MASTER

INTERIM REPORT ON THE DEVELOPMENT OF AN
AIR PULSER FOR PULSE COLUMN APPLICATION

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September 22, 1961

PHILLIPS
PETROLEUM
COMPANY

ATOMIC ENERGY DIVISION

NATIONAL REACTOR TESTING STATION
US ATOMIC ENERGY COMMISSION

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Printed in USA

IDO-14559
AEC Research and Development Report
Chemical Separations Processes
for Plutonium and Uranium
TID-4500 (16th Ed.)
Issued: September 22, 1961

IDAHO CHEMICAL PROCESSING PLANT

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AIR PULSER FOR PULSE COLUMN APPLICATION

by

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ACKNOWLEDGEMENT

The authors wish to express their appreciation for the assistance of Sergio Gossman, Reactor Physics and Engineering, in setting up the analog computer circuitry; to E. E. Erickson, E. L. Rowe, and S. J. Horn for their assistance in evaluating equation coefficients and in the final solutions of the design equations; and to L. A. Jobe for his assistance in evaluating air system time constants.

ABSTRACT

The Idaho Chemical Processing Plant for several years has been studying various pulsing systems, used in extraction columns for processing irradiated nuclear fuel elements, in an effort to eliminate the mechanical difficulties in present pulsing systems. An air pulsing system has been demonstrated, and this report discusses experimental work, pulser design, and plant operational experience with this system. The authors conclude, from work completed thus far, that air pulsing of extraction columns is a considerable improvement over other systems.

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INTERIM REPORT ON THE DEVELOPMENT OF AN AIR PULSER FOR PULSE COLUMN APPLICATION

I. INTRODUCTION

Pulsed, sieve-plate columns are widely used as liquid-liquid contactors in atomic energy facilities processing irradiated nuclear fuel elements. These columns, although efficient contacting devices, require a mechanical device to generate the phase-dispersing pulse. It has been necessary in the past to locate the pulsing mechanism within, or partly within, the radiological shielding of the plant. In case of breakdown of the moving parts of the pulser, when so located, it is necessary to remove the pulser physically from the cell by remote manipulating devices and replace the defective pulser with a new one, or to decontaminate the cell and equipment within the cell so personnel can enter and repair the defective part. Either approach is time-consuming, expensive, and requires that the plant be shut down.

A program has been underway at the Idaho Chemical Processing Plant (ICPP) for several years to evaluate various pulsing systems that would eliminate these difficulties. The criteria for such a pulser are that: (1) no moving parts are required within the shielding, (2) the system is simple and reliable, (3) the operating range spans frequencies of from 40 to 100 cycles per minute at column amplitudes of from 0.25 to 1.0 inch, and (4) the operating point is capable of adjustment within this range without a column or pulser shutdown.

A direct air pulsing system as designed for the ICPP meets these criteria admirably. Pulsers of other types fail on one or more of these points.

A system such as the column air pulser combination is not necessarily stable, and the range in frequency and pulse amplitude is not obvious. Consequently, a mathematical evaluation of such a system was made in early 1959. The conclusion then was that the air pulser system would be stable and would have a satisfactory operating range. As a result, experimental facilities were constructed in early 1960 to better define the parameters and unknowns. The results of the investigation carried out in these facilities are given in this report.

The experimental program on air pulsers is continuing with the aim of refining the design equations and extending the knowledge of fluid behavior under transient conditions in a column system.

II. CONCLUSIONS AND RECOMMENDATIONS

The major conclusion that can be drawn from the work completed to date is that the air pulsing of extraction columns is both feasible and practical. Theoretical calculations, a test system, and a trial plant installation all show that the system performs very satisfactorily.

A continuing experimental program will permit refinement of the design equations. As these equations become more rigorous, the calculated operating limits of any given system may be expected to approach the actual limits. The present state of the art requires that departures from the design of a tested prototype be held to a minimum. Since the test unit and the plant CPM "A" (first cycle extraction) column are geometrically very similar, an air pulser could be designed for this particular column with confidence.

Both the test system and the trial plant installation have performed very reliably. The inherent simplicity of the air pulser system is difficult to over-emphasize. The possible points of failure are limited and are located in non-radioactive areas. The in-cell portions, normally unapproachable, consist only of piping, with no valves or any other moving parts.

Reproducibility of the system has been excellent. A given cam-drive speed and a given air-reservoir pressure produce a fixed pulse frequency and amplitude. Neither the frequency, the amplitude, nor the mean pulse-leg fluid position varies significantly. Day-to-day variations in pulse amplitude for given pressure-frequency settings have been negligible.

The life expectancies of the system components have not been approached in the test period to date. Component wear is not expected to be of any great consequence. Should any item fail, the failure would be immediately detectable, and the faulty component could be repaired or replaced without delaying operations for lengthy decontamination procedures.

It is planned to complete the presently scheduled test program and to develop the exact system parameter equations. At that time, these equations should be carefully evaluated to determine the possibility of using sufficient simplifying assumptions to eliminate the need for analog computation in the design of future systems. A semi-empirical approach may prove to be well within the accuracy limits required for an air pulser system design.

III. THEORETICAL ANALYSIS OF THE AIR PULSING SYSTEM

1. AIR PULSER OPERATION

A schematic drawing of the experimental column arrangement is shown in Figure 1. As can be seen, the system comprises a 10-inch inside diameter pulse column to which is connected a leg two inches in inside diameter. Instrumentation is arranged to measure instantaneous pressures at various points in the system and instantaneous flows between the column and the leg. Valves V_1 and V_2 admit and release air to and from the air space above the liquid level in the leg. In practice, these valves are opened and closed by a speed-regulated cam arrangement. The air is supplied from an air reservoir that serves to damp the pressure fluctuations. Pressure in the reservoir is regulated very closely by a proportional-type pressure controller. There are only two controls on the system: the speed control on the mechanism that opens and closes valves V_1 and V_2 , and the pressure controller that adjusts the air pressure supplied to V_1 .

Fig 1 Experimental column schematic

Assume the column and leg shown in Figure 1 are filled with liquid above the plate section. Valve V_2 is open and V_1 closed so that liquid level equalizes between the column and leg. Air is supplied at constant pressure to valve V_1 . V_2 now closes and V_1 opens. This valve action admits air pressure into the chamber above the liquid level in the leg, and this pressure depresses the level in the leg, transferring some liquid from the leg into the column. V_1 now closes and V_2 opens. This vents the air pressure from the chamber above the liquid level in the leg, and since the level in the leg was depressed from its equilibrium position, there is a greater hydrostatic head in the column than in the leg, so fluid flows from the column to the leg and the leg liquid level rises. The interchange of fluid between the leg and the column results in a pulsing action of the column liquid. The magnitude of the column pulse is set largely by the air pressure applied through V_1 , and the frequency is set by the time cycle at which valves V_1 and V_2 are opened and closed. Amplitude, however, for a given pressure setting, is not independent of frequency. In practice, for any given frequency-amplitude combination, the liquid level in the leg will stabilize at some mean position $\bar{X}$ (see Figure 1) and will move up and down the distance, ΔX , as dictated by the pressure-frequency settings.

2. MATHEMATICAL REPRESENTATION OF THE SYSTEM

2.1 Fluid Mass and Inertia

The fluid mass in the leg and column will resist any tendency of an externally applied force to change its velocity. If the mass is expressed in terms of mass per unit area, the mass resistance to change in velocity, or momentum, will be proportional to the length of fluid involved and the density of the fluid. Thus, the inertia of the fluid in the leg can be represented as $\frac{\rho_L}{g} X \ddot{X}$; where ρ_L is the density of the fluid in the leg, g is the gravitational

constant, $\ddot{X} = \frac{d^2 X}{dt^2}$, and X is the height of fluid in the leg. Likewise, the

inertia of the fluid in the column can be represented by $(\rho_m/g)H \left[\frac{A_L}{A_c} \right] \ddot{X}$;

where ρ_m is the mean density of the fluid in the column, H is the height of fluid in the column, and $\frac{A_L}{A_c}$ is the area ratio of leg to column. All rates

of change are expressed in terms of movement in the leg, since most velocity measurements on the experimental column are made in the leg.

The column will contain mixtures of two phases in the plate section, an organic phase above the interface, and various proportions of organic-aqueous mixtures in other zones. Consequently, a mean density of all the column contents must be used in expressing the inertia of the system. It must also be recognized that the organic holdup in the column can change with throughput, and this variable has to be evaluated in terms of its effect on pulse amplitude. The inertia forces present in the column and leg can then be written as:

$$F = \frac{\ddot{X}}{g} \left[\rho_L X + \rho_m H \left(\frac{A_L}{A_c} \right) \right] \quad (1)$$

2.2 Fluid Friction

Expressing fluid friction for transient flow conditions involves some uncertainties. If a fluid is accelerated from rest, it is unknown just what the flow characteristics (streamline or turbulent) are at any given instant; and if the flow characteristics are unknown, the friction factors and consequently the pressure loss due to friction are unknown. Flow characterization during a flow transient is one of the phenomena being investigated in the experimental column.

An assumption must be made at this time to make possible a calculation of friction losses. It was assumed that flow is turbulent in nature throughout

the pulse cycle, so turbulent friction factors were used. This assumption is based upon the premise that eddy currents generated at maximum pulse velocities do not have time to dissipate during low or zero-flow portions of the pulse cycle. Consequently, friction loss in the leg is expressed as

$$\text{leg friction force} = \frac{2 f \rho_L (R + X) (\dot{X})^2}{gD} \quad (2)$$

where f is the friction factor and D is the line diameter. In an actual system there may be bends, enlargements, contractions, and entrance losses to evaluate. These can be conveniently expressed in terms of equivalent lengths of line, represented by R in Equation (2). With the coefficients as used in Equation (2), the units of leg friction would normally be in pounds per square foot. The remaining terms have already been defined.

Pressure drop through the plates is expressed in terms of a square-edged orifice coefficient. This expression is

$$\text{plate friction force} = \frac{\rho_m N \left(\frac{A_L}{A_O} \right)^2}{2 g C^2} (\dot{X})^2 \quad (3)$$

where

A_O, A_L = plate free area (including annulus area) and pulse leg area, respectively

N = the number of plates in the column

C = orifice coefficient

$\dot{X}$ and g were defined previously. The plate friction will be in pounds per square foot.

Determination of the orifice coefficient, C , requires some means of expressing a two-phase system so that a Reynolds number can be calculated. For example, the phases might be mixed thoroughly prior to passage through the plates, in which case physical properties based on volumetric phase ratios would represent the system adequately. On the other hand, if phases had time to disengage between plates as in a mixer-settler type of operation, distinct phases would pass through the plates, and a mean, based on time of phase passage through the plates, would have to be used. Column operation normally is of the former type, so physical properties based on volumetric means are used.

2.3 Final Equation

The final equation representing the air pulser performance can now be written:

$$\left[\frac{\rho_m H}{g} \left(\frac{A_L}{A_c} \right) + \frac{\rho_L X}{g} \right] \ddot{X} + \left[\rho_m \left(\frac{A_L}{A_o} \right)^2 \frac{N}{2gC^2} + 2f \rho_L \frac{(R+X)}{gD} \right] (\dot{X})^2 + \rho_m H - \rho_L X = -F(P,t) \quad (4)$$

The $(\dot{X})^2$ term is better written as $\dot{X} |\dot{X}|$ or value of $\dot{X}$ multiplied by its magnitude so that the sign of the velocity retains its identity. The $\rho_m H$ term is the liquid head in the column that acts against the applied air pressure, and $\rho_L X$ is the head in the leg that acts with the applied air pressure. Thus, the term $\rho_m H - \rho_L X$ is the force that acts to restore the level in the leg to its equilibrium position when the applied air pressure is removed. The term $F(P,t)$ is the air pressure that is applied to the liquid in the leg in which the pressure is a function of time and varies with the system geometry, which has not been expressed in explicit terms at this time. The treatment of this term for a given case is discussed in a later section. A very simplified method of expressing this term is in the form of a square wave where the pressure rises abruptly to a steady value and remains there for a period of time equal to half a cycle, and then decreases abruptly to zero where it remains for the other half cycle. The actual shape of this pressure-time relationship is discussed in Section V.

Solution of Equation (4) will give the wave shape of the pulse, the mean value of X (or liquid height in the leg), the fluid acceleration, and the fluid velocity as functions of applied pressure and frequency. Also, the effects of changes in geometrical and physical parameters can be determined.

The experimental column was set up primarily to check the validity of the assumptions made, and, consequently, the accuracy of the equation. Once such a check has been completed, the equation will be valid in designing a pulser of any geometry and for any extraction fluids.

Due to the X terms multiplying the second derivative and derivative squared, and the presence of a derivative squared term, solution of Equation (4) is not practical by classical means. Non-linear equations of this type are solved by use of computers or by arithmetic approximation methods. In this instance, an analog computer was used in solving this equation for ICPP air pulser design.

IV. EXPERIMENTAL PROGRAM

1. DESCRIPTION OF EQUIPMENT

1.1 Extraction Column and Accessories

The experimental column used for the air pulser development program is a 10-inch-diameter, perforated plate column. The plate cartridge contains 123 plates, spaced two inches apart. The plates are 3/32-inch aluminum with 1/8-inch holes on a 1/4-inch triangular pitch, having 23 per cent free area. Top and bottom disengaging heads are included for two-phase operation. Figure 1 shows column instrumental components, and Figure 2 shows the system piping. The use of carbon steel and aluminum as materials of construction precludes the use of acidic extraction streams.

The major portion of the vertical pulse leg is 2-inch Pyrex pipe to permit direct observation of the liquid level and any anomalies such as emulsion formation, splashing, or secondary interfaces. The lower three feet of the vertical portion, and the line into the column, are 2-inch carbon-steel pipe. The pulse leg joins the column below the bottom perforated plate and above the lower disengaging head.

1.2 Air Pulser Mechanism

Air for the pulser is obtained from a 50-pound air supply. The air pressure is reduced through a self-contained pressure regulator to about 25 psig and throttled through a control valve into an air reservoir. This dual regulation system was found necessary to hold the cycle-to-cycle pressure fluctuations in the air reservoir below 0.1 psi. Figure 3 shows the air supply and control system.

The air reservoir is a carbon-steel tank with a volume of about 12 cubic feet. With this volume the reservoir pressure drops about 2.5 per cent of the gauge pressure during each pulse cycle. The capacity of the air supply system is sufficient to return the reservoir pressure to the set point during the exhaust half of each cycle.

The pulse air inlet and exhaust valves are the heart of the air pulser system. The valves are nominal 1-inch NPT, poppet type, with oversized ports and offset inlet and outlet to minimize pressure drop. They were manufactured by Hydro-Aire Co., Burbank, Calif., and are shown in Figure 4.

The pulse control valves are operated by a pair of motor-driven cams. The cam drive assembly is shown in Figure 5. Each cam is composed of two plates, which permit an adjustment in operating position from 120 to 240° by rotating one plate with respect to the other. The relative position of the two cams can be changed by rotating one cam about the common shaft. The cams operate on the valves through a roller-bearing cam follower and a valve pushrod, threaded to permit clearance adjustments.

CPP-S-1920

Fig. 2 Experimental column equipment flowsheet

A 1/2-horsepower, variable-speed, dc motor drives the cam through a worm gear reduction unit and a sprocket and chain. Speed control is achieved by feedback of a dc voltage generated by a tachometer on the motor shaft. This signal voltage is compared to a divided reference voltage, and the error signal is used to correct the armature voltage. The reference voltage is divided with a 10-turn potentiometer equipped with a vernier dial. The Servo-Tek Products Co., manufacturers of the motor-speed control package, claim a speed control accuracy of 0.1 per cent can be maintained. Actual observations of the unit in this application indicate less than 0.5 per cent speed fluctuation.

Fig 3 Experimental pulser air supply and control schematic

1.3 Measurement Instrumentation

Figure 1 shows the primary data points in the system. Pressure transducers, Consolidated Electrodynamics Corp. Type 4-312A with a 0 to 50 psig range, are used to follow the system pressures. The excitation voltage is supplied by a battery through a variable potentiometer. The output signal of the transducers (about 24 millivolts full scale) is read with a Sanborn Model 150 oscillograph, using a stabilized dc preamplifier.

Fluid velocities in the pulse leg are measured with a magnetic flowmeter. This instrument is the transducer part of a standard Foxboro unit. The 2-inch meter is of type 304 stainless steel with a 10-mil lining of Kel-F. The meter output is 0.55 millivolt per foot per second fluid velocity. This signal is demodulated to remove the 60-cycle component and read with the Sanborn oscillograph using an ac-dc preamplifier. The demodulated signal also is passed through a differentiating circuit, permitting a direct reading of fluid acceleration. A typical flowmeter signal before demodulation is shown in Figure 6.

A Tektronix Type 533 oscilloscope, with a camera attachment, also was provided as part of the air pulser instrumentation system. Either the pressure transducer or flowmeter outputs may be fed to the oscilloscope to examine transients too fast for the oscillograph to follow.

BILL OF MATERIAL

ITEM	PART NUMBER	MATERIAL	FINISH
1	HOUSING	CRES STEEL TYPE 303	PASSIVATE
2	SPRING	CRES STEEL TYPE 302	PASSIVATE
3	BOLT	CRES STEEL TYPE 347	PASSIVATE
4	O RING	72 SYNTHETIC RUBBER	
5	POPPET	CRES STEEL TYPE 17-4PH	MICROPLATE
6	BODY	CRES STEEL TYPE 303	MICROPLATE ID

SPECIFICATION

TYPE: MANUAL OPERATED POPPET TYPE AIR SHUTOFF

OPERATING CONDITIONS:

INLET PRESSURE-100 PSIG MAX

INLET AIR TEMPERATURE-0° F TO 150° F

INTERNAL LEAKAGE- 0.05 LBS PER MINUTE (MAX) AT 100 PSIG AND 70° F

EXTERNAL LEAKAGE- 0.5 LBS PER MINUTE (MAX) AT 100 PSIG AND 70° F

AMBIENT TEMPERATURE-0° F TO 150° F

PRESSURE DROP- 3.0 PSI MAX WITH INLET AIR AT 25 PSIG & 70° F & WITH AN AIR FLOW OF 150 SCFM

SERVICE LIFE-3,000,000 CYCLES

CPP S-1921

Fig 4 Poppet valve details

Fig. 5 Air pulser valve operating mechanism.

2. OPERATIONAL TESTING AND DATA

2.1 Preliminary Tests and Calibrations

Initial operation of the column air-pulser system brought out several deficiencies that required correction. These included refinement of the air-pressure control system on the air reservoir from a standard pressure regulating valve to a proportional controller, revision of the grounding methods on the instrument electrical system to eliminate electrical noise, shortening the leads on the air pulser valve-speed control system to improve control, and readjustment of signal leads on the electromagnetic flowmeter to decrease the zero-flow signal. After these changes were made, the system operated satisfactorily.

Calibration of the electromagnetic flowmeter has not been completed and efforts are continuing to get satisfactory data. The pressure transducers were calibrated using static water heads in the column.

Correction of the above difficulties resulted in a very reliable pulser system. Simplicity of control, reproducibility of operating conditions at given control settings, and a high degree of stability during day-to-day operation were apparent. Column-pulse frequencies (valve-drive motor speeds) were maintained over a 10 to 100 cycle per minute range without difficulty. Conversely, air pressure control settings from 5 to 20 psig were not affected by changes in pulse frequency. Pulse amplitude variation was within very acceptable limits and liquid position in the pulse leg varied less than one per cent during the same periods. Reproducibility of pulse amplitude was good when controls were returned to prior set points after operating under different conditions for long periods of time.

2.2 Single-Phase Runs

Several runs were made in the column using water to obtain pressure losses through the system, and to obtain information on general operability. Instantaneous pressures and flows (when the flowmeter is calibrated) will permit characterization of flows and checking the validity of the design equation. An example of pressure losses through the system is shown in Table I and an example of the instrument recordings of these pressures is shown in Figure 7.

Fig. 6 Oscilloscope trace of flowmeter signal before demodulation.

TABLE I
AIR PULSER INSTRUMENT TEST RUN

Test run: October 11, 1960

Conditions: Frequency, 49 cycles/min; air pressure, 10 psig (reservior gage); pulse leg liquid displacement, 10 ft 7-7/8 in. (average); pulse leg pulse amplitude, 23-1/4 in.; 10-in. column pulse amplitude, 0.93 in. (calculated).

<u>Transducer</u>	<u>Peak Signal (a)</u> <u>(mv)</u>	<u>Peak Pressure (a)</u> <u>(psig)</u>	<u>Pressure Drop (b)</u> <u>(psig)</u>
PT-1	0.35	0.70	9.86
PT-2	0.55	1.22	9.34
PT-3	0.60	1.23	9.33
PT-4	0.75	1.60	8.96
PT-6	1.20	2.64	7.92
PT-7	4.56	10.56	0

(a) Peak signals and pressures are total signals minus static heads.

(b) Pressure drops = difference in peak pressure between PT-7 and the specific transducer referred to.

2.3 Two-Phase Runs

A broad inclusive program was planned using tributylphosphate-Amsco and water; however, at this time only those runs to supply design information for the ICPP "A" column air pulser are completed. Results of these runs are shown in Table II. A comparison of the experimental results calculated from the design equation is of interest, so the runs shown in Table II are plotted with the calculated results in Figure 13, as shown on page 28. It is evident that the two results are in good agreement.

Fig 7 Experimental column pressure recordings (see Table I for run conditions)

TABLE II

TWO-PHASE RUNS IN THE EXPERIMENTAL COLUMN (G-111 SIMULATION EXPERIMENTS)

Test runs: December 19 and 20, 1960

Two-phase system: Water and 3-1/2% TBP in Amsco.

Pulse Frequency (cpm)	Organic Rate - (gpm)	Aqueous Rate - (gpm)	Air Pressure (psig)	Interface Depth (in.)	Pulse Amp. - (in.) <u>Leg</u> <u>Column</u>		Leg Level (a) (in.)
<u>12/19/60</u>							
60	3	3	6	4-1/2	7-1/4	0.29	20
60	5	5	6	5	7-1/2	0.30	30
<u>12/20/60</u>							
60	1	1	6-1/4	6-1/4	7-1/2	0.30	26
60	1	1	9-1/4	5-3/4	13-1/2	0.54	75
60	1	1	12-1/8	5-3/4	21	0.84	128
60	1	1	15	5-1/2	~33-1/2 (b) ~1.34 (b)		176
80	1	1	15	5-1/4	18-1/2	0.74	190
80	1	1	12	5-3/4	10-1/2	0.42	145
80	1	1	9	6-1/8	6-3/4	0.27	75
80	1	1	6	6-1/4	3-3/4	0.15	20

(a) Distance from column organic overflow centerline to upper pulse position of liquid in leg.

(b) High turbulence in liquid-air interface made accurate measurements impossible.

V. DESIGN OF A PLANT PULSER SYSTEM

1. EQUATION SOLUTION AND DESIGN APPLICATION

1.1 Plant Pulser Difficulties

Pulsers currently in use at the ICPP consist of a remote stainless-steel diaphragm installed in the cell adjacent to the column and an accessible Neoprene diaphragm installed in an access corridor. A water-filled hydraulic linkage connects the two diaphragms. The accessible diaphragm is deflected by a reciprocating piston acting on an oil-filled linkage. Several difficulties have arisen in operating a pulser of this type. The diaphragms tend to get out of phase, due to leakage out of the system or entrapment of air in the hydraulic linkages. This results in erratic pulses generated in the extraction columns, and frequent maintenance is needed to keep the linkages properly filled and diaphragms phased. Rupture of the in-cell diaphragm results in radiation hazards to personnel in the vicinity of the accessible diaphragm, and extensive

decontamination is necessary to permit replacement of the ruptured diaphragm. Aside from operating and maintenance difficulties with this type of pulser, the initial cost of such a system is high (\$20,000 to \$30,000 for the CPM "A" column pulser equipment alone) and considerable cell space and piping is required for its installation.

Even before the experimental work on air pulsers had been completed, it was evident that these pulsers had considerably fewer objectionable features than the existing pulsers. Consequently, it was decided to install an air pulser on the CPM "A" column (G-111) plus all the in-cell piping required to complete air pulser installations on the "B" (H-100) and "C" (H-103) columns at a later date. G-111 geometry is very similar to that of the experimental air pulsed column, so the design can be accomplished with the data available at this time.

1.2 G-111 Air Pulser Design

1.21 Physical Layout. The air pulser had to be designed to fit into an existing plant, which necessitated a design that is somewhat less than optimum. Existing sleeves from cold areas into the cell had to be utilized, and tight time schedules permitted only very minor revision of equipment and piping in the cell. It was thought desirable, since some safety features of the air pulser had not yet been determined, that the existing diaphragm pulsers remain operable. The physical layout in Figure 8 retains the existing pulsers. The pulse leg is tied to the existing pulse line into the column as close to the column as possible. In this position, the air doing the pulsing contacts fresh solvent rather than the column aqueous phase. Since the aqueous phase is more radioactive than the fresh solvent by 10^3 to 10^4 , this arrangement lessens the possibility of the pulse air picking up contamination and depositing it in the valves and pulser vent system.

The air supply line is looped to a height of 12 feet above the cold makeup area floor. Aqueous-organic mixed phase in the column has a higher density than organic by itself, so under static conditions, organic could flow into the cam-driven valve system and out the vent line if the loop were not present. It is evident that the air supply and exhaust lines have a greater number of bends and longer length of line than the pulser as such requires, and has many features that would be avoided under ideal conditions. However, the arrangement did not reduce the effectiveness of the pulser within the desired operating ranges.

1.22 Evaluation of Coefficients. Equation (4) was developed to describe mathematically the behavior of the fluid in a pulsed system. The use of this equation in designing such a system requires the evaluation of the coefficients in the equation in terms of the physical system as shown in Figure 8. In addition to geometry, the physical properties of the fluids involved must be known. The fluids were assumed to have the properties shown in Table III.

TABLE III
G-111 COLUMN FLUID PHYSICAL PROPERTIES

	<u>Density, (g/cc)</u>	<u>Viscosity, (cp)</u>
Aqueous feed	1.286	3.50
Extractant (Organic - 3.25 vol % TBP in Amsco)	0.770	1.40
Mixed phase		
20 vol % organic	1.184	3.08
30 vol % organic	1.131	2.88
40 vol % organic	1.079	2.66

Inertia Terms. The mass of the fluid in the leg is easily represented, since it consists of a single fluid. Thus,

$$\text{Fluid mass in pulse leg} = \frac{\rho_L X}{g} = \frac{(0.77 \times 62.4)X}{32.2} = 1.492X$$

The acceleration in other sections of the column besides the leg is converted to leg acceleration by multiplying by an area ratio. Acceleration of the fluid in the connecting lines is composed of the following items:

$$4\text{-in. connecting line} \left(\frac{1.286 \times 62.4}{32.2} \right) \left(\frac{8}{12} \right) \left(\frac{0.0233}{0.0884} \right) = 0.439$$

$$4\text{- x } 3\text{-in. reducer} \left(\frac{1.286 \times 62.4}{32.2} \right) \left(\frac{4}{12} \right) \left(\frac{0.0233}{\frac{0.0884 + 0.0513}{2}} \right) = 0.278$$

$$3\text{-in. section} \left(\frac{1.286 \times 62.4}{32.2} \right) \left(\frac{20}{12} \right) \left(\frac{0.0233}{0.0513} \right) = 1.890$$

$$\text{Total} = 2.607$$

Mass of fluid in the various column sections is as follows:

$$\text{Above interface} \left(\frac{0.77 \times 62.4}{32.2} \right) \left(\frac{0.0233}{3.08} \right) \left(\frac{5}{12} \right) = 0.0047$$

$$\text{Below interface } \left(\frac{1.286 \times 62.4}{32.2} \right) \left(\frac{0.0233}{3.08} \right) \left(\frac{13.5}{12} \right) = 0.021$$

$$\text{Plate section column } \left(\frac{1.131 \times 62.4}{32.2} \right) \left(\frac{0.0233}{0.546} \right) (22.83 - 1.08) = 2.04$$

$$\text{plates } \left(\frac{1.131 \times 62.4}{32.2} \right) \left(\frac{0.0233}{0.546 \times 0.234} \right) (1.08) = 0.432$$

$$\text{Below lower plate } \left(\frac{1.286 \times 62.4}{32.2} \right) \left(\frac{5.5}{12} \right) \left(\frac{0.0233}{0.546} \right) = 0.049$$

$$\text{Total} = 2.547$$

$$\text{Total for column and lines } \left(\frac{\text{lbs mass sec}^2}{\text{ft}^3} \right) = 5.154$$

The total force lost due to inertia can now be written as

$$(5.154 + 1.492X) \ddot{X} \frac{\text{lbs}}{\text{ft}^2}$$

The fraction of the inertial force dissipated in various segments of the system due to inertial resistance can be determined from the magnitudes of the coefficients. A good approximation of X is 20 feet for a normal operating condition; thus, the total mass term becomes

$$5.154 + (1.492) \times (20) = 35.0$$

Thus, the inertial force in the leg exceeds that in the remainder of the system by a considerable margin due to the greater accelerations in the leg.

Friction Terms. Evaluation of friction requires a knowledge of friction factors and orifice coefficients. The friction factor can be set up on the analog equipment using a function generator. This generator was set to feed in, as input, a Reynolds number comprising $\left(\frac{D\rho}{\mu} \right) |\dot{X}|$ terms, resulting in a $\left(\frac{D\rho}{\mu} \right) (f)$ $|\dot{X}|$ output (f being the friction factor). The $\left(\frac{D\rho}{\mu} \right)$ term is constant for any

given geometry and is divided out of the function generator output by pot setting-gain relationships within the analog circuitry. This then leaves the term f , which when multiplied by $\dot{X}$ is a direct function of friction loss.

The orifice coefficient is handled in a different manner. Since the fluid velocity through the plates is considerably lower than the velocities in the pulse leg, and the orifice coefficient does not vary appreciably over

a wide range of velocities in the region of interest, a mean orifice coefficient is used based upon an average velocity through half a pulse cycle.

For general information, Table IV summarizes the mean fluid velocities at various locations in the pulsed system.

TABLE IV
AVERAGE VELOCITY VALUES AS A FUNCTION OF FREQUENCY

<u>Pulse Frequency</u> <u>(cycles/min)</u>	<u>Average Velocities (Vm), (ft/sec for 1-in. column amplitude)</u>		
	<u>Column</u>	<u>Plates</u>	<u>Leg</u>
100	0.278	1.189	6.50
75	0.208	0.889	4.86
60	0.167	0.714	3.90
50	0.139	0.594	3.25

The areas in the system are:

$$S_1 = \text{Area of Column} = 78.5 \text{ sq. in.}$$

$$S_2 = \text{Area of Leg} = 3.36 \text{ sq. in.}$$

$$S_3 = \text{Area through plates} = 18.4 \text{ sq. in. (allowing for a 1/64-in. annulus between plate and column)}$$

For a frequency of 100 cpm and a one-inch column pulse amplitude, the Reynolds number through a hole in the plates is 451. The ratio of plate free area to column area is 0.234, so a corresponding orifice coefficient is $C = 0.68$ [1]. This coefficient was used throughout all the analog calculations. The friction loss through the plates can now be computed from

$$F_p = \frac{\rho_m}{2gC^2} \left(\frac{A_L}{A_C} \right)^2 N |\dot{X}| \dot{X}$$

The flow mechanism involved must be considered in evaluating frictional losses. It has not been established in these studies whether the flow through

[1] J. H. Perry, Chemical Engineers Handbook, Third Edition, p. 405, New York, McGraw Hill (1950).

the pulse cycle is consistently streamline, consistently turbulent, or somewhere in between. It was assumed that the eddies distinguishing turbulent from streamline flow would not have time to dissipate during the low- or no-flow portions of the cycle, and consequently the flow would remain turbulent at all times.

It is desirable to have a comparison of frictional losses in the system. A comparison was made assuming a constant friction factor for the pulse leg and connecting lines for 100 cpm and a 1.0-inch column pulse amplitude. This comparison is shown in Table V. The values given in this table would have to be multiplied by $|\dot{X}| \dot{X}$ for the pulse leg to get the actual frictional pressure drop, but comparison of the coefficients will show relative losses in the system.

TABLE V
SUMMARY OF FRICTION MAGNITUDES IN G-111 COLUMN SYSTEM

(Basis: 100 cpm, 1-in. column amplitude)	
<u>Section</u>	<u>Magnitude</u>
Column plates	10.465 $ \dot{X} \dot{X}$ (a)
Pulse leg (including 90° bend)	0.104($X + 10.3$) $ \dot{X} \dot{X}$
Entrance (2 to 4 in.)	0.673 $ \dot{X} \dot{X}$
Line friction (4 in.)	0.020 $ \dot{X} \dot{X}$
Reducer (4 to 3 in.)	0.028 $ \dot{X} \dot{X}$
Line friction (3 in.)	0.843 $ \dot{X} \dot{X}$
Enlargement (4 in. to column)	0.257 $ \dot{X} \dot{X}$

(a) This term utilizes an orifice coefficient rather than an average friction factor.

It is evident by inspection of Table V that friction in the column plates far exceeds the friction from other sources.

Hydraulic Heads. The hydraulic head in the pulse leg (filled with organic) will be $\rho_L X = (0.770 \times 62.4)X = 48.0X$.

Hydraulic head in the column itself is summarized in Table VI, assuming a 30 per cent organic holdup in the plate section.

Summing the inertia, friction, and hydraulic terms determined above, the final equation for the conditions of 100 cpm and a column pulse amplitude of one inch for an in-column organic holdup of 30 per cent is

$$[5.149 + 1.492 \dot{X}] \ddot{X} + [0.001969 \dot{X} (\text{Re}) f + 0.02028 (\text{Re}) f + 10.465 |\dot{X}|] \dot{X} + 48.0 \dot{X} - 1778 = -F(P,t) \quad (5)$$

In the equation, $|\dot{X}| \dot{X}$ is written rather than $(\dot{X})^2$ so that the identity of the sign of $\dot{X}$ can be retained in the machine calculation. The value of the Reynolds number uses $|\dot{X}|$ for the velocity term. $F(P,t)$ is the driving function input.

Input Pressure - Time Wave Shape. Ideally, $F(P,t)$ could be represented by a square wave function. However, a wave shape such as that shown in Figure 9 was observed during the experimental column operation. This wave shape can be represented approximately by an equation of the form

$$T^2 \ddot{P} + 2\xi T \dot{P} + P = P_a \quad (6)$$

where P_a is the applied pressure, T is the time constant of the system, and ξ is the damping coefficient of the system. The period of the pressure wave in the system is evident from Figure 9 as being

$$\text{Period} = \frac{2\pi T}{\sqrt{1-\xi^2}}$$

TABLE VI
SUMMARY OF G-111 COLUMN HYDRAULIC HEADS

<u>Section</u>	<u>Height, (ft)</u>	<u>Density, (lbs/ft³)</u>	<u>H</u>
Above interface	0.416	48.1	20.0
Below interface to top plate	1.125	70.6	79.5
Plate section	22.83	70.6	1612.0
Below bottom plate to center of pulse inlet line	0.833	80.2	<u>66.8</u>
TOTAL			1778.3 lb/ft ²

AIR PRESSURE = 8.1 psig
PULSE FREQUENCY = 37.5 cycles/minute

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Fig 9 Sanborn chart showing air pressure-time relationships for air input system of experimental column

Since it is known that the equation has positive coefficients, the solution of the equation (assuming P_a is a step function) has the form

$$P = P_a + P_a e^{-\frac{\xi t}{T}} \left(\sin \sqrt{1 - \xi^2} \frac{t}{T} - \cos \sqrt{1 - \xi^2} \frac{t}{T} \right)$$

From the damping segment of the equation ($e^{-\frac{\xi t}{T}}$), and the shape of the decay curve as shown in Figure 9 (ie, a curve joining the amplitude peaks) the value of $\xi \frac{t}{T}$ can be determined. Substituting the equivalent for ξ into the equation for the period, the value for T can be determined.

In the design of the plant pulser, it was assumed that the time constant

$T = \frac{k}{L_e V}$. Time constant for the plant column can thus be written as

$$T_p = \frac{L_e V_e}{(L_e)_p V_p} T_e$$

where T_p is the time constant for the plant system; k is a proportionality constant; T_e is the time constant for the experimental column; and V_p and

V_e the volumes of the plant and experimental column air systems, respectively; L_e the length of line in the experimental column air system; and $(L_e)_p$ the length of line in the plant column air system expressed in equivalent length of the experimental column system. Thus, $F(P,t)$ can be approximately generated for a column geometry that is different from the experimental column.

1.23 Solution of Design Equation. Equation (5) is obviously non-linear and its solution by hand methods would be very tedious. Linearization of this equation is possible, but the errors resulting from such a linearization would be difficult to determine. To avoid both difficulties, this equation was set up on an analog computer.

Analog circuitry for the solution of Equation (5) is shown in Figure 10. Provisions are made for generating $|X|$ (or magnitude of $\dot{X}$), as shown in the amplifier-diode circuitry that follows potentiometer 1 A. The diode function generator (DFG 2) generates the friction factor, f , as a function of Reynolds number as previously discussed. A square wave generator (SWG) generates the $F(P,t)$ or input pressure. Otherwise, the symbols and circuitry used are straightforward and follow conventional analog nomenclature.

Parameters recorded from the machine, on an eight-channel Sanborn recorder, were taken from points R-2, 3, 4, 5, 6, 7, and 8. These parameters are $2X$ (suppression can be optionally applied at the Sanborn recorder to

Fig. 10 Analog circuitry for solution of the design equation.

subtract out the static X values and thus pulse amplitude is recorded),

$$\frac{100}{750} \text{ (Re)f, } \frac{100}{1.5 \times 10^5} \text{ Re, } 1/2 \dot{X}, -5 \dot{X}, 2X \text{ (records total } X \text{ value)}$$

and $\frac{5}{400} P(t)$, respectively.

Provisions also were made to impose an oscillation or “ringing” input on the square wave forcing function. This input was applied to switch SWA for specific runs (see Table VII). The circuitry used to generate the “ringing” input is shown in Figure 11. The methods used in adjusting the magnitude and frequency of the oscillations applied to the square wave already have been discussed.

A section of the chart from the analog giving the equation solution for parameters of frequency, pressure, and forcing function input is shown in Figure 12. Obviously, the column pulse wave shape is smooth and good extraction column performance can be expected from such a wave shape.

Results of a series of runs for various parameters are shown in Table VII. Comparison of runs 4 and 4A in this table shows that the type of input, ringing imposed upon a square wave, has only a slight effect upon pulse amplitude and liquid level in the pulse leg.

Runs 1A, 2A, and 3A were made using an average friction factor. If these runs are compared with runs 2, 3, and 4, it is evident that there is little difference in the pulse amplitude and that for all practical purposes an average friction factor could be used. Runs 5A, 6A, and 7A were made to determine what errors would result if an average orifice coefficient of 0.60 was used rather than the correct average of 0.68. Comparing these runs with runs 2, 3, and 4, it is evident that errors of approximately 10 per cent resulted.

Fig. 11 Analog circuitry simulating air pressure "ringing" function input.

Fig 12 Analog recordings - solution of design equation for G-111 column run 12

TABLE VII

ANALOG COMPUTER RUN SUMMARY

Organic Holdup	Run No.	Frequency (cpm)	Applied Pressure (psig)	Column Pulse Amp. (in)	X Ave. (ft)	$\dot{X}$ max. (ft/sec)	$\ddot{X}$ max. (ft/sec ²)
30%	2	60	9	0.533	25.4	3.94	24.1
	3		14	1.05	17.5	7.35	58.9
	4		19	1.73	11.25	10.35	125.5
	5	70	10	0.456	22.73	3.98	26.9
	6		15	0.904	15.86	7.95	67.0
	7		20	1.505	9.63	10.8	15.4
	8	80	10	0.341	22.5	3.48	26.4
	9		15	0.692	15.4	6.90	64.5
	10		20	1.215	9.50	10.30	144
	11	90	11	0.333	21.0	3.74	30.2
	12		16	0.622	14.5	6.8	71.5
	13		20	1.011	8.75	10.3	250
	14	100	11	0.256	20.8	3.26	30.0
	15		16	0.520	14.1	6.40	71.0
	16		20	0.857	9.00	9.75	148
	17	50	8	0.645	25.5	3.96	20.7
	18		14	1.435	17.1	7.90	63.0
	19		18	2.100	12.7	9.95	114.5
	20	40	7	0.863	26.9	4.14	18.4
	21		11	1.536	22.2	7.00	42.4
	22		15	2.330	16.0	8.90	77.5
	23	30	6	1.240	28.8	4.30	16.3
	24		9	2.003	25.0	6.30	32.4
	25		11	2.520	21.8	7.30	46.0
40%	1	60	9	0.556	21.8	4.40	27.2
	2		14	1.120	14.6	8.10	71.0
	3		19	1.856	9.0	10.5	146
	4	80	10	0.371	21.7	3.74	28.6
	5		15	0.755	14.1	7.30	75.0
	6		20	1.351	8.12	11.1	177
	7	40	7	0.908	26.4	4.02	17.2
	8		11	1.635	20.8	6.75	38.0
	9		15	2.46	15.6	9.05	73.5
20%	1	60	9	0.474	25.2	3.74	23.0
	2		14	0.952	19.6	7.10	55.0
	3		19	1.587	13.4	10.30	109.5
	4	80	10	0.320	25.1	3.34	24.0
	5		15	0.640	17.6	6.35	61.0
	6		20	1.114	11.3	10.25	170
	7	40	7	0.804	30.4	4.02	17.2
	8		11	1.447	24.0	6.75	38.5
	9		15	2.197	18.8	9.05	73.5
30%	1A	60	9	0.520	25.1	3.94	25.8
	2A	60	14	1.032	16.4	7.15	64.0
	3A	60	19	1.703	10.0	10.35	131
30%	4A	60	19	1.715	----	10.60	149
30%	5A	60	9	0.477	24.6	3.88	23.6
	6A	60	14	0.973	17.25	6.90	60.5
	7A	60	19	1.575	11.10	9.50	124.5

Zero not recorded
Best values of X,
 $\dot{X}$, and $\ddot{X}$ of 2 runs

Used Avg. value
of friction factor
= 0.00612

Ring pressure
input

Used value of ori-
fice coefficient =
0.60 (vs 0.68 for
others)

A plot of the runs tabulated in Table VII is shown in Figure 13. This figure illustrates the frequency, pressure, and pulse amplitude relationships that can be achieved from an air pulser. The lower operating limit shown in this figure was established at a point where the organic in the pulse leg starts to enter the smaller diameter air supply line. At this point the design equation is no longer valid and the results would be uncertain. This limitation is due to the specific geometry of the system and does not represent a limitation of the air pulser itself. Also shown on this figure is the effect of changes in column organic holdup upon the pulse amplitude. A variation in organic holdup of this magnitude represents rather extreme conditions of column operation and would not be encountered in routine operation.

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The points (Θ) shown on Figure 13 are points determined from measurements on the experimental column operating with a two-phase system. In spite of some geometrical differences between the plant and experimental columns, the agreement between calculated and experimental points is good.

2. SAFETY ASPECTS OF G-111 PULSER

- (a) Power or mechanical failures resulting in the pulser exhaust valve remaining open could produce

a displacement of radioactive solvent from the pulse leg into the cold working area piping due to density differentials between the extraction column and pulse leg fluid contents.

(b) Any failure which left the pulser air inlet valve open could cause pulse air to blow through the column. This could produce column upsets and possible entrainment of radioactive solutions into the vessel off-gas system. Such an event would be more in the nature of an operational difficulty rather than a serious safety hazard, since the potential release of radioactivity involved would be contained by a system designed for such events.

To circumvent these possibilities, a 12-foot seal loop was installed in the cold working area at the top of the column pulse leg. This seal loop was fitted with high and low pressure delayed action switches to sense prolonged open positions of the pulser inlet or exhaust valves. Malfunctions causing the air inlet valve to remain open more than one second (twice the normal open period at 60 cycles per minute) are sensed by the high pressure switch which triggers a spring-loaded solenoid latch on the pulser exhaust valves to vent the pulser air supply system and prevent blowing of the column. The low pressure switch detects an open exhaust valve time over one second and actuates a pneumatically operated ball valve at the top of the pulse leg. This block valve prevents displacement of hot solvent into the cold area piping. Failure of the electrical power supply results in triggering of both the exhaust valve latch and the block valve on the pulse leg. As a result, the system is fail-safe. The air-operated block valve and the pulser exhaust valve latch must be re-set manually before the system can start up again.

A key switch was provided to lock out these safety features on column start-up. The keys to this switch remain under administrative control. After column pulser operation is established, this switch is returned to normal operating position, and if malfunctions exist, the safety devices produce an immediate pulser shutdown, as described under one of the above cases. Thus, the column pulser cannot be started as long as malfunctions, capable of producing a safety hazard, exist.

Fig 14 Relationship between applied pulse pressure and average liquid height in the pulse leg

As a further safety back-up, the air line from the pulse leg, the pneumatically operated block valve, and the poppet valves themselves are shielded with lead to prevent possible irradiation of personnel who might be in this area if radioactive solutions ever enter these lines.

VI. PLANT OPERATIONAL EXPERIENCE WITH AIR PULSERS

The air pulser installation on the high-capacity TBP extraction "A" column was completed, cold tests were made, and a limited amount of operating experience with hot feed obtained. The operating range of the air pulser and the column extraction efficiency were investigated during the cold runs. A summary of general operational observations concerning the air pulser system, column behavior, and raffinate uranium concentration is presented in Table VIII.

TABLE VIII
RESULTS OF COLD TESTS ON G-111 COLUMN AIR PULSER SYSTEM

Pulser Control Settings			U Conc.	Test	Per Cent	General
Frequency (cycles/min)	Air Pressure (psig)	Column Pulse Amplitude (in.) (a)	in Raffinate (gm/l) (b)	Duration (hr)	of Full Flow	Column Behavior
45	9.2	1.0	6.3×10^{-4}	4.5	75	Steady
70	15.3	1.0	4.4×10^{-4}	1.0	75	Steady
100	18.5	0.75	9.7×10^{-5}	1.5	75	Fair (c)
100	18.5	0.75	$<5.0 \times 10^{-5}$	3.0	75	Flooded (c)
60	13.0	1.0	$<5.0 \times 10^{-5}$	6.0	75	Steady
75	14.5	0.8	$<5.0 \times 10^{-5}$	6.0	75	Steady
90	17.0	0.75	$<5.0 \times 10^{-5}$	6.5	75	Steady
100	17.0	0.60	$<5.0 \times 10^{-5}$	3.0	75	Steady
100	18.3	0.70	$<5.0 \times 10^{-5}$	13.0	75	Steady
100	18.3	0.70	$<5.0 \times 10^{-5}$	1.5	100	Flooded (d)
90	17.0	0.75	$<5.0 \times 10^{-5}$	(e)	100	Steady

(a) Amplitudes taken from analog computer data for given frequency and pressure. See Fig 13

(b) Minimum detectable uranium is 5.0×10^{-5} g/l.

(c) A gradual decline in the interface liquid level was indicated during this 4-1/2-hr operating period. Flooding occurred 4-1/2 hr after control settings were changed.

(d) Flooding occurred 1-1/2 hr after control settings were changed.

(e) Steady operation on continuous basis after last change at 100 per cent feed rate.

From these cold tests, the maximum pulse energy input to the A column for satisfactory column operation was defined approximately as 100 cycles per minute at a 0.7-inch pulse amplitude for full-rated plant capacity. Certain generalizations can be made concerning the air pulser system. These are:

- (a) Extraction efficiency is at least as good with air pulsers as with the mechanical-hydraulic pulse system.
- (b) A much wider range of pulser energy input is available than with the existing pulsers. Forty-five to sixty cycles per minute represents the entire controllable frequency range of the mechanical pulsers for pulse amplitudes of 0.75 to 1.0 inch.
- (c) Changes in operating conditions are accomplished with a minimum of time and effort. The reliability of the control system was demonstrated by good duplication of the resultant operating conditions at given control set points. These factors represent a definite improvement over the mechanical pulsers.
- (d) Initial installed costs for the air pulser equipment are about 12 per cent of those for the mechanical pulsers.
- (e) No maintenance or repairs were required by the air pulser components during the cold tests, which indicates general equipment reliability.

Following the cold tests, the plant started up on normal feed from irradiated fuel. Toward the end of the ensuing 10-day run, a slight instability in behavior of the A column was noted. This instability was no more serious than similar previous experiences with the mechanical pulsers, and the run was completed with no maintenance downtime. Inspection of air pulser equipment following the hot run revealed swelling and dislocation of the O-ring seals in the air pulser control valves. This condition, probably caused by inadvertent introduction of lubricants into the valves during installation, prevented complete closing of these valves. It was considered noteworthy that even though this equipment malfunction may have been primarily responsible for the column instability, previously mentioned, it did not preclude satisfactory completion of the scheduled run. Design changes in these and similar valves for additional air pulser installations at the ICPP have been made to prevent recurrence of this difficulty.

The successful demonstration of an air-pulsed extraction column in routine ICPP operation has led to the acceptance of such a system as a substitute

for the trouble-ridden mechanical-hydraulic pulsers currently in use. Design of air pulser installations for the B and C columns in the CPM first-cycle extraction system and all three first-cycle STR-SIR columns is proceeding. All five of these new air pulsers will utilize equipment components similar to those installed for the CPM A column, with minor revisions and improvements. Differences in physical size and geometry between the STR-SIR columns and the CPM A column, plus the delay in procurement of final design data from the experimental unit, will necessitate the derivation of pressure-frequency-amplitude curves for the STR-SIR columns during cold tests in the plant. A transparent plastic pulse leg will be installed on each of these columns during the cold tests, and amplitude measurements will be made directly. The transparent sections will be replaced by welded stainless-steel pipe of the same inside diameter before beginning regular operation of the columns.