no electrical output until electrical interrogation occurs. Thus it needs no electrical power of its own.

All levers are pivoted in a row on the same shaft and arranged in four groups of four each. Proceeding from right to left the first group represents the "units" decade in the counting sequence, the second group the "tens" decade, the third the "hundreds," and the fourth the "thousands." The cams are constrained, through appropriate mechanical transfer mechanisms, to engage the levers in such a sequential way that by closing the correct combination of reed switches the rotation of the input shaft is accumulated in digital form to correspond with the count on the numerical display of the mechanical counter. To illustrate, consider the first group of four levers which represent the units decade. Each lever is assigned the digital value shown in the sketch accompanying table 1. Assembled in the table are data that show which levers must be in the switch-closed position to reproduce the indicated numerical count. The entire sequence for the units decade is given, as well as arbitrarily chosen higher count numbers. As the count progresses into the 10's, 100's, and 1000's decades, additional lever groups come into play up to the limit of four. The highest number that

Table 1. -- Numerical count versus lever position in shaft position digitizer.

| Numerical count | Lever(s) in switch-closed position |
|---|---|
| 1 | a |
| 2 | b |
| 3 | a and b |
| 4 | c |
| 5 | a and c |
| 6 | b and c |
| 7 | a, b, and c |
| 8 | d |
| 9 | a and d |
| 10 | a(2) * |
| 11 | a(2) and a(1) |
| 58 | a(2), c(2), and d(1) |
| 374 | a(3), b(3), a(2), b(2), c(2), and c(1) |
| 8,429 | d(4), c(3), b(2), a(1), and d(1) |
| 9,999 a/ | a(4), d(4), a(3), d(3), a(2), d(2), a(1), and d(1) |

* = Lever-group no. (see sketch below).
a/= Upper limit on count.




Lever arrangement on pivotal-support shaft can be accumulated or registered is 9,999 and this upper limit is equivalent to a total linear travel of the outside drive chain of 99.99 ft.

Certain mechanical intricacies of the SPD unit are not detailed in this report because they are well described in the cited patent report. Each such mechanical feature, however, contributes in its own unique way to the overall enhanced reliability and performance excellence of the unit. A typical example is the "jump transfer" assembly which by absorbing lost motion in the input shaft and gear train thereby eliminates ambiguity in the least significant digit of the mechanical counter and the BCD output.

Added overall advantages are that the SPD unit is inexpensive to produce and requires no electrical power of its own. It can also be used as a simple counting device, the only requirement being that the action to be counted must be capable of turning the input shaft a stipulated amount to correspond with one unit in the counting mechanism. The SPD unit is used in this manner to count lockages, and for that particular use its input shaft is replaced with a rotary-type stepping switch (see "Lock Pressure Switch" discussion).

## Shaft Output Follower (SOF)

The design of this electromagnetic device (see fig. 3) capitalized on the availability of the shaft position digitizer (SPD), and the extent to which the two devices are similar can be realized by comparing figures 2 and 3. It is housed in the same type rectangular metal case that is used for the SPD. The labeling in figure 3 highlights most of the added features, which are briefly described hereafter.

Because the basic purpose of the shaft output follower (SOF) is to monitor (follow) changes in water level, a float wheel replaces the chain sprocket on the input shaft (fig. 3). Fastened to the float-wheel hub is a counterweight drum on which is spooled enough lightweight nylon line to allow counterweight travel of about one-twelfth the expected range in water-level fluctuations. Float suspension is with a fine (0.011 in. diam.) stainless-steel wire spooled on the float wheel.

Mounted on the input shaft, between the float wheel and case, (not visible in fig. 3), is a switch arm that is actually a small printed circuit board. This establishes the basic part of a three-position switch -- UP, OFF, and DOWN. The UP and DOWN positions are implemented by two glass-encapsulated reed switches, placed parallel to each other along opposite edges of the circuit-board surface that faces the float wheel. A small set screw is also mounted on the circuit board at each reed-switch location to serve as a mechanical stop. A very small finger-like magnet is fastened on the back side of the float wheel in such a way that it extends into the gap between the two reed switches and the two set-screw stops. The float wheel can "free wheel" or drift on the input shaft

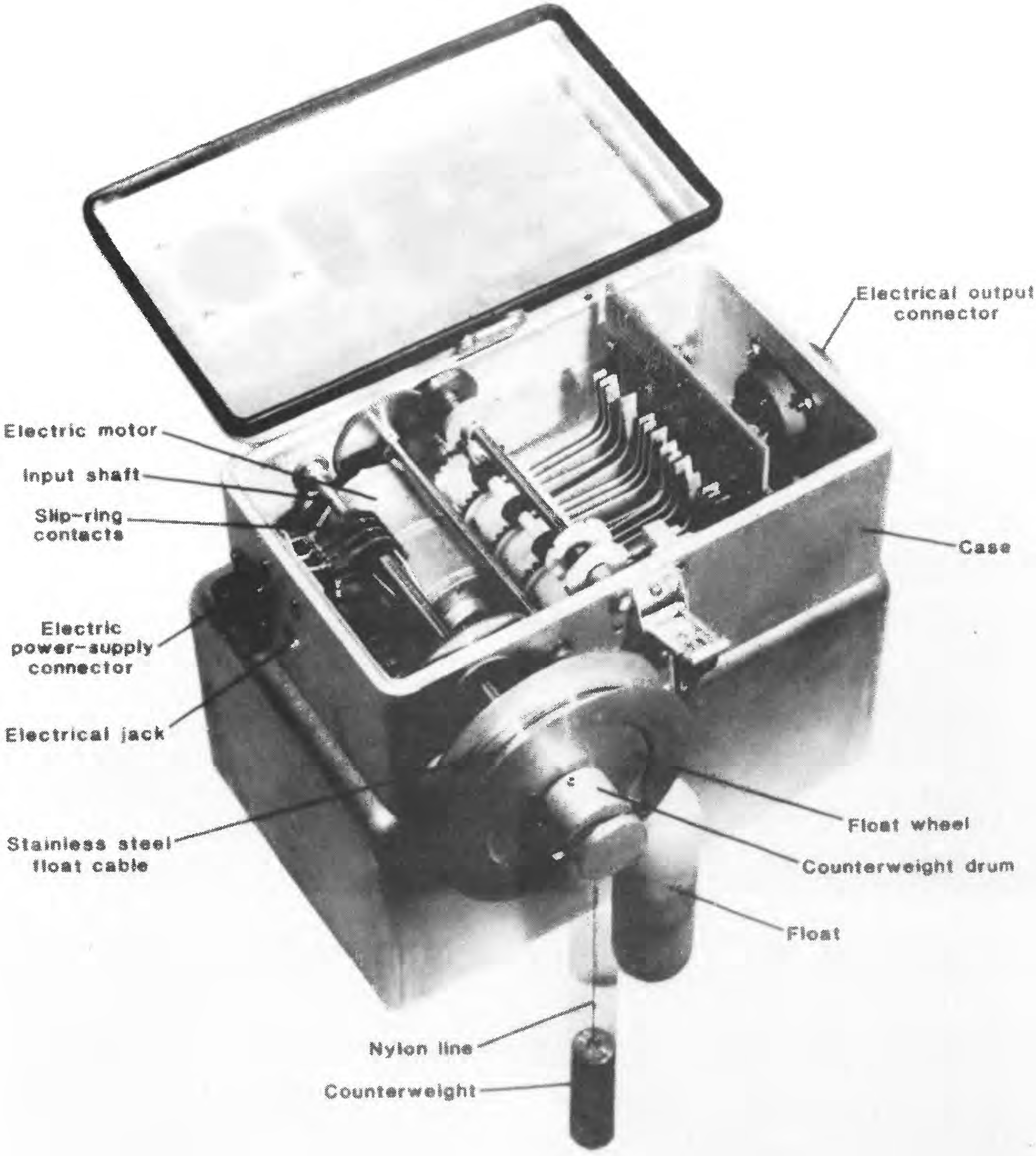



Figure 3.--Shaft output follower and nomenclature.

a small angular amount that is limited by the set-screw stops. When float motion causes the float wheel to move through the small drift angle, the magnet is swung close enough to the UP or DOWN reed switch to effect closure. When there is no float motion, and the float wheel is sensibly stationary, the magnet is midway in the gap and neither reed switch is closed. This is the OFF position for the overall three-position switch.

Inside the case three paired slip-ring contacts on the input shaft (see fig. 3) serve to link the three-position switch with the electrical power supply connector and the small Barber-Colman 6-volt DC reversible electric motor. The only function of the motor is to turn the input shaft, through a single reduction gear, in one direction or the other dependent on switch closure in the UP or DOWN position. Thus the motor is programmed to "follow" the float motion.

Not shown in figure 3, but an important accessory in any installation of the SOF, is a disabling switch assembly. The jack for the electrical connection is labeled in figure 3. The disabling switch is mounted near the float cable in a way that will cause it to be triggered, should the float rise an inordinate amount and threaten contact with the float wheel.

The remainder of the SOF functions exactly as described for the SPD. The mechanical counter and interrogated readouts now display, however, the float positions to the nearest 0.01 foot as they change with water-level movement. Weight of the SOF unit is 12 lbs.

## Lock Pressure Switch

In its simplest descriptive terms, the lock pressure switch is a micro switch mounted behind a neoprene diaphragm and inside a hollow brass cylindrical housing (see fig. 4). The diaphragm is not shown in figure 4, and the brass supporting plate obviously hides most of the cavity in which the micro switch is mounted. The brass cylinder is 3-3/4 in. in diameter and 1-5/8 in. long. The cover plate that protects and secures the diaphragm is an annular ring of brass, 1/4 in. thick. The complete assembly with brass connector fitting for oxygen hose (fig. 4) weighs about 3-1/2 lbs.

The oxygen hose serves the dual purpose of (1) a "venting" tube open to the atmosphere, from the back side of the micro switch, to eliminate any chance of one-sided pressure-change effects due to changes in atmospheric pressure or temperature; and (2) a protector for the light two-conductor shielded electrical cable that must run from the micro switch to a safe or sheltered spot away from the installation point on the lock wall. The ultimate electrical connection is to the digital data-collection console unit, or more specifically to the counting digitizer (see SPD unit) that is installed therein. The input shaft of that particular digitizer is actually replaced with a rotary-type stepping switch, geared appropriately to the camshaft and the mechanical counter.

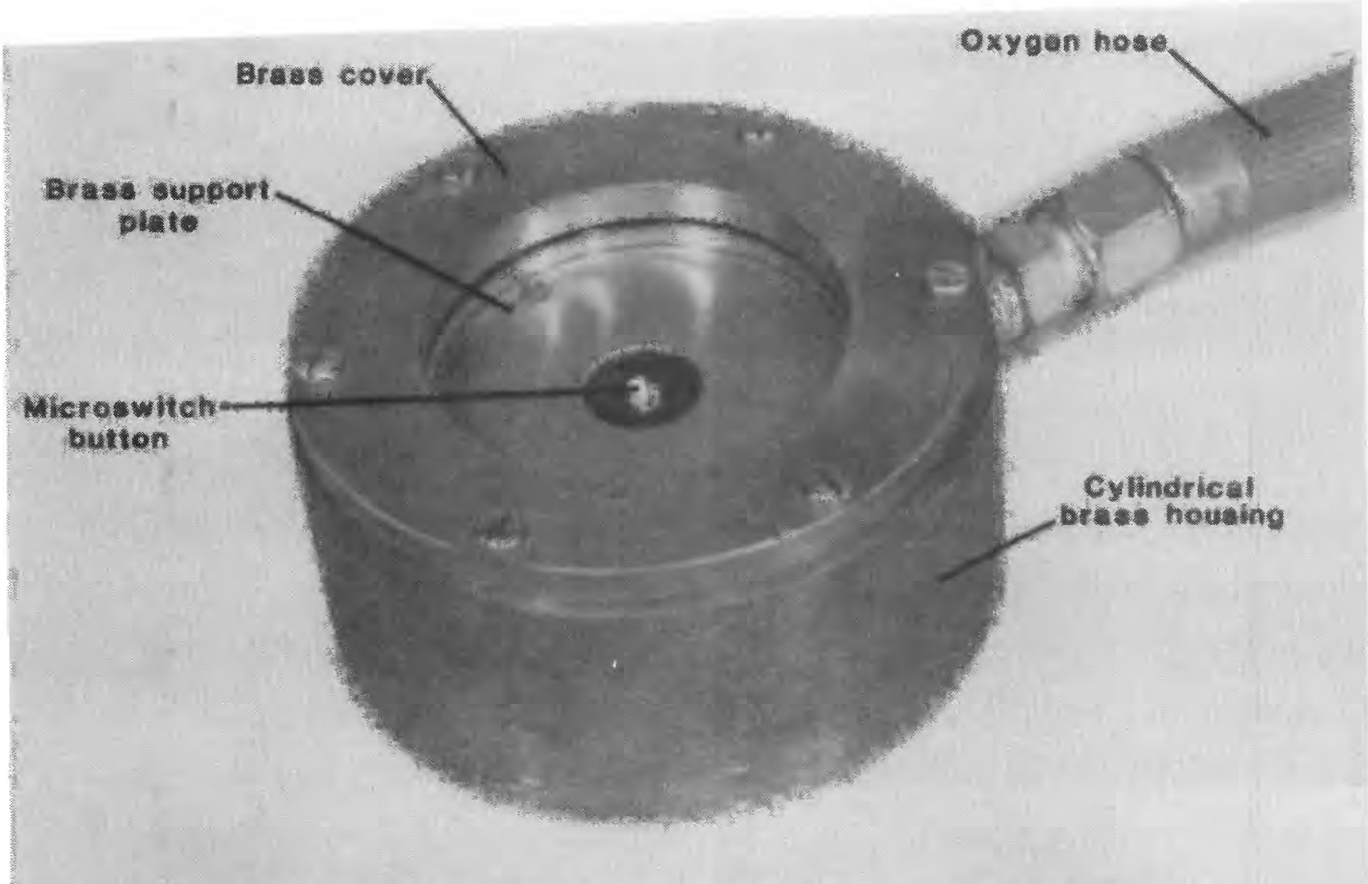



Figure 4.—Lock pressure switch and nomenclature.

Dependent upon the data requirements at the particular installation site the micro switch can be wired to count each time the lock empties, or each time it fills, or both.

## STACOM Manometer

The manner in which the present STACOM manometer evolved, from the original "bubble-gage" type manometer that was first used in 1956, is well described by Craig (1982) in his service manual for Survey manometers. Because that publication offers very thorough coverage of the STACOM manometer, with photographs, diagrams, and sketches, only a limited description is appropriate here.

The original device was conceived and patented by two Survey employees, Edgar G. Barron (dec.) and Harold O. Wires (dec.), and is described and illustrated in great detail under U. S. Patent No. 2,942,466 dated June 28, 1960.

The basic operating layout for the STACOM manometer, when used to measure fluctuations in stream stage, is shown schematically in figure 5. The fundamental physical principle is that of balancing the pressure head of water on the bubble orifice in the stream against a differential pressure head of mercury in the manometer, using a nitrogen-gas line as the connecting medium. If the nitrogen gas is introduced at a rate sufficient not only to fill the tubing (fig. 5) but also to bubble freely into the stream at the fixed orifice, then the pressure throughout the tubing is everywhere essentially equal to the pressure at the orifice. This is the key to ensuring that the pressure head of water at the orifice is delivered undiminished to the pressure-cup reservoir (fig. 5) of the mercury manometer, where the measurement process begins.

A pressure head delivered to the pressure-cup reservoir in the right half of the manometer must be offset or counterbalanced by some higher mercury level in the reservoir on the left half of the manometer, which is open to the atmosphere. The required differential in mercury levels in the two sides of the manometer is created by moving the pressure-cup reservoir the needed amount up or down (to correspond with a fall or rise in stream stage) while the reservoir on the left side of the manometer (fig. 5) is held fixed. The carriage on which the pressure-cup reservoir "rides" is attached to a link of the stainless-steel chain loop that is driven by a geared servomotor, actuated by a tilting float switch on the fixed side of the manometer.

Operation of the float switch warrants a little added explanation. In the schematic layout of figure 5 a vertical "pivot staff" is shown asymmetrically mounted on the so-called "float" that is inside the fixed reservoir. Actually, the float is suspended from two horizontally-opposed jeweled pivot bearings located part way up the staff. Thus the float acts as if it were "hinged" to the left side (fig. 5) of the reservoir wall, so that the slightest incipient movement of the mercury level will cause a tilt, and that motion will be magnified by the pivot staff. If the mercury level tends

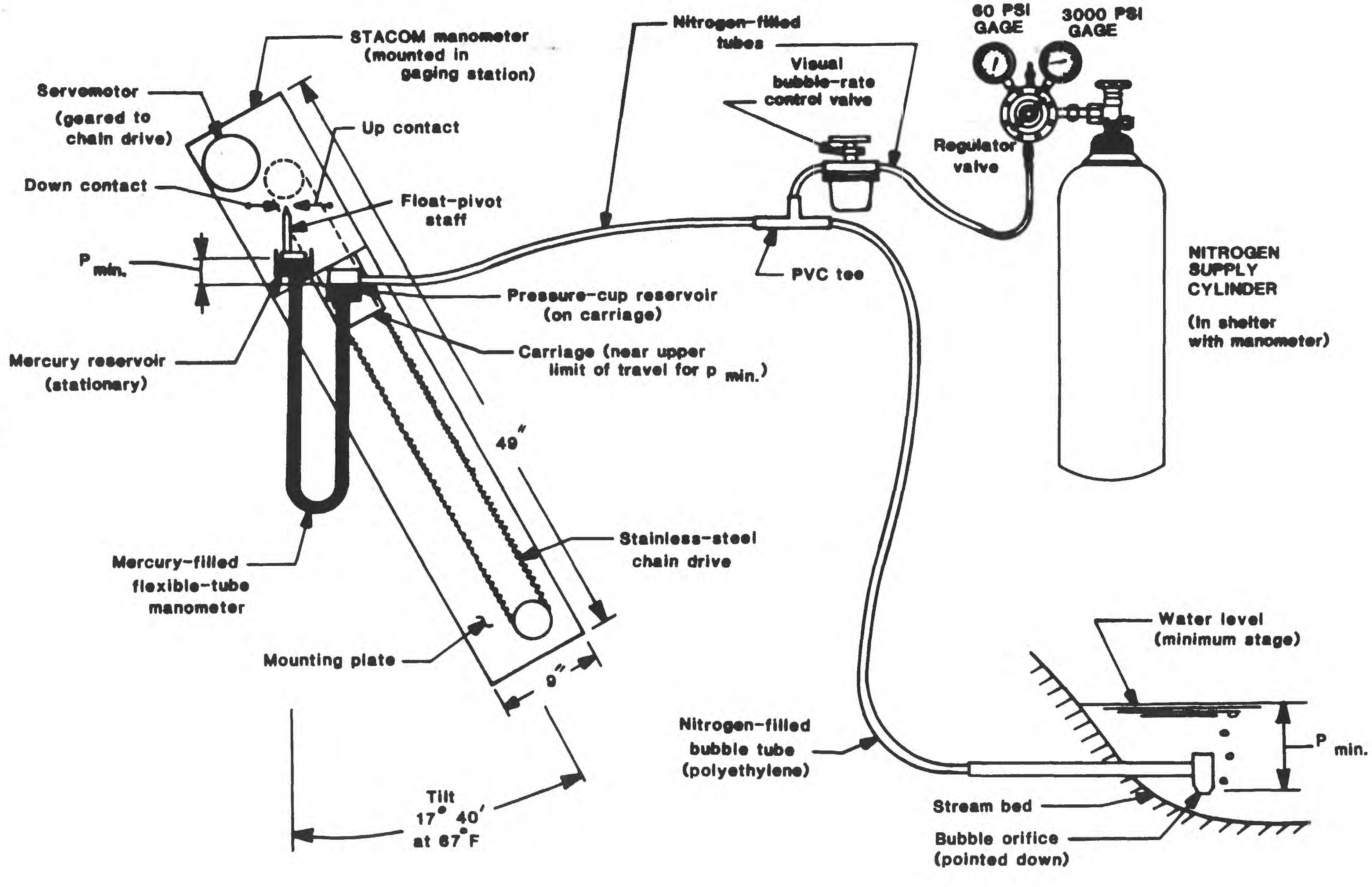



Figure 5. — Schematic of basic operating layout for the STACOM manometer

to rise--signifying an increase in pressure head on the bubble orifice (a rise in stream stage)--the float will tilt up, the pivot staff will swing left until it engages the "down contact" (see fig. 5), and the servomotor will then start moving the pressure-cup-reservoir carriage in the down direction. That movement will continue until the correct new and greater differential pressure head is found in the mercury manometer, the float no longer tilts, and the pivot staff breaks the down contact by returning to the "null" position. Similarly, if the mercury level tends to lower (a decline in stream stage) the float will tilt down, the pivot staff will swing right and engage the "up contact", and the servomotor will move the pressure-cup-reservoir carriage in the up direction until the null position (lower differential pressure head) is again found.

The carriage travel permitted by the mounting plate size shown in figure 5 is most commonly suitable and will allow the measurement of changes in stream stage totaling as much as 35 feet. A mounting plate about 9 inches longer is available, however, which will accommodate changes in stream stage of as much as 50 feet.

Because mercury is about 13.6 times denser than water, a 10-foot change in water level is equivalent to only an 8.824-inch difference in mercury levels in the manometer. Thus, for the manometer to achieve its stipulated capability for sensing a change of as little as $\pm$ 0.01 ft. in water-pressure head it must detect a differential in mercury levels of only 0.009 in. Furthermore, for the vertical component of travel of the carriage to bear this precise relationship to changes in water-pressure head, given the choices available for servomotor drive gears, chain-sprocket size, and counter gears, the entire manometer mounting-plate assembly must be "tilted" at some computable angle with the vertical (see fig.5). If it is assumed that an ambient air temperature of 67°F will commonly be encountered in manometer installations, the tilt angle then is computed to be 17° 40'.

Nitrogen gas is the near-ideal connecting medium because it is universally available, cheap, dry, and inert. Its weight is about the same as air, and a standard cylinder (contents 112 $ft^3$) will provide the needed supply for a year or more. The rate at which nitrogen is bubbled through the submerged orifice is based on the maximum expected rate of change in stream stage. The one-year estimated life for the nitrogen-supply cylinder presupposes an average bubble rate of about 40 bubbles per minute, each one of which releases 0.01 $in^3$ of gas.

Some of the nomenclature for the STACOM manometer is repeated in figure 6, which is an oblique photograph showing principal manometer features.

Not covered thus far, but deserving brief explanation, is the physical principle underlying the temperature-compensation feature of the manometer. With no attempt at correction the error in a differential-pressure reading on a mercury manometer is 0.01 percent

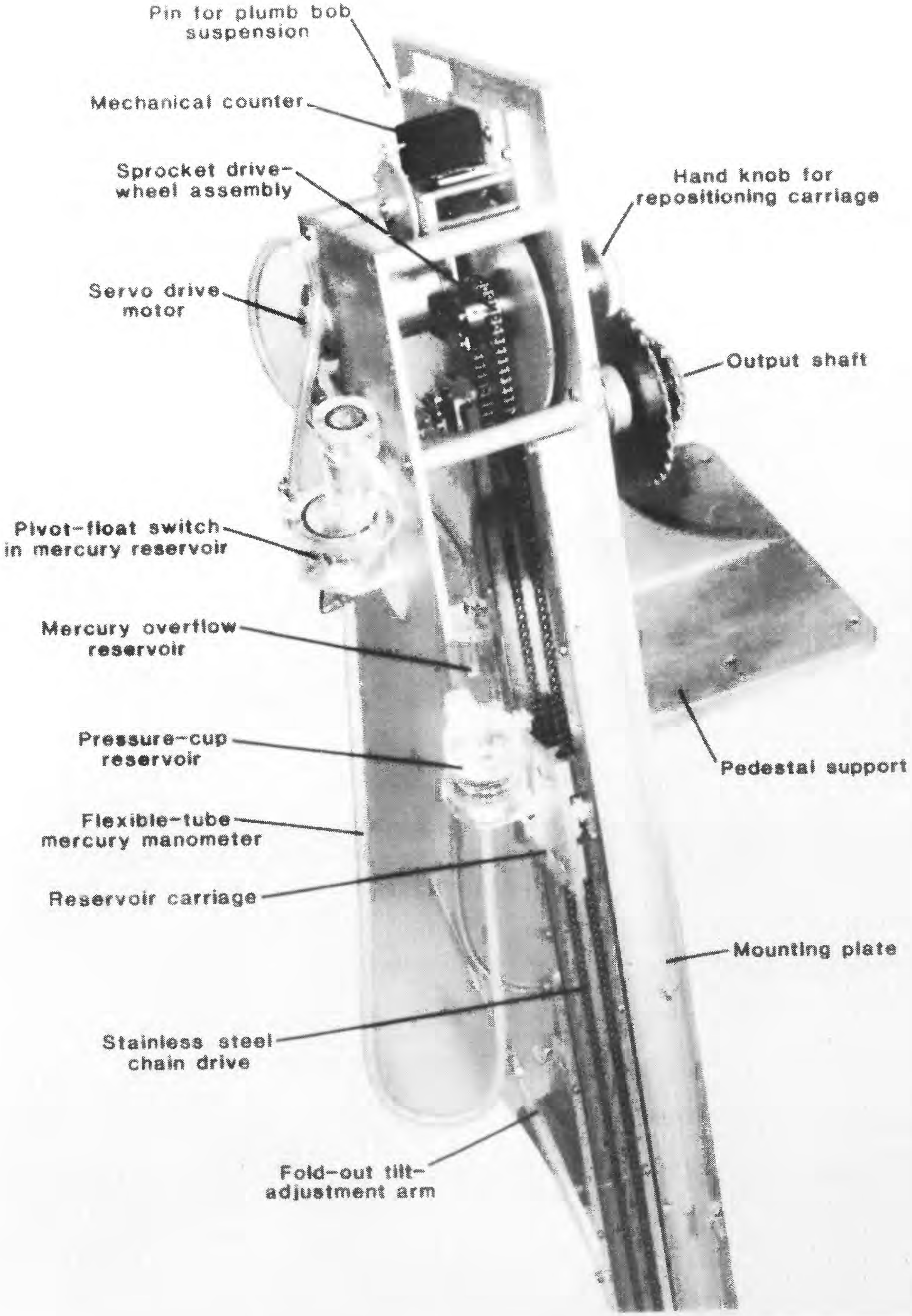



**Figure 6.--STACOM manometer and nomenclature.**

for each degree (F) change in the ambient temperature, due to a corresponding change in the specific gravity of mercury. The introduction of the temperature-compensation device reduces the foregoing pressure-reading error to 0.001 percent per degree change in ambient temperature. In many manometer installations the need for such a device is obviated by the frequency of service visits to the station, and the practice of resetting the manometer to the outside reference gage on each visit. At other installations, however, the device must be used to hold errors within reasonable bounds. This is especially true for STACOM manometers with an extra long carriage mounting plate, used to measure pressure-head changes in the 100-foot range.

The basic physical principle, around which the temperature-compensation device is designed, is explained by noting that for an increase in ambient temperature there will be a decrease in the specific gravity of the mercury. This means that the same amount of mercury--in the manometer reservoirs and tube--must now occupy a somewhat larger volume of space, and this added space could be "found" through slight rises in mercury level in both reservoirs. However, inasmuch as this manometer is designed to operate with a fixed mercury level in the left-hand reservoir (fig. 5) the added space can only be found by lowering the pressure-cup reservoir the slight amount needed to maintain that desired fixed mercury level. This is tantamount to saying that the volume of mercury in the pressure-cup reservoir will be allowed to increase (by lowering the carriage) until the requisite added space is found. The added volume is found with a very small vertical component of motion because the surface area of mercury in the reservoir is large.

The way chosen to lower the carriage slightly is by decreasing (with respect to the vertical) the tilt angle of the whole manometer mounting plate. The necessary angular change can be computed, for any specified change in ambient air temperature, inasmuch as the physical properties of mercury and all the pertinent geometry are known. The pivot point for this "tilt" must obviously be ideally coincident with some point in the desired fixed surface level of mercury in the left-hand reservoir (fig. 5). The angular change in tilt is very nearly one minute of arc, for a change in temperature of 1°F. Thus the tilt angle will only need to be changed about one degree, for a change in air temperature of 60°F.

The foregoing discussion can be turned around and it is equally valid if the ambient air temperature should decrease. In this event the specific gravity of the mercury would increase, the pressure-cup reservoir (carrige) would need to be raised slightly, and the tilt angle would need to be increased slightly.

The attachment for manually accomplishing the needed temperature adjustments is a pre-calibrated fold-out arm on which a small spirit level is permanently mounted. The arm bears graduation marks in degrees Fahrenheit that have been pre-computed to correspond with the appropriate tilt angles. With the arm in its level position the desired graduation mark need only be made to intersect a plumbline suspended from a pin permanently fixed at a suitable point near the top of the manometer mounting plate, to establish and set the correct tilt angle. A servo-driven mechanism is also available, as an attachment, to adjust the tilt angle automatically, whenever a sensor indicates the need for a temperature correction.

Any motion of the pressure-cup-reservoir carriage (fig. 6) -- in response to changes in stream stage -- is transmitted, through a suitable gear train, to both a 4-place mechanical counter and an output shaft. A count of "one" in the first or units decade of the counter is equivalent to a change in stream stage of 0.01 ft. Rotation of the output shaft need only be linked by a suitable chain drive to the input shaft of the desired recorder, for a continuous record of stream stage. In river-control-structure instrumentation the hookup is usually to an SPD unit, which thereby allows the stream-stage to be recorded periodically as that unit is interrogated at some stipulated interval.

## Digital Data-Collection Console

Whatever the mix in type and number of individual measuring instruments at a given river-control structure, the final challenge is to collect -- in one central recorder -- the individual suites of measurement data. The unit designed to do this is the digital data-collection console, installed under cover in a convenient operations or maintenance room. Multi-conductor cables connect this unit with all measuring instruments (digitizers). Over such cables the instruments are electrically interrogated, at some preselected sequence and interval -- commonly once an hour -- and the electrical responses (representing the digitized measurements) are recorded by a digital punch-tape recorder housed in the console. In this report an "interrogation cycle" is defined as the process of singly interrogating, in a specified order, each measuring instrument in the entire array at a given river-control structure. The interrogation cycle is programmed to proceed automatically and upon completion the unit remains on standby until it is time for the next cycle. A schematic layout for an overall measurement and recording system is shown in figure 7 for a hypothetical river-control structure.

The console unit is housed in a metal cabinet 49 in. high, 22 in. wide, and 26 in. deep; total weight is about 225 lbs. The sheet-metal wall panels are removable for easy access to the inside (see fig. 8). The cabinet houses, in addition to the digital recorder, an SPD counting unit (if lockage counting is required); a rack on which the necessary electronic circuit "cards" are mounted; direct current power supplies for various control functions; backup rechargeable batteries to power the whole system should there be an interruption or failure of the 110 volt primary power source; an electronic crystal-oscillator (32768 Hz) clock that serves as the master timing and control device in the automatic recording of data (each recorded measurement is accompanied by the current time of day, read in hours and minutes); and six electrical input/output connectors. The console unit also features a pair of windows for

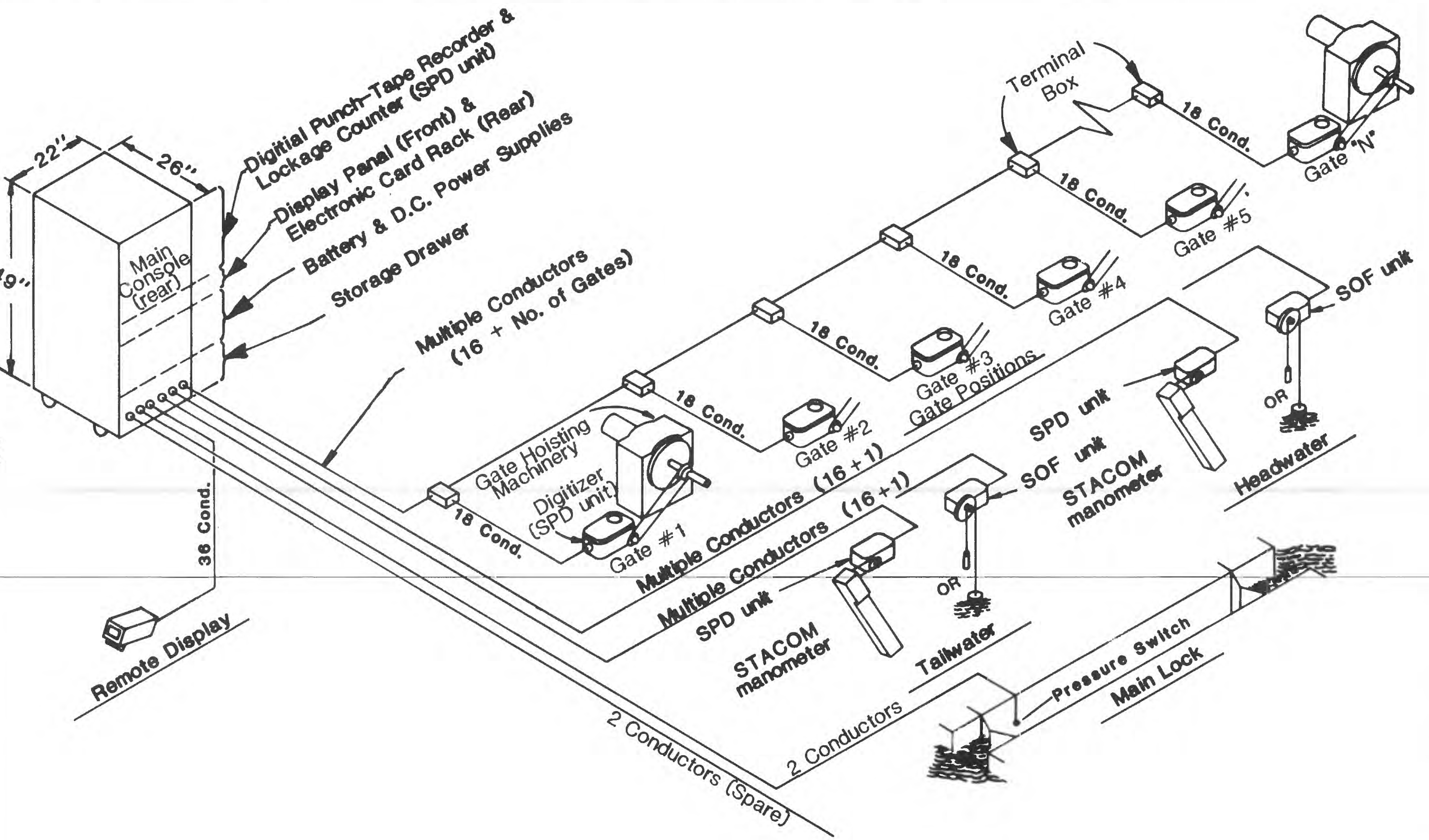



Figure 7.-- Schematic arrangement of instrument system at a hypothetical river-control structure.

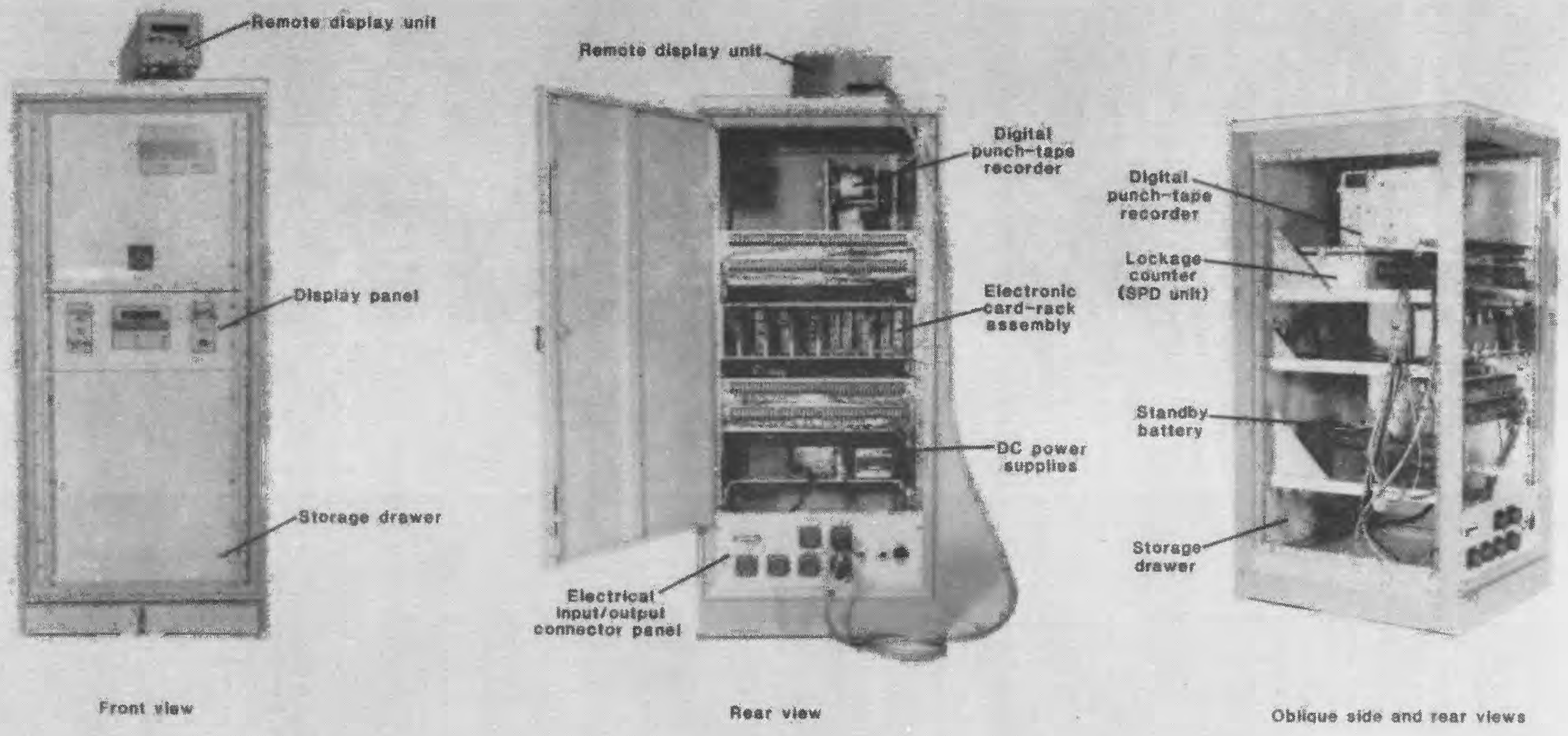



Figure 8.--Digital data-collection console and nomenclature.

numerical displays and a set of manual controls whereby an operator may call up, for visual display and/or recording, the latest reading at any selected measuring instrument.

Insights on the operation of the data-collection console are best developed from explanations built around the generalized electronic schematic shown in figure 9. As already mentioned, the master clock (card 1 in fig. 9) is the heart of the whole system inasmuch as it provides the single precise ($\pm$ 3 min. per month) time base to which all recorded measurements are referenced. It initiates each interrogation cycle, at the preset time interval, by triggering a start pulse that is fed into the programmer (card 21). The start pulse can also be triggered manually with a punch switch on the display panel of the console.

The catechism for a complete interrogation cycle can be developed from the following numbered steps, that are repeated -- essentially as described -- as each measuring instrument (digitizer) is interrogated:

1. The programmer (card 21) is built to provide an individually coded signal to the multiplexer (card 13), in a predetermined sequence, for each of the measuring instruments (digitizers) that is to be queried in the interrogation cycle. A given code signal relates to a particular channel number in the multiplexer, which is assigned to a particular digitizer. Receipt of the start pulse launches the predetermined sequence and the programmer sends its <u>first</u> coded signal to the multiplexer (card 13). The programmer also readies the digital recorder to receive data.

2. The multiplexer (card 13) recognizes the first signal as unique to channel no. 1 and reacts by closing switch no. 1 in the relay section (card 15).

3. When relay no. 1 (card 15) closes, it thereby grounds the enabling line to the assigned digitizer. This in turn grounds any of the parallel conductors, connected to that digitizer, that happen to be -- at that interrogation instant -- tied to <u>closed</u> reed switches inside the digitizer. The parallel conductors (data relay lines) feed into a data buffer (card 17).

4. The data buffer (card 17) features an LED (light emitting diode) photocoupler for each parallel conductor. Thus if a conductor is grounded its LED will illuminate and activate a corresponding phototransistor, which feeds into solenoid-drive circuitry (card 5) as well as a display buffer (card 9). All conductors grounded in step 3 thus feed simultaneously into cards 5 and 9.

5. The solenoid-drive circuitry (card 5) operates the punch solenoids in the digital recorder; the display buffer (card 9) activates the visual display on the front panel of the console

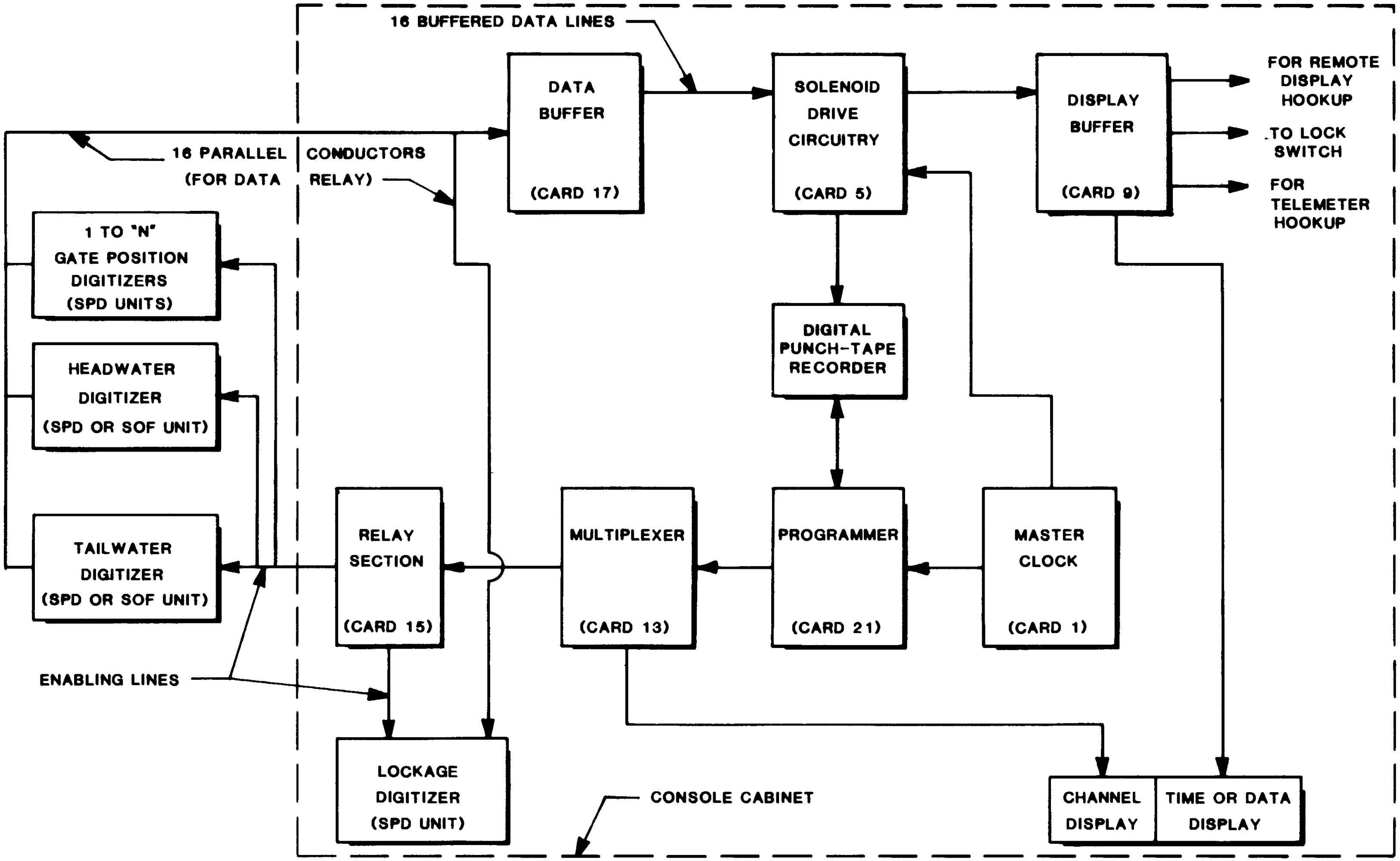



Figure 9. -- Generalized electronic schematic for the digital data-collection console

unit, and also feeds into the remote-display unit. Thus the complete measurement coming from the digitizer just interrogated is simultaneously recorded and displayed.

When the digitized measurement has been punched on the recorder tape, the programmer (card 21) is cleared -- through control logic -- to return to step 1 and send its <u>second</u> coded signal to the multiplexer (card 13). Thus steps 1 through 5 are repeated for the second assigned digitizer. That 5-step process reiterates until the measurements from all digitizers have been recorded, whereupon the programmer (card 21) waits until the clock (card 1) triggers the next start pulse for the next interrogation cycle.

The first few console units set up at river-control structures were designed and built without the multiplexer and data-buffer components (cards 13 and 17). It quickly became evident that repeated failures (record losses) were being caused by electrical transients in the long (thousands of feet) data lines. These lines tend to act as antennas, and because river-control structures are generally high and well exposed the opportunity for lightning strikes is great. Lightning-induced transients in the data lines could and did destroy unprotected integrated circuits on the electronic cards in the console units.

Two redesign steps were taken to minimize the foregoing problems. First, the multiplexer and data-buffer components (cards 13 and 17) were introduced, which immediately isolated the long data-relay lines from the integrated circuits in the console unit. Second, the direct current power supplies were split so that one powers only the datarelay lines for the brief interval during which they are being interrogated, and the other powers only the circuits in the console unit. All installations now feature these redesign steps, and the incidence of failures from lightning-strike transients has been significantly reduced.

## RIVER-CONTROL STRUCTURES INSTRUMENTED

In the twelve-and-a-half year period from June 1968 to December 1980 nineteen river-control structures were instrumented. Those structures and their locations are listed in table 2, and all instrument systems except one continue in service (1983). No two systems are alike, prinicpally in the sense that the number of measuring instruments (digitizers) installed at a single river-control structure ranges from a low of 4 to a high of 17. This numerical spread reflects primarily the differences in number of tainter gates at one control structure versus another.

Paramount among other differences in the nineteen individual instrument systems is the range in length of data-relay lines that link the console unit to the respective digitizers. The shortest lines tend to be at river structures with few tainter gates, in which cases the principal distances are to the points selected for headwater and tailwater measurements -- usually of the order of 1,000 to 2,000 ft. The longest lines, then, are at the river structures with the large numbers of tainter gates, in which cases

Table 2. -- River-control structures instrumented.

| Structure Name | Location | Date Instrumented |
|---|---|---|
| Greenup Locks & Dam | Ohio R. nr. Greenup, Ky. | June 1968 |
| Coffeeville Lock & Dam | Tombigbee R. nr. Coffeeville, Ala. | Nov. 1968 |
| Dardanelle Lock & Dam | Arkansas R. nr. Russelville, Ark. | Feb. 1969 |
| Markland Locks & Dam | Ohio R. nr. Warsaw, Ky. | June 1969 |
| Dam No. 7 | Arkansas R. nr. Little Rock, Ark. | Apr. 1970 |
| Dam No. 13 | Arkansas R. nr. Fort Smith, Ark. | Apr. 1970 |
| Belleville Locks & Dam | Ohio R. nr. Belleville, W. Va. | Oct. 1970 |
| Toledo Bend Reservoir | Sabine R. nr. Leesville, La. | Jan. 1972 |
| Racine Locks & Dam | Ohio R. nr. Pt. Pleasant, W. Va. | May 1974 a/ |
| Claiborne Lock & Dam | Alabama R. nr. Claiborne, Ala. | Aug. 1974 |
| George W. Andrews Lock & Dam | Cattahoochee R. nr. Columbia, Ala. | Sep. 1974 |
| Warrior Lock & Dam | Black Warrior R. nr. Eutaw, Ala. | Mar. 1975 |
| Cannelton Locks & Dam | Ohio R. nr. Tell City, Ind. | June 1975 |
| Columbia Lock & Dam | Ouachita R. nr. Columbia, La. | Sep. 1975 |
| Uniontown Locks & Dam | Ohio R. nr. Evansville, Ind. | Sep. 1976 |
| Kaw Dam & Lake | Arkansas R. nr. Ponca City, Okla. | Apr. 1977 |
| Gainesville Lock & Dam | Tombigbee R. nr. Gainesville, Ala. | May 1978 |
| Aliceville Lock & Dam | Tombigbee R. nr. Aliceville, Ala. | July 1979 |
| Columbus Lock & Dam | Tombigbee R. nr. Columbus, Miss. | Dec. 1980 |

a/ Removed Nov. 1982.

the distance numbers may nearly double. One exception to the foregoing spread in distances is at Gainsville, Alabama, where the console unit is housed at the lock, which is over a mile from the dam and its five tainter gates.

## CONCLUSION

Short of a full-blown and exhaustive investigation into the service history of each installed instrument system, the general statements that emerge from field-maintenance personnel suggest attainment of about an 80-percent level (overall average) in completeness of record. At several installations this performance percentage has held in the mid-nineties range; nowhere has the reported percentage dropped below 70.

On the whole, the maintenance problems that have arisen -- electronic or mechanical -- seem to be characterized by the unpredictable "acts of nature" and man, rather than outright failures. This says much for the basic soundness of the present design and fabrication of the individual components that make up a complete system.

The intrinsic nature of research and development precludes the luxury of dwelling on past accomplishments. New ideas are continuously being spawned, even as the "current model" of an instrument component or system is being built and fielded. As remarkable as the present dam-instrumentation system has proven, it is not hard to identify features that could be improved, were a new generation to be designed today. A list of feasible improvements might well include:

1. Elimination of the long data-relay lines (prone to disruption by nature and man) by substituting FM transceivers to relay measurement data from each digitizer to the console unit.

2. Elimination of STACOM manometers and SOF units by substituting pressure transducers of comparable resolution.

3. Addition of simple safety monitors, keyed to such significant factors as dam integrity and critical water levels, to enhance the overall utility of the installed instrument system.

4. Addition of a microprocessor which could calculate the flow value on site.

5. Addition of telephone and data-collection-platform capability to allow remote interrogation of readings.

In the several scientific fields that support the design and fabrication of instruments like those described in this report, state-of-the-art advances hold considerable promise for new developments. The economy and budget constraints will dictate how quickly those developments are realized and implemented in the dam-instrumentation system.

## SELECTED REFERENCES

Collins, Dannie L., 1977, Computation of records of streamflow at control structures: U.S. Geological Survey Water-Resources Investigations 77-8, 57 p.

Craig, J. D., 1982, Installation and service manual for U.S. Geological Survey Manometers: U.S. Geological Survey Techniques of Water Resources Investigations, Book 8, Chapter A2, 57p.

Winter, I. A., 1934, Improved type of flow meter for hydraulic turbines: American Society of Civil Engineers Trans., v. 99, Paper 1875, p. 847-866.

Wires, Harold O., 1971, Continuous measurement of discharge through control structures: U.S. Geological Survey Open-File Report, 9 p.