**ENGINEERING  STANDARD**

**FOR**

**PROCESS  DESIGN  OF  VACUUM  EQUIPMENT**

**(VACUUM  PUMPS  AND  STEAM  JET - EJECTORS)**

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## 0. INTRODUCTION

"Pressure Reducing/Increasing Machineries and/or Equipment" are broad and contain variable subjects of paramount importance. Therefore, a group of process engineering standards are prepared to cover the subject.

This group includes the following standards:

**STANDARD CODE**  **STANDARD TITLE**

IPS-E-PR-745  "Process Design of Vacuum Equipment (Vacuum Pumps and Steam Jet Ejectors)"
IPS-E-PR-750  "Process Design of Compressors"
IPS-E-PR-755  "Process Design of Fans and Blowers"

This Standard covers:

## VACUUM EQUIPMENT

## (VACUUM PUMPS AND STEAM JET EJECTORS)

This Standard covers the process aspects of engineering calculations for vacuum systems and the relevant equipment.

Since the working mechanism of certain types of vacuum pumps such as positive displacement types are the same as gas compressors, these types are not discussed in detail in this standard and therefore the "Design Criteria" section mainly discusses about the "Ejectors", which are the most frequently used vacuum devices in O, G and P processes.

## 1. SCOPE

This Recommended Practice is intended to cover guidelines for selection of proper type vacuum system, process calculation stages for vacuum systems including capacity, estimation of air leakage and rough estimation of utility consumption and a typical P & I diagram for a vacuum system.

## 2. REFERENCES

Throughout this Standard the following standards and codes are referred to. The editions of these standards and codes that are in effect at the time of publication of this Standard shall, to the extent specified herein, form a part of this Standard. The applicability of changes in standards and codes that occur after the date of this Standard shall be mutually agreed upon by the Company and the Vendor/Consultant.

**IPS     (IRANIAN PETROLEUM STANDARDS)**

| | |
|---|---|
| IPS-E-GN-100 | "Units" |
| IPS-M-ME-256 | "Ejectors" |
| IPS-E-PR-250 | "Performance Guarantee" |
| IPS-E-PR-750 | "Process Design of Compressors" |

**HEAT EXCHANGE INSTITUTE Inc.**

"Standard for Steam Jet Ejectors", 3rd. Ed. 1980
"General Construction Standard for Ejector Componenets other than Ejector Condensers", 1st. Ed.

**ISO     (INTERNATIONAL ORGANIZATION FOR STANDARDIZATION)**

| | |
|---|---|
| 3529/2 | "Vacuum Technology-Vocabulary" Part 2: "Vacuum Pumps and Related Terms" |
| 1st. Ed. 1981 | |

## 3. SYMBOLS AND ABBREVIATIONS

| | | |
|---|---|---|
| $A$ | = | Quotational Price. |
| $B$ | = | Steam Cost Per Ton. |
| $C$ | = | Cooling Water Cost Per 1000 $m^3$. |
| $F$ | = | Capital Charge Percentage. |
| $g$ | = | Acceleration of Gravity = 9.806 $m/s^2$. |
| $G_s$ | = | Steam Consumption, Tons Per Year in (t/a). |
| $G_w$ | = | Cooling Water Consumption, in (1000 $m^3$/a). |
| $H$ | = | Height, in (meters). |
| $L$ | = | Air Leakage, in (kg/h). |
| $M_n$ | = | Molecular Mass of Noncondensable Gas, in (kg/kmol). |
| $M_v$ | = | Molecular Mass of Condensable Vapor, in (kg/kmol). |
| $P_1$ | = | Initial Pressure in System, in [mm Hg (abs.)]. |
| $P_2$ | = | Final Pressure in System, in [mm Hg (abs.)]. |
| $P_c$ | = | Condensate Pressure in Condenser, in (kPa). |
| $P_n$ | = | Partial Pressure of Non-Condensable Gas, in [mm Hg (abs.)]. |
| $P_o$ | = | Barometric Pressure at Liquid Level, in (kPa). |
| $P_v$ | = | Partial Pressure of Condensable Vapor, in [mm Hg (abs.)]. |
| $Q$ | = | Throughput of a Vacuum Pump, in (Pa. $m^3$/s). |

$$S \quad = \quad \text{Volume Flow Rate of a Vacuum Pump, in } (m^3/s).$$

| | | |
|---|---|---|
| $S$ | = | Volume Flow Rate of a Vacuum Pump, in $(m^3/s)$. |
| $t$ | = | Time, in $(h)$. |
| $T$ | = | Absolute Temperature, in $(K)$. |
| $V$ | = | Volume, in $(m^3)$. |
| $W$ | = | Capacity of Ejector, in $(kg/h)$. |
| $t$ | = | Time, in $(h)$. |
| $W_n$ | = | Mass Flow Rate of Non-Condensable Gas, in $(kg/h)$. |
| $W_v$ | = | Mass Flow Rate of Condensable Vapor, in $(kg/h)$. |
| $uP$ | = | Pressure Difference due to Friction Losses, in $(kPa)$. |
| $\rho_L$ | = | Mass Density of Liquid, in $(kg/m^3)$. |

## 4. UNITS

International System of Units (SI) in accordance with IPS-E-GN-100 shall be used.

## 5. GENERAL

Vacuum equipment, as called by ISO (International Organization for Standardization),"Vacuum Pumps", are defined as devices for creating, improving and/or maintaining a vacuum.

In OGP industries the name "Vacuum Pump" is conventionally used for rotating machine vacuum devices, and vacuum equipment are divided into two main groups, Vacuum Pumps and Steam Ejectors.

### 5.1 Definition of Vacuum Pumps and Related Terms

Definitions of vacuum pumps and related terms of ISO-3529/2 (see 2.), are generally accepted in this Standard. The following selected definitions are recommended emphatically.

#### 5.1.1 Vacuum pump

A device for creating, improving and/or maintaining a vacuum. Two basically distinct categories may be considered: gas transfer pumps (5.1.2 to 5.1.14) and entrapment or capture pumps (5.1.15).

#### 5.1.2 Positive displacement (vacuum) pump

A vacuum pump in which a volume filled with gas is cyclically isolated from the inlet, the gas being then transferred to an outlet. In most types of positive displacement pumps the gas is compressed before the discharge at the outlet. Two categories can be considered: reciprocating positive displacement pumps (5.1.5) and rotary positive displacement pumps (5.1.6 to 5.1.8).

#### 5.1.3 Oil - sealed (liquid - sealed) vacuum pump

A rotary positive displacement pump in which oil is used to seal the gap between parts which move with respect to one another and to reduce the residual free volume in the pump chamber at the end of the compression part of the cycle.

#### 5.1.4 Dry - sealed vacuum pump

A positive displacement pump which is not oil-sealed (liquid-sealed).

#### 5.1.5 Piston vacuum pump

A positive displacement pump in which the gas is compressed and expelled due to the movement of a reciprocating piston moving in a cylinder.

### 5.1.6  Liquid ring vacuum pump

A rotary positive displacement pump in which an eccentric rotor with fixed blades throws a liquid against the stator wall. The liquid takes the form of a ring concentric to the stator and combines with the rotor blades to define a varying volume.

### 5.1.7  Sliding vane rotary vacuum pump

A rotary positive displacement pump in which an eccentrically placed rotor is turning tangentially to the fixed surface of the stator. Two or more vanes sliding in slots of the rotor (usually radial) and rubbing on the internal wall of the stator, divide the stator chamber into several parts of varying volume.

### 5.1.8  Roots vacuum pump

A positive displacement pump in which two lobed rotors, interlocked and synchronized, rotate in opposite directions moving past each other and the housing wall with a small clearance and without touching.

### 5.1.9  Kinetic vacuum pump

A vacuum pump in which a momentum is imparted to the gas or the molecules in such a way that the gas is transferred continuously from the inlet to the outlet. Two categories can be considered: fluid entrainment pumps and drag vacuum pumps.

### 5.1.10  Ejector vacuum pump

A kinetic pump which use the pressure decrease due to a Venturi effect and in which the gas is entrained in a high-speed stream towards the outlet. An ejector pump operates when viscous and intermediate flow conditions obtain.

### 5.1.11  Liquid jet vacuum pump

An ejector pump in which the entrainment fluid is a liquid (usually water).

### 5.1.12  Gas jet vacuum pump

An ejector pump in which the entrainment fluid is a noncondensable gas.

### 5.1.13  Vapor jet vacuum pump

An ejector pump in which the entrainment fluid is a vapor (water, mercury or other vapor).

### 5.1.14  Diffusion pump

A kinetic pump in which a low pressure, high-speed vapor stream provides the entrainment fluid. The gas molecules diffuse into this stream and are driven to the outlet. The number density of gas molecules is always low in the stream. A diffusion pump operates when molecular flow conditions obtain.

### 5.1.15  Entrapment [capture] vacuum pump

A vacuum pump in which the molecules are retained by sorption or condensation on internal surfaces.

### 5.1.16  Inlet

The port by which gas to be pumped enters a pump, also called "Suction Chamber", (see Fig. 6).

### 5.1.17  Outlet

The outlet or discharge port of a pump.

### 5.1.18  Pump fluid

The operating fluid of an ejector or diffusion pump.

### 5.1.19  Steam chest

The compartment between the motive steam inlet port and the nozzle inlet (or nozzle plate) of an ejector, (see Fig. 6).

### 5.1.20  Nozzle plate

The plate on which nozzles (or nozzle extensions) of an ejector are mounted, (see Fig. 6).

### 5.1.21  Nozzle

The part of an ejector or diffusion pump used to direct the flow of the pump fluid in order to produce the pumping action.

### 5.1.22  Nozzle throat

Smallest cross-section of the nozzle.

### 5.1.23  Nozzle extension

The part (a small piece of pipe) between steam chest (or nozzle plate) and the nozzle, (see Fig. 6).

### 5.1.24  Nozzle clearance area

The smallest cross-sectional area between the outer rim of a nozzle and the wall of the pump casing.

### 5.1.25  Nozzle clearance

The width of the annulus determining the nozzle clearance area.

### 5.1.26  Jet

The stream of pump fluid issuing from a nozzle, in an ejector or diffusion pump.

### 5.1.27  Diffuser

The converging section of the wall of an ejector pump.

### 5.1.28  Diffuser throat

The part of a diffuser having the smallest cross-sectional area.

### 5.1.29 Volume flow rate of a vacuum pump [symbol: S; unit: $m^3.s^{-1}$]

It is the volume flow rate of the gas removed by the pump from the gas phase within the evacuated chamber. This kind of definition is only applicable to pumps which are distinct devices, separated from the vacuum chamber. For practical purposes, however, the volume flow rate of a given pump for a given gas is, by convention , taken to be the throughput of the gas flowing from a standardized test dome connected to the pump, divided by the equilibrium pressure measured at a specified position in the test dome, and under specified conditions of operation.

### 5.1.30 Throughput of a vacuum pump [symbol: Q; unit: $Pa.m^3.s^{-1}$]

The throughput flowing through the inlet of the pump.

### 5.1.31 Starting pressure

Pressure at which a pump can be started without damage and a pumping effect can be obtained.

### 5.1.32 Backing pressure

The pressure at the outlet of a pump which discharges gas to a pressure below atmospheric.

### 5.1.33 Critical backing pressure

The backing pressure above which a vapor jet or diffusion pump fails to operate correctly. It is the highest value of the backing pressure at which a small increment in the backing pressure does not yet produce a significant increase of the inlet pressure. The critical backing pressure of a given pump depends mainly on the throughput.

**Note:**

**For some pumps the failure does not occur abruptly and the critical backing pressure cannot then be precisely stated.**

### 5.1.34 Maximum backing pressure

The backing pressure above which a pump can be damaged.

### 5.1.35 Maximum working pressure

The inlet pressure corresponding to the maximum gas flow rate that the pump is able to withstand under continuous operation without any deterioration or damage.

### 5.1.36 Ultimate pressure of a pump

The value towards which the pressure in standardized test dome tends asymptotically, without introduction of gas and with the pump operating normally. A distinction may be made between the ultimate pressure due only to noncondensable gases and the total ultimate pressure due to gases and the total ultimate pressure due to gases and vapors.

### 5.1.37 Operating pressure

The absolute pressure, expressed in mm Hg or kPa(abs.), that a vacuum pump or ejector unit can maintain in a system operating at design capacity, (see 6.1.3) and normal operating conditions.

### 5.1.38 Compression ratio

The ratio of the outlet pressure to the inlet pressure, for a given gas.

## 5.2  Vacuum Pumps Classification

ISO classification of vacuum equipment (vacuum pumps) is shown in Fig. 1, (see 2.).

## 5.3  Type Selection Considerations

Vacuum equipment can be roughly divided into "Steam Ejectors" and "Vacuum Pumps", as mentioned in previous sections. Three major factors should be considered in the type selection stage for vacuum devices. These factors are operating requirements (i.e., suction pressure), suction gas properties and cost. As a general procedure for type selection, the flow chart shown in Fig. 2 can be used.

### 5.3.1  Operating conditions

Application range of different type of vacuum equipment can be found in Fig. 3.

In selecting the type of vacuum pump, the characteristics of the individual types and the process conditions involved must be fully considered. Contact with the vendors is also necessary. The characteristics of vacuum pumps are given in Table. 1.

For ejector, once the operating pressure is determined, the number of stages can be determined from Fig. 3.

### 5.3.2  Comparison of costs

Generally speaking, steam ejectors require less initial cost and have no moving parts, and hence they have high reliability. On the other hand, their disadvantage is that their utility cost is high. Meanwhile, in the case of vacuum pumps, although they cost 5 to 20 times as much as steam ejectors and require high maintenance cost, their utility cost is lower.
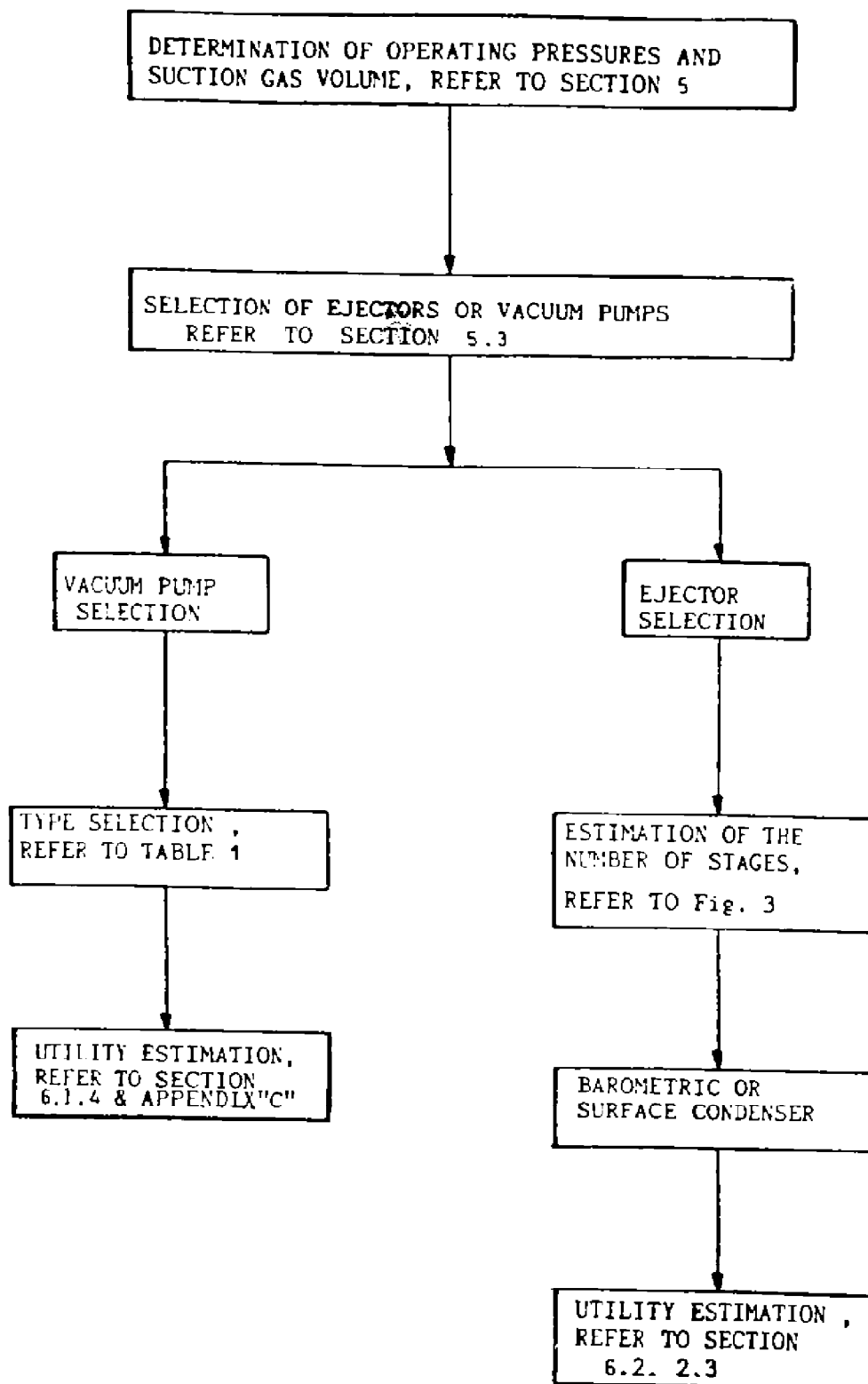
Regarding the operating costs, a general measure will be that, where the suction gas volume is large and the operating pressure is high, vacuum pumps will require less operating cost than steam ejectors.

### 5.3.3  Properties of suction gas

**a)**  In the case of steam ejectors which produce a large quantity of waste liquid, their use will be disadvantageous unless the cost of the waste liquid treatment is cheap.

**b)**  Where corrosive gases must be handled, steam ejectors, which can be manufactured of almost any material, will be advantageous.
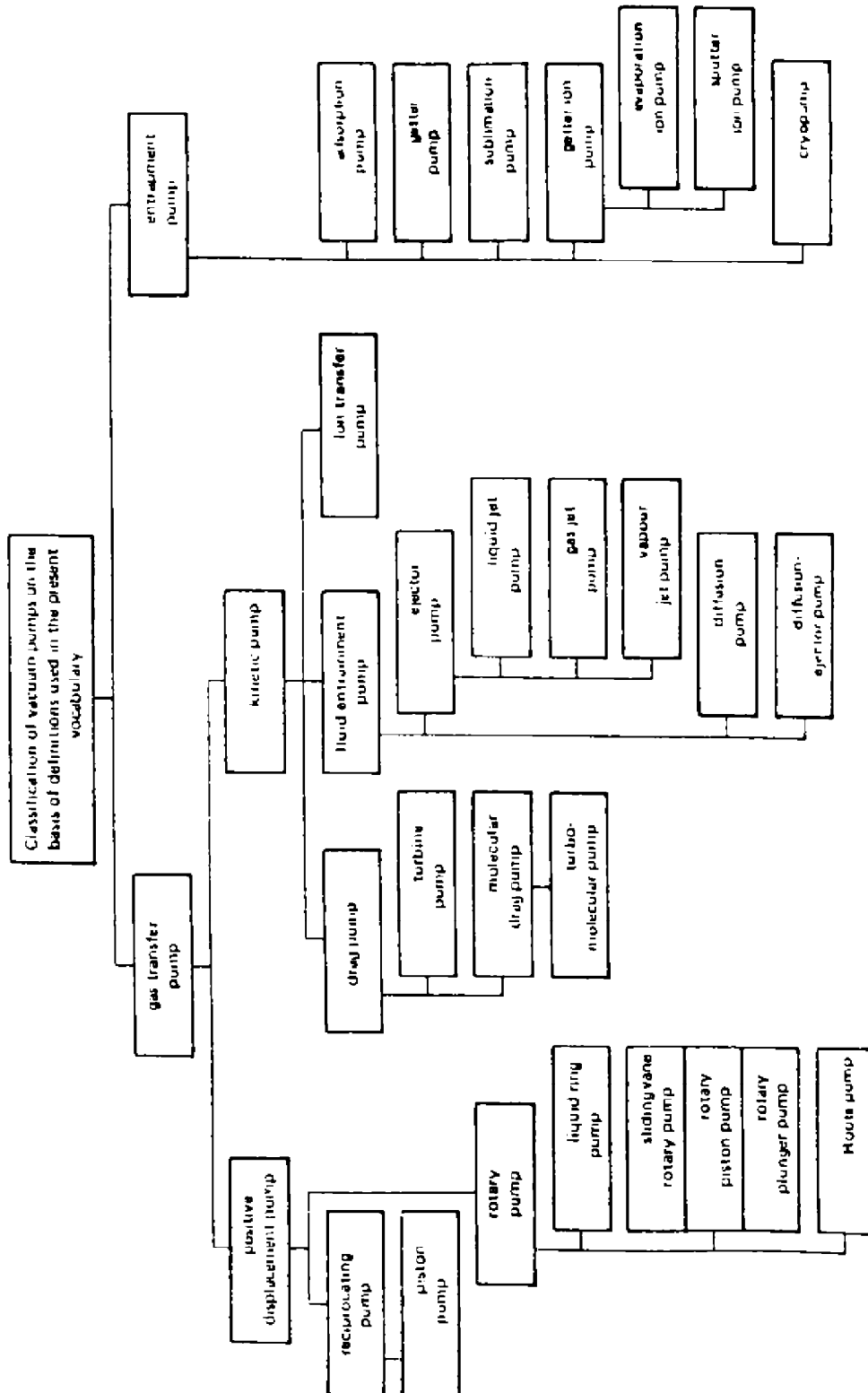
**CLASSIFICATION TABLE OF VACUUM PUMPS**
**Fig. 1**

```
┌─────────────────────────────────────────────────────────┐
│ DETERMINATION OF OPERATING PRESSURES AND                │
│ SUCTION GAS VOLUME, REFER TO SECTION 5                   │
└─────────────────────────────────────────────────────────┘
                            │
                            ▼
┌─────────────────────────────────────────────────────────┐
│ SELECTION OF EJECTORS OR VACUUM PUMPS                    │
│       REFER  TO  SECTION  5.3                            │
└─────────────────────────────────────────────────────────┘
                            │
            ┌───────────────┴───────────────┐
            ▼                               ▼
┌───────────────────────┐       ┌───────────────────────┐
│ VACUUM PUMP           │       │ EJECTOR               │
│ SELECTION             │       │ SELECTION             │
└───────────────────────┘       └───────────────────────┘
            │                               │
            ▼                               ▼
┌───────────────────────┐       ┌───────────────────────┐
│ TYPE SELECTION ,      │       │ ESTIMATION OF THE     │
│ REFER TO TABLE 1      │       │ NUMBER OF STAGES,     │
│                       │       │ REFER TO Fig. 3       │
└───────────────────────┘       └───────────────────────┘
            │                               │
            ▼                               ▼
┌───────────────────────┐       ┌───────────────────────┐
│ UTILITY ESTIMATION,   │       │ BAROMETRIC OR         │
│ REFER TO SECTION      │       │ SURFACE CONDENSER     │
│ 6.1.4 & APPENDIX"C"   │       │                       │
└───────────────────────┘       └───────────────────────┘
                                            │
                                            ▼
                                ┌───────────────────────┐
                                │ UTILITY ESTIMATION ,  │
                                │ REFER TO SECTION      │
                                │    6.2. 2.3           │
                                └───────────────────────┘
```

**SELECTION PROCEDURE FOR VACUUM EQUIPMENT**
**Fig. 2**
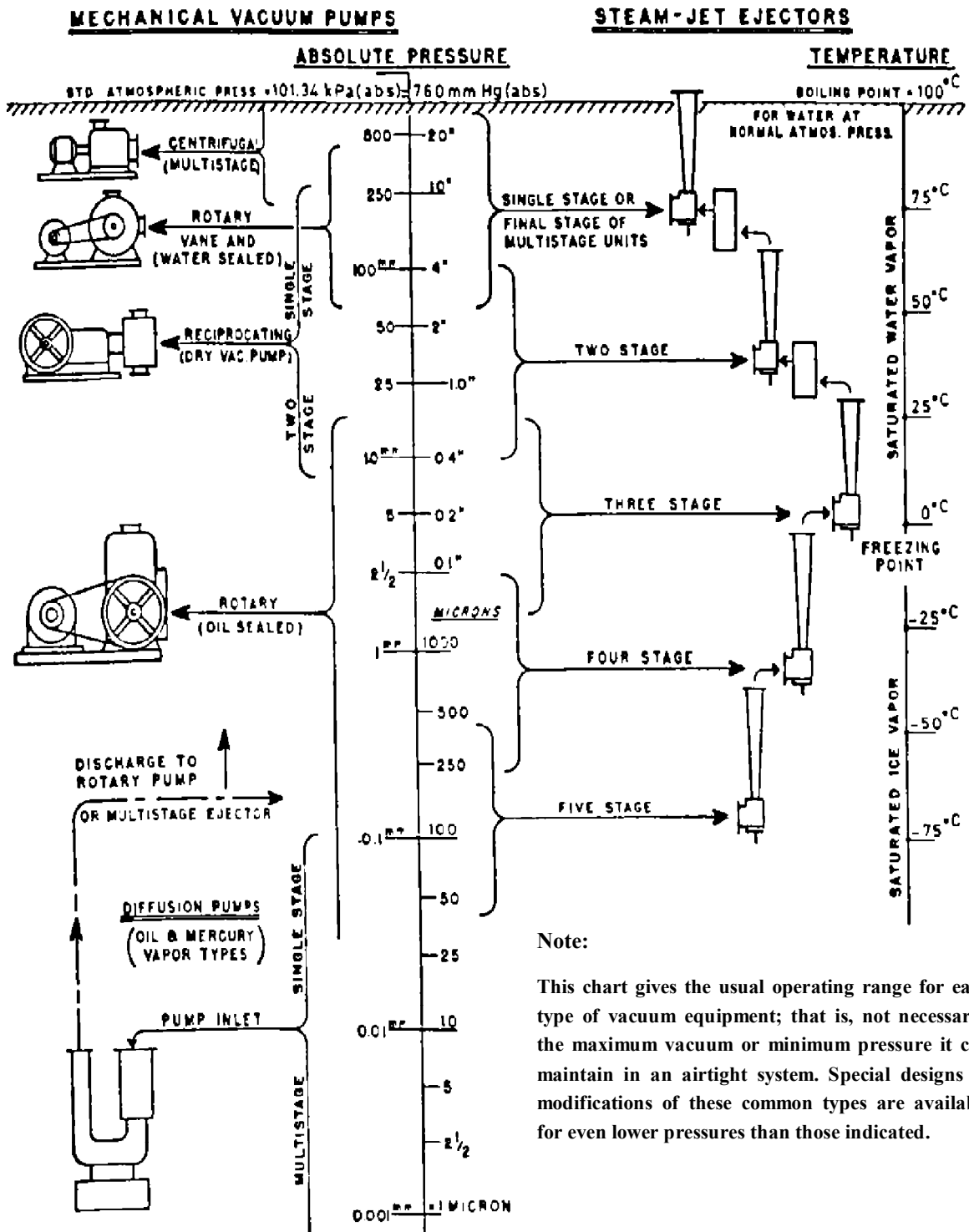
**APPLICATION RANGE OF VACUUM EQUIPMENT**
**Fig. 3**

**TABLE 1**
**CHARACTERISTIC OF VARIOUS VACUUM PUMPS**

| Type | Operating Pressure* (mm Hg) | Suitability for Suction Gas | | | Note |
|---|---|---|---|---|---|
| | | St'm | Low-Boil'g Gas | Dust | |
| RECIPROCATING One Stage Two Stage | 5 - 760 $10^{-1}$ - 760 | + + | + ⊕ | ⊕ + | Corrosive gases can be handled. Required large Space for installation. |
| NASH (Water seal) | 50 - 760 | + | + | + | Suitable for chemical Processes. Consumes much power. Liquid sealed circuit necessary. |
| Roots One stage Two stage | 300 - 760 100 - 760 | + + | + + | ⊕ ⊕ | Large exchaust volume Consumes much power. |
| Rotary (Oil seal | $10^{-4}$ - 760 | — | — | — | Low resistance against corrosive gases. |
| Mechanical booster | $10^{-3}$ - 10 | + | ⊕ | ⊕ | Large exchaust volum. Consumes less power. Auxiliary pumps necessary. |

**Note:**

    **\***    **It is possible to lower operating pressure by adopting heavy liquid sealing.**

    **+**    **Strong.**

    **⊕**    **Slightly strong.**

    **⊕**    **Slightly weak.**

    **- Weak.**

## 6. DESIGN CRITERIA

The basic design stage of vacuum pumps and ejectors, can be divided into two distinct parts, first is the calculation of parameters or factors which are common for all vacuum devices, such as those concerning the suction conditions. On the other hand, there are some calculations which regards specifically on; and differs for; each equipment type. In the following sections, each part is individually discussed, except that since vacuum pumps are considered principally as compressors, no special basic calculation method for this type is presented here and methods presented in IPS-E-PR-750, "Process Design of Compressors", shall be used for this purpose.

Typical P&I diagrams for vacuum pump and ejector vacuum systems are shown in Appendix B.

## 6.1 Common Basic Calculation

The following procedure should be followed for calculating the suction parameters required to fix a vacuum system and to design the equipment basically.

    **a)** Determine vacuum required at the critical process point in the system.

    **b)** Calculate pressure drop from this point to the process location of the suction flange of the first stage vacuum equipment.

**c)** At the vacuum device suction condition determine:

      **I)** Kilogram per hour of condensable vapor.

      **II)** Kilogram per hour of non-condensable gases which are:

            - dissolved
            - injected or carried in the process
            - formed by reaction
            - air leakage

## 6.1.1 Suction pressure

The suction pressure of a vacuum device is expressed in absolute units. If it is given as millimeters of vacuum it must be converted to absolute units by using the local or reference barometer.

In actual operation suction pressure follows the ejector capacity curve, varying with the non-condensable and vapor load to the unit.

## 6.1.2 Discharge pressure

As indicated, performance of a vacuum unit is a function of backpressure. In order to insure proper performance, the atmospheric discharge units shall be designed for a back pressure of 6 kPa (ga.) unless otherwise specified. The pressure drop through any discharge piping and aftercooler must be taken into consideration. Discharge piping should not have pockets for condensation.

## 6.1.3 Capacity of the unit

The capacity of a vacuum unit is expressed as kilograms per hour total of non-condensable plus condensables to the inlet flange of the unit. For multistage ejector units, the total capacity must be separated into kilograms per hour of condensables and noncondensables. The final stages are only required to handle the non condensable portion of the load plus the saturation moisture leaving the intercondensers.

An example of actual capacity calculation for process vapor plus noncondensables can be found in Appendix A.

### 6.1.3.1 Air leakage

Few vacuum systems are completely airtight, although some may have extremely low leakage rates. Considering the air and noncondensables:

**(kg/h air + non-condensables)= air-inleakage + process released air + process released non-condensables**

The amount of air leakage shall be calculated from the formula:

$$L = 1.58 \times 10^{-3} \frac{V(P_2 - P_1)}{t} \qquad \text{Eq. 1}$$

**where**:

$\dfrac{P_2 - P_1}{t}$    is the rate of drop of pressure in kPa in the vessel.

See Fig. 4, recommended by "Heat Exchange Institute (HEI)",which has been used conventionally for estimation of air leakage.

### 6.1.3.2  Dissolved gases released from water

When vacuum units pull non-condensables and other vapors from a direct contact condenser (barometric, low level jet, deaerator) there is also a release of dissolved gases, usually air, from water. This air must be added to the other known load of the unit. Fig. 5 presents the data of the "Heat Exchange Institute" for the amount of air that can be expected to be released when cooling water is sprayed or otherwise injected into open type barometric or similar equipment.
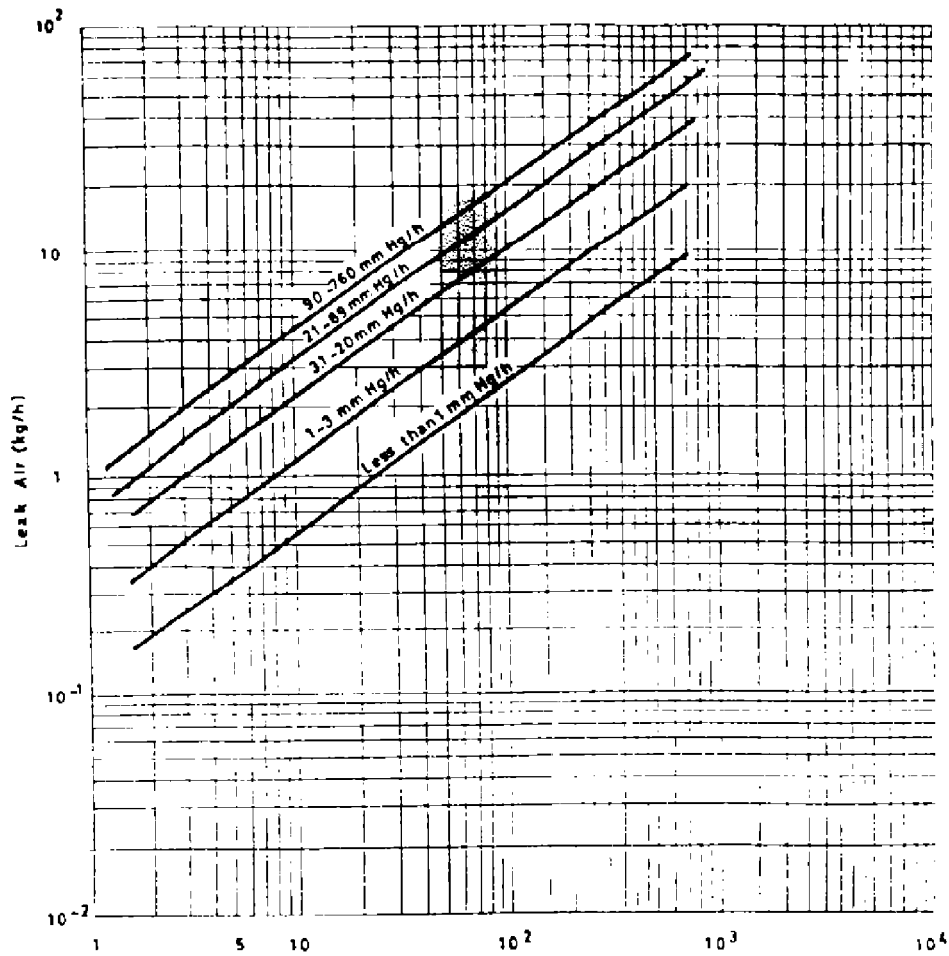


**SYSTEM VOLUMES (m³)**
**AIR LEAKAGE VALUES**
**Fig. 4**
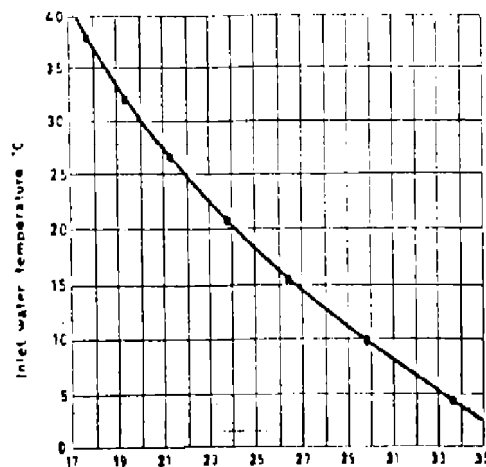
**AIR RELEASED FROM WATER kg air /1000 m³/h WATER**
**DISSOLVED AIR RELEASED FROM WATER ON DIRECT CONTACT IN VACUUM SYSTEMS**
**Fig. 5**

### 6.1.4 Utility requirements

Although utility consumption is usually determined by vendors, as a rough estimation, methods presented in 6.2.2.3 (for ejectors) and Appendix C, (for vacuum pumps) can be used.

## 6.2 Ejectors

### 6.2.1 General

### 6.2.1.1 Ejector parts, nomenclature

With the view of stablishing standard terminology, the four sketches in Fig. 6 are shown of basic steam jet ejector stage assembly. It should be noted, however, that these sketches are merely illustrative for the purpose of indicating names of parts. (see 2., HEI).
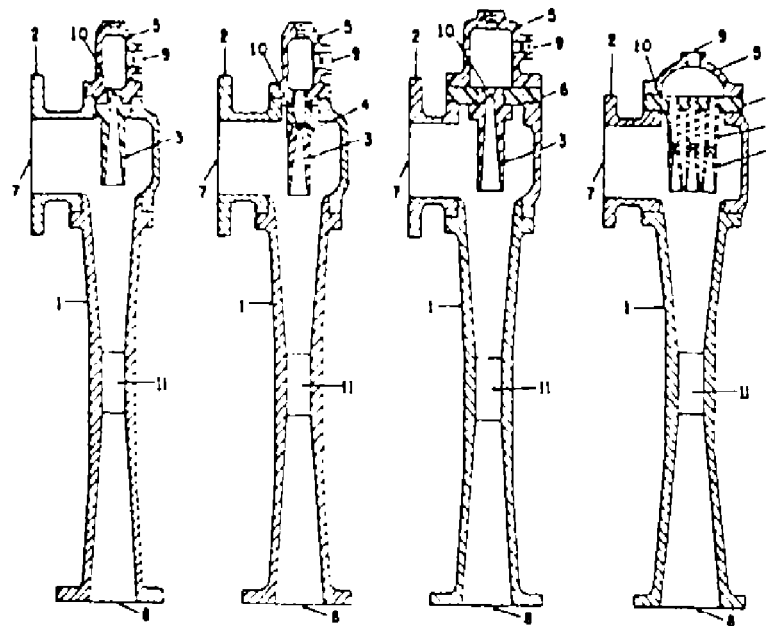
**TYPICAL STEAM JET EJECTOR STAGE ASSEMBLIES**
**Fig. 6**

| | |
|---|---|
| 1. Diffuser | 7. Suction |
| 2. Suction Chamber | 8. Discharge |
| 3. Steam Nozzle | 9. Steam Inlet |
| 4. Nozzle Extensions (if used) | 10. Nozzle Throat |
| 5. Steam Chest | 11. Diffuser Throat |
| 6. Nozzle Plate (if used) | |

### 6.2.1.2  Definition of terms

Definition of terms used in this part of the Standard are given in the following paragraphs (see 2.1, Ludwig and HEI).

#### a)  Absolute Pressure

Is the pressure measured from absolute zero; i.e., from an absolute vacuum.

#### b)  Static Pressure

Is the pressure measured in the gas in such manner that no effect on the measurement is produced by the velocity.

#### c)  Suction Pressure

Is the absolute static pressure prevailing at the suction of the ejector expressed in millimeters or micrometers (microns) of mercury.

**d) Discharge Pressure**

Is the absolute static pressure prevailing at the discharge of the ejector expressed in millimeters of mercury.

**e) Breaking Pressure**

Is that pressure of either the motive steam or the discharge, which causes the ejector to become unstable.

**f) Recovery Pressure (Pick up Pressure)**

Is that pressure of either the motive steam or the discharge, at which the ejector recovers to a condition of stable operation.

**g) Absolute Temperature**

Is the temperature above absolute zero. It is shown by the symbol (T) and Expressed in degrees kelvin (K), which is equal to degrees Celsius (°C) plus 273.15.

**h) Suction Temperature**

Is the temperature of the gas at the suction of the ejector.

**i) Stable Operation**

Is the operation of the ejector without violent fluctuation of the suction pressure.

**j) Capacity**

Is the mass rate of flow of the gas to be handled by the ejector. Capacity is shown by the symbol (W) and the unit is kilograms per hour (kg/h).

**k) Dry Air**

Atmospheric air at normal room temperature is considered dry air. The very small mass of water in it is considered insignificant and is ignored. For example, the mass of water vapor in atmospheric air at 50 percent relative humidity and 27°C is less than 0.011 kg per kg of air.

**l) Equivalent Air**

Is a calculated mass rate of air that is equivalent to the mass rate of gas handled by the ejector at the suction conditions. The unit is kilograms per hour.

**m) Equivalent Steam**

Is a calculated mass rate of steam that is equivalent to the mass rate of gas handled by the ejector at the suction conditions. The unit is kilograms per hour.

**n) Molecular Mass**

Is the sum of the atomic masses of all the atoms in a molecule.

### o) Mol

Mol is a mass numerically equal to the molecular mass.

### p) Mol Fraction

Mol fraction of a component in a homogeneous mixture is defined as the number of mols of that component divided by the sum of the number of mols of all components.

### q) Total Steam Consumption

Is the total mass rate of flow passing through nozzles of all ejector stages at specified conditions of steam pressure and temperature. The unit is kilograms per hour.

### r) Total Water Consumption

Is the total rate of flow passing through the ejector condensers at specified inlet temperature. The unit is cubic meters per hour ($m^3$/h).

### s) Critical Flow

Is the flow through a nozzle when the downstream absolute pressure is below critical pressure, i.e., the downstream absolute pressure must be less than 50 percent of the upstream absolute pressure.

### t) Subcritical Flow

Is the flow through a nozzle when the downstream absolute pressure is above critical pressure, i.e., there is a relatively low pressure drop across the nozzle.

### u) Temperature Entrainment Ratio

Is the ratio of the mass of air or steam at 21°C temperature to the mass of air or steam at a higher temperature that would be handled by the same ejector operating under the exact same conditions.

### v) Molecular Mass Entrainment Ratio

Is the ratio of the mass of gas handled to the mass of air which would be handled by the same ejector under the exact same conditions.

## 6.2.1.3 Operating Principles

Operating principles of a steam jet ejector and capabilities and limitations of ejector systems may be found in different textbooks and standards. HEI standard (see 2.) is recommended for such purpose.

## 6.2.1.4 Ejector unit types

Some of the various types of ejector units commonly used are illustrated in Fig 7(a) to (h). This figure is taken from HEI standard.

For detail explanation of each unit type, reference is made to Fig. 9 and paragraph E5 to E13 of this standard (see 2.1).
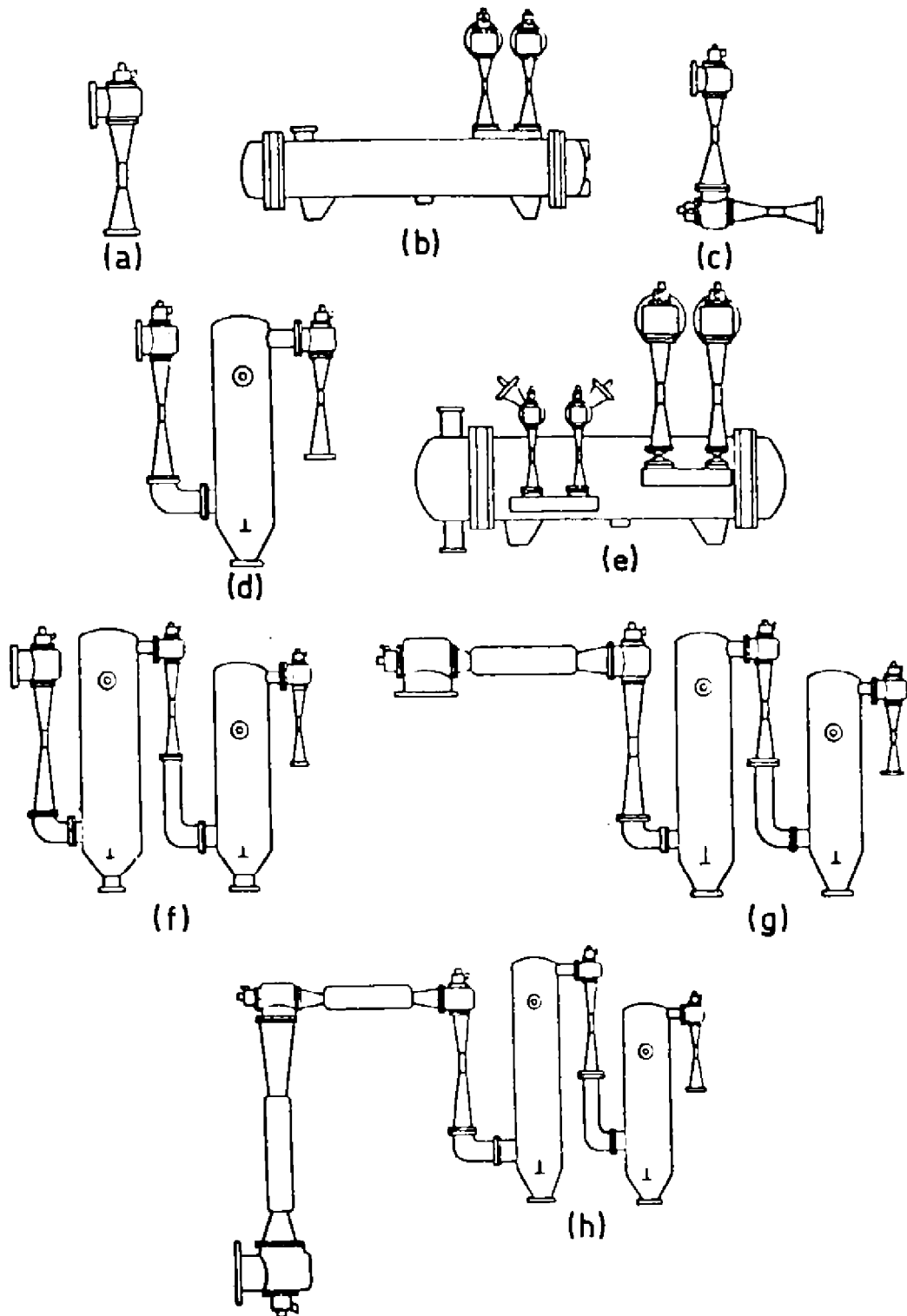
**COMMON TYPE OF EJECTOR UNITS**
**Fig. 7**

### 6.2.2 Design considerations for ejectors

#### 6.2.2.1 General

**6.2.2.1.1** For construction design considerations and factors such as design pressure, etc., refer to "HEI, General Construction Standards for Ejector Components other than Ejector Condensers", (see. 2.) and IPS-M-ME-256 (see 2.).

**6.2.2.1.2** The design and construction shall be proven in practice, robust and reliable. Unless otherwise specified, the ejectors shall be designed in accordance with IPS-M-ME-256, "Ejectors".

**6.2.2.1.3** Safety, ease of operation, inspection, maintenance, repair and cleaning are of major concern. Nozzles, nozzle inspection ports and pressure taps shall be readily accessible.

**6.2.2.1.4** Where there is danger from freezing during operation affecting parts that can not be drained, protection against such freezing shall be provided.

**6.2.2.1.5** Provisions shall be made for cases where there is danger of plugging due to the carry over of high viscosity or high melting point liquids.

**6.2.2.1.6** Adequate personnel protection or insulation shall be provided for all surfaces hotter than 60°C.

**6.2.2.1.7** Performance of the ejector shall be guaranteed by the contractor in accordance with IPS-E-PR-245 "Performance Guarantee" (see 2.).

#### 6.2.2.1.8 Economic criterion

Steam jet vacuum ejectors shall be designed or selected such that an optimum is obtained between capital and operating costs.

For the purpose of the calculation it is, however, sufficient to apply the criterion that:

$$\textbf{F.A + (B.Gs+C.Gw)} \text{ is a minimum.} \qquad \text{(Eq. 2)}$$

(For definition of symbols see section 3).

where the range of size of ejector options is such that changes may be required in the supporting structure, the appropriate differential capital costs should be taken up in the calculation.

#### 6.2.2.2 Design factors and parameters

The following factors should be carefully specified for process design (rating) and selecting an ejector system for vacuum operation.

#### 6.2.2.2.1 Capacity

The following capacity requirements shall be specified:

**a)** The absolute pressure to be maintained.
**b)** The total mass in kilograms per hour of the gas to be entrained.
**c)** The temperature of the gas to be entrained.
**d)** Composition of the gas to be entrained. The mass of each constituent shall be specified in kilograms per hour.
**e)** If the gas is other than air or water vapor, its physical and chemical properties shall be fully specified.

**Note:**

**When actual performance curves for the temperature and vapor mixture in question is not available, the capacity should be evaluated on an equivalent air basis, using HEI method (see 2.), an example of such evaluation is presented in Appendix A.**

### 6.2.2.2.2 Steam conditions

The following characteristics of the operating steam shall be specified:

**a)** Maximum steam line pressure and temperature.
**b)** Maximum steam pressure and temperature at the ejector steam inlet.
**c)** Minimum steam pressure at the ejector steam inlet.
**d)** Design steam pressure and temperature.
**e)** Quality of the steam, if it is not superheated, at the ejector steam inlet.

To prevent the nozzle throat of the ejector from becoming too small to be practical and to ensure of having stable operation of the unit, the manufacturer may elect to use design steam pressure lower than the available steam pressure at the ejector steam inlet.

It is recommended that the design steam pressure never be higher than 90 percent of the minimum steam pressure at the ejector steam inlet.

This design basis allows for stable operation under minor pressure fluctuations.

The higher the actual motive steam design pressure of an ejector the lower the steam consumption. When this pressure is above 2500 kPa (ga.), the decrease in steam requirements will be negligible.

For ejector discharging to the atmosphere, steam pressures below 415 kPa (ga.) at the ejector are generally uneconomical.

To ensure stable operations the steam pressure must be above a minimum value. This minimum is called the "Motive Steam Pickup Pressure", and is stated by the manufacturer.

Effect of steam pressures on ejector capacity is shown in Fig. 8.
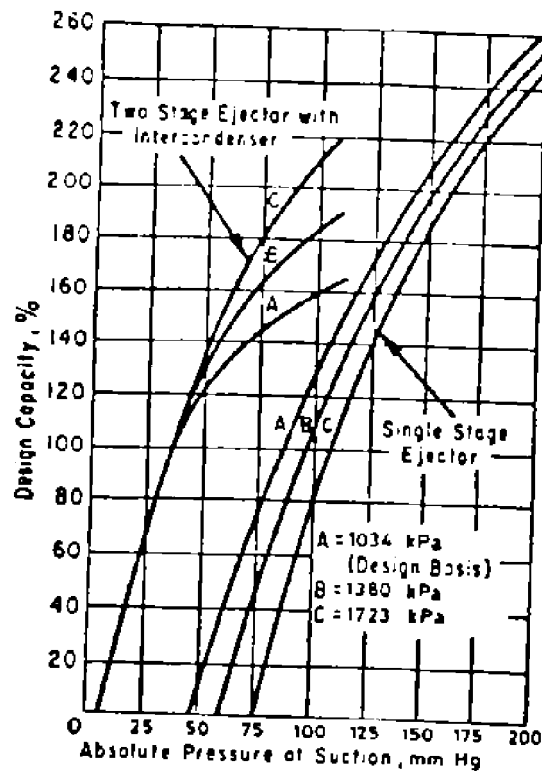


**EFFECTS OF EXCESS STEAM PRESSURE ON EJECTOR CAPACITY**
**Fig. 8**

### 6.2.2.2.3  Discharge pressure

The pressure against which a single stage or the last stage of a multistage ejector must discharge shall be specified in kilopascals absolute or millimeters of mercury absolute pressure. The normal barometric pressure in millimeters of mercury shall be specified.

### 6.2.2.2.4  Division of load over two parallel elements

When any stage of an ejector line-up consists of two parallel elements (ejectors) the following shall apply:

**a)**  The two elements of the stage shall be designed to handle 1/3rd and 2/3rd respectively of the total design load of that stage. This will give better matching of ejector capacity to load, resulting in energy savings.

**b)**  Provision shall be made to individually isolate each ejector on the vapor side in order to prevent recycling of gas through an idle parallel set. Proper arrangements for safety valve or suitable design pressure should be considered.

### 6.2.2.2.5  Barometric legs

Barometric legs of sufficient height shall be installed to safeguard against air ingress and to prevent flooding of the condensers during normal operation. It shall also be ensured that the liquid content of the accumulator vessel is sufficient to fill up the barometric legs.

Barometric legs shall be run separately into a vertical header connected to the condensers vessel, see Appendix B. This separation shall be maintained in order to prevent interference with the respective flows, caused by the difference in condensate rundown temperatures. Except when necessary for personnel protection purposes, thermal insulation or steam tracing should not be applied, unless the liquid hydrocarbons have a waxy nature.

### 6.2.2.2.6  Condensate outlet temperature

The system shall be so designed that the condensate temperature at each condenser outlet shall not exceed the cooling water inlet temperature by a margin greater than 25°C.

### 6.2.2.3  Estimation of utility requirements

Utility consumption is mainly determined by the vendors. However, steam consumption may be roughly estimated as follows:

**6.2.2.3.1**  Where the suction gas is rich in non-condensable gases, the steam consumption may be estimated from Fig. 9 by converting the suction gas volume to its equivalent air volume.

**6.2.2.3.2**  where a large quantity of condensed vapor is present in the suction gas, steam consumption may be estimated by estimating the pressure and the suction gas volume at the individual stages of an ejector.

### 6.2.2.4  Ejector selection procedure

The following is a suggested procedure for rating and selecting an ejector system for vacuum operation:

**1)**  Follow the steps mentioned in 6.1.
**2)**  Select the number of stages from Fig. 3.
**3)**  Estimate the steam consumption (see 6.2.2.3).
**4)**  Prepare "Process Specification Sheet", to be forwarded to manufacturers.
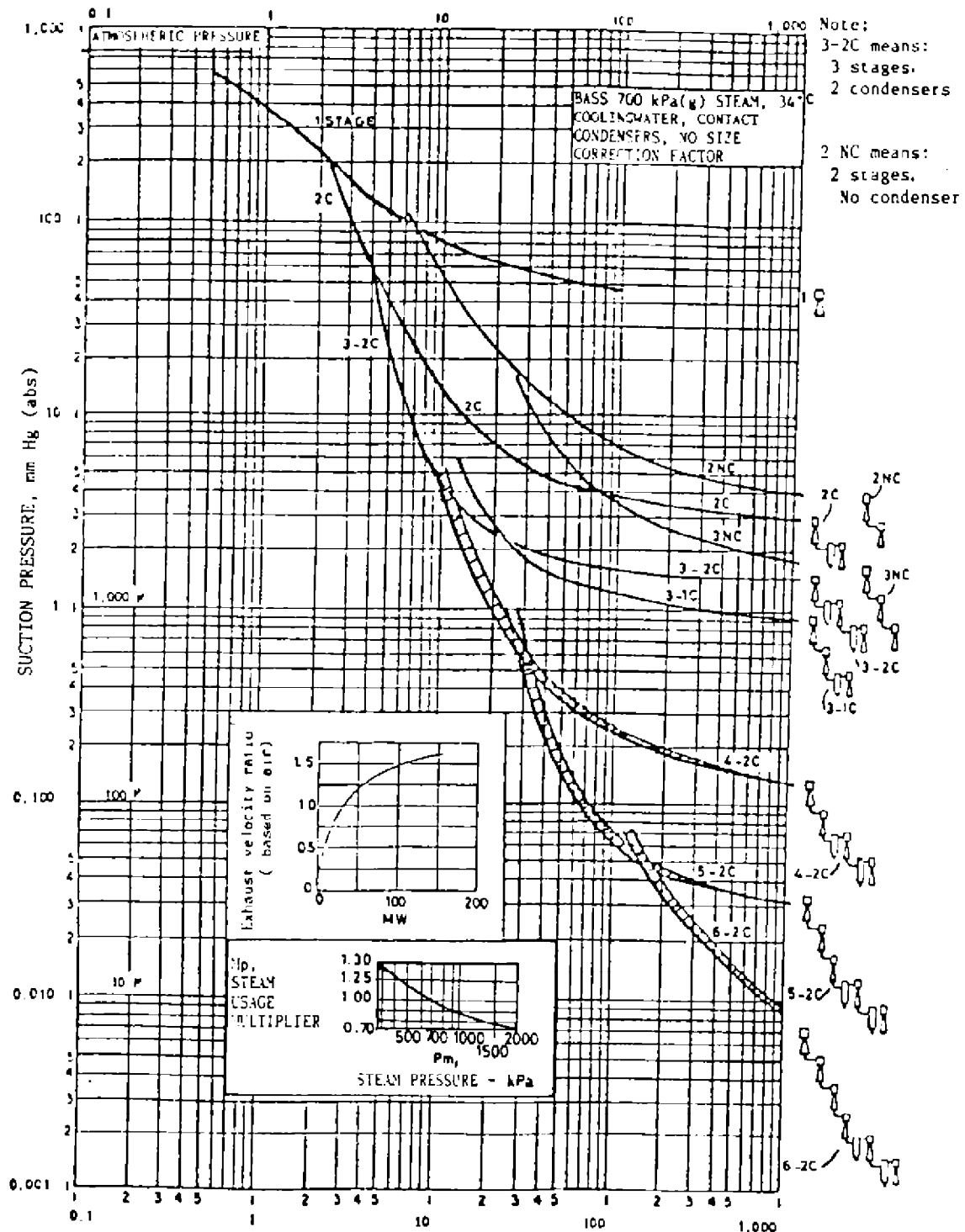
Ra, Kg MOTIVE STEAM PER Kg AIR LOAD
(ADD 20 PERCENT FOR TYPICAL SIZE CORRECTION FACTOR)

**ESTIMATION CHART FOR STEAM EJECTOR**
**Fig. 9**

### 6.2.2.5  Process specification sheet

Various forms of process specification (or data) sheets can be arranged for ordering ejectors or ejector vacuum systems.

Regardless of the form of such sheets, the following data should be brought in the process specification or data sheet, for the vendor (or vendors), to be able to design the required system:

**1-** Service.
**2-** Preferred Condenser Type.
**3-** Suction Pressure, mm Hg (abs.).
**4-** Suction Temperature, °C.
**5-** Maximum Discharge Pressure, mm Hg (abs.).
**6-** Steam:  Min. Pressure, kPa(abs.).
Temperature, °C.
Quality, %.
**7-** Water:  Source.
Max. Inlet pressure, kPa.
Max. Inlet Temperature, °C.
Max. Outlet Temperature, °C.
**8-** Volume of Evacuated System, m$^3$.
**9-** Expected Air Leakage, kg/h.
**10-** Max. Evacuating Time, min.
**11-** Ejector Load:

**a)** Condensables:

- Rate, kg/h.
- Molecular Mass.
- Cp, kJ/(kg.K).
- Latent Heat, kJ/kg.

**b)** Non-Condensables:

- Rate, kg/h.
- Molecular Mass.
- Cp. kJ/(kg.K).

**12-** Corrosive Substance (if any), mol% .

**APPENDICES**

**APPENDIX A**

**Example: Actual capacity for process vapor plus non-condensable**

A distillation column is to operate with a horizontal overhead condenser, Fig. A.1, pressures are as marked. The estimated air leakage into the system is 4 kg/h. The molecular mass of the product vapor going out the condenser into the ejector (at 27°C) is 53. The vapor pressure of the condensing vapor is 3 mm Hg abs. at 27°C.
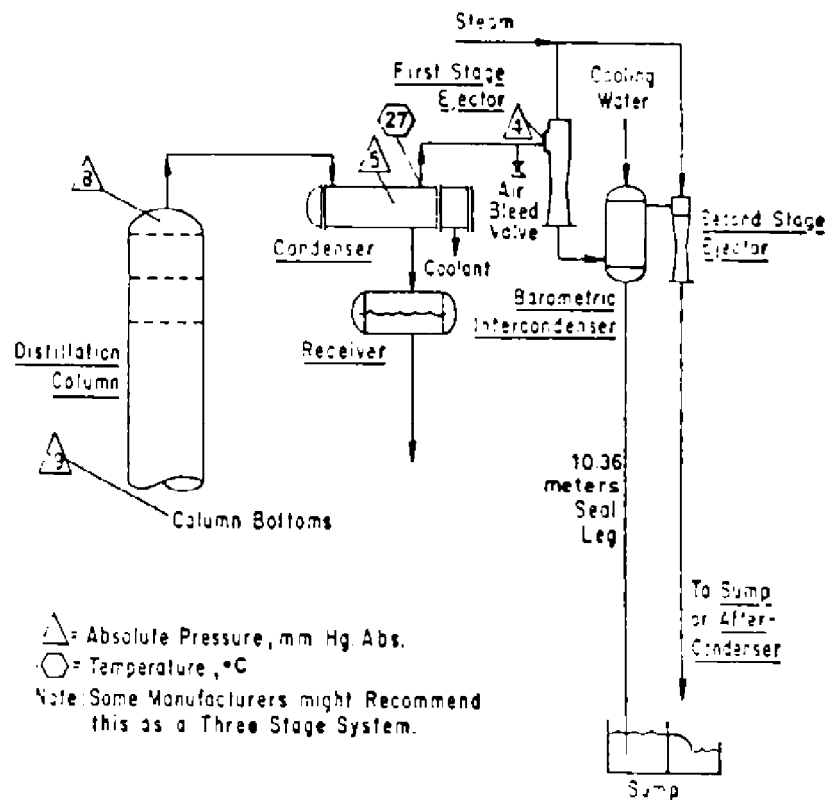


**VACUUM SYSTEM FOR DISTILLATION**
**Fig. A.1**

Partial pressure air = 5-3=2 mm. Hg

Vapor required to saturate at 27°C and 5 mm abs. total pressure:

$$W_V = \frac{W_n.M_v.P_n}{M_n.P_n} = \frac{4 \cdot 53 \cdot 3}{29 \cdot 2} = 10.965 \qquad \text{Kg/h}$$

Molar rate of air = 4/29 = 0.13793 kmol./h

Molar rate of vapors = 10.965/53 = 0.20688 kmol/h

25

Total molar rate = 0.13793 + 0.20688 = 0.3448 " "

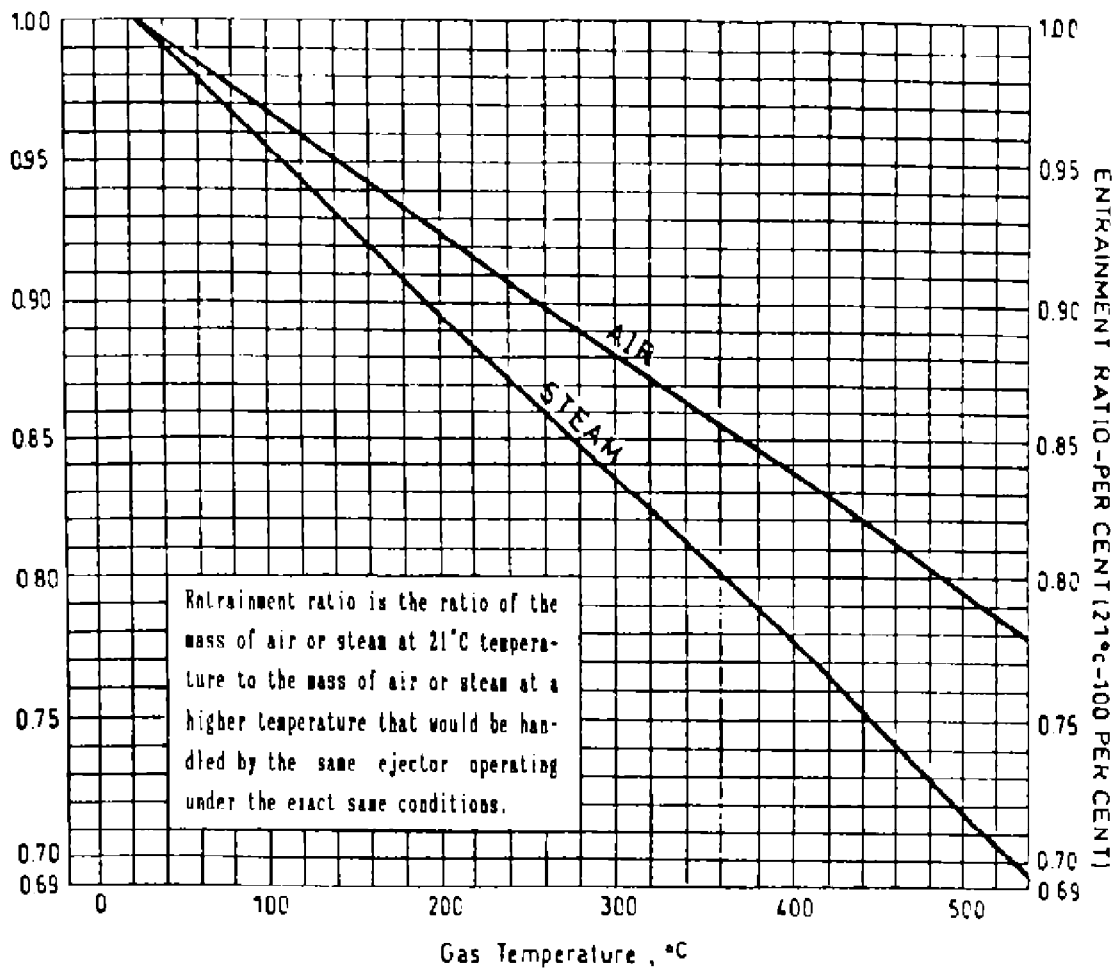Average molecular mass $= \dfrac{(4+10.965)}{0.3448} = 43.4$

Molecular correction (from Fig. A.3) = 1.18
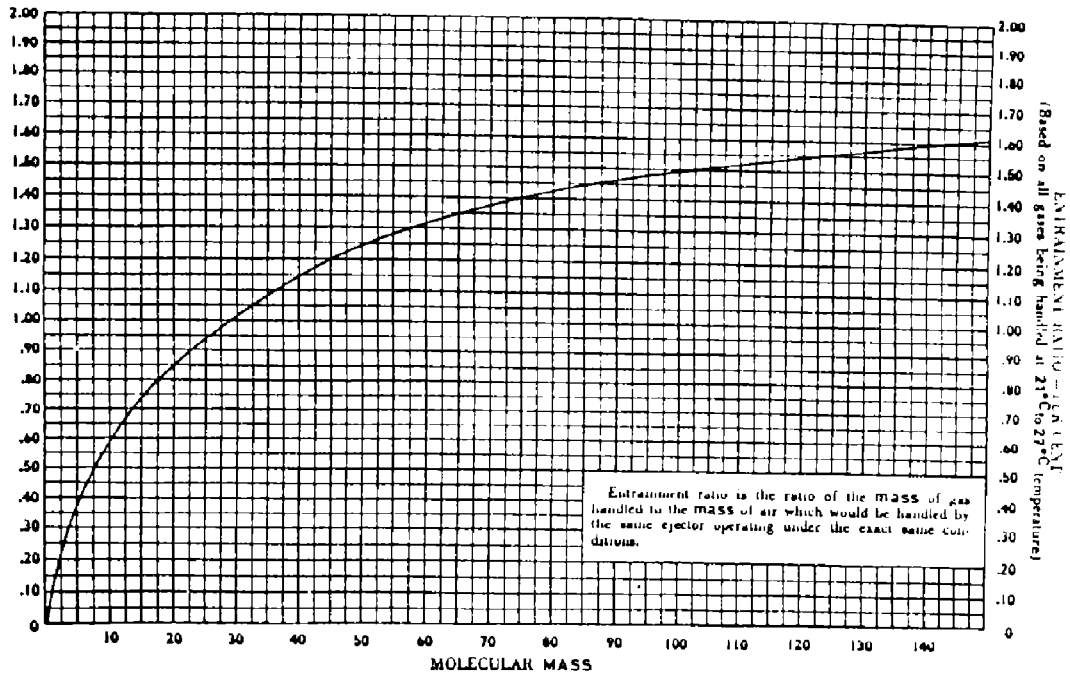
Air equivalent (at 27°C) = 14.965/1.18 = 12.68 kg/h

Temperature correction (Fig A.2, using air curve) = 0.999

21°C (70°F) air equivalent for mixture = 12.68/0.999 = 12.695 kg/h

This is the value to be compared with a standard manufacturer's test or performance curve at 21°C.



**TEMPERATURE ENTRAINMENT RATIO CURVE**
**Fig. A.2**

**MOLECULAR MASS ENTRAINMENT RATIO CURVE**
**Fig. A.3**

## APPENDIX B
## TYPICAL PIPING AND INSTRUMENT DIAGRAMS (P & IDS) AROUND VACUUM SYSTEMS

### B.1 Steam Ejector Vacuum System

A Typical P & ID showing a vacuum system using steam ejector is shown in Fig. B.1.

**Note that:**

**1** How the height of the condenser drain (seal) is specified. This height, in most cases is conventionally limited to be 15 m (min.).This is better shown in Fig. B.3.

**2** Pressure in a vacuum system using steam ejectors can be controlled:

    **a)** By introducing air or inert gas from outside,
    **b)** By spilling back the motive steam, or,
    **c)** By recycling the non-condensable gases in the system.

Methods (b) and (c) should be employed in such cases where noncondensable gases are definitely present in the system and the introduction of air into the system is not desirable or where the quantity of off-gas must not be increased.

In the case of Method (b), if non-condensable gases are not present in the system, the flow of the steam spilled back may be reversed to the equipment.
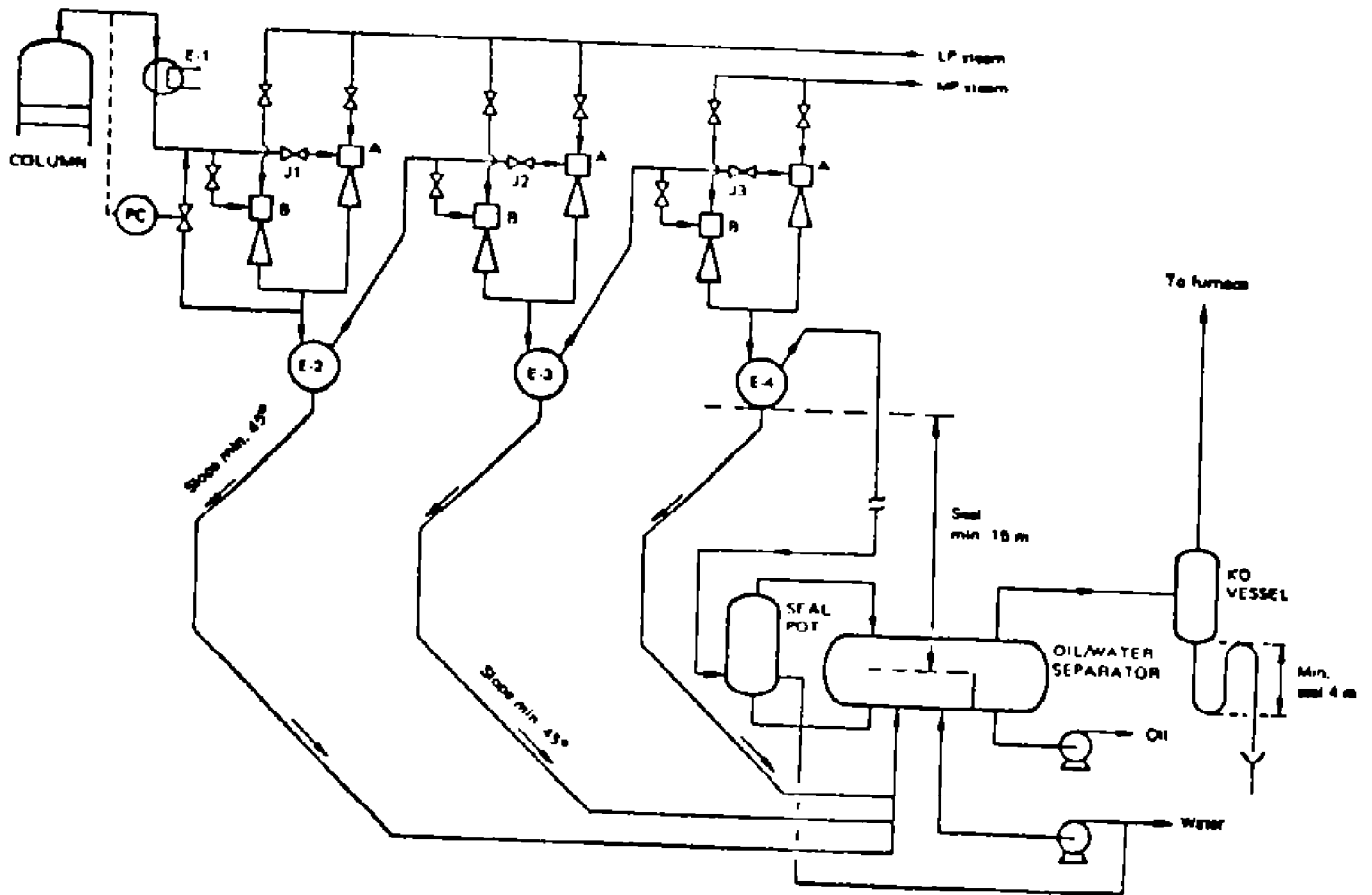
### B.2 Vacuum Pump System

Fig. B.2 is a P & ID showing vacuum system using a liquid ring sealed vacuum pump. Method (a) in the figure is possible only in cases where non-condensable gases are present in the system.

$$H = \frac{(P_0 - P_C) + \Delta P}{P_L \times g} \qquad (Eq. B.1)$$
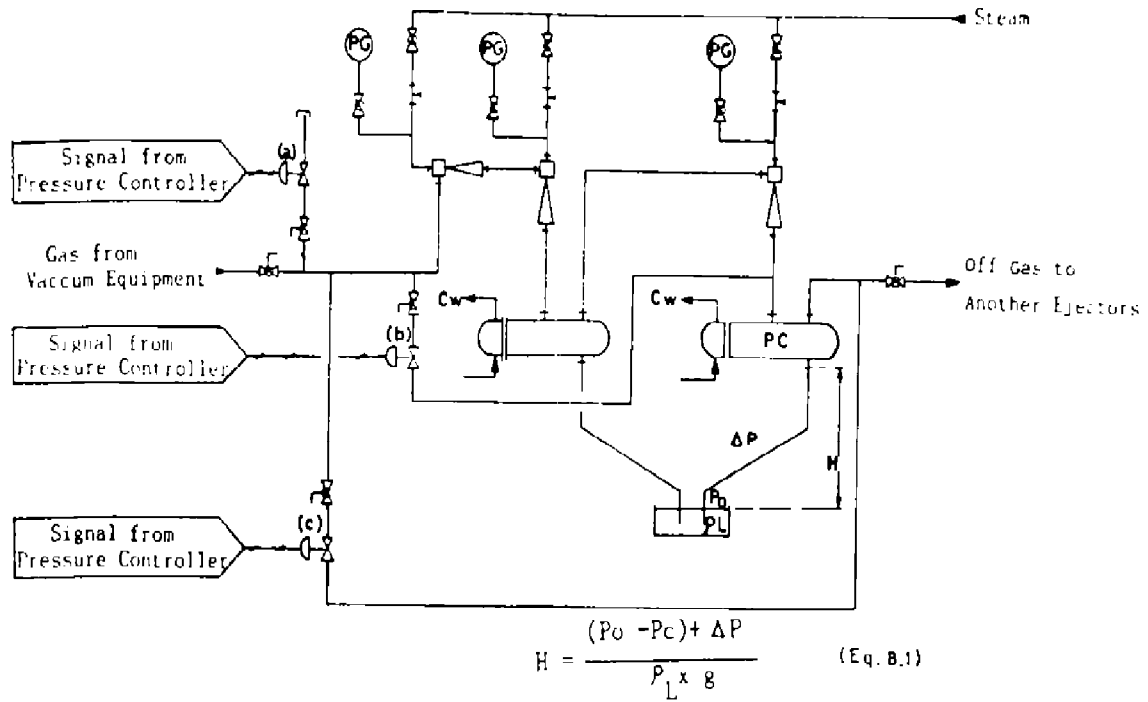
**TYPICAL P & I DIAGRAM FOR STEAM EJECTORS VACUUM SYSTEM**
**Fig. B.1**
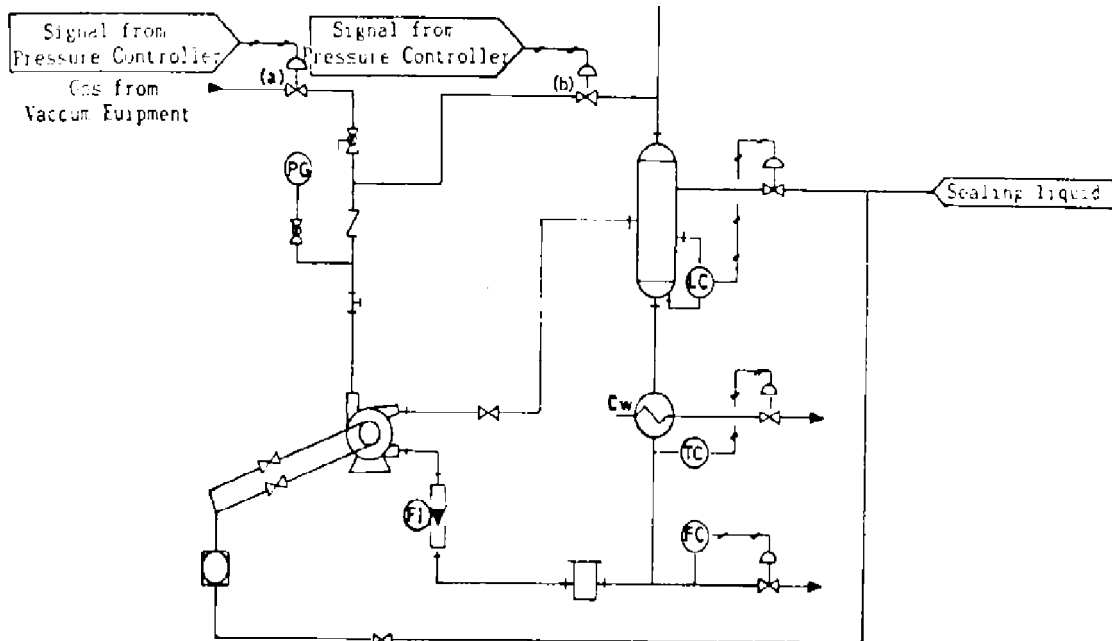


**TYPICAL P & I DIAGRAM FOR VACUUM PUMP SYSTEM**
**Fig. B.2**

**TYPICAL EJECTOR LAYOUT**
**Fig. B.3**

**APPENDIX C**

**Estimation of Power Consumption for Vacuum Pumps**

The kilowatts of all types of vacuum pumps may be estimated as follows:

**1** Liquid ring Sealed Pumps:

$BkW = 7.680 \times (S.F.)^{0.924}$,       S.F.= 0.05 - 35

**2** Reciprocating Vacuum Pumps:

$BkW = 3.974 \times (S.F.)^{0.963}$,       S.F.= 1.0 - 25

**3** Rotary Piston Vacuum Pumps:

$BkW = 4.242 \times (S.F.)^{1.088}$,       S.F.= 0.03 - 8

**Where**:

$$S.F.(\text{Size Factors}) = \frac{2.2 \times Air\,Volume\,(Kg/h)}{Operating\,Pressure\,(m\,Hg)} \qquad (\text{Eq. C.1})$$

BkW = Breake Power in Kilowatts

**Notes:**

**1) Where evacuating time become a bottle-neck in designing, the evacuating time may be made longer or start-up equipment may be separately installed to reduce utility consumption.**

**2) Where reduced operation is conceivable in systems where a large quantity of non-condensable gases is produced, parallel installation of vacuum devices should also be considered.**