ANALYZING SYSTEMATIC ERROR IN "BEAD METHOD" MEASUREMENTS OF METEORITE BULK VOLUME AND DENSITY. R. J. Macke[1], D. T. Britt[1], and G. J. Consolmagno[2], [1]Department of Physics, University of Central Florida, Orlando, FL 32816-2385, macke@alum.mit.edu, [2]Specola Vaticana, V-00120, Vatican City State.

Introduction: Measurements of meteorite porosity depend on two separate quantities: grain density, generally determined by ideal gas pycnometry; and bulk density, for which measurements the Archimedean bead method has gained favor among a number of investigators [1,2,3]. This method involves submersing a meteorite in a container filled with small (~40-80 μm dia.) glass beads, which mimic a fluid without the numerous drawbacks to be found in using a true liquid. This method assumes that the behavior of beads closely approximates that of an incompressible fluid with uniform density, but our experience shows that it is not entirely the case. Humidity, variations in shaking/settling methods, and the location of the sample in the container have all been shown to result in bead packing variations which can produce small density variations in the final sample values. In addition, the finite size and limited mobility of the beads may prevent uniform flow into cavities or around parts of the meteorite that press against the walls of the container. As a result, measurements of meteorite bulk density are subject to systematic variations which need to be taken into account prior to calculating porosity. This study attempts to quantify the systematic error present in the method.

The Bead Method: The bead method is discussed in further detail in [1,4]. The bulk volume of a meteorite is determined by placing it fully into an open-topped container of known volume and possessing a flat rim. The container is filled with beads, which are allowed to settle according to some method, after which the top is scraped flat with a straight-edge. The mass of the whole system is measured. Random error is determined by repeating the process multiple times and using the mean and standard deviation. The process is then repeated for a container with the meteorite absent.

At different times, different methods of settling the beads have been applied. Two methods that have recently been favored include vigorously shaking the container for a set time using a mechanical platform to compact the beads; and gently tapping the container with a soft instrument, such as the bristles of a brush, to encourage stray beads to flow into unoccupied cavities with minimal disturbance to the system. These methods have appeared to give comparable results in the past [4], but have not been applied systematically to the same samples for comparison purposes.

The bulk volume of the meteorite is the volume of the container minus the volume occupied by beads.

Bead volume, in turn, is the mass of beads in the container divided by the density of beads. (The bead density in question is the density of a quantity of beads packed together to the same degree as those in the container. This density includes the unoccupied space between beads, and so will be less than the density of one individual bead.) Mass of beads is simply the total mass with the mass of the meteorite and of the empty cup subtracted. Bead density is determined from the measurements made without the meteorite. It is the mass of beads in the meteorite-free container divided by the container volume. Combining these factors and simplifying, the bulk volume of the meteorite can be easily calculated:

$$V_m = V_c \left[\frac{m_{T0} - (m_T - m_m)}{m_{T0} - m_c} \right], \quad (1)$$

where

- V_m = the meteorite volume,
- V_c = the volume of the container,
- m_{T0} = the total mass of the container filled only with beads,
- m_T = the total mass of the container filled with beads and meteorite,
- m_m = the mass of the meteorite, and
- m_c = the mass of the container.

Bulk density, then, is the meteorite mass divided by this volume.

Known Sources of Error: As seen in Equation 1, measurement of bulk volume is dependent on the volume of the container, the total mass of bead-filled containers (with and without meteorite) and other factors.

Finding the container volume has proved to be more problematic than one would at first expect [4], and some container-volume measurements may be off by as much as a few cm^3. This in turn systematically skews all bulk volume measurements in the same direction as the error in container volume.

Variations in bead density (which influence total mass measurements) also influence error. If the density of beads in the meteorite-free container differs considerably from that of the container with the meteorite, then the basic assumption that was made in calculations does not apply. It is known that temperature, humidity, and the method used to settle beads in the container all influence density. To minimize the effect, it is important that all measurements pertaining to a particular meteorite take place under the same environmental conditions and according to the same settling methods, insofar as that is possible. Generally, measurements are made as close together in time as possible, so that local environmental conditions will not have changed significantly. However, we have noted that the laboratory facilities for many meteorite collections possess only rudimentary climate control, particularly for institutions that predate modern construction. In these cases, temperature and humidity may vary significantly over relatively short time scales. Environmental conditions at the beginning of a measurement may differ from those at the end of the measurement. For this reason, it is often advisable to "sandwich" meteorite measurements between bead-density calibration runs (those measurements made with the meteorite absent from the container).

The presence of the meteorite itself may also influence bead density by compressing beads more than they would otherwise be compressed (since meteorites are generally more dense than the beads themselves). The geometry as well as the mass of the meteorite may influence this compression. Massive samples with large, flat surfaces seem to have the greatest effect. Such flat surfaces are quite common among meteorites of many collections, since many samples have been cut at least once, leaving at least one smooth face. Some possible ways to minimize the effect of this face include laying the sample face-down in the container and holding the sample immobilized by wedging it against the sides of the container. The former is inadvisable in containers that do not have perfectly flat bottoms or for samples whose face is not perfectly flat, since beads will not flow properly into parts of the region under the face that are not in contact with the bottom of the container. This will result in overestimates in bulk volume, and corresponding underestimates of bulk density. Immobilizing the sample by wedging it into the container is also inadvisable for even moderately friable samples, which may lose pieces in the process. It is also inadvisable for use in flexible containers, which may deform in such a way as to alter their volume.

Systematic Error Measurements: The purpose of this study is twofold: to determine the amount of systematic error present in various methods of pouring and settling beads, and to find the method that will minimize systematic error. The former is necessary in order to correct results of the hundreds of measurements that have already been made using this method. The latter will help minimize systematic error in future measurements, thus yielding more reliable porosity estimates. Due to the complexity of the problem, we are not as yet able to characterize all sources of error and their relative weights, but by using samples of known density as standards we can quantify their overall effect on the final measurements.

We used as standards in this study a set of eleven quartz crystals of varying masses, ranging from 9.3 g to 121.3 g. These crystals have zero porosity, and therefore bulk density should match grain density. Grain densities for all samples were verified using a Quantachrome helium pycnometer. We then applied the bead method to each crystal in the set and compared with the expected result. We systematically varied methods of pouring and of settling beads. We repeated the tests for three commonly-used container sizes.

Initial results from the method involving soft tapping of the container indicate the presence of a small but measurable systematic error in the direction of an underestimate of bulk density. This would yield overestimates of porosity. This is not entirely surprising; the tapping method may result in cavities (presumably toward the underside of the sample) being incompletely filled, thus contributing to a volume overestimate. However, the discrepancy is not mitigated by attempts to partially submerge the sample in a half-inch bed of beads prior to pouring and settling.

We will report in greater detail on the results of this study, including the manner in which systematic error for each method is affected by variations in sample mass and container volume.

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