current approximation to a primary scale above 25 kbar is the piston-cylinder system. However, significant improvement must be made in this technique before its reliability will be greater than indirect extrapolation techniques directly tied to the primary scale at lower pressures.

2.1. The Free-Piston Gage

The use of a piston-cylinder pressure system for which both the force and the area are directly measurable as a primary pressure scale is the obvious approach. However, a consideration of the lack of reproducibility and the unknown nature of the frictional forces between the piston and the cylinder as well as the packing inserted to prevent leakage around the piston in a hydrostatic system leads one immediately to the consideration of techniques where friction can be reduced drastically or, if possible, eliminated.

Work before 1920[3] demonstrated that by oscillating a close fitting packing-free piston through a finite angle or by continuously rotating such a piston one could obtain pressures reproducible to better than one part in 10^3 provided care was taken to obtain an adequate initial fit between piston and cylinder. This result represents a dramatic improvement over a piston with packing. Force is applied in such a system by directly loading the free piston with weights placed on an appropriate hanger which rotates with the piston and simultaneously balances the pressure applied to the bottom of the piston as it protrudes into the pressure chamber. Michels (1923, 1924) strongly recommended the use of a continuously rotating cylinder, and most investigators in recent years have used this technique.

The removal of the piston packing, of course, allows leakage of the pressure transmitting fluid past the piston, and the piston slowly falls. Therefore, fluid must be supplied to the pressure chamber if the piston is to remain "floating". The leak must be slow enough to allow adequate time for balancing and adjustments. It is significant to realize that the free-piston gage acts completely like a barometer for a fixed-volume system since an increase in weight on the piston simply compresses the enclosed liquid and increases the chamber pressure while simultaneously measuring this pressure.

Historically, the continuous stimulus to obtain higher precision and higher accuracy led to further analysis, theoretical and experimental, of the leakage flow and the elastic distortion of the system. An analysis of the viscous flow through the crevice around the piston shows that the viscous forces (which in this system represent the only vertical frictional force) can be completely accounted for by the introduction of an effective piston area A_e in place of the measured area A_0 of the piston. This effective area is to a first approximation equal to the mean area of the piston and the cylinder providing the two are concentric.

The introduction of an effective area, the determination of which is discussed later, allows one to make allowance for noncircular pistons or cylinders, inaccurate measurement of the piston or cylinder dimensions at zero pressure, and changes of dimensions with time, as well as the most dominant effect, the distortion of the piston and cylinder caused by the chamber pressure itself. The refinement of measurements by the use of the free-piston gage and the reliability of pressure determination made with the gage depend on the proper evaluation made of this effective area and how it changes with pressure and under various operating conditions.

For low pressures, where the mercury manometer discussed below has its greatest utility and accuracy, a direct comparison between the two gages will yield an experimental measurement of the effective area based on the mercury manometer as the primary scale. Extensive intercomparison of this type has led to a better understanding of the free-piston gage. Michels (1923, 1924) and Keyes and Dewey (1927) showed theoretically that the effective area is not dependent on the viscosity of the fluid in the crevice. Beattie and O. C. Bridgeman (1927) reported on experimental verification of this result to within an accuracy of 0.002 percent for good lubricating oil at low pressure, but Dadson (1958) reports a small variation of the effective area depending upon the fluid used. Beattie and Bridgeman further showed that measurable variation of effective area of approximately 0.05 percent can occur due to aging of the metal parts over a period of five years. Further change is surely caused by wear if the piston is used excessively. When the piston was balanced in a different position along its axial length, variation of the effective area amounting to a few parts in 10^4 was measured by Roebuck and Ibser (1954) and others. These measurements illustrate nonuniform dimensions of the piston and cylinder along their axial length. This effect is not commonly understood and is spoken of as a taper error. The so-called cork-screw effect becomes evident when the balancing force for a fixed pressure depends on the direction of rotation of the piston. This effect, of course, is caused by helical microgrooves produced within the piston-cylinder system as the two are lapped to their final fit. Michels (1923, 1924) and also Bett and Newitt (1963) demonstrated the existence of a minimum angular rotation speed of the piston below which the piston will not be concentric with the cylinder. This condition causes a change in the viscous-flow pattern and a resulting change in effective area. All of the above-mentioned limitations can be and have been overcome by more modern machine processes, but an understanding of these effects is essential for checking the operation of a free-piston gage and the construction of a gage for use as a primary scale.

[3]See extensive bibliography by Meyers and Jessup (1931).

Numerous articles have also been written describing ways of applying torque to keep the piston rotating without applying a vertical force and also novel ways of placing weights on and off the balance. It is the concensus of many authors that the simplest system of applying weights is the best and that measurements should be made while the piston is "coasting".

In addition to being cognizant of the above pitfalls, one must make a variety of rather standard and obvious corrections when high precision work is done. These corrections have been well outlined by Cross (1964), Johnson, et al. (1957), and Johnson and Newhall (1953). They include: (a) temperature expansion of the pistons and cylinder, (b) local variation of the gravitational constants, (c) air buoyancy of weights, (d) fluid head to the pressure measuring chamber, and (e) fluid buoyancy on the piston.

If an accuracy better than a few parts in 10^4 is desired, great care must be taken to determine the effective area A_e at low pressures and then to determine the variation of this area with pressure. Dadson (1955, 1958) used special measuring techniques developed by Taylerson (1953) on two separate piston-cylinder systems and calculated an area ratio. He then balanced the two systems against each other to directly measure the area ratio. The calculated and observed ratios agreed to approximately one part in 10^5 when proper care was taken.

Using the above-mentioned modern machining and measuring techniques Dadson (1955, 1958) has shown that at a few atmospheres pressure agreement of approximately one part in 10^5 can be obtained between properly operated piston-cylinder gages and a mercury manometer. If the mercury manometer itself is considered as the primary scale, the effective area can, however, be measured to a high precision since the balancing process is sensitive to a few parts in 10^6. At higher pressures, the elastic deformation of the piston and cylinder caused by the internal pressure changes the effective area a comparatively large amount and in a somewhat unknown manner. The effort to refine a primary pressure scale based on the free-piston gage has been dominated during the last decade by theoretical and experimental attempts to evaluate this particular change in effective area. This effort has resulted in an effective increase in accuracy of approximately an order of magnitude at pressures above one kbar.

This elastic distortion is so severe for a standard free-piston gage that different piston-cylinder systems are often needed to cover different pressure ranges in order to prevent excessive fluid flow through the enlarged crevice. This high rate of leakage reduces the sensitivity of measurements involving the instrument and at the higher pressures represents a very serious limitation of this simple free-piston gage. Nevertheless, Konyaev (1961) has shown that if rapid piston movement is allowed, a single piston cylinder can be used from 0 to 25 kbar. Bridgman (1909a, 1911a) designed a re-entrant cylinder system illustrated diagrammatically in figure 1, in which the pressure exerted, as indicated by the arrows, closed the crevice at higher pressures and eliminated the problem of leakage. This geometry, however, is not favorable for the evaluation of elastic distortion errors. Early attempts to experimentally evaluate the elastic distortion by reference to a mercury manometer, Michels (1923, 1924), Beattie and Edel (1931), and H. Ebert (1935), were inconsistent and misleading and were such as to be inconclusive as to the order of magnitude of the effect. Theoretically, the problem is very complex even if an idealized, perfectly cylindrical geometry is assumed at zero pressure. Factors involved are the highly pressure-dependent viscosity of the liquid, the shape of the crevice as a function of axial length, and the elastic deformation of a finite length piston and cylinder. A further complication at the higher pressures is a change of elastic parameters of the metal with pressure.

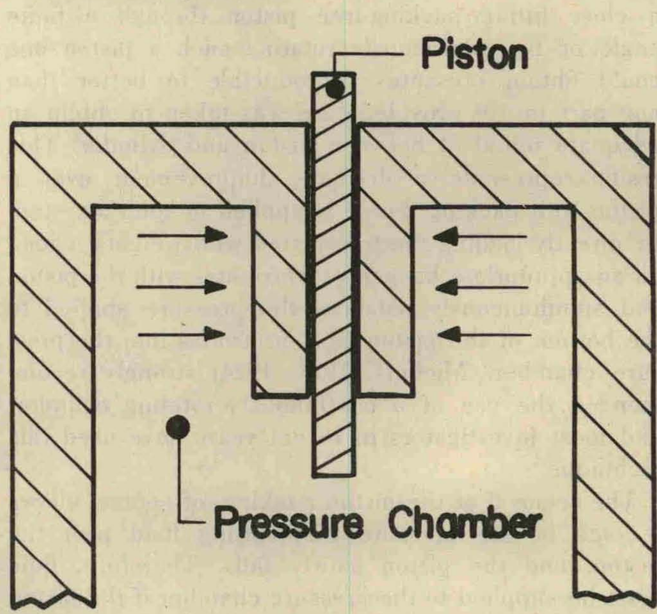

FIGURE 1. Bridgman's re-entrant type cylinder showing use of counter pressure to decrease gap at high pressures.

Three somewhat unrelated approaches have been extensively pursued in an attempt to evaluate the elastic distortion errors. First, a detailed analysis of the deformation has been made using elastic theory with unproven assumptions followed by an evaluation of the assumptions based on experimental intercomparisons of gages so analyzed. Since a well constructed free-piston gage can be balanced with a sensitivity of 0.01 bar at pressures of 10 kbar, predicted discrepancies of gages of different construction can be readily checked against each other and yield an indirect check on the assumptions of the theory. Second, a controlled-clearance piston gage was developed by Johnson and Newhall (1953) in which the distortion of the cylinder is eliminated by use of a counterpressure applied in an annular ring surrounding the cylinder as shown in figure 2. In this geometry, the piston extends well outside the