SURVEY AND EXPERIMENTAL TESTING OF NONGRAVIMETRIC MASS MEASUREMENT DEVICES

by

William E. Oakey

Richard Lorenz

FINAL REPORT

Contract No. NAS 9-14941

SwRI Project 16-4498

Prepared for

NASA Lyndon B. Johnson Space Center

Houston, Texas

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Approved:

Douglas N. Travers
Vice President
Electromagnetics Division

ABSTRACT

Three experimental nongravimetric mass measurement devices were tested and evaluated. In addition, a direct mass readout method was successfully developed and demonstrated. This readout method is intended to replace an earlier oscillation period readout method which required additional manual calculations to determine mass.

Of the three experimental devices, one proved to be an acceptable candidate for further refinement and eventual use. This was a low mass (milligram range) air-bearing oscillator of the spring-mass type. A contract modification increased the original scope to include design, fabrication and testing of a prototype version of this type of mass measurement device. This device was completed, and tests demonstrated accuracy in the range of 0 to 25 grams from 0.26% to 1.35%. Recommendations are made for increasing the measurement accuracy in an improved device.

The prototype 25 gram capacity mass measurement device was delivered to NASA, along with the required documentation.

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I. INTRODUCTION

Although the mass measurement devices used in the NASA Skylab mission performed well, it was anticipated that simpler, more compact and lower cost systems of equal or improved performance could be developed for future space missions. The Skylab mass measurement devices were based on spring-mass oscillators. However, in theory other types of nongravimetric mass measurement devices could be developed, involving basic physical principles relating to mass, acceleration, inertia, and momentum. A program was therefore undertaken for survey and experimental testing to identify feasible mass measurement techniques from candidates proposed by Dr. W. E. Thornton. This program was accomplished over the period 1 March 1976 through 28 February 1977. A direct mass readout system development to eventually replace the oscillation period readout system used in the Skylab mass measurement devices was also part of the program effort.

A contract modification in January provided for development and delivery of a 25 gram capacity mass measurement device using a spring-mass oscillator on an air bearing, and a direct mass readout system. This prototype device was completed in April 1977 and delivered to NASA on 19 April 1977.

II. PROGRAM PLAN

The program plan was built around two work statements of the contract. The original statement of work called for the following tasks:

2.1.1 Repair, adapt, modify, and evaluate the performance of existing prototype or experimental nongravimetric mass measuring systems to be provided by the NASA Technical Monitor. These will include the following:

2.1.1.1 Accelerated gravimetric balance.

2.1.1.2 Very low mass (milligram range) air-bearing oscillator, spring-mass type.

2.1.1.3 Centrifugal direct readout device for liquid mass measurements.

2.2 Fabricate and demonstrate a model of a direct mass readout device for a spring mass measuring system. This task will include evaluation of arithmetic processing integrated circuits appropriate for converting oscillation period measurement to mass. A breadboard demonstration model using the selected integrated circuit will be constructed using an LED or equivalent dispaly. A demonstration will be performed utilizing a spring mass measurement system and an electronic counter with digital output format. The output format will be specified by the Technical Monitor two months after contract award.

A modification to the contract included the following statement of work, in addition to the original tasks:

3.1 Task I - Design and fabrication of a mass measurement device with the following features:

(a) 25 gram capacity.

(b) Extremely lightweight replaceable weighing pan to reduce tare mass to a minimum. The weighing pan should be rugged enough to withstand laboratory use.

(c) Structure to hold samples to weighing pan. Samples could be biological tissues including small animals, chemical samples and the like which will be contained in GFE containers.

(d) Suitable means for offsetting and releasing the weighing pan.

(e) Air bearing support for weighing pan.

(f) Air supply and regulation to meet the needs of the bearing support.

(g) Electronics to:

°Detect each zero crossing.

°Start and stop timing cycles.

°Time and store five operating cycles (five cycles are counted for readings after three or more cycles following release.)

°Convert period of cycles to direct mass readout through internal program. This program must be capable of reprogramming to accommodate changes in calibration, etc. It is desirable to use a CMOS (Complimentary Metal Oxide Semi-conductor) or equivalent constantly operating micropower memory. However, a card-read memory before each operation will be acceptable.

(h) Totally battery operated and rechargeable. Operating time before recharging will be a minimum of 200 weighing cycles (500 cycles desired).

(i) Direct mass readout and zero crossing mechanism.

(j) Matched helical tension springs of Isoelastic or similar material.

(k) Resolution goal $\pm$2mg.

(l) Accuracy goal $\pm$5mg.

(m) Maximum oscillation frequency at minimum mass goal 2cps.

3.2 Task II - Run a predelivery acceptance test to see that the hardware satisfactorily complies with the Task I requirements.

3.3 Task III - Prepare a complete set of working-type drawings in sufficient detail to allow future reproduction of pertinent operating circuitry and components.

3.4 Task IV - Prepare a final report that will supplement the drawings of Task III in defining the characteristics and performance of the hardware.

III. EVALUATION AND TESTING

A. Accelerated Gravimetric Balance

For evaluation of this technique, a commercial steelyard (portable beam scale) was purchased. Figure 1 is a sketch of the scale. Its original capacity of 0 - 200 pounds was changed to 70 - 170 pounds by removing precise amounts of metal from both the fixed balance weight and the movable weight. Various locking and adjusting screws, as well as miscellaneous stop pins were removed. The suspension system was modified to prevent locking up under zero gravity conditions. Finally, the movable weight was provided with a flat spring to bear against the scale. This allows rapid adjustment of the movable weight and assures that the weight will remain in place when set without the need for tightening a lock screw. The modified scale weighed five pounds compared to about twenty pounds for the original scale.

This scale cannot be tested on earth, since its use depends on substituting an acceleration (swinging through a circular path) for normal earth gravity. Therefore, it was turned over to NASA for zero-g testing.

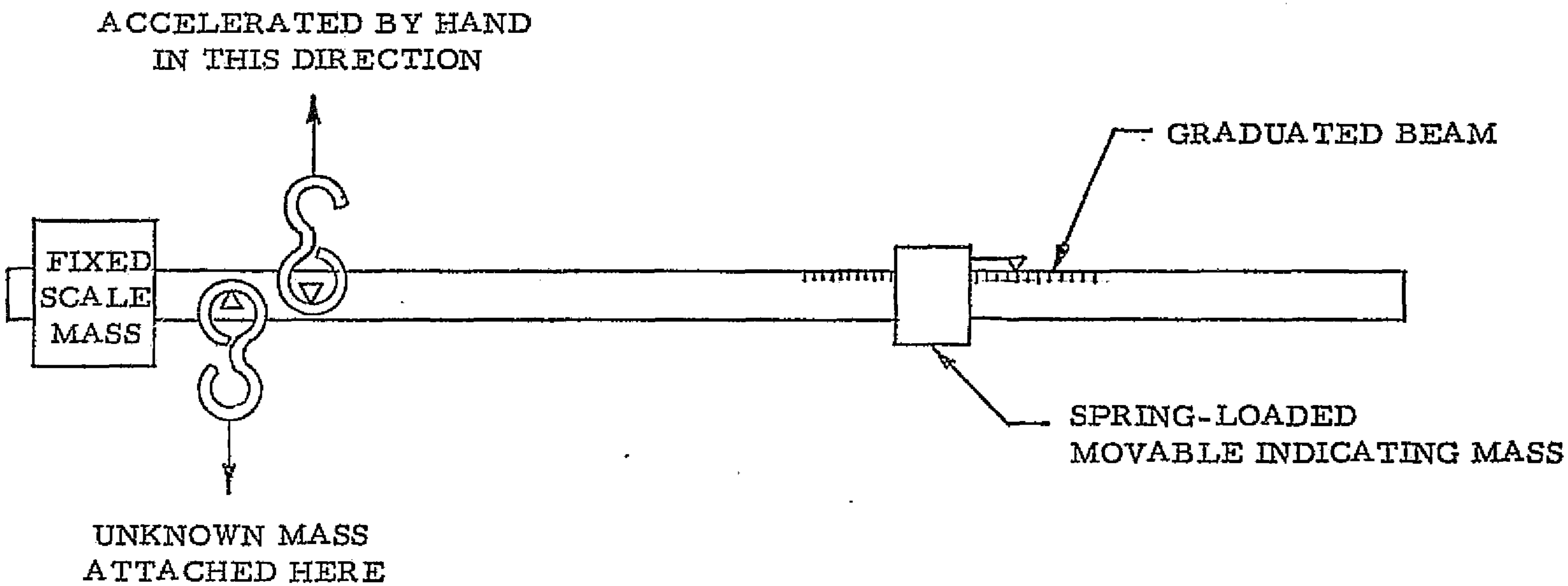


FIGURE 1. PORTABLE BEAM SCALE

B. Low-Mass Air-Bearing Oscillator, Spring-Mass Type

1. Description of Test Equipment

The principal elements of this device were:

(a) A V-shaped air bearing supplied with low-pressure air from a regulated shop air supply. Air pressure was measured with a water manometer.

(b) A V-shaped weighing pan, made of balsa-wood for low tare mass. Attached to the pan was a metal blade for the zero crossing detector, and a loop of thread at each end for attaching oscillator springs. (Items a & b were fabricated outside of SwRI.)

(c) Oscillator springs attached one at each end of the weighing pan. The opposite ends of each spring were attached to fixed points on the base of the device.

(d) A hand-operated sear and release mechanism to first lock the pan, and then release it to oscillate.

(e) An optical zero-crossing detector from an existing mass measurement device.

(f) Various cylindrical masses to be placed in the weighing pan for mass determination. It was intended for the oscillator to have a capacity of about 50 grams, so the cylindrical test masses selected weighed from 11.50 grams to 45.00 grams. These test masses were steel and their diameters varied from 1/8" to 1/4".

(g) An experimental direct mass readout to convert intervalometer readings (periods of oscillation) to actual mass.

2. Test Results

a. Error Determinations

Various air pressures from five inches of water to thirty-five inches of water were applied to the air bearing, the aim being to use as low a pressure as possible to float the weighing pan plus the heaviest mass on the air bearing. Higher air pressures tend to lift the weighing pan off the air bearing, thus producing inaccurate readings.

After experimenting with air pressures, adjusting the zero-crossing detector, and modifying the sear-release mechanism, satisfactory reading were generated. The formula used, developed from a linear regression fit of calibration data, was: $M = 2,854 \times 10^{-10}T^2 - 2.720$, where M = mass in grams, and T = period of oscillation. A typical set of successive mass readings is presented below. Air pressure was 33" of water.

0 grams	9.85 grams	21.10 grams	24.00 grams	31.50 grams	45.00 grams
0.21	9.76	20.96	23.95	31.35	45.12
0.22	9.75	20.98	23.88	31.40	45.15
0.20	9.73	21.04	23.87	31.34	45.13
0.20	9.72	21.01	23.84	31.36	45.10
0.20	9.75	21.08	23.82	31.36	45.06

Average absolute error for 0 grams was 0.20 grams. Average percent error for other masses were:

9.85 grams: 1.0%
21.10 grams: 0.3%
24.00 grams: 0.6%
31.50 grams: .05%
45.00 grams: 0.003%

b. Resolution

Resolution tests were run at zero mass and at 9.85 grams. following are typical readings:

0 grams	5 mg. added	9.85 grams	5 mg. added
0.161	0.165	9.722	9.727
.160	.165	9.725	9.730
.160	.165	9.721	9.727
.162	.165	9.720	9.725
.162	.165	9.721	9.730
.160	.165	9.721	9.727

This resolution was considered satisfactory for the device in its present form.

C. Centrifugal Device for Liquids

1. Description of Test Equipment

This device, designed and fabricated outside SwRI, consisted of a bar about three feet long mounted at the center on a ball bearing at the top of a pedestal. The pedestal was held vertically upright by three horizontal members spread radially from the bottom of the pedestal. In this arrangement, the bar was free to rotate about the center of the pedestal in a horizontal plane. Figure 2 is a sketch of the device.

At each end of the bar, equidistant from the center of rotation, a container was suspended from a spring, a block, and a pivot by three lightweight chains. These containers were intended to hold liquids for mass measurement. A handle grip was provided on one side of the bar for manually accelerating the bar and its suspended containers rotationally.

The fixed acceleration mechanism consisted of a short rod of fixed weight suspended from one side of the bar by flat springs at each end of the rod. As the bar and suspended containers were accelerated, centrifugal force caused the rod to move outward (away from center) until it tripped a latch mechanism. In theory, the latch mechanism would always be tripped only when the rotating system reached a particular angular acceleration; that acceleration being dependent only on the stiffness of the spring system and the weight of the rod. The mass in the containers would be determined from the relationship $f = ma$, where f = force, m = mass, and a = acceleration.

When the bar was rotated, cords attached to the blocks from which the containers were suspended moved outward due to flexure of the springs attaching the blocks to the bar. These cords rotated a disk on the bar until the latch mechanism tripped, at which time a lock held the disk in that position. An indicator point was provided to locate stopping positions on the disk.

In the "zero mass" configuration, both containers were empty, weights and springs were balanced, therefore latching and locking should stop the disk at the same place, as shown by the indicator, each time the bar was accelerated. If known liquid masses were placed in one container, and the bar accelerated until the latch actuated, the indicator should point to a particular point on the disk for each mass. In this way the disk could be calibrated by marking the disk for each known liquid mass. Unknown liquid masses could then be determined by referring to the calibrated disk.

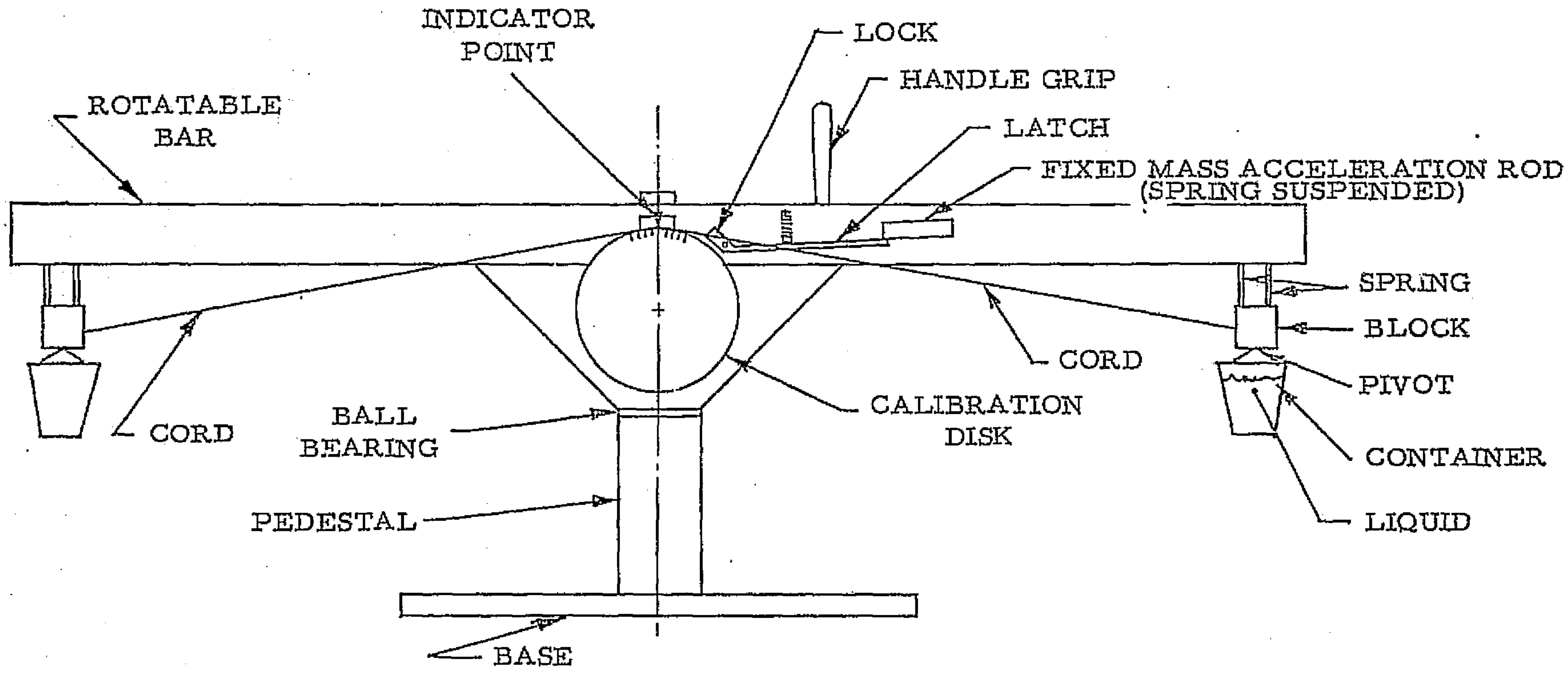


FIGURE 2. CENTRIFUGAL DEVICE FOR LIQUID MASS MEASUREMENTS

2. Test Results

a. General Discussion

This test device proved difficult to calibrate and to obtain repeatability. The acceleration required to trip the latch, for example, using a sample mass of 238 grams, showed repeatability errors ten times as great with a "high" acceleration as with a "low" acceleration. Since the device was accelerated manually, it would be difficult to instruct an operator to use a particular acceleration.

In an attempt to eliminate errors due to varying acceleration, the latch was modified so that it became "set" when a certain acceleration was attained, and then "released" at a predetermined deceleration after the operator had released the hand grip. Other modifications included were replacing the somewhat corroded steel springs in the latch mechanism with new flat beryllium copper springs, remounting the rotating bar so it was square with the vertical pedestal, and clamping the device to a bench to prevent some instability noticed when quantities of water over about 800 ml were rotated. Possible friction variations in the latch mechanism were inherent in the design and could not be readily corrected.

b. Sample Test Results

(1) Spreads of readings with 238 gram sample and device as received, except 400-ml plastic beakers replaced the wide shallow metal weighing pans, and the supporting chains were shortened.

Condition	% Spread of Stop Point On Disk Circumference
No attempt to control acceleration	7.3
"High" acceleration	21.3
"Low" acceleration	2.2
Sample shifted to opposite beaker; no attempt to control acceleration	5.6
Sample removed (zero mass condition)	2.2

(2) Spreads of readings after modifications to device described under paragraph 2. a.

Condition	% Spread of Stop Point On Disk Circumference
400 ml beakers masses up to 200 ml water	1.9
400 ml beakers masses from 240 to 400 ml water	5.8
1000 ml beakers masses from 0 to 550 ml water	4.0
1000 ml beakers masses from 550 to 900 ml water	4.3
Base of device clamped to bench 0 to 300 ml water	1.0
Base of device clamped to bench 350 to 1000 ml water	7.2

c. Dead Weight Test of Latch Mechanism

It was suspected that the release latch did not always release at the same application of centrifugal force. To check this, the centrifugal device was locked in a non-rotating position. Then dead weights were applied to operate the latch by means of a cord and pulley, the cord being attached to the fixed mass which in operation moves out and trips the latch. Following are a series of dead-weight readings, in which water was added to a beaker gradually until the latch tripped, then the water weighed in each case.

265.6 grams	282.0
277.2	279.5
278.7	281.0
284.7	276.0
269.0	276.6
282.5	

The lowest weight was 265.6 grams, and the highest was 284.7 grams. This is a spread of 19.1 grams, or approximately 7%. This is too great an error to compensate for in other parts of the device.

At this point, effort on the centrifugal device was terminated. It was outside the scope of the program to design, fabricate, and test an alternate latch mechanism.

D. Demonstration of a Direct Mass Readout System

A breadboard electronics system was constructed which demonstrated the ability to interface with a commercial calculator and to display mass rather than the period of oscillation. This breadboard electronics operated as a special purpose intervalometer, interfacing with the mechanical portion of an existing SMMD and a Texas Instruments SR-52 calculator. The demonstration was successfully accomplished.

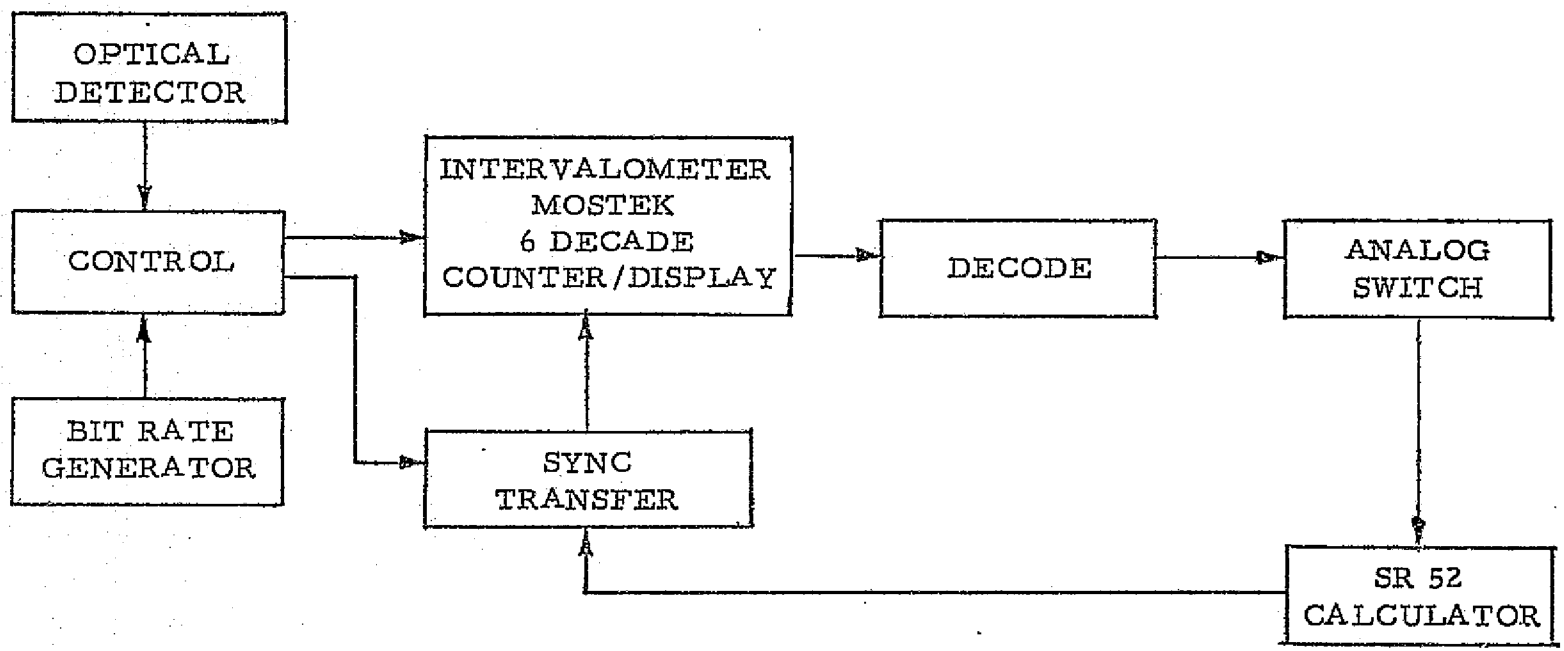
A block diagram of the system is shown in figure 3. The weighing pan motion is optically detected at the equilibrium position, the optical detector controlling the start and stop timing count of the intervalometer circuit. The intervalometer consists of a Mostek 6 decade counter/display LSI circuit which measures and stores the accumulated weighing pan period (five cycles total) up to six digits. From this accumulated period, the mass can be determined. The six digit period is electronically transferred to an SR52 calculator which performs the necessary mathematical calculation. A photograph of the system is shown in figure 4.

Following initiation of the reset button, the system is controlled by the optical detector (thus the weighing pan motion). The ninth tray cycle automatically transfers system control to the internal clock of the calculator. The calculator clock synchronizes the transfer of data from the intervalometer. The intervalometer output is commutated by the calculator clock so that each of the six digits are presented to the calculator in the proper sequence. The last data transfer consists of an A command which instructs the calculator that data transfer is complete and to begin the calculation.

The Texas Instruments SR52 calculator was chosen for use in the system. The following functions were evaluated in this decision:

(1) Performance
(2) Ease of Interface
(3) Cost
(4) Indirect Store and Recall Function in Program Memory

The interface to the calculator was performed using digitally controlled analog gates which parallel the keyboard switches. The keyboard switches are still an active portion of the calculator. The calculator is programmed by magnetic cards. Pre-recorded programs for calibration and operation have been furnished. After each calculator power interruption (on-off switch, etc.), the calculator must be re-programmed by reading the magnetic card.



BLOCK DIAGRAM

FIGURE 3. DIRECT MASS READOUT SYSTEM

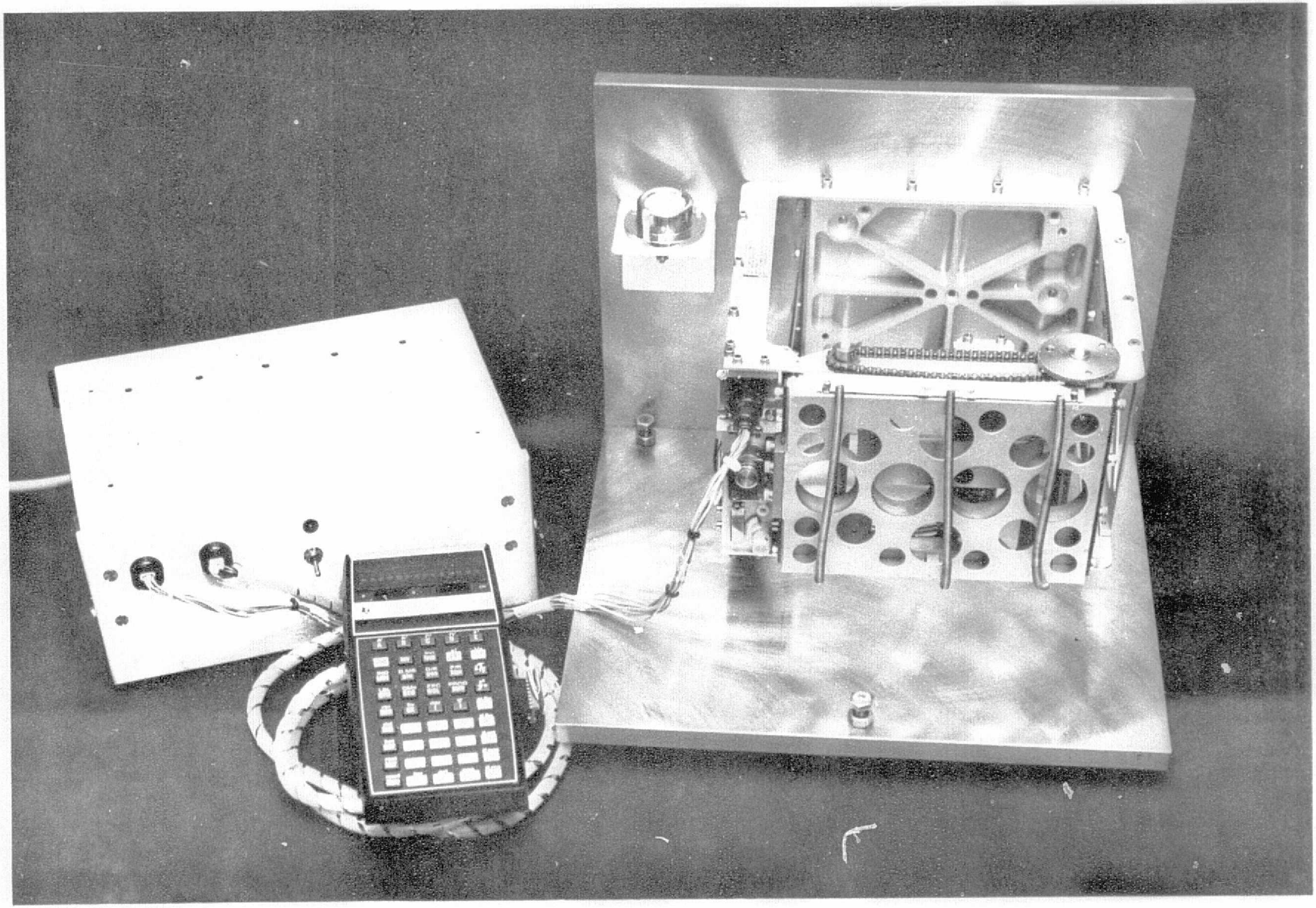


FIGURE 4. DIRECT MASS READOUT SYSTEM BREADBOARD

IV. 25 GRAM CAPACITY MICRO-MASS MEASUREMENT DEVICE

A. Contractual

Modification 2S to the contract, dated 21 January 1977, was executed to extend the contract scope with additional time and funding for the purpose of designing and fabricating a prototype micro-mass measurement device, having a capacity of 25 grams. The purpose of this development is to demonstrate a micro-mass measurement equipment configuration which can be part of the Life Sciences Common Operational Equipment (CORE). Requirements, goals, test schedules, program control, documentation and delivery dates were enumerated in the Work Statement attached to the contract modification.

B. Design and Development

The design of the Micro-Mass Measurement Device (MIMMD) was based on principles developed and tested in the low mass air bearing oscillator and the direct mass readout demonstration model discussed earlier in this report. Drawing No. 4498-001 (figure 5) shows the MIMMD assembly and will be referred to in describing the device. Figure 6 is a photograph of the device.

1. Mechanical

A boxlike structure is used to enclose the electronics and its battery power supplies for direct mass readout. The bottom of the structure provides for leveling screws, while the mechanical components are mounted on the upper surface.

The major mechanical components perform similar functions as those used in the low mass air bearing oscillator mentioned above. However, the design provides for a greater degree of accuracy, ruggedness, reliability, and compactness. For those reasons, the components have been strengthened, fabricated to closer tolerances, and in some areas, made from different materials.

In figure 5 the major components and overall dimensions of the assembled device are called out. The weighing pan is locked when loading a specimen and may be removed for cleaning by detaching the springs at each end. The springs are slanted downward away from the weighing pan to provide a force component for holding the pan against the air bearing in a zero-g environment. These springs are covered to protect them from damage. A level and leveling screws are provided for use in one-g. The weighing pan lock-release mechanism is operated with the lock-release lever. The pan is loaded in the locked position, offset from center. When released, the springs cause the pan and its contents to oscillate. By means of the zero-crossing detector and the electronics system, the mass of the contents is determined and read out in digital form to the nearest milligram. Operation and calibration procedures are included in Appendices A and B.

2. Electronics System

The electronics system operates as a special purpose intervalometer to interface with the various types of oscillating mass measurement systems, including the MIMMD. The design utilizes CMOS digital logic circuits to minimize power requirements. The logic diagram of the system is shown in figure 7. Special features of this circuit include a bit generator operating from a crystal oscillator. By setting internal miniature

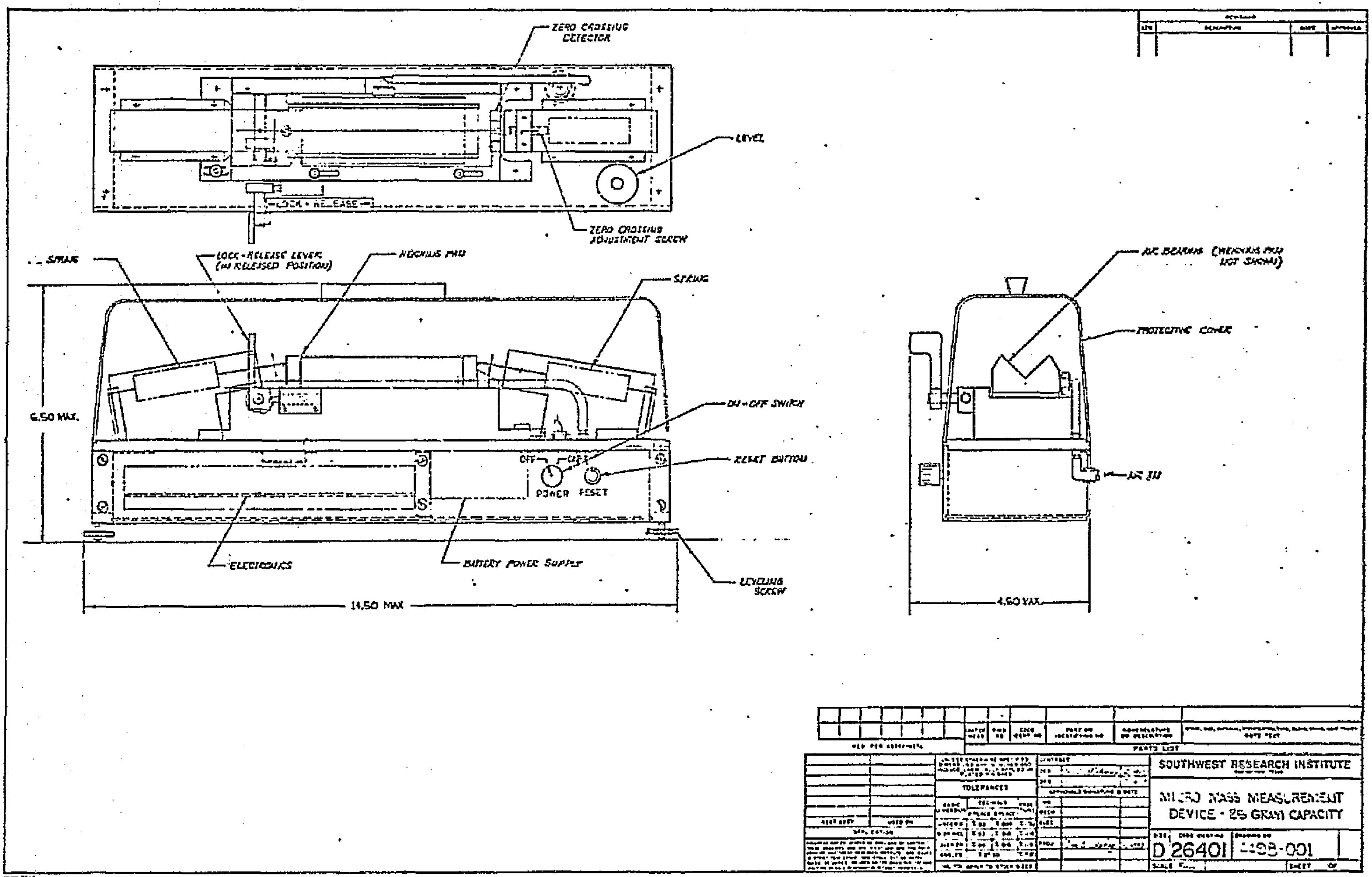


FIGURE 5. MIMMD ASSEMBLY

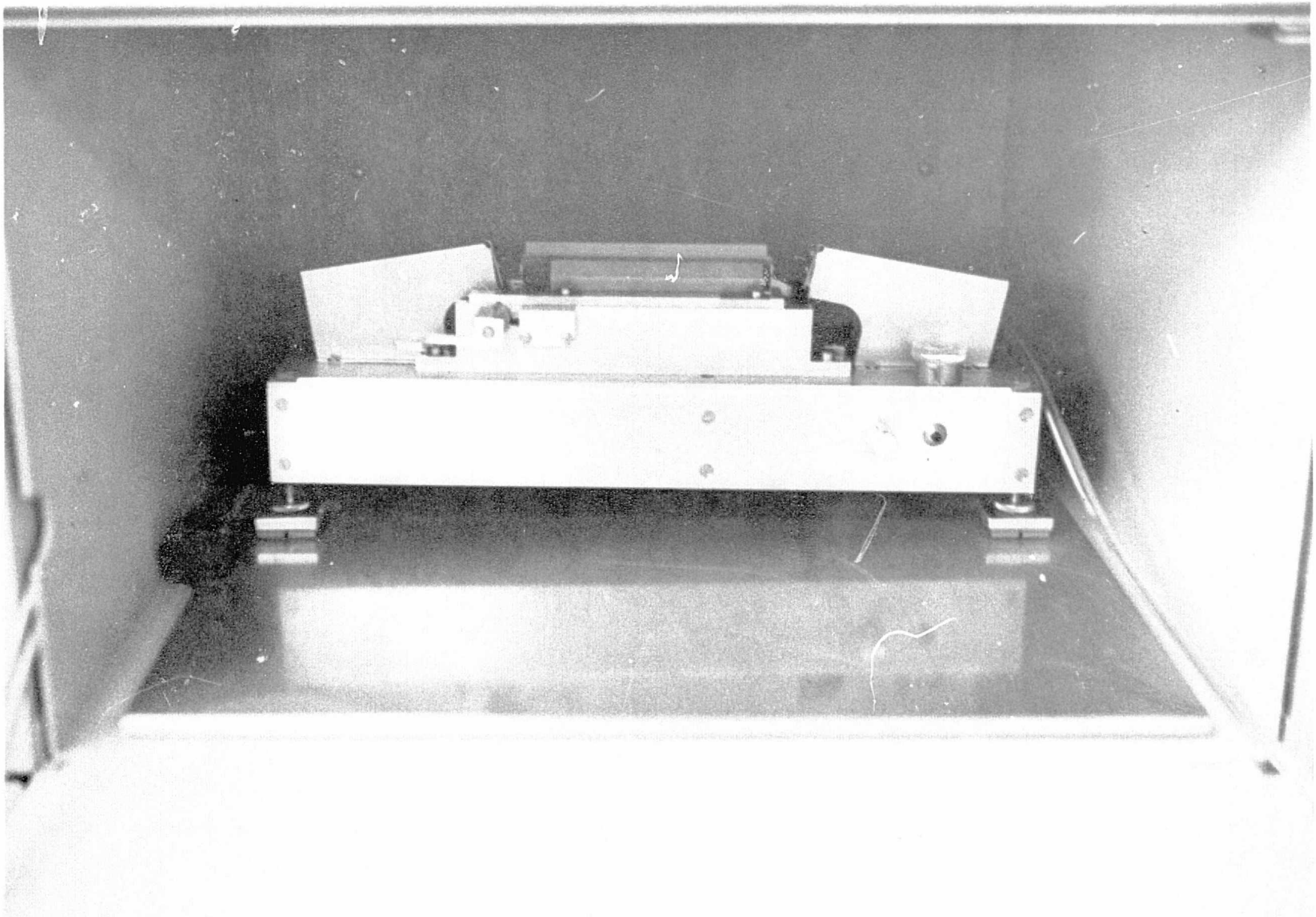


FIGURE 6. PHOTOGRAPH OF MICRO-MASS MEASUREMENT DEVICE

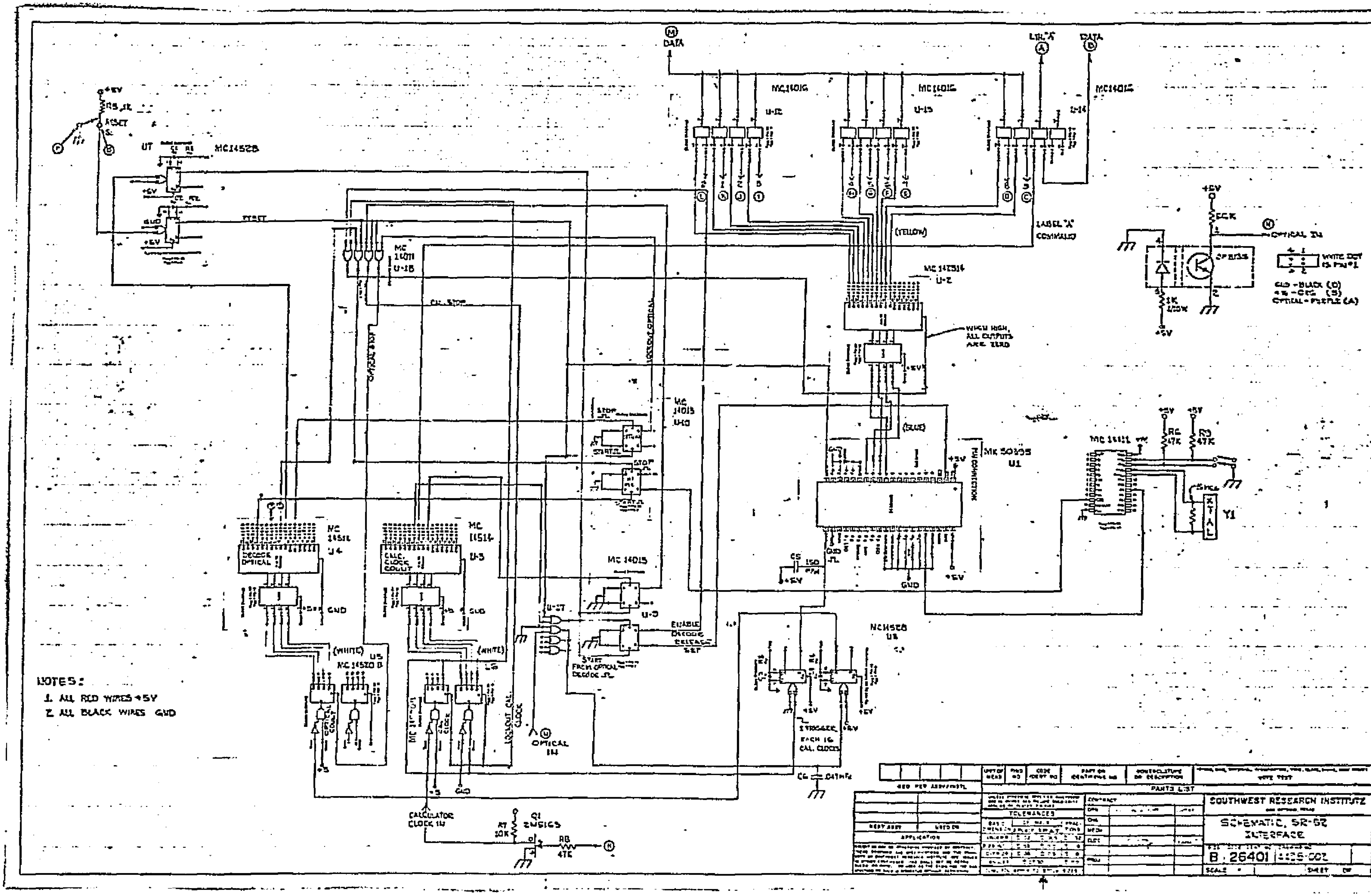


FIGURE 7. LOGIC DIAGRAM OF DIRECT MASS READOUT SYSTEM

rocker switches, the intervalometer input frequency can be changed to accommodate the wide range of oscillation periods for the various mass measurement systems.

The electronics system ignores the first three mechanical cycles of weighing pan oscillation in order to allow any transient vibration caused by the release mechanisms to dissipate. The total of the next five periods is timed by the intervalometer. The ninth tray oscillation transfers control of the electronics to the SR-52 calculator which controls the transfer of the six time digits. Upon transfer completion, the electronics transfers an "A" control to the calculator which is the instruction to perform the stored program.

In the final MIMMD configuration, a fifth degree polynomial equation is used to convert the period reading to mass. Unequally spaced calibration points are allowed by using Newton's divided difference formula for calculations. This formula is as follows:

$$M = (T^2 - T^2_{m=0})\, f(T^2_{m=0}, T^2_1) + (T^2 - T^2_{m=0})\,(T^2 - T^2_1)\, f(T^2_{m=0}, T^2_1, T^2_2) \ldots$$

where

M	=	mass
T^2	=	measured period squared
$T^2_{m=0}$	=	calibration period squared for zero mass
T^2_1	=	first period squared calibration point
T^2_2	=	second period squared calibration point

For more detail on this procedure, see Advanced Engineering Mathematics, C. R. Wylie, Jr., McGraw-Hill Book Company, Inc. Calibration and programming procedures are given in Appendix B of this report.

Power for the electronics package is furnished by two Nicad battery packs. Pack 1 supplies +8.75 volts from 7 size AA cells. Pack 2 supplies -6.25 volts from 5 size AA cells. Each pack will operate for approximately 10 hours with a system drain of 45 milliamps. Charging should be at 45 milliamps and a voltage not to exceed 1.4 volts per cell.

A constant voltage battery protector has been supplied. A series resistor limiting the current flow to 45 ma for cell potentials of 1.4 volts/cell is in series with the output. This circuit is actually a power supply-battery interface to ensure that continuous overcharging cannot occur. The power supply furnishing current to the protection interface should be current limited to approximately 60 ma and set for a no-load voltage of approximately 16 volts. The diagram shown in figure 8 illustrates the connections between the power supplies and the protection device.

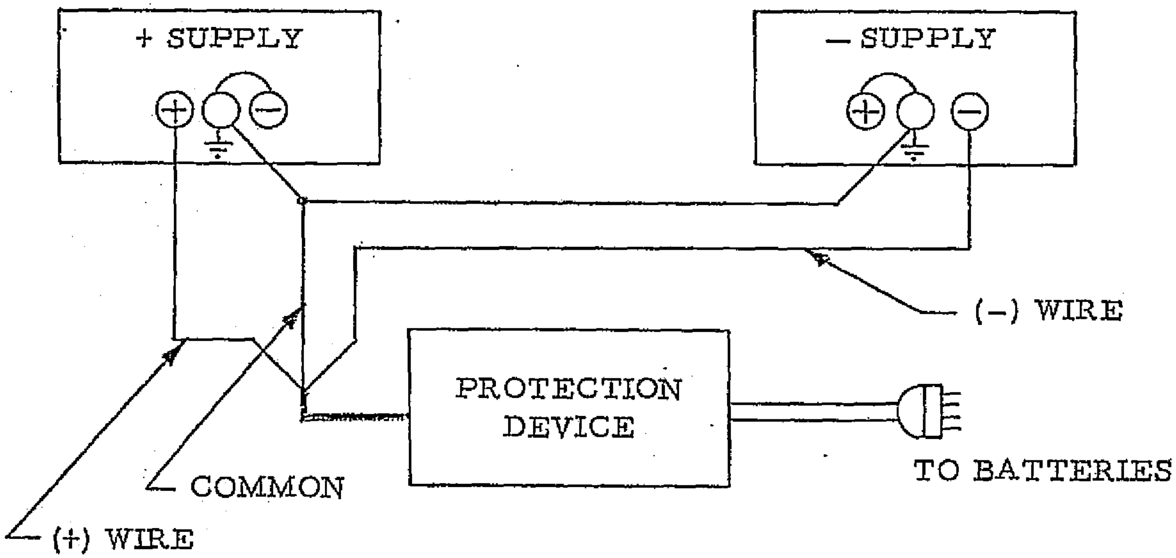


FIGURE 8. POWER SUPPLY AND PROTECTION DEVICE CONNECTIONS

C. Shop Testing Summary

Initial experimentation with the MIMMD showed higher errors and less repeatability than was desired. Most of this resulted from varying pressure and flow of air to the air bearing. The small Austen DC air pump did not have the capacity to enable the regulator to deliver air at a constant low pressure (around 27" of water). Also the air pump was noisy and produced vibrations in the overall system. A typical set of readings taken with this system is shown below. Calibration was made on a straight line calibration curve.

Actual Mass	Indicated Mass	% Error
0	0.10	----
4.961	4.94	0.42
9.929	9.86	0.69
14.904	14.84	0.43
20.061	20.08	0.09
24.648	24.76	0.45

The DC air pump was replaced with a larger Thompson AC pump delivering 20 psi, and a larger regulator which was capable of handling the required input-output pressure ratio. In addition, the pump and regulator were removed a distance of two to three feet from the air bearing and weighing pan assembly. This com' ination delivered constant pressure air to the air bearing, and repeatability and accuracy of the MIMMD were improved.

A set of stainless steel rods from 3/16" to 5/16" in diameter had been made up for use as calibrating masses. Their weights were approximately five grams apart, from 5 grams to 25 grams. Actual weights of the calibrating masses were measured on a Mettler balance. Also, whenever readings were taken, one was taken with an empty weighing pan, and this was designated "zero mass".

Using the new pump and regulator to deliver air pressure equivalent to 27" of water, and with the stainless steel rod calibration weights, a test series for accuracy was run with the results shown below. A fourth degree polynomial calibration curve was used in this test series.

Actual Mass	Indicated Mass	% Error
0	0.004	----
4.961	4.966	0.10
9.929	9.931	0.02
14.904	14.904	0.00
20.061	20.072	0.06
24.648	24.656	0.03

After the accuracy tests were run, a simulated specimen in a 22 mm diameter plastic pill bottle was weighed. It indicated mass was 14.968 grams; its actual mass was 14.930 grams. This is an error in indicated mass of 0.26%. The error was attributed to the large diameter of the pill bottle compared to the small diameter of the calibration rods, putting the centers of gravity unequally distant from the air bearing surface. For this reason, a new set of tubular metal calibration masses was fabricated. Their diameters were approximately equal to the diameter of the pill bottle. These calibration masses were used in all subsequent tests.

D. Predelivery Acceptance Tests

On 12 April 1977, the predelivery acceptance tests were conducted at SwRI in San Antonio. The test procedures and test results are included in Appendices C and D. The test results were only partially satisfactory. The following changes were incorporated in the MIMMD as a result of these tests:

(1) A thinner, more flexible rubber strip was used to hold down calibration masses and specimens. The thicker strip originally used could exert sufficient force at the attachment points to temporarily warp the weighing pan.

(2) The air pump was considered too noisy and was replaced with a quiter one.

Accuracy was not as high as desired. In the range of 0 to 25 grams, mass errors of from 0.35% to 0.66% were observed, and a simulated specimen showed an error of 0.83%.

E. Final Accuracy Tests

Final accuracy tests were run at NASA-JSC on 19 April 1977. Changes in the hold-down strip and air pump had been made. In addition, a fifth degree polynomial fit to the calibration data was used. Ten tubular masses were tested after calibrating, and the results were as follows:

Actual Mass (Grams)	Indicated Mass (Grams)	% Error
0	-0.003	-----
5.113	5.111	-0.04
7.856	7.853	-0.04
10.089	10.095	+0.06
12.415	12.410	-0.04
14.566	14.554	-0.08
17.745	17.746	+0.01
19.890	19.855	-0.17
22.252	22.238	-0.06
25.304	25.293	-0.04

Abs. Avg % Error = 0.06

V. CONCLUSIONS AND RECOMMENDATIONS

A. Evaluation of Experimental Mass Measurement Systems

1. Accelerated Gravimetric Balance

This device could prove feasible, depending on the results of NASA's zero-g tests. Manually accelerating the balance and unknown mass, while moving the balance weight along the beam, may prove to be a difficult maneuver. However, movement of the balance weight could be motorized if this device does appear otherwise feasible.

2. Centrifugal Device for Liquid Mass Measurements

The basic limitation of this device is friction in the sear release. Another problem exists which would always affect accuracy to some degree. This problem is that different quantities of liquid in the same container have different mass centers. In effect, centrifugal force acts at the mass center, and the containers swing out toward the horizontal axis during rotation. Therefore, if the distance of the mass center from the center of rotation varies with the quantity of liquid, an appropriate correction should be made in the mass readout for each case. There is no means for accomplishing this in the existing device, and it would appear to be a difficult problem to solve while keeping the device relatively simple.

3. Low Mass Air Bearing Oscillator

The low mass air bearing oscillator showed definite promise, and was further developed into the existing version of the MIMMD.

B. Direct Mass Readout

The direct mass readout electronics system has proved satisfactory, and only final packaging techniques require additional consideration.

C. Development of the MIMMD

The low mass air bearing oscillator showed sufficient promise that an advanced 25 gram capacity instrument was developed from it. This device shows a high degree of accuracy provided that masses weighed have the same general configuration, and are centered on the length of the weighing pan. However, the latter constraint is probably limited to a one-g environment. With respect to the configuration of masses to be weighed, there appear to be two possible approaches. The first is to use standard size cylindrical containers for all specimens. Even then a small specimen in a large container will have a different combined center of mass than a larger specimen in the same size container, and some inaccuracies in weighing may occur. Further testing should be done in this area when GFE container sizes are determined.

Another approach to container configuration would be to modify the air bearing and weighing pan so the combined C. G. of the container and specimen would be at or below the line of force of the oscillator springs. This should prevent a "rocking" tendency, which may exist with relatively large diameter containers in the present weighing pan, as they change direction at the end of each oscillation.

The air supply system for the air bearing should be integrated with the main weighing system if possible. The problem will be to find a low-capacity pump of a type other than the diaphragm pump (which tends to vibrate and to be noisy). In addition to the pump, other components required to make up a complete system consist of a regulator, pressure gauge, filter, and accumulator. With all these components, maintaining a relatively small overall size will present problems, but a suitable design appears feasible.

APPENDIX A

MIMMD OPERATION PROCEDURE

Control lever is down; weighing pan is locked; plastic cover is on.

1. Remove plastic cover.
2. Place specimen in pan under hold-downs.
3. Replace plastic cover.
4. Turn air on.
5. Turn power switch and calculator on.
6. Press "reset" button.
7. Raise control lever to vertical stop in a smooth motion.

    a. As control lever is raised, this sequence occurs:

        (1) Pan is unlocked allowing spring system to hold pan lug against face of sear (sear is in "up" position).

        (2) Sear is released allowing pan to oscillate.

        (3) Zero crossing and electronics system counts length of several oscillation periods, calculates mass, and displays it on calculator readout.

8. Lower control lever slowly to stop. This puts tray in original locked position.
9. Record calculator reading.
10. Repeat steps 6, 7, 8 and 9 four times.
11. Turn off air, power, and calculator.
12. Average the four best readings out of the set of five for measured mass.

APPENDIX B

DIRECT MASS READOUT CALIBRATION PROCEDURE-- 5th DEGREE POLYNOMIAL CURVE FIT-- FOR MASS MEASUREMENT DEVICES

1. Enter program "READ T^2" into calculator

2. Manually record five readings of period for each of five calibration masses plus the zero mass.

3. Throw out one of the five readings for each of the six calibration points. The reading thrown out should be the T^2 which deviates the most from the apparent average.

4. Average each set of the four T^2 readings and manually record.

5. Read into the calculator program POLY 1 and follow directions from the coding form.

6. Read into the calculator program POLY 2 and follow directions from the coding form.

SR-52 User Instructions

TITLE: READ T^2 PAGE 1 OF 2

STEP	PROCEDURE	ENTER	PRESS			DISPLAY
	Key in program or					
	read mag card.					
	Operate system.					

TITLE READ T² PAGE 2 OF 2 **SR-52 Coding Form**
PROGRAMMER DATE

LOC	CODE	KEY	COMMENTS	LOC	CODE	KEY	COMMENTS	LOC	CODE	KEY	COMMENTS
000 112	46	LBL	*								
	11	A									
	42	STO		040 152							
	00	0									
	01	1						080 192			
005 117	40	x^2	*								
	42	STO									
	00	0		045 157							
	02	2									
	81	HLT						085 197			
010 122											
				050 162							
								090 202			
015 127											
				055 167							
								095 207			
020 132											
				060 172							
								100 212			
025 137											
				065 177							
								105 217			
030 142											
				070 182							
								110 222			
035 147											
				075 187							

TEXAS INSTRUMENTS
INCORPORATED

LABELS	
A	
B	
C	
D	
E	
A'	
B'	
C'	
D'	
E'	

REGISTERS	
00	
01	T
02	T^2
03	
04	
05	
06	
07	
08	
09	
10	
11	
12	
13	
14	
15	
16	
17	
18	
19	

FLAGS	
0	
1	
2	
3	
4	

TITLE Poly 1 PAGE 1 OF 3

◄A►				

◄B►				

STEP	PROCEDURE	ENTER	PRESS			DISPLAY
		T_0^2	STO	0		
		T_1^2	STO	0	1	
		T_2^2	STO	0	2	
		T_3^2	STO	0	3	
		T_4^2	STO	0	4	
		T_5^2	STO	0	5	
		M_0	STO	1		
		M_1	STO	1	1	
		M_2	STO	1	2	
		M_3	STO	1	3	
		M_4	STO	1	4	
		M_5	STO	1	5	
	Do not use "CLR" after this step.	10	STO	6	9	
	"CLR" erases register 60-69 data.	11	STO	6	8	
		0	STO	6	7	
		1	STO	6	6	
		95	STO	9	6	
		2	STO	9	7	
			A			
	Data is stored in registers					
	ϕ1 through 15 and will be used					
	by the next program.					

TITLE Poly 1 PAGE 2 OF 3
PROGRAMMER DATE

SR-52 Coding Form

LOC	CODE	KEY	COMMENTS
000 112	46	LBL	*
	12	B	
	09	9	
	05	5	
	42	STO	
005 117	09	9	
	07	7	
	01	1	
	00	0	
	42	STO	
010 122	09	9	
	06	6	
	36	IND	*
	43	RCL	
	09	9	
015 127	07	7	
	36	IND	*
	42	STO	
	09	9	
	06	6	
020 132	01	1	
	22	INV	
	44	SUM	
	09	9	
	07	7	
025 137	44	SUM	
	09	9	
	06	6	
	43	RCL	
	09	9	
030 142	06	6	
	75	-	
	02	2	
	01	1	
	95	=	
035 147	22	INV	
	80	IFPOS	*
	00	0	

LOC	CODE	KEY	COMMENTS
	01	1	
	02	2	
040 152	81	HLT	
	46	LBL	*
	11	A	
	36	IND	*
	43	RCL	
045 157	06	6	
	09	9	
	75	-	
	36	IND	*
	43	RCL	
050 162	06	6	
	08	8	
	95	=	
	55		
	53	(	
055 167	36	IND	*
	43	RCL	
	06	6	
	07	7	
	75	-	
060 172	36	IND	*
	43	RCL	
	06	6	
	06	6	
	54	)	
065 177	95	=	
	98	PRT	*
	36	IND	*
	42	STO	
	06	6	
070 182	09	9	
	01	1	
	44	SUM	
	06	6	
	09	9	
075 187	44	SUM	

LOC	CODE	KEY	COMMENTS
	06	6	
	08	8	
	44	SUM	
	06	6	
080 192	07	7	
	44	SUM	
	06	6	
	06	6	
	43	RCL	
085 197	06	6	
	06	6	
	98	PRT	
	75	-	
	07	7	
090 202	95	=	
	22	INV	
	80	IFPOS	*
	00	0	
	04	4	
095 207	03	3	
	43	RCL	
	09	9	
	07	7	
	42	STO	
100 212	06	6	
	06	6	
	00	0	
	42	STO	
	06	6	
105 217	07	7	
	43	RCL	
	01	1	
	00	0	
	36	IND	
110 222	42	STO	
	09	9	

LABELS	
A	
B	
C	
D	
E	
A'	
B'	
C'	
D'	
E'	

REGISTERS	
00	
01	
02	
03	
04	
05	
06	
07	
08	
09	
10	
11	
12	
13	
14	
15	
16	
17	
18	
19	

FLAGS	
0	
1	
2	
3	
4	

TEXAS INSTRUMENTS
INCORPORATED

TITLE Poly 1 . PAGE 3 OF 3

PROGRAMMER DATE

SR-52 Coding Form

LOC	CODE	KEY	COMMENTS
000 112	06	6	
	01	1	
	22	INV	
	44	SUM	
	09	9	
005 117	06	6	
	01	1	
	00	0	
	42	STO	
	06	6	
010 122	09	9	
	01	1	
	01	1	
	42	STO	
	06	6	
015 127	08	8	
	01	1	
	44	SUM	
	09	9	
	07	7	
020 132	43	RCL	
	09	9	
	07	7	
	98	PRT	*
	75	-	
025 137	08	8	
	95	=	
	22	INV	
	80	IFPOS	*
	00	0	
030 142	04	4	
	03	3	
	41	GTO	
	00	0	
	00	0	
035 147	02	2	

LOC	CODE	KEY	COMMENTS
040 152			
045 157			
			DATA
			DATA
050 162			DATA
			DATA
			DATA
			DATA
			DATA
055 167			DATA
060 172			
065 177			
070 182			
075 187			

LOC	CODE	KEY	COMMENTS
080 192			
085 197			
090 202			
095 207			
100 212			
105 217			
110 222			

LABELS: A, B, C, D, E, A', B', C', D', E'

REGISTERS: 00, 01, 02, 03, 04, 05, 06, 07, 08, 09, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19

FLAGS: 0, 1, 2, 3, 4

TEXAS INSTRUMENTS INCORPORATED

TITLE Poly 2 PAGE 1 OF 4

◄A►				

◄B►				

STEP	PROCEDURE	ENTER	PRESS			DISPLAY
	For new cal data, read side A and B.					
			RCL	0	0	
			STO	9	3	
			RCL	0	1	
			STO	9	4	
			RCL	0	2	
			STO	9	5	
			RCL	0	3	
			STO	9	6	
			RCL	0	4	
			STO	9	7	
			RCL	1	0	
			STO	8	8	
			RCL	1	1	
			STO	8	9	
			RCL	1	2	
			STO	9	0	
			RCL	1	3	
			STO	9	1	
			RCL	1	4	
			STO	9	2	
	Write mag card side A and					
	B operate system					

TITLE Poly 2 PAGE 2 OF 4

PROGRAMMER DATE

SR-52 Coding Form

LOC	CODE	KEY	COMMENTS	LOC	CODE	KEY	COMMENTS	LOC	CODE	KEY	COMMENTS	LABELS
000 112	46	LBL	*		09	9			08	8		A
	11	A			09	9			36	IND	*	B
	40	X^2	*	040 152	75	-			49	PROD	*	C
	47	CM_s	*		09	9			09	9		D
	42	STO			08	8		080 192	09	9		E
005 117	01	1			95	=			01	1		A'
	09	9			22	INV			22	INV		B'
	09	9		045 157	80	IFPOS	*		44	SUM		C'
	03	3			00	0			09	9		D'
	42	STO			01	1		085 197	08	8		E'
010 122	09	9			06	6			43	RCL		REGISTERS
	09	9			09	9			09	9		00
	00	0		050 162	02	2			08	8		01
	00	0			42	STO			80	IFPOS	*	02
	42	STO			06	6		090 202	00	0		03
015 127	09	9			09	9			06	6		04
	08	8			00	0			07	7		05
	43	RCL		055 167	04	4			36	IND	*	06
	01	1			42	STO			43	RCL		07
	09	9			09	9		095 207	06	6		08
020 132	75	-			09	9			09	9		09
	36	IND	*		43	RCL			36	IND		10
	43	RCL		060 172	09	9			49	PROD	*	11
	09	9			09	9			09	9		12
	09	9			75	-		100 212	09	9		13
025 137	95	=			01	1			36	IND		14
	36	IND	*		95	=			43	RCL		15
	42	STO		065 177	42	STO			09	9		16
	09	9			09	9			09	9		17
	08	8			08	8		105 217	44	SUM		18
030 142	01	1			22	INV			01	1		19
	44	SUM			80	IFPOS	*		08	8		FLAGS
	09	9		070 182	00	0			01	1		0
	09	9			09	9			22	INV		1
	44	SUM			02	2		110 222	44	SUM		2
035 147	09	9			36	IND	*		09	9		3
	08	8			43	RCL		TEXAS INSTRUMENTS INCORPORATED				4
	43	RCL		075 187	09	9						

TITLE Poly 2 PAGE 3 OF 4

A				

B				

STEP	PROCEDURE	ENTER	PRESS			DISPLAY
	For operating with previously used					
	cal data, read side A and B--Operate					
	System.					
	T^2 is stored in Reg. 19.					
	New mass is stored in Reg. 18.					

TITLE Poly 2 PAGE 4 OF 4

PROGRAMMER ________ DATE ________

SR-52 Coding Form

44

LOC	CODE	KEY	COMMENTS
000 112	09	9	
	22	INV	
	44	SUM	
	06	6	
	09	9	
005 117	43	RCL	
	09	9	
	09	9	
	80	IFPOS	*
	00	0	
010 122	05	5	
	08	8	
	43	RCL	
	01	1	
	08	8	
015 127	98	PRT	
	22	INV	
	52	EE	
	57	FIX	*
	03	3	
020 132	81	HLT	
025 137			
		DATA LEVEL	
030 142		DATA LEVEL	
		DATA LEVEL	
		DATA LEVEL	
035 147			

LOC	CODE	KEY	COMMENTS
040 152			
045 157			
050 162			
055 167			
060 172			
065 177			
070 182			
075 187			

LOC	CODE	KEY	COMMENTS
080 192			
085 197			
090 202			
095 207			
100 212			
105 217			
110 222			

LABELS	
A	
B	
C	
D	
E	
A'	
B'	
C'	
D'	
E'	

REGISTERS	
00	
01	
02	
03	
04	
05	
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FLAGS	
0	
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TEXAS INSTRUMENTS INCORPORATED

APPENDIX C

PREDELIVERY ACCEPTANCE TEST PROCEDURES FOR MICRO-MASS MEASUREMENT DEVICE (NASA Contract NAS 9-14941; SwRI Project 16-4498-003)

The predelivery test procedure shall be based on features of the device outlined in paragraph 3. 1 of the contract Statement of Work. Subparagraphs (a) through (m) are stated below, with the test procedure for each subparagraph stated in each case.

a. 25 gram capacity.

Test Procedure:

(1) During tests for subparagraphs (k) and (l), one of the calibrating masses shall weigh 25 grams.

b. Extremely lightweight replaceable weighing pan to reduce tare mass to a minimum. The weighing pan should be rugged enough to withstand laboratory use.

Test Procedure:

(1) Demonstrate how weighing pan is removed and replaced.

(2) Determine ruggedness by inspection and handling the pan.

(3) Weigh the pan to show light weight.

c. Structure to hold samples to weighing pan. Samples could be biological tissues including small animals, chemical samples and the like which will be contained in GFE containers.

Test Procedure:

(1) Demonstrate hold-down structure for GFE tubular containers.

d. Suitable means for offsetting and releasing the weighing pan.

Test Procedure:

(1) Demonstrate offsetting and releasing the weighing pan.

e. Air bearing support for weighing pan.

Test Procedure:

(1) Demonstrate by inspection.

f. Air supply and regulation to meet the needs fo the air bearing support.

Test Procedure:

(1) Demonstrate by inspection.

g. Electronics to:

°Detect each zero crossing.

°Start and stop timing cycles.

°Time and store five operating cycles (five cycles are counted for readings after three or more cycles following release.)

°Convert period of cycles to direct mass readout through internal program. This program must be capable of reprogramming to accommodate changes in calibration, etc. It is desirable to use a CMOS (Complimentary Metal Oxide Semi-conductor) or equivalent constantly operating micropower memory. However, a card-read memory before each operation will be acceptable.

Test Procedure:

(1) Demonstrate operation and construction of electronics system.

h. Totally battery operated and rechargeable. Operating time before recharging will be a minimum of 200 weighing cycles (500 cycles desired).

Test Procedure:

(1) Measure power used and time consumed during ten typical weighing cycles. Determine number of weighing cycles and operating time batteries will supply at rated capacity.

i. Direct mass readout and zero crossing mechanism.

Test Procedure:

(1) Test by demonstration.

j. Matched helical tension springs of Isolelastic or similar material.

Test Procedure:

(1) Test by inspection.

k. Resolution goal ±2mg.

Test Procedure:

(1) Weigh 10 gram calibration mass by taking five consecutive readings on the device. Average the best matching four readings.

(2) Add a two milligram mass to the pan and take five more consecutive readings. Average the best matching four readings.

(3) Compare the averages arrived at in steps (1) and (2). These average readings should differ by at least two milligrams, but no more than four milligrams.

(4) Repeat steps (1), (2) and (3) using the 25 gram calibration mass.

l. Accuracy goal ±5mg.

Test Procedure:

(1) Run sets of five oscillation period readings each on 0, 5, 10, 15, 20 and 25 gram calibrating masses. Average the four best matching readings for each set.

(2) Using the averages obtained in step (1), run program on the calculator furnished to obtain the mass equation. Set up calculator with this program to read out direct mass.

(3) Measure the masses of five specimens in the range of 0 to 25 grams which have each been weighed in a Mettler balance or equivalent. At the option of the NASA representative, the calibration masses may be used. Readings from the micro-mass measurement device should match the weights of the specimens (or calibration masses) within ±5mg.

m. Maximum oscillation frequency at minimum mass goal 2cps.

Test Procedure:

(1) Determine the zero-mass frequency from the zero-mass readouts of the device.

APPENDIX D

RESULTS OF PREDELIVERY ACCEPTANCE TESTS FOR MICRO-MASS MEASUREMENT DEVICE
(NASA Contract NAS 9-14941; SwRI Project 16-4498-003)
12 April 1977

(a) Test a was accomplished in the following subparagraphs k and l.

(b) Paragraph b was accomplished and in subparagraph b(3) the pan weighed 4.81 grams.

(c) The structure for holding samples was considered to put too much force on the speciman. We will use a thinner, more flexible rubber strip in the final configuration.

(d) Demonstration was satisfactory.

(e) Demonstration was satisfactory.

(f) The air pump was considered too noisy. A replacement for this pump will be necessary.

(g) The electronic system was considered satisfactory.

(h) The procedure outlined was not followed. The battery powered pump may be replaced with an AC pump for the ground test. The battery for the electronics had been run for 200 weighing cycles before the acceptance test.

(i) Demonstration was satisfactory.

(j) Demonstration was satisfactory.

(k) The resolution with the 10 gram calibration mass was 1.5 milligrams. The resolution on the 25 gram mass was 2 milligrams.

(l) The results of this test procedure are shown in the table on the following page.

Actual Mass (Grams)	Read-Out Mass (Grams)	% Error
0	-0. 008	-----
4. 961	4. 938	-0. 46
9. 929	9. 894	-0. 35
14. 904	14. 844	-0. 40
20. 061	19. 975	-0. 43
24. 648	24. 516	-0. 66
10. 661 (simulated specimen)		
hold-down used	10. 805	+1. 35
10. 661 (simulated specimen)		
hold-down not used	10. 749	+0. 83

(m) The oscillation frequency for 0-mass was measured to be 1. 07 Hz.