Determining the volume of E1 weights
Automatic testing facility for determining the volume of solids

Introduction
The determination of mass using conventional testing facilities is generally carried out in air under normal conditions. The mass of air (1 m³ weighs approximately 1.2 kg), however, causes a systematic error in the procedure. Every solid body is affected by buoyancy in relation to the amount of air it displaces (Archimedes' Law). Air buoyancy makes a 1-kg stainless steel weight appear to be approx. 0.15 g lighter than it is. If the test weight has the same density as its mass reference, the air buoyancy can be discounted, since weights that have the same mass will have the same buoyancy. But if the test weight has a lower density than its mass reference, then it takes up more space with 1 kg than the 1-kg mass reference. Thus, the test weight is subjected to more buoyancy and seems lighter than it actually is.

This is why determination of density is indispensable for precise determination of mass, which is essential for metrology institutes, accredited calibration services and similar laboratories. This is reflected in international regulations, such as OIML R111 for a one-kilogram E1 weight, which allows a mass tolerance of only 0.5 mg. Such precision cannot be attained in the determination of mass without determining the density of the weights and making the necessary correction for buoyancy.

Requirements and objectives
Building on years of excellent cooperation, the BEV and the Institute of Production Engineering of the Vienna University of Technology, together with Sartorius AG in Goettingen, Germany, have developed and built a fully automatic testing facility for determining the volume of weights. The goal was to enable hydrostatic density determination in accordance with OIML R111 (class E1 for multiple solid bodies or weights). The procedure is based on mass comparison, as opposed to weighing, with specific steps taken to ensure that the temperature in the measurement chamber is as stable as possible. The result is a testing facility that analyzes the density of up to eight weights ranging from 1 g to 1 kg. With this approach, uncertainty of measurement is not related to mechanical factors, and thus depends on ambient conditions and the quality of the measuring instruments.

Summary
Determination of the volume of weights is necessary for the correction of air buoyancy, and thus is an essential capability for today's metrology institutes. The Austrian Federal Office of Metrology and Surveying (BEV) and the Vienna University of Technology, at the request of and in cooperation with Sartorius AG in Goettingen, have developed a fully automatic load alternator for weighing below the mass comparator, for use in volume determination of E1 weights and plummets using 1-kg mass comparators. Thus, the hydrostatic weighing principle can be applied for serial volume on masses from 1 g to 1 kg through direct comparison with a single volume reference (e.g., a silicon sphere). This is implemented with a newly developed, fully automatic insertion mechanism for both completely submerged weights and substitution weights. This system is used at the BEV for volume measurements in connection with the determination of mass, as well as in other metrology institutes and accredited calibration laboratories.

Fig. 1: Volumetric mass comparator VD1005: prototype at the BEV
**System design**

The testing facility is constructed in the form of a tower (Fig. 2). A double-walled storage container for liquids is installed on the lowest level. The outer layer contains normal water and serves to regulate the temperature; it is supplied and regulated by an external thermostat. Baffle plates provide for a homogeneous flow of water around the internal container at all times. A stable temperature is ensured by means of a 40-mm layer of insulation around the entire system and the use of insulated metal inserters. Additionally, the insulation of the individual levels of the testing facility prevents convection currents around the mass comparator. The inner vessel – the measurement cell – has been kept as small as possible in order to use as little as possible of the highly purified measuring liquid and, with the exception of a small entry portal, is completely surrounded by the liquid in the outer layer. Even regulation of the temperature on all sides makes it possible to reduce the formation of temperature layers to a negligible level. The temperature of the measuring liquid is monitored by two diagonally mounted high-precision sensors (25-ohm standard platinum-resistant thermometers (SPRT) in compliance with ITS 90). For both the substitution weights and the test weights, a position below the mass comparator was chosen. (Figs. 3 and 4). This eliminates off-center loading problems on the weigh cell. The specially developed load alternator makes it possible to insert the 1-g to 1-kg weights and density references spheres with no rearrangement required, and to position them precisely in the suspension device of the mass comparator. The insertion mechanism positions the weights on the magazine spaces in the measuring fluid vessel.

The entire control system as well as all electronic components are housed in a control cabinet (Fig. 1). The system is controlled by an industrial computer, which is also used to evaluate the data. To determine environmental parameters, the unit has sensors for air pressure, humidity and air temperature. A number of additional sensors are provided in order to exclude errors in the measuring process.
Measurement procedure
Unlike other systems, this unit uses a mass comparator to compare each test weight directly with a volume reference. This means, however, that either the test weights must have a reference of their own with a similar mass, or the measured weight of each object must be corrected through reference to a different mass by using substitution weights in air. Both of these methods are enabled by this unit. Thus it is possible to adapt test weights with different masses directly to a volume reference (e.g., a silicon sphere). Although the density of the measurement fluid as a transmitter is constantly monitored, it is of secondary importance due to this mass dissemination capability. It is important, however, to make sure that the density remains constant during the course of a measurement (approximately 2 minutes). The software’s user interface prompts the operator to prepare the measurement inserting the reference weights, the test weights and the appropriate substitution weights. This entails use of the weight insertion mechanism; it is important at this point to make sure there are no air bubbles on the weights once they are immersed in the liquid. A total of nine spaces are available for the reference and test weights. Once the sequence and number of cycles have been entered, the measurement can begin.

Software
The software (Fig. 5) assists the operator in the preparation and execution of the measurements. In addition to the fully automatic measurement program, operators have the option of performing individuals steps separately (single-step mode). In addition, the program shows the operator all the measurement data from the sensors in real time as well as the current progress of the measurement.

The result of each measurement is the volume, the density and the mass of each test weight, with complete documentation of the conditions of measurement and default values. Measurement values and all associated data can be provided as raw value output or on printouts that contain a complete evaluation of the measurement data.

In validation and testing of the initial system at the BEV, in-house comparative measurements of the density of solid bodies — in this case with a plummet (Pyrex sphere; mass approx. 119 g, volume approx. 97 m³) — with the new testing facility showed a deviation in volume of less than 0.9 mm³ and in mass of less than 0.07 mg. Comparisons with reference weights at the BEV also showed excellent results. One unit is already being used to measure the volume of weights with a mass of 1 g to 1 kg in the scope of mass determinations at the BEV, and for ongoing in-house and external calibrations.

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