Resume of Work on Mass Measurement Devices

1. Mass with length and time form the triad of primary measurements from which all other measurements are derived. Mass in contrast to length, for example, cannot be measured directly but must be derived from indirect measurements. One of the properties of mass is that it has an attraction for all other masses. In the presence of a very large mass, such as the earth, an attraction is exerted toward all other masses on the face of the earth, the magnitude of which is directly proportional to the mass of a given object. This attraction is gravity. The measurement of mass on earth is and has been since the dawn of history by weight. This weight is simply the force of the attraction of gravity for a given object. The magnitude of this force is directly proportional to the mass. The great variety of scales in use on earth today are all "gravimetric" devices which depend upon this universal attraction of gravity.

2. In orbital space flight, this attraction of gravity is offset by the centrifugal motion required to stay in orbit such that this force is no longer available for measurement of masses. The measurement of mass by weight is so simple and successful that no other method of mass measurement has been available for use under zero gravity conditions. Obviously, the need for mass measurement still exists and is, in some cases, even more important for space research. These needs will not decrease in the future as increasing amounts of scientific research are done in space. It may be safely assumed that as larger vehicles become available for longer on-station studies that many of the current researches that are conducted on earth in the fields of chemistry, physics, and biology will be studied under space conditions. The situation in space without a mass measurement device is precisely that which would prevail in current earth laboratories if all gravimetric scales were suddenly removed.

3. In the current phase of space research, which is primarily that of providing the necessary propulsion, guidance and assuring life support system which is compatible with man's survival in space, scientific studies have centered on these problems. One of the major problems has been man's physiological reaction to space. One aspect of this problem is man's cardiovascular adaptation to the weightless environment. In order to perform this study, means of measuring the man's

mass as a function of time under zero-G, the mass or volume of his excretory products, and the mass of intake are required. Some form of accurate mass measurement is thus needed for the measurement of man, of food and liquid intake, and fecal and urinary output. Liquid intake and output would be more reasonably performed by volume measuring devices, but to date none have proven suitable.

4. These problems have been identified in various theoretical studies for several years, and several proposed systems for mass measurement have been made by a number of corporations and individuals. The most active group has been Lockheed Missiles and Space Division, who have built a number of large prototype mass measurement devices which are nothing more than laboratory demonstration devices but which have not had the requisite accuracy. Douglas Aircraft also had a contract for investigation of the problem, but they too were unable to meet the accuracies required. These required accuracies are on the order of .1 percent, while the contractor has been able to achieve 1 percent or worse. In summary of the problem, an urgent need exists for a mass measurement system which is compatible with the conditions and constraints of operating within the current generation of spacecraft which will cover the mass range of a few grams to say 100 kilograms with an accuracy of .1 percent or better. Because of the urgent requirement for this and the lack of promising work, an in-house program was started approximately one year ago at Aerospace Medical Division which had as its goal the investigation of the non-gravimetric determination of mass, selection of the most promising method for this evaluation, thorough investigation of this method, and construction of models to demonstrate feasibility of such devices. In addition to the attraction of one mass for another, there are other characteristics of mass including inertia. This inertial characteristic of mass was first given quantitative expression by Newton. This is the familiar expression, "Force is equal to mass times acceleration." This quality of mass provides us with a number of possible methods of its measurement, for example, a known force could be applied to the unknown mass, and the resulting acceleration could be measured; and from these two factors, the mass could be determined. This, for a number of reasons, is not simple in practice. One of the problems, for example, is accurate knowledge of the force applied as well as measurement of the resulting acceleration. This measurement can be simplified by timing the distance taken to traverse two points. However, in practice this requires a relatively long, complicated and precise track in which a mass can be accelerated.

A variation of this system consists of placing springs on either side of the mass, displacing the mass against one of the springs, and then releasing it. The mass will then be accelerated toward the neutral position by the force of the displaced spring; however, when it has reached the neutral position, it has acquired a velocity which will have to be absorbed by the opposite spring. The cycle will then be repeated from the opposite direction with a resulting continuous oscillation until all of the stored energy has been dissipated. In order to determine mass under these conditions, it is only necessary to know the spring constants and the period of time of a complete cycle of the oscillation that the mass performs about its position of equilibrium. It is also essential that the mass move in a straight line to avoid other effects. This was a method chosen for investigation and has been described as a linear spring/mass pendulum. This is also the method used by Douglas and Lockheed Aircraft in their investigations. The period of time that is required for a given mass to undergo a complete cycle of oscillation about the center point is equal to the square root of the mass divided by the spring constant minus another term which is a function of mechanical resistance of the system.

$$T = \frac{M}{K} - F(R,M)$$

T = Period (time) of 1 cycle of oscillation

M = Mass

K = Spring constant

R = Mechanical resistance of system

The difference in our approach to the utilization of this method was in the attempted elimination or reduction to an insignificant value of the mechanical resistance of the system such that it no longer entered the equation in significant quantity. This is in distinct contrast to previous devices which had used wheels, bearings, and similar devices for support. Other significant improvements were in the use of precise springs of an extremely stable nature such that the spring coefficient which appeared in the equation remained constant under all conditions and in the use of an extremely precise zero crossing detector, i.e., the device which determined exactly when the mass crossed zero displacement or equilibrium point. The displacement of the mass required is a function of the accuracy of this detector and for a number of reasons this displacement should be kept at a minimum. The validity of these concepts were explored experimentally with a variety of laboratory devices most of which utilized an air bearing (a device which is virtually frictionless) to support the mass under zero-G conditions and to constrain it to move in simple translatory motion, i.e., along a single straight line. A great deal of effort was expended on the design of springs and in finding a manufacturer which could meet the stringent specifications. An optical zero crossing detector with a distance resolution of a few micro-inches (millionths of an inch) was constructed in-house which allowed the use of relatively short amplitudes of motion, 1/4 inch or less. Timing circuitry, accurate to one millionth of a second was arranged to allow full utilization of the accuracy of this device. With such devices it was relatively simple to demonstrate that accuracies of .01 percent or better could be obtained over mass ranges of a few grams to over 100 kilograms using solid weights. Over this wide range of masses, it is necessary to use two separate mass measurement devices of different capacity just as different scales are required for chemical measurements as compared to those required for the measurement of weight in a doctor's office. The problem of measurement of liquids was also investigated, and it was found that if the liquid were contained in a plastic bag with relatively little entrapped air, the mass the liquids could be determined to a high order of accuracy. By means of a fixed volume, rigid container, the measurement of "specific gravity" (density) was also demonstrated to a rather high order of accuracy, one part in a thousand. Such measurements are, of course, used routinely in clinical work for specific gravity determinations of urine and similar fluids. A very large part of the investigative program was expended on determining optimum arrangements for the measurement of mass under this arrangement. Man is not a rigid mass and when he is shaken or oscillated as in the case of this mass measurement method, parts of the body may not move at exactly the same velocity as other parts, primarily the thoraco-abdominal viscera, or as we say, he "sloshes." In addition, small involuntary movements occur even in the quietest individual as well as forces which are generated by the cardiovascular system and by respiration or as we say here, he "jitters." A great deal of time was spent in investigations of these factors as well as the effects of wind resistance on large objects in this measurement. The accuracy to which man's mass may be determined with the spring/mass pendulum is a function of how slowly he may be oscillated. In space cabin atmospheres, he can hold his breath for a minimum amount of time, say 15 seconds, because of the pure oxygen and the danger of atelectasis. It was earlier shown that for any degree of accuracy to be achieved he must, in fact, hold his breath. Thus, we have the problem of choosing a frequency of oscillation such that the mass measurement will not require breath holding for more than say 15 seconds but which at the same time will yield the necessary accuracy. In the range of approximately one cycle per 3 to 5 seconds, absolute mass measurements may be made to an accuracy of .1 percent, the measurement of a given individual from day to day may be determined to a better accuracy than this. After the fundamental problems were investigated, the necessary electronics , circuits, and other components designed and demonstrated, it was necessary to demonstrate a practical arrangement which could be further tested under more realistic simulation of space flight conditions. The fundamental design was laid out in house with a contract to Southwest Research to do the detailed mechanical and electronic design and to fabricate the necessary electronic components. The mechanical fabrication was done in-house because of the skill of the instrument shop in work of this nature. A small mass scale was constructed in which the air bearing arrangement was replaced by a spring arrangement called a plate fulcra which both supports the mass, fills the function of the previous two springs, and constrains the motions to approximation of simple translatory motion. The scale was designed to measure masses in the equivalent weight range of 50 to 500 milligrams with an accuracy of a few hundredths of a percent. In addition, a 20 to 30 fold reduction in the size and power over the existing electronics had to be accomplished to allow them to be included in a reasonable sized package. This was accomplished by means of integrated circuitry. Internal batteries allow continuous operation for 12 hours or more of this device. Each weighing cycle requires a relatively few seconds. The device was constructed in a package of approximately 1/3 cubic feet which may be qualified to NASA's specification for use in Apollo and similar vehicles, which is completely self-contained and has a demonstrated maximum error of $\pm$.015 percent. The device is operated simply by turning a lever to "on," setting the electronics counter to zero by means of a push button, placing the mass to be measured in the scale's pan, displacing the pan, and allowing approximately five seconds for a weighing cycle to be completed. The measured time is displayed on a six digit decimal readout and the resulting number may be then compared to a graph for accuracies of .1 percent or may be handled with a desk calculator for accuracies of .01 percent. This device has been extensively ground and flight tested in altitude chambers and in F-100 and C-131 zero-G aircraft. This accuracy has been demonstrated under the zero-G conditions. We are currently attempting to have the device flown as an experiment on one of the NASA missions. In addition, a contract is now underway for production of a flight-qualifiable prototype which will cover the range of weights of 500 grams to 100 kilograms which would also allow mass determination of man. The order of accuracies already demonstrated will be maintained with this device. The same electronics which are currently utilized in the small scale may be used on the large scale. This large scale will weigh a few pounds and occupy less than one cubic foot of space.

5. In summary, we have investigated the problems of non-gravimetric mass determination, have constructed or are in the process of constructing hardware which will cover the current range of mass measurements of interest with a reasonably high accuracy of .01 percent for fixed massas and the mass of man to .1 percent. These devices are flight qualifiable and have been extensively tested on earth. This is a very marked improvement of accuracy of any similar existing device with an increase of 10 to 100 times in accuracy and the devices may be fabricated for orbital use in a very short time in contrast to the other devices which could only be described as laboratory experiments. There are many individuals and various organizations who deserve credit for this program; one of the most important of which is the local instrument shop which has done a superb job on the mechanics of this device. Individuals in this organization who deserve a great deal of credit include Mr. Wright and Sgt. Benz, who constructed all of the original air bearings, Mr. McDougal who has played a major role throughout the program and particularly in the construction of the flight-qualifiable mass scale, Mr. Rosenbush who assisted in the construction of this scale and Mr. Sparkman, the shop supervisor and especially Mr. Garbich, the shop director. Messrs. Fogwell, Oakie, and Lorenz of Southwest Research have played a significant role particularly in construction of the small scale. John Chattilon and Sons of New York City have been the only

vendors who have been able to supply springs capable of adequate performance. Major Violett of the AMD F-100 detachment at Kelly AFB and the C-131 zero-G crews at Wright-Patterson AFB including Sgts Sears and Bush gave generously of their aid. Mr. Lurie of biostatistics has aided in its evaluation. Mr. Adams of Biomedical Engineering provided instruments, laboratory facilities and some technical support.

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Office of Director for Crew Test & Evaluation

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Bill

John Dick from Douglas

says:

① They were working on mass measuring @ the Santa Monica office. Have stopped work on this.

② It is no longer a Contract End Item - something they must provide to the AF on contract.

③ They were not getting required accuracies - with rigid bodies they were getting ≈ 0.2% - 0.5%

④ They are sending a copy of the "final report" to us - probably take 2 weeks

Don