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British Occupational Hygiene Society
Technical Guide No. 3

Fugitive Emissions of Vapours from Process Equipment

by

The B.O.H.S. Technology Committee

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Fugitive Emissions of Vapours from Process Equipment

by
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Editors' Note: This Technical Guide is a summary of the state-of-the-art concerning vapour emissions from fugitive sources such as pumps, valves and flanges. Measurement and control techniques are given together with statements on the problems of data analysis. The views expressed in this Monograph are those of the Authors and not necessarily of the society.

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1 INTRODUCTION

This Technical Guide provides information on 'fugitive' sources of gas and vapour emissions from process equipment. These are unplanned, continuous escapes of process material and are now recognized in the chemical and petroleum refining industries as being potential sources of exposure for operators working in such plants. This Guide is therefore primarily directed towards Occupational Hygiene although several aspects will also be applicable to the environmental field.

Escapes from process equipment that occur as a result of worker intervention (e.g. sampling, cleaning, batch additions, etc.) tend to be large, but infrequent, well recognized and readily controlled by standard practices. Fugitive emissions however are the numerous and sometimes continuous escapes from openings in the system required by process need. These are more insidious being usually less significant on an individual basis but in combination representing a possibly serious emission problem. Fugitive emissions occur from dynamic seals (e.g. on valve stems, pump shafts, agitator shafts) or from static seals such as flange gaskets.

Table 1[1,2] shows that 15-20% of total volatile organic chemical emissions are from fugitive sources. Using a 'standard' hypothetical refinery, defined by the Environmental Protection Agency (EPA)[3] as 330,000 barrels per day, an estimate of the volatile hydrocarbon escape is 6.7 tons per day (Table 2) with valves providing nearly 50% of the total. Note that this is an EPA estimate rather than an industry estimate at this time.

TABLE 1[1,2]

Sources ofvolatile org. chemical emissions from chem. process plants

Source	% of total emission
Process vents, stacks	65 - 70
Fugitive	15 - 20
Waste disposal	2 - 5
Storage tanks/transport vents	8 - 10

TABLE 2

Estimated fugitive hydrocarbon emissions from sources in process units of a hypothetical 330,000 bpd refinery*

Source	Emission rate lb/hour	Emission rate tons**/year
Valves	305	1,270
Flanges	25	104
Pump seals	60	250
Compressor seals	29	121
Drains	48	200
Relief valves	21	87
API separators	138	574
	626	2,606

Total hydrocarbon escape is therefore at the rate of 6.7 tons/day.

*EPA New Source Regulations[3]

**Short tons

There are, of course, many ways of controlling fugitive emissions and indeed in most instances the emission can be reduced to effectively zero, but only at a price.

To have a knowledge of the cost:effectiveness of control measures requires information not only of leak-rates from process equipment in general, but also of the separate types of leak control mechanisms. With this information it may be possible to estimate the probability of worst case contaminant levels in the workplace from dispersion equations.[4]

Fugitive emissions are not constant. Figure 1 shows a typical change in the leak rate during the lifetime of a valve packing. Many variables exist but possibly the predominant ones are:

(a) Packing (seal) type.
(b) Maintenance regime.
(c) Valve pressure/temperature <u>rating</u>.
(d) Operating cycle.

The nett result, however, is that the description of a statistical sample of a valve population by single spot readings will produce a very broad and apparently confused distribution. Figure 2 shows a sample of the data collected for the EPA on valves in hydrogen service.

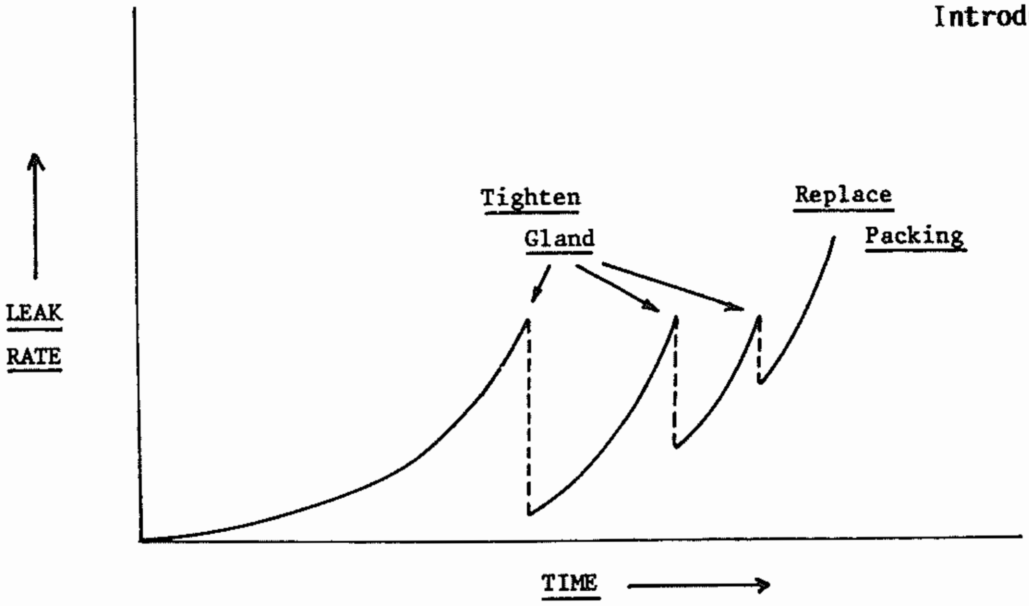


Fig.1. Typical valve leakage patterns with time/maintenance.

The definition of the correct population distribution is obviously necessary in any predictive use of data. With a sample such as this, however, it proves impossible to define a distribution that fits exactly and various types have been tried. Each assumption involves error which in turn will need quantifying. Future work would therefore benefit significantly by eliminating some of the variables.

Interest from the Environmental Protection Agency has resulted in much of the investigative work in this area being performed in the United States of America. However, European plants should not accept U.S. data without question. Different equipment suppliers, workforce, etc. may create a different data base. One of the key U.S. lessons, however, is that the work to produce a data base is best carried out on a co-ordinated, industry-wide basis rather than by individual companies. In order to achieve this the BOHS Technology Committee set up a Working Party in 1983 to provide documentation for the education of workers in the hygiene field in Europe which would allow the development of a test protocol to satisfy the data base requirements.

This Guide therefore provides information on:

(a) Legislation.
(b) Measurement techniques.
(c) Sampling strategy and data analysis.
(d) Control techniques.

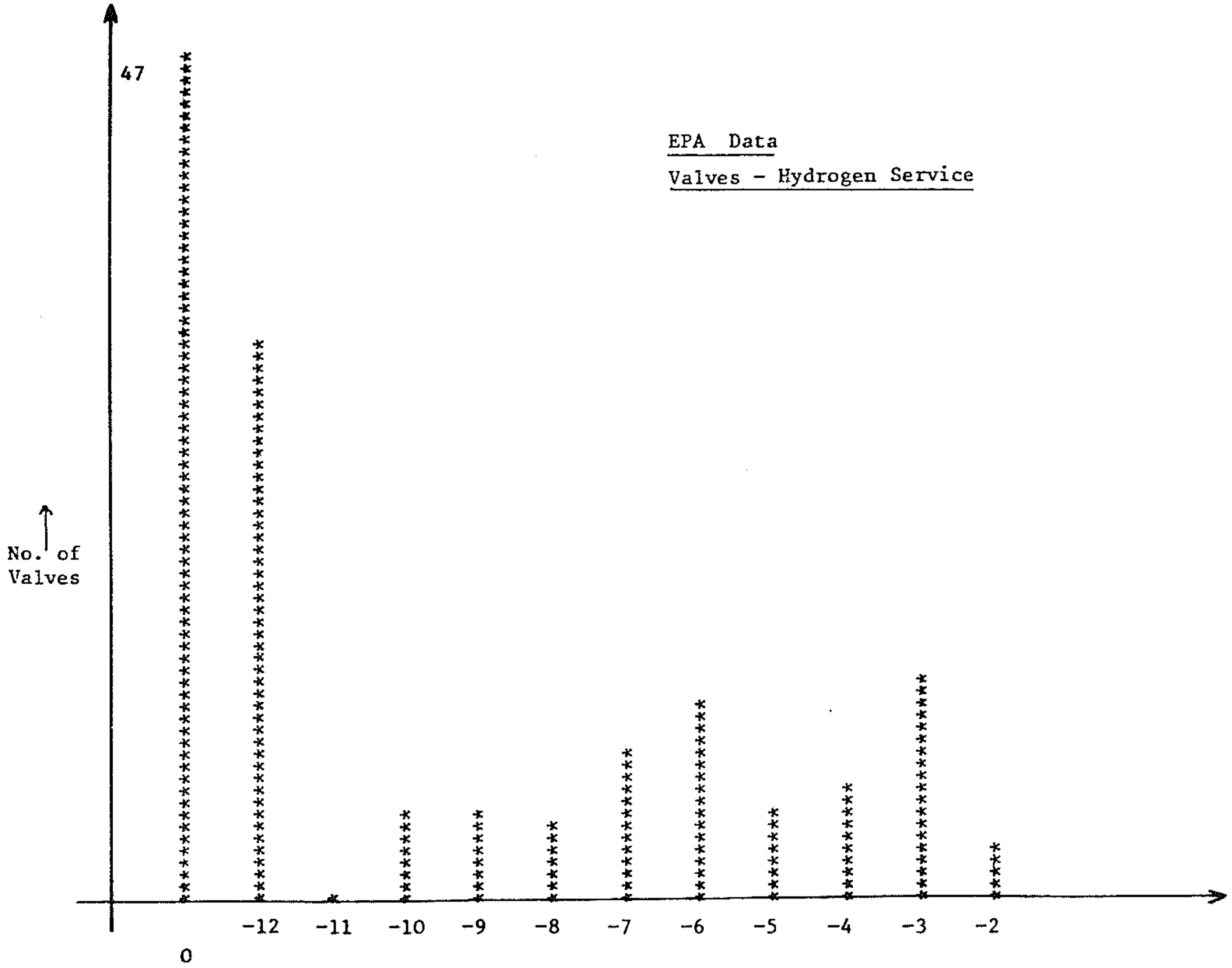


Fig.2. Leak rate (lb per hour converted to natural logarithms).

Of primary importance is Chapter 5, Control Techniques, and the references cited should be consulted to gain full benefit.

The chapters on Legislation, Measurement Techniques, and Sampling Strategy and Data Analysis provide the forum for debate in this field and therefore they are not intended to be comprehensive but form the basis of discussion for the second objective.

2 LEGISLATION

Fugitive emissions are not covered specifically in any current legislation in Great Britain.

In Great Britain the Health and Safety at Work etc. Act 1974 (HSW Act) is the principal piece of legislation in the field of occupational health and safety. It is directed towards securing the health, safety and welfare of people at work and to protecting persons other than those at work against risks to their health and safety arising out of work activities. The duties are expressed in general terms but are comprehensive and are designed to encourage employers amd employees to take a wide-ranging view of their roles and responsibilities. The duties are mostly qualified by the term 'so far as is reasonably practicable' and this concept applies to the costs and benefits of controlling fugitive emissions.

Certain specific duties are laid down in Regulations made under the HSW Act or in earlier statutes. For example, The Factories Act 1961 contains some specific requirements on the control of emissions of dust and fume in the factory premises. The Alkali etc. Works Regulation Act 1906 is directed towards controlling the emissions of 'noxious or offensive gases' from scheduled works by the application of 'best practicable means'. The forthcoming Control of Substances Hazardous to Health Regulations will outline basic principles of control in occupational hygiene and will clarify the status of occupational exposure limits.

In the U.S.A., specific regulations in relation to fugitive emissions from petroleum refining installations have already been implemented. In 1984 similar regulations will be implemented for 'volatile organic chemical' operations. These have been promulgated by the Environmental Protection Agency (EPA) through amendments to the 1970 Federal Clean Air Act. Further proposals have been made to regulate 'new sources' of fugitive emission. Emphasis has been placed on the control of environmental pollution rather than the limitation of occupational exposure to within occupational exposure limits (OEL) for toxic substances. The U.S. regulatory body for the workplace, i.e. OSHA, have claimed that the EPA regulations are superfluous since the OSHA workplace regulations already cover fugitive emissions.

As this document is concerned with the occupational environment in Great Britain, the main duties of related legislation are summarized in Appendix I. These are limited to Occupational Health as this is the area of prime interest.

3 MEASUREMENT TECHNIQUES

3.1 Introduction

The inherently diffuse nature of fugitive emissions militates against their direct quantification. A variety of techniques has been proposed but all involve assumptions or approximations, and it is necessary to consider the reason for investigating the emissions in order to select the most appropriate approach.

Interest in fugitive emissions may stem from several unrelated considerations:

(a) To investigate problems at a specific plant:

i. Employee exposure within the plant. If new toxicological information on a substance indicates that previously acceptable background concentrations may be of health significance, fugitive emissions will probably be one important source of exposure;
ii. Air pollution (where the plant as a whole is regarded as a single source);
iii. The quantification of product loss for economic reasons;
iv. Identification of leaks for the planning of routine maintenance. This need have no direct connexion with environmental issues and is essentially an extension of the visual inspections carried out by any maintenance department.

(b) To derive data on leak-rates of different pieces of equipment under simulated operating conditions so that the significance of the issues listed above may be <u>predicted</u> for new plants.

Where interest is confined to the effects of the emissions at some point remote from the point of release, well-established techniques such as personal monitoring of employees or boundary fence measurements may be used and the results compared with air quality criteria. However, should it become necessary to implement control measures or if air pollution criteria specify plant emissions on a mass basis, it will be necessary to quantify the emissions at source.

3.2 Available techniques

Leaks from plant equipment may consist of vapours or liquids. Where a liquid has an appreciable vapour pressure it may contribute to ambient atmospheric concentrations through subsequent partial evaporation. This complicates attempts to quantify gaseous emissions. The following discussion of measurement techniques is therefore restricted to the treatment of vapour leaks.

The ideal measurement technique would:

(a) be quick and simple to carry out so that a large sample of sources could be surveyed;
(b) provide quantitative data on mass emission rates;
(c) be reliable and reproducible.

Unfortunately none of the available techniques possess all of these desirable attributes so that, in practice, a degree of compromise is inevitable. Details of the known studies that have utilized these techniques can be found in Appendix II.

3.3 Soap Bubble Method

This traditional method of locating gaseous leaks, which consists of putting soap solution on the surface and observing the formation of bubbles, may be carried out quickly and cheaply but provides only a qualitative indication of leakages and is not applicable to hot or rotating surfaces (e.g. pump shafts). While useful as a maintenance tool, this method is of very little value in the investigation of environmental concerns.

3.4 Concentration at the point of leak

This is essentially a development of the bubble method. It relies on the use of a suitable direct-reading instrument to determine the concentration at the surface of the equipment, e.g. around the circumference of a flange. Various protocols have been used, e.g. Radian Corporation acting for the US EPA used the maximum value found around a fugitive emission source (termed the screening value), whereas elsewhere it has been proposed to use the mean value of four equidistant measurements around the circumference. The data obtained are highly dependent on the geometry of the plant equipment, the response time of the instrument, and the prevailing wind conditions as well as on the size of the leak. It cannot, therefore, be converted to a mass emission rate and its interpretation must remain empirical. An attempt by the US EPA to derive a correlation between screening values and mass emission rates for certain types of plant fittings showed very wide scatter in the results for individual sources.[5]

This technique is moderately manpower intensive with an individual measurement taking up to one minute. Personal access to the plant equipment is necessary and this poses a difficulty in the case of hot or inaccessible items.

3.5 Bagging

In order to obtain an accurate estimate of leakage on a mass basis it is necessary to contain the emission in a known flow of air and then to measure the resultant concentration. Such a system is shown schematically in Figure 3.

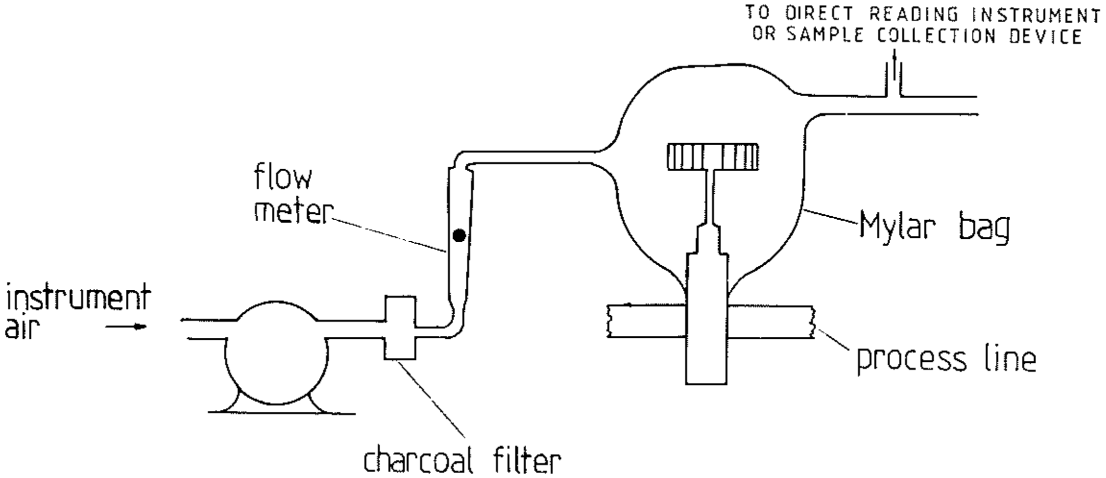


Fig.3. Schematic diagram of the bagging technique.

Once an equilibrium concentration has been reached the mass emission rate is given by the product of the air flow rate and the resultant concentration. If desired, it is a simple matter to apply corrections for the volume of the escaping vapour and for variations in ambient temperature and pressure.

This technique has the advantages that it is not necessary to know the precise volume of the bag, nor is a perfect seal around the equipment essential. It is merely necessary to ensure a continuous flow of air out of the bag past the detection instrument. Absorption of vapour onto the inside of the bag is not a problem as saturation eventually occurs but may be minimized by the use of Mylar bags.

The main drawback to the technique is the time required per measurement (around 30-50 minutes for small valves and flanges), to which may need to be added laboratory time for analysis if a direct reading instrument is not used. It is, therefore, highly manpower intensive. Furthermore, the requirement for electric power for the air pump or, alternatively, a source of compressed air is a major inconvenience. It is impracticable to survey hot, very large or inaccessible equipment by this method. The apparatus can be used on pump shafts but there are obvious practical difficulties.

3.6 Box method

The inconvenience, time requirement and the need for an air supply for the bagging technique led to the development of the box method. A container of known volume is placed around the leaking article and the rate of rise of concentration measured. This may then be related to the emission rate by:

mass emission = rate of conc. increase x effective volume of box

This technique has been used in laboratory studies of leakage but in field use it is very difficult to obtain reliable results for several reasons:

(a) the volume of the equipment inside the box must be estimated and subtracted from the original box volume;

(b) it is very difficult to achieve a satisfactory seal between the box and the equipment;

(c) imperfect mixing inside the box results in rapid concentration fluctuations at the detector;

(d) vapour may be absorbed into the material of the box.

This method does not have a time advantage over the bagging technique although it is less cumbersome. However, it also has the same limitations with regard to hot, large or inaccessible equipment.

3.7 Area monitoring

Mobile

A method for routinely monitoring the condition of a plant consists of an operator with a suitable direct reading instrument following a set path through the plant and noting ambient concentrations at predetermined distances upwind and downwind of pieces of plant equipment. The results obtained clearly depend on wind conditions and cannot be related to mass emission rates nor do they characterize individual leaks. This method may, however, serve as a useful semi-quantitative check on plant performance once a body of past data for the plant has been built up.

The method allows large plant areas to be surveyed relatively quickly with a moderately low manpower and equipment requirement. The degree of warning of leaks is, of course, directly dependent on the frequency of surveys.

Static monitoring

The use of fixed monitors to warn of equipment failure and sudden releases of hazardous materials is well established. Similar equipment has been proposed for use as a continuous check on overall levels of fugitive emissions if provision is made for the continuous recording of ambient concentrations. However, unless very large numbers of monitors are used - at considerable capital cost - stationary monitors will necessarily be remote from the majority of potential sources and thus insensitive to all but a widespread deterioration in the condition of the plant. Any attempt to derive mass emission rates for a plant on the basis of the results of fixed monitoring would have to depend on mathematical dispersion models and seems, at very least, problematical.

3.8 Conclusions

In situations where time and manpower present no problem, the existing bagging and box methods are adequate and could usefully be developed into a British Standard Method.

The subsequent use of these data in order to <u>predict</u> ambient concentrations within plants is currently dependent on mathematical models of contaminant dispersion. A more reliable approach might be to gather data on ambient concentrations and mass emission rates within existing plants and to use these as a basis for predicting the effect of lower leak rates in new plant of a similar type.

The major deficiency at present lies in the absence of a 'standard' technique which will allow rapid routine estimation of mass leak-rates either for individual pieces of equipment or for plants as a whole. The regular assessment of a plant's condition with regard to fugitive emissions is currently dependent on empirical methods which can detect only semi-quantitative changes in performance. For this purpose mobile area monitoring, widespread static monitoring or the concentration at the point of leak methods are suitable.

4 SAMPLING STRATEGY AND DATA ANALYSIS

4.1 Introduction

A sampling strategy is a procedure for deciding when and where to sample, how often and for how long. As the interpretation of any environmental data must depend on the reasons and procedures for its collection, it is convenient to discuss sampling strategy and data analysis together in this chapter. To keep the discussion reasonably short no attempt is made to give comprehensive guidance, but instead the intention is to concentrate on explaining some of the statistical principles involved and their application to the monitoring of fugitive emissions. There may be formidable practical difficulties, as all hygienists will be aware, in implementing the procedures which may be preferred on theoretical grounds. Some valves or seals may be inaccessible, or too hot to sample by conventional techniques. These sources may be precisely the ones where most of the emissions occur. It may be futile to devote substantial time and effort to the accurate measurement of very small emissions from accessible sources, if the total loss is dominated by large emissions from inaccessible, unsampled sources.

Firstly the possible objectives of a sampling programme are discussed. This is followed by an examination of the concepts of statistical sampling and their application to the monitoring of fugitive emissions. Finally, the methods available for data analysis are discussed with particular emphasis on the unusual nature of the population.

4.2 Objectives of a sampling programme

In designing a sampling programme it is essential to consider the purposes for which the fugitive emission data are to be obtained. Some possible objectives are given below.

(a) **Location of problem areas within a plant:** The hygienist may be aware from other information that substantial leaks are occurring at some point in the plant, and wish to detect the source of the problem as rapidly as possible. Often this can be without any formal sampling procedure.

(b) **Evaluation of control measures:** When a problem has been detected and appropriate engineering action taken, it may be necessary to check that this action has had the required effect.

(c) **Spot checks:** Fairly rapid surveys may be required to ensure that the total emissions from a plant are within established guidelines. If these surveys yield equivocal results, more sophisticated studies may be needed to determine whether substantial engineering modifications to the plant are required.

(d) **Estimation of the distribution of levels:** Even when there are no suspicions of any problems in a plant, monitoring of emissions may be needed to determine their possible effect on the workforce, on residential areas in close proximity to the plant and on the general environment. The magnitude of these emissions will depend on many factors, for example the condition of the seal, the operating conditions of the plant, local weather conditions, etc. All plants will produce some emissions, although in a few cases at an undetectable level. The magnitude of these emissions will fluctuate, between plants, from one location to another in a plant, and over time in the same location. These fluctuations will often be of several orders of magnitude, and it is essential that this variability be considered in the interpretation of the results. Errors in measurement are likely to be small by comparision.

Typically then, the hygienist will be concerned with a distribution of emission levels, rather than a single overall level. Although the shape of the entire distribution may be of interest, often attention will be focused on particular features of the distribution, for example, the mean or some other measure of average level, or the probability of exceeding a specified upper control limit.

(e) **Trends:** Superimposed on the random variability mentioned in (d) there may be systematic trends. Average levels may increase over time, due to inadequate maintenance; or emissions may be worse in some areas of the plant than others. Detection of such trends is essential to the selection of adequate control measures.

(f) **Prediction equations:** More formally, it may be desirable to devise equations for predicting emission levels from other variables, such as plant operation and temperature; maintenance schedules;

ventilation; and type of source. The mathematical form of these equations may be suggested by physical or engineering considerations, but empirical validation in field conditions is essential before they can be used with confidence. Field data may be needed for the estimation of certain coefficients in the equation, and for the assessment of the variability of actual levels around the predicted value.

(g) **Industry-wide assesments:** Estimates of total emissions from an entire industry or group of industries may be needed by regulatory authorities concerned with the environmental impact of fugitive emissions. In enforcing control limits such authorities may need to devise inspection programmes aimed at detecting the worst offenders. The distinction between these two objectives is similar to that between (d) and (a) above, though on a larger scale.

4.3 Statistical sampling: concepts and application

Fundamental to any sampling strategy is an adequate notion of the population to be sampled. The 'adequacy' here depends very much on the context. If the issue is whether routine maintenance has adequately dealt with a known problem with one individual seal, no great sophistication is needed to see that measurements of emission levels from that particular seal after the maintenance has been carried out are required. But when attention shifts from an individual seal to the 10,000 or more potential sources in an integrated chemical plant, the hygienist must distinguish between the population about which information is required and the much smaller number of sources that in reality are able to be monitored. The process of selecting the sources to examine is called statistical sampling, and the resulting collection, a statistical sample. The words 'sample' and 'sampling' are used in a slightly different sense here from their usual meaning in occupational hygiene.

The hygienist may wish to learn about the extreme members of the population, for example, the heaviest leakers. Any procedure for selecting these is likely to be highly inefficient unless it is based on considerable prior knowledge. For example, to give a 95% probability that at least one of the 'worst 10%' of sources in a large population should be included in a randomly selected statistical sample, the sample size (i.e. the number of sources sampled) must exceed 29. It would be much better, obviously, to select from only the 10% _if_ knowledge is available as to which these are likely to be.

Often however the goal is to choose a sample which is representative of the entire population, not of its extreme members. Formal statistical sampling procedures can then be very useful, although they may still be hard to implement. Although the meaning may seem obvious intuitively, 'representative sampling' is a difficult concept.to make operational. Decisions about whether particular sources are or are not 'representative' of the population of interest are inevitably subject to conscious or unconcious bias.

In statistical sampling, bias is avoided by the device of ensuring that each item in the population has a known probability of being included in the sample. An essential requirement is a numbered list of the population to be sampled. This list is often called a sample frame. It should include all potential sources of emission in the plant. In simple random sampling, a strictly random mechanism, usually a Table of random numbers, is used to select the desired number of items from the list. This ensures that all possible samples of the desired size are equally likely to be selected. Often it is preferable to divide the population into groups (strata) before sampling, and sample separately within each stratum. For example we may sample separately from valves and from seals. Stratified sampling, as this procedure is called, allows the sample selection to be weighted towards those categories of greatest interest. When there is strong prior information or suspicion that a particular type of source is likely to leak heavily, these sources should be treated as a separate stratum , and a higher proportion selected.

As well as avoiding bias, statistical sampling allows probability limits to be placed on the likely magnitude of the difference between the sample mean, or other summary measure, and the corresponding population value.

There are considerable practical difficulties in the implementation of the statistical sampling strategies. The labour of producing a list of the population and selecting samples should not be prohibitive for large scale surveys now that computers are widely available. However, as mentioned earlier, many of the sampled items may be inaccessible, or incapable of being measured for operational reasons. These may be precisely the sources that leak most and their replacement by other, more accessible sources in the sample would reintroduce the bias which statistical sampling is designed to avoid. Various approaches are possible in this situation.

(a) More sophisticated techniques may be devised for carrying out the measurement, even if those techniques are less accurate.
(b) Leak-rates may be estimated indirectly (e.g. by mass balance equations).

(c) Past experience with similar types of source may be used to predict likely leak-rates from the present source, and give error limits on the prediction.

In any case the hygienist has responsibility for documenting how all numerical values were derived. As is routine practice in epidemiological studies, where the problem of non-availability may be even greater, the 'response rate' (number of sources actually measured/number selected) should be quoted and the reasons given for any significant non-availability. Note that less formal sampling methods may conceal, but not avoid, the problem of bias due to non-availability.

It should be stressed that the preceding discussion applies mainly to large scale surveys concerned with accurately quantifying the distribution of levels of emission from all or a specified class of source within a plant or group of plants (objectives, section 4.2). Such sophistication will often not be necessary in routine checking, where the hygienist's personal experience and knowledge of the processes involved will usually be sufficient to fill in any major gaps in the sampling programme.

To assess random variation, or systematic trends over time ((e), section 4.2), repeated sampling of the same source may be needed. The derivation of accurate prediction equations ((f), section 4.2) requires sampling of emissions over wide ranges of (known) values of the explanatory variables.

Statistical sampling can also be used to select from a 'population' of plants a 'sample' for further study ((g), section 4.2). It may then be desirable to ensure that the probability of selection of any plant is proportional to its size. So-called multistage sampling can be used, combining a weighted first stage sampling of plants with a second stage sampling within each selected plant.

Statistical advice should be sought on the analysis of data from stratified, weighted, or multistage samples, as summary values may require adjustment.

4.4 Analysis of data

As indicated earlier, leak-rates from a particular type of source may show considerable fluctuation of either a random or systematic nature, and this variation must be taken into account in analysing and interpreting data from monitoring studies. The data shown in Figure 2 in Chapter 1 demonstrate that this variation can encompass several orders of magnitude.

It is commonly assumed that the random fluctuations in environmental sampling data can be described statistically by a log-normal distribution. This assumption is often a reasonable approximation and leads to methods of statistical analysis which are fairly simple to carry out. Methods developed for the analysis of normally distributed data are applied to the (natural) logarithms of the raw values (see, for example, Higgins(1980)[6]). A sophisticated exposition oriented towards U.S. practice is given by Leidel, Busch and Lynch.[7] Taking logarithms will reduce, eliminate or even reverse the strong positive skewness which is generally evident when the data are plotted on an arithmetic scale. Note that the log transformation has already been applied to the data of Figure 2.

The log-normal distribution is not always appropriate, however, and it can lead to biased estimates of mean levels even when formal goodness of fit tests indicate that it is consistent with the observed data. To see why this is so it is necessary to consider the properties of the distribution in a little more detail.

4.4.1 The log-normal distribution properties

To say that leak-rates follow a log-normal distribution is to say that their natural logarithms, i.e. logs to base e, follow a normal (Gaussian) distribution. In the usual statistical notation, let μ and σ denote the mean and standard deviation of the normal distribution, i.e. the distribution of transformed data. Then e^{μ} and e^{σ} are called respectively the geometric mean and geometric standard deviation of the original values, i.e. before transforming the data into logarithms. These quantities differ from the arithmetic mean and standard deviation of the original data which are arrived at without transforming into logarithms.

In fact the arithmetic mean is given by the formula

$$\text{arithmetic mean} = \exp\{\mu + \frac{\sigma^2}{2}\} \qquad \text{Eq.1}$$

Since the geometric mean = e^{μ}, then the ratio of

$$\frac{\text{arithmetic mean}}{\text{geometric mean}} = \exp\{\frac{\sigma^2}{2}\}$$

If $\sigma = 2.5$ (which is quite common for this situation), then the ratio of the arithmetic mean to the geometric mean is $e^{3.125} = 22.8$ (i.e. the arithmetic mean is 22.8 times the geometric mean). It is vital therefore to determine if the original data are in fact better transformed before calculating the mean.

It is usual to estimate μ and σ from the sample mean $\bar{y}$ and sample standard deviation S_y of the logarithms (y) and substitute these estimates into Eq.1 to estimate the arithmetic mean. A somewhat better procedure was developed by Finney (1941).[8] The two methods will give similar results if the number of values is large.

The simple substitution of $\bar{y}$ and S_y for μ and σ in Eq.1, and Finney's modifications of this procedure are valid only if the data are truly log-normal. A simple alternative estimator, of course, is the arithmetic mean of the raw (i.e. untransformed) values. This estimator does not require log-normality. If, in fact, the leak-rates are log-normally distributed, the substitution estimators will be much more efficient (i.e. have smaller standard error) than the raw arithmetic mean, which is why the substitution estimators are often used. However, if the log-normal assumption is not correct, the substitution estimator will be biased. If the distribution of the logarithms is positively skewed (i.e. with a long right tail), the substitution estimators will tend to underestimate the true arithmetic mean and vice versa. In the EPA study cited earlier by Wetherold et al. (1981),[9] there was some suggestion of a negative skewness in the transformed values, resulting in a noticeable tendency for the substitution estimator to overestimate the true arithmetic mean. Although the resulting bias is likely to be small in comparision with the other uncertainties inherent in this type of data, it should be borne in mind in the analysis of data used for setting emission limits.

4.4.2 Other distributions

Various distributions other than the log-normal have been suggested for the analysis of environmental sampling data. Berry and Day (1973)[10] have suggested a gamma distribution, Lynn[11] has used beta distributions, and Hershfield[12] has suggested extreme value distributions. Statistical methods for these distributions are somewhat more complex than for the log-normal distribution, but this is of little consequence in the analysis of definitive large scale studies. For routine use, the log-normal distribution is generally satisfactory, provided some checks are carried out (e.g. by probability plots of the logarithms) to detect gross lack of fit.

The effect of departures from log-normality can be seen by fitting a more general class of distribution which includes the log-normal as a special case. The so-called 'generalized gammma' distribution (see, for example, Kalbfleisch and Prentice (1979)[13]) is a possible candidate, as it includes the log-normal and gamma distributions. Lynn[11] suggested the use of Pearson curves, with a similar motivation.

4.4.3 Overshoots of a specified level

Roach (1982)[14] has pointed out that parametric assumptions such as that of a log-normal distribution are even more dubious when excursions above a particular level are concerned than in estimating mean values. This is what is done in effect when probability plots are extrapolated to determine the proportion of samples that will lie above a specified value. Effectively, the main body of the data determines the shape of the fitted frequency curve. This shape may not be at all appropriate in the upper percentiles of interest. As for mean values, it would seem desirable to supplement any such theoretical extrapolations with direct calculation of the proportion of emissions above the specified level.

4.4.4 Limits of detection: zero values

It is often necessary to consider separately the 'leaking sources' i.e. those which are found to have non-zero leak-rate, however small, and the 'non-leaking sources' i.e. those which have a zero, or undetectable, leak-rate. A quick calculation can be carried out using the limits of detection of the apparatus, the proportion of non-leakers, and the leak-rates of the leaking sources, to determine whether the 'non-leakers' might in fact be contributing a significant proportion of the total emissions. This might happen if there were very many non-leakers, contributing similar emissions in total to a small number of leakers, even though the contribution of each non-leaker was undetectably small. If this happens, mean emission levels can be estimated only with great uncertainty. It also becomes important to consider the extent to which the distribution of leak-rates among the leakers can be extrapolated to include the non-leakers.

If the calculation suggests that the 'zero-leakers' can be contributing only a negligible proportion of the total leak-rate, even on the most pessimistic assumption that all their leak-rates were only just under the limits of detectability, then the leakers and non-leakers can be considered separately. Effectively this means estimating the proportion of leakers and then fitting the chosen statistical distribution to the observed frequency distribution of leaking sources.

4.5 More sophisticated techniques

For analysing complex relationships between leak-rates and other explanatory variables, or for investigating correlations in time or space (position), more sophisticated statistical techniques may be needed. Multiple regression can be used to examine dependence on explanatory variables. To reduce skewness, a logarithmic transformation is often applied to the leak-rates, but this runs into previously mentioned difficulties over changing from the geometric to the arithmetic scale. A possible alternative approach, which preserves the direct interpretation of the coefficients, is to use the GLIM computer program (Baker and Nelder (1978)[15]) with identity 'LINK' and log-normal or gamma 'ERROR'.

Time series analysis can be used to investigate correlations in leak-rates over successive periods (if a leak-rate is high today, is it likely also to be high tomorrow). These techniques may help to determine whether environmental levels are due primarily to sudden surges in emissions, or are a result of steady losses.

Detailed statistical analysis of many sets of data collected under different conditions may be needed to validate the more complex models that have been proposed for predicting environmental levels within, or outside, a plant in terms of engineering, ventilation and climatological variables. The performance of such models in field conditions needs regular scrutiny.

5 CONTROL TECHNIQUES

The information in this chapter is designed to make the hygienist more aware of the alternatives and problems facing the design engineer when it is necessary to 'seal' a potentially leaking joint. Only by understanding the mechanisms of the seal can the hygienist hope to estimate the benefits and pitfalls. For this reason the information is relatively detailed but in a descriptive rather than technical fashion. Since the data currently available on actual leak-rates are not comprehensive in terms of seal types, the leak-rates are given in relative terms. Costs are also only given as indices to avoid variation between manufacturers.

5.1 Types of seal

A seal is a device for making a leak-tight joint whether for the purpose of preventing the intake of air, or the escape of a confined fluid.

They can be divided into two broad classes:

1. **Static seals:** where there is no relative movement of the seal's surfaces; for example, pipe joints and manhole covers.
2. **Dynamic seals:** where the seal must be made between surfaces that move relative to each other.

   The relative motion in a dynamic seal may be rotary, as in a centrifugal pump, or reciprocating, as in a piston pump or compressor.

   The seals used for dynamic applications are of two basic types:

   (a) **Contact seals:** where the seal bears against the mating surface under a positive pressure.
   (b) **Clearance seals:** which operate with a positive clearance between the two sealed surfaces.

Selection of the type of seal of course involves a number of process and other variables. Leak-tightness is not usually the most significant of these as far as the designer is concerned.

5.1.1 Static seals

The methods used to make a leak-tight seal joint between the two static surfaces fall into two main categories:

1. **Gasketed joints** (Fig.4), in which a gasket material is used between the faces, and which rely on an externally applied force to maintain the seal.

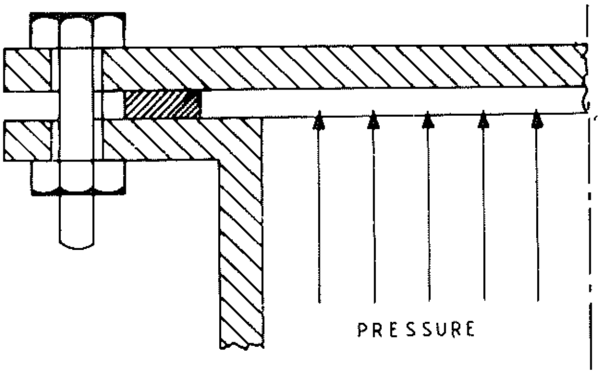


Fig.4. A gasketed flanged joint.

2. **Automatic face seals** (Fig.5) in which the system pressure, together with a small amount of pre-compression of the seal, is used to maintain the seal contact.

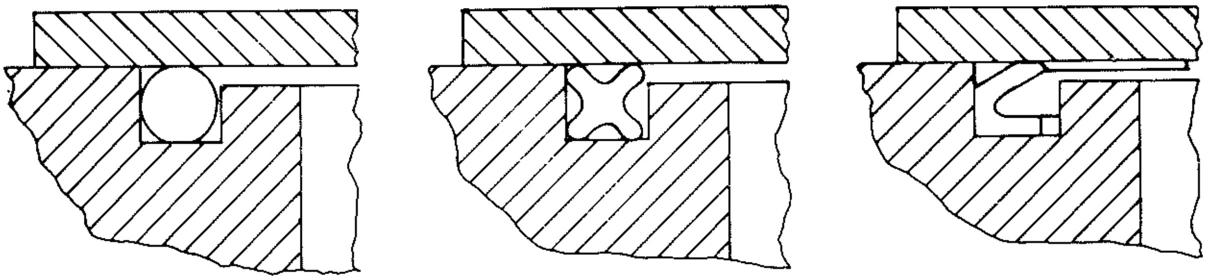


Fig.5. Automatic face seals.

(a) Bolted flanged joints

Bolted, gasketed, flanged joints are used extensively in the process industries where a 'semi-permanent' joint is required for ease of assembly or maintenance; such as for pipe joints, vessel covers, manholes and instrument connexions.

(b) Gaskets

It is impractical to machine the flange faces to the degree of the surface finish that would be needed to make a satisfactory seal under pressure without a gasket. Gaskets have semi-plastic properties which enable them to deform and flow under load to fill the surface irregularities, yet retain sufficient elasticity to take up the changes in the flange alignment that occur under load.

A great variety of proprietary gasket materials is used, and reference should be made to the manufacturers' catalogues and technical manuals when selecting gaskets for particular applications. The most commonly used gasket materials are synthetic rubbers, plastics, asbestos, and metal-reinforced and metal-clad asbestos.

The principal factors to consider in selecting gasket materials are:

(i) The process conditions, e.g. pressure, temperature and the corrosive nature of the fluid.

(ii) Whether the joint will need to be frequently broken and reassembled.

(iii) The type of flange used.

Vegetable fibres and synthetic rubber gaskets can be used up to 100°C. Solid PTFE and compressed asbestos up to 260°C, and metal-reinforced asbestos gaskets up to 450°C. For higher temperatures a range of other gaskets is available, e.g. soft metal gaskets. A comprehensive summary of the factors to be considered in gasket selection, and the types of gasket used, is given by Childs.[16]

(c) Flange faces

Flanges are classified according to the type of face used. There are two basic types:

(i) **Full-faced flanges** (Fig.6): where the face contact area extends outside the bolt circle, over the full face of the flange. These are simple and inexpensive, but their use is limited to low pressures.

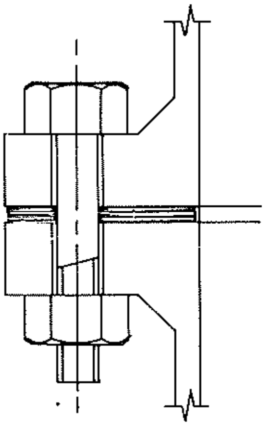


Fig.6. Full-face flange.

(ii) **Narrow-faced flanges** (Fig. 7, 8, 9): where the face contact area is located within the bolt circle.

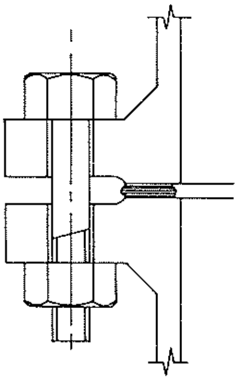


Fig.7.
Gasket within
bolt circle.

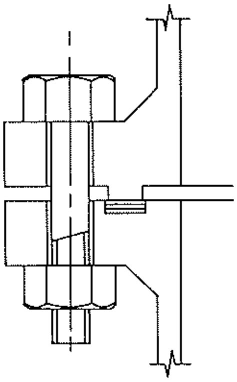


Fig.8.
Spigot and
socket.

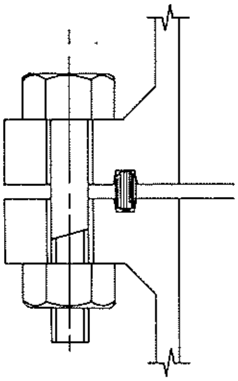


Fig.9.
Ring type
joint.

The raised face, narrow-face, flange shown in Fig.7 is the most commonly used type for the severe conditions experienced in the process industries.

Where the flange has a plain face, as in Figs.6 and 7, the gasket is held in place by friction between the gasket and flange surfaces. With the 'spigot and socket' type (Fig.8) and 'tongue and groove' types, the gasket is confined in a groove, which helps to prevent premature failure (blow-out). Matched pairs of flanges are needed for these types, which increase the cost, but they are more suitable for high pressures and vacuum service. Ring joint flanges (Fig.9), with metal gaskets, are used for very high pressures.

The flange bolts must be sized to maintain this minimum gasket pressure under load. The bolt loads will be high, and HTS (high tensile steel) bolts are used. The bolts may be subject to creep, which will progressively reduce the applied gasket pressure and may lead to premature leakage.

Absolute leak tightness can of course be achieved by either no flange at all (welded pipe) or welding the flanges together. These have maintenance problems, of course, but welded pipe will have a capital cost saving compared with the others.

5.1.2 Dynamic seals

The two principal types used on process equipment are:

1. **Packed-glands** (stuffing boxes): used for reciprocating and rotating shafts.

2. **Mechanical seals** (face-seals): used only with rotating shafts.

In addition to these, there is a great variety of other designs, usually of a proprietary nature, which are used for light duties, such as dirt exclusion and oil seals, and as components of the two principal types. Some of these seals will be described in the next section.

5.1.3 Miscellaneous seals

(a) O-rings

The O-ring is one of the simplest and most versatile types of seal; it is used for a wide range of dynamic and static applications. Basically an O-ring seal consists of a ring of circular cross-section nipped in the cavity. They are used for static applications up to very high pressures, and as dynamic seals up to 350 bar (5000 psi). The principle of the O-ring seal is shown in Fig.10. On assembly the ring is subject to a slight compression determined by the dimensions of the groove. The internal operating pressure further deforms the ring, forcing it into the side of the groove and completing the seal. Correct sizing of the groove and ring is important. If the gap is too large, the ring will fail by extruding too far into the gap. Although the design may be such that no gap is present on assembly, a small gap may be opened up due to the extension of the flange bolts under pressure. In dynamic applications, and under cycling 'static' pressure, any tendency to extrusion will lead to localized wear and eventual failure by nibbling.

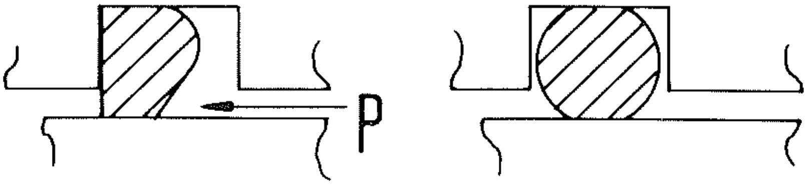


Fig.10 Principle of the O-ring seal.

In some apllications, a wedge section ring is used in combination with an O-ring to prevent extrusion under load (Fig.11).

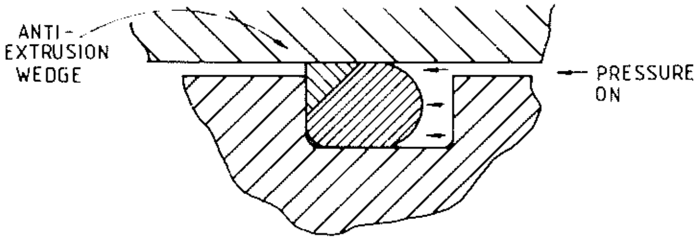


Fig.11 Anti-extrusion wedge.

The design of O-ring seals is covered fully by Warring.[17]

(b) **Flexible lip seals**

Flexible seals with a U- or V- section, in which the 'lips' of the seal make contact with the surface to be sealed (Fig.12), are frequently used for sealing reciprocating shafts. They are arranged so that the internal pressure opens the seal, forcing the lips against the surfaces, and so are often called automatic seals.

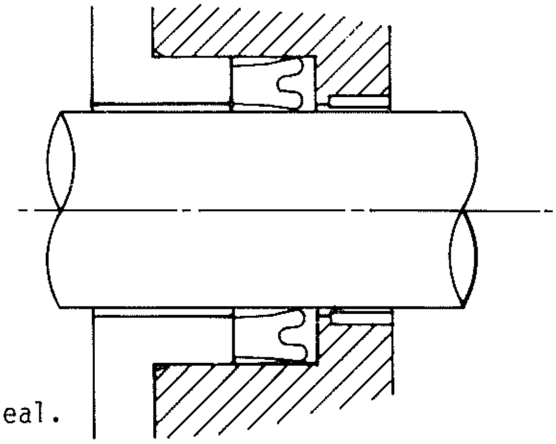


Fig.12 U-ring seal.

V- ring (chevron seals) are of a heavier cross-section than U-rings and are normally used as a stack of rings (Fig.13).

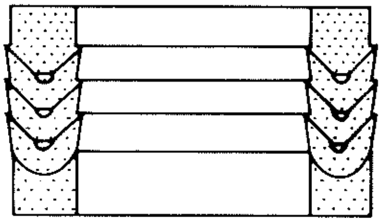


Fig.13 Stacked V-rings.

Flexible lip seals are extensively used in pneumatic and hydraulic equipment and as a back-up to mechanical seals.

Flexible lip seals can tolerate relatively large clearances between the shaft and housing. Soft rubber seals are used for the moderate pressures, and hard rubber and fabric-reinforced rubber for high pressures (175 bar). Various proprietary designs are available (Warring).[17]

5.1.4 Clearance seals

Bushing seals

The bushing seal is the simplest type of clearance seal; it is in effect a long bush with a relatively close clearance (Fig.14).The throttling action provided by the annular gap limits the rate of leakage. Simple bushing seals are only effective for sealing liquids, and where some leakage can be tolerated. Some types of bushing seal employ floating and spring loaded rings. The spring loaded rings contact the shaft and are not, therefore, true 'clearance seals'. The rings are made from bearing metals (Babbit metal and bronze) or carbon. Spring loaded carbon ring seals are used to seal both liquids and gases.

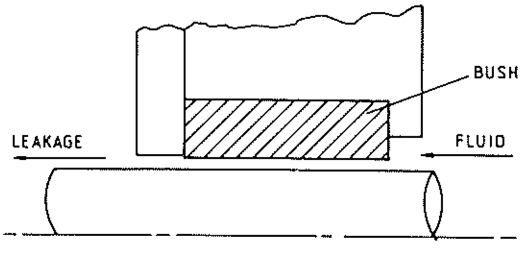


Fig.14 Simple bushing seal.

Labyrinth seals

Labyrinth seals are clearance seal in which the leakage rate is controlled by providing a long tortuous path through which the escaping fluid must past (Fig.15).

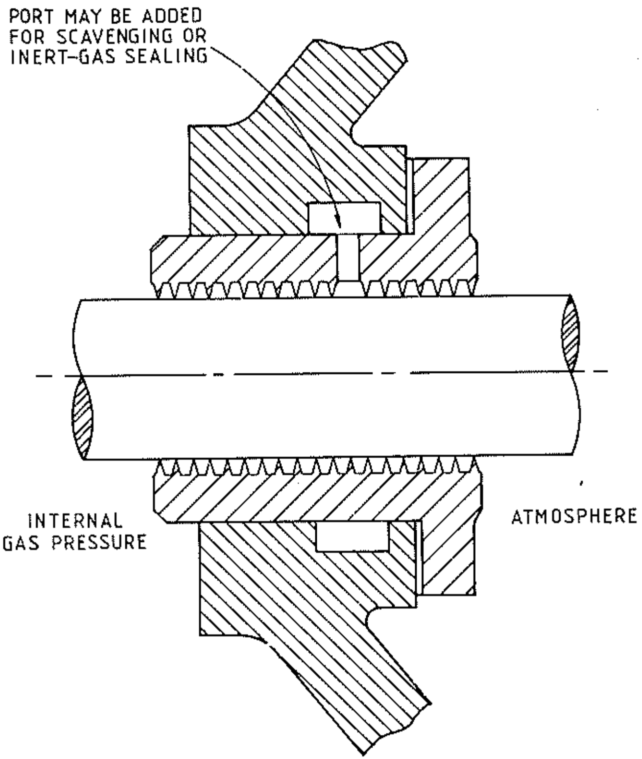


Fig.15 Labyrinth seal.

The turbulence created at each throttling and expansion step in the labyrinth dissipates the pressure energy and controls the leakage rate. Labyrinth seals are used on both rotating and reciprocating shafts, and to seal both liquids and gases.

5.2 Packed glands (Stuffing-boxes)

The packed gland seal (stuffing-box seal) is probably the oldest and most universally used type of shaft seal. Its applications range from sealing the stem of the water taps in every home, to providing the seal on industrial pump, valve and agitator shafts. The seal consists of a gland housing (stuffing-box), gland follower, and rings of packing (Fig.16).

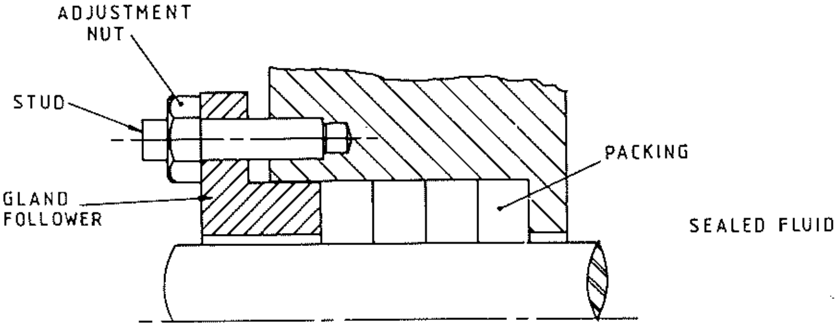
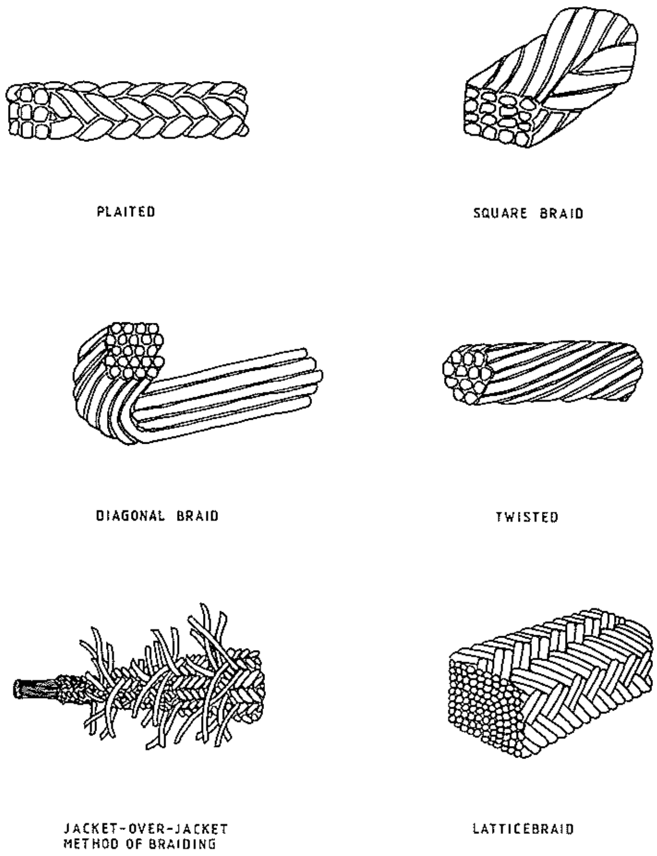


Fig.16 Packed gland.

The gland follower is tightened up to place the packing under pressure, and this compressive force is transferred as a radial pressure to the shaft surface, making the seal. To make a completely tight seal, a compressive force on the packing of 2 or 3 times the force produced by the system pressure is needed. With rotating shafts, this high pressure can lead to excessive wear, and lower pressures are normally used, allowing some small leakage which can also have lubricating and heat transfer benefits.

Proprietary packings are used normally. These consist of plaited or braided fibres, lubricated with various lubricants (Fig.17). Vegetable, mineral, and metallic fibres are used, with mineral oils and greases, silicone oil, graphite, and PTFE as lubricants. The principal packing materials used in the process industries are those based on asbestos fibres and synthetic fibres, lubricated with graphite or PTFE. Details of some typical packings and their applications are given in Table 3. The packing manufacturers' literature should be consulted when selecting packing for critical duties. A good summary of the factors to be considered in the selection and use of packings for packing glands is given by Hoyle.[18]



PLAITED

SQUARE BRAID

DIAGONAL BRAID

TWISTED

JACKET-OVER-JACKET METHOD OF BRAIDING

LATTICEBRAID

Fig.17 Types of packing.

TABLE 3

Packing performance characteristics

Type	Construction	Rubbing speed m/sec	Temp. °C	Pressure bar	Application	pH
Cotton	Plaited or braided with grease graphite or mica lubricant	7.5	90	-	Seals for water.	6-9
Hemp	Plaited or braided with grease graphite or mica lubricant	-	-	-	Seals for water.	5-9
Flax	Plaited or braided with grease graphite or mica lubricant	-	70 to 120	-	Rotary seals or pumps and slow reciprocating seals; ship's stern glands, etc.	-
Textile	Plaited or braided cotton, nylon, rayon, hemp, etc, with PTFE impregnation	-	-	-	Seals for water services, solvents, weak alkalis, oils, greases, foodstuffs, etc.	-
Asbestos (dry)	Rounded or square plaited or braided white asbestos	-	500	-	Autoclaves, boiler stop valves, etc.	
Asbestos (lubricated)	Rounded or square plaited or braided white asbestos with graphite, mica or mineral oil lubricant		-40 to 300		Steam services, evaporators cannisters, liquors, etc.	5-12
Asbestos (wire reinforced)	Square section plaited or braided with brass or Inconel wire reinforcement. Impregnated with graphite or mica lubricant		-50 to 750	250 to 650	Water, air, steam, solvents, hydrocarbons, weak acids and alkalis.	4-11
Asbestos (PTFE)	Plaited or braided asbestos yarn coated with PTFE dispersion	15	280	100	Acids, solvents, oils hydrocarbons, etc (not caustic solutions).	0-8
Asbestos (glass fibre)	Plaited or braided asbestos yarn and glass fibre with added lubricant	5	200	250 to 300	Corrosive duties with equivalent chemical resistance to blue asbestos, except caustic solutions.	0-11
Blue asbestos	Braided asbestos fibres with added lubricant	15	280	60	Limited production because of health hazard and not made in many countries.	0-12
Asbestos (lead)	Manufactured from asbestos fibres and granulated lead with added lubricant	-	-	-	-	-
PTFE	Yarns or tape	-	200 to 250	-	Soft packings, services involving corrosive media.	0-14
PTFE and lubricant	PTFE braided and impregnated with graphite and/or molybdenum disulphide lubricant	20	-100 to 250	30+	Water, steam, acids, alkalis, solvents, oils, greases, hydrocarbons, etc.	0-14
	Braided pure PTFE fibres treated with PTFE dispersion	10	-200 to 300	100	Sealing all media.	0-14
PTFE (graphite)	Extruded fibrillated PTFE and graphite with mineral oil lubricant	10	-100 to 250	100	Water, acids, alkalis, oils solvents, degreasing fluids, oxidizing agents, foodstuffs, etc.	0-14
Aramid-PTFE	Braided PTFE coated Kevlar yarn impregnated with lubricant and PTFE	10 to 20	-220 to 300	200-1000	High duty 'super packing'.	1-14
PTFE-silk	Braided PTFE - silk yarns with added lubricant	5	280	200	Water, steam, acids, oils, alkalis, oxidizing agents, dye stuffs, etc.	0-14
Graphite yarn	Woven or braided graphite yarn treated with graphite powder	-	-200 to 600	-	High temperature services.	0-14
Carbon fibre	Amorphous carbon yarns treated with graphite powder	-	-200 to 600	-	High temperature services.	0-14
Expanded graphite	Flexible plait or tape form	35	-200 to 600	300	High temperature services, foodstuffs, etc.	0-14

To work effectively the packing must remain in a lubricated condition. For 'static' applications such as valve stems, this means that a lubricant must be selected that will not dry out, such as graphite or PTFE. For dynamic applications it is normal to allow some leakage through the packing, which serves to keep it lubricated. Where more certain lubrication is needed, a lantern ring is incorporated in the seal assembly (Fig.18) so that grease or other lubricants can be forced into the packing. With pumps, a flush is often taken from the pump discharge to lantern ring to cool and lubricate the packing.

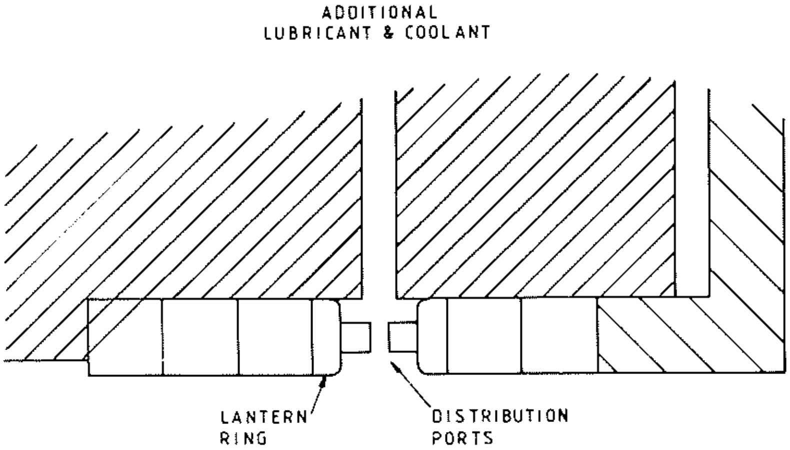


Fig.18. Lantern ring.

The sealing effectiveness of the various packing is very much dependent on how well they are assembled and how well and often the gland follower is tightened. From a general viewpoint, however, emissions over a packing lifetime will be less when the packing provides its own lubrication. These packings also tend to last longer. To avoid the vagaries of fitting the packing, the optimum is to have it supplied as pre-formed rings of 100% foliated carbon (graphite); this may prove to be a major advance in the control of fugitive emissions. From a cost aspect these tend to be more expensive (sometimes up to 3 times) than the regular braided asbestos type but the extended life and reduced maintenance requirements make them an attractive proposition in the long term.

5.3 Mechanical face seals

Mechanical face seals, generally called simply 'mechanical seals', can be used for rotating shafts only, e.g. in pumps, agitators and compressors.

The seal is formed between the flat faces perpendicular to the shaft, one face rotating with the shaft and the other stationary (Fig.19). The seal is formed, and the face lubricated by a very thin film of fluid (of the order of 0.001 mm thick). A particular advantage of this type of seal is that it can provide a very effective seal without causing any wear on the shaft; the wear is transferred to the special seal faces. Some leakage will take place past the seal faces (to lubricate the faces), but the rate of leakage is smaller than with the standard packing gland.

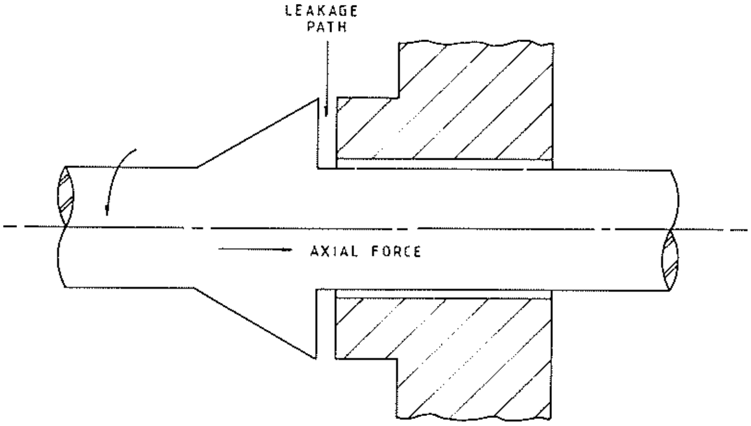


Fig.19. Simple face seal.

A great variety of mechanical seal designs is available and seals can be found to suit virtually all duties. Only the basic designs will be described here. Full details and specifications of the range of seals available can be obtained from the manufacturers' catalogues.

The basic mechanical seal

The components of a mechanical seal are shown in Fig.20.

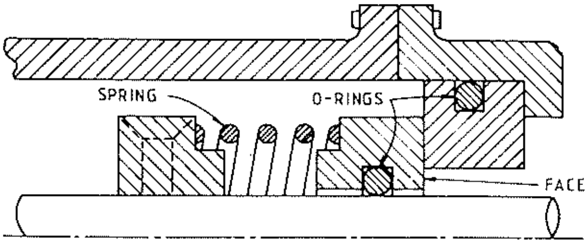
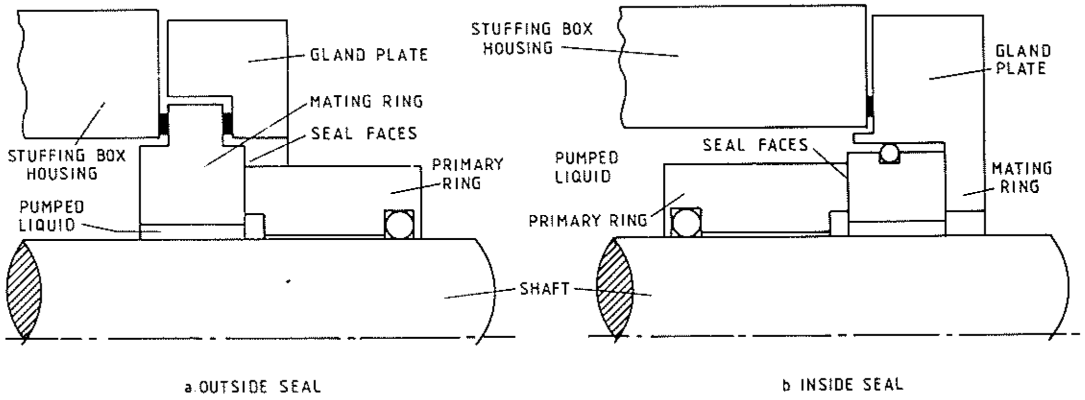


Fig.20. Components of a basic mechanical seal.

(a) A stationary sealing ring (mating ring).
(b) A seal for the stationary ring; O-rings or gaskets.
(c) A rotating seal ring (primary ring), mounted so that it can slide along the shaft to take up wear in the seal faces.
(d) A secondary seal for the rotating ring mount: usually O-rings, or U- or chevron-seals; wedge-shaped seals are also used.
(e) A spring to maintain contact pressure between the seal faces; to push the faces together.
(f) A thrust support for the spring, either a collar keyed to the shaft, or a step in the shaft.

The assembled seal is fitted into a gland housing (stuffing-box) and held in place by a retaining ring (gland plate).

Mechanical seals are classified as inside or outside seals, depending on whether the primary ring (rotating ring) is located inside the housing, running in the fluid, or outside (Fig.21 a,b). Outside seals are easier to maintain; but inside seals are more commonly used in the process industries, as it is easier to lubricate and flush this type.



a OUTSIDE SEAL b INSIDE SEAL

Fig.21. a,b. Outside and inside seal arrangements

Balanced and unbalanced mechanical seals

The pressure acting on the back of the primary ring of an inside seal will force the faces together (Fig.22a). With seals operating at high stuffing-box pressures, the force acting on the seal faces can be excessively high and this can cause rapid wear of the seal faces. The force acting on the seal faces can be reduced by changing the relationship between the closing area, on which the fluid pressure acts, and the seal face area. This can be done by stepping the shaft, or by using a stepped sleeve (Fig.22b), thus reducing the area on which the stuffing-box pressure acts, whilst maintaining the same seal face contact area. When this is done the seal is said to be 'balanced'. The use of 'unbalanced' seals is limited to stuffing-box pressures up to around 15 bar (200 psi), depending on the shaft speed.

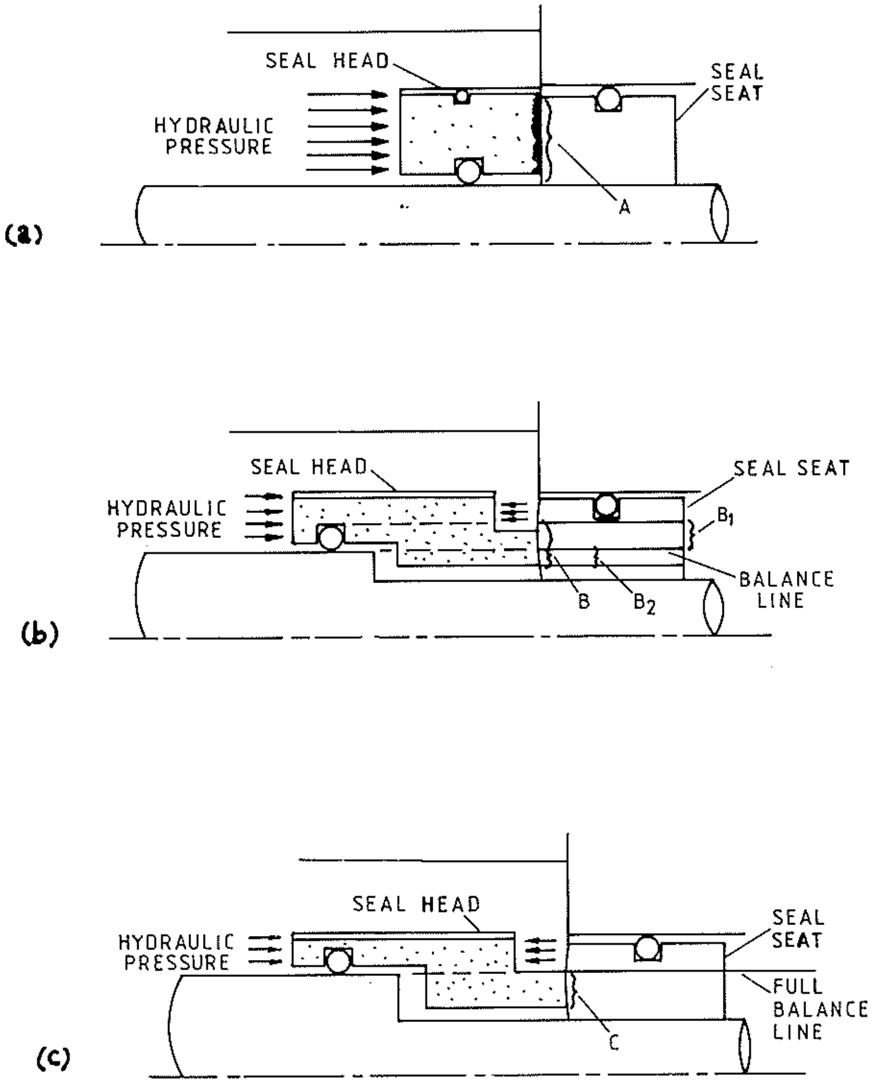


Fig.22. a,b,c. Seal balancing.

Materials used

Standard commercial mechanical seals are available in a wide range of materials of construction, to suit most duties. The seal components are constructed in all the usual corrosion resistant metals and alloys: stainless steel, Hastelloy, titanium, etc.

Seal faces are available in a range of materials, including stainless steel, copper alloys, tungsten carbide, ceramics, and carbon. Some typical seal face materials and their applications are given in Table 4. The PV (Pressure x Velocity) values shown in the table are the product of the face pressure and the rubbing velocity at the faces. This criterion is used in the design and selection of seals.

TABLE 4

Seal face materials and their applications

Face materials	Face material 'PV' limits, bar m/s			
rotating:stationary	Water and aqueous solutions		Other fluids	
	unbalanced	balanced	unbalanced	balanced
stainless:carbon	5.5	-	30	-
lead bronze:carbon	23	-	36	-
stellite:carbon	49	85	52	580
chrome oxide:carbon	70	440	-	-
alumina ceramic:carbon	36	250	88	420
tungsten carbide: tungsten carbide	44	500	71	420
tungsten carbide:carbon	70	700	88	1225

Most mechanical seals use carbon for one seal face.

Carbon is mechanically weak against distortion, but it is used because it has excellent self-lubricating properties (important during start-up conditions when the seal may run dry) and good thermal conductivity.

The secondary seals (O-rings and other types) are made in a variety of synthetic rubbers and plastics; for example, 'Viton', 'Hyperlon', PTFE, chosen to resist the process conditions.

Springs

Single and multiple helical spring designs are used. Multiple springs (Fig.23) give a more even face and a smaller overall seal size (length), and are more suitable for high shaft speeds. They are, however, more susceptible to corrosion and clogging than the heavier section single springs.

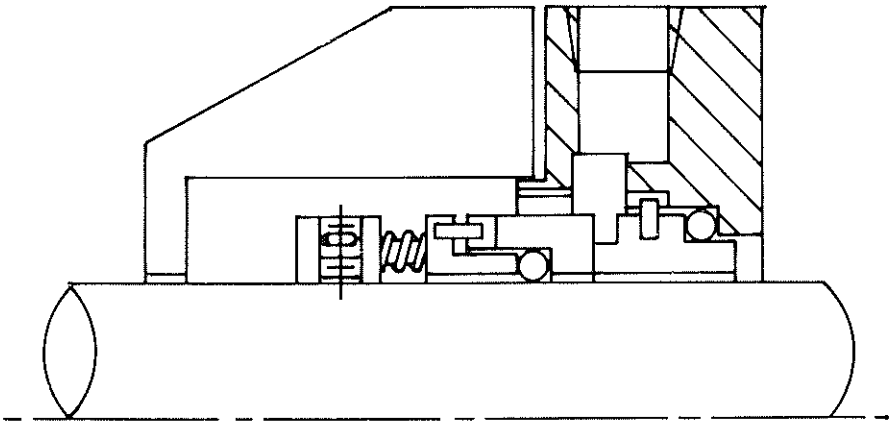


Fig.23. Multiple springs.

Bellows mechanical seals

A bellows can be used to connect the moving seal ring to the drive collar, thus avoiding the need for a dynamic secondary seal. Bellows of elastomeric materials, typically PTFE, are used in conjuction with metal springs; or a metal bellows can be used to provide both the seal and the spring action (Fig.24).

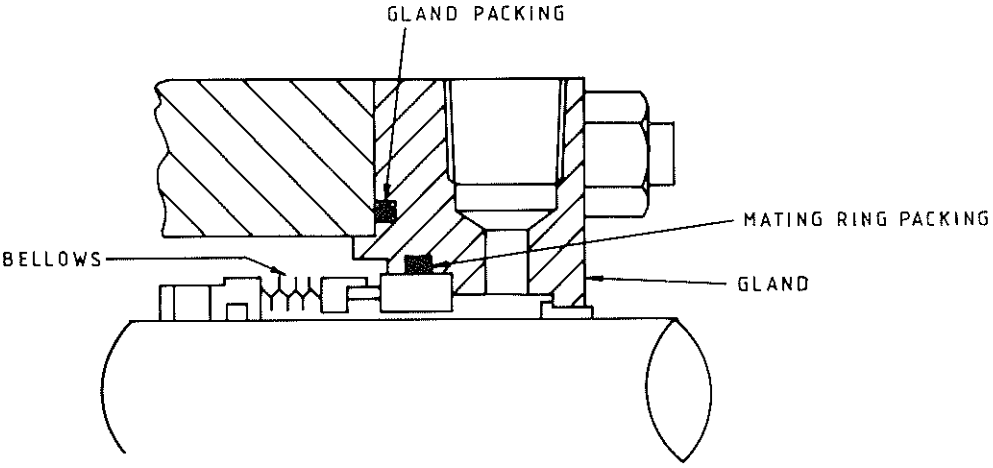


Fig.24. Bellows seal.

Another advantage of a bellows is that it provides a balanced seal without the need to step the shaft. The fluid in the stuffing-box goes between the bellows convolutions and exerts pressure in both directions, so the effective diameter compared with the seal face area is reduced (Fig.25).

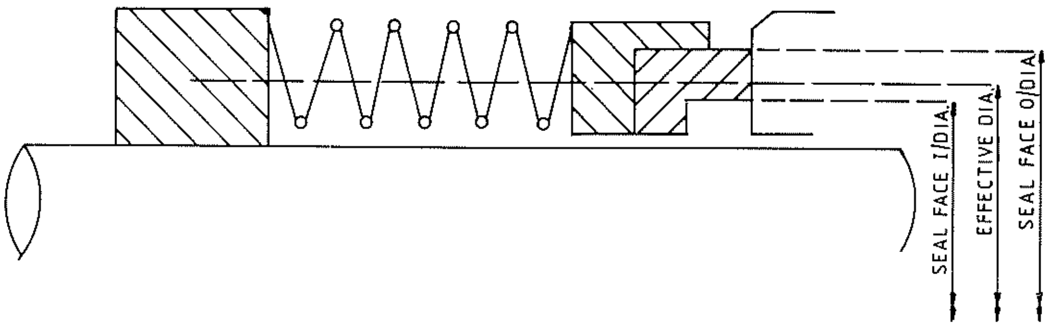


Fig.25. Pressure balancing of bellows seal.

Metal bellows are manufactured in a range of corrosion resistant alloys.

Seal flushing

The seal faces must operate with a thin film of liquid between them to lubricate the faces and to prevent excessive wear, overheating, and premature failure. The frictional heat generated at the seal faces will tend to vaporize this thin liquid film, and it is essential to keep the faces below the temperature at which the liquid boils. This is normally achieved by providing a liquid flush to the seal. If a clean liquid is being pumped, this can be used as the flush, the flush being taken from the pump discharge. If the pumped liquid is unsuitable as a seal flush (and for gas seals) an external flush must be provided. The external flush liquid must be compatable with the process fluid. The quantity of flush liquid needed can be reduced by providing a restrictive seal, such as a lip seal or throttle bushing, between the stuffing-box and gland follower (Fig.26).

Auxiliary flush systems

Auxiliary equipment is often used with mechanical seals to clean-up, cool and control the circulating flush liquid. Conventional heat exchangers are used to cool the flush liquid. Hydroclones and filters are used to remove solid particulate material. Cyclones are preferred, as filters need to be changed frequently. Efficiency of the filter should give a good service factor on the seal. Many different arrangements are used for seal flushes, depending on the type of seal and the nature of the process, and the seal manufacturer and pump supplier should be consulted to determine the needs and best arrangement. With suitably designed flushing systems and seal face materials, mechanical seals are capable of handling corrosive and abrasive liquids, and also process liquids that are likely to solidify or crystallize.

A typical auxiliary system for cooling the flush liquid and removing solid particles is shown in Fig.27.

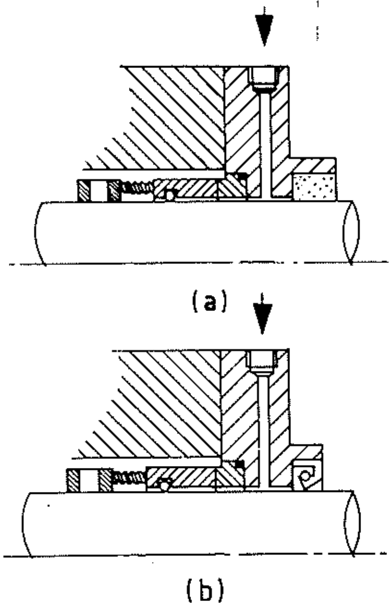


Fig.26. Restrictive seals limiting leakage of flush fluid, (a) Bush, (b) Lip seal.

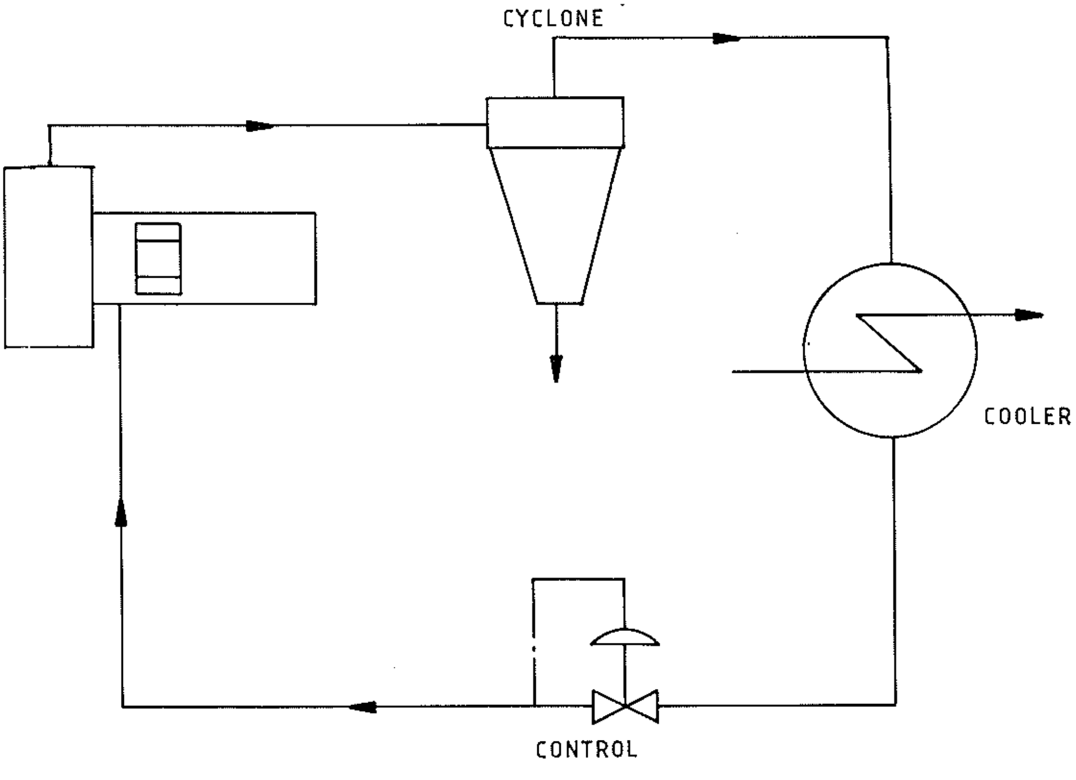


Fig.27. Typical seal flush auxiliaries.

Double mechanical seals

A single mechanical seal is not a zero leakage device; some very slight leakage must take place through the seal faces, for lubrication. Where it is necessary to reduce the leakage even further a double mechanical seal is generally selected (Fig.28). The arrangement shown in Fig.28 with the seals mounted 'back to back' is the most commonly used one. The space between the seals is flushed with a liquid compatible with the process fluid and provides a buffer between the two seals. The flush liquid is at a higher pressure than the stuffing-box pressure, so some leakage through the inner seal will take place into the process fluid.

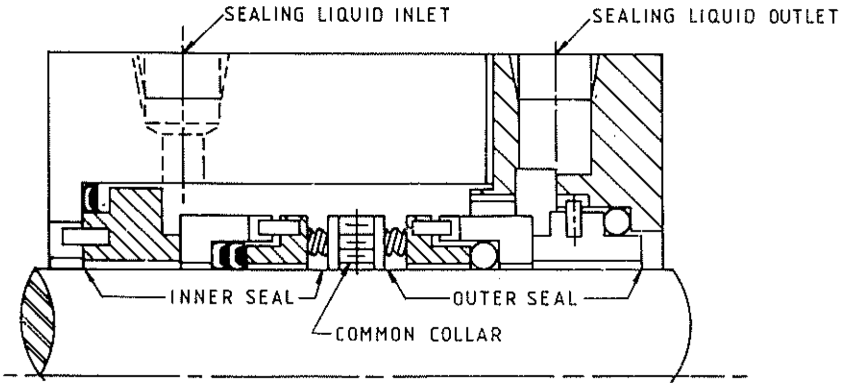


Fig.28. Double seal.

Another arrangement used to prevent process fluid from escaping into the atmosphere is the 'tandem seal' shown in Fig.29. In this arrangement the two seals face in the same direction and the seal flushing liquid is at a lower pressure than the stuffing-box pressure. Leakage will therefore take place into the flush fluid. For this reason the tandem seal is usually regarded as leaking more than the double seal. The prime use of the tandem is in situations where blow out due to inner seal failure would cause a major upset, e.g. through explosion hazards or acute toxicity.

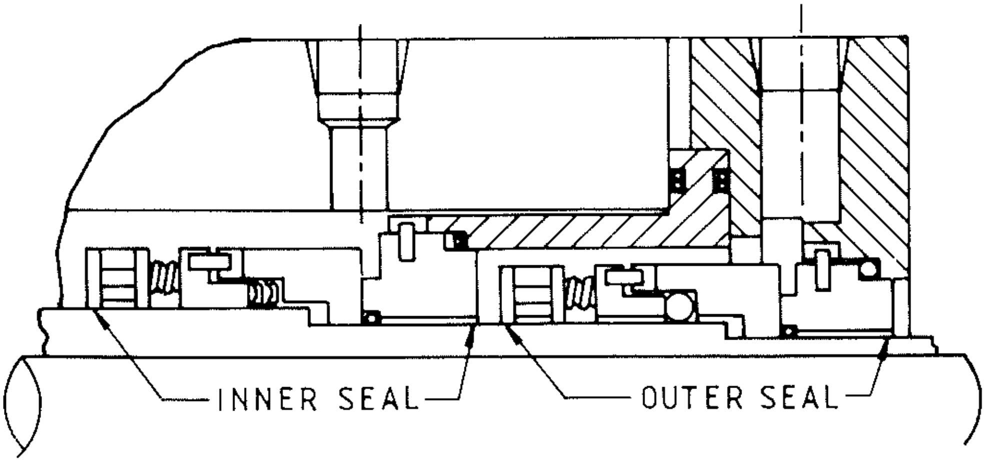


Fig.29. Tandem seal.

Mechanical seal failure

Most seals fail during start-up but in general terms the principal factors that lead to seal failure are:

1. Incorrect seal and auxiliary system selection.
2. Inaccuracy of fitting and maintenance.
3. Failure of the efficiency of the flush, e.g. low/high flow, contamination.
4. Loss of integrity of the secondary seals.
5. Plant malpractice, e.g. process upsets or mis-operation.
6. Vibration (pump cavitation).

If the correct seal type and materials are selected, an adequate seal flushing is provided and the seal is correctly installed, a mechanical seal can be expected to give trouble-free service until the seal faces need renewal.

Correct installation is of paramount importance. Seal manufacturers provide comprehensive instructions on installation, and these should always be followed.

The flatness of the seal face is important in reducing the leakage to a negligible amount, and the faces are lapped to very close tolerances. The face will be flat as supplied, and must be protected during storage and installation to ensure that nothing destroys this flatness.

The pump shaft and bearings must be in good condition and correctly aligned. Excessive axial movement can cause wear or fretting of the shaft and failure of the secondary seal. It can also cause overloading and chattering of the springs and subsequent failure.

The squareness of the gland face should also be checked and the stationary seal must be installed square with the shaft. If it is not square, the sliding part of the seal will move backward and forward during each revolution.

A good summary of the precautions to be taken when installing mechanical seals is given in reference 19.

As part of the Industrial Hygienist approach to control by design, the methods of mechanical seal fitting must be examined. Some companies use segregated ventilated, dust controlled areas to install mechanical seals. For double seals handling highly toxic streams this would certainly be a standard recommendation.

5.4 Applications

5.4.1 Pump seals

Packed glands are used for reciprocating and centrifugal pumps. The major disadvantages of packed glands for use with pumps, compared with mechanical seals, are: the relatively high leakage rate, the higher shaft power loss, and the possibility of shaft wear. However, they can be installed and maintained by less skilled maintenance personnel; and when they do fail they fail gradually with plenty of warning, unlike single mechanical seals which can fail catastrophically.

Lubricated packed glands can be fitted with a back-up seal and drain (Fig.30), to control leakage into the atmosphere.

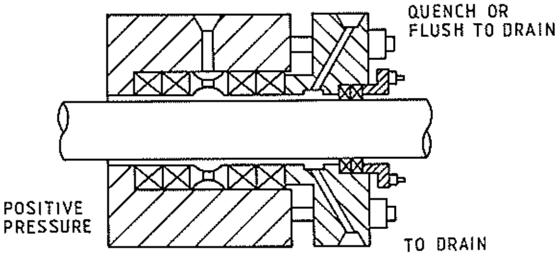


Fig.30. Packed gland with flush and backing seal.

Mechanical seals are normally recommended for use with process pumps. Double seals should be used when leakage of toxic or flammable fluids into the atmosphere must be prevented. Single seals can be backed up with throttle bushings (Fig.31) or a short packed gland, with a flush, to control leakage of the process material into the atmosphere, and as a protection against failure of the mechanical seal.

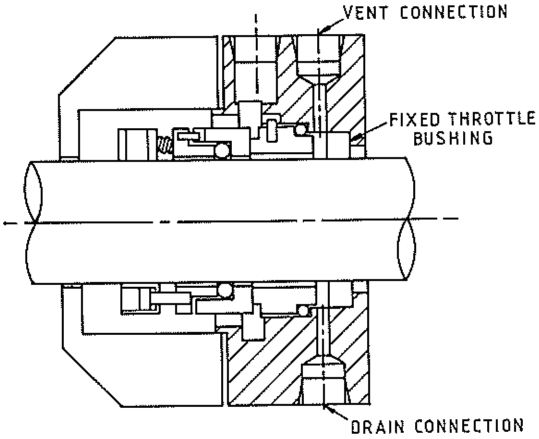


Fig.31. Mechanical seal backed with bush.

Double seals can be fitted with simple devices to detect failure of the inner seal and to shut down the pump or sound an alarm.

Seal-less pumps, with no seal between the pump and drive motor, are available and are used for difficult duties. The motor and pump are enclosed in a single pressure vessel, and the armature and stator protected by metal cans (hence the name 'canned pumps'). The motor runs in the process fluid. The use of canned pumps to control environmental pollution is discussed by Webster.[20] Table 5 gives indications of the relative level of leakage that may be expected from these seal types.

5.4.2 Compressors

Sealing a positive displacement or centrifugal compressor shaft is considerably more difficult than sealing a pump shaft. Labyrinth seals are used on both types, and are relatively trouble-free, but the leakage rates are high with this type of seal - typically 1 to 2% of the compressor flow. The leakage can be collected and vented or the seal chamber purged with an inert sealing gas, if this is compatible with the process requirements.

Carbon seals are also used. These operate on the principle of capillary flow through the close clearances provided by the carbon 'bushes'. The same restrictions apply to this type as to the labyrinth seals, though the leakage rates will be lower.

Oil film seals and mechanical seals with an oil flush provide a more positive seal. The circulating oil will become contaminated with the process gas, and provision must be made for separating the dissolved gases and neutralizing or venting toxic components.

A good description of the types of seal used for centrifugal compressors is given by Nelson.[21]

5.4.3 Agitators

The type of seal that can be used for an agitator shaft will depend on the location of the agitator, i.e. top, bottom or side entry. Top-entry shaft seals will not be in contact with the agitated liquid and will need to be fitted with an external flush for cooling and lubrication.

The simplest seal for top-entry shafts is a hydraulic seal (Fig.32). This type is clearly limited to low pressure operation and non-toxic vapours; it can easily be blown through process mal-operation. Simple lip seals are also used for low pressure, non-critical applications.

TABLE 5
Fugitive emission rates from pump shaft seals

Seal type	Shaft emission rate index
Regular packing without external lube sealant	100
Regular packing with lantern-ring Oil-injection (vacuum service or abrasive service)	10
100% graphite packing (alone or with lube injection)	10
Single mechanical seal (self-flushing or external flushing, floating or fixed bushing)	1.2
High-temperature seal Vapour phase seal	1.2
Single mechanical seal plus auxiliary packing	1.2
Tandem mechanical seal (Barrier fluid at lower pressure than the stuffing-box)	0.15
Double mechanical seal	0.004
Bellows seal (Must include auxiliary packing)	NIL
Diaphram pump (double)	NIL
Canned pump (Not including extra fittings)	NIL

Packed glands and mechanical seals are used to seal agitator shafts where the vessel operates at any significant pressure. Double mechanical seals are recommended for applications where even slight leakage of process vapour to the atmosphere must be prevented. When mechanical seals are used, provision must be made in the agitator design to keep the shaft run-out to within acceptable limits. This can be a problem with side-entry and top-entry shafts, and pedestal (bottom) bearings may be necessary for top-entry agitators. A good discussion of agitator design and the influence this has on seal design is given by Ramsey and Zoller.[22] In terms of relative seal effectiveness, the same data can be used as for pumps, although the absolute levels will tend to vary with shaft size and speed.

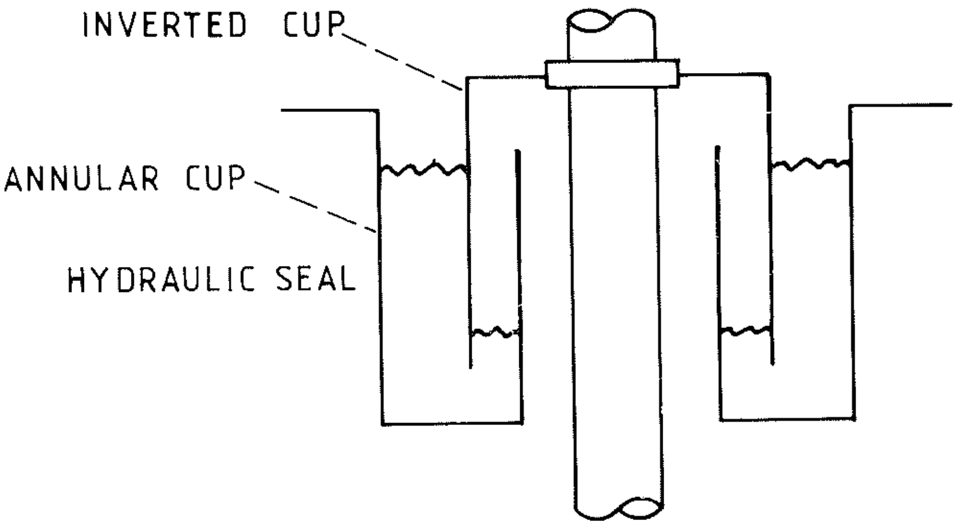


Fig.32. Water lute seal for an agitator.

5.4.4 Valves

In most valve designs the valve stem (shaft) extends through the valve body and a seal is required at the stem to body joint. The valve stem will either slide or rotate, or use a combination of both types of motion, to operate the valve.

The type of seal used will depend on the type of valve. For gate and globe valves, packed glands are used. Globe valves are used extensively for the manual and automatic control of fluid flow. A packing material that retains its lubrication should be used in a valve stuffing-box, e.g. graphite-asbestos and PTFE-asbestos. The packing may be braided, solid, or loose fibres. Packing designs also include O-rings and chevron-rings. Occasionally, a lantern-ring is incorporated in the stuffing-box and the packing lubricated periodically with a suitable grease.

Packed glands are always prone to leak, and for absolute leak security a packless valve should be used. Two basic types are available: those which use a metal bellows to seal the shaft (Fig.33), and those in which the seal is made using a flexible diaphragm (Fig.34).

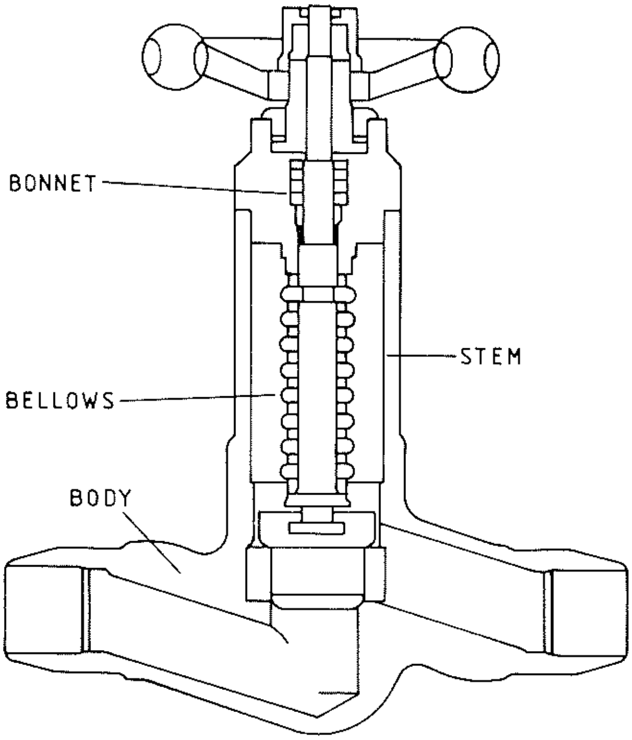


Fig.33. Bellows sealed valve.

Bellows seal valves were developed for use in the nuclear power industry and are available in a range of sizes and pressure ratings (up to 300mm dia. and 150 bar).

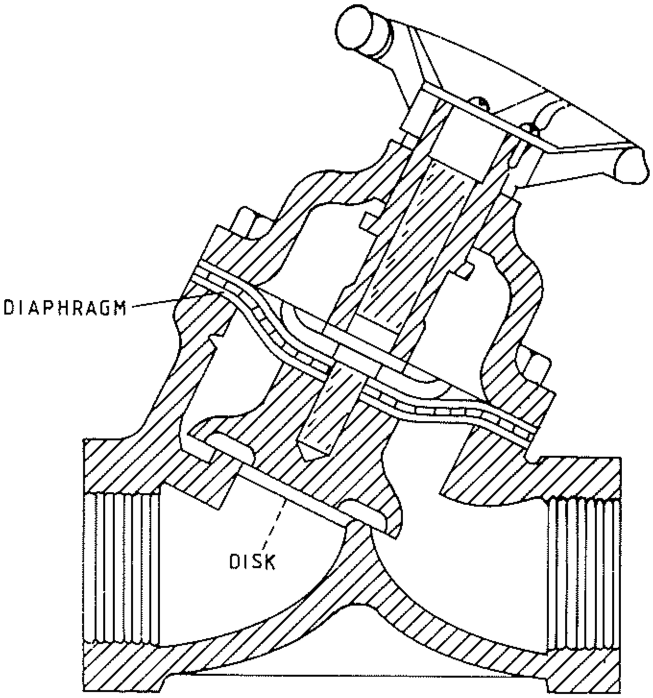


Fig.34. Diaphragm sealed valve.

Valves can leak to the atmosphere through the bonnet-to-body seal. Screwed joints are used for the bonnets of small valves and gasketed flange joints for large valves. The bonnet joint can be sealed with a weld if absolute security is required. Plug, ball and butterfly valves are used as stop valves. These tend to be non-rising stem valves and are rarely sealed with anything but packing or an O-ring. Because they are non-rising stem, they tend to leak less.

Table 6 shows the relative leak rates of various valve seal types.

TABLE 6

Index estimates of valve stem emission rates

(N.B. These rates apply to stem emissions only. Associated flanges, etc. should be considered separately.)

Valve type	Emission rate milligram/sec
Rising stem valves and regular packing	
(a) Rating up to and including 20 bar	100
(b) Rating greater than 20 bar	2
Rising stem valves and 100% graphite packing	
(a) Rating up to and including 20 bar	12
(b) Rating greater than 20 bar	0.2
Non-rising stem valves	0.3

5.5 Costs

Table 7 gives cost indices for the more typical seal types for valves and pumps.

TABLE 7
Emission control cost indices

Seal type	Cost index (total)
Pumps	
Packed	100
Single mechanical	110
Double mechanical	120
Single mech. + back-up	112
Tandem	130
Bellows	125
Canned	120 - 200
Valves	
Packed	100
Bellows	143
Diaphragm	225
Clamp	229

APPENDIX I: RELEVANT U.K. LEGISLATION

A. Health and Safety at Work etc. Act 1974

A.1 General duties

The general duties are qualified by the term 'so far as reasonably practicable'. This means that one must assess on the one hand, the risks of a particular work activity or environment, and on the other hand, the physical difficulties, time, trouble and expense which would be involved in taking steps to reduce or eliminate the risks. If, for example, the risks to health and safety of a particular work process are very low, and the cost or technical difficulties of taking certain steps to avoid those risks are very high, it might not be reasonably practicable to take those steps. However, if the risks are very high, then less weight can be given to the cost of the measures needed to avoid those risks. The comparision does not include the financial standing of the employer. A precaution which is 'reasonably practicable' for a prosperous employer is equally 'reasonably practicable' for the less well off. An assessment of the risks needs to be made before the work commences. The phrase 'so far as is practicable', without the word 'reasonably', implies a stricter standard. The expression ' best practicable means' involves similar considerations. The person on whom the duty is imposed must use the most effective means to comply with the duty, taking into account local conditions and circumstances, the current state of technical knowledge, and the financial implications.

A.2 Duties of employer to employees

The general duties of employers to their employees are set down in section 2 of the Act.

Section 2 (1)

'It shall be the duty of every employer to ensure, so far as is reasonably practicable, the health, safety and welfare at work of all his employees'.

Section 2 (2) further provides that:
'without prejudice to the generality of the above, the matters to which that duty extends include in particular:

Section 2 (2) (a)
'the provision and maintenance of plant and systems of work that are, so far as is reasonably practicable, safe and without risks to health'.

This is a general requirement covering all plant, which the Act defines as including machinery, equipment and appliances used at work. It does not supersede the more detailed and specific provisions covering certain equipment contained in existing legislation, but it goes beyond such provisions in requiring a more wide-ranging assessment of risk.

Section 2 (2) (b)
'arrangements for ensuring, so far as is reasonably practicable, safety and absence of risks to health in connection with the use, handling, storage and transport of articles and substances'.

This subsection is concerned with the materials and articles used at work. 'Substance' is defined (in section 53) as 'any natural or artificial substance, whether in solid or liquid form or in the form of a gas or vapour', so that the subsection covers everything used at work and all work activities.

Section 2 (2) (c)
'The provision of such information, instruction, training and supervision as is necessary to ensure, so far as is reasonably practicable, the health and safety at work of his employees'.

Section 2 (2) (d)
'So far as is reasonably practicable as regards any place of work under the employer's control, the maintenance of it in a condition that is safe and without risks to health and the provision and maintenance of means of access to and egress from it that are safe and without such risks'.

Section 2 (2) (e)
'the provision and maintenance of a working environment for his employees that is, so far as is reasonably practicable, safe, without risks to health and adequate as regards facilities and arrangements for their welfare at work'.

A.3 Duties of employer to other persons

In addition to his responsibilities to his employees an employer will also have duties for the protection of other persons, for example, members of the public. These are stated in section 3 of the Act.

Section 3 (1)
'It shall be the duty of every employer to conduct his undertakings in such a way as to ensure, so far as is reasonably practicable, that persons not in his employment who may be affected thereby are not thereby exposed to risks to their health or safety'. Self employed persons have a similar duty.

A.4 Duties of the responsible person

Section 4 of the Act lays duties with respect to health and safety on those who are in control of any non-domestic premises, where people work who are not their own employees, or where these people use plant or substances provided there for their use.

A.5 Duties on designers and manufacturers

Section 6 places duties on persons who design, manufacture, import, supply, erect or install any article, plant, machinery, equipment or appliances for use at work, or manufacture, import or supply any substance for use at work. It is also placed duties for research on designers and manufacturers. The provisions are set out below. Every employer is likely to be affected by these provisions as a purchaser and user of articles and substances and, in addition, many will have duties as a member of one of the classes of persons quoted in the section.

An 'article for use at work' is defined as:

(a) any plant, machinery, equipment or appliance designed for use or operation (whether exclusively or not) by persons at work, and
(b) any article designed for use as a component in any such plant.

A 'substance for use at work' is any natural or artificial substance whether in solid or liquid form or in the form of a gas or vapour intented for use (whether exclusively or not) by persons at work.

Section 6 (1)
'It shall be the duty of any person who designs, manufactures, imports or supplies any article for use at work

(a) to ensure, so far as is reasonably practicable, that the article is so designed and constructed as to be safe and without risks to health when properly used;

(b) to carry out or arrange for the carrying out of such testing and examination as may be necessary for the performance of the duty imposed on him by the preceding paragraph;

(c) to take such steps as are necessary to secure that there will be available in connection with the use of the article at work adequate information about the use for which it is designed and has been tested, and about any conditions necessary to ensure that, when put to that use, it will be safe and without risks to health'.

Section 6 (2)

'It shall be the duty of any person who undertakes the design or manufacture of any article for use at work to carry out or arrange for the carrying out of any necessary research with a view to the discovery and, so far as is reasonably practicable, the elimination or minimisation of any risks to health or safety to which the design or article may give rise'.

Section 6 (3)

'It shall be the duty of any person who erects or installs any article for use at work in any premises where that article is to be used by persons at work to ensure, so far as is reasonably practicable, that nothing about the way in which it is erected or installed makes it unsafe or a risk to health when properly used'.

There are complementary duties in relation to substances for use at work.

B. Factories Act 1961

Section 63 of the Act (which appeared originally in the 1937 Act) requires all practicable measures to be taken to protect employed persons against the inhalation of dust or fumes given off from any process. Although the use of exhaust appliances sited as near as possible to the point of origin of dust or fume is cited, control at source (e.g. by modifying the potential for fugitive emissions) may be considered as being included in this requirement.

C. Control of Substances Hazardous to Health

These regulations, which are expected to be published in draft in August 1984, are intended to include the principles of process design and control so that occupational exposure limits will be complied with and exposures reduced to the lowest level that is reasonably practicable. This will cover elimination, substitution, containment, ventilation, etc.

APPENDIX II: DATA FROM PREVIOUS STUDIES

This Appendix summarizes the data gathered from major documented studies in this field. It is not intended to be comprehensive but provides an opportunity to view the broad range of problems that can exist in developing a data base of this kind. Neither is it intended to be a critique, therefore the reader is recommended to follow up the references and draw conclusions from the full reports rather than these summaries.

A. Los Angeles Air Pollution Control District (1958)[23]

This study provided the only data on refineries at that time and formed the basis of the Environmental Protection Agency's (EPA) compilation of Air Pollution Emission factors.[24] Key data from the study are listed in Table A1.

Eleven refineries in the Los Angeles area were covered in this work. Sources were assessed for leaks using a soap solution and then quantified if a leak existed. Liquid leaks were measured by 'collection' (in bags for gravimetric analysis) and gas/vapour leaks by enclosing in a polythene bag and using an explosimeter on the bagged air. Because of the poor sensitivity of the instrument, small leaks were estimated at one value, i.e. anything not registering on the explosimeter but said to 'leak' by the soap solution method would be given the same leak-rate value.

The key problems.with this study are:

(i) The soap solution test cannot be applied to all fittings (temperature extremes prohibit the use). This study therefore has a major gap in its sampling strategy and cannot represent the whole population of fittings.

(ii) Explosimeters are of limited sensitivity and variable accuracy.

B. Environmental Protection Agency (1974)[25]

The EPA commissioned Air Products and Chemicals Inc. to carry out a survey of atmospheric emissions from the petrochemical industry in 1973-74. Fugitive emissions are given low priority and usually estimated merely as other emissions.

Although the reports include 'estimations' of fugitive emissions they simply represent guesses by the manufacturers based on material balances. Since little or no breakdown by equipment is given this work is of no importance in the context discussed here.

C. BASF Study by Alois Bierl (1977)[26]

(See Table A2.)

In total, BASF examined over 9,000 leak sources using primarily a bagging technique and different analytical techniques depending on the chemical emitted, the phase and the size of the leak involved. These methods were much more sophisticated than the Los Angeles study and would have significantly reduced the operator/analytical error involved in the data collection. Another advance on the Los Angeles study was the fact that Bierl achieved a greater categorization of equipment types which again would have reduced the error involved.

In general, the Bierl study gave results at least an order of magnitude lower than the Los Angeles data.

D. Environmental Protection Agency (1979) Radian Study [3, 5, 9]

(See Table A3.)

Commissioned by the EPA this study was carried out starting in 1979 (final report 1981) by the Radian Corporation. The objective was to define the total emissions from petroleum refineries but, finding fugitve emissions to be significant, this aspect was expanded. Thirteen refineries in the U.S.A. were covered giving 5,649 leak sources in all. Streams were stratified into gas/vapour, light-liquid and heavy-liquid (heavier than kerosene). Leak sources were 'bagged' with Mylar bags and the emitted chemical collected in the air stream created either by a vacuum pump or pressurized plant air (cleaned). After a period of flushing the air stream was sampled using a syringe, a Teflon bag and a 3-way valve. This air sample was then taken away for analysis by gas chromatography. Radian also developed a correlation of the actual leak-rate with the maximum air concentration (ppmv) at the point of leak. The purpose of this was to allow definition of a technique for a full monitoring regulation without needing to use the full bagging technique.

Table A3 also shows that the Radian data listed as emission factors are not the original arithmetic means but a 'mixed' mean to account for the high levels of zero leakers.

E. Environmental Protection Agency (1979) Monsanto Study[27]

(See Table A4)

At the same time as the Radian work in refineries, EPA commissioned Monsanto Research Corporation to do the same program in chemical plants. Monsanto used identical analytical techniques to examine leak sources from four manufacturing units, i.e. monochlorobenzene, butadiene, dimethyl terephthalate, ethylene oxide/glycol.

Sources were randomly selected (from P α I diagrams) and at least 40 of each source type were tested.

The Monsanto data are in general much lower than both the 1958 study and the Radian 1979 study. There is also considerable variation from process to process.

F. California Air Resources Board (1979)[28]

This work was carried out on valves and flanges as a check on the 1958 Los Angeles data for these fittings. Six refineries were covered checking on 13,685 valves and 24,826 flanges. Accurate measurements of leaks were taken initially using a gas chromatograph (GC) and then a visual scaling system correlated to the GC data already generated. Results gave a valve leak occurence of 9% (compared to 13% in the 1968 study) and an emission factor of 2 gm/h (compared to 3.75 gm/h for the 1958 study). The flange leak-rate was concluded to be negligible as in the 1958 study. Because of the difference in the non-leakers these data are essentially the same as far as the arithmetic mean of the 'leakers' is concerned, i.e. 22 gm/h in this study versus 28.8 gm/h in the 1958 study.

G. Schroy, J.M.: Prediction of Workplace Contaminant Levels (1979)[29]

This paper was presented at a Symposium of Control Technology in 1979. Schroy (Monsanto) put forward a compilation of emission factors to be used for industrial hygiene calculations of workplace exposure. These factors were solely extracted from the literature (see Table A5) and consisted in the main of Bierl's work[26] with gaps filled by AP-42 factors - 3rd edition, 1977.[30]

H. NIOSH (1981)[31]

This in-house NIOSH report is entitled 'Control of Emissions from Seals and Fittings'. The concept was to put together all of the information on control technologies and a state-of-the-art summary of the New Source standards proposed by the EPA[32] (see section J below). The report accepts the Radian 1979 data put forward by the EPA.

I. Rockwell International (1981)[33]

The American Petroleum Institute (API) contracted Rockwell International to determine emission factors for components in petroleum production operations. The study covered 21 facilities located in four geographic regions, on-shore and off-shore. A total of 173,609 components were monitored for leaks in well drilling, oil and gas producing and gas plant operations.

Measurement used a soap solution scale (0-4) visually assessed and previously correlated with a gas chromatograph (GC) method or, where the soap test was not feasible (hot, cold, etc.), then the full GC sample procedure (similar to the Monsanto and Radian technique) was carried out.

The extreme range of streams handled here, i.e. heavy crude, light crude, condensate, gas, etc., and the difference in process operations make a comparision with normal processing units impossible. The conclusions of the report however are that emission factors for refinery operations (Radian) are <u>not</u> applicable to production operations. In any event, the factors for production operations are at least an order of magnitude lower than the factors used in refinery operations.

J. Environmental Protection Agency (1981)[34]

To assist the EPA in drawing up regulations for the standards for new sources (in terms of fugitive emissions and maintenance requirements), Radian was asked to carry out this extension to the earlier project. The work was intended to develop data to determine the effectiveness of routine maintenance in the reduction of fugitive emissions from in-line valves.

Three manufacturing units were examined, ethylene, cumene and vinyl acetate. Selection of valves was based on maintenance requirements so that, although emission data are available, they cannot be used as a representative population.

TABLE A1
Emission rates (gram/hour) from Los Angeles Air Pollution Control District, 1958[23]
(Refinery operations)

Equipment type	Units tested	Arithmetic mean emission rate based on all sources
Pump seals	473	79
Valve seals	9,521	3.8
Flanges	326	NIL
Compressor seals	326	161
Relief valves	165	55

TABLE A2
Emission rates (gram/hour) from BASF work by Bierl, 1977[26] (Chemical operations)

Equipment type	Units tested	Arithmetic mean emission rate based on all sources
Pump seals	67	6
Valves		
Slide α regulating	1,800	2.8
Heavy duty	400	0.084
Ball	125	0.014
Flanges		
10 - 20 bar		
Gas service	5,000	0.02 gm/h per metre outer flange circumference
Liquid service	600	0.2 "
40 - 80 bar		
Any service	950	0.01 "
Recip. Compressors	13	13
Relief valves	50	2.8

TABLE A3
Emission rates (gram/hour) from Radian work for EPA, 1979[5] (Refinery operations)

Equipment source	Units tested	Arithmetic mean emission rate based on all sources	
Pump seals			
Light liquid	470	113	(86.45)*
Heavy liquid (Kerosene)	292	20.9	(9.17)
Valves			
Gas/vapour	563	26.8	(20.5)
Light liquid	913	10.9	(7.7)
Heavy liquid	485	0.23	(0.22)
Flanges	2,094	0.25	(0.296)
Compressor seals	142	635	(293)
(Hydrocarbon service)			
Relief valves	148	86.2	(62.7)

* Figures in parentheses give the data arithmetic mean whereas those not in parentheses give the emission factors calculated using a mixed distribution theory.

TABLE A4
Emission rates (gram/hour) from Monsanto work,1979[27] (Chemical plants)

Manufacturing units

Equiment type	Monochloro benzene	Butadiene	Dimethyl terephthalate	Ethylene oxide Glycol
Pump seals	23/7.7	160/63	20/3.3	82/13
Valves	1.5/0.05	120/17	37/1.5	1.6/0.07
Flanges	82/2.2	0/0	110/3.4	1.0/0.03
Compressors	-	59/54	-	11/5.9
Relief valves	-	14/5	0/0	0/0
Agitators	200/200	-	218/145	-
Process drains	-	-	-	68/40
Sample valves	-	-	91/40	-

(-) no data available

Numbers represent: arithmetic mean of sources that leak/ arithmetic mean of all sources.

Appendix II

TABLE A5
Compilation emission rates (gram/hour) by Schroy, Monsanto, 1979[29]
(Chemical operations)

Equipment type	Emission rates (gram/hour)
Flanges	
10 - 20 bar	
Gas service	0.02 gm/h per metre outer flange circumference
Liquid service	0.2 "
40 - 80 bar	
All services	0.01 "
Valves	
Gate and control	
10 - 20 bar	6
40 - 80 bar	0.1
Ball	0.015
Pressure relief	2.8
Pressure relief and rupt. disc.	NIL
Pumps or centrifugal compressors	
Packed	80
Single mechanical	
Process fluid flush	6
Water flush	0.02
Double mechanical	NIL
Reciprocating compressors	
Rod packing	
single	161
double	13
Agitators	Use packed or double mechanical seal data for pumps except losses for agitator = lossespumpx$\frac{\text{face velocity}}{1.9}$ (m/s)
Tanks	
Floating roof	60% of API Bulletin 2517 calculations

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