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DIFFUSION PLANT SEPARATION THEORY

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Exam Preview:

1. If the confined gas is isotopic (a mixture of particles of different molecular weights), the heavier particles of the gas will have a greater tendency to diffuse through the barrier because of their greater average velocities.
 - a. True
 - b. False
2. According to the reference material, which of the following terms matches the definition: the ability of a barrier to transmit gas, it is usually expressed as γ ?
 - a. Separation factor
 - b. Permeability
 - c. Mixing efficiency
 - d. Stage separation
3. Viscous flow occurs when molecules flow as a group in the manner of ordinary flow through a tube. Referring back to permeability, it is known that the flow through a barrier increases as the pressure increases. Also, as the pressure increases, so does the viscous component of flow
 - a. True
 - b. False
4. According to the reference material, which of the following terms matches the definition: the ability of a barrier to separate isotopes?
 - a. Permeability
 - b. Stage separation
 - c. Separation factor
 - d. Mixing efficiency

5. According to the Process Gas Flow section of the reference material, in the Badger stage, about ___% of the process gas entering a converter diffuses through the tubing and flows to the stage above. This fraction is called the "cut."
 - a. 35
 - b. 40
 - c. 45
 - d. 50
6. According to the reference material, the actual separation achieved by a stage is expressed in terms of the mass fraction of the light component and for the purpose of this discussion is designated by the capital letter R.
 - a. True
 - b. False
7. Using the Diffusion section of the reference material, if the flow through a barrier has decreased 30% due to plugging of the barrier holes, the permeability would be ___%.
 - a. 50
 - b. 60
 - c. 70
 - d. 80
8. According to the reference material, in a production cascade, a cut of approximately 0.7 is the optimum value with respect to operating efficiency and production.
 - a. True
 - b. False
9. According to the reference material, the isotopes with which we are concerned are those of _____. In order that the isotopes of _____ may be separated by the gaseous diffusion process, it is necessary that the _____ be in a gaseous state.
 - a. Uranium
 - b. Plutonium
 - c. Thorium
 - d. Curium
10. Using TABLE A-1 Converter Stage Size vs. Location, what is the diameter, in inches, that corresponds to an Equipment type of 31, and length of 221 inches?
 - a. 155
 - b. 105
 - c. 90
 - d. 47

BASIC SEPARATION THEORY

Introduction

The fundamental principles upon which a gaseous diffusion plant is based are as follows.

1. All the particles (atoms, molecules, or ions) which make up the gas are continuously moving in straight lines in all directions. The particles collide with anything in their path (e.g., other particles or the walls of the container), thereby altering the course of moving particles but not their average velocities.
2. All of the particles have the same average kinetic energy. Accordingly, if the masses of the particles are different, so must their velocities be different with the lighter particles having the greater average velocities.

On the basis of the two principles stated above, if a quantity of gas is confined by a porous membrane or barrier, some of the gas will escape through the pores in the barrier. If the confined gas is isotopic (a mixture of particles of different molecular weights), the lighter particles of the gas will have a greater tendency to diffuse through the barrier because of their greater average velocities. Consequently, the gas which has passed through the barrier will be enriched in the light constituent while that gas which has not diffused through the barrier will be depleted in the light constituent.

Isotopic Separation

The isotopes with which we are concerned are those of uranium; namely U^{235} and U^{238} . In order that the isotopes of uranium may be separated by the gaseous diffusion process, it is necessary that the uranium be in a gaseous state. This is accomplished by combining the uranium with fluorine to form uranium hexafluoride, which is a gas at workable temperatures and pressures. Another advantageous quality of uranium hexafluoride is that fluorine has no isotopes to further complicate the separation process. In general, the following discussion is concerned with the separation of $U^{235}F_6$ and $U^{238}F_6$.

Separation Factor

The ability of a barrier to separate isotopes is expressed by a value called the *separation factor*. It is denoted by the Greek letter α , and is defined as the mole ratio of light component to heavy component in the gas passing through the barrier at a given point divided by a similar mole ratio on the high pressure surface of the barrier at the same point. The separation factor can be expressed by the following equation.

$$\alpha = \frac{\frac{y}{1-y}}{\frac{x}{1-x}}$$

In this equation, y and x are the mol fraction of light component on the low and high pressure sides of the barrier respectively. It should be emphasized that α , as shown in Figure A-1, is a point value, and that x and y are concentrations at a given point on the two surfaces of the barrier. In practice, point values are usually not determined. The average α 's of the surface of samples are calculated from experimental separation data.

As previously stated, the separation of isotopes is dependent upon the difference in the mass of the particles. Under ideal conditions, the separation factor would be equal to the ratio of the square roots of the molecular weights. For a mixture of U^{235}F_6 and U^{238}F_6 , this value is 1.0043 and is commonly referred to as the ideal separation factor. In actual practice, however, these ideal conditions cannot be duplicated. For example, to approach the ideal separation factor, only a small fraction of the total gas involved could be diffused through the barrier. For such a process to be productive, the plant size and its power consumption would be too large to be economically feasible. Limitations of plant size and power consumption have, necessitated a reduction in the separation factor to a lower value. This lower value is called the actual separation factor.

Stage Separation

The ratio of the total molar rate of flow through the barrier within a converter to the total rate of flow into the same converter is called the *cut* and is designated by the Greek letter Θ .

$$\Theta = \frac{\text{Molar flow of enriched stream}}{\text{Molar flow of input stream}}$$

In a production cascade, a cut of approximately 0.5 is the optimum value with respect to operating efficiency and production.

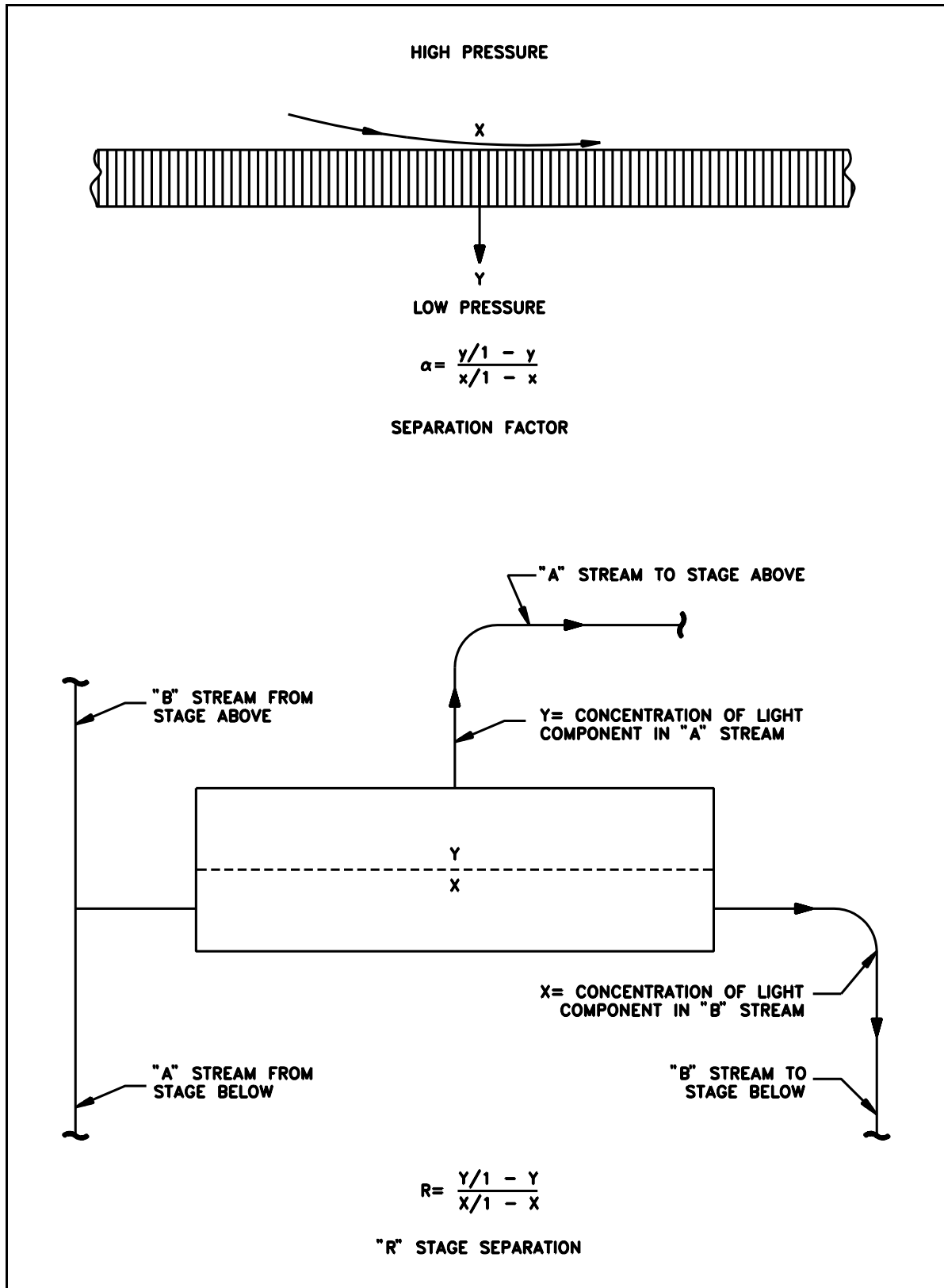


Figure A-1 "R" Stage Separation

The actual separation achieved by a stage is expressed in terms of the mol fraction of the light component and for the purpose of this discussion is designated by the capital letter R. It can be defined as follows: if Y is the concentration of light component in the enriched stream leaving a converter and X is its concentration in the depleted stream leaving the same converter, then

$$R = \frac{\frac{Y}{1 - Y}}{\frac{X}{1 - X}}.$$

This definition is similar to that of the separation factor, but, as shown in Figure A-1, the value of R is based on the overall separation of a stage while that of the separation factor is based on the performance of the barrier alone. The relation between the two is given by the following equation.

$$R = E \alpha \frac{1}{\Theta} \ln \frac{1}{1 - \Theta}$$

E is a correction factor called the *mixing efficiency*. It can be explained as follows: since the light component passes through the barrier more rapidly than the heavy component, the layer of gas at the surface on the high pressure side of the barrier becomes more depleted in the light component than the bulk of the gas on the high pressure side. Thus, there is a concentration gradient perpendicular to the surface of the barrier which results in a decrease in separation. In the particular process of separation of uranium isotopes, the value of R in the preceding equation differs very little from unity ($R = 1.003$) and is somewhat inconvenient for use in calculations. By subtracting 1 from each side of the equation, equating the symbol ψ (psi) to $R - 1$, and by making a slight approximation, the equation becomes

$$\psi = \frac{Y - X}{X(1 - X)}.$$

This equation is used frequently in the plant in making separation tests.

Barrier Measurements

The ability of a barrier to transmit gas is usually expressed as γ (gamma), the *permeability*. This is a measure of the total flow through a barrier and may be defined as the ratio of the number of molecules which pass through the barrier to the number which would pass through the space if the barrier were not there. This total flow through a barrier is known to be a combination of several different types; namely, diffusive flow, film flow, and viscous flow. As was previously explained, the type of flow that is of greatest importance for a gaseous diffusion plant is diffusive flow. However, as film flow and viscous flow affect the separation through a barrier, they cannot be ignored.

Film flow refers to the transport of molecules under the influence of the force field between the molecules and the barrier surface. When such force fields are significant, a large number of molecules will not have sufficient velocity normal to the surface to escape from this field so that their motion will be confined to the barrier surface and barrier pore surface. Such molecules would pass through the barrier as a film on the surface of the pores.

Viscous flow occurs when molecules flow as a group in the manner of ordinary flow through a tube. Referring back to permeability, it is known that the flow through a barrier increases as the pressure increases. Also, as the pressure increases, so does the viscous component of flow. The relation between permeability and viscous flow can best be shown by the following equation.

$$\gamma = \gamma_o [1 + S(P_f + P_b)]$$

In this equation where P_f equals the fore or high side pressure and P_b equals the back or low side pressure. γ_o equals the permeability, γ , when

$$P_f + P_b = 0.$$

S is called the slope factor and is inversely proportional to the viscosity of the gas.

In the above equation, the term $S(P_f + P_b)$ is a measure of the viscous component of flow. Figure A-2 illustrates the variation of permeability with the slope factor and changes in pressure.

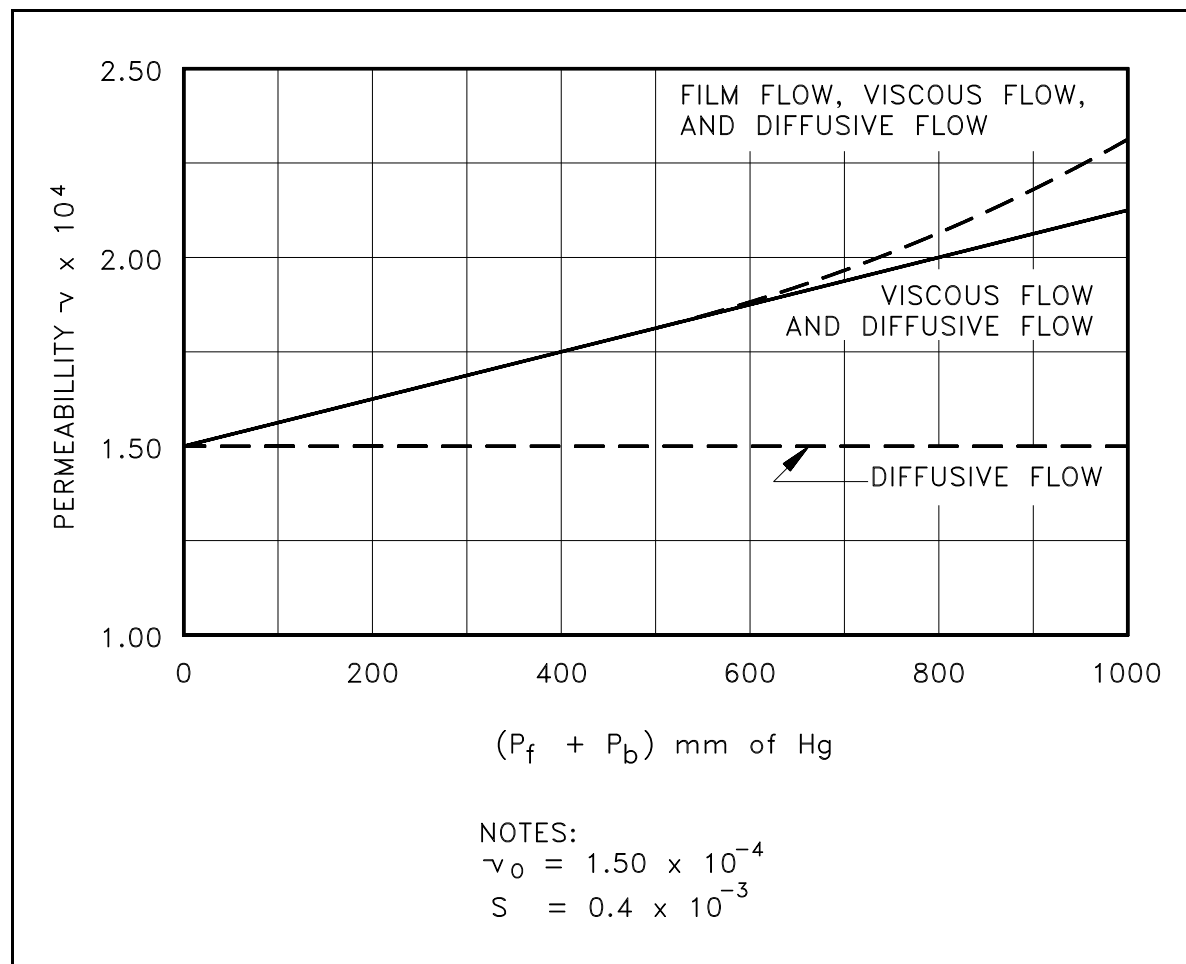


Figure A-2
 Variation of Permeability with the Slope Factor and Change in Pressure

It should be noted that in practice, permeability is expressed in two different ways; design and actual. Design permeability is expressed as a ratio as previously stated. It is usually determined by testing the barrier with a non-toxic gas such as nitrogen. Actual permeability is expressed as a percentage of the design permeability and is determined from tests with the barrier in actual operation in the cascade. Its primary value is in determining the performance of a barrier after being in use for a period of time.

Cascade Theory

In the operation of a diffusion cascade, it is often necessary to charge the plant with feed material of different assays or concentrations of $U^{235}F_6$. This feed must be fed into the cascade at a point where the assay of the gas already being processed is the same as that of the feed to be charged.

To choose this feed point, therefore, it must be possible to calculate the concentration of $U^{235}F_6$ in the process gas at any point in the cascade. These calculations can be made by knowing two things: first, the concentration of $U^{235}F_6$ in the process gas at several points in the cascade (determined by laboratory and instrument analysis); and second, the increase in the concentration of $U^{235}F_6$ accomplished by each stage. This is called the stage enrichment and should not be confused with the separation accomplished by a stage previously discussed. Therefore, by knowing the stage enrichment and the $U^{235}F_6$ concentration at some point in the cascade, it is possible to determine the concentration at other points.

The feed material ordinarily charged into a plant contains a very small percentage of $U^{235}F_6$ with the remainder being $U^{238}F_6$. Consequently, a far greater amount of the feed flows downward in the cascade and is removed as tails than is removed at the top of the cascade as $U^{235}F_6$ or product. For this reason, as we progress upward in the cascade from the feed point, the total flow through the converters becomes progressively smaller. It follows, therefore, that in the ideal design each stage would be different in size from the adjacent stages. However, since the cost of construction of a production cascade is of great importance, a lower cost may be achieved by the use of many identical units. For this reason, the cascade is composed of a series of sections, each of which contains a large number of identical stages. The change in equipment size is accomplished in a step-wise manner by varying the equipment size of each so-called section.

Circuit Balances

Of major importance in a production cascade is the ability to calculate pressures, temperatures, and flows of the process gas which cannot be practically or economically measured by instrumentation. Since the cascade is made up of sections each of which contains a large number of identical stages and since the stage is the smallest separating unit of a cascade, these calculations are made on a stage basis. This system of calculating temperatures, pressures, and flows is commonly referred to as a circuit balance and consists of a series of calculations made from those pressures and temperatures ordinarily measured by instrumentation in the cascade, and from experimental data obtained from test loop studies.

For illustration purposes, the pressures, temperatures, and flows in a typical X-31 stage which are taken by instrumentation, plus those to be calculated, are shown in Figure A-3. It is obvious that the cost to install instruments in every stage to measure all of the values indicated would be prohibitive.

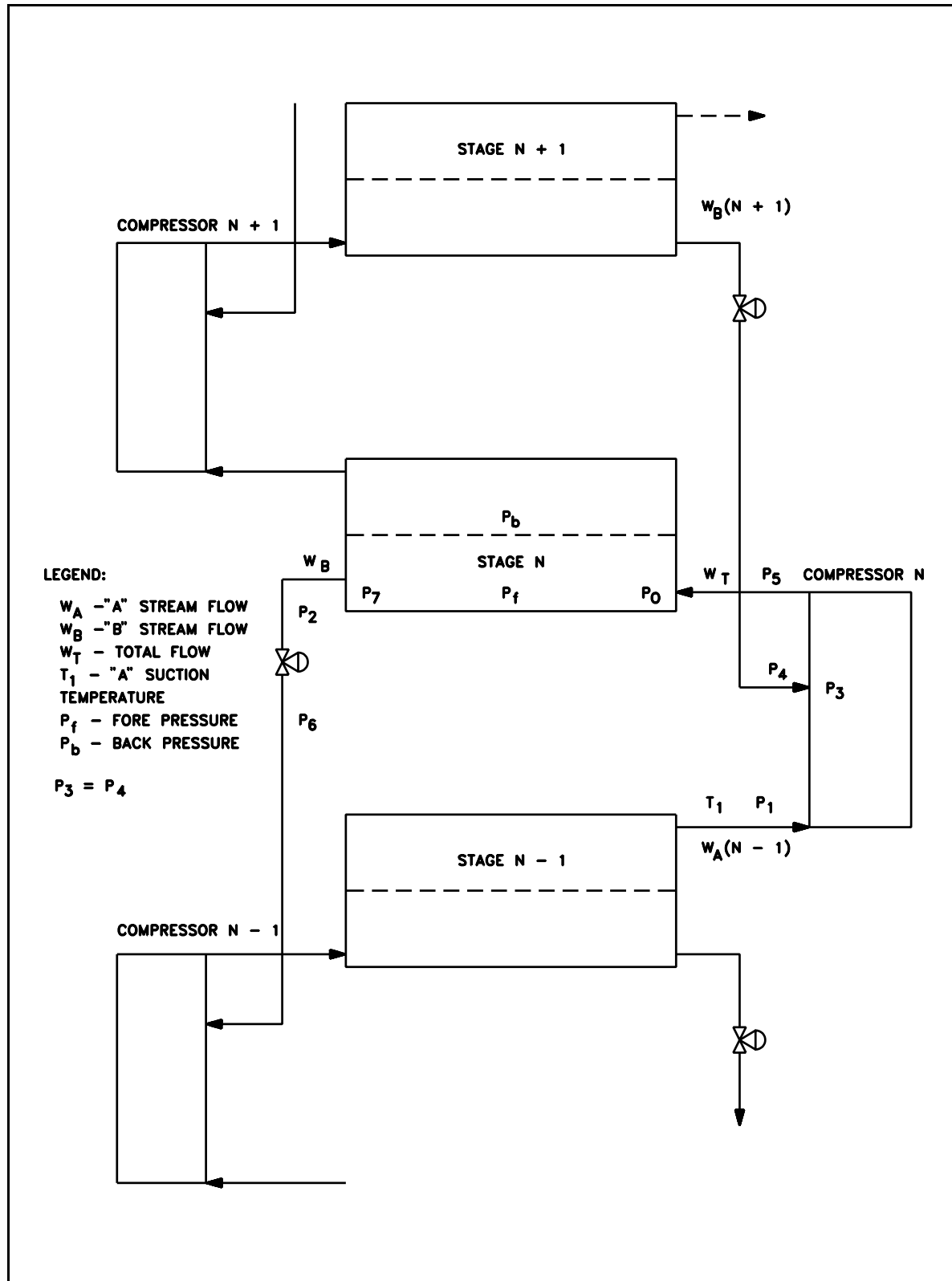


Figure A-3
Pressures, Temperatures, and Flows in a Typical V-31 Stage

Because of their number and complexity, the mathematical formulas used in calculating the pressure points in Figure A-3 will not be presented. The operator will read and record only those values which are measured by instruments and will not be required to perform any of the mathematical calculations involved in completing a circuit balance. However, the following discussion will give an indication as to the procedures involved in determining these values. To calculate a circuit balance for Stage N in Figure A-3, pressures P_1 and P_2 and temperature T_1 are recorded. Then, knowing P_1 and T_1 and a constant previously determined in a test loop, it is possible to calculate the flow $W_A(N - 1)$. Since the "A" barrel of the compressor has essentially a constant suction volume in the normal operating range, the interstage flow is proportional to the compressor "A" suction pressure and temperature. Next, it is known that the flow in a cascade must operate at a steady state condition to prevent an accumulation of deficiency of inventory in any one section. It may therefore be assumed that the flow downward to a stage is equal to the flow upward from the same stage. (This assumption is not valid for all stages in a cascade but for practical applications the error is negligible.) From this assumption, W_B is equal to $W_A(N - 1)$. With P_2 , W_B , and pressure drop data obtained in the test loop, P_7 can be calculated.

In a test loop, data is taken on converters of different sizes and types to determine pressure variations with different amounts of flow and cut. If W_A is found in the same manner as $W_A(N - 1)$, it is then possible with the test loop data to calculate P_b . Also, with the converter data, and knowing W_B , P_7 , and W_T ($W_T = W_A + W_B$), P_o and subsequently, P_f are found.

Again using pressure drop data, P_5 can be calculated from W_T and P_o . With P_5 , P_3 is calculated by knowing the "B" pressure ratio of the compressor.

From the calculated values obtained from a circuit balance, it is possible to make further calculations which indicate the operational and productive characteristics of the cascade. For example, P_f , P_b , and the flows through a converter must be known before the actual permeability of the barrier can be calculated. Also, these values make it possible to accurately predict horsepower requirements under varying conditions of flow and pressure. Another important application of the circuit balance is in the determination of inventory in the cascade where pressures and temperatures not otherwise measured are required.

CONVERTERS

Converters

The actual separation of $U^{235}F_6$ from $U^{238}F_6$ in a gaseous diffusion plant is accomplished in the converter. The converter, sometimes referred to as a diffuser, contains the barrier tubing through which diffusion takes place. In the previous section we studied the flow through the converter as a part of a stage. In this section we will see what takes place inside the converter.

In all, the entire cascade contains over 4000 converters -- one in each stage. The stage size varies with the location in the cascade as shown in the table below.

TABLE A-1				
Converter Stage Size vs. Location				
Equipment Type	Converter Type	Length (inches)	Diameter (inches)	Number Used In Cascade
33	000	291	155	640
31	00-2	221	105	500
29	0	185 or 215	90 or 105	600
27	7	129	47	720
25	8	129	38	1560

Converter Construction

Externally, the converter resembles a large cylindrical tank resting on its side (see Figure A-4). There are openings at each end for the necessary piping connections. The outlet end of the converter contains the "A" and "B" stream process gas outlets. The other end contains the mixed process gas inlet and the stage coolant inlet and outlet. The cylindrical tank is called the shell and is constructed of steel with welded joints. Its internal surface is nickel plated. There are three external reinforcing flanges around the outside of the shell. The many hundreds of barrier tubes, or tube bundles, contained in one converter are held in place by the spool, or spool piece. The spool consists of struts and a central tube, or core, which is perforated and allows part of the "A" stream leaving the barrier tubes to reach the converter outlet. On either end of the core are tube sheets into the holes of which the barrier tubes are sealed by rolling or swagging. Tube sheets are also mounted on the core between the end tube sheets to support the barrier tubes.

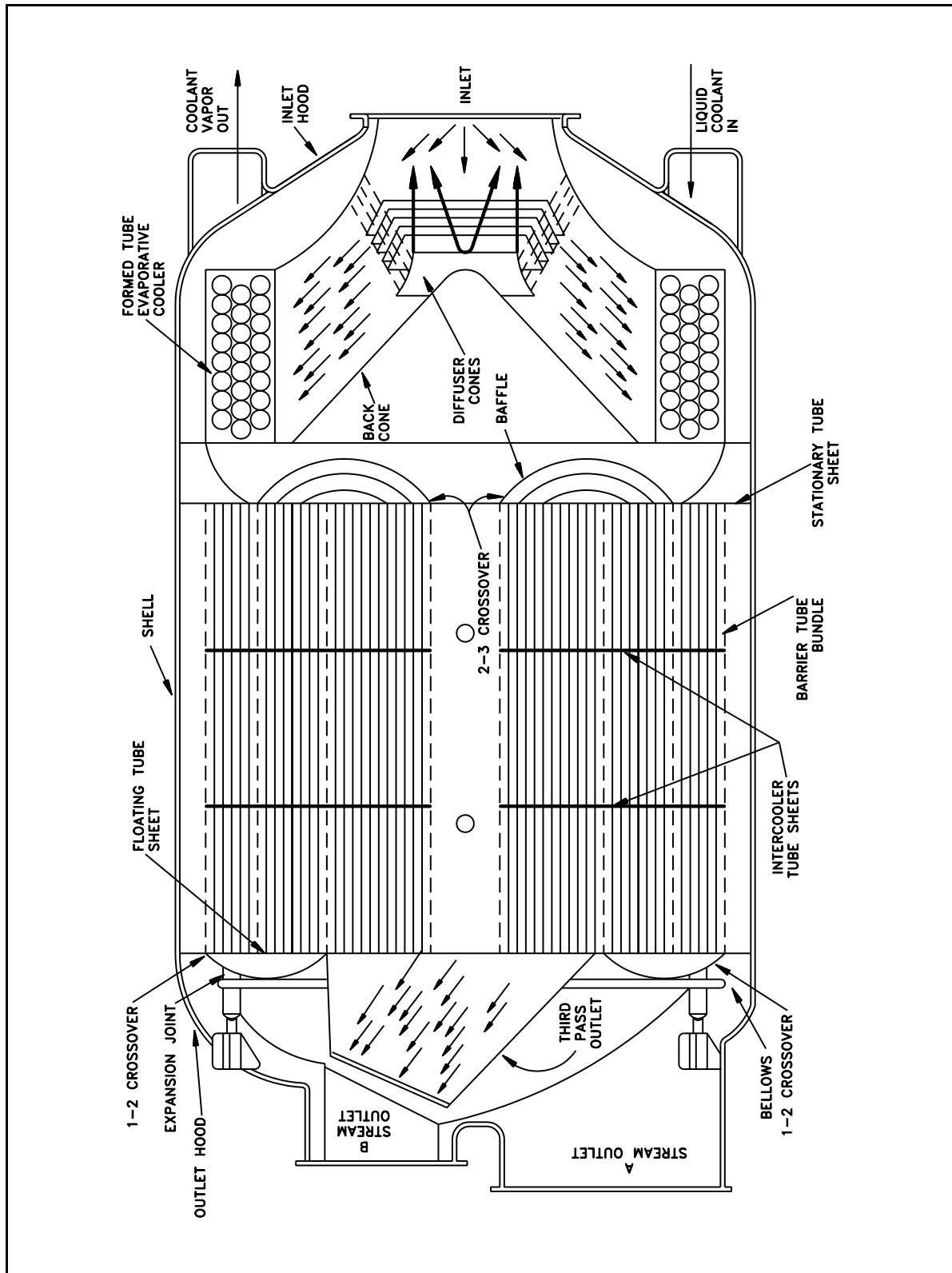


Figure A-4 - Typical Converter

The remainder of the converter equipment, with the exception of the gas cooler, is designed to direct the process gas flow inside the converter.

The Gas Cooler

The gas cooler's purpose is to remove the heat of compression from the process gas which has just been discharged from a compressor. Certain type of stages use a gas cooler contained within the converter as shown on Figure A-4. The gas coolers may be separate units placed between the compressors and the converters.

Barrier Tubing

In the early stages of converter design, it was recognized that barriers made in the form of flat sheets and stacked in a container would offer the most barrier area per unit volume. For practical reasons, the barrier had to be made in the form of tubes. More engineering knowledge was available for tubular construction and the urgency of the problem did not allow any unnecessary development time. The use of tubes also allowed more satisfactory replacement of damaged barrier material. As a result, the barrier is made in the form of thin-walled tubes.

Process Gas Flow

We can now trace the process gas flow within the converter. In the AB cooled converter of Figure A-4, the process gas enters one end of the converter at the center and is directed to the outside of the shell by a series of baffles. It flows through the gas cooler and is directed to the outer section, or pass, of the barrier tubes. All of the flow enters the outer, or first pass, and flows through the tubes. Part of the flow diffuses through the barrier tube walls and the remainder of the flow passes through the tubes and is directed by a crossover to the second pass of tubes. This crossover is sometimes called a doughnut because of its shape. The process gas flow which does not diffuse through the barrier tube walls of the second pass is directed by a second crossover to the third pass. The first crossover is sometimes referred to as the 1-2 crossover because it directs gas flow from the first pass to the second pass. Similarly, the second crossover is called the 2-3 crossover. The undiffused process gas which passes through the third pass is directed to the "B" outlet of the converter and flows to the stage below. The process gas which was diffused through the barrier tubes in all three passes is collected and flows to the "A" outlet and on to the stage above.

Since some of the process gas flowing into the first pass will diffuse through the tube walls, a reduced amount of process gas flow will enter the second pass. In order to maintain the same flow velocity, the second pass contains fewer tubes than the first pass. Similarly, the third pass will contain still fewer tubes. The velocity of process gas through the tubes affects the flow through the tube walls and thus affects the separation efficiency. The efficiency is highest when the flow velocity is the same in all of the tubes.

In the Badger stage, about 50% of the process gas entering a converter diffuses through the tubing and flows to the stage above. This fraction is called the "cut." A cut of 50% has been found to yield the best separation. As mentioned previously, the "cut" in a Badger Cluster stage may be more or less than 50% depending upon its position in the cluster.

Diffusion

It is necessary to have a higher pressure inside the barrier tubes than outside in order to have a flow through the walls of the tubes. This inside pressure is called the fore pressure or high side pressure (H.S.P.), and is measured at an arbitrary point inside the tubes near the middle of the second pass. The pressure outside the tubes is the back pressure or low side pressure (L.S.P.), and is measured at an arbitrary point outside the tubes near the middle of the second pass.

The fore pressure is regulated by a control valve in the "B" stream, or down flow, from the converter. Actually, the control valve regulates the pressure immediately above it. This is called the control pressure and is the pressure which is indicated at the cell panel. It is slightly lower than the fore pressure due to the pressure drops in the converter and piping.

The rate of diffusion through the tubing walls for any given pressure drop across the barrier is determined by the permeability of the barrier. Mathematically, this is a dimensionless quantity which is the ratio of the rate of gas flow through the barrier to the rate of gas flow through the same area which would take place if the barrier were not there. The term, usually called permeability, is used to relate the actual permeability to the design permeability. For example, if the flow through the barrier has decreased 10% due to plugging of the barrier holes, the permeability would be 90%.