with either the similarity method or the controlled-clearance gage. On reading Dadson's papers one is impressed with the care in construction and analysis which characterizes his work using the similarity method. His work on the determination of the mercury point shows the same care and precision techniques. This experimental integrity adds considerable confidence to this measurement. The similarity method, however, is subject to much greater fundamental uncertainty when compared with the controlled-clearance gage, especially at the higher pressures. For example, the correction terms for use of metals with differing Poisson ratios in the similarity method as indicated above are of the same order as the total elastic corrective terms in the controlled-clearance gage. Furthermore, the use of two measurements in the similarity method rather than the one in the controlled-clearance gage tends to give error accumulation. In the calibration of the mercury freezing pressure, the determination of Newhall, et al. using the controlled-clearance gage involved only one measurement and lacked adequate sensitivity in the determination of the transition point due to the use of the change in volume as an indicator of the transition. The lack of repeated measurements reduces confidence in the error flag.

In contrast, Yasunami's work, using the controlled-clearance gage, appears to be of very high quality. The work was characterized by very high sensitivity of detection, a large number of repeated measurements, and the use of a relatively large diameter piston (1.1 cm). Unfortunately, the large piston required the use of a lever (of rather large arm ratio) which throws a serious uncertainty into the mercury-point determination. It is interesting to note that Yasunami's higher value differs from the other measurements in the direction explainable on the basis of friction. One limitation common to a different degree in all recent determinations of the mercury point is the lack of knowledge of the temperature or temperature effects on the piston. For example, temperature gradients within the piston have not been considered at all.

In the selection of a standardized instrument upon which a primary pressure scale can be based, the controlled-clearance piston gage has several rather strong features to recommend it in preference to other presently available techniques. First, the instrument can be used over a very wide pressure range. Second, the change in effective area with pressure is of the order of 20 percent of that exhibited by regular free-piston gages. This implies that errors in elastic constants with pressure will not be as serious. Third, sensitivity of the system does not decrease drastically at the higher pressures due to excessive fluid leakage. Fourth, the analysis of the variation of effective area with pressure is well based with assumptions and idealizations involved in only minor correction terms. Fifth, special materials involving appropriate elastic parameters are not required.

The fact that no other workers have attempted to compete with Dadson and coworkers indicates a feeling among others in the field that his analysis has been extended nearly to its limit. This is not the case for the controlled-clearance gage. Several rather obvious but time-consuming studies need to be carried out using a controlled-clearance gage. First, in light of Dadson's measured variations of the values of λ depending on fluids used, measurements should be made using a controlled-clearance piston with different fluids in order to see if the assumptions involved in the extrapolation to the "zero-leak" condition are valid for low and high viscosity liqiuds. This, of course, is the most serious uncertainty in the controlled-clearance technique. Second, the use of pistons of different elastic properties would give an internal check on the change of elastic parameters with pressure. Third, a reliable pressure multiplier (perhaps of the type used by Zhokhovskii and coworkers) needs to be developed. Such a multiplier would allow the use of larger diameter pistons at the higher pressure, thus making initial area measurements more precise and also decreasing the percentage error associated with uncertainties in gap width. Fourth, a more careful analysis of the piston-temperature problem should be made.

It appears from the work of Johnson and Heydemann that such a primary scale can be extended to pressures of at least 26 kbar, and since fluids with reasonable viscosity are available above this pressure, it appears possible that with appropriate technical development the primary scale could be extended well above 30 kbar.

2.2. The Mercury Manometer

Historically the mercury manometer has been considered by most workers as the most suitable fundamental pressure standard due to its inherent simplicity. The height of the column, the density of the mercury, and the gravitational field at the geographical point are the only fundamental quantities involved, and since all three could be measured with rather high accuracy at a rather early date, the mercury manometer became a very natural standard. The simplest manometers used a column open to the atmosphere, and the temperature of the mercury which influences the density was simply measured at one point and assumed constant throughout. A significant number of such columns were constructed and operated to heights of 300 meters during the period from 1840 to 1900. Present-day columns a few meters in height use the highest purity mercury, well-controlled temperature baths, and elaborate height-measuring techniques. Since the pressure is low, all pressure heads associated with connecting lines must also be considered, and care must be taken to measure accurately the position of the mercury meniscus and to minimize surface tension effects. Serious problems with temperature control are associated with manometers for pressures above a few atmospheres due to their inherent height.

As early as 1894 Stratton (1894) proposed the use of a multiple-tube manometer which consisted of a number of alternating columns of mercury and a low-density liquid (water or some suitable organic). In 1915 Holborn and Schultze (1915) first described the differential mercury manometer which consists of a single mercury column, to each end of which is attached a free-piston gage. Since a free-piston gage can reproduce a given pressure with a precision and order of magnitude better than its inherent accuracy, known pressures can be transferred from the top to the bottom of a mercury manometer using the free-piston gage, and higher pressures can be developed while maintaining the accuracy of the mercury manometer. The compactness, relative convenience, and suitability for temperature control of either the multiple manometer or the differential manometer allowed the extension of the mercury manometer to higher pressures while maintaining the accuracy of the small open-column manometers.

As mentioned above, extensive intercomparisons with free-piston gages using this type of mercury manometer as a standard instrument led to the rather thorough understanding of the free-piston gage. Notable developments and refinements in these manometers were made by Wiebe (1897), Crommelin and Snid (1915), Keyes and Dewey (1927), Meyers and Jessup (1931), Roebuck and Ibser (1954), and Bett and Newitt (1963).

Keyes and Dewey (1927) built a differential manometer usable to approximately 600 bar with reported accuracy of approximately one part in 10^4. Meyers and Jessup in a rather extensive work described a five-column multiple manometer useable to 15 bar with an accuracy better than one part in 10^4. Operation of the five columns as a unit in a differential manometer extended the pressure range to 75 bar with a precision of a few parts in 10^3. No mention of accuracy was made. Roebuck and Ibser (1954) were able to measure pressures to 200 bar with an accuracy better than one part in 10^4 using a multiple manometer consisting of nine columns 17 meters in length with temperature controlled to approximately 0.3 °C. The most recent and by far the most extensive use of a mercury manometer to calibrate free-piston gages is the work of Bett, Hayes, and Newitt (1954) and Bett and Newitt (1963) using a differential manometer constructed to operate at 2500 bar with a column nine meters high. Temperatures were controlled to approximately 0.02 °C, and extreme care was taken to determine density and purity of mercury, and other variables influencing pressure heads.

Intercomparison with free-piston gages yielded the first definitive quantitative measurements of the change of effective area with pressure in a free-piston gage. Anticipated accuracies were approximately three parts in 10^5 at 500 bar and six parts in 10^5 at 2500 bar. Calibrations of free-piston gages were carried out to 700 bar using a cumulative method of transferring each pressure from the bottom to the top of the mercury column (60 to 70 transfers). Measurements to 1400 bar were made using a differential method in which the effective area of the free-piston gage was assumed to vary linearly with pressure as was indicated in the cumulative method. In this differential technique, the differential manometer measures only a change in pressure associated with a change in effective area of the piston but has the advantage that errors are not cumulative.

Coefficients λ for the change of effective area of the piston gage with pressure of 3.55×10^{-7}/bar and 2.83×10^{-7}/bar were obtained using the cumulative and differential methods respectively for the same free-piston gage, which corresponds to a difference of approximately one part in 10^4 at 1400 bar. The difference was attributed to error accumulation, and the result of the differential technique was given preference by the authors. No such discrepancy was observed for a gage calibrated to approximately 100 bar. This coefficient for the change of effective area with pressure is compared with a value of 4.2×10^{-7}/bar given by Dadson (1955, 1958) for a similarly constructed free-piston gage. This discrepancy in the determination of λ between the mercury manometer and the similarity method of Dadson cannot be traced to a single effect. Bett and Newitt seriously questioned the current data on compressibility of mercury.

Recent data by Davis and Gordon (1967) on the compressibility of mercury indicate a discrepancy from previous data much less than that needed to explain the different values of λ obtained by the two different methods. It is not unreasonable that some of the discrepancy in λ can be due to Dadson's similarity approximations. The extension of a differential manometer to higher pressures using the well-constructed and well-designed apparatus of Bett and Newitt demonstrated some rather serious limitations of the mercury manometer at the higher pressures. First, the knowledge of the compressibility of mercury and any other liquids in the manometer and the variation with pressure of these compressibilities represent a serious limitation to increased accuracy. Second, the error accumulation due to a large number of transfers is not completely understood. This of course, is associated with the free-piston gages used for transfer and perhaps indicates a weakness in our analysis of free-piston gages given before. Third, the inherent human factor involved in numerous transfers is questionable.

While free-piston gage construction and understanding have improved due in large measure to studies using mercury manometers, the improvement in accuracy of the mercury manometer and its extension to higher pressures have not kept pace. As stated pre-