DEVELOPMENT OF PROTOTYPE MASS MEASUREMENT SYSTEM FOR SPACEFLIGHT PHASE II

By

Biotechnology
Lockheed Missiles & Space Company
Sunnyvale, California

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LANGLEY RESEARCH CENTER

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R. B. Maine
A. L. Weitzmann

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SUMMARY

With long duration space missions the next major goal of the space program, one important physiological measurement will be a record of the crew's weight. This measurement and other physiological data points will define the crew's well-being and capability to perform a successful mission.

While man's mass is an important data point, other items in space will need a device for mass determination. For example, urine samples, food samples, and a wide range of items associated with various research experiments will require measurement.

This report covers the design, fabrication, and KC-135 zero gravity flight test of a prototype mass measurement system (MMS) suitable for both zero, partial gravity, and one gravity environments.

The mass measurement device operates on the principle based on the simple harmonic motion of an oscillating mass, coupled with the precise timing of the oscillations.

To prove the application of this principle, the Phase I mass measurement program (ref. 1) was initiated to design, fabricate and test a prototype MMS for ground test performance evaluation. Test results indicated that the principle was sound and that accuracies of better than $\pm$ 0.25 pounds were possible in the weight range of 5 to 40 pounds, and $\pm$ 0.50 pound accuracy could be achieved in the 41 to 250 pound range. The accuracy of human subjects was within $\pm$ 1.0 pound. The recommendations of the Phase I program outlined the design of a MMS to be flown on a KC-135 aircraft flying a zero gravity parabola for performance evaluation of the MMS in that environment.

The Phase I hardware was further ground tested and evaluated at NASA's Langley Research Center to determine the best performance characteristics of the two carriage systems developed and select the system for MMS Phase II program.

The Phase II MMS used the multiple conventional ball bearing cluster carriage assembly developed during the Phase I program. However, a new pallet assembly was designed and fabricated to withstand the 2.5 g loads imposed when flying the zero gravity parabola. The electronic timing system remained unchanged. A Hewlett-Packard printer was added to the system to provide a printout record of the MMS performance.

(ref. 1) Maine, R. B.; Weitzmann, A. L.: Development of Prototype Mass Measurement System for Spaceflight. NASA CR-66174, 1966.

A three-axis accelerometer system was mounted to the MMS mounting plate to measure and record transient accelerations during the zero gravity portion of the flight.

The hardware was flight tested on August 7, 8 and 9, 1967, at Wright-Patterson Air Force Base, Dayton, Ohio.

Rigid masses from 5 to 250 pounds, and three human subjects, were tested on the MMS. Performance was very satisfactory with accuracy average over the 5 to 250 pound range of 0.2 pounds. The inferred accuracy in weighing human subjects was 0.5 pounds.

The MMS was converted into the acceleration threshold measurement configuration and test flown using two test subjects. The results indicate that the device can determine man's threshold to accelerations in the area of 5 cm/sec^2 in the zero gravity environment.

The results of the Phase I and II MMS program show that the concept of simple harmonic motion for measuring mass in the zero gravity environment is sound and that hardware can be produced to perform within desired goals utilizing this concept. The next stage of development of this system would be design, fabricate, and flight qualify end item spacecraft hardware for use in future long duration space missions.

INTRODUCTION

In response to an unsolicited proposal (ref. 2) the NASA-Langley Research Center late in February, 1966, directed the Lockheed Missiles and Space Company (LMSC) to develop prototype equipment specifically designed to monitor mass changes of astronauts, and to determine the mass of spacecraft materials during orbital flight. The adaptability of the mass measurement system (MMS) for experimental objectives such as measurement of human threshold accelerations was investigated. This program proved the concept of the oscillating spring mass system, developed prototype hardware with performance within contract goals, and recommended that the next step in the hardware development would be the fabrication of a KC-135 flight prototype MMS.

NASA-Langley directed LMSC in February, 1967 to proceed with the KC-135 flight program. The previous MMS program became known as Phase I, and the program which this report describes, Phase II.

The Phase II MMS program was to utilize as much hardware as possible developed and fabricated during the Phase I program. This hardware was performance tested under 1-gravity conditions at NASA-Langley Research Center. Test results and evaluations defined selection of the type of carriage/rail system to be used. The electronic pulser and counter was also selected for Phase II program use.

The major tasks involved in the Phase II program were to:

- Design and fabricate the MMS pallet to meet structural requirements imposed on the load pallet during the KC-135 flight parabola.
- Design and fabricate a removable carriage support to be used during maximum loads of parabola entry and pull-out.
- Design and provide instrumentation and recording equipment to monitor MMS operation during the flight tests.
- Define, design, and fabricate springs release system for use in an acceleration threshold measurement mode of the MMS.
- Resolve all MMS/KC-135 interface requirements with NASA/MSC and Wright-Patterson AFB, and provide necessary interface hardware.

(ref. 2) LMSC: Mass Measurement System for Spacecraft, LMSC 894133, 1965.

- Prepare and conduct a test program.
- Furnish a test subject and one observer for the flight tests.
- Conduct flight test experiment.
- Perform design analyses and prepare a preliminary design for an optimum space qualified MMS.

This report describes in detail the results of the effort conducted for each of the tasks. The conclusions and recommendations outline subsequent phases required to provide a spacecraft operational MMS for AAP experiments and beyond.

DESIGN CONFIGURATION AND FABRICATION

A number of additions and modifications were made to prepare the MMS for the KC-135 flight tests. It was decided to use a configuration employing eight conventional ball bearings, because the motion was smoother and quieter than a Saginaw bearing configuration. Smooth, quiet motion is important in experiments to establish the human threshold of linear acceleration sensing. The prototype MMS developed for the KC-135 flight test is illustrated in fig. 1.

A silent release device was needed for threshold detection purposes, and an electromagnet was employed to provide it. In order to permit setting the carriage at various release points, the electromagnet can be slid forward or rear-ward and clamped in the desired position. Another requirement for acceleration threshold testing is elimination of tactile, audible and visual cues by wearing opaque goggles, and tactile cues by providing a two inch thick foam pad for the seat and seat back. For determination of human acceleration sensing threshold, a slower reciprocating motion is desired than for mass measurement. Therefore softer springs were obtained simply by providing two identical additional springs to be hooked onto the existing springs (one at the front, the other at the rear). This increased the length of the springs which necessitated providing a spring hook boom at each end.

Carriage and Rail

The conventional bearing configuration employs eight Fafnir double row, double sealed ball bearings. Four of the bearings are mounted on an ordinary straight axle shaft, while the other four are mounted on eccentric axle shafts. Consequently, these latter four bearings can be moved inward or outward by rotating the eccentric shafts on which they are mounted. This provides adjustment to fit the square shaft on which they ride. A groove was cut into the outer race of each ball bearing and a silicone rubber O ring was installed in each groove. The groove was shallow enough to allow each O ring to protrude beyond the outer diameter of the bearing by approximately 0.015 in. This ensures that all of the ball bearings will be rolling in unison.

Except for the bearings, shafts, fasteners, and certain latch components, nearly all of the remaining carriage parts and shaft supports are made of aluminum. The carriage on which the conventional ball bearings are mounted is a built-up welded assembly in which the axle shaft holes were

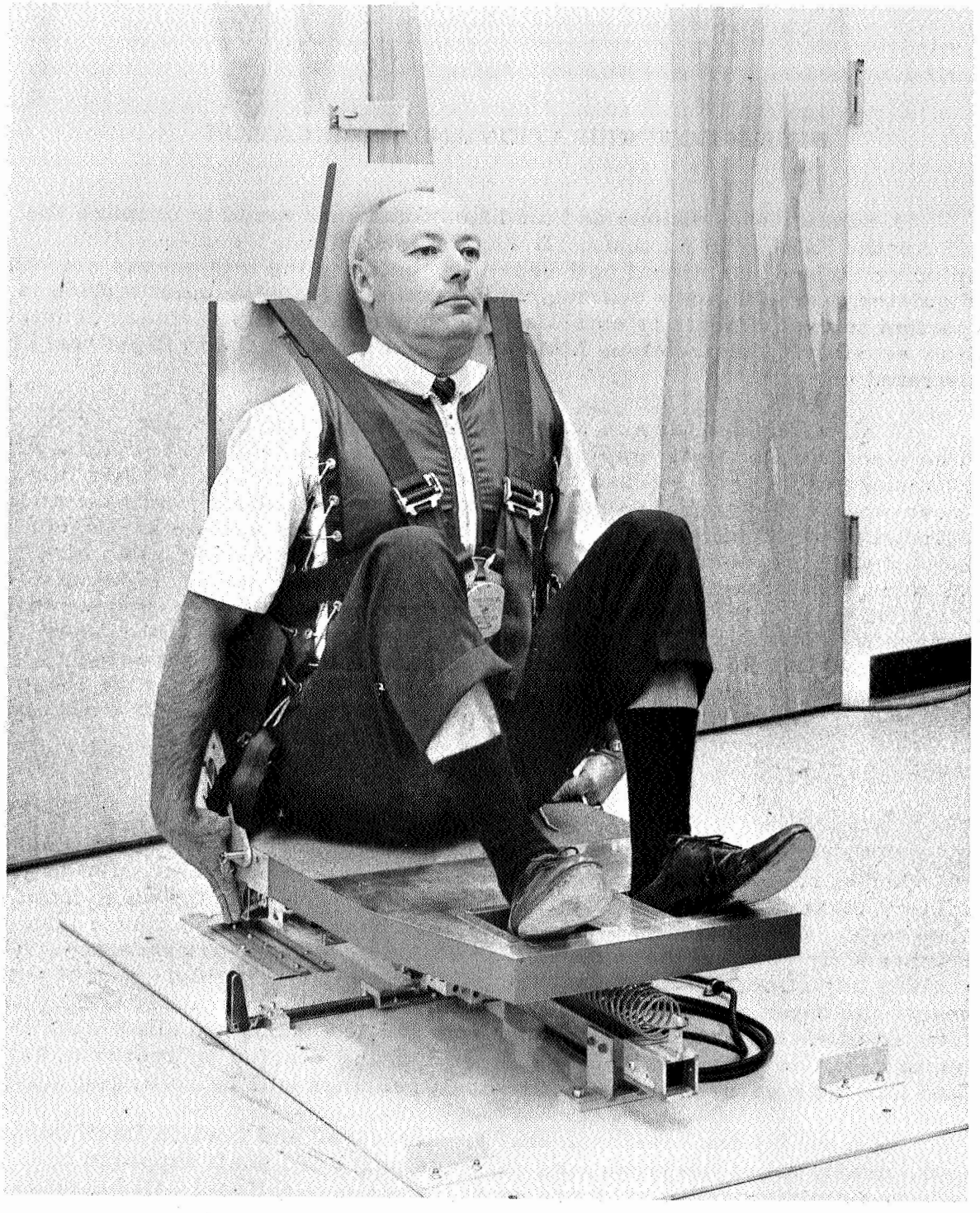


Fig. 1 Prototype Mass Measurement System Phase II

machined after completion of welding to eliminate misalignments due to welding warpage. Figure 2 illustrates the major structural members of the MMS.

The KC-135 flight trajectory imposed downward acceleration forces of at least 2.5 g. To prevent the MMS rail from bending under such loads (with 250 lb on the seat) and also to lock the seat in its central position, a sliding wedge was provided as shown in fig. 2.

Pallet

The honeycomb slabs forming the seat and seat back were also made stronger and more rigid by increasing their thicknesses from 0.75 inch to 2 inches and 1 inch, respectively. Provision was made for securing odd shaped articles on the seat (with the back up) by means of ropes which can be used to draw any object down into the corner formed by the seat and the seat back. Each rope has an eye splice at one end so that it can be anchored to a hook at the rear of the seat. The rope is then looped around the object and pulled through a cam cleat at the base of the seat back. In addition to six of these ropes, elastic bands were provided, along with appropriate buckles and brackets, to hold the object down on the seat during zero g as illustrated in fig. 3.

To restrain objects of smaller size and weight, the pallet back is placed in the folded down position. A clamping device pinned to fittings which are fastened to the back surface of the pallet back furnishes the restraint. The clamping device can be seen in fig. 4.

Man Restraint System

The MMS was designed to accommodate the typical flight crew population of pilot and scientist astronauts whose body dimensions fall within the middle 90 percent of the Air Force flying population. Design values for body geometry therefore fall between the 5th and 95th percentiles of the full range of user personnel. Of particular interest to MMS design are the lightweight sandals worn with the constant-wear garment for shirt-sleeve operations in the Apollo. Both width and length of the footrest were evaluated to determine minimum design dimensions to accommodate a 95th percentile man wearing these sandals.

Basic body dimensions necessary to design the MMS were established. The MMS and associated controls, man restraint system, and positioning references were designed to accommodate the range of astronaut body movements necessary to actuate, manipulate, or control the various man-machine interface hardware.

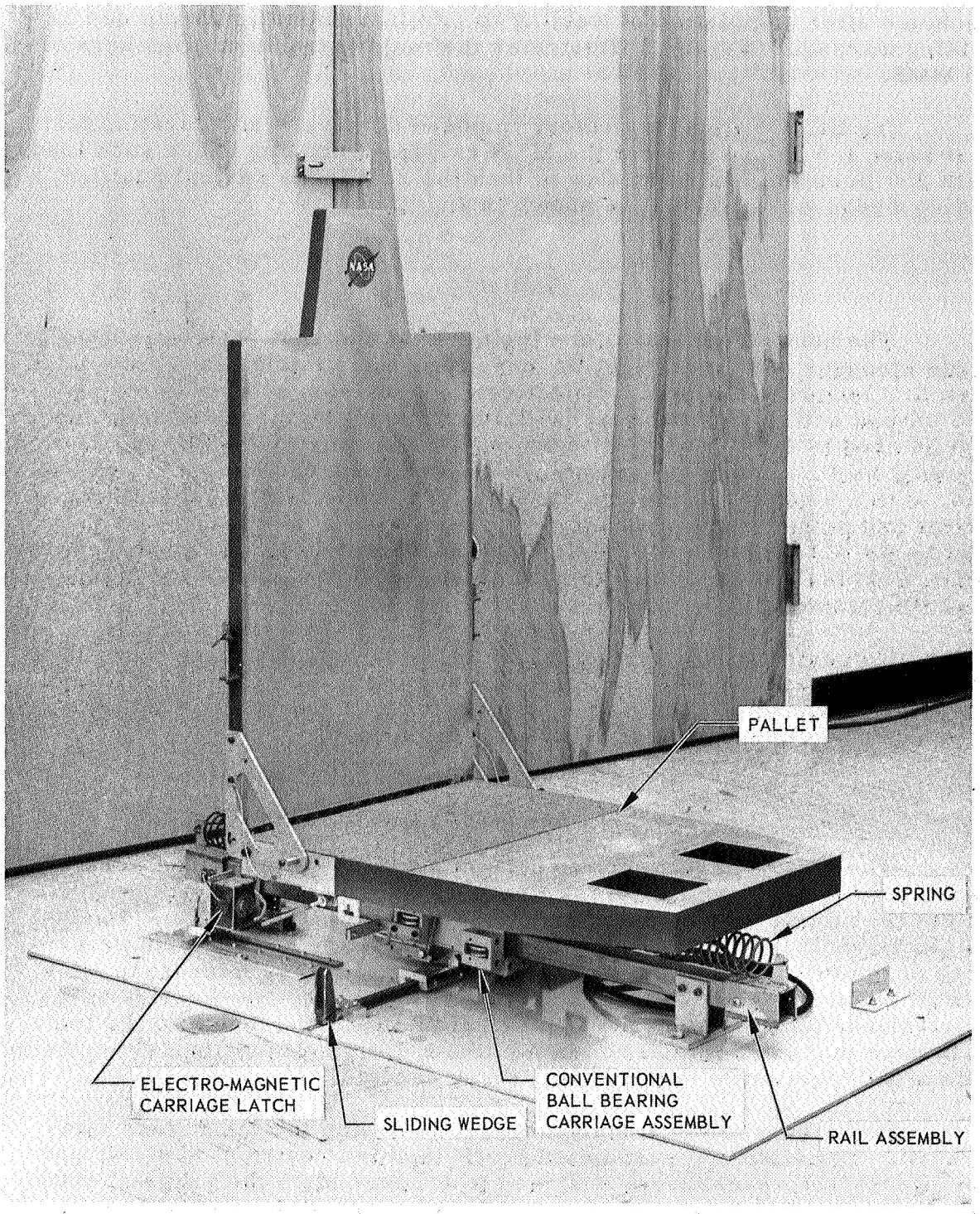


Fig. 2 MMS Structural Configuration

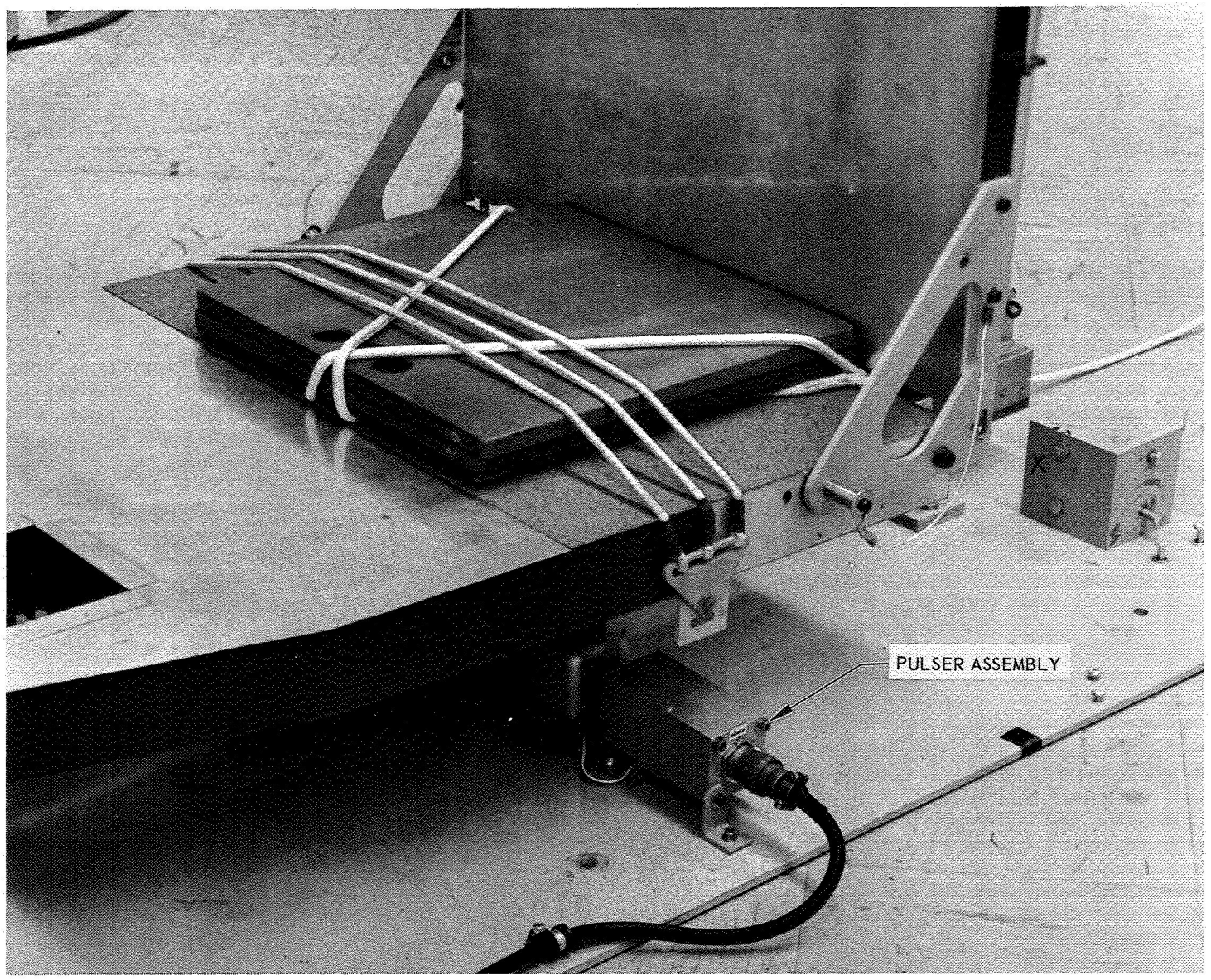


Fig. 3 Inanimate Restraint System (Pallet Back Up)

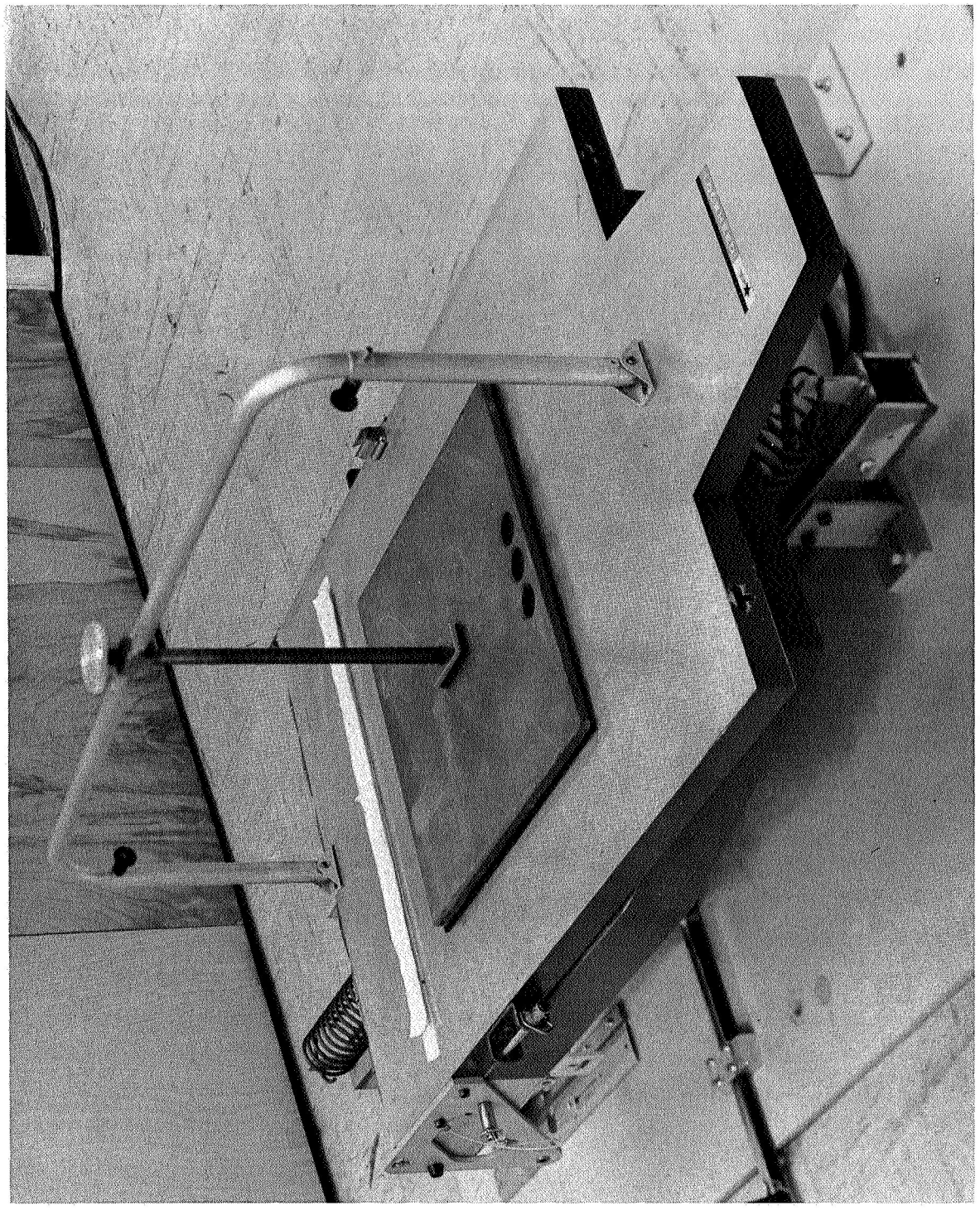


Fig. 4 Inanimate Restraint System (Pallet Back Down)

The restraining system consists of a zippered vest covering the chest and abdomen. The vest, pulled tight in all directions, applies positive pressure to this portion of the body. The vest is adjustable for people in the 5 to 95 percentile astronaut population. Vest shoulder straps pass through the back attachment fittings and on to the quick-release device and the edge of the pallet. Side straps pass through a roller fitting attached to the seat back. When the straps are pulled, load is placed on a series of bungee cords on each side of the vest, holding the subject securely. Figure 5 shows the man restraint system.

Electrical Design

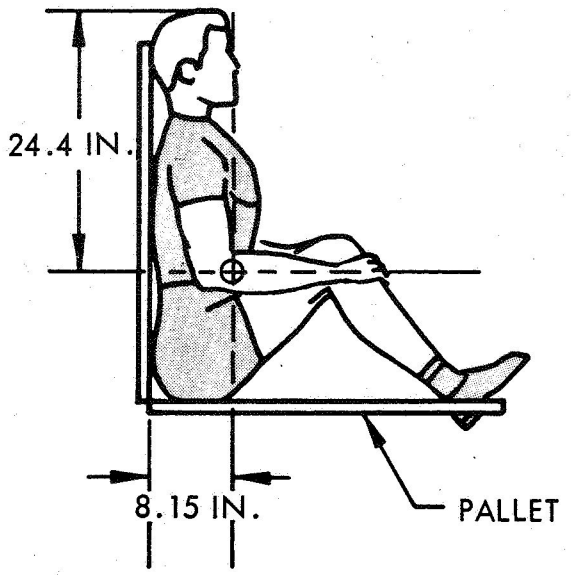
To measure the time for the pallet to travel a discrete number of cycles requires a sensing device to indicate pallet position, a cycle counting device, and a time counting system. Figure 6 shows a schematic of the electrical system. In addition to the timing measurement, it is necessary to provide a "hard copy" printer for a permanent record of the time interval. This equipment is shown in fig. 7. It is also required to measure acceleration in three mutually perpendicular axes. A tape recorder installation as shown in fig. 8 was utilized.

Timing. - Measurement of the time required for one complete oscillation of the pallet and subject is accomplished by a light sensor and digital counter under the pallet, and a counter-timer which measures intervals to 5 significant figures, or 0.0001 second. A shutter on the pallet crosses a light beam as the pallet reaches the center of its travel. The light sensor turns on the counter-timer and starts the pulser counting the number of passes of the shutter. The pulser installation is shown in fig. 3. On the third pass (one complete oscillation of the pallet) the counter stops the counter-timer and the time interval for one oscillation appears on its readout display to the nearest 0.1 millisecond. The counter can be set to count 7 passes (3 complete oscillations) by a switch on the side of the counter. This switch adds a digital 4 to the required count before stopping the counter. A permanent record of the time interval is made by transferring the information digitally from the counter-timer to a printer. Depressing the "print" switch on the printer records the information from the timer display onto a 3 inch paper tape.

Total system timing error is 1×10^{-4} sec, due primarily to ± 1 count on the counter-timer.

Accelerometers. - Three accelerometers were mounted on the base of the MMS in the 3 mutually perpendicular axes of the aircraft to verify true zero-g conditions during test operations. Each accelerometer was supplied with 14 ma of current at 5 vdc from 6 vdc batteries. Each was balanced to produce zero output with zero-g acting on the sensitive axis, with output amplified to produce $\pm$ 0.5 vdc into the tape recorder under the influence of $\pm$ 1-g on the sensitive axis. Each accelerometer channel was

PALLET CONFIGURATION SHOWING APPROXIMATE CENTER OF GRAVITY FOR 50TH PERCENTILE INDIVIDUAL



MAN RESTRAINT SYSTEM

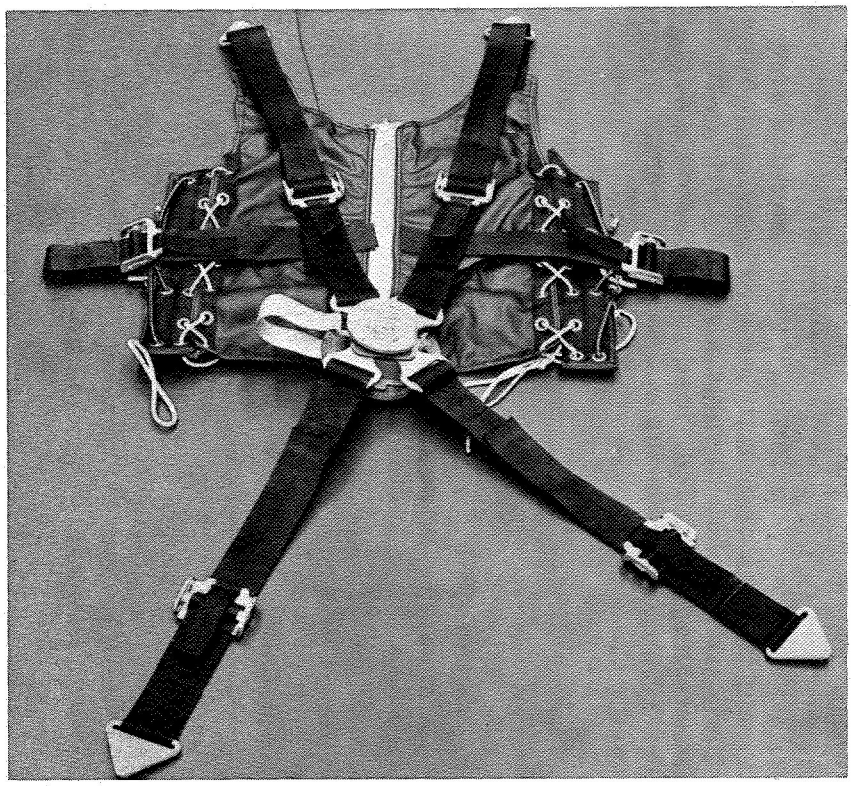


Fig. 5 Man Restraint System

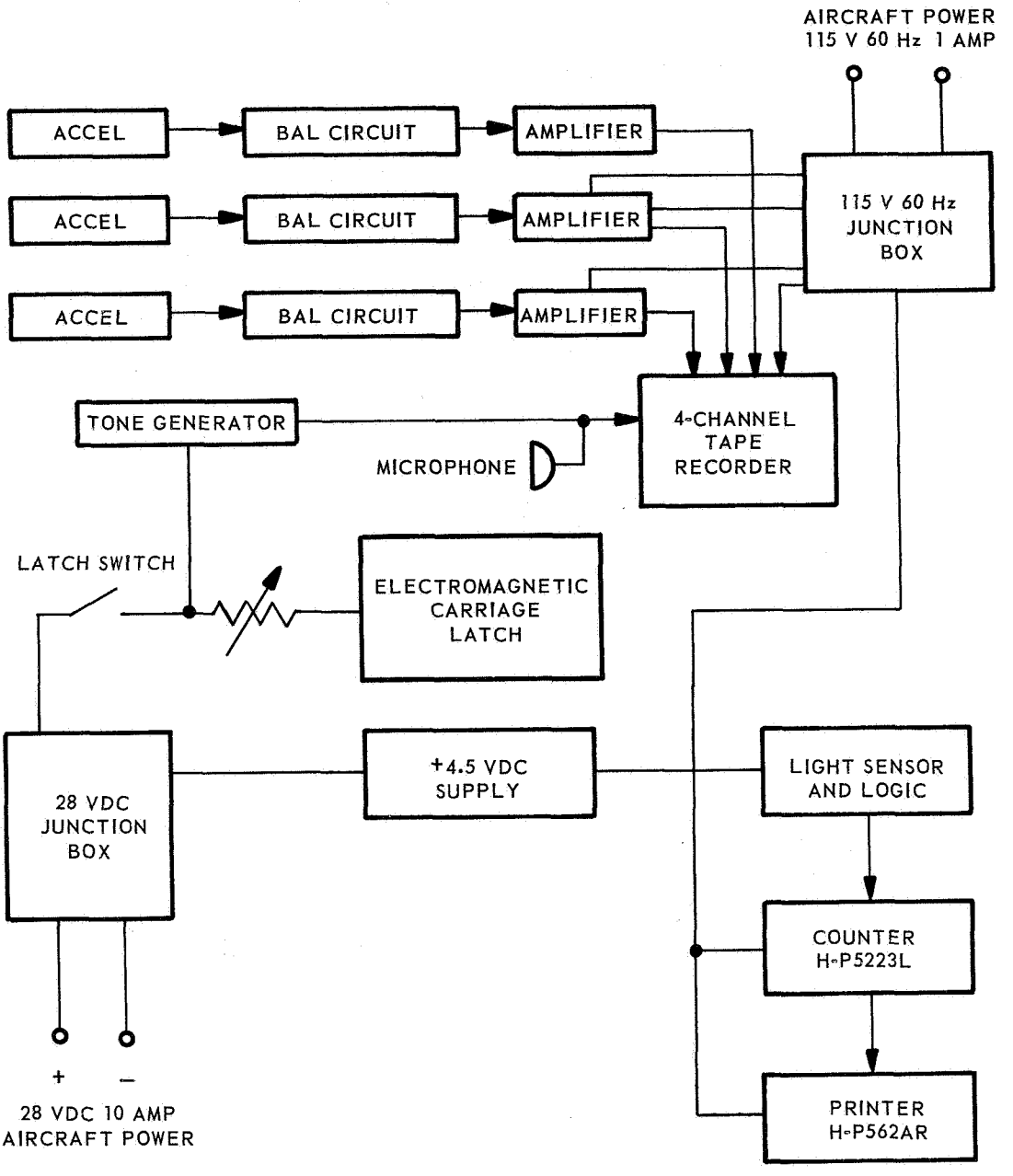


Fig. 6 Electrical System Schematic Diagram

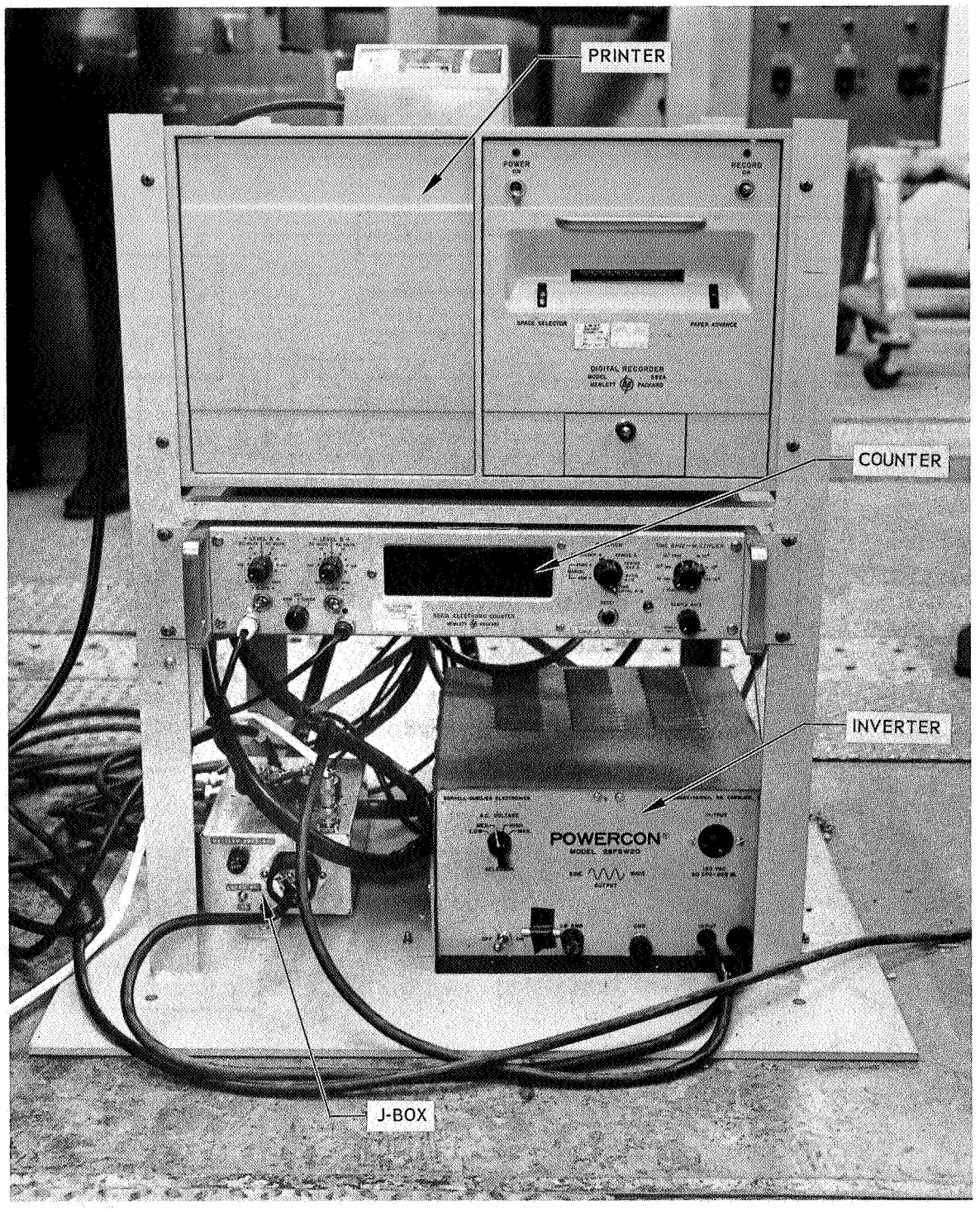


Fig. 7 Printer/Counter Readout System

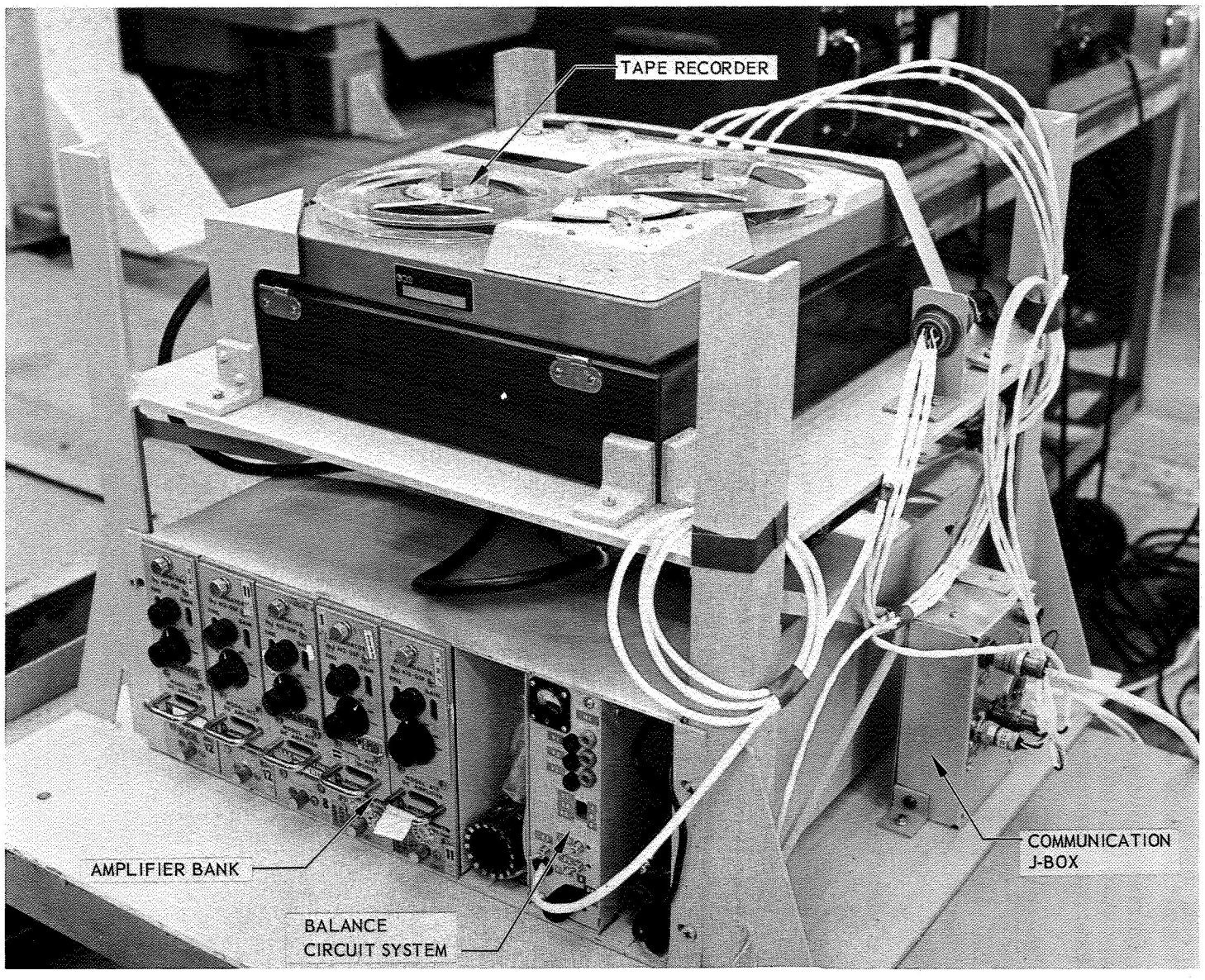


Fig. 8 Tape Recorder/Accelerometer Amplifier System

independent of the others by virtue of having a separate battery, voltage adjustment, balance potentimeter, and recording channel.

During reduction of the mass measurement data, any anomalies in the data could be compared with the accelerometer readings to determine if any external forces were operating during the tests.

Recording. - A 4-channel instrumentation recorder was used to record the three accelerometer outputs plus voices of the subject and observer and a tone which indicates that the magnetic latch is energized. The latter is used during test of acceleration sensitivity in place of the mechanical latch used for mass measurement.

Channel 2 of the recorder was a direct record channel, so it was used for the voices and tone. Channels 1, 3 and 4 were FM channels with a frequency response from dc to 1250 Hz. These were used to record the amplified outputs of the accelerometers. The voice channel identified the particular test being monitored by the accelerometers and gave details and observations of the test.

During tests of acceleration sensitivity the observer records the amount of acceleration or displacement to be used, the latch and tone are turned on and the subject's earphones are cut off. At the appropriate time the latch and tone are turned off and the subject is accelerated. When he senses the acceleration he speaks into his microphone. The delay between acceleration and sensation can be determined accurately when the tape is played back in the laboratory. Speed accuracy of the recorder is $\pm$ 0.25% or less.

OTOLITH THRESHOLD MEASUREMENT

Concern has been expressed by many space scientists over vestibular organ reaction to long-term exposure to weightlessness. There seems to be agreement that the vestibule will adapt to the zero-g condition over the course of an extended space mission. Difficulties are anticipated, however, during the reentry phases of such a mission due to the sudden change from hypogravic to hypergravic accelerations. The vestibular apparatus is not expected to re-adapt sufficiently to the high g milieu. As a result, the astronaut is likely to suffer motion sickness and other distresses to the extent that his performance of critical reentry tasks may be seriously degraded.

It is now generally accepted that the otolith receptors, rather than the semicircular canals, play the principal roles in the production of motion sickness. With the exception of the work of Graybiel, Miller, and others at Pensacola, little has been done to develop devices that can be used in both ground and space tests for applying accurate and reliable stimuli to the otolith receptors. This is particularly true in the case of linear acceleration, the prime stimulator of the otolith organ.

Early in the development of the mass measurement system it was conjectured that with minor modification the unit could also serve as an otolith stimulator. Since this versatility could be accomplished simply and at low cost it was judged a worthwhile pursuit. Preliminary otolith threshold tests were conducted with a device that simulated the spring-mass action of the mass measurement system. The test results indicated that typical and reliable otolith thresholds can be measured by means of the spring-mass principle. The test section of the present report discusses the results of tests with the prototype MMS designed for space flight in which otolith thresholds were measured under both laboratory and flight conditions.



TEST PROGRAM - MASS MEASUREMENT

The MMS Phase II Test Program was divided into two basic test phases: (1) ground tests, and (2) the flight test. A summary of test plans and procedures is presented in this section.

Test Objective

The objective of the Phase II test program is to confirm the operational performance of the modified MMS under one gravity as well as zero gravity conditions. Results of the tests are analyzed and performance evaluations made. This data is then used as inputs to guide the design of an operational spacecraft MMS.

The performance goals for a rigid mass are as follows:

5 to 40 pounds	$\pm$	0.25 pounds
41 to 250 pounds	$\pm$	0.50 pounds at mid point of range

The performance goals for animate objects (human subjects) are as follows:

5 to 40 pounds	$\pm$	0.50 pounds at mid point range
41 to 250 pounds	$\pm$	1.0 pounds at mid point range

Design verification tests were conducted to insure that the modified Phase II hardware was in operational readiness prior to start of calibration testing.

Test Plan

The detailed test plan was prepared to insure smooth operational testing and also to insure that the test processes are adequate to determine the desired test objectives.

The test plan covered two phases of testing: (1) ground tests, and (2) flight tests. A summary outline of each of these phases is presented.

Ground Test Plan. - The ground test plan covered five major tasks. They are as follows:

- Hardware and Equipment - MMS configured for aircraft zero-g tests with all test support equipment.

- Test Set Up - Install MMS in the LMSC development test laboratory. Level and check mechanical and electrical operation.

- Calibration - Verify operation of MMS and electronic timing system--determine optimum number of oscillations--operate system utilizing calibration weights under one "g" conditions to verify MMS readiness for simulated zero-g environment--place MMS in simulated zero-g environment--calibration runs back down 5 to 60 pounds and back up 40 to 250 pounds--weigh six human subjects with a weight range from 130 pounds to 200 pounds.

- Design Verification Test - This test series is designed to verify hardware performance goals as defined in test objectives.

- Acceleration Threshold Measurement - Place MMS in acceleration threshold measurement mode of operation under simulated zero-g conditions and determine baseline acceleration data on three (3) selected human subjects.

Flight Test Plan. - The flight test plan covered nine major tasks. They are as follows:

- Hardware and Equipment - Ship hardware from LMSC, Sunnyvale, Calif., to Wright-Patterson Air Force Base, Dayton, Ohio. Inspect hardware on arrival at Wright-Patterson for any shipping damage.

- Test Set-Up - Verify with WPAFB, Zero-g Test Director, the selected location of MMS hardware is nearest aircraft cg on the longitudinal axis.

- Basic Installation - KC-135 - Install all test equipment in aircraft utilizing the 20" grid bolt pattern provided. Verify all electrical interfaces.

- Calibration - Mechanical and electrical checks will be made to verify system operation. Operate MMS in the aircraft using selected calibration weights to insure complete system operation. Compare performance with data obtained from laboratory tests.

- Preflight Test - Prior to each test flight, the operational readiness of the MMS as integrated in the KC-135 will be confirmed.

- Threshold Measurement Test - Prior to engine start, a series of measurements will be taken using the three (3) test subjects. Results will serve as the second increment of baseline data for later analysis.

- Personnel - All flight personnel shall be fully qualified per Air Force procedures prior to flight test and be fully acquainted with the test hardware, flight characteristics, and detail test procedures.

- Flight Tests - During the zero gravity period of the parabolic flight profile, the MMS will be tested using certified calibration weights of 12-inch square steel plates in both the back-down and back-up configurations. The second series of tests will utilize human subjects. The third series of tests consist of weighing approximately four (4) miscellaneous parts of objects.

- Threshold Measurement Flight Test - These tests will be conducted in the same manner as the laboratory test and pre-flight test so that a basis of comparison can be made.

Ground tests show that oscillating time for a 250 pound mass is less than 2.5 seconds. With each zero-g parabola the period of weightlessness is approximately 30 seconds. Based on the above information, it was postulated that two measurements could be made per parabola. Table 1 shows the proposed test profile.

Test Procedures

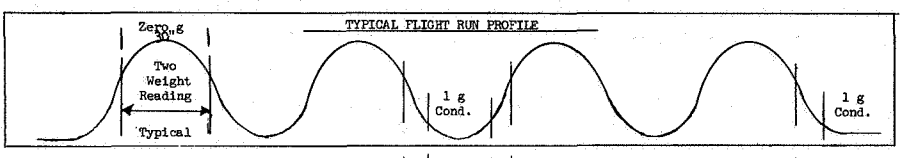
The test procedures are listed for the two phases of testing. The procedures for both phases established in detail the steps required for operation of the complete MMS in both Ground and Flight Test environment. The procedural steps are as follows:

GROUND TESTS

- Test Set-up
- Equipment Checkout and Calibration
- System Operation Checkout
- Calibration Weighing
- Design Verification
- Acceleration Threshold Measuring

Table 1

MASS MEASUREMENT SYSTEM
PHASE II
FLIGHT TEST PROGRAM, KC-135



CERTIFIED WEIGHTS

Run No.	Weight Compliment	Mass Weight	Duration	Weight Compliment	Mass Weight	Duration
1	Tare			W-1	5#	60"
2	W-1 & 2	20#	60"	W-1, 2, & 3	30#	60"
3	W-1, 2, 3, & 4	40#	60"	W-1, 2, 3, 4, & 5	60#	60"
4	Remove weights, back up position, Reapply W-1, 2, 3, & 4		60"	W-1, 2, 3, & 4	40#	60"
5	W-1, 2, 3, 4, & 5	60#	60"	W-1, 2, 3, 4, 5, & 6	80#	60"
6	W-1, 2, 3, 4, 5, 6, & 7	100#	60"	W-1, 2, 3, 4, 5, 6, 7 & 8	150#	60"
7	W-1, 2, 3, 4, 5, 6, 7, 8, & 9	200#	60"	W-1, 2, 3, 4, 5, 6, 7, 8, 9, & 10	250#	

Approximately five (5) minutes will be required to remove weights from pallet and place in storage.

An additional three to five (3-5) minutes are required to position human subject in preparation for next phase of weighing.

HUMAN SUBJECTS

1	W-11	?#		W-11	?#	60"
2	W-12	?#		W-12	?#	60"
3	W-13	?#		W-13	?#	

Approximately three (3) minutes will be required in rearranging configuration from human subject weighing to the Random Parts.

RANDOM PARTS

1	W-14	?#	60"	W-15	?#	60"
2	W-16	?#	60"	W-17	?#	

End of weighing tests - remove and store weights.

FIGURE I

THRESHOLD MEASUREMENTS

	Displacement	Displacement		Displacement	Displacement	
			Subject Number 1			
1	0.5"	1.0"		1.5"	2.0"	
2	0.5"	1.0"		1.5"	2.0"	
3	0.5"	1.0"		1.5"	2.0"	
4	2.0"	1.5"		1.0"	0.5"	
5	2.0"	1.5"		1.0"	0.5"	
6	2.0"	1.5"		1.0"	0.5"	60"

Repeat for two additional human subjects.

A minimum total of eighteen (18) flight runs are required.

FLIGHT TESTS

- Test Set-up
- Equipment Checkout and Calibration
- Calibration Weighing, Preflight
- Threshold Measurement, Preflight
- Mechanical/Electrical Checkout, Preflight
- Calibration Weighing, Zero-g Flight
- Weight Determination, Zero-g Flight
- Threshold Measurements, Zero-g Flight

Ground Calibration Test

Weights. - The ten steel weights which were fabricated for use in the flight tests were also employed in the ground calibration tests. They were calibrated to within .001 pound. Figure 9 illustrates the packaging arrangement for the weights.

Simulated Zero-g Tests. - To simulate the unloading of the carriage bearings which would exist in zero-g, it was decided to support the seat and carriage by means of a cable suspended from a point approximately 90 feet above the loaded center of mass of the seat and carriage assembly. In order to accurately adjust the tension of the cable so that it exactly counteracted the weight of the moving elements of the MMS, the clearance between the vertical ball bearings and the rail were increased, and each of these ball bearings were tested for zero load by rotating them as the main cable turnbuckle and/or the front and rear branch cable turnbuckles were adjusted. Of course, readjustment was required each time weights were added or removed. To minimize the random effects of cable slip, only one cycle of oscillation was timed per test run. Six such test runs were made for each total mass. Twenty-two different total masses ranging from 40 to 250 pounds were tested with the pallet back up, and six different total masses between 5 and 50 pounds were run with the pallet back down. Spot checks of some of the above listed masses were re-run with the overhead cable slack, in order to separate the effect of unloading the bearings from the effect of having the overhead cable attached. Six human subjects ranging from 128 lb to 221 lb tested under simulated zero-g were also again tested with the overhead cable slack. Each subject was weighed on a scale having quarter pound graduations; readings were interpolated to a tenth of a pound. The simulated zero-g laboratory test is shown in fig. 10.

One-g Tests. - The six human subjects were retested with the overhead cable completely removed. Similar retests were performed on deadweight, five with the pallet back up and four with the pallet back down, including zero weight (tare). Each test was performed six successive times to provide sufficient data for an accurate value of time per cycle.

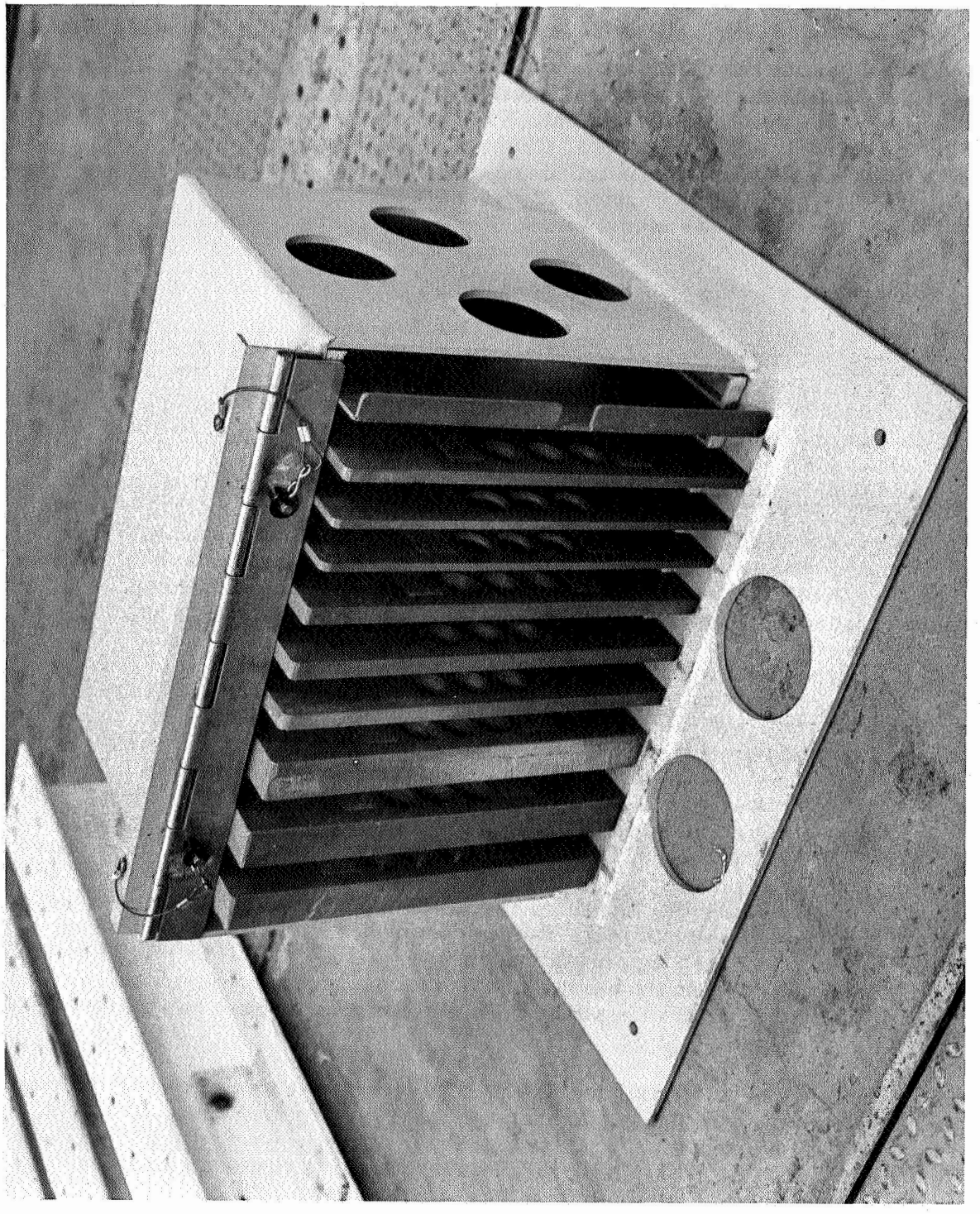


Fig. 9 Inanimate Weight Storage Container

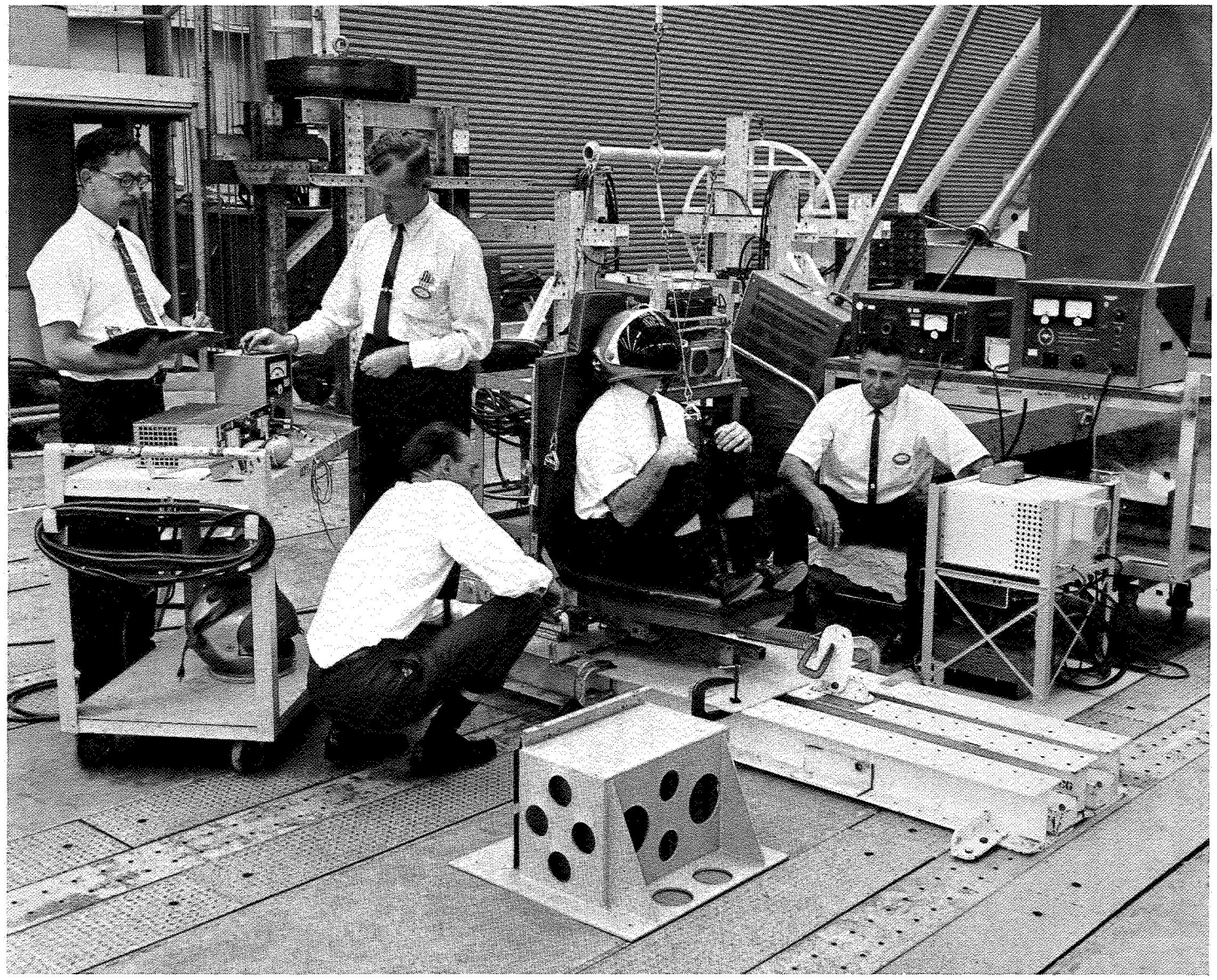


Fig. 10 Simulated Zero Gravity Laboratory Test Configuration

These tests were carried out in accordance with the test plan and detail test procedures. The results of these calibration tests proved hardware performance was within contract requirements. The performance data was put on a computer program for preparation of interpolation tables at .10 pound increments. This was done for rigid masses under simulated zero-g conditions at 1.00 pound to 60 pounds, pallet back down, 30.00 pounds to 260.00 pounds pallet back up, and for humans at 100.00 pounds to 259.90 pounds. These tables are used to compare the test results of the simulated zero gravity ground calibration runs to the results of the KC-135 Zero Gravity Tests.

The calibration tests also proved the complete MMS readiness for the KC-135 flights. The complete acceleration monitoring system was checked and the X, Y and Z accelerometers calibrated.

Preflight Test

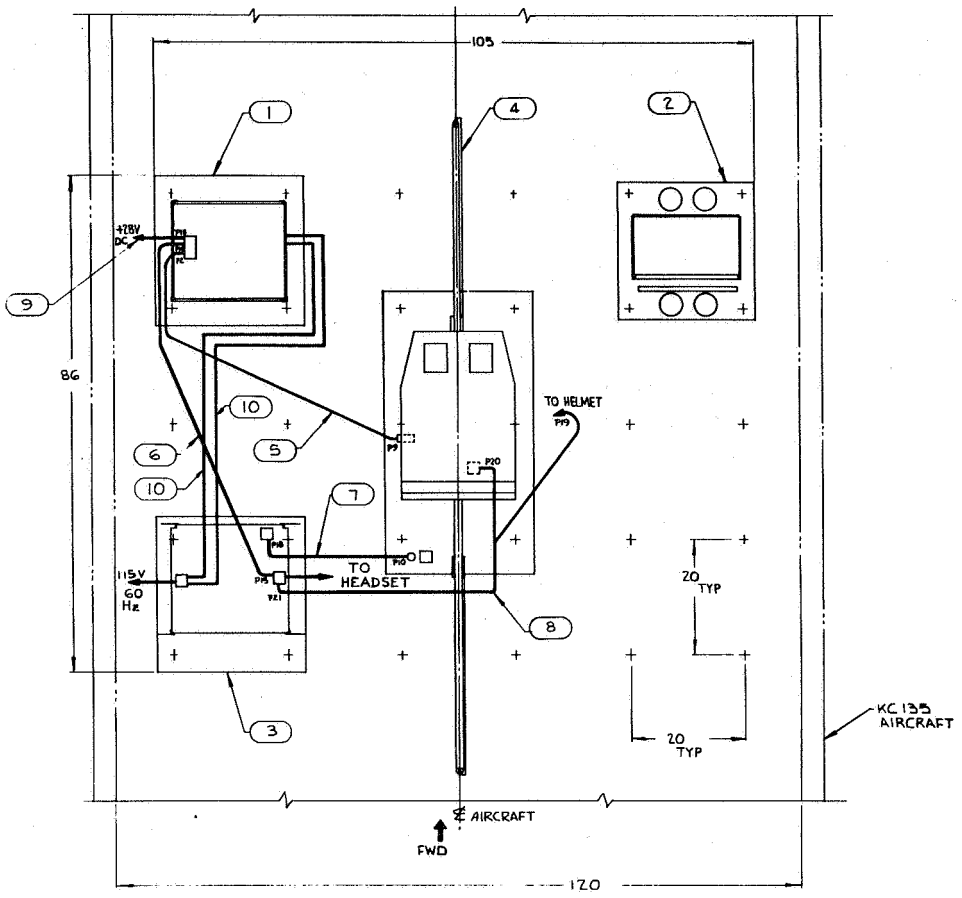
The MMS was arranged on the floor of the test facility building per the test procedures and in the same configuration as the system would be installed in the KC-135 aircraft. The arrangement can be seen in fig. 11.

All mechanical phases of the hardware were checked for correct operation. All electrical interfaces were connected and system power energized. A series of test runs were made to establish system tare. It was noted that the pulser/counter electrical interface was not functioning properly.

The counter and printer require 115 v 60 Hz for operation. To meet this power requirement a 38 vdc to 115 v 60 Hz inverter was procured to power these instruments. Operation was satisfactory when the system operation runs were made at LMSC but not at the WPAFB Lab. It was determined that the long lines and high inductance of the 28 vdc power source at WPAFB caused spikes from the inverter to be reflected into the sensor circuitry. Filter capacitors were added to the + 28v and + 4.5v lines in the sensor with partial success.

The system operation was checked using 28 v for the sensor circuitry and 115 v 60 Hz for the counter and printer operation. System performance was satisfactory in this electrical configuration. A check was made to determine if the specific KC-135 aircraft to be used during the flight tests had 115v 60 Hz available. This proved to be true and the decision was made not to use the inverter and power the counter, printer, tape recorder and acceleration amplifiers with the aircraft 115v 60 Hz power.

The Air Force supplied a standard AF type headset and microphone. The MMS observer communication system was modified to 8 ohms and 3 ohms to match the impedance of the AF system. This was done so that the aircraft communications and the MMS communication would be compatible.



PARTS LIST

QTY REQD	CODE IDENT	PART OR IDENTIFYING NO.	NOMENCLATURE OR DESCRIPTION	MATERIAL DESCRIPTION OR NOTE	MATERIAL SPECIFICATION	ZONE	ITEM NO.
2		8120-0078	A.C.PWR.CORD	Hewlett Packard			10
1		CP101940-521	CABLE ASSY				9
1		-519					8
1		-517					7
1		-515					6
1		CP101940-513	CABLE ASSY				5
1		CP101851	CARRIAGE & PALLET				4
1		CP101873	ACCELEROMETER EQUIPMENT				3
1		CP101849	WEIGHT STORAGE CABINET				2
1		CP101872	TIMING EQUIP.				1

Fig. 11 MMS KC-135 Aircraft Installation

A final operational check was made of all MMS equipment in the WPAFB Lab. and the system proved operational per the test plan and procedures and ready for installation in the KC-135 aircraft.

Flight Test

MMS Equipment Installation. - The MMS was transported from the WPAFB to the flight line and placed inside the aircraft. Location of the equipment in the aircraft was per the test procedures with minor modifications. Figure 12 shows the arrangement of the MMS system components within the aircraft. The only modification was that the distance between the components was made greater to insure better movement of test personnel between the components.

The aircraft interior padding in the area directly under the MMS mounting base plate was removed and the base plate was bolted to the solid aircraft floor. This was done to insure no slippage between the floor and the pallet during the oscillating period. All MMS support equipment was bolted into place with no aircraft/MMS interface problems.

The X, Y and Z accelerometers were bolted in place on the bracket provided on the MMS mounting base plate as the last step in the installation procedure.

The electrical interface was made between the various MMS components and the aircraft. This interface was made with all aircraft power off.

Per the test procedures the complete MMS system was checked for mechanical operation of all units. Arrangements were made with the aircraft crew chief to turn on aircraft power supplied by the ground APU. The MMS electrical and instrumentation equipment was energized per test procedures and checked for operation. At the completion of this check the MMS was mechanically and electrically ready for calibration weighing.

The pre-flight calibration weighing was a performance check made in the aircraft using aircraft electrical power and followed procedures to be used during the actual zero gravity flight. The purpose was twofold; (1) the check insured the operational readiness of the MMS, and (2) training of the MMS test crew was provided to perfect operational procedures. Performance of the MMS during this check was satisfactory and the complete system was ready for the airborne tests.

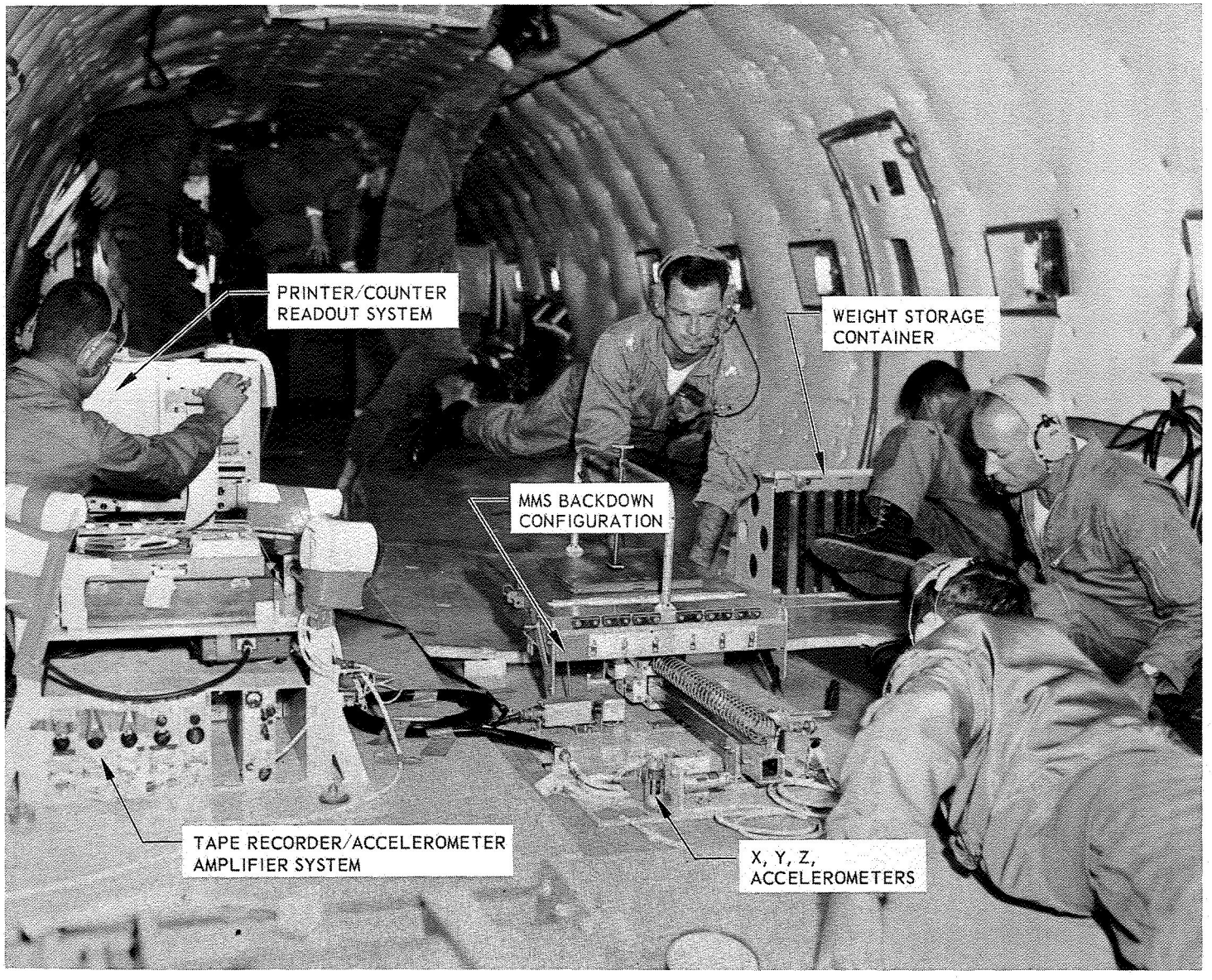


Fig. 12 KC-135 MMS Flight Configuration

Pre-Flight Check. - Prior to take-off, a flight checklist was used in accordance with the test procedures to insure that the system was in operating condition. This checklist contained only those steps required to operate the system, sequence of application of weights, and shut down of the system. This checklist was used each day of the flight tests.

Shakedown Flight. - Due to previous KC-135 aircraft commitments at Oklahoma City, it was proposed and agreed that the MMS flight test crew fly on this mission and enroute to Oklahoma City fly a given number of zero gravity parabolas in the assigned test range area. This would allow a shakedown operational run for the MMS hardware and also provide experience for the MMS test crew in the zero gravity environment.

The MMS was configured with the pallet back in the down position. The goal for the first few parabolas was to obtain a MMS system tare.

A total of 9 zero gravity parabolas were flown and calibration weights of 5 lb and 20 lb were tested on the device. Performance of the MMS hardware and instrumentation was satisfactory during the shakedown test.

While the shakedown test was not called for in the test plan and procedures, it proved most valuable as a zero-g operational check on the MMS and provided much needed training for the MMS test crew.

Flight Test - Rigid Mass. - The second day of flight testing was per the test plan and procedures calling for zero gravity calibration of rigid mass and the testing of three human subjects on the MMS.

The first series of tests was 5 lb thru 60 lb with the device in the pallet back down position. Figure 13 shows the MMS in this configuration operating in the zero gravity environment. Table 2 gives the weight identification and loading sequence.

A total of 7 parabolas were flown in this configuration. Two parabolas were flown at weight level W-1 and W-3. Some of the readings were taken at the end of the parabolas and to be sure of at least two good readings in the zero gravity environment it was necessary to re-run W-1 and W-3.

The second series of tests were 40 lb to 250 lb in the pallet back up configuration. Figure 14 shows the MMS in this configuration. Table 2 gives the weight identification and loading sequence.

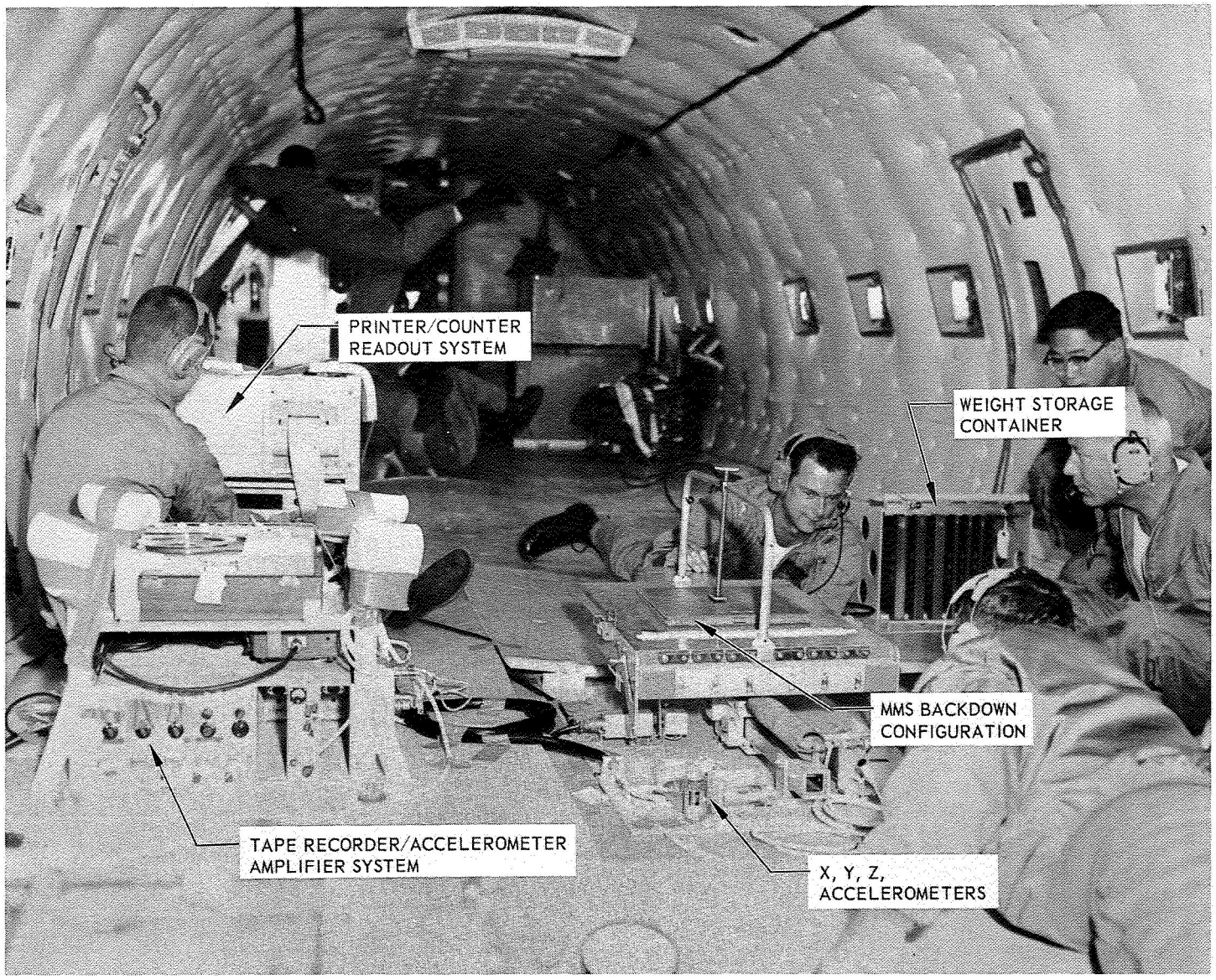


Fig. 13 MMS Zero Gravity – Rigid Mass Measurement

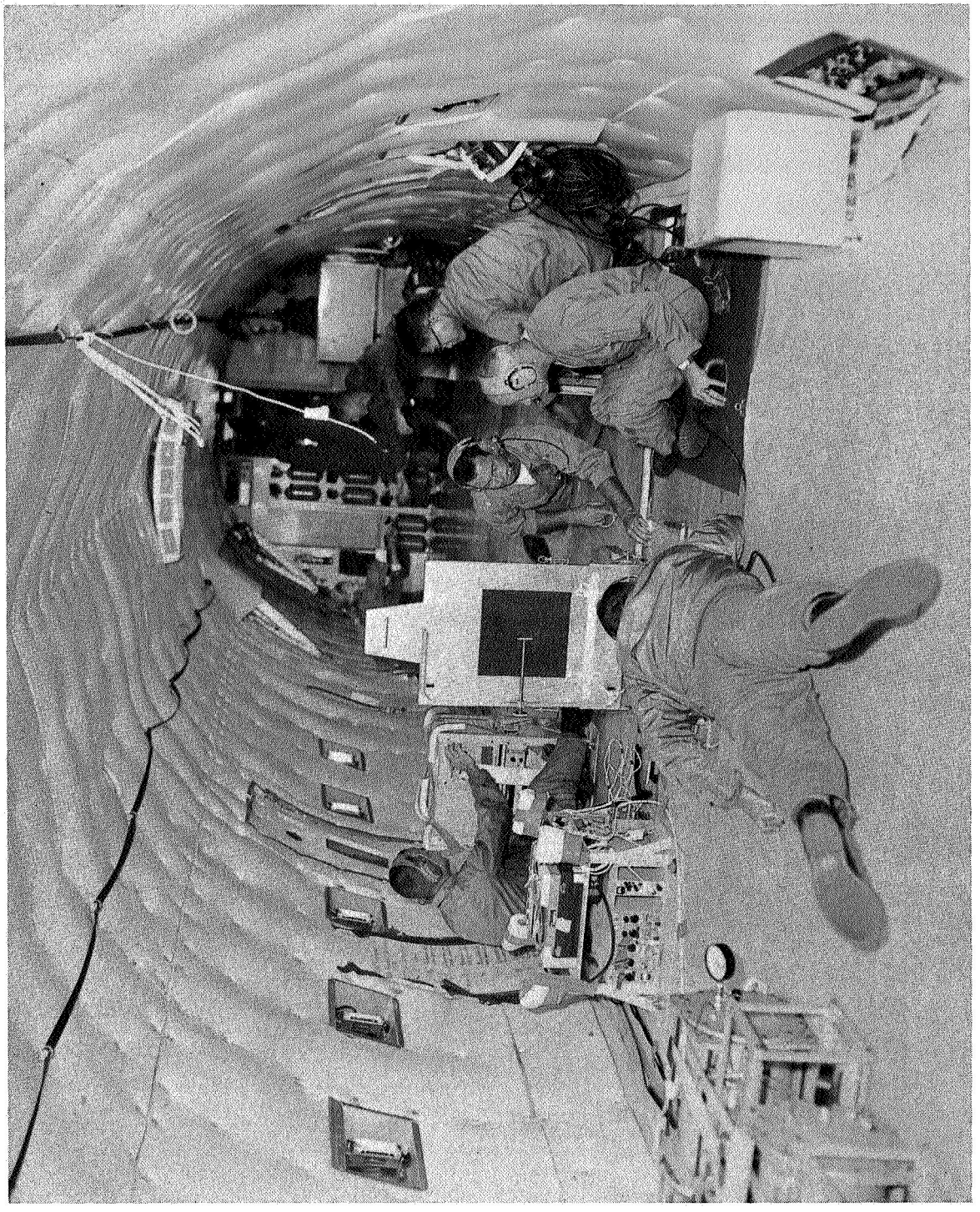


Fig. 14 MMS Zero Gravity Pallet Back-Up Configuration

Table 2

Loading Sequence

Pallet Back Down Weight and Sequence	Unit Weight (lb)	Accumulative Weight (lb)
W-1	5	5
W-2	15	20
W-3	10	30
W-4	10	40
W-5	20	60
Pallet Back Up		
W1, W-2, W-3 & W-4	--	40
W-5	20	60
W-6	20	80
W-7	20	100
W-8	50	150
W-9	50	200
W-10	50	250

Flight Test - Human Subjects. - Three human subjects were tested on the MMS. The weight spread was quite wide at 113 lb, 181 lb, and 200 lb. The subjects represented good sound physical specimens with little fatty tissue. One subject was a civilian employee at WPAFB and the other two subjects were Air Force personnel.

The man restraint system was placed on the pallet and the first subject was strapped in place. This was done under one-g conditions. Two parabolas were flown for a total of 5 data points. The second subject received two zero gravity exposures for a total of 3 data points. The third subject flew two parabolas for a total of 3 data points. The subject can be seen in fig. 15 under zero gravity conditions.

This concluded the test mission with a total of 22 zero gravity parabolas. Equipment operation during the mission was satisfactory with oscillating times recorded and a verbal record of each weighing situation on the tape recorder. The overall KC-135 test configuration can be seen in fig. 16. After the landing at WPAFB the MMS was converted to the threshold acceleration measurement configuration. The system was checked and readied for flight test.

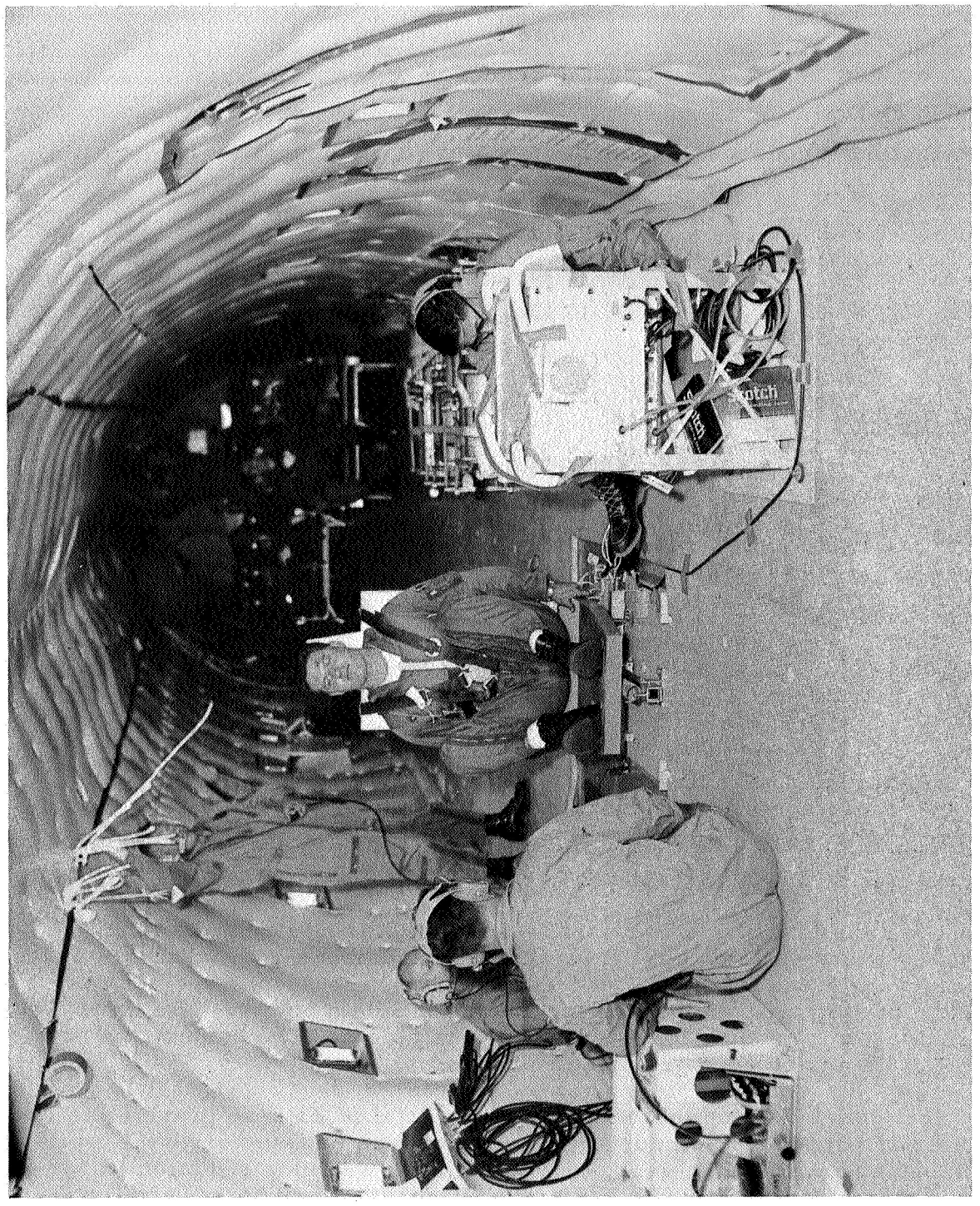


Fig. 15 MMS Zero Gravity – Human Test Subject

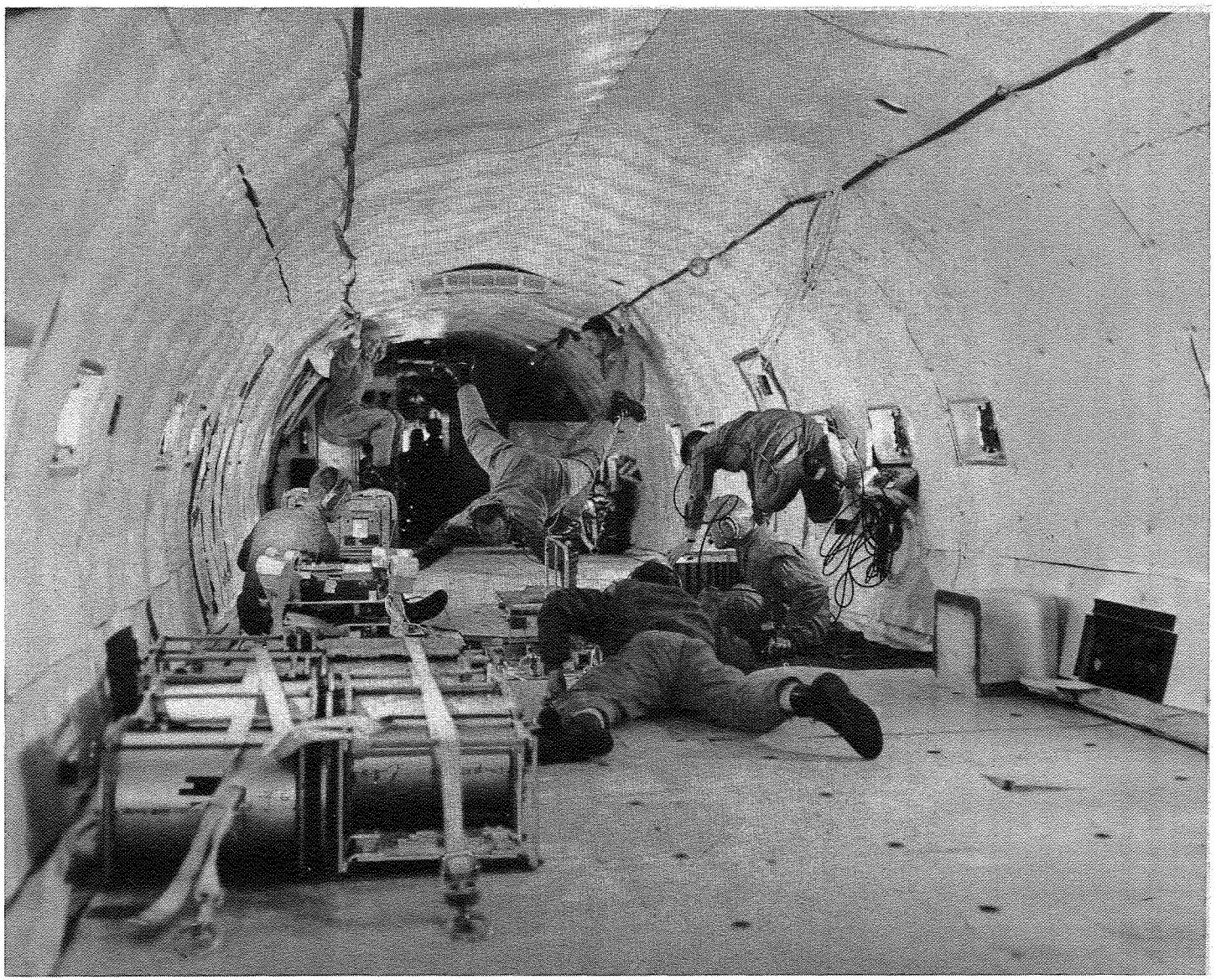


Fig. 16 MMS Zero Gravity Overall Test Configuration

Threshold Acceleration Measurement Flight Test. - The third and last day of flying was spent testing two human subjects with the MMS in the threshold acceleration mode. A total of 12 parabolas were flown for test data. This test is described in detail under the Otolith Threshold Measurement Test Program.

Test Results

The procedure used to calibrate the MMS has been previously described in general terms. This section presents the results of the calibration and a brief analysis of the MMS from a statistical viewpoint. Several sets of runs were made in the calibration process: flight tests using the zero-g portion of a parabola; ground tests in the normal one-g situation; and, ground tests in which a suspension cable system was used in an effort to simulate zero-g. A set of rigid calibration masses and human subjects were the test objects. The MMS has two configurations; back down for measuring smaller masses, and back up for measuring larger masses and humans.

KC-135 Zero Gravity Transient Acceleration. - Some concern was given to the effect of low transient accelerations on the aircraft while in the zero gravity parabola and the effect such accelerations would have on the MMS performance. These low acceleration loads would cause a variable friction load on the MMS bearing system which would in turn effect the repeatibility of the MMS oscillating period.

To measure these loads, three accelerometers were installed on the MMS base plate on the X, Y and Z axis of the aircraft (See fig. 12). The acceleration data was put on 3 channels of a 4 channel magnetic tape recorder.

A typical acceleration trace is shown in fig. 17. The complete zero gravity parabola can be easily followed on the Z-vertical axis trace. In reading from the bottom of the figure to the top, the two-g pull up and climb can be seen followed by transition into zero-g with the accelerometer reading zero for about 21 seconds. This is again followed by a transition period, pull out, and into another climb for the next parabola.

The Y-lateral axis during all the test flights indicated that lateral accelerations were almost non-existent. However, the cocking of the MMS can be seen by short spikes on the trace. These spikes can also be seen on the X-longitudinal trace. This coupled with the verbal description on the tape recorder and number of MMS recorded measurements on the printer provided excellent identification of measurements taken for a given period of time. Thus, the transient accelerations, if any, could be analyzed for any given measurement.

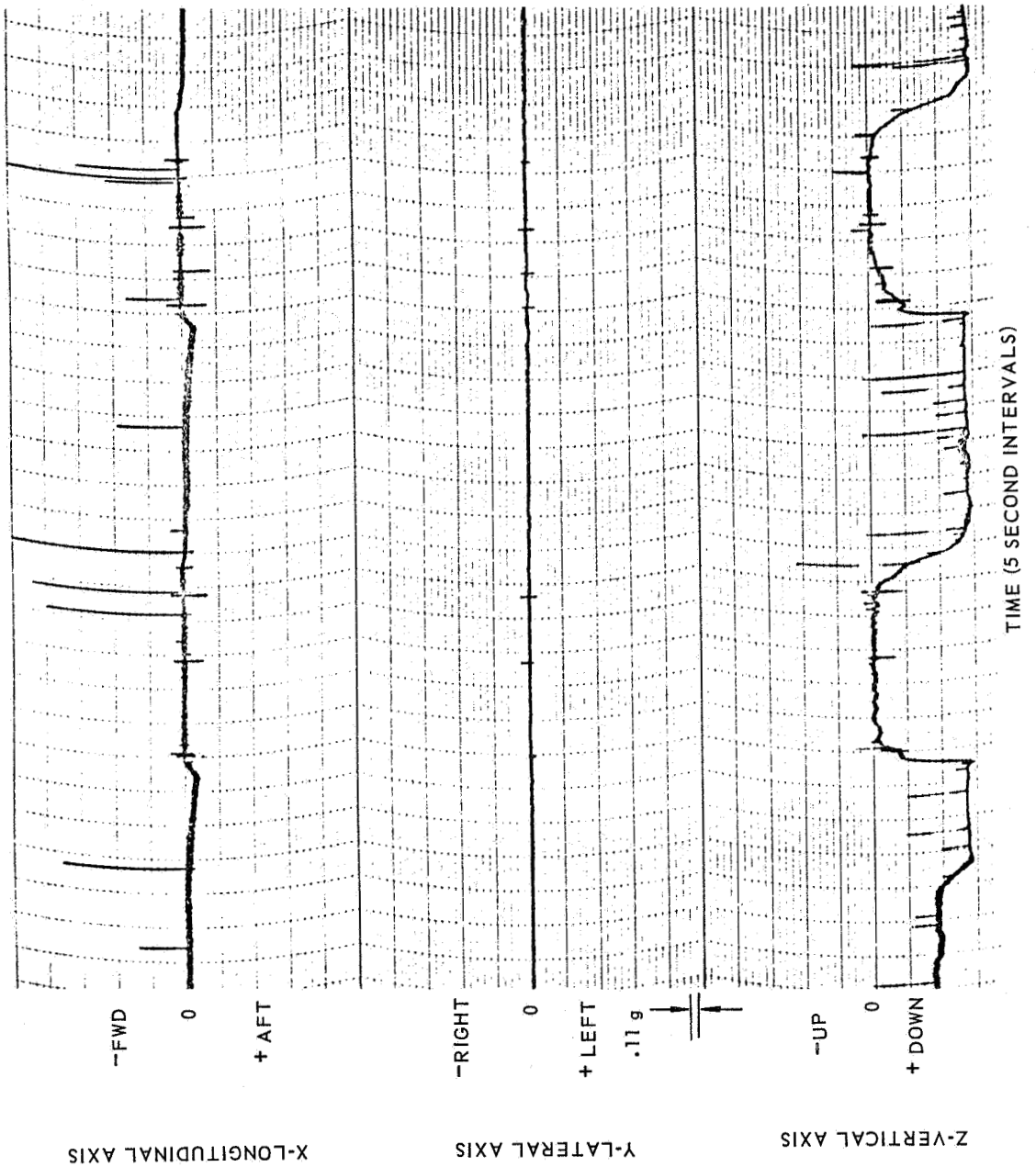


Fig. 17 Typical KC-135 Acceleration Trace

The X-longitudinal axis shows some variation in forward acceleration. But most interesting, the oscillating period for each measurement can be seen. This may be caused by the dynamic effect of the oscillating MMS on the total aircraft system while in the zero gravity environment flight. This is at least theoretically true. However, since the accelerometer is mounted to the MMS base plate, this could be caused by relative movement between the MMS mounting plate and the floor of the aircraft. While this movement is small, some effect on MMS performance would be a consideration. However, this acceleration is so small that it is considered negligible.

The accelerometers used had a range of $\pm$ 3 g to a specification of $\pm$ 1%. The measurements during the zero-g portion of the flights were well below the maximum range limits and the acceleration system performed satisfactorily.

Flight Test Results. - Data obtained in the zero-g flight test are given in Table 3. The mass shown includes all mass placed on the MMS, i. e., for the rigid mass-back up configuration, the mass of 0.3197 lb of the restraint strap is included in the tabulated values, and for the human subjects the mass of 4.2 lb for the harness is included. The time shown is the average of at least three replicate determinations of the period for one oscillation, after discarding obviously erroneous values caused by the aircraft leaving the zero-g portion of the parabola during an oscillation. The calibration technique applied was identical to that used during prototype MMS development.

Applicability of Simple Harmonic Motion Equation. - Experimental results were compared with calculated values using the simple harmonic motion equation. The MMS operational mode of pallet back down was selected since it will have the least aerodynamic drage. The equation for simple harmonic motion was used with several masses (tare + known deadweight) and corresponding period of oscillation from the zero gravity test. Based on several values, an average spring constant (k) of 33.38 lb/ft was derived. Using the equation for simple harmonic motion:

$$T = 2\pi\sqrt{\frac{W}{gk}}$$

and substituting $k = 33.38$

$$W = 54.45\ T^2$$

Using a known period of oscillation for an actual weight, a comparison as shown in Table 3 was performed. This table shows fairly close correlation between calculated and actual weight. For example in the 59.77 lb case, the difference is approximately 0.8%. These differences are attributed to the fact that the basic equation for undamped simple harmonic motion does not take damping into account. There are certain components of the MMS that cause damping. These factors are independent of load on the

bearing but they are always present when the MMS is in motion. These components are the rubber O rings and bearing shields.

Because of the lack of complete correlation with the simple harmonic motion equation, LMSC initiated a computer curve fit program to establish empirical equations that take all variable factors into account.

Table 3

Comparison Between Actual Weight and Calculated Weight

T (sec.)	T^2	Calculated Weight	Actual Total Weight	Weight Difference	% Change
0.7982	0.6371	34.69	34.42	0.27	0.8
1.289	1.6615	90.47	91.20	0.73	0.8
1.046	1.0941	59.57	59.77	0.20	0.3

Calibration. - Figure 18 presents one-g and zero-g experimental data taken during the course of testing. Noted on this figure are various mass measurement operational modes; within graphical accuracy, one curve reasonably correlates all of the data. To more accurately calibrate the MMS (i.e., determine the mass that corresponds to a recorded period determination) the period vs. mass data was subjected to a digital computer curve fit program in which fourth order polynomials in each variable are cross matched. The polynomials are in x, exponential x, ln x, 1/x, 1/exp x, and 1/ln x. Thus a 4 x 6 x 6 or 144 set of cross matches is prepared. The program computes coefficients, standard deviations and residuals for the 10 best fits. The selected fit is then used to prepare a closely spaced table of mass vs. time, from which unknown mass can be determined by linear interpolation to 0.01 pound significance. Three statistical measures (accuracy, reproducibility and sensitivity) have been calculated for the MMS. Because of the need to minimize test data points in the flight test, these measures must be considered as preliminary.

Measurement Accuracy. - Accuracy is defined as the difference between the "true" value and the indicated value. The calibration masses are National Bureau of Standards traceable and accurate in the order of parts per million. The MMS accuracy test consists of examining the periods obtained with the known masses and comparing these masses to those that would be predicted for that period using only the calibration table. The results as shown in Table 4 indicate an average accuracy of 0.02% for rigid-mass back-up, a poorest accuracy of 0.08%, and a best accuracy of 0.00%. For rigid-mass back-down, the average accuracy is 0.05%, the worst accuracy is 0.07%, and the best accuracy again is 0.00%. An accuracy value of zero means that there is no difference between "true" mass and indicated mass to within 0.01 pound. Only three zero-g data points were taken for human subjects so that a calibration table could not be prepared.

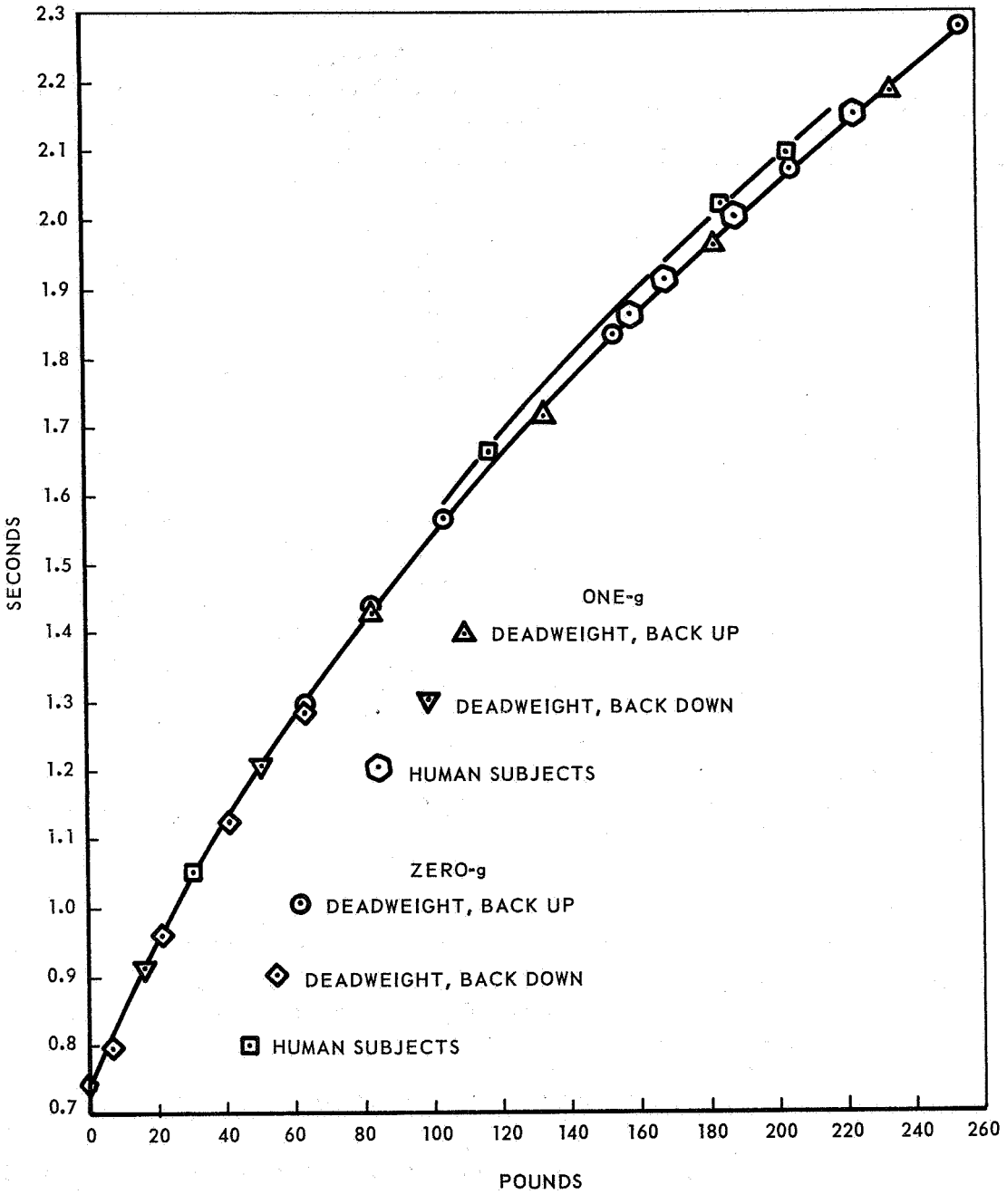


Fig. 18 Mass Measurement Data

Table 4

MMS Calibration Data

(Analysis of Zero-g Flight Test Data)

Actual Mass (lb) (1)	Observed Period (sec) (2)	Mass Inferred From Observed Period in Calibration Tables (lb) (5)	Deviation (Actual-Inferred) (lb) (3)
A. Rigid Mass - Back Down			
5.26	0.79821	5.26	0.00
20.48	0.95543	20.47	0.01
30.61	1.04640	30.63	-0.02
40.67	1.12993	40.66	0.01
62.03	1.28890	(out of range)	--
B. Rigid Mass - Back Up			
40.99	1.13840	41.01	0.02
62.36	1.29680	62.30	0.06
83.51	1.43820	62.30	0.06
104.48	1.56477	104.56	0.02
155.16	1.83450	155.15	0.01
205.91	2.07330	205.92	-0.01
256.10	2.28138	256.10	0.00
C. Human Subjects			
118.7	1.66090	121.7	-3.0 +0.2)
186.7	2.01660	193.4	-6.7 -3.3) (4)
205.7	2.09587	211.0	-5.3 -2.7)

(1) Calibrated mass plus any straps or harnesses used; i.e., total mass places on the MMS. For human subjects, corrected for 1.5 lb error in scale used at WPAFB.

(2) Average of three or four replicates; last figure not statistically significant.

(3) The deviation for human subjects is discussed in the Error Analysis.

(4) Deviation corrected for internal damping.

(5) Based on rigid-mass calibration tables.

Using the calibration table prepared for rigid masses in zero gravity, deviations of -3.0, -6.7 and -5.3 lb were found.

Much of the deviation may be attributed to the slosh effect by which non-rigid masses internally damp harmonic motion. Using the observed 1-g difference between humans and rigid masses to correct the deviation, the values of +0.2, -3.3 and -2.7 lb were calculated. The magnitude of these deviations for human subjects far exceeded that observed in previous data, and necessitated an intensive investigation and hardware inspection upon the return of the equipment to Sunnyvale. The results of this investigation are given in the section on error analysis. By using only the indirect calibration methods available, it appears possible to make an absolute determination of a human's mass within about 0.5 lb, as discussed in the error analysis section. The sensitivity and reproducibility of the MMS, which are the parameters of interest for following the mass change of a human, are within the 0.02 lb and 0.5 lb values derived below.

Measurement Reproducibility. - Reproducibility refers to the difference between successive measured values for the same experimental conditions. The flight data shows that the average range (highest-lowest) of successive sets of measurements for rigid masses was 1.2 milliseconds for the back-down configuration, and 2.5 milliseconds with the back up. This translates into a mass variation of 0.1 lb and 0.5 lb, respectively. As the recommended procedure is to take several replicates and average these for each mass determination, and only three or four replicates were possible, the practical meaning of this data is speculative but in testing the prototypes MMS six replicates were used and similar ranges obtained. This would indicate that the reproducibility of the MMS for say the average of three replicates of the same mass taken at two different times should be well within the quoted figures of 0.1 lb and 0.5 lb for the two configurations. In any case for MMS application, frequent calibration with a fixed mass would be advisable.

Measurement Sensitivity. - Sensitivity of a device refers to the smallest deviation of the measured variable that can be observed. The calibration tables indicate that for the back-up tests 1 millisecond change in period corresponds to 0.2 lb. As the electronic circuit and timer used reads to 0.1 millisecond, a sensitivity of 0.02 lb is indicated, corresponding to 0.01% change in mass for a 200 lb mass. Similar figures apply for rigid mass or human calibration runs. For the back-down configuration about 1.8 millisecond corresponds to 0.2 lb, leading to a sensitivity of about 0.01 lb.

Error Analysis

Following the zero-g aircraft tests of the mass measurement hardware, an inspection revealed a weldment failure in the structure between the pallet and the bearing assembly. The welded parts had separated and considerable deformation had taken place. The effect of this separation on the performance of the system was evaluated and found to be such that

it would reduce the frequency of oscillation. It is not possible to define the magnitude of this effect; however, the following theoretical considerations describe the effect.

If the weld separation was progressive and accompanied by permanent deformation, then work was done by the mass measurement system. This work represents additional damping of the system. For illustration, consider the effect of viscous damping on a freely vibrating system. The frequency of the damped oscillation is given by

$$W_d = \sqrt{1 - d^2}\ W_n \qquad \text{(Ref. 3)}$$

where

d = damping ratio

W_n = frequency of undamped system

For a damped oscillating system the damping is less than critical, consequently, $d < 1$. For the undamped system, $d = 0$. Therefore, the effect of damping is to reduce the oscillation frequency which results in an erroneously high mass determination.

Internal damping by non-rigid bodies has been observed in all tests conducted by LMSC of the MMS, and must be presumed to occur in any mass measurement based on the spring-mass oscillation principle. The direction of the change from a rigid body is such that a non-rigid body shows a higher apparent mass than a rigid body of the same mass. For the MMS tests to date, this effect has uniformly been observed as an apparent increase in mass for human subjects*. There are indications that obese subjects show a larger deviation than trim subjects and they always also show a larger range of oscillation time.

(ref. 3) Thomson, W. T.: Vibration Theory and Applications Prentice-Hall, New Jersey, 1965, pp 36-39.

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* Based on rigid-mass calibration.

Both the effect of the crack and the effect of internal damping cause an apparently high mass to be calculated. Since a calibration curve for human subjects in zero-g could not be obtained (due to the few data points available) and it had been observed from the one-g data that the period for a given mass is higher for human subjects than it is for rigid objects, a calibration curve was constructed for zero-g human subjects. This curve was based upon the human-to-rigid mass differences determined in one-g tests, upon the zero-g rigid mass calibration. Entering the constructed curve with period data from zero-g tests, corrected inferred human mass values were found, from which adjusted deviations were calculated. The adjusted deviations are +0.2 lb for a 118.7 lb subject, and -3.3 and -2.7 lb for 186.7 and 205.7 lb subjects. It may be hypothesised that the 3.3 and 2.7 lb deviations are caused by motion of the crack with the higher masses on the pallet, which may not have been significant at the low mass loading. One point in favor of this hypothesis is that in a post-flight series of mass determinations with the crack present, a set of deviations of -1.1, -1.2, -1.1, -1.4 and -8.1 lb was calculated using the human mass calibration table, and that the first four deviations correspond to 159 to 167 lb subjects, while the 8.1 lb deviation is for a 246 lb subject. It may be observed that a fit of (+0.2, 118.7 lb), (-3.3, 186.7 lb), and(-2.7 lb, 205.7 lb), (the 0-g deviations) passes through a deviation of -1.5 lb at 160 lb, and through -5.5 lb at 250 lb.

Insufficient data is available to verify this hypothesis, but it is believed that in the absence of the crack, and using a corrected 0-g rigid mass calibration as a correction factor that a measurement accuracy of 0.5 lb could be obtained, and that in the absence of the crack and using five or more human subjects as calibration points that a measurement accuracy in the range of 0.25 lb could be achieved. It is further concluded that to obtain this value of absolute accuracy any spring-mass oscillation principle measuring device must be calibrated in zero-g, but that the previously quoted reproducibility and sensitivity of the MMS are maintained in the zero-g environment. To achieve these values of accuracy and sensitivity, it is essential to use a calculated calibration table, as graphical analysis is an order of magnitude less precise than the MMS device itself.

Conclusions. - Data obtained during the simulated zero-g tests performed in the Lockheed test laboratory were consistent within themselves (i.e., data scattering was low) but the results were inconsistent when compared with results of the zero gravity or ground tests, without the cable. First, the taut cable (approximately 90 feet long) acted as an additional spring tending to restore the carriage to its central position. Second, the cable whipped in its own mode of oscillation, thereby superimposing an unknown variation on the cables restoring force. This whipping occurred both in the simulated zero-g tests with tension on the overhead cable, and with the overhead cable slack, although the amplitude of whip was greater with the cable slack. Therefore, the tests performed with the overhead cable were not considered significant.

When the data of the various tests performed with the pallet back up are compared, some interesting results appear. For the tests which employed the calibrated deadweights, both the one-g and the zero-g data points fall on the same curve. In addition, the one-g points for human subjects were weighed in zero-g, but all three data points fall above the combined curve (i.e., one oscillation required more time than it would have in one-g). In view of the fact that there was no appreciable difference between zero-g and one-g for deadweights, the following conclusions are made:

- The change in damping due to heavier or lighter bearing loads is negligible.
- The apparent mass of human subjects is several pounds heavier than indicated if only rigid mass calibration is employed. (This is probably due to increased visceral "slosh" and/or body decoupling from the seat during zero-g.) Therefore, a zero-g calibration should be employed for use of this device to weigh astronauts in orbit.
- The sensitivity and reproducibility of the MMS, which are the parameters of interest for following the mass change of a human, are well within 0.02 lb (sensitivity), and 0.5 lb (reproducibility).

With the pallet back folded down, no human subjects were weighed, and deadweights were limited to approximately 60 pounds. It was found that the "back down" data points (both zero-g and one-g) fell on the same curve as the deadweights with back up. From this it is concluded that the change in damping due to somewhat more or less frontal drag area is very slight.

TEST PROGRAM - OTOLITH THRESHOLD MEASUREMENT

The MMS Phase I program report discussed the results of preliminary tests to determine if typical otolith threshold could be measured from subjects on simple harmonic motion produced by the energy interchange of a spring-mass system. A laboratory model of an oscillating pallet was used that consisted of a seat and backrest constructed of plywood. The pallet was suspended from cables 35 feet in length and driven in linear motion by a spring mechanism.

The results of tests with four subjects indicated that reliable otolith thresholds could be measured with the device that were typical of otolith thresholds obtained with common laboratory devices such as parallel swings, and test cabs propelled over linear tracks.

It was recommended that the prototype MMS be modified during Phase II so that linear acceleration thresholds could be evaluated. This section discusses tests with the unit in which otolith thresholds were measured both on the ground and in the KC-135 zero-g tests.

Test Objectives

The purpose of the tests was to determine if the MMS modified for the generation of discrete linear accelerations could be employed to stimulate the otoliths of human subjects in hypogravic environments.

Test Plan

Three subjects were recommended to test the validity of measuring linear acceleration thresholds with the MMS. The subjects were chosen principally on the basis of their ability to satisfy the criteria of: (1) the Romberg postural equilibrium tests and the Graybiel-Fregly Ataxia battery, (2) the test battery to qualify for the KC-135 zero-g flights. The latter test requirement includes the class 3 physical, and physiological and survival training tests. The test strategy was to duplicate as closely as possible the test conditions of the ground and flight tests such that essentially only the zero-g independent variable would distinguish the two test situations.

Ground Test Procedures. - The equipment for both the ground and flight tests consisted of the MMS-501 configuration modified so that accelerations could be produced that encompassed the human otolith threshold range (5 to 10 cm/sec^2).

Major modifications to the MMS to accommodate the linear acceleration mode were as follows:

- o Incorporation of softer springs to provide the slower accelerations necessary for otolith threshold levels.
- o An electromagnetic releasing device for the seat to enable silent and consistent acceleration onsets.
- o A track clamp and scale assembly so that the electromagnetic latch can be set at discrete points of displacement from the resting position of the seat.
- o A two-inch thick foam pad for the seat and backrest to reduce tactile cues due to the fore and aft motion.
- o A helmet containing a microphone, and an opaque visor and earmuffs to eliminate visual and audio cues.
- o A tape recorder for recording the responses and comments of the subject, the instructions, identification of test runs, and comments of the experimenter; and the output of the three accelerometer (during the KC-135 flights).

Procedures employed in order to check on the accuracy of the calibration curves on the accelerometers consisted of making timing runs. An electronic stopwatch was used for accurate measurement of a half a cycle of simple harmonic motion. The dc voltage was noted on the voltmeter and the initial displacement of the MMS was accurately measured on a scale. Several timing runs were made and resultant calculated accelerations were compared with the manufacturer calibration curves. Calculated values agreed favorably with the calibration curves. Figure 19 shows the test setup and fig. 10 shows an actual test run.

The ground test procedures were initiated with the subject donning the helmet and being attached to the pallet with the restraining harness, fig. 10. The subject was then told to sit comfortably, to keep his head fixed, and to try to concentrate only on the motion sensation. The subject was advised when the pallet was latched. The seat was released at shortly varying increments of time after the latching operation. The subject was asked to indicate both the onset and offset of motion.

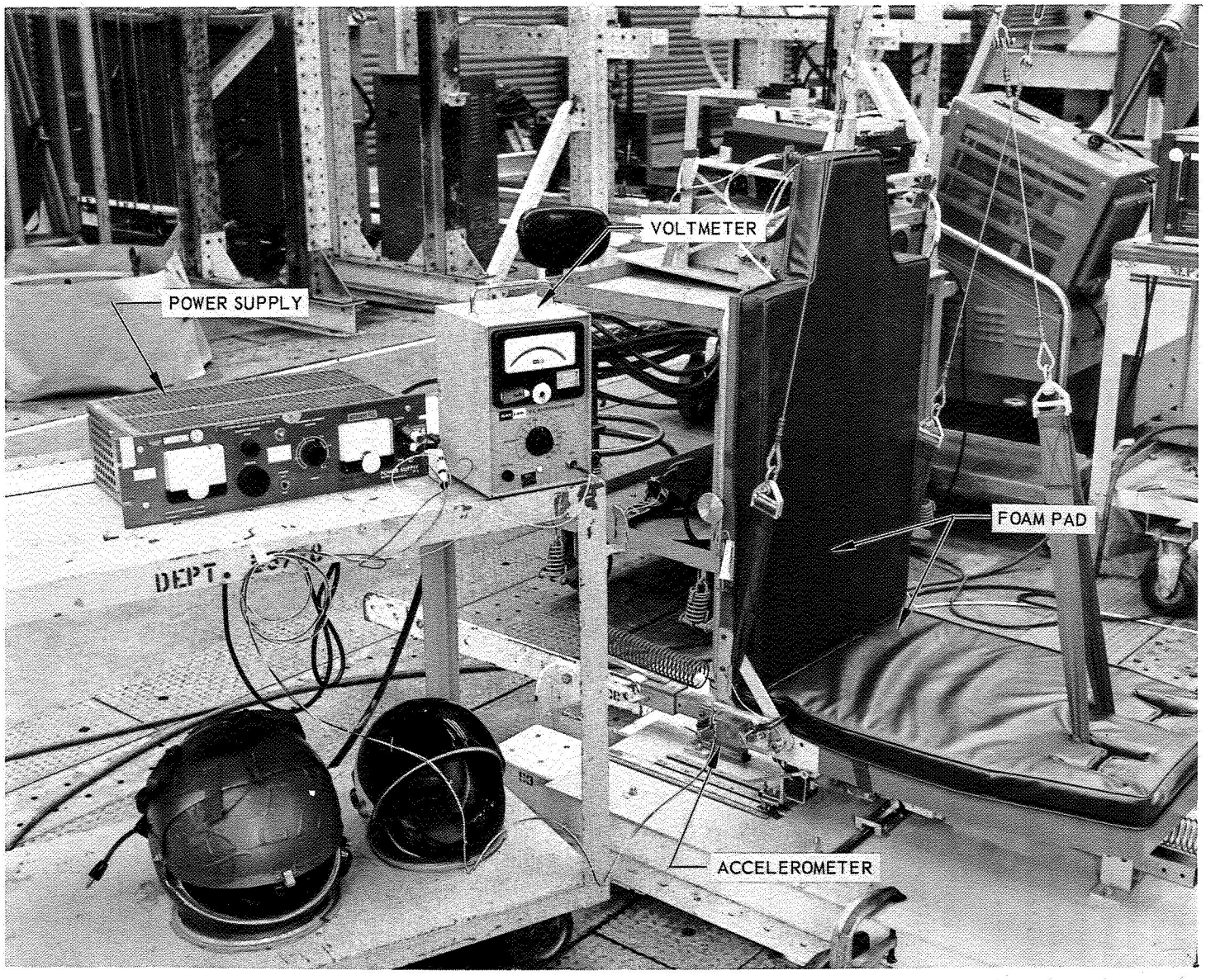


Fig. 19 Otolith Threshold Measurement Ground Calibration Configuration

Test trials were administered according to the psychophysical method for determining sensory thresholds known as the "method of limits." In the ascending order acceleration stimuli were generated by an initial 0.5 inch displacement of the pallet from its resting position and allowing it to oscillate until it stopped. This was followed by successive 0.5 inch increments of displacement until threshold was reached. In the descending order the initial displacement was well above that required for threshold. The displacements were then decreased by 0.5 inch steps until the subject reported that he no longer sensed motion.

Each of the three subjects were administered five ascending and descending trials. The "just noticeable" threshold was assumed to be the average value of the five thresholds reported by the subject during the ascending series. The "just unnoticeable" threshold was assumed to be the average value of the five thresholds reported by the subjects during the descending series.

After this initial test run the subjects were released from the pallet. The MMS was then placed in a simulated zero-g condition by adjusting the turnbuckles attached to the suspension cables such that the weight of the pallet and the subject would not load the bearings. Following this procedure the five test trials described previously were repeated with each of the three subjects.

KC-135 Zero-Gravity Tests. - It was planned to apply the ground test procedures before and during the KC-135 flights. It was not possible however to schedule the pre-flight tests. The flight tests were conducted according to the ground procedures with the exception that one of the three subjects who participated in the ground tests could not be used for the flight test. He was replaced by another subject who had previously satisfied the USAF requirements for parabolic flights. No pre-flight ground data has been acquired on this subject, however, the standard ground tests were administered after the flight. One subject became ill and therefore was unable to serve as a zero-g flight subject. The ground test helmet was replaced by opaque goggles and headset, and only one ascending and descending test trial was administered to each of the two flight subjects.

Five parabolic maneuvers were required for one of the subjects and seven parabolic maneuvers were required for the second subject.

Test Results

Ground Tests. - The "just noticeable" and the "just unnoticeable" thresholds of two of the subjects were those responding to accelerations produced by a 0.5 inch displacement of the pallet from its resting position (7 cm/sec^2). The third subject threshold was that corresponding to accelerations produced by a 1.0 displacement of the pallet from its resting position (9 cm/sec^2).

Flight Tests. - As stated previously one of the subjects tested on the ground was available for the flight tests. This subject reported sensation of motion produced by a 1.5 inch displacement of the seat and again at a 2.0 inch displacement. The other subject who had not undergone preflight ground testing was able to detect motion only at a 4.0 inch pallet displacement. This subject was administered the ground test regime after the flights. His "just noticeable" and "just unnoticeable" threshold under ground conditions were those responding to accelerations produced by a 0.5 inch pallet displacement. Thus three of the four subjects who were ground tested had threshold levels of about 7 cm/sec^2. The flight thresholds varied from 18 cm/sec^2 to above 30 cm/sec^2.

Conclusions. - Due to the small number of subjects no conclusions can be made between the threshold levels measured during ground tests and those measured during flight tests. On the basis of responses of the two flight subjects it is indicated that the MMS modified for otolith threshold measurements should prove a useful device for generating reproduceable linear acceleration stimuli to the otoliths in the hypogravic environment. It might well be considered for use in zero-g parabolic flights to determine the baseline otolith threshold levels of astronauts who are scheduled for extended space flights.



PRELIMINARY DESIGN

The final elements of the preliminary design task were initiated at the conclusion of the KC-135 flight test program. Major contributions of the flight test program to the preliminary design were:

- o Test procedural steps proved sound and form the basis for flight planning
- o Test equipment that was space oriented, (e. g.; optical counting method, pallet, etc.) operated satisfactorily under the zero-g environment and would be adapted for space application with minimum modification
- o Test experiment time for mass measurement appeared compatible with planned space experiment measurement time
- o Restraint system operated satisfactorily during the test program, however, the floating phenomena reported by subjects during the zero-g runs indicates that some design improvement should be incorporated
- o Restraint technique for the rigid mass (back up) configuration requires improvement

Major considerations that influence the preliminary design of a spaceflight version of the MMS are: Experiment requirements and definition; Spacecraft constraints and capabilities; and Design and performance requirements such as minimum weight, power, size, etc. This section discusses some of the major factors and presents a preliminary design of the spacecraft version of the MMS.

Experiment Definition

The Apollo Applications Program experiment requirements specifies the need for a Body Mass Measurement Device. Stated objectives for the M058 Experiment are:

- o Confirmation of ground based predictions of mass measurement accuracy in space.

- o Provision to other biomedical experiment of a means of determining physiological changes by mass measurement of food waste, urine specimens, etc.

LMSC has reviewed the 10 presently approved biomedical experiments and identified six of those experiments that could utilize the MMS. A summary of these six experiments has been listed on Table 5.

Experiments utilize the MMS in two ways: (1) Direct measurement contributing to the validity of the experiment, and (2) supporting the experiment with statistical data.

Experiment M050 objective is to determine the metabolic cost of operational activities under zero gravity conditions and to determine if man's metabolic effectiveness in doing mechanical work is progressively altered by exposure to a space environment. The mass measurement system furnished supporting statistical data.

Experiment M051 objective is to assess the amount of cardiovascular deconditioning induced by space flight. Of particular interest is establishing the time course of this change. A rate of change of mass is an important supporting parameter to be measured and will support the cardiovascular evaluation. Supplementing the cardiovascular evaluation would be a measurement of the cardiac output. This can be performed by using the MMS as a free floating platform and having the astronaut positioned on it with appropriate body located accelerometers.

Experiment M052 objective is to assess changes in the musculoskeletal system during space flight. The mass measurement system is utilized in weighing the urine pooling of the crew on a 24 hour collection of 100 ml sample. The mass of each sample is measured. Additionally the mass of each astronaut is taken on a regularly scheduled basis.

Experiment M053 objective is to assess the vestibular function during zero-g. In order to conduct this experiment it is necessary to provide rotational capability up to 30 rpm, tilting of the platform up to $\pm 45^{o}$ both laterally, forward and backwards, various acceleration and deceleration levels, and instrumentation mounting provisions. In addition, it is necessary to establish the linear acceleration threshold levels for the astronauts. The MMS suitably modified to provide rotation and with spring changes to provide low linear acceleration levels could be utilized to perform this experiment. The present Rotating-Litter Chair developed by Johns Hopkins Applied Physiology Laboratory can accommodate the rotary requirements, however it is not suitable for conducting the other vestibular investigations.

Table 5

AAP Biomedical Experiments Requiring MMS

EXP. NUMBER	EXPERIMENT OBJECTIVES	TYPES OF MEASUREMENTS
M050	Metabolic Cost of Inflight Tasks	MMS Supporting Statistical Data
M051	Response of Human Circulatory Dynamics to Provocative Testing During Prolonged Spaceflight	Ballistocardiograph for Cardiac Output (MMS) Mass Measurement Supporting Statistical Data
M052, M057	Evaluation of Muscle Mass and Strength in Relation to Confinement and Weightlessness	Change in Body Mass (MMS)
M053	Assessment of Changes in Sensitivity of the Otolith Mechanism and its CNS Connections to Linear Accelerations as a Result of Prolonged Weightlessness	Frequency or Period of Oscillation(MMS) Amplitude of Oscillation (MMS) Position of Body in Reference to Direction of Motion (MMS) Relative Time (MMS)
	Effects of Head Movement on Semicircular Canal Functions in Weightlessness and in a Rotating Vehicle	Angular Velocity and Angular Acceleration (MMS)
	Assessment of General Neurological Status of the Astronauts Under Prolonged Weightlessness	Ocular Counter-Rolling (MMS) Egocentric Visual Location of Horizon (MMS) Oculogravic Illusion (MMS) Oculogyric Illusion (MMS) Threshold of Linear Accelerations to Head (MMS)
M059	Body Mass Measurement	Body Mass Measurements

Experiment M057 objective is to evaluate effectiveness of an exercise system for maintaining cardiovascular fitness, muscle strength and endurance. A significant parameter is the change of body mass which is determined by utilizing the MMS.

Experiment M058 objective is to provide a body mass measurement device for regularly monitoring the astronaut's mass change and also provides other biomedical experiments a method of supporting their statistical data.

A definitive experiment plan is beyond the scope of this present effort, however, this type of plan is required to fully describe the application of the MMS in the Apollo Applications Program. This experimental plan must treat the experimental approach by showing the function of the MMS in relationship to the total experimental program. A functional analysis is required to fully describe the procedures and operational techniques employed to carry out the measurement. An operational analysis of the equipment and a description of experiment equipment including the prelaunch, orbit, and recovery aspects would summarize the total requirements of the MMS. This experiment plan definition is normally carried out in the Flight Development Phase which would be the logical follow-on to the present effort.

Experiment Equipment/Spacecraft Interface Analysis

There are several candidate carriers proposed for the AAP such as the Refurbished Command Module (RCM), Lunar Module (LM), and the Orbital Workshop (OWS). The latter configuration appears as the most likely candidate to accommodate the MMS and will be discussed in this section. This configuration normally consists of the Command Module (CM), the Multiple Docking Adapter (MDA), the Airlock Module (AM), and the OWS which is a spent S-IVB stage. The MMS would normally be carried in a stowed position aboard the MDA along with other biomedical equipment. The major constraint for packaging the MMS is that it must be contained in an envelope not greater than 20 x 30 x 40. This constraint is so that the package can be transported from the MDA through the AM and into the OWS and will pass through a hatch opening of 43 inches.

Some overall ground rules that have direct application to MMS are:

- Access to the spacecraft for package integration is limited to 24 days prior to lift-off.
- The docked combination of the CM, MDA, AM, and OWS is maintained in a gravity gradient condition, with a minimum of reaction control system fuel expended.

- Operation days 1 through 4 inclusively are used for operational requirements such as rendezvous and docking with the MDA, connecting airlock umbilicals to the CSM, and preparing the S-IVB workshop for habitation.

- Communications (voice, biomedical monitoring, caution, and warning systems) between all crewmen and vehicle systems and between any crewman from any location in the space station are assumed available and necessary at all times.

- The volume and weight of all returnable items/data, etc. are compatable with entry cg and available stowage space in the CM.

Airlock Module. - The airlock module (AM) is a tunnel forming the core of a unit around which are clustered four truss modules. Three of these modules mount cryogenic tanks, the fourth provides the mounting for the space lithium hydroxide cartridge and experiment equipment. Electrical power is obtained from the CSM fuel cells in exchange for AM provided reactants. The complete unit mounts in the Spacecraft Launch Adapter in the position normally allocated to the LM. The normal interface with the MMS is in providing electrical power to the S-IVB tank and in providing intracrew and network communications. The AM provides almost no stowage or installation area for MMS equipment once the AM becomes an integral passage tunnel and EV airlock in a cluster assembly. It is conceivable that the MMS might be stowed in the AM tunnel at liftoff. Figure 20 shows the interior stretch-out of an AM tunnel.

Multiple Docking Adapter (MDA). - The MDA is an assembly that will be used as a means of docking several spacecraft about a common junction connected to the AM, which in turn provides an access capability to the S-IVB orbital workshop. Figure 21 illustrates the MDA in a typical AAP Cluster A orbital configuration. The normal interface with the MMS is in providing an experiment package transport from the point of liftoff until such time on orbit as the time to set up the equipment in the OWS. Figure 22 shows a cutaway of the MDA showing stowage of a typical biomedical experiment canister such as would be used to house the MMS.

S-IVB Orbital Workshop. - The S-IVB is a bipropellant tank structure designed to withstand all flight-induced loads when fully loaded with propellants and pressurized. The AAP crew will have to activate the OWS once the spacecraft has docked in the 260 nm orbit of the rendezvous mission. The initial task after all spacecraft transposition and docking procedures have been completed will be activation by the crew of the modified Gemini environmental control system installed in the airlock, after which the spent stage will be purged and pressurized. After activation of the power system, structual assembly, etc., the experiment equipment

LEGEND

A PERSONAL HYGIENE
B WASTE MANAGEMENT
C ASTRONAUT SUIT STOWAGE (2 PLACES)
D UTILITY LIGHTS
E EXPERIMENTAL PANEL ASSEMBLIES
F EVA UMBILICALS
G LIGHT ASSEMBLY (9 PLACES)
H VENTILATION DUCT
I HANDRAILS
J CIRCUIT BREAKER PANEL
K FORWARD INSTRUMENT PANEL
L CENTER INSTRUMENT PANEL
M AFT INSTRUMENT PANEL

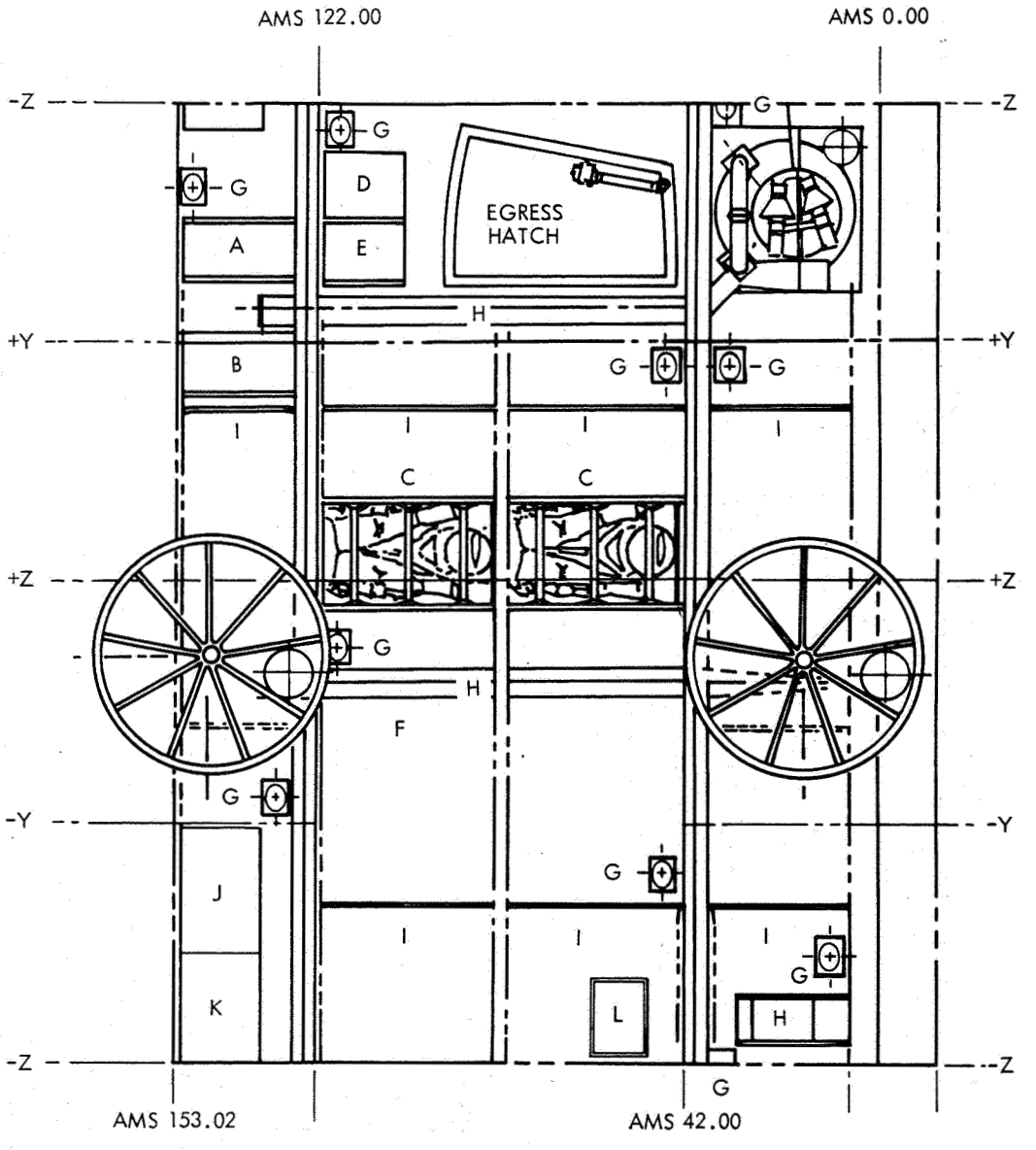


Fig. 20 AM Tunnel, Interior Stretch Out

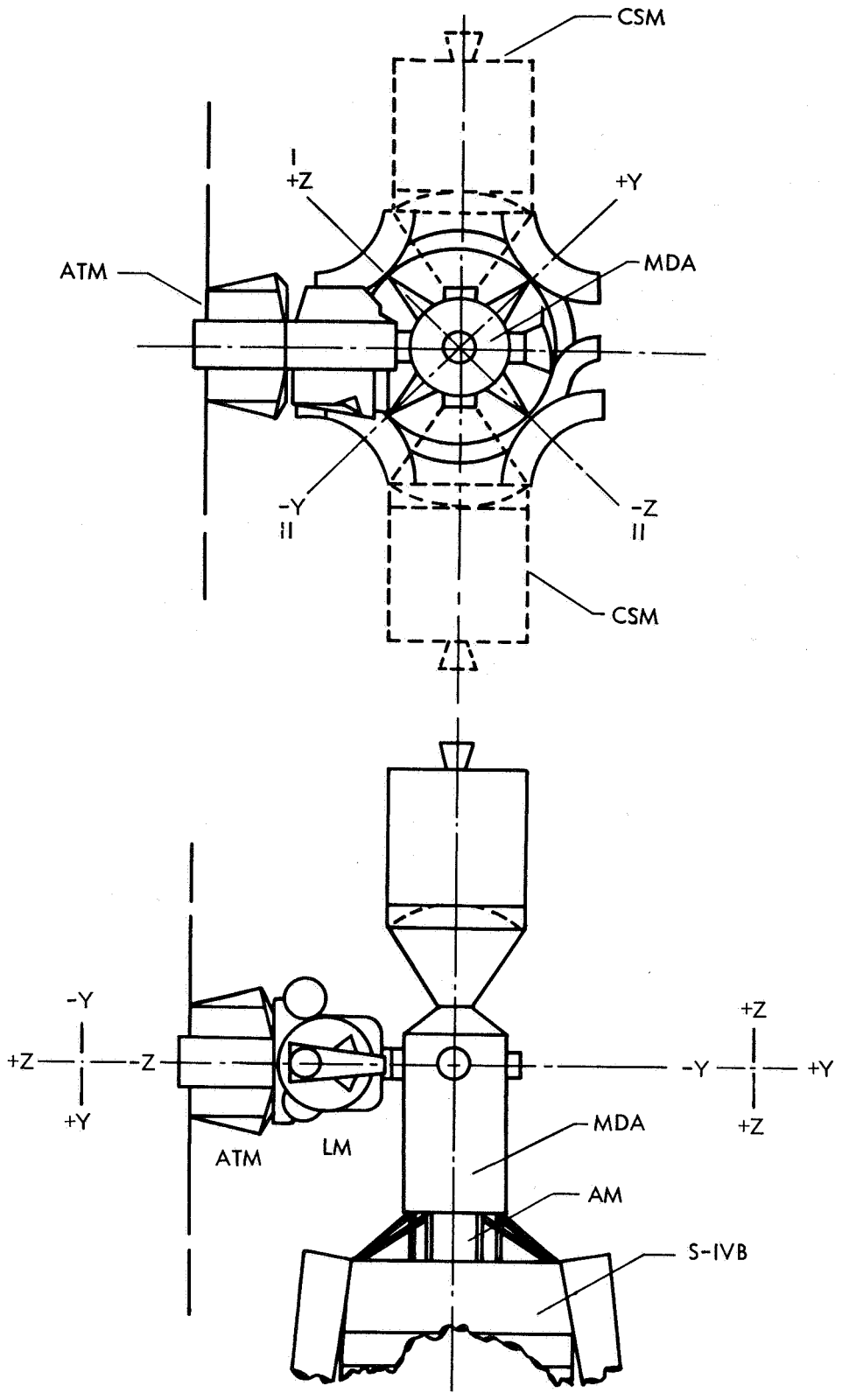


Fig. 21 MDA in a Typical Cluster A Orbital Configuration

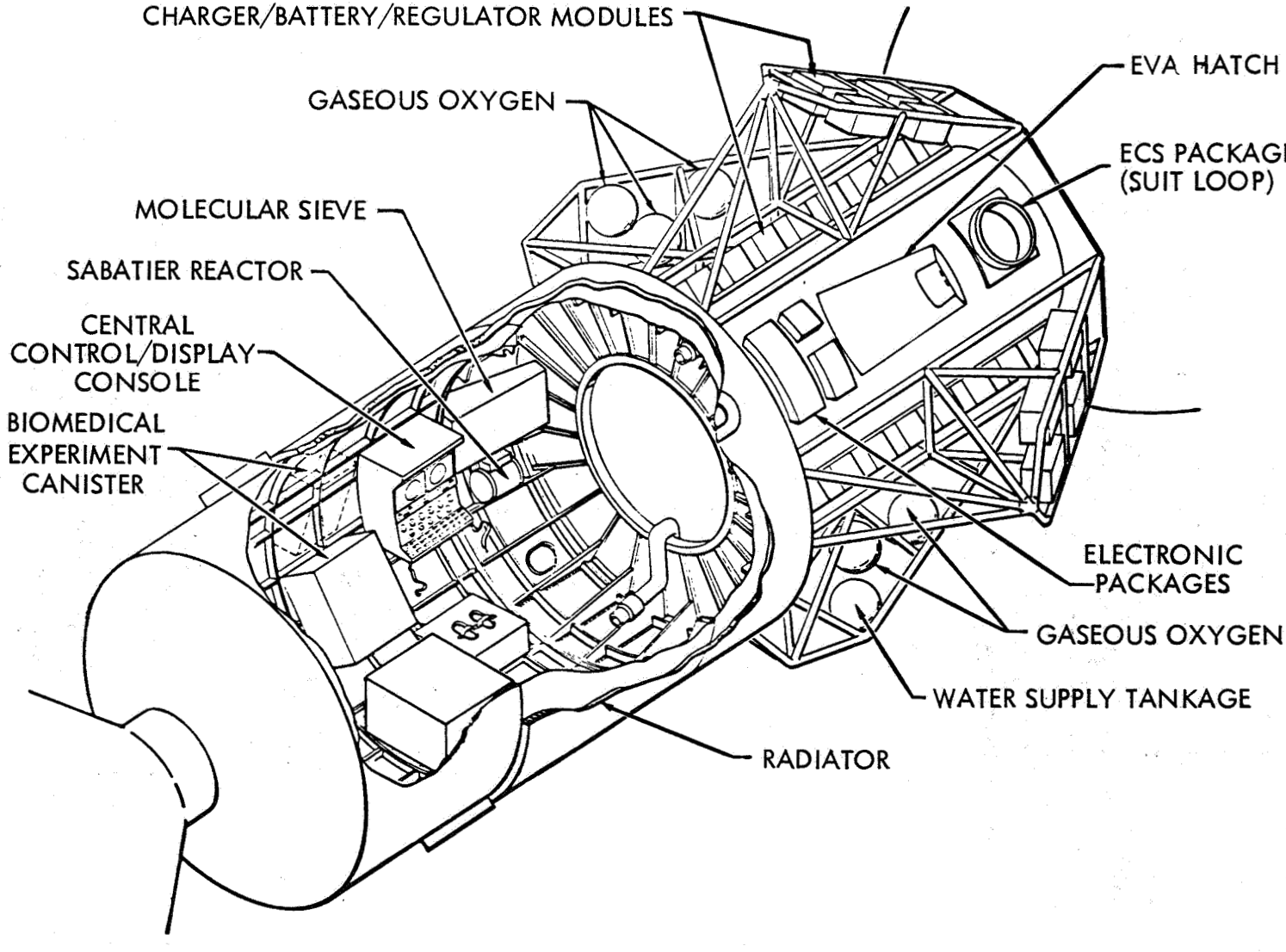


Fig. 22 Cutaway of MDA, Showing Installation of Experiment Canister

will be brought forward from the MDA. Figure 23 shows a preliminary conceptual layout of the MMS together with other major biomedical equipment.

Summary. - The preliminary design of the MMS must take into account the versatility requirement inherent in the various experiments. It also must take into account the interfaces between the experiment equipment and spacecraft. Normal spacecraft operating environment is assumed. Non-operating mode will range from vacuum to 25 psi and will include 30-g shock loading together with a normal ascent trajectory load of up to 7-g. The major consideration is the constraint imposed by packaging envelope requirements.

MMS Spacecraft Version

The Phase II version of the MMS performed well in a zero-g environment during the KC-135 tests. There were a few details in which it was deemed that ease of operation could be improved, and of course further reduction of size and weight are important. It is believed that the weight of the MMS can be reduced to 28 pounds.

Figure 24 shows the preliminary design of a spacecraft version with an estimated weight of 28 pounds.

Pallet. - The seat and back are again designed using aluminum honeycomb, but the thickness is reduced from that of the Phase II version. The height (and folded length) of the back is diminished by making the headrest a sliding panel which retracts into the back. This reduces the overall length of the MMS approximately 9 inches when the back is folded down for stowage.

To reduce the length still further in the stowage configuration, the seat is located further to the rear with respect to the carriage, thereby centering the length of the seat directly over the center of the carriage. This will cause the mass of a human subject to be centered aft of the carriage, creating a moment which increases the bearing load during operation in a one-g environment. However, there will be no such effect in a zero-g environment.

Carriage. - Since the bearing loads in a zero-g environment are very small, the size of the bearings will be decreased, reducing the weight of eight bearings and their shafts from 1.51 pounds to 0.55 pounds. The new ball bearings will be stainless steel for corrosion resistance and have double teflon shields for reduced friction. The aluminum carriage will be reduced one inch in length and its cross section from a four-inch square to a three-inch square.

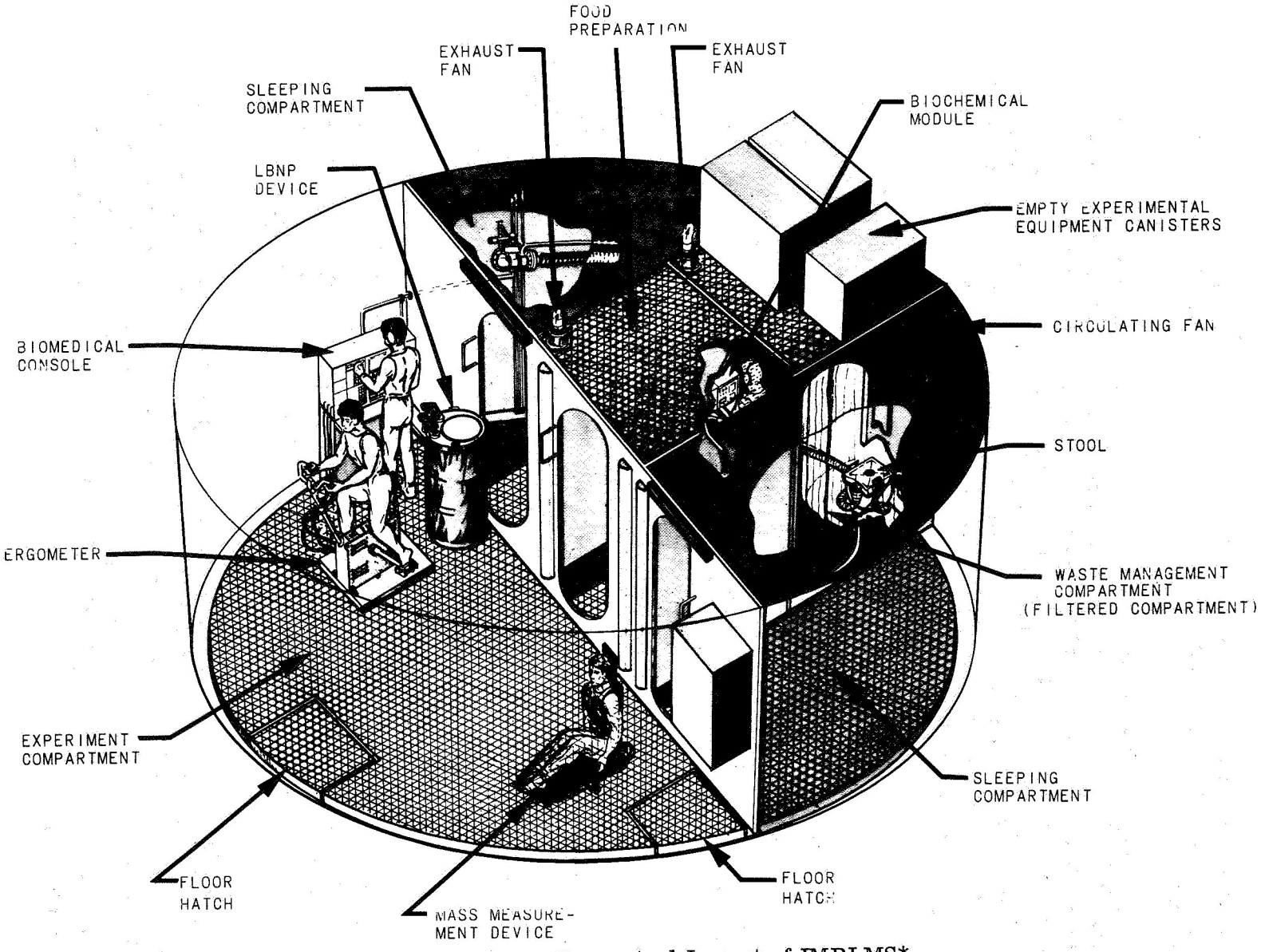


Fig. 23 Preliminary Conceptual Layout of IMBLMS* in the S-IVB OWS Compartment

*Integrated medical and behavorial laboratory measurement system

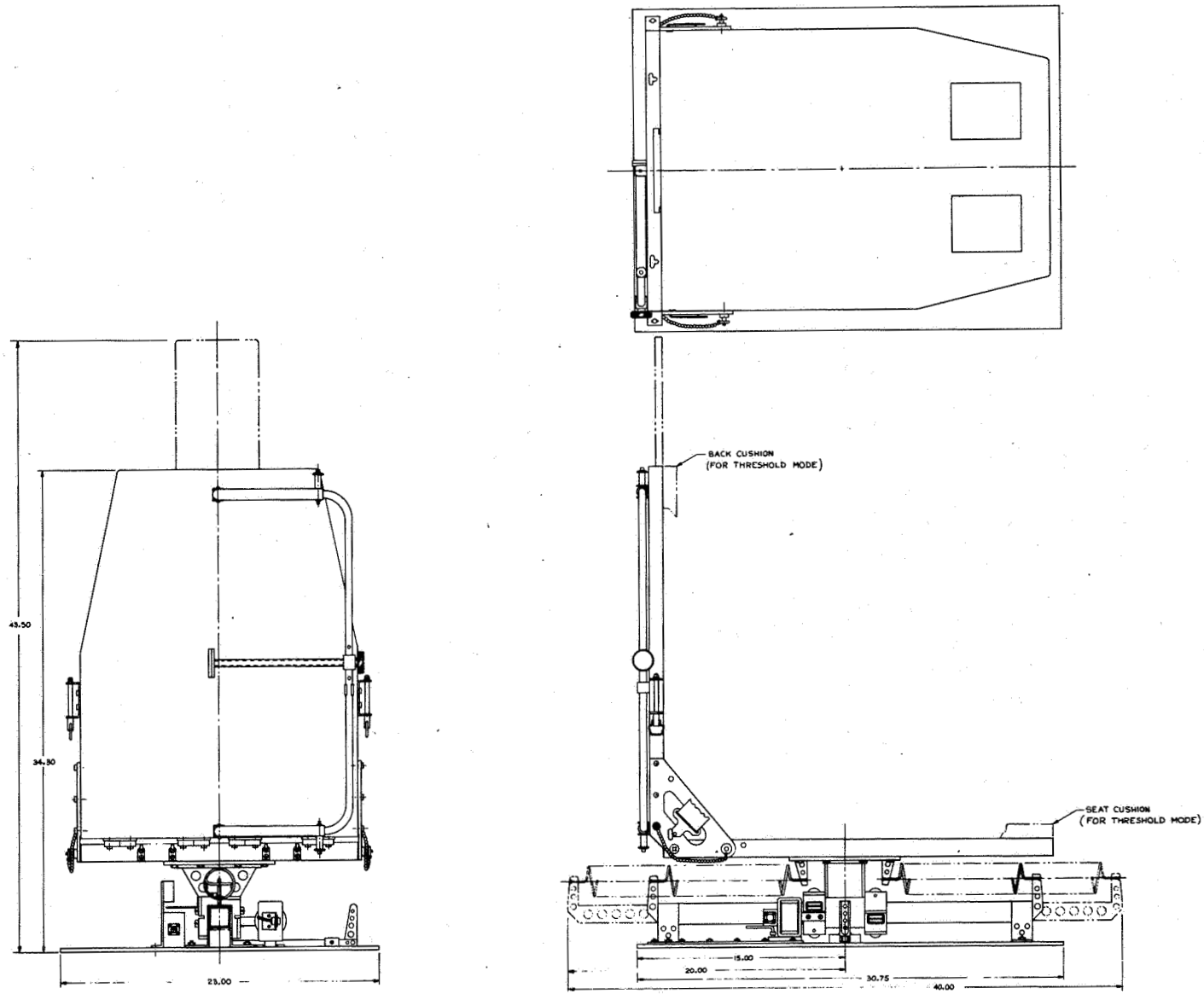


Fig. 24 Preliminary Design of Spacecraft MMS

Rail. - The rail will be lightened by reducing its wall thickness and by reducing its length. Without reducing the Phase I and II stroke length of approximately 8-3/4 inches on both sides of center, the length of the rail will be 15 inches less. This is made possible by using extendable spring hook booms which will slide into the hollow rail for stowage.

Release System. - The electromagnetic release system employed for the Phase II acceleration threshold sensing experiments operated satisfactorily and therefore it is proposed to use this system for operation both in the acceleration threshold and mass measurement modes. This eliminates the need for the mechanical latching mechanism. The electromagnet will have to be stronger for use in the mass measurement mode; it is believed that a two-pound electromagnet requiring less than eight watts will fill the requirement. Of course the eight watt power would only be required during a few seconds for each weighing.

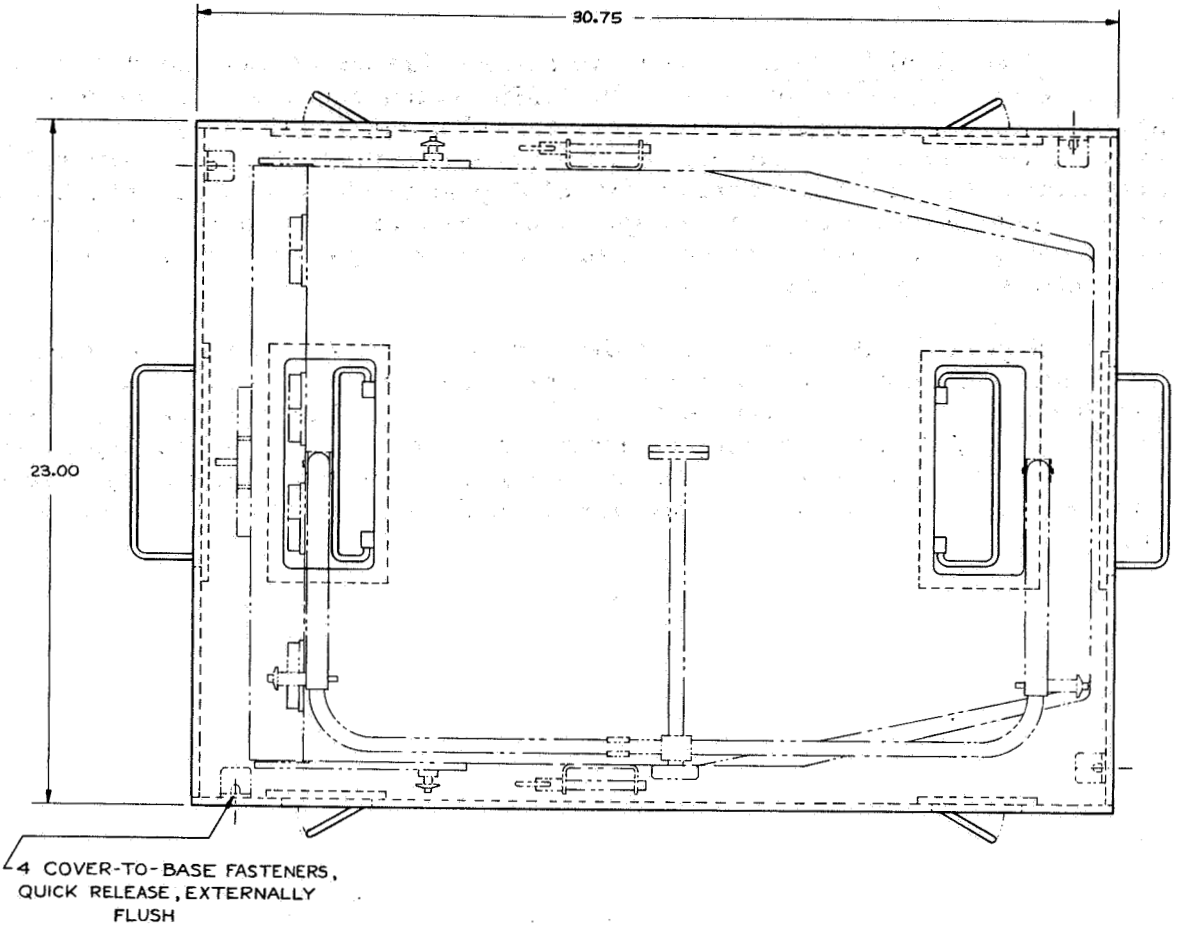
Restraint System. - The results of the KC-135 flight test has indicated the need for some improvement in the donning complexity of the restraint system. The floating phenomena reported even though the straps were tightened infers that more complete evaluation might be required. More extensive zero-g testing could be utilized before establishing firm design requirements for a flight restraint system. Techniques that might be explored are: Multiple tension pickup straps covering portions of the body, and various body orientations.

Pulser. - The lamp, phototransistor, and solid state pulser housings are reduced in size and rearranged so that the light beam is vertical. The shutter projects out horizontally from the carriage, thereby making this assembly more compact and less exposed to interference by any adjacent equipment or personnel.

Transport and Stowage Canister. - The MMS is mounted on a quarter inch slab of aluminum honeycomb which performs two functions. In addition to serving as a base plate for the MMS it also forms the bottom of a transport and stowage canister which is to be fabricated from aluminum honeycomb. The base slab to the upper portion of the canister is attached by means of four flush Camlok fasteners. See fig. 25. Folding, recessed handles are provided on the top, bottom, ends and sides. Detents will hold these handles either in their extended or retracted positions.

Four fastening devices will be used to secure the MMS baseplate to the spacecraft in its operating location after the canister top has been removed.

Sufficient room is provided in the canister to stow the seat cushions, the harness and the electric cables. The empty weight of the canister will not exceed nine pounds.



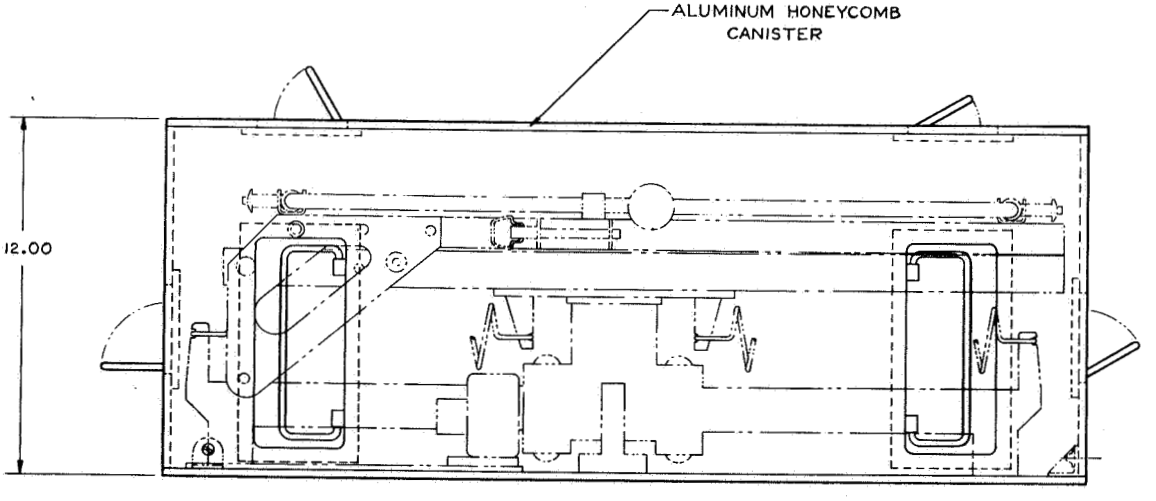
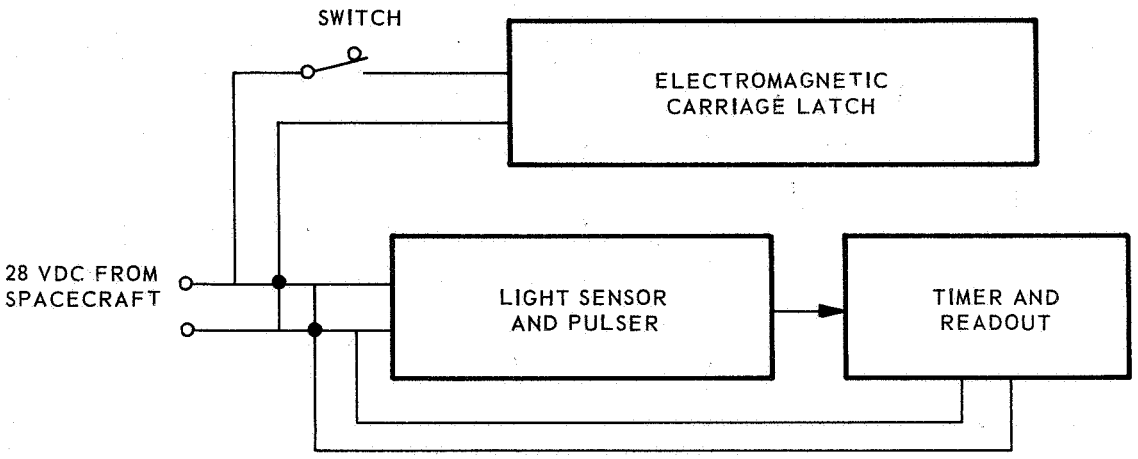


Fig. 25 Transport and Stowage Canister

Electrical System.- The solid state pulse which Lockheed developed to sense the beginning and end of the MMS oscillation can be readily packaged to meet spacecraft environmental conditions, and its power requirement is very small. A small, lightweight solid state electronic timer is also available and will provide a direct digital readout of time, which can subsequently be converted to weight either by use of a conversion chart or by computer. Figure 26 shows the electrical system with an electromagnetic carriage latch.

Figure 27 shows the block diagram of a more extensive system. This includes an accelerometer for direct measurement of acceleration sensing threshold, a readout directly in pounds (rather than time) and provision for supplying this weight readout to the spacecraft telemetry system. The conversion from time to weight can be accomplished either by a small special purpose computer, or by the general purpose computer aboard the spacecraft.



NOTE: ELECTRICAL BLOCK DIAGRAM FOR THRESHOLD OF ACCELERATION SENSING AND MMS WITH READOUT IN TIME (USING SPACECRAFT POWER).

Fig. 26 Spacecraft Electrical Block Diagram – Basic System

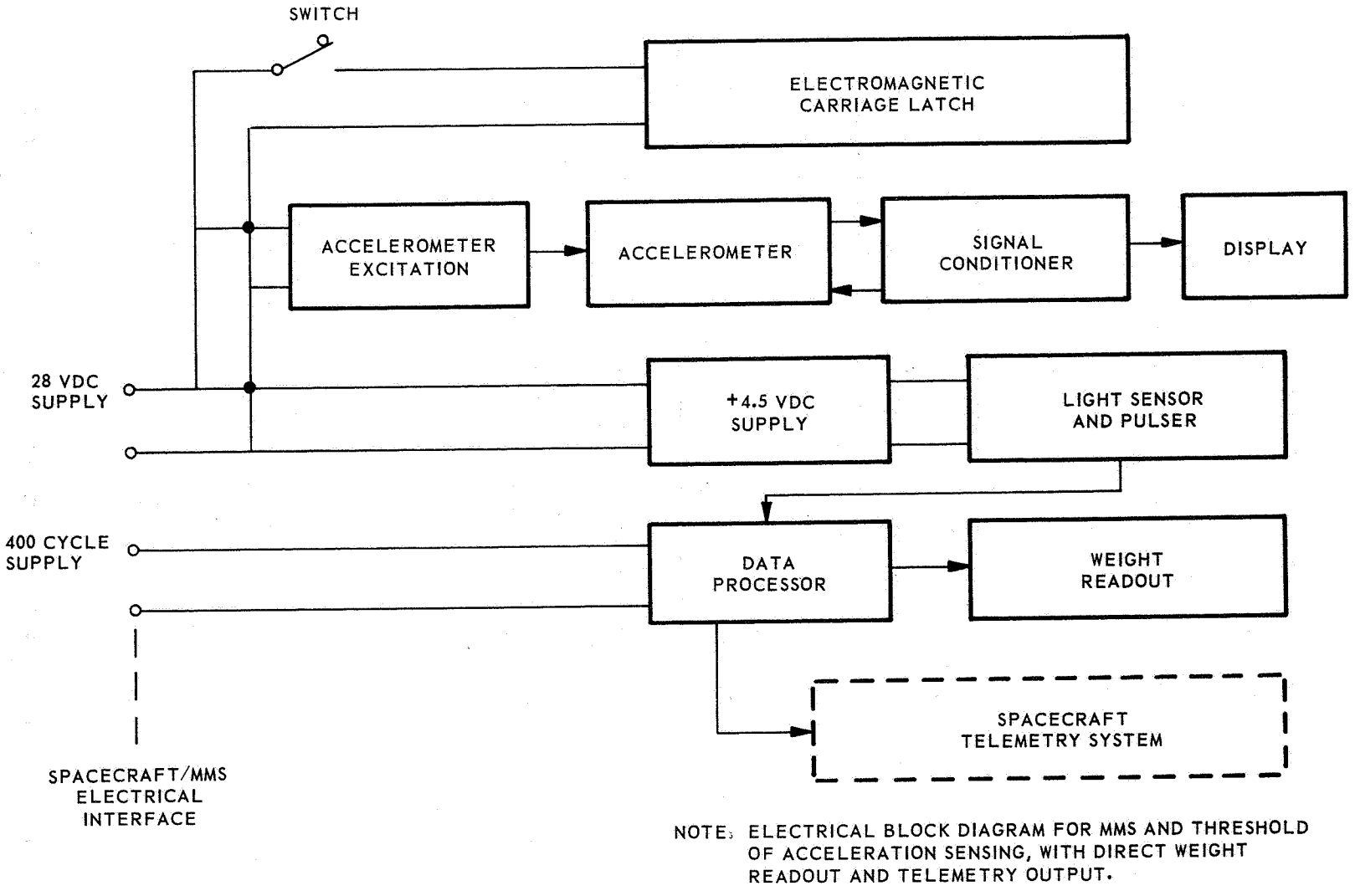


Fig. 27 Spacecraft Electrical Block Diagram – Advanced System

CONCLUSIONS AND RECOMMENDATIONS

The MMS program has demonstrated that through a multiphase development effort a system can be designed, fabricated, and tested to meet demanding design goals. The orderly progression through the various development steps has permitted incorporation of improved design features and a realistic appraisal of the requirements involved in the development of versatile experiment equipment.

A review of the MMS Phase II hardware performance indicates the design is sound and that only minor changes would be required to improve this performance.

The inanimate restraint system utilized with the back in the down position proved very satisfactory under the zero gravity conditions. The restraint system used for inanimate objects in the back-up configuration was satisfactory to approximately 150 pounds, beyond that point some float may have been experienced.

The man restraint system proved satisfactory under the zero gravity conditions. The restraint system was donned under one-g conditions prior to entry into the zero gravity environment. However, experience in the zero gravity environment gained during this test phase indicates that the restraint system would not be difficult to don by the astronaut, but would require some assistance by a second astronaut in placing the straps over the shoulders. It is recognized that it would be most desirable if this could be a one-man operation. However, the test subjects stated that even with the restraint system extremely tight, some feeling of float was experienced in the zero gravity environment. Since any relative motion between the subject and the device has a major effect on performance, it is recommended various restraint techniques be designed and tested under zero-g conditions. Egress from the restraint system under zero gravity conditions is easy and can be accomplished without assistance.

The apparent mass of human subjects is several pounds heavier than indicated if only rigid mass calibration is employed. (This is probably due to increased visceral "slosh" and/or body decoupling from the seat during zero-g.) Therefore, a zero-g calibration should be employed for use of this device to weigh astronauts in orbit. The sensitivity and reproducibility of the MMS, which are the parameters of interest for following the mass change of a human, are well within 0.02 lb (sensitivity), and 0.5 lb (reproducibility).

Performance of the carriage, rail and release system proved satisfactory. The release system could be improved by utilizing an electrical release rather than mechanical. The reason is twofold: (1) electrical release is a requirement for threshold measurement, and (2) release of

the MMS pallet when in the inanimate mode could be accomplished more smoothly and precisely. This change is reflected in the spacecraft preliminary design.

The MMS electrical system performance was satisfactory.

The threshold measurement system under zero gravity conditions elicited apparent otolith responses similar to those obtained under ground test conditions. The response magnitude differed significantly not only between subjects but were consistently greater than the normal ground level values. Since there were only two test subjects and a limited number of trials, LMSC believes that no judgement can be made as to the otolith response phenomena under zero-g. This performance demonstrated the capability of this device as an acceleration threshold simulator and warrants further zero-g investigations.

The overall MMS system performance is considered satisfactory. The hardware has met or exceeded all performance requirements.

LMSC recognized that experiment equipment proposed for the AAP should possess a commonality use factor because of the design constraints imposed by the spacecraft. These constraints are primarily concerned with size, weight, power, and reliability. Investigations into measurement equipment requirements led LMSC to consider multiple uses for the MMS, and to incorporate the capability of the system to measure linear acceleration thresholds as well as masses ranging from 5 to 250 lb.

Review of biomedical experiments proposed by NASA for the AAP indicated that a requirement existed for a biomedical measurement system that could monitor astronaut mass or inanimate object's mass, perform vestibular investigations, and supply a stable platform for conducting physiological measurements such as ballistocardiogram.

The ground test and KC-135 flight test program carried out in Phase II has demonstrated that a versatile biomedical measurement system can be developed for the AAP. This system can implement present equipment such as that proposed for measuring mass (M056 and M058) and that proposed for conducting vestibular experiments (M053) with a substantial reduction of weight and a significant increase in measurement capability.

To achieve the objective of development of a comprehensive biomedical measurement system it would be necessary to initiate Phase III Design and Development of Flight Hardware. Phase III should include the following tasks.

- Review, identification, and definition of biomedical experiments that require the comprehensive MMS

- Development of an Experiment Definition Plan that specifies objectives, performs functional analyses, and documents engineering requirements

- Determination of spacecraft interfaces and preparation of preliminary Interface Control Document

- Development of detail design drawings

- Fabrication, and qualification testing of the MMS

Early initiation of Phase III will permit the development of the flight MMS in a timely, economical, and orderly manner and in time for successful integration into the extensive biomedical investigations planned for AAP.

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APPENDIX A

Lockheed Missiles and Space Company
Sunnyvale, California

PRIMARY STANDARDS LABORATORY

REPORT

FOR

Ten (10) Mild Steel Plates

SUBMITTED BY

55-79 (102)

The weights covered by this report were compared against Class M and S mass certified by the National Bureau of Standards.

At the time of comparison the weights covered by this report had an apparent mass vs brass value as indicated on the table below. Inasmuch as the material used in these weights is subject to excessive mass loss, no assignment of accuracy will be made.

Designation	Apparent Mass vs Brass	
	Metric (g)	Avoirdupois (lb)
W1	2386.603	5.2615
W2	6903.758	15.2202
W3	4592.739	10.1253
W4	4565.739	10.0657
W5	9689.894	21.3626
W6	9593.593	21.1502
W7	9561.341	21.0792
W8	22941.116	50.5765
W9	23017.728	50.7454
W10	22767.615	50.1940

The values under the heading Apparent Mass vs Brass are those which the weights appear to have when compared in air, under normal conditions, against normal brass standards. Normal conditions being defined as 20°C and air density of 0.0012 g/cm^3. Normal brass has a density of 8.4 g/cm^3 at 0°C and a cubical expansion of 0.000054/°C.

AMBIENT TEMP: 20°C
REL. HUMIDITY: 43%
DATE: 14 June 1967

PREPARED BY Victor M. DeLeonardis
APPROVED BY [signature]

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LIBRARY CARD ABSTRACT

Lockheed Missiles & Space Company, Development of Prototype Mass Measurement System for Spaceflight, Phase II, Summary Final Report prepared under NASA contract NAS 1-7135 by R. B. Maine and A. L. Weitzmann, September, 1967.

The need for a device to determine the mass of man and other animate and inanimate objects in the zero gravity environment of space is of importance in ascertaining the physical condition of the flight crew and the successful completion of certain scientific experiments to be conducted in future space vehicles. This report defines the modifications to the Phase I Prototype Mass Measurement System for KC-135 zero-g flight tests. Results of ground calibration tests and flight tests are presented.