NORTH ATLANTIC TREATY ORGANIZATION

ADVISORY GROUP FOR AEROSPACE RESEARCH AND DEVELOPMENT

(ORGANISATION DU TRAITE DE L'ATLANTIQUE NORD)

PRINCIPLES OF BIODYNAMICS

Section A

This set of printed sheets consists of

FOREWORD
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CHAPTER V

Chapter V is to be added to the four chapters already issued. The amended Foreword and Contents should replace those at present in the volume.

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FOREWORD

Shortly after the first satellites were earth-orbited in the late Fifties, there was an influx of biomedical investigators in the field of Aerospace Medicine. The Biodynamics Committee of the Aerospace Medical Panel of AGARD-NATO observed in 1961 that, because of the burgeoning of scientific talent into the aerospace biomedical fields, there was a need to inform the new scientists of the basic principles which had been accumulated over many years of earlier aeromedical research. Several things supported this fact; reports in which the investigators apparently were not familiar with related bibliographic data began to appear; projected investigations proposed as new research were often projects which had been successfully carried out by previous investigators; and new terminologies were being formulated with an apparent unawareness of established nomenclatures.

In view of this confused state, younger Flight Surgeons and beginners in aerospace medical research, were justifiably confused as to the state of the aerospace arts and sciences. In an attempt to clarify the confusion that might exist in the area of its own specialty, the Biodynamics Committee of the Aerospace Medical Panel, AGARD-NATO received permission from the Aerospace Medical Panel to compile a "Comparative Table of Acceleration Terminologies," including the then existing six terminologies with the hope of restraining these from being further increased in number.

The Biodynamics Committee concluded that it could be of further assistance in the field of aerospace medicine by compiling a loose-leaf Manual consisting of a series of monographs covering the generally accepted basic information in the field of aerospace biodynamics for the purpose of providing a source of fundamentals for aerospace biomedical personnel in the operational and research fields. It is hoped that it will be possible to include in this Manual sections on:

A. Prolonged Acceleration: linear and radial

B. Angular Motion

C. Impact Deceleration

D. Vibration

E. Combined Stressors

Each of the sections will comprise a number of chapters by experts in the field, covering the terminology, the physics, and physiology, and tolerance limits.

It is hoped that our nominated authors will be able to contribute to this manual, and that the loose-leaf format will allow amendment and extension as contributions are received. Meanwhile, we offer herewith the first section, consisting of five chapters on Prolonged Acceleration, Linear and Radial.

In 1962 the First "Comparative Table of Acceleration Terminology" was compiled by the Biodynamics Committee and widely promulgated. General acceptance of its use was endorsed not only by the Aerospace Medical Panel of AGARD, but by the Aerospace Medical Association, and the National Aeronautics and Space Administration of the United States

Government. In 1965, this Table has been revised to meet the changes that have occurred in the past three years. The new table which replaces the original table is inserted as Chapter I of this section of the Biodynamics Manual.

At the time of the Twenty-Second Aerospace Medical Panel meeting in Fuerstenfeldbruck, Germany, in addition to the revised Table of Comparative Terminologies, there were also other monographs ready for publication. The Biodynamics Committee endorses these papers for immediate publication. The first issue of the loose-leaf Manual will thus comprise a single section, but it is felt that it contains enough factual information to make it of value to the student of the applications of biodynamics in Space insofar as linear and radial acceleration is concerned. It is hoped that interest will be stimulated and that suggestions may be made in order that succeeding sections may best fulfil the need which our Committee has envisaged.

Charles F. Gell, M.D., D.Sc.
Chairman, Biodynamics Committee

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Prolonged Acceleration: Linear and Radial

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CHAPTER V

DESCRIPTIVE CATALOG OF AEROSPACE MEDICAL BIODYNAMICS FACILITIES IN THE UNITED STATES

Edited and compiled by

Charles F. Gell, M.D., D.Sc.

FOREWORD

The following text and pictorial display present the newest equipment and latest modifications of older equipment used in the biodynamic studies conducted in United States Government facilities. The text is essentially complete and is a compilation of equipment used for biodynamic research in the following US government agency laboratories.

Naval Aerospace Medical Institute
Aerospace Medical Research Department
Aerospace Crew Equipment Laboratory
6570th Aerospace Medical Research Laboratories
6571st Aeromedical Research Laboratory
United States Air Force School of Aerospace Medicine
Manned Spacecraft Center
Ames Research Center
Civil Aeromedical Institute
National Aviation Facilities Experimental Center
Section of Physiology, Mayo Foundation and Mayo Clinic.

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DESCRIPTIVE CATALOG OF
AEROSPACE MEDICAL BIODYNAMICS FACILITIES
IN THE UNITED STATES

US Naval Aerospace Medical Institute
US Naval Aerospace Medical Center
Pensacola, Florida

This Institute was the first aerospace medical facility in the US Navy to become involved in acceleration research. The original Pensacola centrifuge served during and immediately after the second world war as the primary acceleration research tool in the US Navy. It was outrated by the US Navy's Johnsville centrifuge in 1950, but the Pensacola centrifuge then continued its yeoman utility as the first rotating dark room for the study of disorientation evolving from angular acceleration environments.

The US Naval Aerospace Medical Institute has three devices that may be classed as acceleration systems. They are the original Pensacola centrifuge, the human disorientation device, and the Coriolis acceleration platform.

The Original Pensacola Centrifuge (Fig.1) has a 20-ft radius and is capable of angular velocities up to 60 r.p.m. Maximum onset rate to reach 9 G is 1.48 G/sec. The device consists of a bearing-supported 56-ton flywheel and a free-wheeling superstructure which may be friction-coupled to either the flywheel or the building by means of an air-actuated clutch. The flywheel is friction-driven by a rubber tire coupled to a natural gas-powered engine.

Presently there is a 10-sided room constructed about the center column of the centrifuge for experiments on man's adaptability to rotating environments. With this room installed, the device is limited to a maximum angular velocity of 20 r.p.m. for safety purposes.

At the ends of the 20-ft radii are free-swinging cradle assemblies to support various chairs and cockpit simulators which may be installed.

Physiological measurement and data collection are accomplished by two sets of eighteen circuit-shielded slip rings. The connectors and slip ring assemblies permit recording of ECG, EMG, EEG and ENG as desired.

Typical recent use of this device has not involved high-magnitude linear acceleration components and thus the physiological endpoints normally used in centrifuge experimentation are not approached in these experiments. Endpoints critical to the present line of experimentation are nausea, vomiting and other physiological effects associated with motion sickness.

The Human Disorientation Device (Fig. 2) consists of a cab which can be rotated about either of two axes. The cab contains a "chair" with adjustable shells and harness which will restrain a man (or an animal holder) in any position with respect to the direction of gravity or the axes of rotation of the cab. The vertical axis is fixed and the horizontal axis is mounted in a gimbals. Each axis is independently driven by a d.c., shunt-wound motor, the speed of which is proportional to the output of a closed-loop, velocity-control system.

An electronic programmer is available for precise programming of magnitudes, durations, and directions of angular velocity about either axis of rotation. The device operates in two ranges:

(a) 0.02 to 6.0 r.p.m. with accelerations between 0.1 deg/sec^2 and 30 deg/sec^2.

(b) 0.2 to 60 r.p.m. with accelerations between 1 deg/sec^2 and 300 deg/sec^2.

Thorough provision has been made for instruments to detect and record the performance of the device and for the transmission of bioelectric signals and behavioral data from the cab through slip rings to recording equipment.

Endpoints critical to the present line of experimentation are nausea, vomiting and other physiological effects associated with motion sickness.

The Coriolis Acceleration Platform (Fig. 3) has a 20-ft radius and is capable of angular velocities up to $33\frac{1}{3}$ r.p.m. in either direction. Its drive system is a large torque motor which permits excellent control of angular velocity and angular acceleration. Doors at the sides of the 10-ft radius central room permit movement of a platform along the 40-ft radial track. A rotating capsule driven by another torque motor can be mounted on the platform. The track platform drive is a d.c. motor with a high torque to inertia ratio, permitting direct coupling to a special drum that drives the platform through a wire rope system. Relative to the track, the platform can reach linear velocities of 16 ft/sec and peak accelerations of 3 G. Maximum Coriolis acceleration generated by platform movement and CAP rotation is 3 G. The circular room has life support facilities capable of sustaining as many as 10 subjects during rotation for periods up to three weeks. The total resultant peak G which could be produced by using all drive systems simultaneously exceeds 8 G, but the device is limited by safety switches to 3 G peak accelerations. The primary functions of CAP are (i) to generate precisely controlled linear and angular stimuli independently or in combination and (ii) to permit studies of prolonged continuous rotation.

Physiological measurement and data collection are accomplished by slip rings or by onboard recordings. The connectors and slip ring assemblies permit recording of ECG, EMG, EEG and ENG as desired.

This device is used as a means of investigating disorientation and physiological effects of unusual vestibular stimulation. Endpoints critical to the present line of experimentation are nausea, vomiting and other physiological effects associated with motion sickness.

Aerospace Medical Research Department
US Naval Air Development Center
Johnsville, Warminster
Pennsylvania

Dynamic Flight Simulator (Human Centrifuge Computer Complex)

The Aerospace Medical Research Department of the US Naval Air Development Center houses the human centrifuge computer complex known as the Dynamic Flight Simulator which is in constant use in the investigation of stress as it affects man's behavior and physiological functions.

The main housing for the centrifuge is a cylindrical reinforced steel and concrete building, 124 ft in diameter. In the center of the 11,000 ft^2 operating floor is a 180-ton, 4000-horsepower motor, the rotor of which is attached to a 50-ft tubular steel arm (Fig.4). Located at the terminal end of this arm is a two-gimbal support system providing two degrees of freedom; a continuous 360 degrees of rotation about the pitch (backwards and forward rotation) and roll (left and right rotation) axes (Fig.5). Provisions are made for a third degree of freedom, yaw, with the yaw gimbal and its drive motor situated inside of the inner, or pitch gimbal. The roll and pitch gimbals are rotated by means of electric-hydraulic motors mounted on the counterweight of the arm. These gimbals permit a subject seated within the gondola to be continuously positioned with respect to the resultant of the radial, tangential and vertical components of acceleration when the arm is set in motion.

The 10-ft, 4-in.-diameter spherical gondola consists of three major components: (1) the center structural section; (2) the upper cap; (3) the lower cap. The upper and lower caps are spherical segments attached to and removable from the cylindrical center section. The center structural section (Fig.6) supports all gondola payloads and is designed for external pressurization to one atmosphere. The caps serve as wind-screens only and are not capable of withstanding external pressurization. Special vacuum caps are required in order to evacuate the gondola for pressure-altitude simulation. The implementation of rotary joints permits the passage of hydraulic fluid (2000 lb/in^2), compressed air, vacuum, conditioned air, water and other elements that may be required for project operation within the gondola. The outer and inner gimbal control motors drive the gimbal rings through tubular steel shafts running the length of the arm. The gimbal motor control circuits are linked to the centrifuge control and observation stations by means of slip rings on the main motor shaft. Additional slip rings at both axes of the gondola gimbal system transmit physiological, television, instrument control signals, etc., to and from the gondola. The entire centrifuge room is carefully shielded to protect the delicate physiological instrumentation circuits from magnetic and electric interference. Floor, walls and ceiling of the centrifuge chamber are sheathed with 1/16 in. copper.

Close study of the subject during operation of the centrifuge is effected through the use of television and movie cameras. As required, the recording of electrocardiogram, electroencephalogram, respiration, blood pressure, and other physiological parameters may be implemented.

The centrifuge arm, capsule, gimbals, counterweight, and gimbal control mechanism together weigh in excess of 45 tons. This tremendous mass must be rotated under close control to develop acceleration from a dead stop to approximately 180 m.p.h. (40 G's) in a little less than 7 seconds. In addition, by making minor changes in the main motor control circuitry, and removing the 28-ft outboard section of the arm including the gondola, radial acceleration up to 100 G's may be applied to a 5000-lb payload attached to the end of the remaining 22-ft inboard section.

In order to increase the utility of this centrifuge, free swinging carriage have been constructed to hang at the 37½-ft suspension point on the arm. These carriages are used primarily for engineering testing of inanimate objects and equipment. Electronic devices and other aeronautical equipment, such as serial photographic cameras and G-suits, may be tested for their workability under prolonged G stress of magnitudes commensurate to those experienced in actual flight.

As a dynamic flight simulator the centrifuge is contributing to the solution of problems associated with high performance aircraft and space vehicles before they enter the more hazardous flight environment. Contributions are particularly significant in the areas of pilot tolerance, pilot restraint, cockpit instrumentation, control system design, controllability, flight techniques including emergency procedures, and pilot training.

The function of the dynamic flight simulator may be described as follows: The pilot in the gondola is facing the instrument display and operating the control system to execute a flight mission. The pilot's control motions are fed into a large general purpose computer (Fig.7) which changes the instrument indications to show to the pilot his progress through a maneuver. This closed loop is, of course, that which is present in the usual fixed base flight simulator. The control motions of the pilot, together with the aerodynamic equations of the aircraft, are also used in computing accelerations. These signals are converted through a coordinate transformation system and compensating network into drive signals to the centrifuge. These signals drive the centrifuge in such a way that the pilot receives a good approximation of the acceleration he would receive in actual flight in this aircraft had he made the same control motions. Also, the fact that the position of the capsule is controlled in all planes provides means for exact investigation of any desired stress pattern under consideration.

The following tables present the physical and functional performance criteria of centrifuge components:

1 Centrifuge Arm

(a) Physical Description

(1) Length of arm from axis to subject station . . . . 50 ft

(2) Weight of total rotating structure including main motor, gondola, and payload . . . . 297,000 lb

(3) Moment of total rotating structure . . . . 30,440,000 lb ft^2

(4) Approximate percentage correction of overturning moment by counterweight 70%

(5) Resonant frequency . . . . 2.8 c/s

(b) Main Centrifuge Drive Motor

(1) Nominal rating . . . . 4000 hp

(2) Maximum horsepower available . . . . 16,000 hp

(3) Maximum torque . . . . 1,700,000 ft lb

(4) Maximum speed . . . . 48.5 r.p.m.

(5) Maximum armature voltage . . . . 600 volts

(6) Maximum armature current . . . . 20,000 amp

(c) Performance of Centrifuge Arm with 1000 lb Payload

(1) Maximum G level . . . . 40 G

(2) Average rate of change of G above 1.6 G . . . . 10 G/sec

(3) Maximum angular acceleration . . . . 1.8 rad/sec^2

(4) Maximum tangential acceleration in gondola . . . . 2.8 G

(5) Normal operational transfer function . . . . $\dfrac{e^{s(0.20\ \text{sec})}}{s + 2.08\ \text{rad/sec}}$

2. Outer Gimbal Axis - Controls Subject's Roll Attitude

(a) Physical Description

(1) Weight of total rotating structure about gimbal axis including gondola and payload . . . . 6300 lb

(2) Moment of total rotating structure about gimbal axis including gondola, payload, and motor end of hydraulic transmission 134,300 lb ft^2

(3) Outer gimbal ring surrounds spherical gondola and is octagonal in shape.

(b) Outer Gimbal Drive System

(1) Nominal rating of drive motor . . . . 75 hp

(2) Maximum output torque of hydraulic transmission . . . . . 1000 ft lb

(3) Overall gear ratio between output end of hydraulic transmission and outer gimbal . . . . 30 to 1

(c) Overall Performance of Outer Gimbal Axis

(1) Maximum angular acceleration . . . . 6.5 rad/sec^2

(2) Maximum angular velocity . . . . 30 r.p.m.

(3) *Continuous* rotational capability in either position or rate control.

(4) Normal operational transfer function . . . . $\dfrac{e^{-s(0.14\ \text{sec})}}{s + 3.59\ \text{rad/sec}}$

3. Inner Gimbal Axis - Controls Subject's Pitch Attitude

   (a) Physical Description

      (1) Weight of total rotating structure about gimbal axis including gondola and payload . . . . 2934 lb

      (2) Moment of total rotating structure about gimbal axis including gondola, payload, and motor end of hydraulic transmission 53,100 lb ft²

   (b) Inner Gimbal Drive System

      (1) Nominal rating of drive motor . . . . 40 hp

      (2) Maximum output torque of hydraulic transmission 700 ft lb

      (3) Overall gear ratio between output end of hydraulic transmission and inner gimbal axis . . . . 27 to 1

   (c) Overall Performance of Inner Gimbal Axis

      (1) Maximum angular acceleration . . . . 9.5 rad/sec^2

      (2) Maximum angular velocity . . . . 30 r.p.m.

      (3) *Continuous* rotational capability in either position or rate control.

      (4) Normal operational transfer function . . . . $\dfrac{e^{-s(0.12\ \mathrm{sec})}}{s + 3.57\ \mathrm{rad/sec}}$

4. Centrifuge Gondola

   (a) General Description

      (1) Spherical, with outside diameter of $10\frac{1}{3}$ ft.

      (2) Upper and lower hemispherical caps which are attached to center structural segment are removable for easy insertion of gondola inserts via overhead crane on monorail.

      (3) Center structural segment is a 10-ft cylinder, 2.6 ft high and ½ ft thick. Special attachment fittings are symmetrically located on the inside wall of this segment to enable it to structurally support the entire gondola insert.

      (4) A circular gondola door is located in upper hemispherical cap and is $3\frac{1}{6}$ ft in diameter.

      (5) Gondola is capable of supporting a 1000 lb payload at 40 G.

   (b) Vacuum Capability

      (1) Normal rating-vacuum equivalent at 100,000 ft altitude.

      (2) Externally controlled through two 2-in. rotary joints.

      (3) Special hemispherical caps are provided which have been tested to 32.5 lb/in^2 external pressure and are essentially reinforced monocaque structure.

5. Slip Rings

(a) Gondola slip ring complement

Section	*Quantity*	*Current Rating*	*Volts AC*	*Shielding*
Physiological	15	1 amp	250	Individual
Instrument and Control	48	5 amp	250	Pairs
Instrument and Control	26	1 amp	250	Pairs
Power	16	35 amp	250	-
Coaxial	19	75 ohm	250	Individual
Total	124	30 mc		

(b) Centrifuge hub axis slip ring complement is the same as the gondola with the exception of 20 additional instrument and control rings rated at 5 amp which serve the arm only.

(c) Increased slip ring requirements can be satisfied by utilising multiplexing techniques on the coaxial circuits, thereby increasing their capacity by some sevenfold.

(d) The physiological circuits are designed for low noise (1 microvolt) and use rhodium plated copper rings with 6 microinch finish, and gold plated wire brushes.

6. Centrifuge Control

(a) Special features include advanced capabilities in:

(1) *System Performance* - Ease of adjustments to permit performance optimization at all axes.

(2) *Safety* - Safe operation with redundant interlocks on each sub-subsystem which essentially makes the entire operation both machine-proof and man-proof.

(3) *Monitoring* - Centrifuge operator has immediate readout of all parameters including television coverage of centrifuge and subject.

(4) *Mode-Control* - Individual control is available for each axis in either manual or remote (computer) control. Each axis also can be placed in position control using either potentiometer or synchro-feedback signals or in velocity control using tachometer feedback signal for the arm.

(5) *Synchronization and Energization* - Prepare synchronization between command and follow-up signals required before energization to permit a bumpless transfer.

(6) *Limit Selection* - All limit selections are easily adjustable.

(7) *Third Gimbal Control Provisions* - Provisions have been made for the control of an eventual third gimbal (yaw axis).

(8) *Compatibility for Control by an Analog Computer* - Permanent wiring of controls and interlock circuitry is provided between the computer and the centrifuge control console.

7. Computer Facilities

(a) For Centrifuge Control

(1) A general purpose analog-computer facility (PACE-231R) is installed adjacent to the centrifuge control console and is essentially a part of it. This consists of 120 amplifiers with a normal compliment of non-linear equipment - servo multipliers, resolvers, comparators, variable and fixed diode generators, limiters, etc.

(2) This PACE computer is used in all centrifuge programs and performs such on-line computational operations as coordinate conversion of pilot's reference frame to the centrifuge gondola reference frame, aerodynamical system relationships, drive motor compensation, G-profile generation, and data analysis.

(3) Closed loop (pilot-controlled) operation of the centrifuge using a computer has enabled the centrifuge to be used as a realistic dynamic flight simulator.

(b) Additional Computer Facilities

(1) Essentially an unlimited back-up of analog and hybrid computer equipment is available from a center computer station through existing telephone lines.

(2) On-line performance monitoring is accomplished at a general purpose performance monitoring console.

(3) A sinusoidal or transient transfer function analyzer plus an additional 70 amplifiers of analog computer equipment is available for continuous analysis of performance on-line.

(4) Magnetic tape recorders using both wide band FM and narrow band FM and strip chart recorders record all permanent data for later analysis.

(5) Digital recording and computational capability is also available if required.

8. Medical Monitoring Capabilities

(a) Closed circuit TV with zoom control provides medical monitor with close frontal view of subjects face under low light level conditions.

(b) EKG, ear opacity, pulse rate, EEG, EMG, blood pressure, and x-ray capabilities are available for monitoring and recording as required.

9. Linear Acceleration Platform Capability

(a) A linear acceleration platform which can be easily installed into and removed from the centrifuge gondola is available for supplying high frequency oscillations in one direction to a centrifuge subject. A complete cockpit can be mounted on the platform.

(b) Performance and load limitations are primarily defined by the hydraulic actuator which powers the platform. These are 9000 lb, 10 c/s and 9 in. total stroke.

(c) The hydraulic actuator is driven by a 3000 lb/in^2 hydraulic supply through the ¾ in. gimbal rotary joints from a source located at the centrifuge hub.

(d) Position control of the actuator is used and can be programmed from an analog computer or function generator.

10. An Interchangeable Capsule Concept

(a) Centrifuge gondola is especially designed to facilitate the easy insertion of a complete installation which includes such items as the seat, instrument panel, hand and foot controls, wiring, etc.

(b) Four ground installation fixtures are available which are portable replicas of the gondola center structural segment. These fixtures are used in the laboratory or at remote locations for prefabrication of gondola installations.

11. Additional Centrifuge Facilities

(a) Facilities are available in an extensive area adjacent to the centrifuge loading platform for the following support functions.

(1) Medical and psychological examination and processing, static testing, briefing and debriefing, suiting, and instrumentation of the gondola subject.

(2) The fabrication, instrumentation, testing, checkout, and storage of gondola inserts.

12. Intercommunication System

(a) An intercommunication system is available which facilitates the programming of signals between the various stations such as the gondola, the instrumentation station, the computer, remote or local, the gondola loading platform, and a Bell Telephone central station.

13. Third Gimbal Axis Compatibility

(a) Engineering provisions have been made in the design of the gondola and rotary points and in the centrifuge system for the eventual insertion of a removable third axis or yaw gimbal capsule.

Aerospace Crew Equipment Laboratory
US Naval Air Engineering Center
Philadelphia, Pennsylvania

This laboratory conducts basic and applied research in the biological, psychological, and human engineering aspects of aviation medicine as it pertains to the personal and safety equipment of naval aircrewmen and to their ability to perform satisfactorily under all of the stresses of their environment.

It also conducts applied engineering research, design, development, test, and operational evaluation of naval aircrewmen personal and safety equipment previously established as a requirement by the Naval Air Systems Command Headquarters. The engineering developments are in concert with known or experimentally defined biological, psychological, and human engineering concepts to insure total bioengineering integrity of the equipment. The laboratory also recommends rules and policies concerning health hazards incident to the use of these equipments in air operations for further promulgation by the Bureau of Naval Weapons.

In the field of biodynamics, the Laboratory has three major equipment devices. These are a Horizontal Accelerator, a Drop Tower, and an Ejection Seat Tower.

The Horizontal Accelerator or HG-1 Catapult is shown in Figures 8 and 9. This horizontal linear accelerator sled and track complex is a hydropneumatic catapult system used to accelerate 300 pounds to peak loadings in excess of 40 G, at a velocity up to 80 knots. The rail length to accommodate the sled is 386 ft long with initial stop made by two MKV arresting engines and a final safety barrier 200 ft beyond. This device is also capable of producing remarkably precise controlled acceleration pulses and has many applications such as the testing of equipment, as well as definition of human tolerances in evaluation of crash restraint systems.

A group of *anthropomorphic dummies* with sophisticated instrument packages installed are used on the HG-1 catapult and other acceleration devices (Fig. 10). These dummies are utilised in a variety of sizes and configurations to simulate the human subject from the 5-to-95 percentile range in the multitude of acceleration studies conducted by the Aerospace Crew Equipment Laboratory. The instrumentation provides telemetered inputs for quantitative data processing and together with high speed photography functions as a research tool for detailed study of the effects of acceleration environments on individual systems within the human body.

The Drop Tower Facility at the Aerospace Crew Equipment Laboratory is a new addition to the Laboratory's equipment (Fig. 11). It consists of a drop tower with a large elevator platform for the study of controlled vertical impact loads on both equipment and human subjects. A unique energy attenuation device is incorporated which enables precise shaping of the impact G force wave for research purposes up to a peak loading of 100 G.

The Ejection Seat Tower (Fig. 12) was one of the earliest facilities to be constructed at the Aerospace Crew Equipment Laboratory. This device is shown to the left of the complex in the foreground of the water tower in Figure 11. The human tolerance limits for explosive charge seat ejection systems were established on this device. The tower is 150 ft high, inclined at 19° vertical from the base. Telemetry instrumentations are conducted on anthropomorphic dummies and human test subjects as they are fired on the tower. Photographic coverage is obtained through high speed cameras positioned to obtain coverage from the start of the shot to the end.

6570th Aerospace Medical Research Laboratories
Air Force Systems Command
Wright-Patterson Air Force Base, Ohio

The Department of the Air Force maintains several major aerospace medical research and development organizations throughout the continental United States. Several of these have major acceleration research facilities which are being constantly upgraded and improved to meet specific acceleration problems. Perhaps the oldest US Air Force organization involved in acceleration research is the 6570th Aerospace Medical Research Laboratories at Wright-Patterson Air Force Base, Ohio, USA. This laboratory has several sophisticated biodynamic simulators planned and under construction; however, only those actually in use at present are included in this presentation. The devices in this category are the Vertical Accelerator, Vertical Acceleration Tower and two vibration simulators which are included in view of the biodynamic problems in low altitude high speed flight.

For the measurement of biological end points a clinical evaluation of subjective or objective changes is made before and after the human exposure. The subject is continuously monitored by electrocardiograph.

The following are descriptions of the specific biodynamic equipment:

The Vertical Accelerator is a vertical vibration machine designed for the simulation of the acceleration produced by vertical gusting encountered during low altitude high speed flight. It has a maximum double amplitude of 10 ft and operates in the 0.5 – 10 c/s range. The devices can be programmed to produce either periodic or random accelerations. The attached photograph (Fig. 13) shows the device as it was configured for a recent study. In operation, the large center drum rotates at a constant speed. The platform carrying the man is mounted on a carriage which engages the rotating drum through 12 small tire-covered wheels located around the circumference of the drum. The carriage motion, up and down the shaft, results from canting of the wheels either clockwise or counter-clockwise. The acceleration pattern for the device can be programmed using various devices such as a signal generator, random noise generator, or a tape recorder input.

The Vertical Acceleration Tower (Figs. 14 and 15) is a guided-free-fall device used for impact testing. The device consists of two vertical guide-rails, a payload carriage with a cantilever arm, a plunger and a water filled cylinder. A variety of support/restraint systems can be hung from this cantilever. One of them is shown in Figure 14. The payload is raised, using a hoist, to the desired drop height, which can be up to 40 ft. This provides terminal velocities up to 50 ft/sec. The plunger, mounted on the rear of the payload carriage is interchangeable and travels with the payload. It displaces water from a water filled cylinder, thereby acting as a brake and regulating the parameters of the deceleration time history. By changing plunger shape and varying the diameter of the water filled cylinder, a variety of acceleration time-histories can be produced. For any combination of plunger and cylinder orifice, increasing drop height increases peak acceleration and decreases duration of impact. In addition, the position of the subject under the cantilever can be varied to produce different impact orientations. The device is capable of developing peak accelerations of 50 G with man-sized loads.

The Western Gear Vibration Machine (Fig. 16) is a high amplitude vibration table manufactured by the Western Gear Corporation. It is capable of providing sinusoidal motion in either the vertical or the horizontal direction, but not simultaneously. The motive power is provided by a pair of scotch yoke mechanisms driven by a d.c. motor. The Western Gear table operates in the 1-20 c/s range and has a maximum double amplitude of 9 inches. It has a maximum force output of 4000 lb and a maximum specimen weight of 1000 lb. The table is capable of accepting a wide variety of support and restraint systems and is used for a wide range of human test programs including tolerance studies, human impedance measurements, and visual acuity studies. The attached photograph shows the table configured for visual acuity study. Distortion is less than 40% up to 15 c/s for a 2.0 G vertical input.

The Vibration Test Stand (Fig. 17) is a vibration table capable of producing sinusoidal motion in either the horizontal or the vertical plane from 5 - 60 c/s. The sinusoidal motion is provided by four vibration generators consisting of two mercury cylinders, a valve and a counterweight. By applying gas pressure to one of the cylinders, mercury is driven out of it and into the other cylinder. This creates an eccentric around the drive shaft and provides the sinusoidal motion. Through proper manipulation of valves, the machine can provide testing under conditions of constant acceleration or constant amplitude. Because of its small load capacity (500 lb), the table is mainly used for animal studies, but it has been used for certain specialized studies with human subjects. A head restraint study is shown in Figure 17. At present this laboratory has two of these tables.

The physical capabilities of the biodynamic simulators at the Aerospace Medical Laboratories, Wright-Patterson Air Force Base, are tabulated in Table I.

TABLE I

Physical Capabilities of Vibration Devices at Aerospace Medical Research Laboratories, Wright-Patterson Air Force Base, Ohio

Device	*Max. Specimen Weight* (lb)	*Table Size*	*Max. Acc. at Max. Load* (g)	*Max. D.A. at Max. Load*	*Max. Force Output* (lb)	*Frequency Range* (c/s)
Vertical Accelerator	400	Depends on seat configuration	3	5 ft	1200	0.5 – 10
Western Gear Vibration Machine	1000	40 in. × 40 in.	4	9 in.	4000	2 – 30
Vibration Test Stand	500	36 in. × 48 in.	10	0.415	5000	5 – 60

Impact Devices

Device	*Max. Specimen Weight* (lb)	*Drop Height* (ft)	*Pulse Shape*	*Pulse Duration*	*Max. Velocity* (ft/sec)	*Max. Acceleration* (g)
Vertical Deceleration Tower	2000	40	Triangular	60 – 200 ms	50	50

6571st Aeromedical Research Laboratory
Air Force Systems Command
Holloman Air Force Base
New Mexico

The 6571st Aeromedical Research Laboratory has three acceleration devices used in biodynamic research on animal and human subjects. These devices are called the Daisy Decelerator, the HYGE Accelerator and the Bopper.

The Daisy Decelerator (Fig. 18) is an impact test device designed to produce a deceleration environment for human, animal and dummy tests. It consists of a 240-ft track which guides a sled holding the test subject. The sleds are accelerated to velocities between 10 ft/sec and 180 ft/sec (as required by the test program), and then released to coast into the hydraulic brake. This brake can produce between 5 G and 200 G on the test subject, as is required by the test. Six sleds are available for various test purposes. A complete instrumentation system is available for collection of most types of physiological and mechanical data. Photometric techniques are available for kinematic measurements. The facility is used for physiological research and equipment development pertinent to impact.

The HYGE Accelerator (Fig. 19) is a 6 in. hydraulically controlled, gaseous energized accelerator used for human, animal, and equipment tests. It will produce the following impact pulses:

150 G, 11 ms half-sine,
150 G, 6 ms sawtooth,
150 G, 10 ms square wave,
20 G, 40 ms trapezoid,
40 G, 40 ms trapezoid.

Maximum thrust of the device is 40,000 lb. Variations in performance may be achieved by changes in pressurization and hydraulic fluid level.

The Bopper Crash Restraint Demonstrator (Fig. 20) is a device used to provide short duration impact pulses to human or animal subjects. Maximum deceleration which can be produced on a human size subject is 25 G, and the maximum velocity attainable is 20 ft/sec. The device is generally used for indoctrination of test subjects and for development of techniques and baseline data in preparation for more involved tests on the Daisy Decelerator. Programming of accurate impact forces is neither as convenient nor as precise as on the Daisy Decelerator or the HYGE accelerator.

US Air Force School of Aerospace Medicine
Air Force Systems Command
Brooks Air Force Base
Texas

The School of Aerospace Medicine at Brooks Air Force Base has recently acquired a new centrifuge with an interchangeable two-man cockpit gondola and a spin capsule. On the opposite end of the centrifuge arm is installed a large animal platform. The Laboratory also has a small animal centrifuge as an independent facility and a Rotational Flight Simulator.

The Human and Animal Centrifuge (Figs. 21 and 22) has as its utilitarian objective the following:

1. Define the objective endpoints to increased gravitational stress in Human subjects.
2. Define optimum seating configuration for human subjects when exposed to high gravitational stress imposed in the $+G_x$ direction using the objective endpoints determined in (1) above.
3. Interpret a cross-correlation of objective endpoints using experimental animals to either extend or validate the previously determined human physiological data.
4. Study human psychomotor performance to determine any decrement when exposed to the above listed stresses in either an experimental or simulated operational condition.
5. Evaluate and cross-correlate the physiological parameters using new sensing devices yet to be developed and tested.

1. *Centrifuge*, physical characteristics.

(a) Centrifuge Arm

(1) Overall radius . . . 276 in. (main) 180 in. (research) capable of $\pm G_{xyz}$

(2) Construction . . . . Cantilever (monohedral)

(3) Natural frequency . . . . . without gondola, 6 c/s

(4) Maximum onset rate . . . . . 6 G per sec (1 – 20 G range)

(5) Horse power rating . . . . . 850 hp constant

(6) Speed control – electrically driven – infinitely variable.

(7) Onset control – electronic pressure (torque) control infinitely variable.

(8) Braking – deceleration – hydraulic (control same as above – friction operated).

(9) Auxiliary equipment.
  (i) Closed circuit television.
  (ii) 200 5-amp, 600-volt, instrumentation channels.
  (iii) Anti-G facilities.

(b) Two-Man Gondola

(1) Diameter . . . . 6 ft

(2) Length . . . . 9 ft

(3) Control . . . . 90^{o} rotation during operation

(4) Maximum G at maximum radius . . 50 G (continuous brief peak)

(5) Payload . . . . 600 lb

(6) Operation . . . . open or closed loop

(c) Spin Capsule

(1) R.P.M. . . . . 0 – 50 r.p.m. with main arm at 53 r.p.m.

(2) Control . . . . electro-hydraulic

(3) Maximum G at maximum radius . . 20 G

(4) Payload . . . . 500 lb

(5) Operation . . . . open or closed loop

2. *Rotational Flight Simulator*, physical characteristics.

The Rotational Flight Simulator (Fig. 23) is used to determine human tolerances to multi-directional forces. The 5000-lb, 10-ft diameter sphere is floated on the air bearing by a cushion of air approximately 0.035 inches thick. Internally mounted inertia rings, powered by hydraulic motors, then provide motion for the sphere in either the yaw, pitch, or roll axes. Power for onboard systems including telemetry, lighting, closed circuit television, and air conditioning is provided by storage batteries.

3. *Small Animal Centrifuge*, physical characteristics.

(a) The specifications for the machine (Fig. 24) are as follows:

(1) G-range . . . . 1 – 75 G (100 G's/46 in. R)

(2) Speed . . . . 0 – 300 r.p.m.

(3) Radius of gyrations . . . . 22 – 46 in.

(4) Centrifugal capacity . . . . 5000 G lb

(5) Weight capacity . . . . . . 100 lb (dead weight)

(6) Wow and drift . . . . Within 0.05% per minute including normal line voltage variations, but excluding line frequency variations.

(7) Test package size . . . . . 24 x 24 x 18 in. high

(8) Drive . . . . 3 hp, 220/vac, 3 phase 60 cycle

(9) Arm . . . . balancing with magnesium platforms

(10) Accessories . . . . 50 slip rings, 5 amp shielded, continuous r.p.m. readout with 600 tooth gear and provision for counter.

Ames Research Center
National Aeronautics and Space Administration
Moffett Field, Califorr'a

The Ames Research Center has four major biodynamics facilities of importance to this compilation of acceleration devices. These are a biosatellite centrifuge, a five-degree-of-freedom simulator, a man-carrying motion generator, and a vertical acceleration and roll device.

1. *Biosatellite Centrifuge* (Fig. 25), physical characteristics.

It has a double-ended arm with boxed cab spaces 6 ft × 8 ft × 8 ft between radii 21 ft and 29 ft. One cab is fitted with a swing platform which remains normal to the resultant acceleration at any steady state angular velocity. Animals and instrumentation may be restrained on the platform for determination of tolerance of high-G stress. Closed circuit TV is a normal means of observing the subject or equipment. Angular velocity may be preprogrammed, for exact repetition of G versus time, by a curve follower input to the electro-mechanical servo drive. There are no provisions for computer control. The centrifuge has been man-rated to 4 G while fitted with a hydraulically servoed seat which was oscillated parallel to the resultant arm acceleration.

Performance

	Travel	*Velocity*	*Acceleration**
Angular	Unlimited	5 rad/sec	–
Radial	–	–	20 G
Radial Onset	–	–	2 G/sec**
* At 25-ft radius		** Above 2 G	

2. *The Five-Degree-of-Freedom Simulator* (Fig. 26)

This motion generator moves a cab in the three rotational degrees of freedom, in a sixty-foot diameter horizontal circle, and vertically with respect to the earth. Hooded, interchangeable cabs are used, which are moved in the angular motions by silent chain drives. Vertical motion and rotation in the horizontal circle is by means of cable winches.

Spacecraft simulations, or other projects requiring the sustained translational acceleration obtainable from the centrifuge force of the arm, are performed in the cab shown in Figure 26. This cab can be fitted with pilot restraint apparatus suitable for use with these accelerations. Gimbal and vertical motions can be used both to provide force cues and to orient properly with respect to the pilot, the sustained acceleration force. Hand controllers of several types and instrument panels for control of a simulated vehicle may be mounted. Physiological measuring apparatus of pilot condition (blood pressure, electrocardiograph, television view of pilot, etc.) is normally used, either for pilot safety monitoring or research data.

A second interchangeable cab is normally used for projects without these sustained accelerations. Typically, angular acceleration of the horizontal arm is used to simulate side force. This cab is fitted with a conventional airplane seat, rudder pedals, wheel or stick, and throttle console. Typical aircraft instruments can be mounted and a television monitor to display the out-of-the-window visual cues, produced by any of the image generators, can be mounted.

Performance

	Acceleration	*Velocity*	*Travel (Maxima)*
Roll	18 rad/sec^2	8 rad/sec	$\pm$ 360°
Pitch	6 rad/sec^2	2 rad/sec	$\pm$ 52°
Yaw	12 rad/sec^2	2 rad/sec	$\pm$ 180°
Vertical (from ambient)	$\pm$ 1 G	16 ft/sec	$\pm$ 2 ft
Arm: Radial	6 G	–	–
Tangential	$\pm$ 1 G	2.5 rad/sec	Unlimited

Drives: Ward-Leonard Electrical Servos

Torque motors drive through silent chain or wire rope onto rubber-faced sectors or grooves.

Program: Closed-loop operation with analog computation.

3. *Man-carrying Motion Generator* (Fig. 27), physical characteristics.

This motion generator is of the centrifuge type (50-ft radius) with five degrees of freedom. The facility can provide computer controlled acceleration, motion, and environment to two interchangeable cab configurations. The cabs can also be operated on fixed supports in the status test area where equipment checkout and 1 G investigation of environmental stress and crew and equipment tasks may be performed. A "midcourse dock" is provided for "out-the-window" display. Facilities are provided for either "closed-loop" or "open-loop" operation. *Cab Configuration I* will accommodate a three-man crew and equipment for space mission research. The motions are intended to be smoothly applicable at very low values so that navigation and guidance procedures using a high accuracy "out-the-window" display may be simulated. *Cab Configuration II* will accommodate one man and equipment for human tolerance and performance investigations. Atmosphere and temperature can be varied as stress inducements.

Performance: (Motions generated - maximum)

Cab No. I

	Acceleration	*Velocity*	*Displacement*
Roll	12 rad/sec^2	6 rad/sec	-
Pitch	5 rad/sec^2	2 rad/sec	Unlimited maximum
Yaw	5 rad/sec^2	2 rad/sec	-
Vertical	± 0.5 G	8 ft/sec	± 2 ft
Arm: Radial	20 G (angular)	3.6 rad/sec	Unlimited

Cab No. II

	Acceleration	*Velocity*	*Displacement*
Roll	18 rad/sec^2	6 rad/sec	-
Pitch	6 rad/sec^2	2 rad/sec	Unlimited
Yaw	6 rad/sec^2	2 rad/sec	-
Vertical	± 2 G	16 ft/sec	± 2 ft maximum
Arm: Radial	50 G (angular)	5.7 rad/sec	Unlimited
Radial onset	7½ G/sec		

Environmental:

Pressure: Sea level to 30,000-ft altitude in 1 minute.
Sea level to 100,000-ft altitude in 10 minutes.
Rapid decompression from 8000 ft to 40,000 ft in 2.5 seconds.

Gaseous: 100% oxygen or mixtures of oxygen and other gases between 3 lb/in^2 abs. and sea level.

Air Temperature: -40°F to +200°F, equilibrium attainable in fifteen (15) minutes.

Wall temperature: (removable panels, boom stationary, and limited gimbal rotation) -40°F to +200°F, equilibrium attainable in fifteen (15) minutes.

Water Vapor Pressure: 5 mmHg partial pressure to saturation at 150°F between sea level and 30,000 ft altitude.

4. *Vertical Acceleration and Roll Device* (Fig. 28), physical characteristics.

This device is designed to facilitate studies of the human pilot control problems resulting from rapidly fluctuating vertical accelerations characteristic of certain advanced aerospace vehicles launch profiles as well as flight through turbulent air in more conventional craft. As can be seen from the accompanying sketch, this device consists of a two-place side-by-side cockpit mounted on a 32-ft tower. Electronically controlled hydraulic servos are utilised to provide both vertical and roll motion. The performance capabilities of the two drive systems are listed on next page.

Performance

Mode	*Vertical*	*Roll*
Travel	± 10 ft*	± 30°
Velocity	± 12 ft/sec	± 4 rad/sec
Acceleration	± 160 ft/sec^2	± 10 rad/sec^2
Natural frequency**	1½ c/s	1½ c/s

* Total travel-useable throw plus that required for snuffing action is approximately 30 ft.

** Frequency compensation networks can allow a ± 5 G normal acceleration to be imposed on the pilot out to 10 c/s.

Manned Spacecraft Center
National Aeronautics and Space Administration
Houston, Texas

The Manned Spacecraft Center in Houston, Texas has two major acceleration facilities utilized principally in bio-medical studies related to manned aerospace flight. These facilities are operated by the Crew Systems Division and are the Impact Test Facility and the Flight Acceleration Facility.

1. *The Impact Test Facility* (Fig.29) is a drop tower for simulating spacecraft impact conditions.

Physical Description:

Capability:

Drop height	0 – 23 ft
Velocity change . . .	0 – 38 ft/sec
Deceleration range . .	8 – 100 G
Wave shape simulation .	½ sine, versine, triangular, trapezoid
Pulse time	0 – 280 ms
Onset rate	0 – 10,000 G/sec

Payload	2000 lb
Deceleration mechanism . .	Hydraulic, perforated cylinder and piston
Wave shape control . . .	Mechanically variable orifice
Orifice arrangement . . .	Predefined by computer program
Data collection	40-channel low-level data acquisition system

Dropping table . . . . 200-cycle natural frequency

Foundation . . . . . . Load transmission into soil is limited to 0.01 G at a lower level of 5 c/s.

2. *Flight Acceleration Facility* (Fig.30), physical characteristics.

This facility is a complete and integrated, man-rated centrifuge system used for the training of three-men spacecraft crews and the development of their equipment under acceleration stresses, for physiological evaluation of men under combinations of space flight stress, and for projections and evaluations of human tolerance to specific acceleration profiles.

Arm lengths:

50 ft (basic).
40 ft with removal of 10-ft section.
60 ft with addition of 10-ft section.

Payload:

3000 lb.

Radial acceleration:

30 G maximum.
20 G nominal.

On-set rate:

5 G/sec from a 2 G base (60% overload with 50-ft arm).

Gondola:

12-ft diameter sphere.

Main motor drive: Direct current.

6700 hp (nominal), 3.2×10^6 lb ft torque.
10,700 hp (overload, 7-sec max), 5.1×10^6 lb ft torque.

Gimbal system: Two-axis, continuous rotation.

First axis (gimbal ring):
1.8 rad/sec^2 angular acceleration.
30 r.p.m. angular velocity.
Second axis (gondola):
10 rad/sec^2 angular acceleration.
30 r.p.m. angular velocity.

Gondola environment:

Altitude . . . . SL to 235,000 ft (3MM)
Temperature . . . $10^o - 90^oC$ at SL
Humidity . . . . 40 - 60% at SL

Control: Man-machine closed loop.

Data collection:

300 + slip rings.
Pulse code modulation.

The temperature and relative humidity environment of the gondola can be controlled between 50°F and 200°F and from 40 percent to 60 percent, respectively, at nominal sea level pressure. Controlled reduced pressure environments can be obtained within the gondola to simulate launch pressure changes to 25 mmHg (5 lb/in^2 abs.) and an ultimate pressure of 3 mmHg (125,000-ft altitude). A comprehensive control system will allow the facility to be operated by a preprogrammed computer in automatic, semi-automatic, or manual modes.

Facility Instrumentation and Control System. In order to utilize the complex capabilities of the centrifuge properly, a rather comprehensive control, instrumentation, and data-handling system is required. A schematic representation of the flow of information from the gondola to the various areas and stations is indicated in Figure 31. The gondola equipment is identified in the upper left portion of the figure and includes suit sensors, gondola sensors, signal-conditioning equipment, and a multiplexer. The signals are fed through the slip rings to a main distribution box which is located in the computer room on the first floor of the administrative wing. From the main distribution box, information is transmitted to the data-processing and recording equipment in the computer room, to the gondola service area to the east control room and the medical monotor's station and to the west control room and the centrifuge operator's station.

The gondola is equipped with a total of 438 slip rings, 219 in each trunnion. The total is sub-divided into five broad categories of use: 54 shielded physiological, 18 coaxial, 210 signal, 126 control, and 30 power. The physiological rings are especially designed for transferring low-level signals necessary for physiological parameters such as electrocardiograms and electroencephalograms. The coaxial rings are used for closed-circuit television and a 244-channel commutator which has a pulse-code-modulated signal output. The output from the commutator is transmitted in parallel and is carried as an 8-bit binary word, a parity bit, a clock signal, and a frame synchronizing signal. Digital-to-analog converters are provided on the receiving end in the computer and control rooms so that the usual visual displays such as pen recorder may be utilised. The signal rings carry command and response information, instrument panel data, intercommunication, and monitoring data from the occupants. The control rings carry interlock, safety, and control signals. Of the 30 power rings, 8 will have a capacity of 150 amperes, 12 will have a 50-ampere capacity, and 10 will have a 10-ampere capacity.

Through a master patch panel in the computer room on the first floor of the office wing a very flexible recording and display system is available. Each control room is provided with three 8-channel pen recorders and an 18-channel oscillograph. The medical monitor room has an 8-channel pen recorder and a multi-channel oscilloscope. These three stations as well as the centrifuge operator's room are equipped with television monitors. There are four television cameras located within the gondola for monitoring the three test subjects and the instrument panel. Data may also be recorded in the computer room on a 14-track magnetic tape recorder in either digital or analog form.

The facility is equipped with two computers. Each of the computers will have the capability of handling at least an 18-bit word, a 5-microsecond cycle time, a 4000-word memory, and a total input-output capacity of 25 channels. Each computer has the capability of extracting information from the memory of the other computer. The computers serve four basic functions. They will control the operation of the centrifuge, monitor the performance to insure safe operation, perform limited real-time data reduction, and may be utilized for post-test data reduction.

The facility may be controlled and operated in automatic, semi-automatic, or manual modes of operation. In the automatic mode the test program is preprogrammed and the test program may be controlled and operated by the computer. Additionally, in the automatic mode the test program may be controlled and operated by the computer but the program can be modified by test subject input signals within preprogrammed limits. In the semi-automatic mode, the centrifuge operator controls the speed of the arm while the other functions are computer controlled. In the manual mode, the test program may be controlled manually by the centrifuge operator with the computer operating with preprogrammed safety values to limit operations which would damage the machine or test subjects. Lastly, the facility can be operated manually without the computer in operation. The manual mode of operation without the computer as a safety monitor would not normally be used for dynamic runs but would be used for static tests and certain checkout operations.

Several different normal and emergency stop modes are possible. A normal stop mode will be under full computer control and will be initiated by the operator or medical monitor. A preprogrammed acceleration profile is followed by using regenerative braking of the main-drive motor while the vector alignment is maintained by the computer and control systems. In the event of a computer malfunction during a test operation, the stop mode is initiated by the operator and both gimbal rings are locked in position. The arm is decelerated by selected dynamic braking and is then switched to manual operation at speeds below 3 r.p.m. The mechanical brake is activated manually to park the arm at the loading platform. In the possible event of loss of all power to the main motor, selected dynamic braking can be accomplished by utilizing emergency batteries for power to the field coils of the main motor. Lastly, manually controlled stops can be accomplished under the control of the centrifuge operator and would normally be accomplished by utilizing regenerative braking and manual control of the gimbal systems.

Civil Aeromedical Institute
Federal Aviation Agency
Oklahoma City, Oklahoma

The Civil Aeromedical Institute has eight biodynamics facilities worthy of mention; they are: the drop test apparatus, the vertical decelerator, the short track, the impact bopper, the "earley bird" motion simulator, the Curtiss Wright Dehmel Boeing 720 flight simulator, the light aircraft turbulence simulator, and the "portable" drop tower.

1. *Drop Test Apparatus* (Fig.32) was designed to study the effects of high vertical impact forces (positive G) combined with high jolt factors and short time intervals on human subjects. It has been used to study protection of shipboard personnel against

underwater explosion forces for the Bureau of Ships, US Navy. Other studies included human voluntary tolerance to vertical impacts as are encountered in civil aviation through passengers evacuating from commercial aircraft, by passengers bracing their feet during a crash landing, and through the seat by passengers during the vertical component of any crash, especially vertical-takeoff-and-landing aircraft. Human subjects in this research were exposed to impact forces applied through the feet while standing with legs held rigid, with knees bent, with legs flexed (squatting), and seated in a rigid chair, and in evaluation of energy absorbing devices and materials. Currently located in main Protection Survival Laboratory.

Physical characteristics and performance.

The equipment consists of a hoist, trip mechanism, and a drop platform with a guiding track. The base platform is mounted on leaf springs with hydraulic pistons for damping is instrumented with strain gauges, and has a maximum motion of one inch. Jolts and G forces at the point of impact are recorded from an electrokinetic accelerometer attached to the floor of the drop platform. The CEC accelerometer with a range of 0.01 – 1000 G, 5 c/s to 40 kc in conjunction with a cathode ray oscillograph has been used to measure input loads, with a Statham ±10 G accelerometer at shoulder level. The guiding track allows for vertical drops of up to 12 ft.

2. *Vertical Decelerator* (Fig. 33), designed to provide greater velocity-time relationships than were possible with the vertical drop test apparatus. To date it has been utilized for studies of forces transmitted to pilots through parachute seat packs, dinghys, and various absorption devices in ejection seats, at the request of the Air Force, preliminary techniques and studies of vital organ displacement and in preliminary tests of experimental restraint systems utilizing primate (Sootey Mangebey) subjects.

Physical characteristics and performance.

It consists of a 40-ft steel tower bolted to a concrete block wall, on which an adaptable carriage (seat, platform, etc.) can be pulled to a desired height by an electric winch. An electro-mechanical trip mechanism releases the carriage for free-fall along two vertical rail guides.

Vertical impacts may be attained up to a maximum velocity of 50 ft/sec (34.1 m.p.h.). Orientation of the subject, however, can be changed to any desired uni-directional position.

The carriage is lifted by steel cables running from an electric motor-driven hoist, although a mechanical winch can also be used. The carriage is kept on the track by a slotted T-rail with a matched groove for the carriage. Braking is provided by the material impacted, with a concrete flooring base.

3. *Short Track* (Fig. 34) is an indoor linear decelerator designed for a wide range of impact studies pertinent to aviation. Particular areas of emphasis include research on seating (commercial airline seats, SST aircraft, general aviation, and experimental concepts for adults, children and infants), and energy absorption devices and materials, combined with continued human impact tolerance studies. This track was constructed in 1962 with a 3000-lb weight through a block and tackle arrangement as the propulsion force.

Physical characteristics and performance.

The equipment presently consists of a 148-ft two-rail track, spaced 5-ft apart, and sunk beneath the floor level of the concrete laboratory floor. Basic carriage is an 8-ft welded-steel sled riding on roller bearings. Deceleration is by means of a C-47 landing wheel hydraulic brake which is cabled to a stop against which the sled impacts. Formed lead cones are calibrated to give specific onset decelerations and placed for each test on the stop mechanism. This track has a parallel ceiling track with one chain hoist and two electric hoists capable of lifting 4000 lb each.

While the carriage is limited to motion in the horizontal plane, the subject (or subjects) may be oriented in any position depending upon the nature of the experiment.

4. *Impact Bopper* (Fig. 35) was designed for low-level deceleration research and is somewhat similar to the Northrop "bopper" at Holloman Air Force Base. It has been used for study of gross human tissue response to horizontal forces exerted by human (cadaver) legs on aircraft seat backs as in an aircraft crash, and is currently being used in a study of dashboard impact forces on the head in automotive accidents.

Physical characteristics and performance.

This apparatus is composed of a 25-ft steel unit containing an 18-ft horizontal track on a steel box frame. A small carriage, which can be modified for various usages, slides on 12 in.-wide by 12 ft-long track. Braking is provided for the carriage by a sandwich friction brake, weighted to stop the carriage from 0 to 16 inches according to requirements. Propulsion is by bongee shock cords with mechanical winch trip mechanism, including a safety shear pin.

Up to 18 strands of ½ in. bongee shock cord can be used. The impact velocity can be varied from 0 to 60 ft/sec in the 12-ft distance. It is capable of loads up to 90 lb and abrupt decelerations up to 300 G at 26,000 G/sec. A speed of 100 m.p.h. can be attained over the 12-ft of track with light loads of around 25 lb. A mechanical lock release for the carriage is released by hand by a controller.

5. *"The Earley Bird" Motion Simulator* (Fig. 36), along with problems associated with pilot vigilance, fatigue, human engineering, and experimental navigation systems, has been utilized to study human pilot responses to abrupt gust conditions including high computed vertical accelerations under combinations of low and high horizontal velocities under instrument flight simulation.

Physical characteristics and performance.

A Link C11A jet-propelled aircraft simulator was modified to reproduce flight performance characteristics in typical light of general aviation aircraft single-engined jet aircraft.

The subject "flies" from a hooded cockpit and responds to either instructions from the operator, who can simultaneously simulate other ground or air stations, or according to a pre-arranged program. A continuous monitor on a scale chart is maintained and the operator can control a large number of variables and inflight conditions including both intensity and frequency of vertical air accelerations.

6. *The Curtiss Wright Dehmel Boeing 720 Flight Simulator* (Fig.37) is one of forty-one (41) in the United States. It is used for refresher and regular training programs for Federal Aviation Agency pilots and navigator inspectors, but much of the time is used in research problems concerning new navigation techniques or equipment, training procedures or operation problems.

Physical characteristics and performance.

This simulator consists of a Boeing 720 airline flight deck having room for a pilot navigator, instructor pilot, and instructor navigator. A projector mounted on top of the cabin in line with the pilot projects an airport facility on a 14 ft × 12 ft screen which is viewed through the optical glass windshield by the crew. This closed circuit TV is picked up from an exact scale model in an adjacent visual display room and the visual portion of a flight can be adjusted to be displayed from 1000-ft altitude to ground level, simulating breakout on landing from instrument flight or take-off or taxiing on the ground. In addition, the analog computer system can program day or night conditions and intermittent cloud conditions. Motion is duplicated as realistically as possible and includes a 22-in. "sink" when the aircraft "lands". Any airport or conditions can be simulated; gross weight can be varied from 110,000 to 280,000 lb; and pressure, altitude, temperature and turbulence can be programmed at random.

A two-axis motion is possible allowing for a maximum of ±12° pitch up and 10° pitch down, or 22° pitch and +50° roll, produced by 1000 lb hydraulically actuated pressure. Vertical accelerations of 32 ft/sec or 1 G are designed although this may be modified.

7. *Light Aircraft Turbulence Simulator.* Vertical accelerations encountered in extreme turbulence in flight have resulted in frequent in-flight structural failures, particularly in light aircraft. The Light Aircraft Turbulence Simulator was constructed to test human responses to various vertical accelerations typical of CAT, thunderstorms, or other turbulent environments.

Physical characteristics and performance.

The basic mechanism of this apparatus consists of an inverted and intact B-52 aircraft hydraulic landing gear system which has been modified to support the cabin of a full-scale instrumented light plane. Pilot closed loop operation is provided with a modified C11B airplane dynamics computer system. Vertical gust force, pitch and roll displacement and some limited axial accelerations can be achieved by hydraulic actuator servo system commanded by computed dynamic response to various atmospheric turbulence programs.

A capability of ±40° roll, ±40° pitch, 10° yaw is thus provided, combined with gust, and vertical acceleration capability within a 0.4 G seconds envelope and a 6 G peak and a maximum continuous mechanical output of approximately 2.5 G sec/minute.

The simulated aircraft dynamics may be varied during operation through a main control and data monitor console. The energy available for single-gust simulation is limited by a system of hydraulic transfer accumulators. The maximum energy in event of power malfunction is thus limited to that remaining in one accumulator guarded by a double redundant system of shut-off valves.

8. *"Portable" Drop Tower.* In order to provide a platform for controlled vertical deceleration tests of a larger magnitude than the two indoor vertical tracks (40-ft and 20-ft), a 95-ft collapsible steel tower was obtained. Since it is portable it allows greater flexibility in field testing. It was primarily obtained for human cadaver and dummy free-fall studies.

Physical characteristics.

This apparatus is an "economy hi-reach" maintenance platform which telescopes from 22-ft to 95-ft in height. Weighing 40,000 lb, the base is 16-ft square, and it has a capacity of 500 lb. Velocities in free fall of 74 ft/sec (50 m.p.h.) are estimated in 95-ft drops.

National Aviation Facilities Experimental Center
Federal Aviation Agency
Atlantic City, New Jersey

The Catapult and Track Facility (Fig. 38) at the National Aviation Facilities Experimental Center in New Jersey was designed and built for the purpose of determining the dynamic characteristics of light aircraft, helicopters and aircraft components when subject to deceleration and impact forces.

Physical characteristics and performance.

This facility is a fixed installation comprised of an air catapult, two Mark IV hydraulic arresting engines and a 300-ft track. The catapult is used to accelerate a free running car, to which the test article is mounted, along with the first 90 ft of track. The car then moves freely along the track until it engages the arresting cable which decelerates the test article at some predetermined rate over the last 60 ft of track. The arresting cable can also be positioned to release the test article to im[illegible] crash barriers at the end of the track.

Movement on this facility is limited to the horizontal direction. Velocity of the free running car can be varied from 40 to 145 ft/sec, the latter being dependent on the weight of the payload. The car is limited to a maximum payload of three tons. The acceleration produced during launch varies with the maximum velocity and may reach peaks as high as 10 G. Deceleration of the car is controlled by the arresting engines which are capable of producing deceleration as high as 40 G.

The *control and interlock systems* enable the test parameters, such as velocity and deceleration to be present and monitored prior to firing. The interlock portion of this system prevents firing until the desired conditions are met. A programmer is also provided to control the operation of cameras and data collection equipment relative to the time of sled firing.

Photographic coverage is available for the entire length of the track from launch throughout arrestment. Data is collected from the free running car by a hard wire and may be recorded either on an oscillograph or magnetic tape along with the car time/position history.

Section of Physiology
Mayo Foundation and Mayo Clinic
Rochester, Minnesota

The *Human Centrifuge* facility at the Mayo Clinic in Rochester, Minnesota, has been used in much of the early acceleration investigation for the Department of Defense. The facility consists of a human centrifuge and sophisticated ancillary equipment for the conduct of human and animal studies. The device is one of the earliest pieces of acceleration research equipment in the United States and is still used in an active research program.

1. *The Human Centrifuge* (Fig.39), physical characteristics.

(a) Centrifuge arm

Double ended truss platform, the axis of the cockpit is 14.6 ft from the center of the centrifuge. The non-cockpit end is 18 ft from the center of rotation and is enclosed in steel mesh.

(b) Cockpit

The cockpit of the centrifuge is free to rotate only around the axis of its suspension from the centrifuge carriage. The axis of the cockpit is 14.6 ft from the center of the centrifuge and is approximately at the heart level of a seated subject.

(c) Motion capabilities

The system will generate an acceleration of 3 G per second up to a maximum of 14 G. Braking is purposely limited to about 1 G per second for the safety of the subject. Cockpit is free to rotate about its Y axis so that G is always applied through the Z axis of the subject.

(d) Description of the mechanical system

The mechanical system is composed of the following basic components:
(1) 220-volt 3-phase a.c. motor.
(2) Variable speed drive.
(3) Two 40,000 lb flywheels.
(4) Carriage with cockpit.

(e) Description of the control system

(1) The flywheels are brought up to the desired speed by an open loop servo system controlling the variable speed drive.

(2) The carriage r.p.m. (or cockpit G) is manually selected and a closed loop servo system controls the clutch and brake to follow the manually operated selector position.

(3) Braking is achieved by servo actuated brake shoes applied against a peripheral steel rim attached to the building.

(f) Description of physiologic recording system

(1) Mercury through-commutater system for low noise level recordings 45, 2 lead channels.

(2) Custom built photokymographic recording assembly with triple camera assembly which allows simultaneous conventional photographic recordings on a slow camera (proper speed 0.25, 0 5 or 25 mm/sec) and a fast camera (25 or 155 mm/sec) and on a third immediate developing camera.

(3) Ampex tape recording assembly Model 1107 with electronics for seven channels. This recording assembly operates in parallel with photokymographic recorders.

(4) The recording assembly includes:

(i) Five simultaneous single and double scale oximeter channels for interchangeable recording of oxygen saturation or the concentration of blue or green dye indicators in blood.

(ii) Ten strain gauge channels for recording of circulatory pressures, acceleration, suit pressures, respiration, etc.

(iii) Channels for recording the electrocardiogram, electroencephalogram, ear opacity pulse, reaction times to light signals, etc.

(g) Safety features

(1) Carriage is stressed for far greater G than can be generated by the drive system.

(2) Observer riding at center of carriage provided with emergency stop signal.

(3) Emergency compressed air cylinder actuates brake in case of loss of normal compressed air supply (compressed air is used for actuating the clutch and brake shoes).

(4) Manual selector controlling carriage speed is spring loaded and returns to zero if released.

2. Studies which are being done at the present time using this centrifuge include:

(a) Studies of the effects of acceleration on cariovascular and respiratory dynamics using chimpanzees, and videoroentgenographic studies of the heart and lungs during exposure to forward acceleration using dogs. A special cockpit has been installed (Fig. 39) for videoroentgenographic studies. The videoroentgen assembly is positioned to record anterior-posterior projections of the thorax. The cockpit is tilted in approximately the position it would assume during an exposure to 3 G.

As illustrated in Figure 39, the roentgen tube (A), 9-in. image intensifier (B), image-orthicon camera (C), and counter weight (D) are mounted on a yoke which can be rotated to any desired position in relation to the cockpit. This makes possible recording of anterior-posterior, lateral or other desired projections of the thorax or other bodily structure. The video signal from the image-orthicon camera (C) is transmitted via the commutator assembly on the central shaft to a videotape recorder (RCA Model TR-2) located in an adjacent recording room.

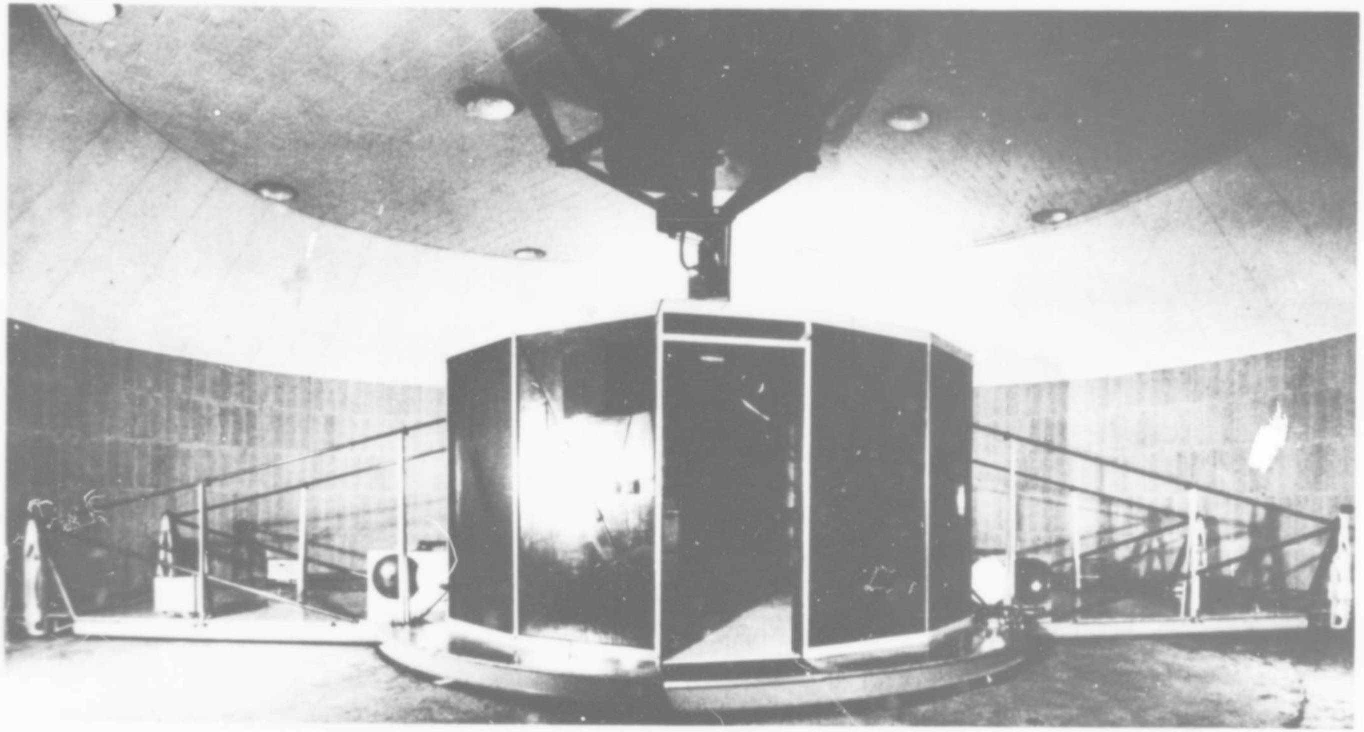

Fig. 1 Original Pensacola Centrifuge, US Naval Aerospace Medical Institute, US Naval Aerospace Medical Center, US Naval Air Training Command, Pensacola, Florida, USA

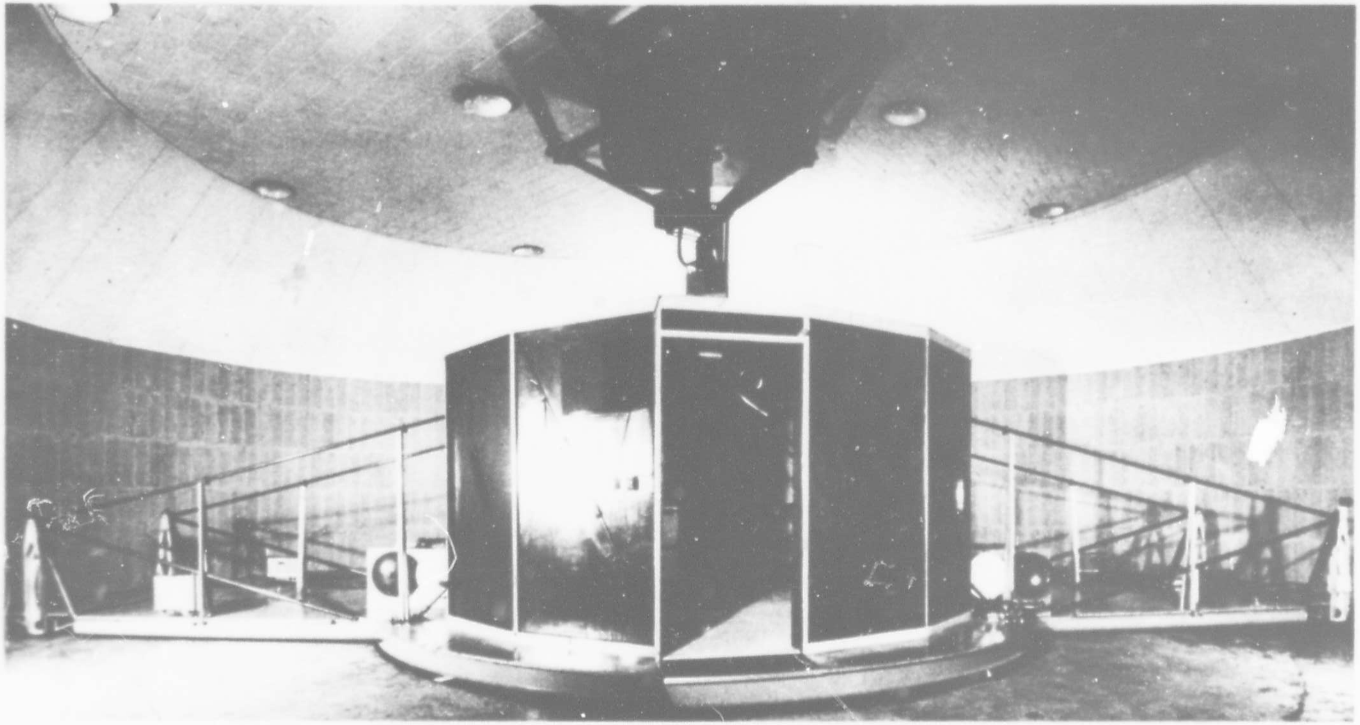

Fig. 1 Original Pensacola Centrifuge, US Naval Aerospace Medical Institute, US Naval Aerospace Medical Center, US Naval Air Training Command, Pensacola, Florida, USA

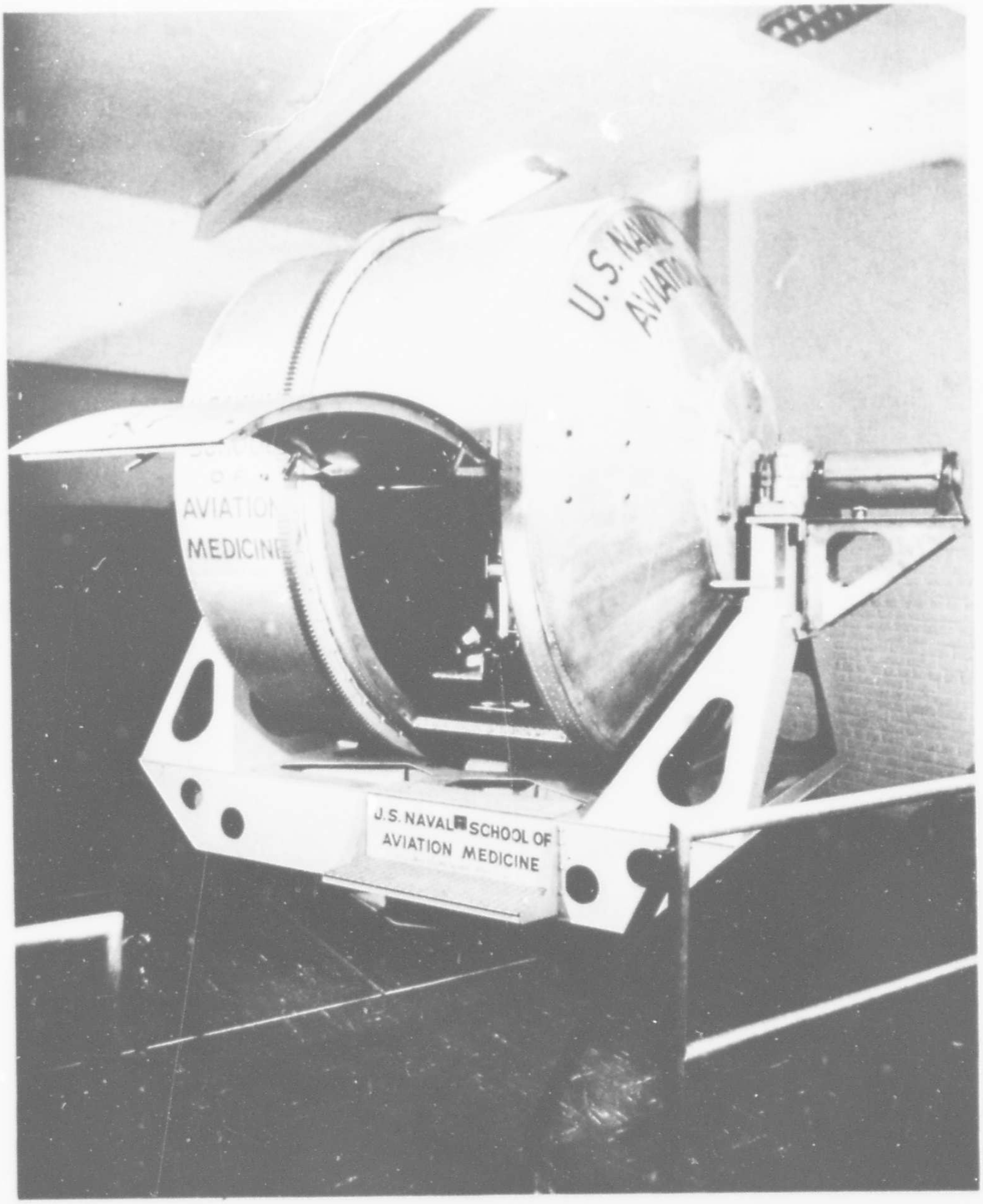

Fig. 2 Human Disorientation Device, US Naval Aerospace Medical Institute, US Naval Aerospace Medical Center, US Naval Air Training Command, Pensacola, Florida, USA

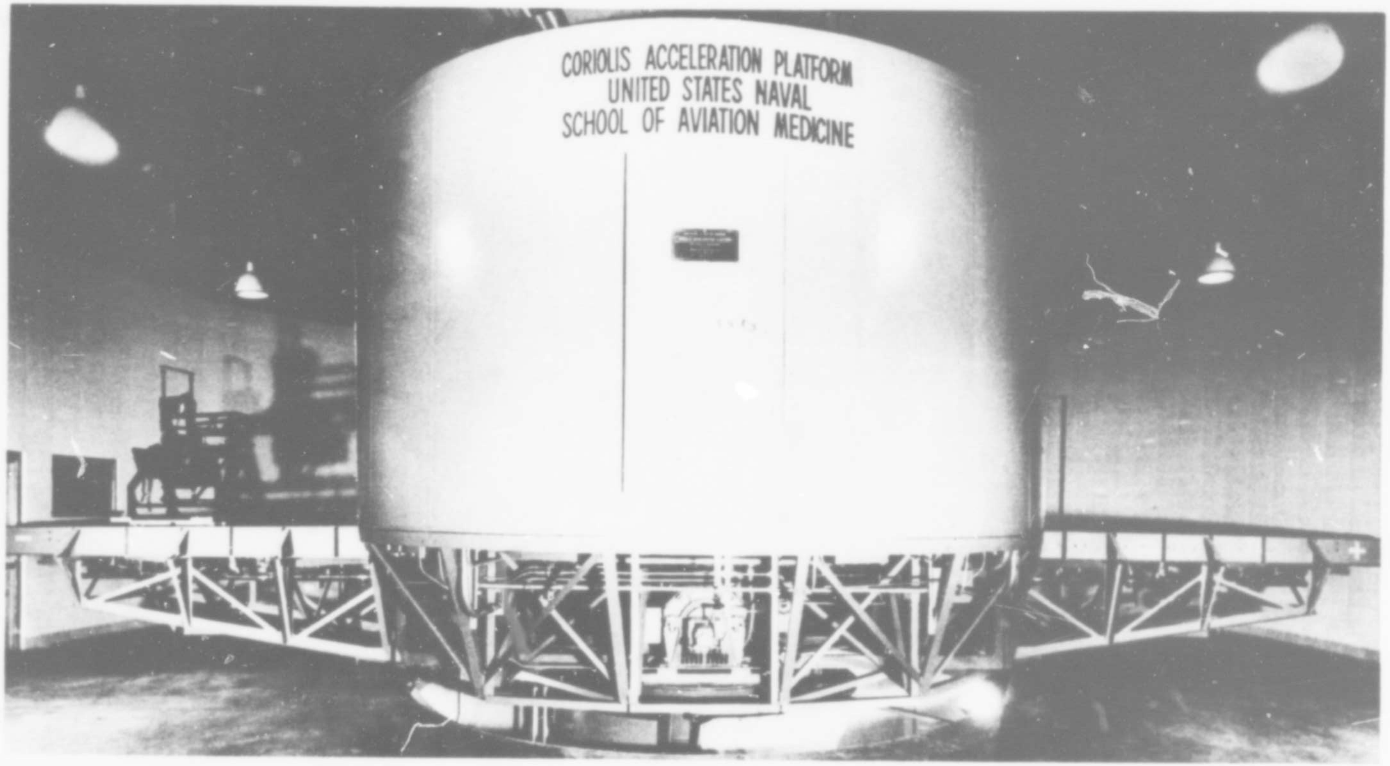

Fig.3 Coriolis Acceleration Platform, US Naval Aerospace Medical Institute, US Naval Aerospace Medical Center, US Naval Air Training Command, Pensacola, Florida, USA

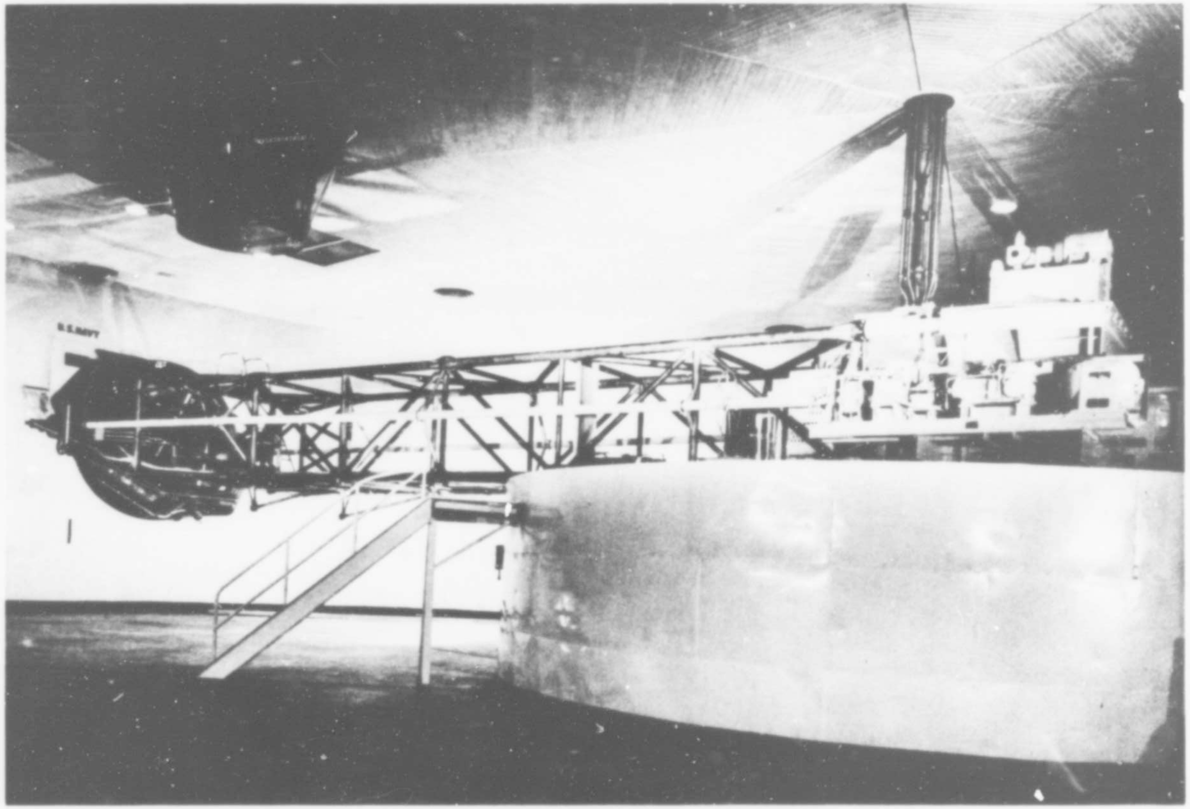

Fig. 4 Dynamic Flight Simulator (Human Centrifuge Computer Complex). View of the centrifuge showing gondola, arm, gimbal motors and 4000 hp drive motor housing. Slip ring conductors lead up from the motor to the floor above. Aerospace Medical Research Department, US Naval Air Development Center, Johnsville, Warminster, Pennsylvania, USA

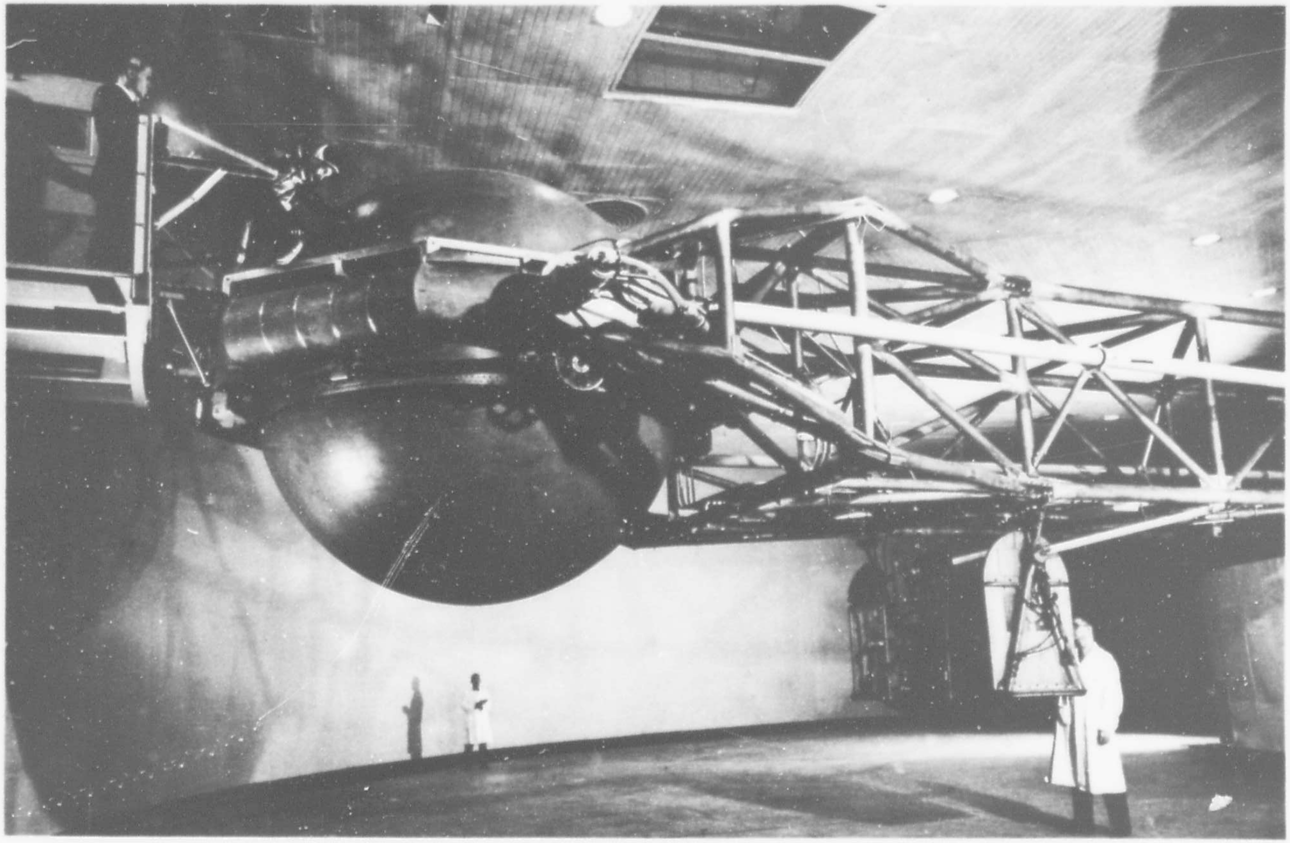

Fig. 5 Human Centrifuge of the Dynamic Flight Simulator, showing gondola, gimbal system free swinging platform and entry platform.
Aerospace Medical Research Department, US Naval Air Development Center, Johnsville, Warminster, Pennsylvania, USA

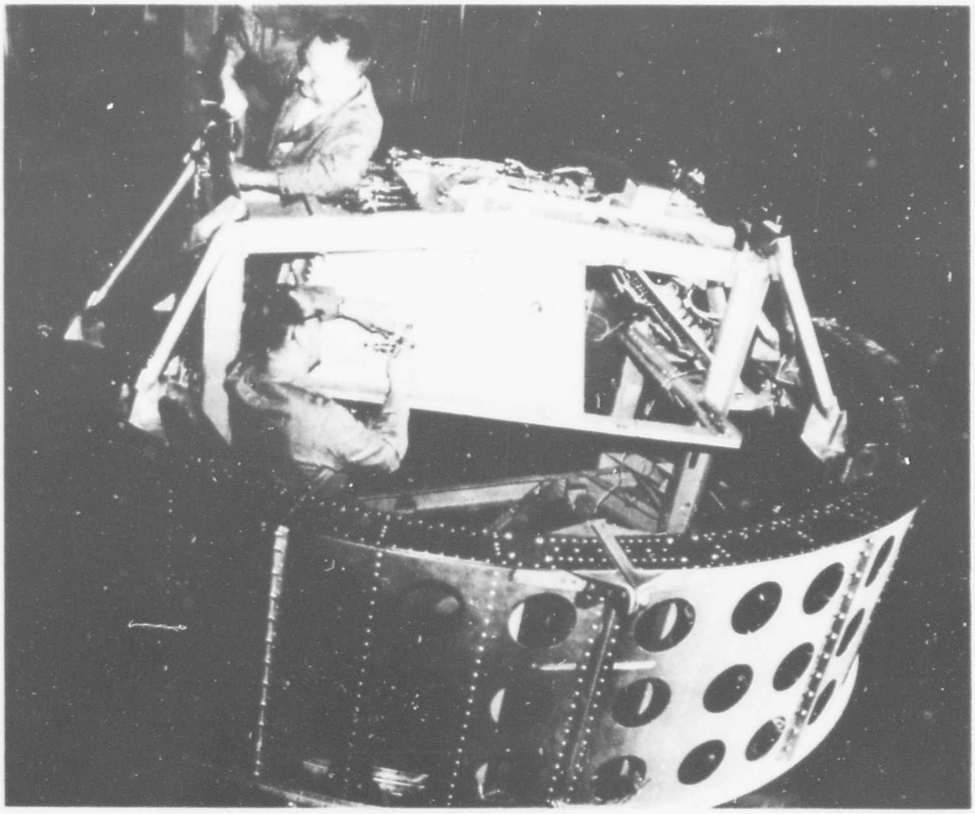

Fig.6 Ground Installation Fixture, Aerospace Medical Research Department, US Naval Air Development Center, Johnsville, Warminster, Pennsylvania, USA

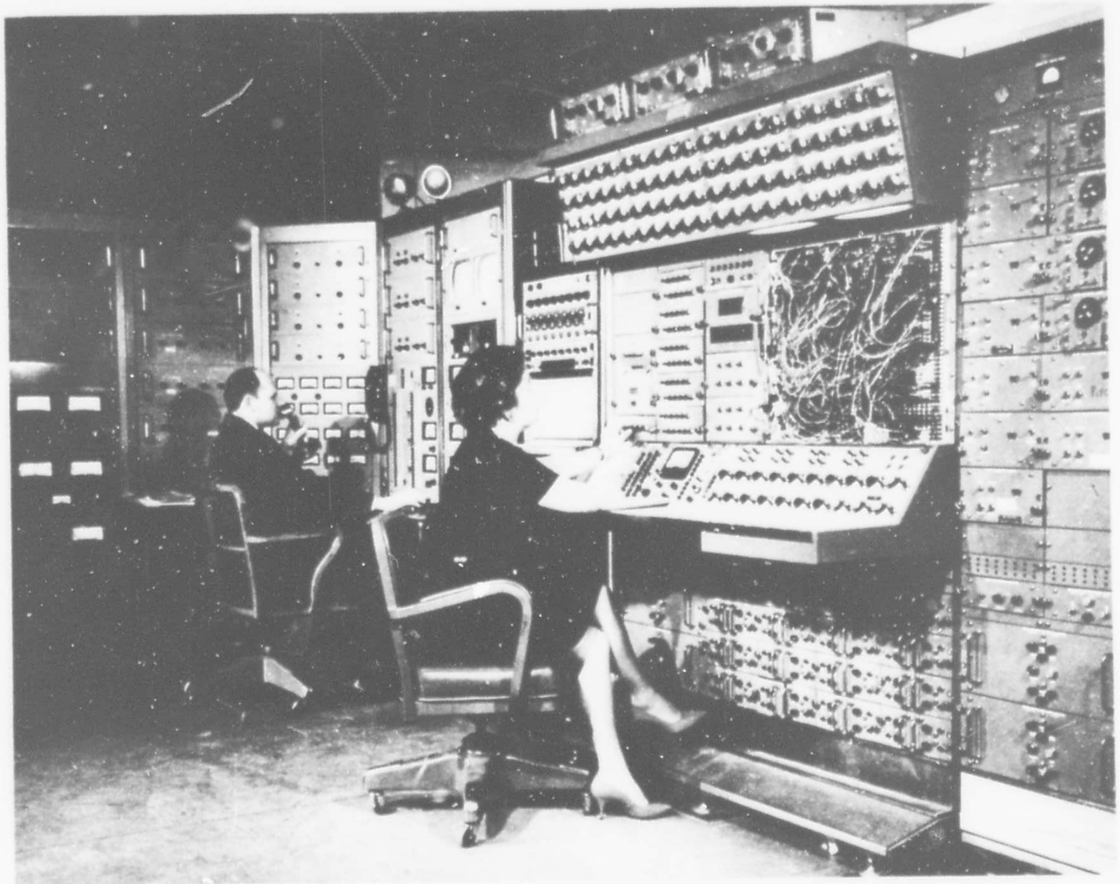

Fig.7 Human Centrifuge Control Centre, Aerospace Medical Research Department, US Naval Air Development Center, Johnsville, Warminster, Pennsylvania, USA

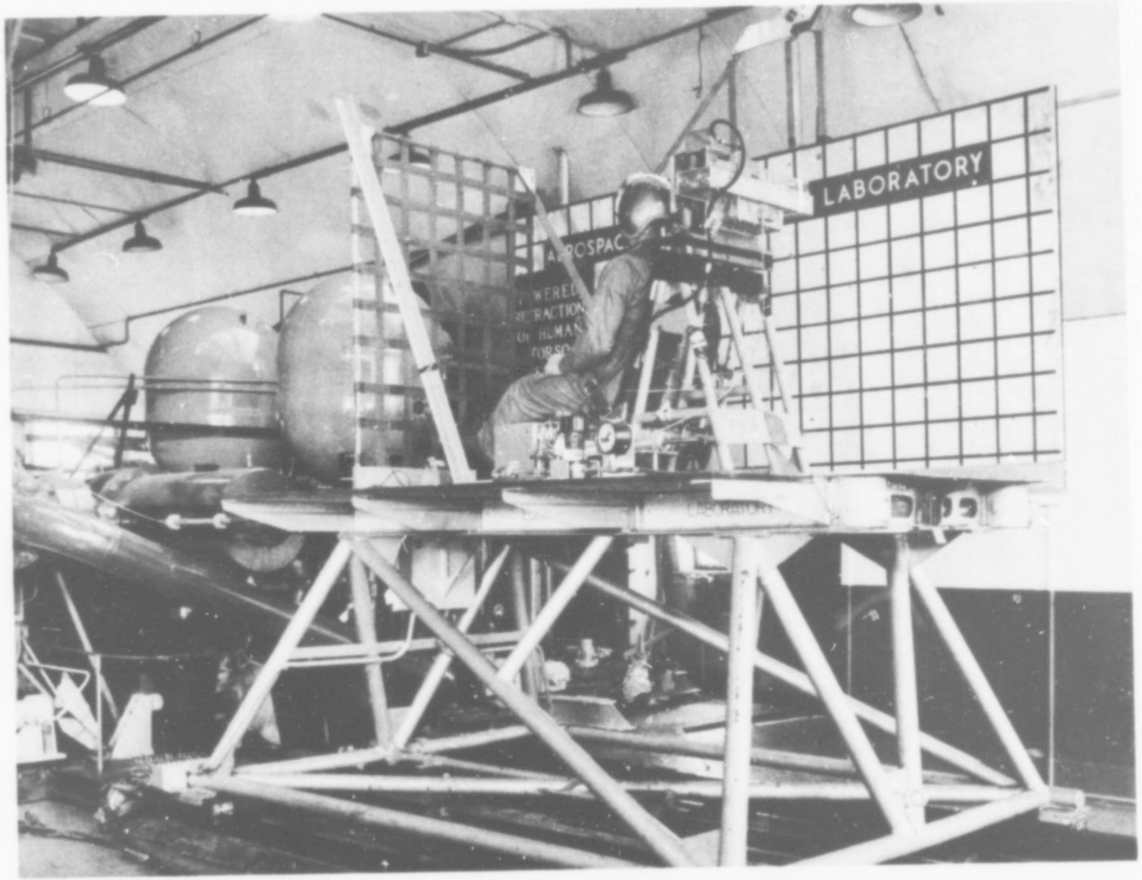

Fig.8 The HG-1 Catapult System, showing compressed air propulsive system and the passenger's cart and seat. Aerospace Crew Equipment Laboratory, US Naval Air Engineering Center, Philadelphia, Pennsylvania, USA

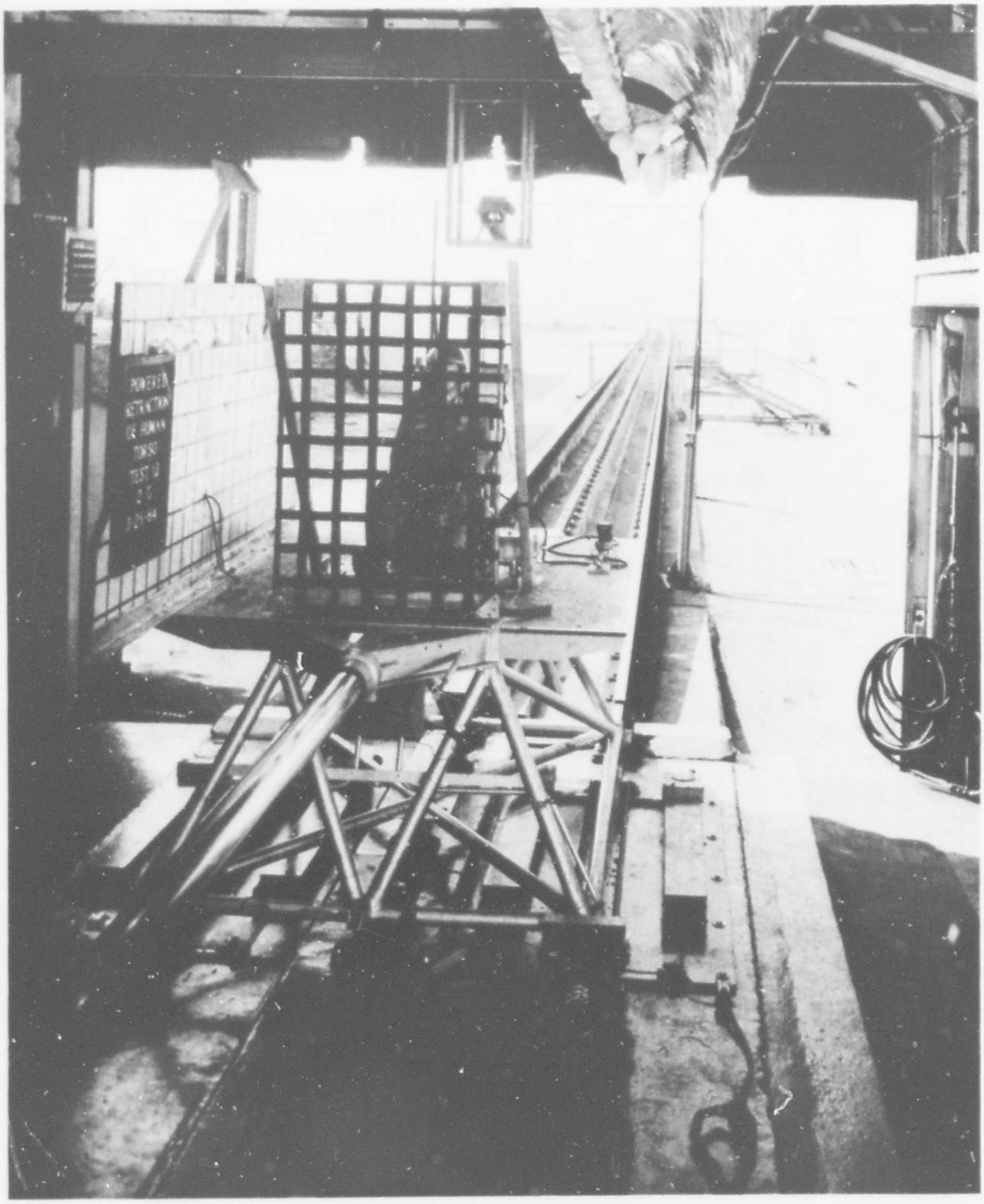

Fig. 9 The HG-1 Catapult System, showing track, car and passenger configuration. Aerospace Crew Equipment Laboratory, US Naval Air Engineering Center, Philadelphia, Pennsylvania, USA

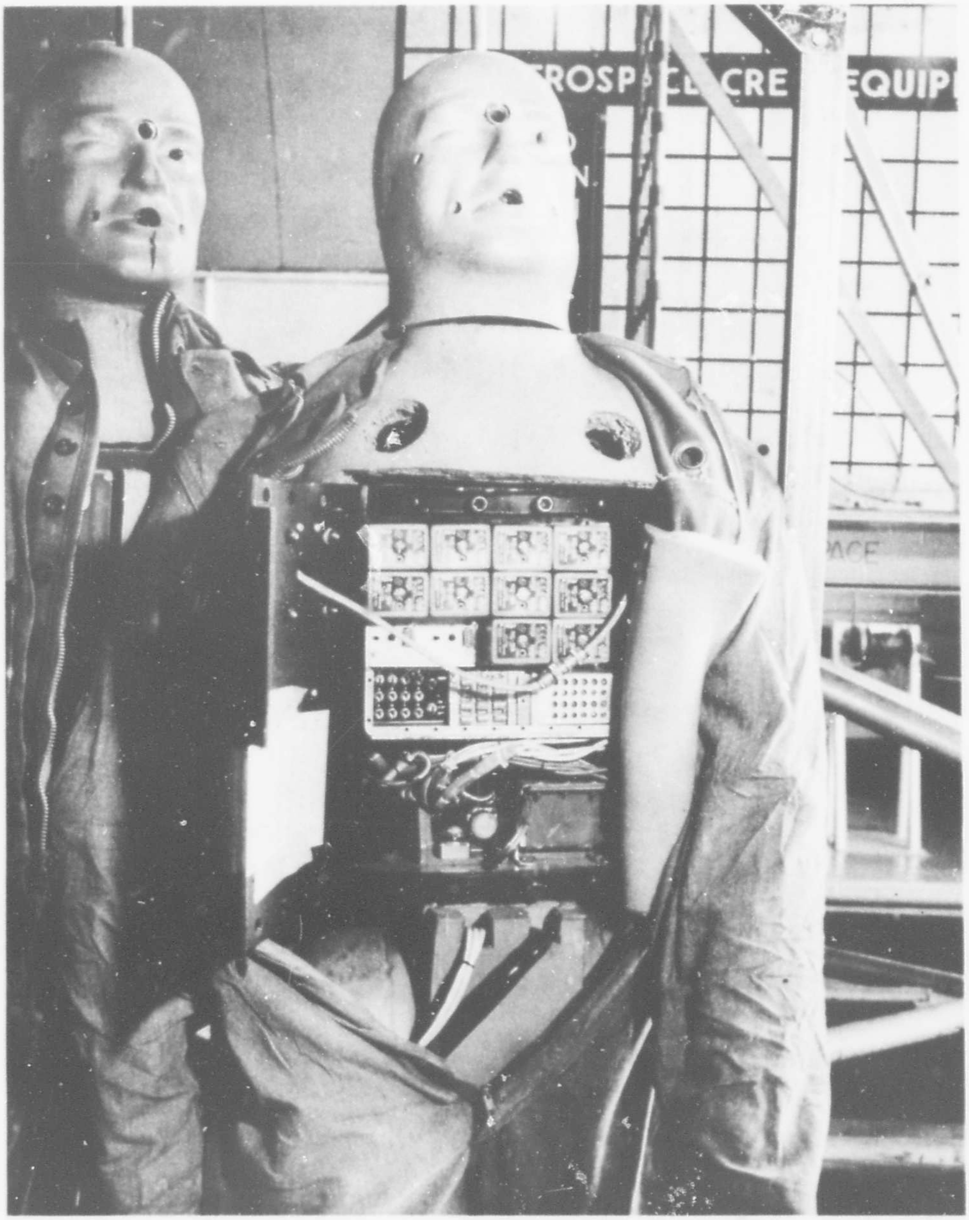

Fig.10 Instrumented anthropomorphic dummies used on the acceleration research facilities. Aerospace Crew Equipment Laboratory, US Naval Air Engineering Center, Philadelphia, Pennsylvania, USA

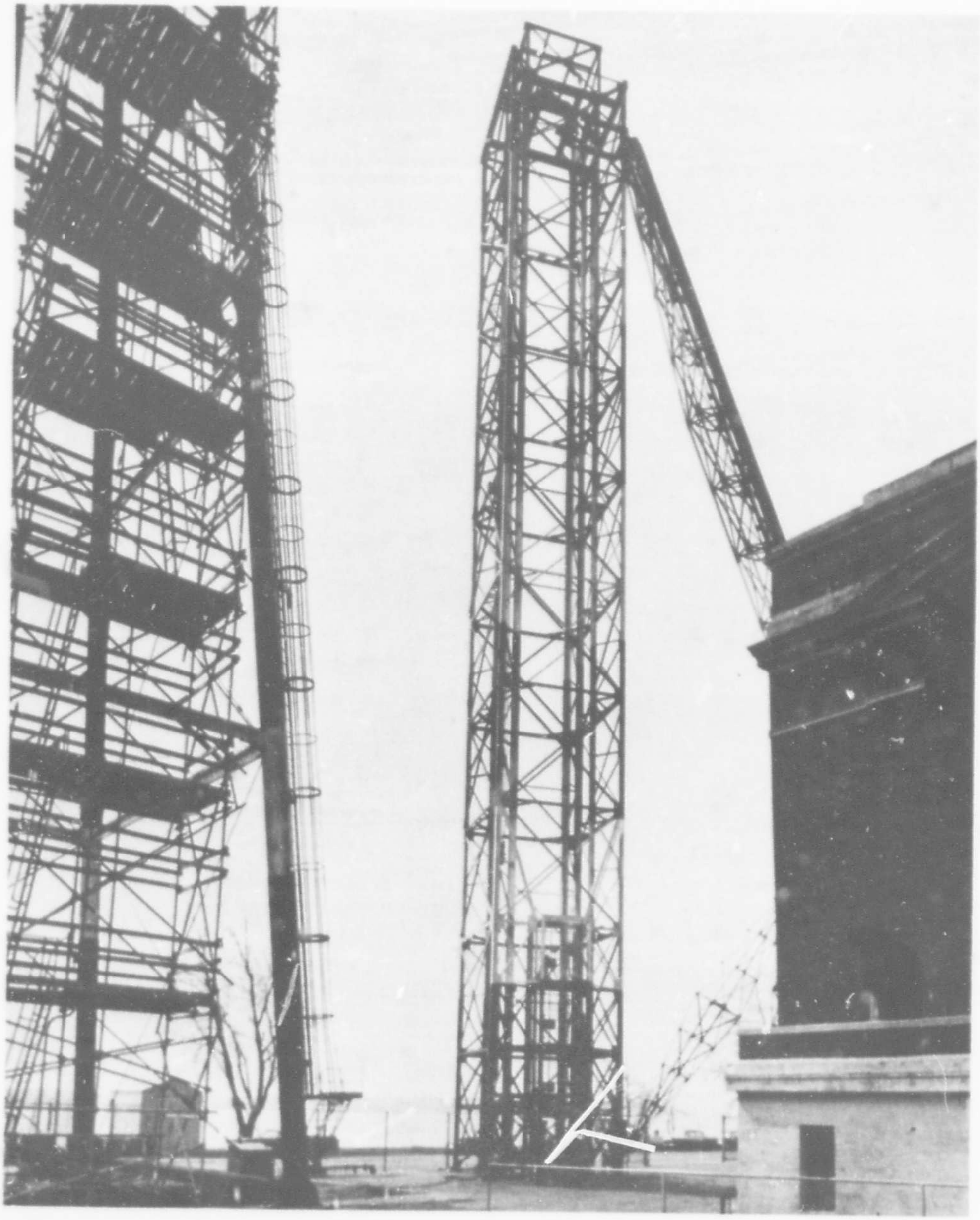

Fig. 11 Drop Tower Facility in foreground with Ejection Seat Facility in the background. Aerospace Crew Equipment Laboratory, US Naval Air Engineering Center, Philadelphia, Pennsylvania, USA

Fig.12 Ejection Seat Facility in the foreground and Drop Tower located between it and the water tower. Aerospace Crew Equipment Laboratory, US Naval Air Engineering Center, Philadelphia, Pennsylvania, USA

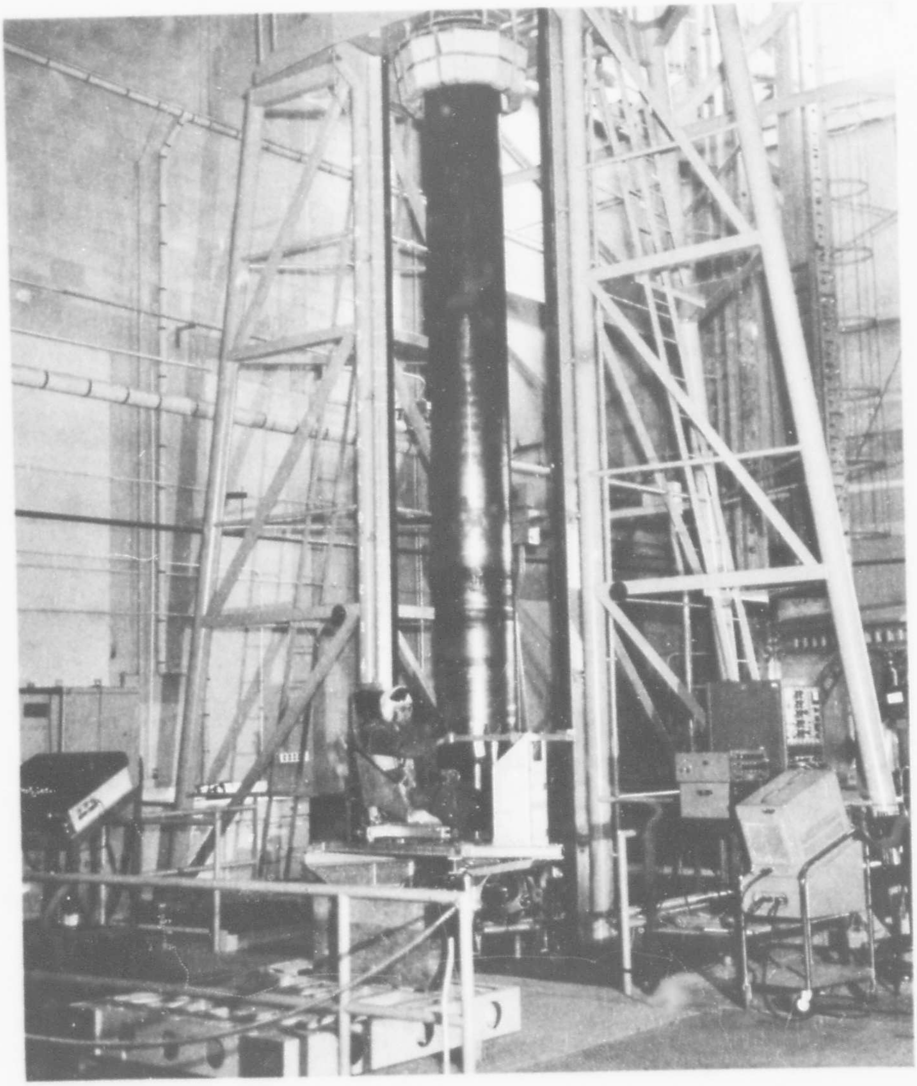

Fig. 13 Vertical Accelerator Tower, peak versus root-mean-square study configuration. 6570th Aerospace Medical Research Laboratories, Air Force Systems Command, Wright-Patterson Air Force Base, Ohio, USA

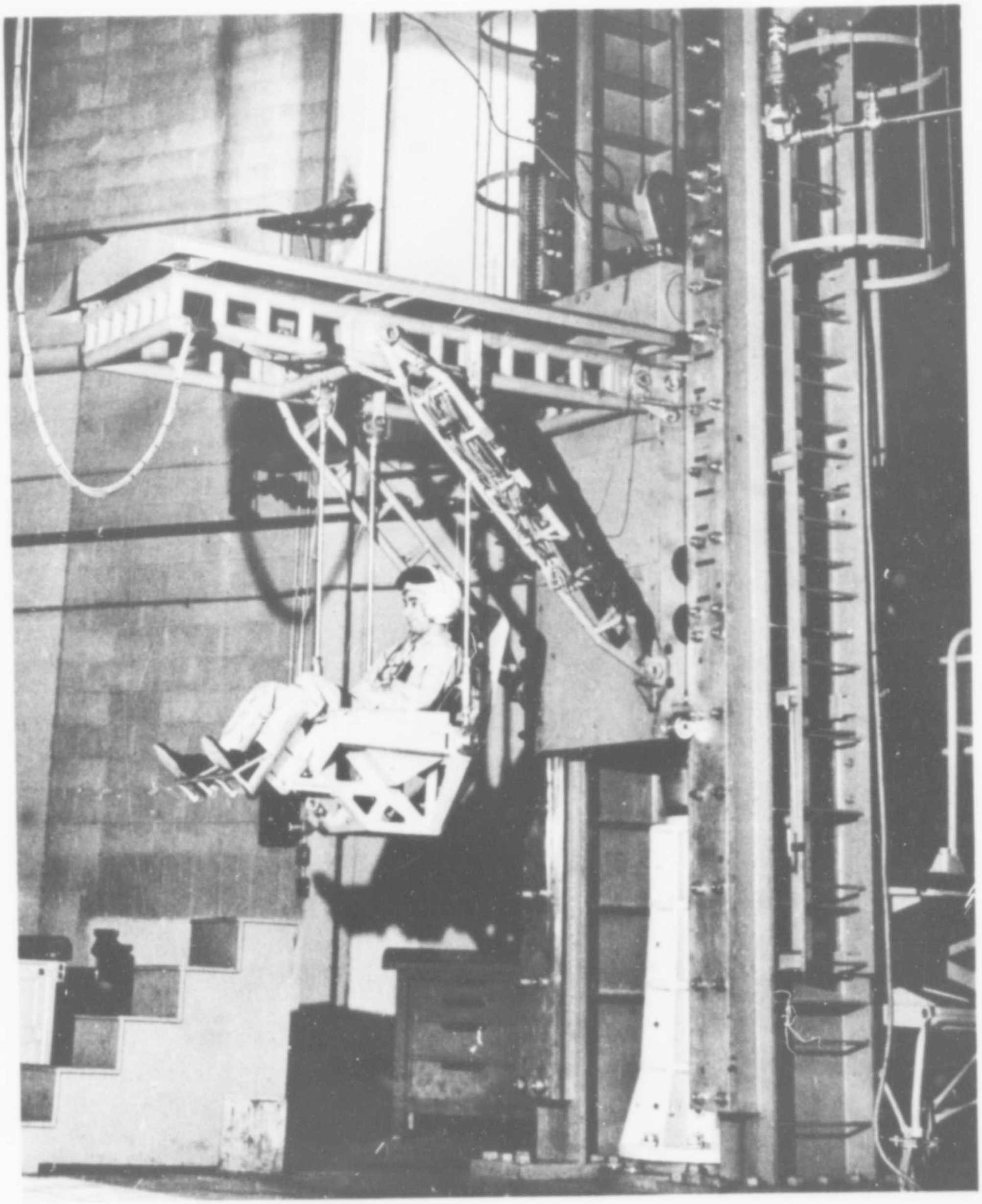

Fig. 14 Vertical Acceleration Tower, subject seated in Gemini seat. 6570th Aerospace Medical Research Laboratories, Air Force Systems Command, Wright-Patterson Air Force Base, Ohio, USA

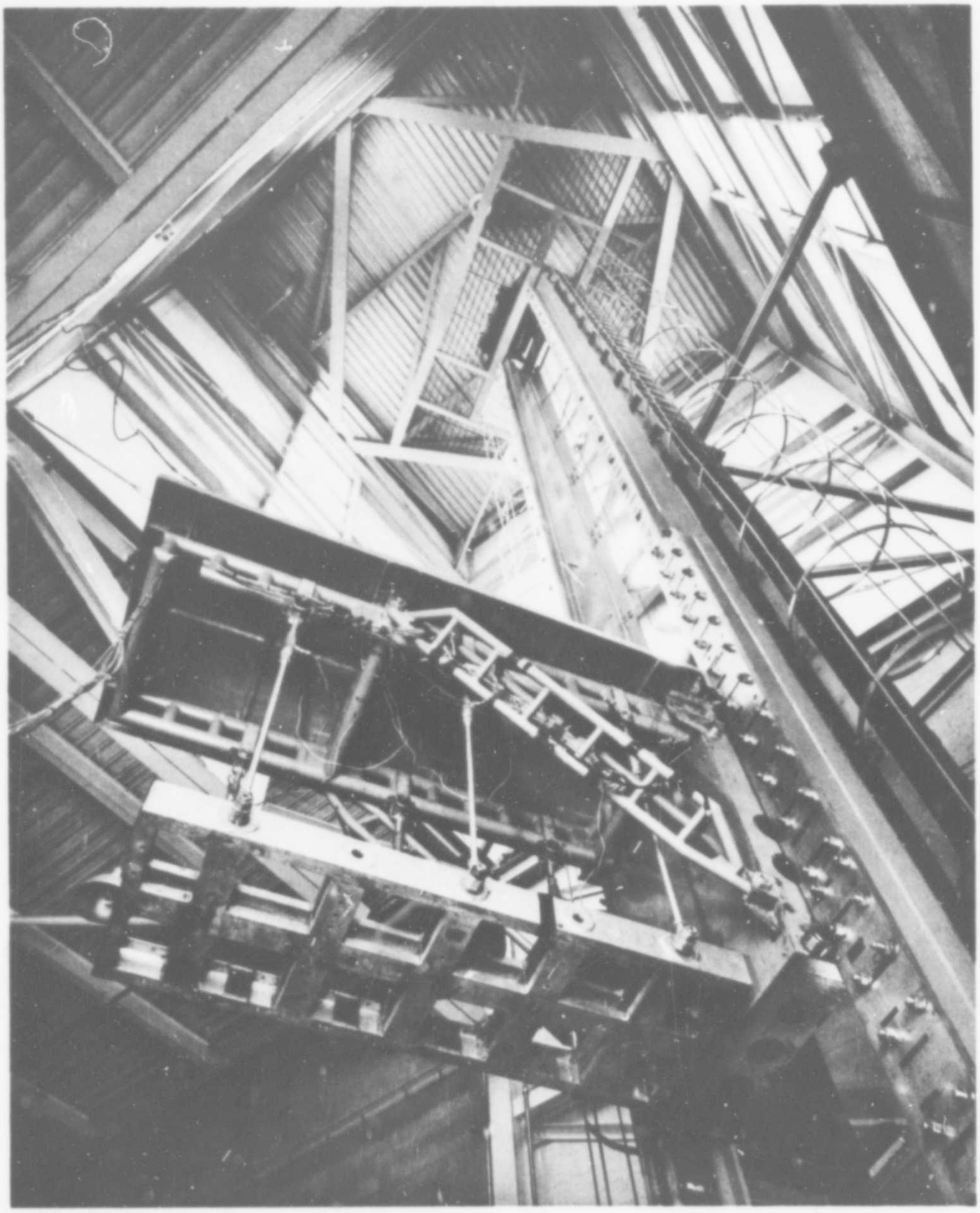

Fig.15 Vertical Acceleration Tower, view looking toward top. 6570th Aerospace Medical Research Laboratories, Air Force Systems Command, Wright-Patterson Air Force Base, Ohio, USA

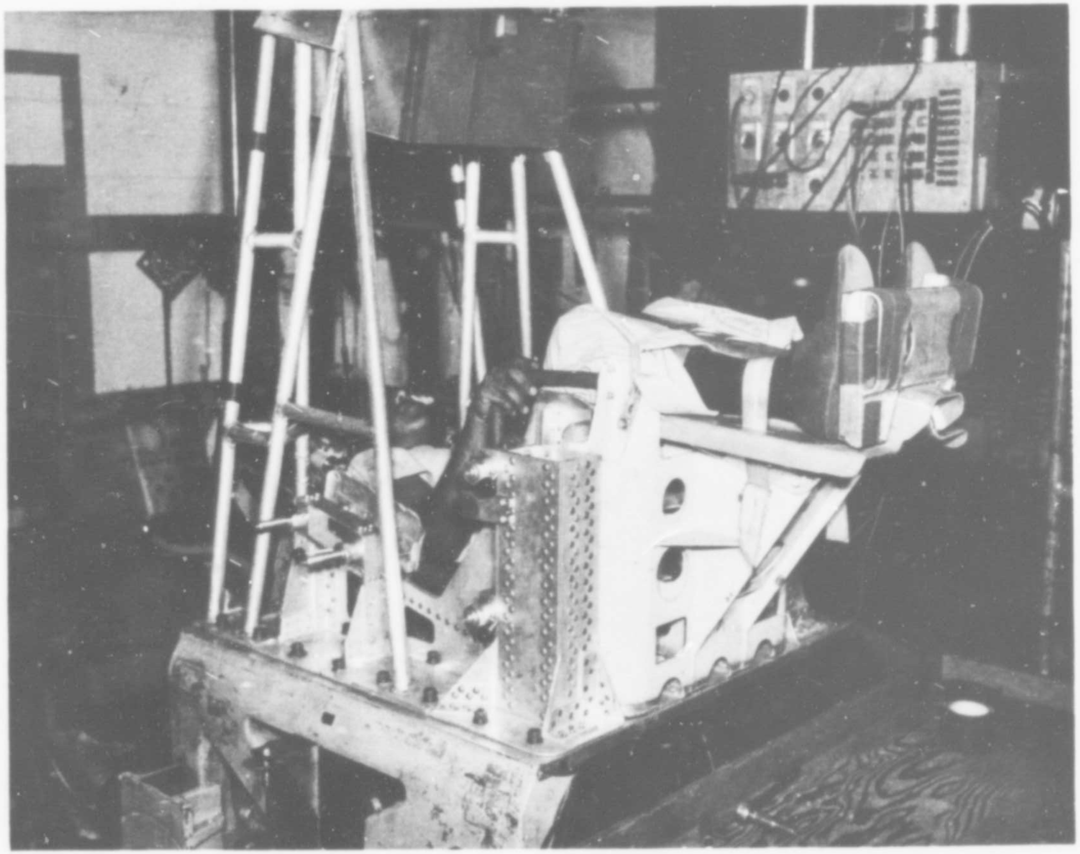

Fig. 16 Western Gear Vibration Machine, visual acuity configuration. 6570th Aerospace Medical Research Laboratories, Air Force Systems Command, Wright-Patterson Air Force Base, Ohio, USA

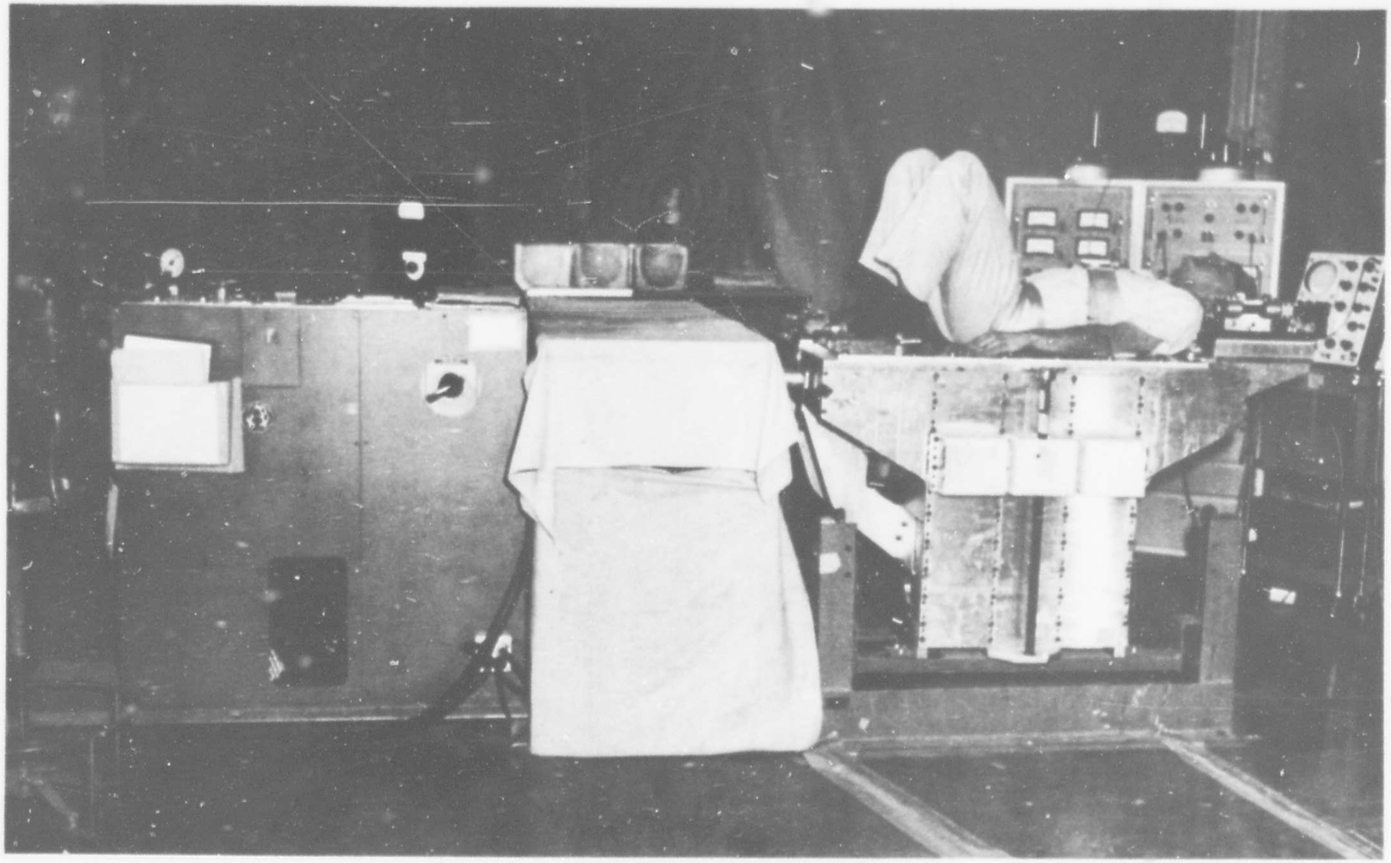

Fig. 17 Vibration Test Stand, head transmission study configuration.
6570th Aerospace Medical Research Laboratories,
Air Force Systems Command, Wright-Patterson Air Force Base,
Ohio, USA

Fig. 18 Daisy Decelerator, 6571st Aeromedical Research Laboratory, Air Force Systems Command, Holloman Air Force Base, New Mexico, USA

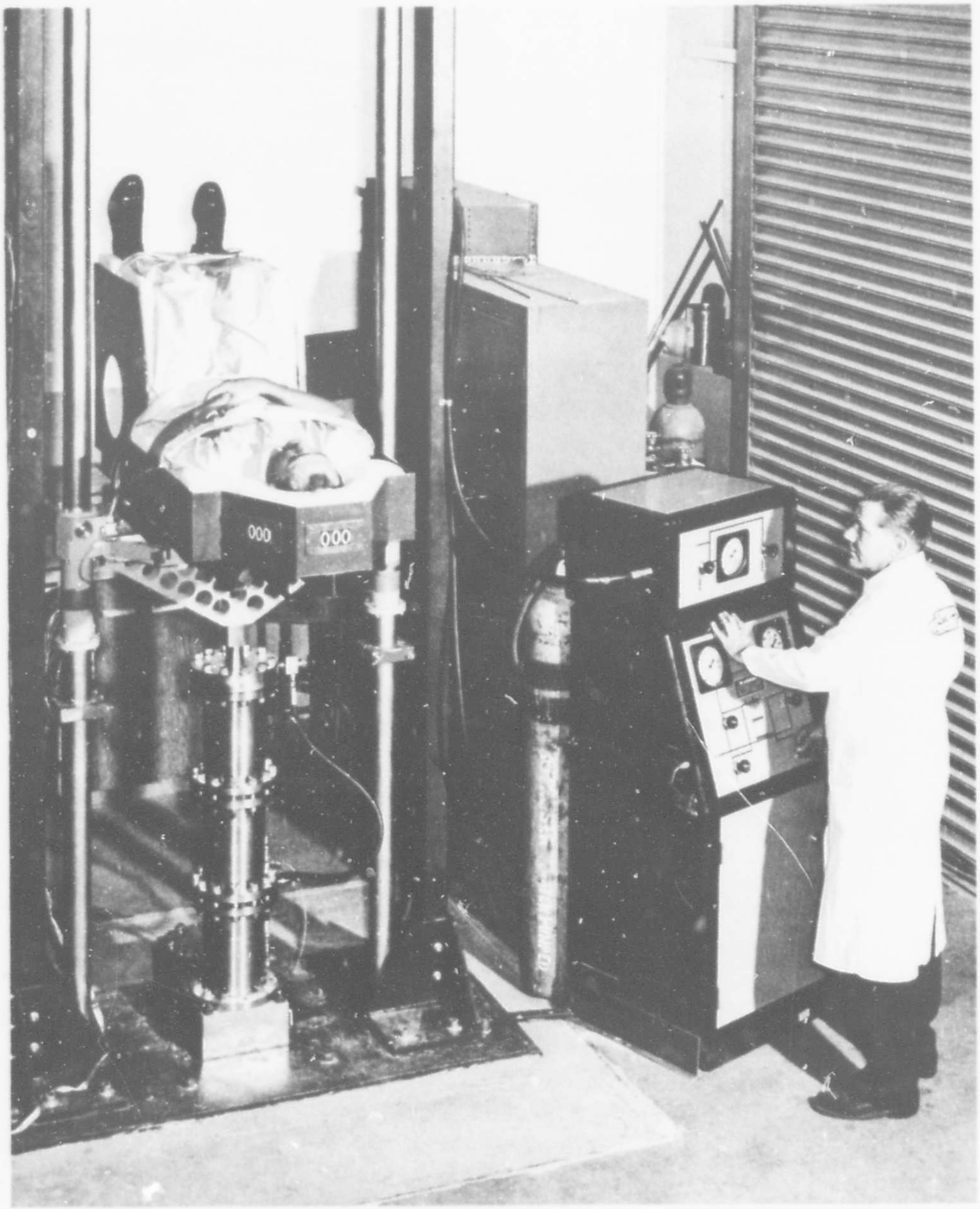

Fig. 19 HYGE Accelerator, 6571st Aeromedical Research Laboratory, Air Force Systems Command, Holloman Air Force Base, New Mexico, USA

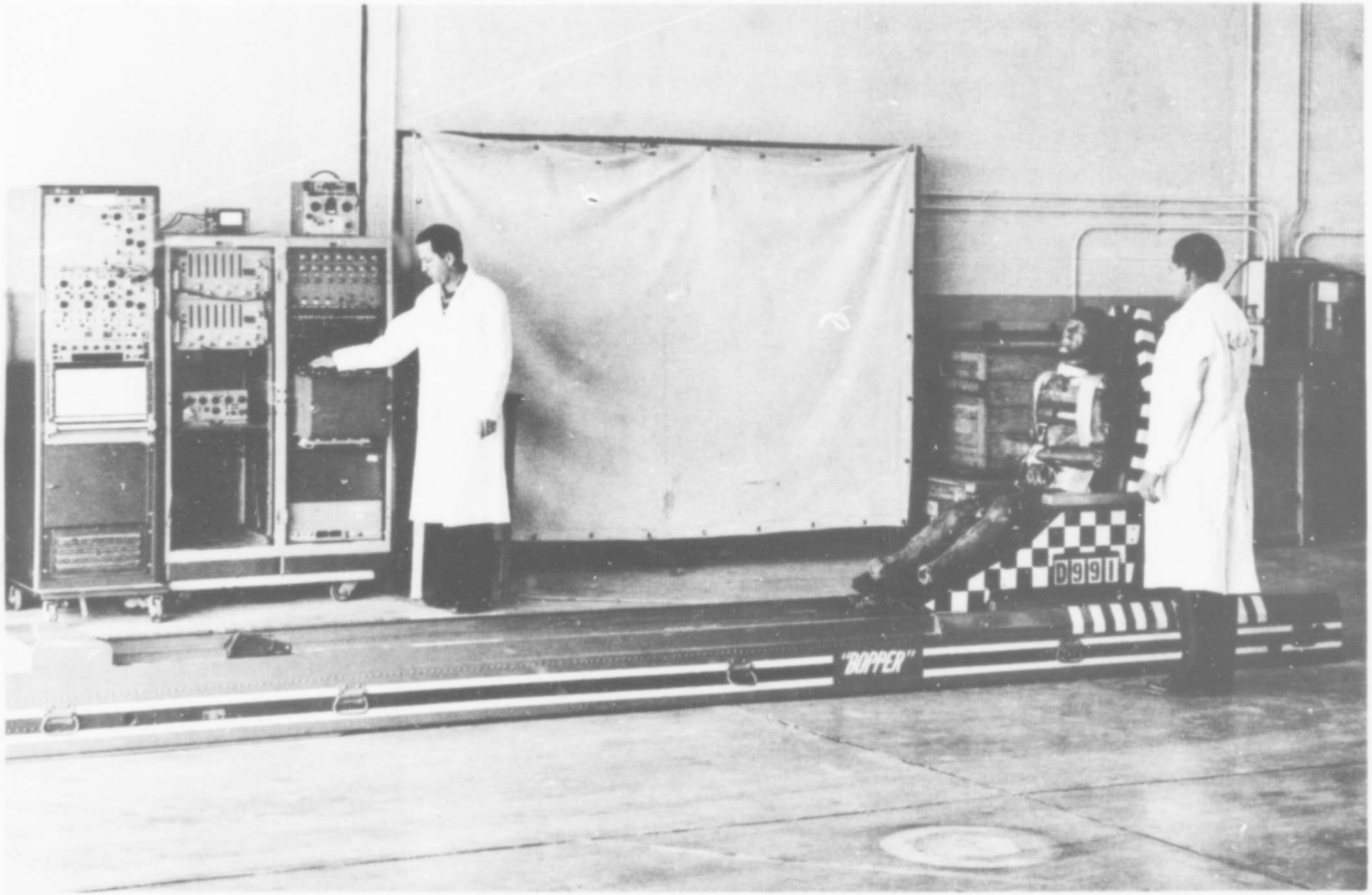

Fig. 20 Bopper Crash Restraint Demonstrator, 6571st Aeromedical Research Laboratory, Air Force Systems Command, Holloman Air Force Base, New Mexico, USA

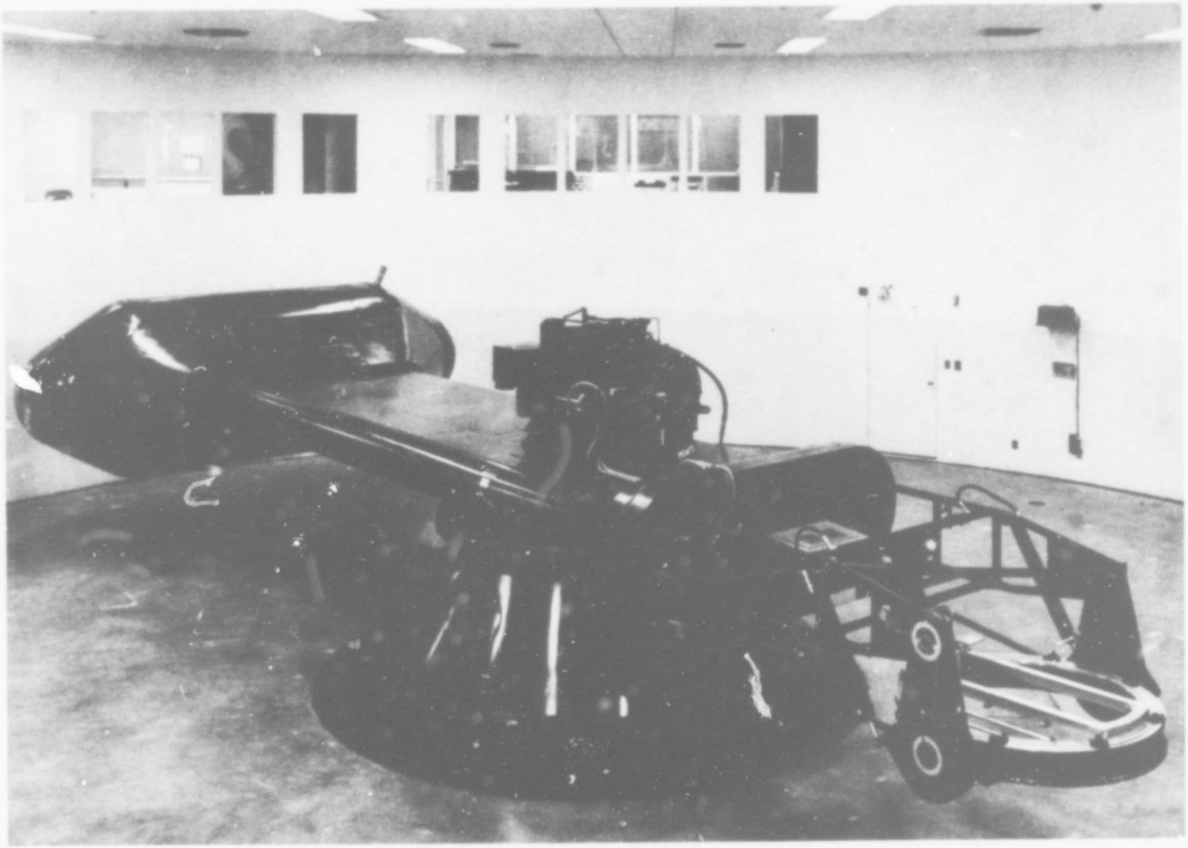

Fig. 21 Human Centrifuge showing mounted Two-Man Gondola. Large Animal Acceleration Stress Platform at the opposite end of the arm. US Air Force School of Aerospace Medicine, Air Force Systems Command, Brooks Air Force Base, Texas, USA

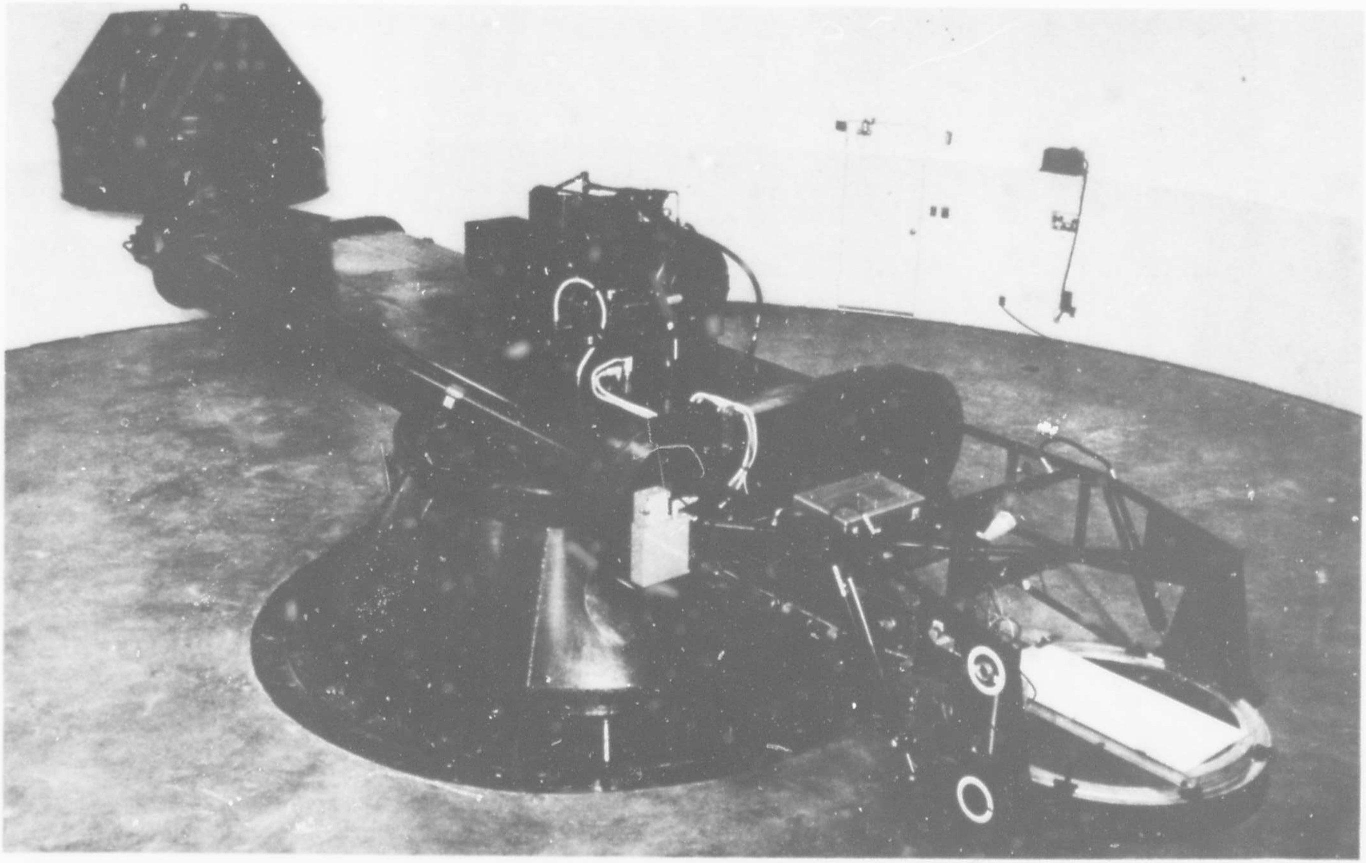

Fig. 22 Human and Animal Centrifuge, showing the Mounted Spin Capsule in place of the Two-Man Gondola. US Air Force School of Aerospace Medicine, Air Force Systems Command, Brooks Air Force Base, Texas, USA

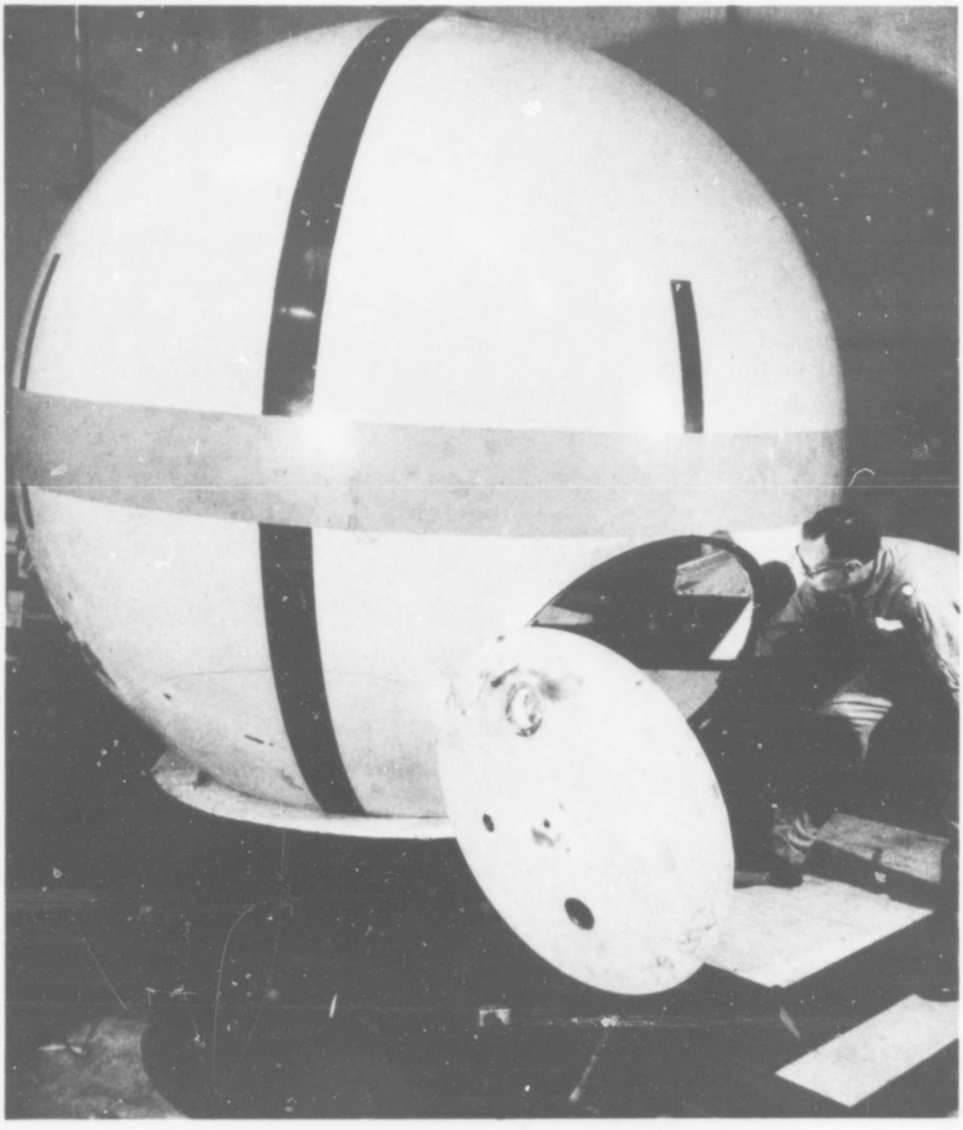

Fig. 23 Rotational Flight Simulator, US Air Force School of Aerospace Medicine, Air Force Systems Command, Brooks Air Force Base, Texas, USA

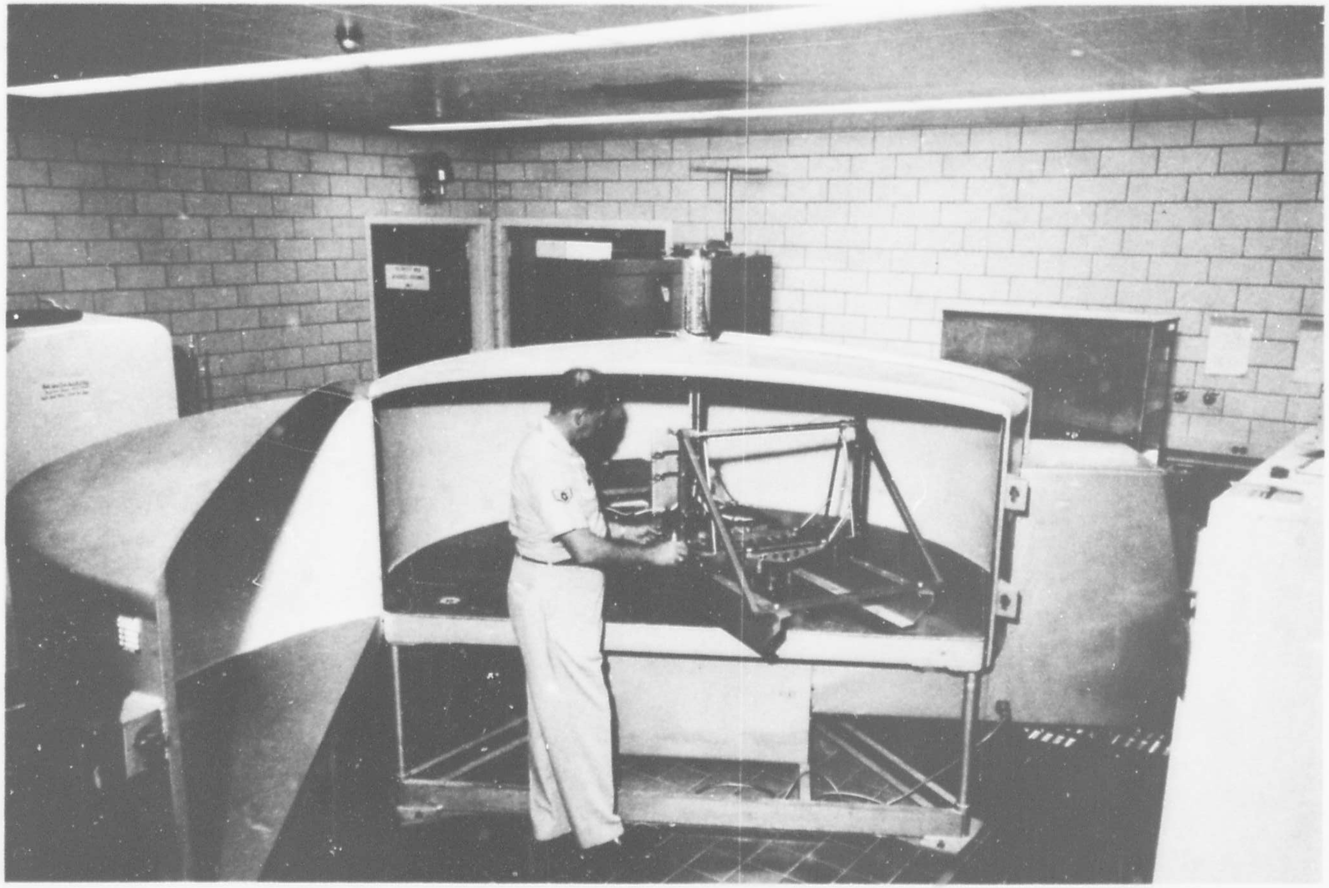

Fig. 24 Small Animal Centrifuge, US Air Force School of Aerospace Medicine, Air Force Systems Command, Brooks Air Force Base, Texas, USA

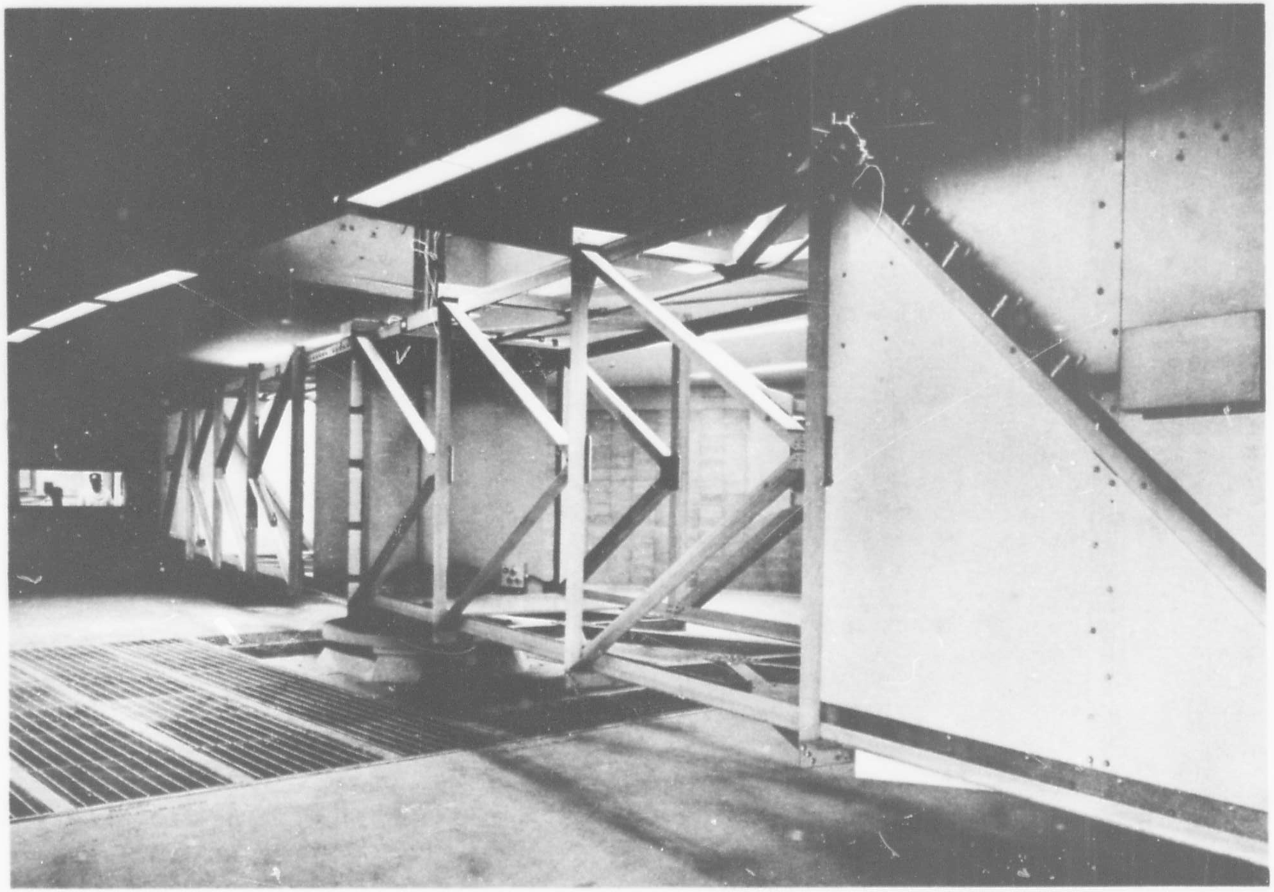

Fig. 25 Biosatellite Centrifuge, Ames Research Center, National Aeronautics and Space Administration, Moffett Field, California, USA

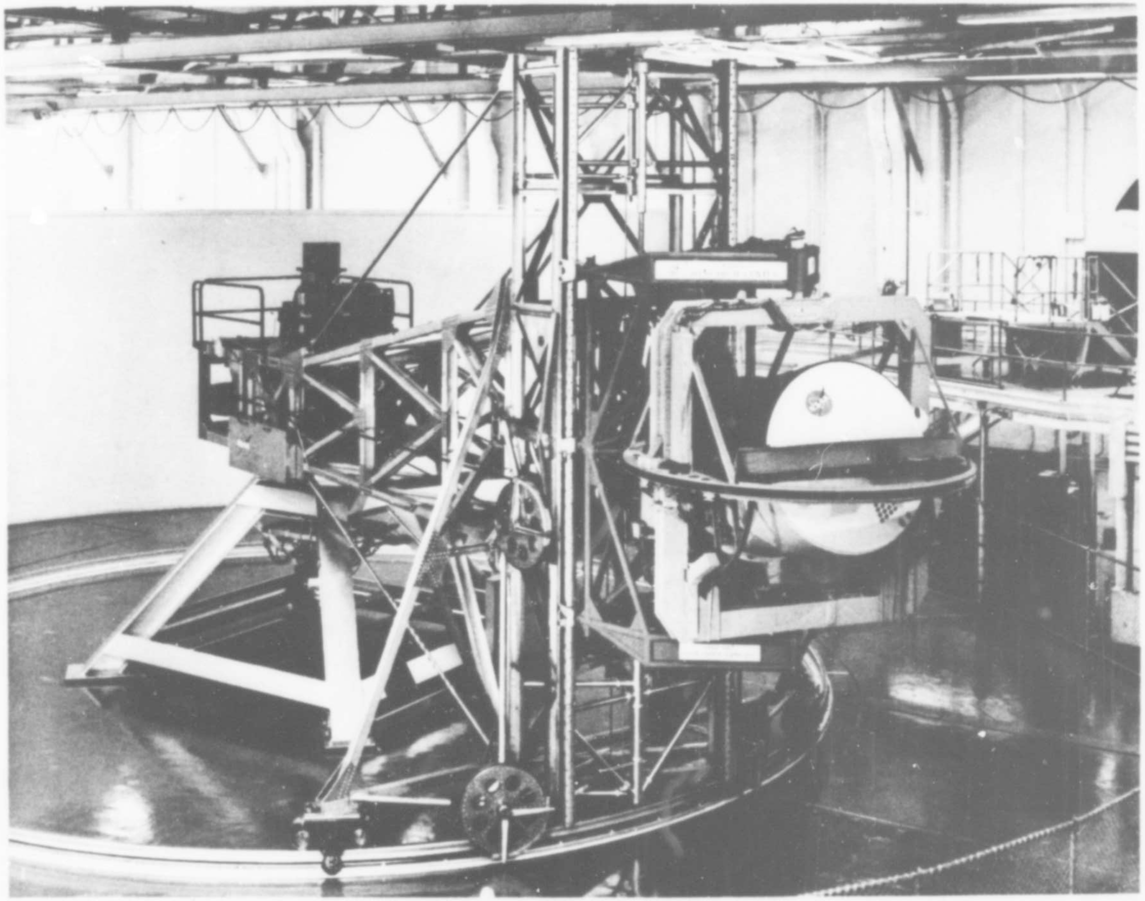

Fig. 26 Five-Degree-of-Freedom Simulator, Ames Research Center, National Aeronautics and Space Administration, Moffett Field, California, USA

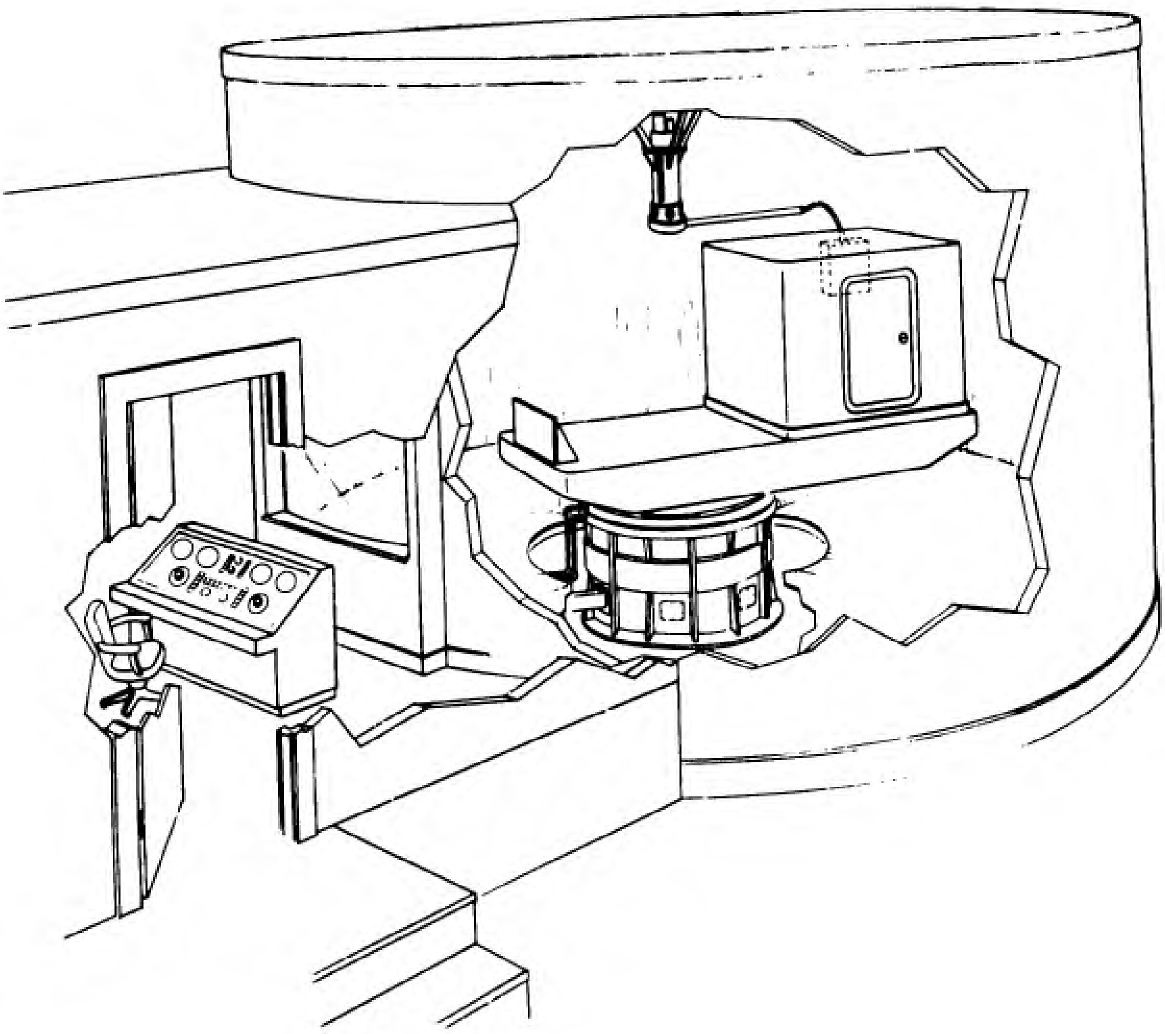

Fig.27 Man-Carrying Motion Generator, Ames Research Center, National Aeronautics and Space Administration, Moffett Field, California, USA

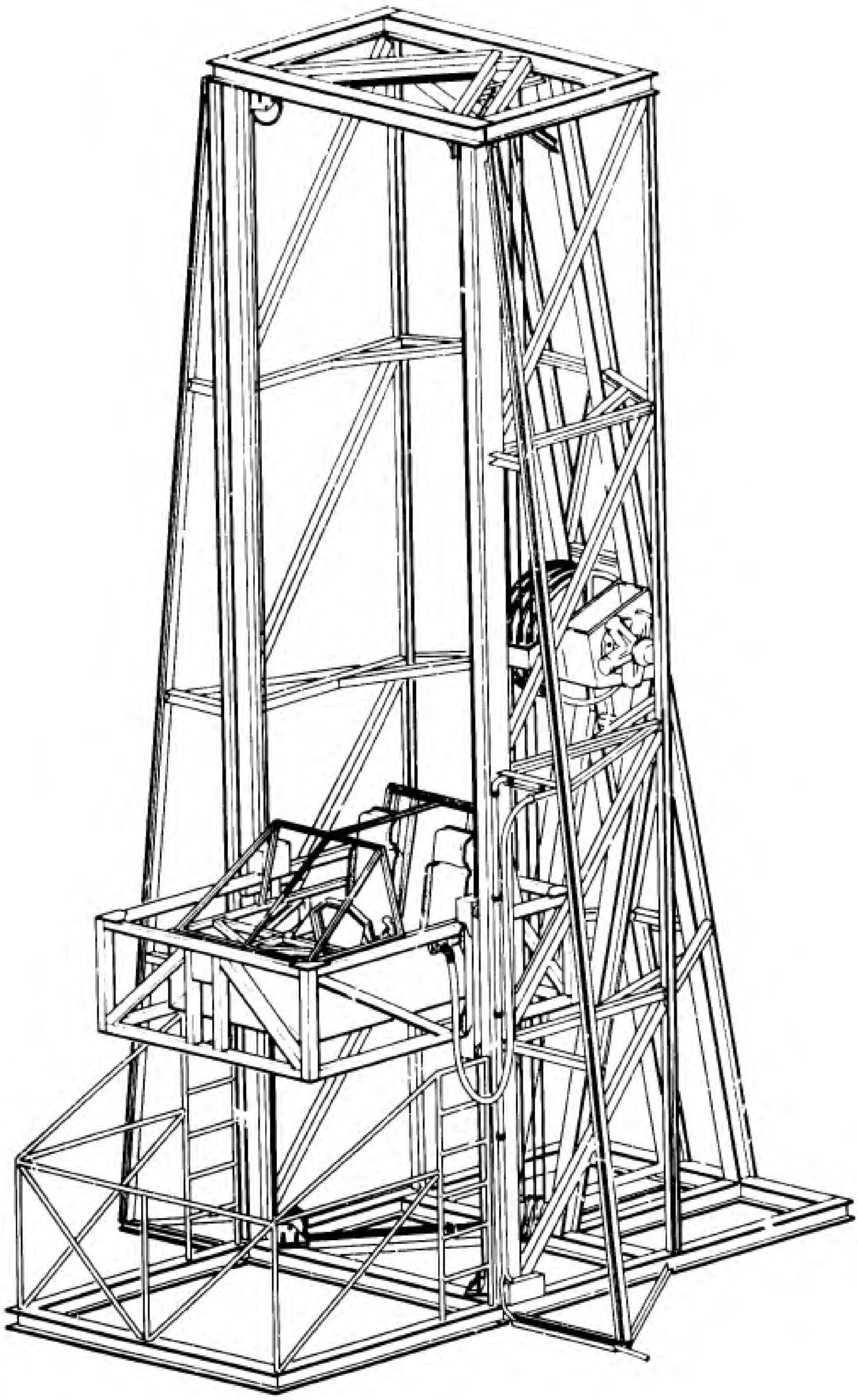

Fig. 28 Vertical Acceleration and Roll Device, Ames Research Center, National Aeronautics and Space Administration, Moffett Field, California, USA

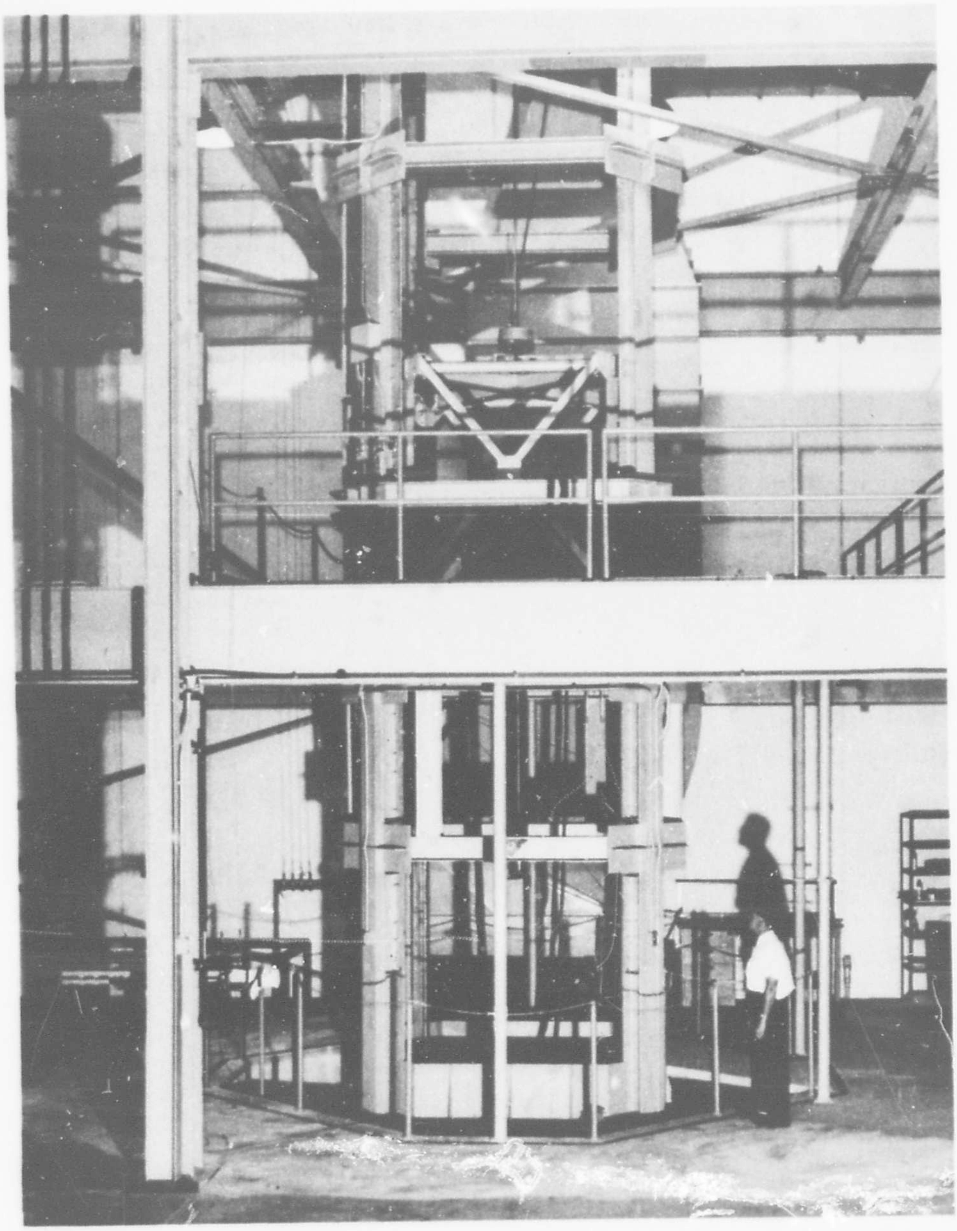

Fig. 29 General view of Impact Test Facility showing carriage above upper platform, deceleration plunger below upper platform, and perforated hydraulic cylinder pit at floor level. Manned Spacecraft Center, National Aeronautics and Space Administration, Houston, Texas, USA

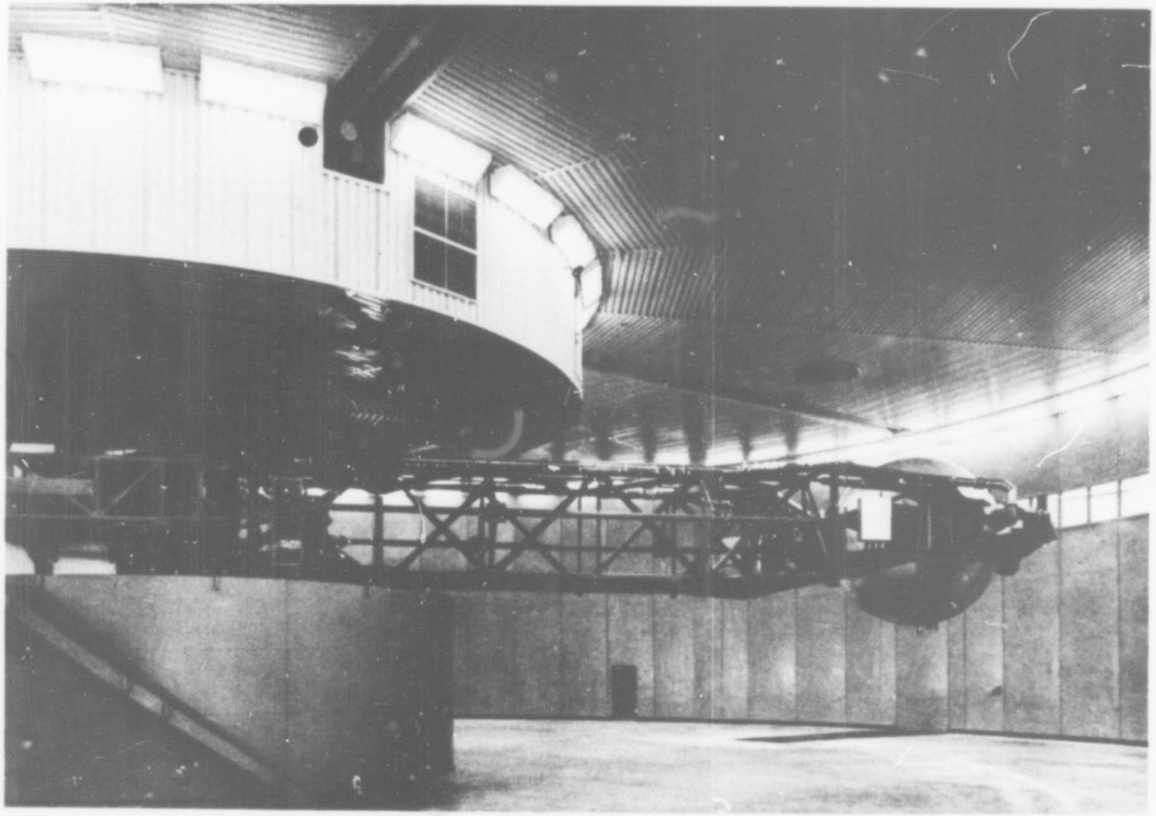

Fig. 30 Flight Acceleration Facility. Ground floor view of Centrifuge Chamber showing arm with gondola in normal position, drive motor housing below arm, and commutator room handling from ceiling. Manned Spacecraft Center, National Aeronautics and Space Administration, Houston, Texas, USA

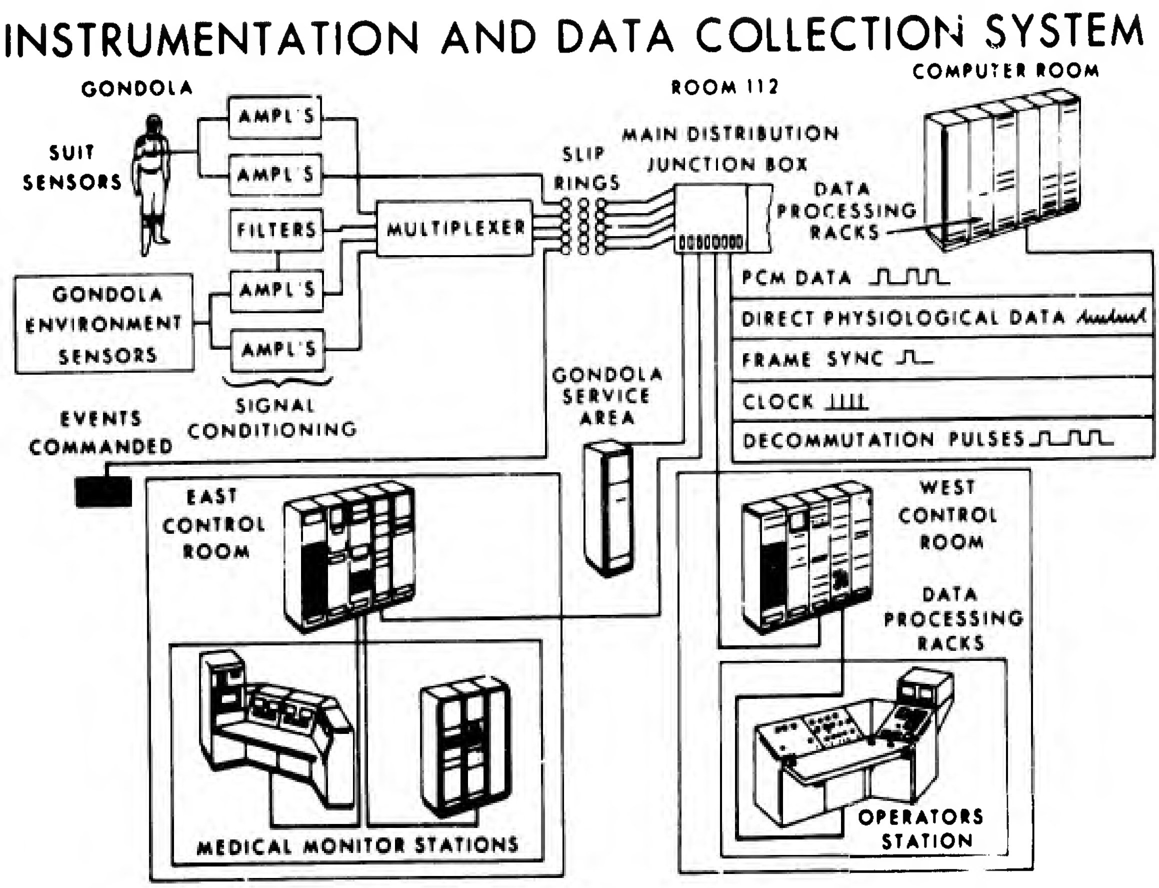

Fig. 31 Schematic representation of the distribution of information from gondola to monitors and recording systems of the Flight Acceleration Facility. Manned Spacecraft Center, National Aeronautics and Space Administration, Houston, Texas, USA

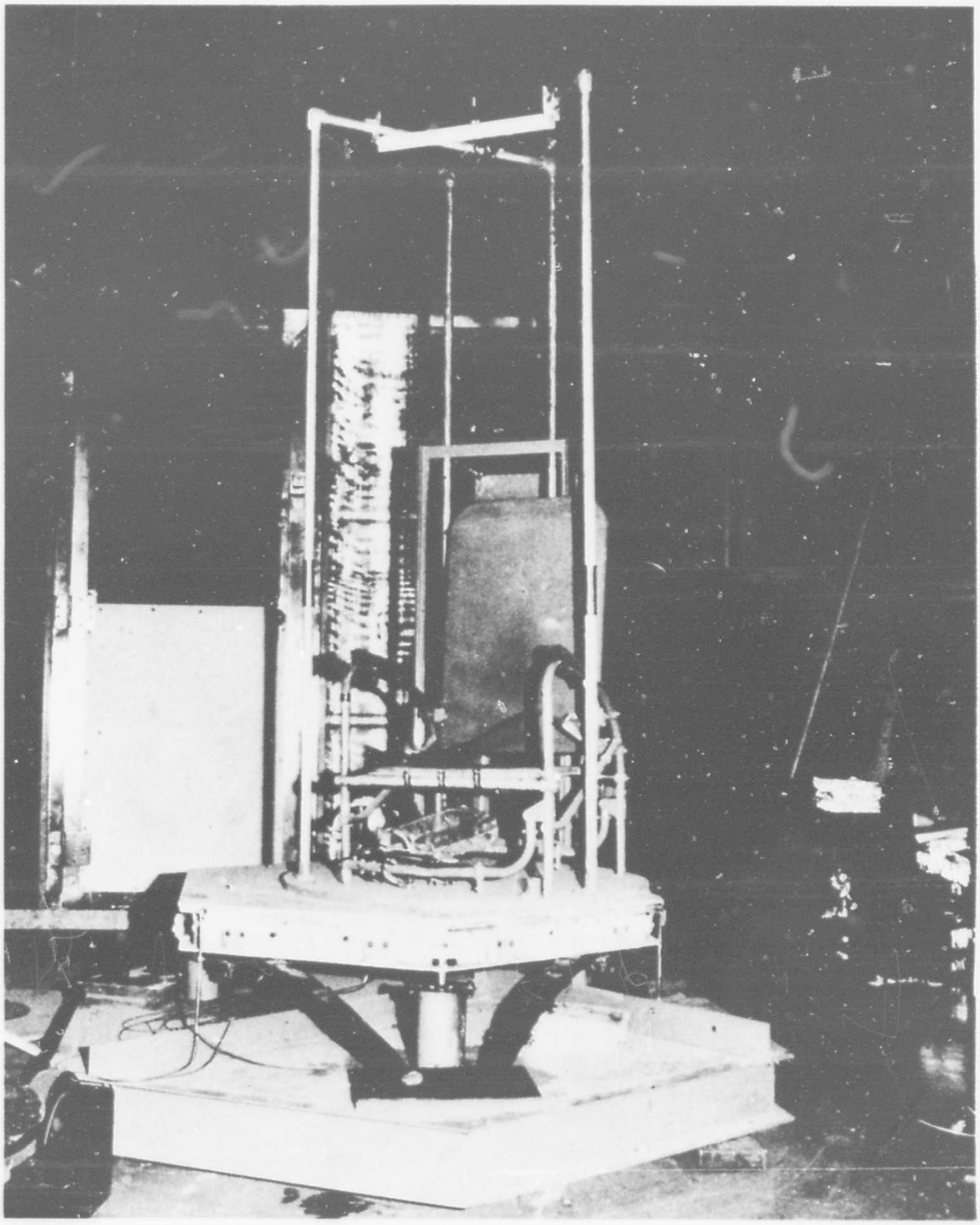

Fig.32 Drop Test Apparatus, Civil Aeromedical Institute, Federal Aviation Agency, Aeronautical Center, Oklahoma City, Oklahoma, USA

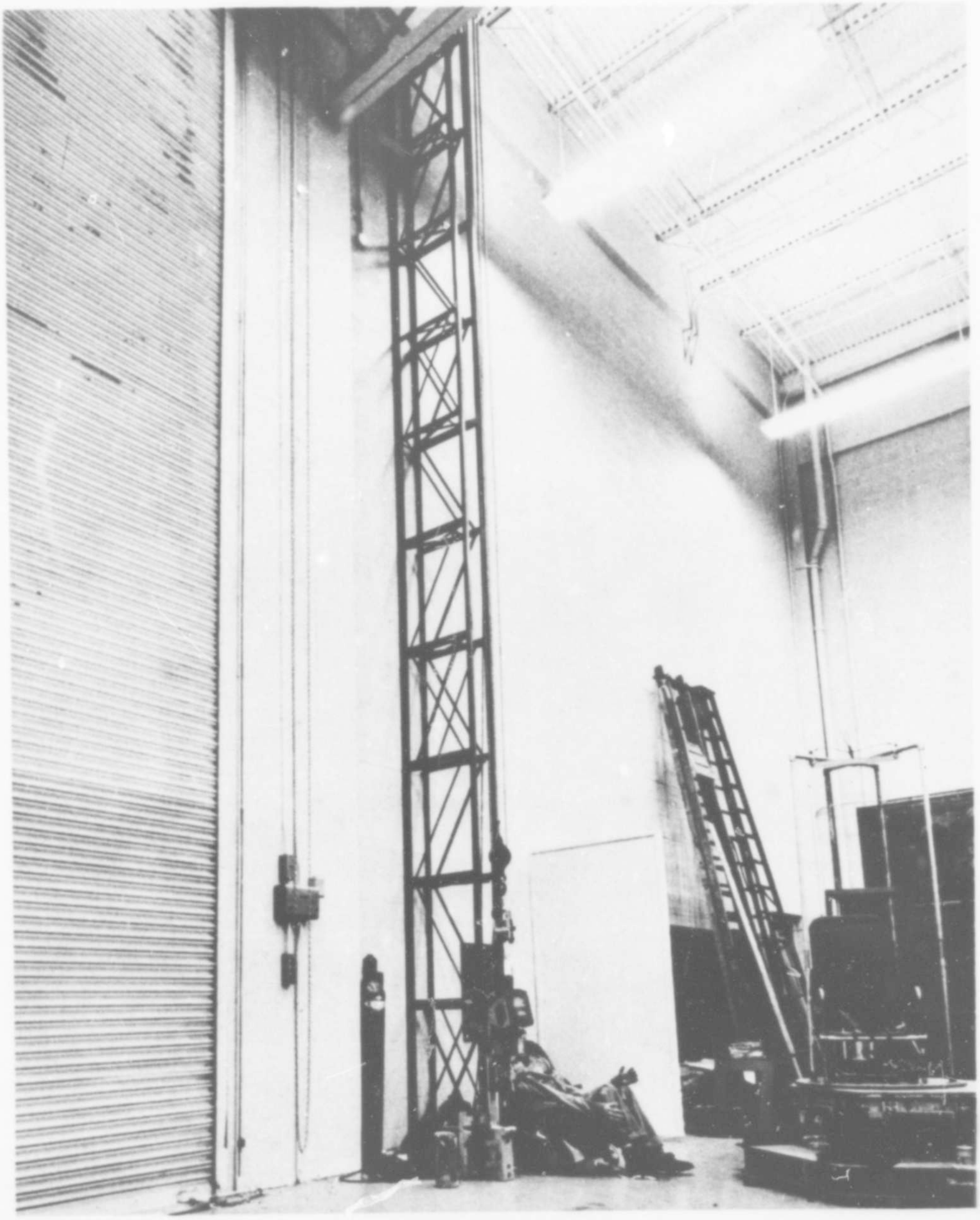

Fig. 33 Vertical Decelerator, Civil Aeromedical Institute, Federal Aviation Agency, Aeronautical Center, Oklahoma City, Oklahoma, USA

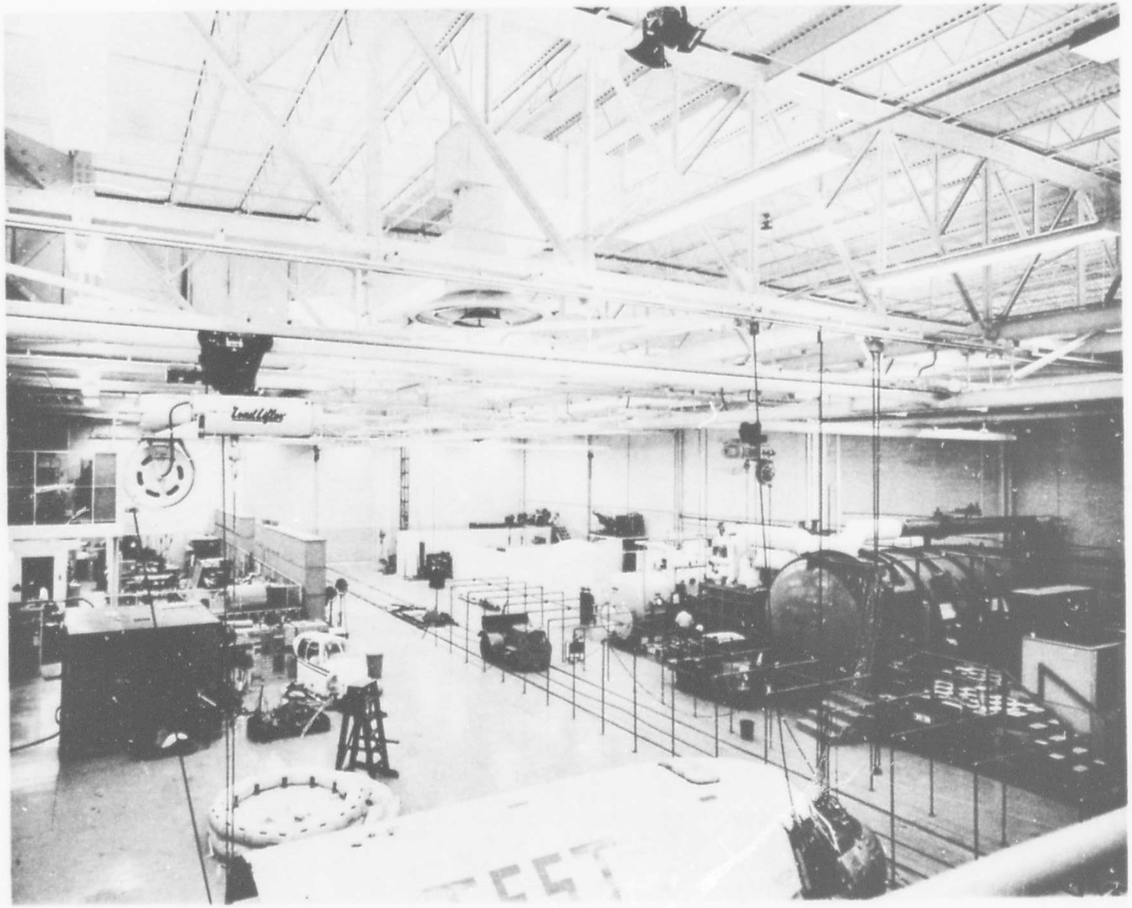

Fig.34 Short Track, Civil Aeromedical Institute, Federal Aviation Agency, Aeronautical Center, Oklahoma City, Oklahoma, USA

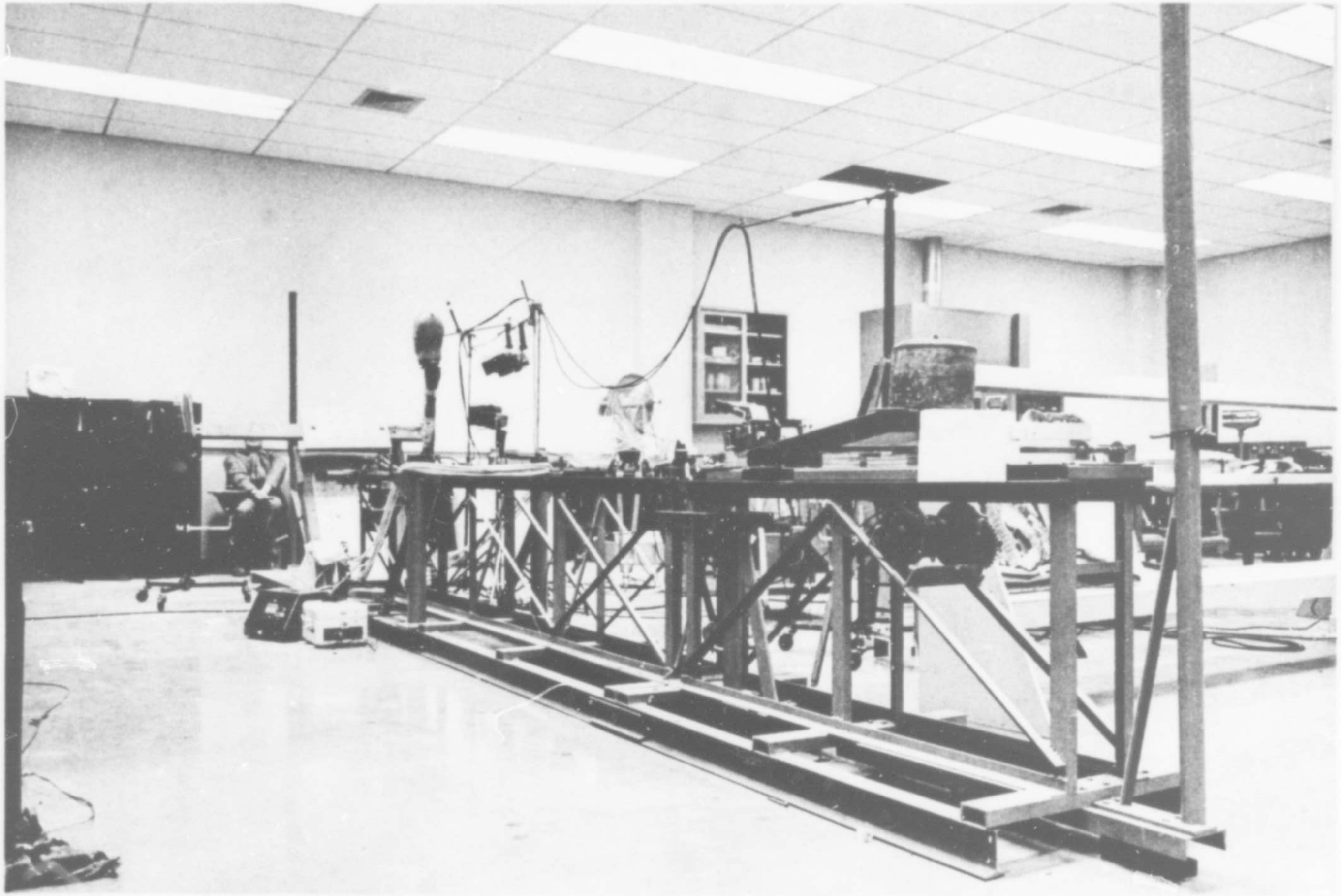

Fig. 35 Impact Bopper, Civil Aeromedical Institute, Federal Aviation Agency, Aeronautical Center, Oklahoma City, Oklahoma, USA

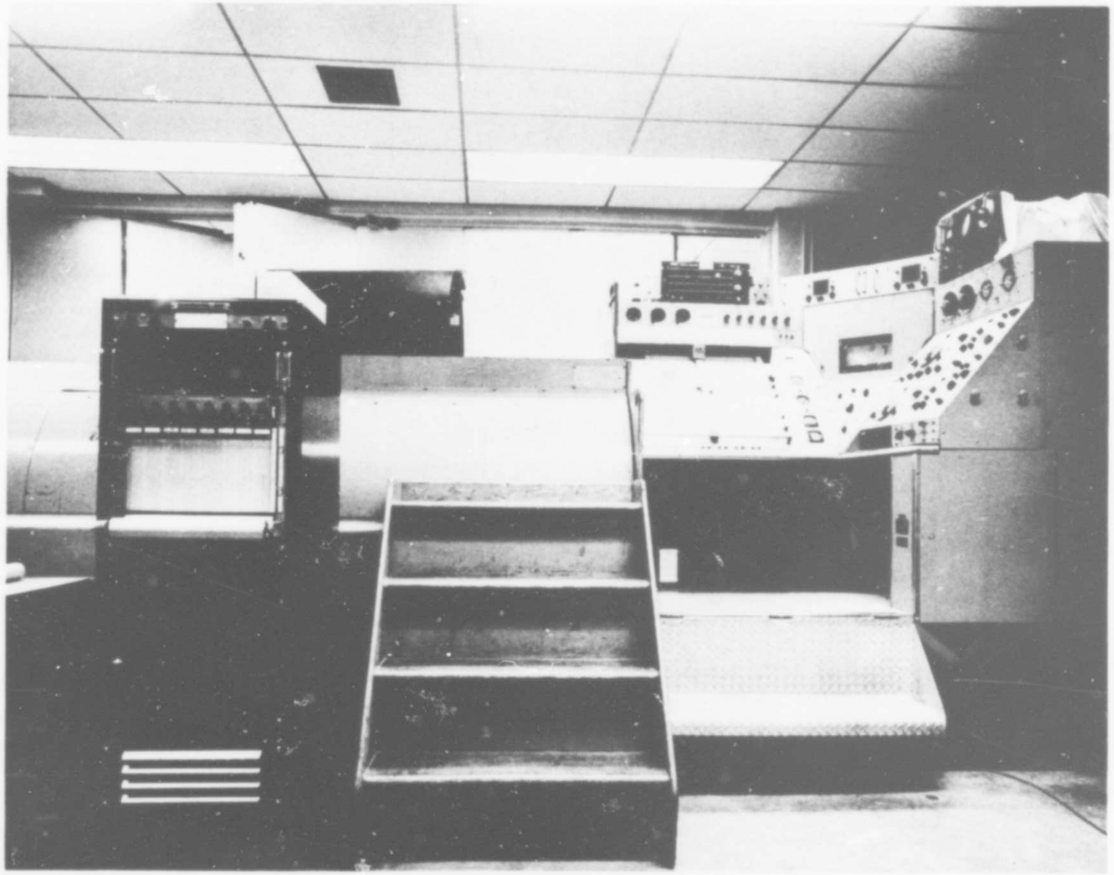

Fig. 36 "The Earley Bird" Motion Simulator, Civil Aeromedical Institute, Federal Aviation Agency, Aeronautical Center, Oklahoma City, Oklahoma, USA

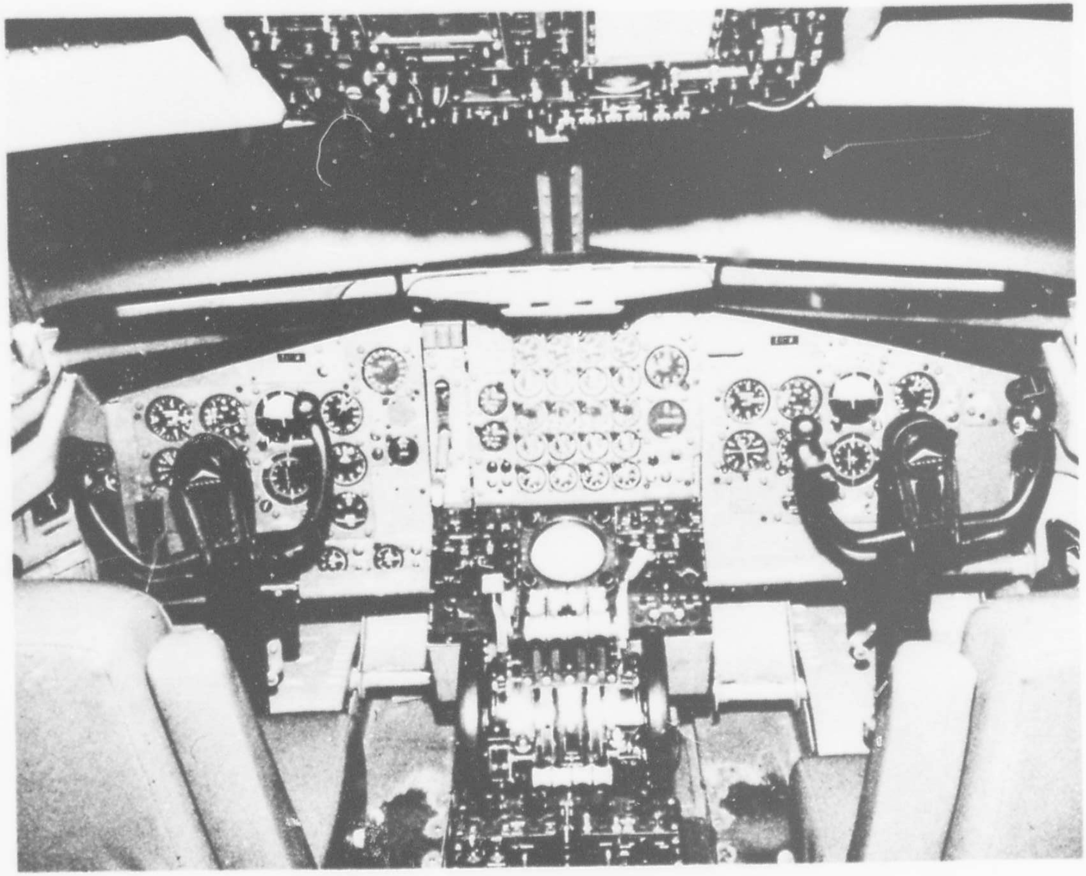

Fig. 37 Curtiss Wright Dehmel Boeing 720 Flight Simulator, Civil Aeromedical Institute, Federal Aviation Agency, Aeronautical Center, Oklahoma City, Oklahoma, USA

Fig. 38 Catapult and Track Facility, National Aviation Facilities Experimental Center, Federal Aviation Agency, Atlantic City, New Jersey, USA

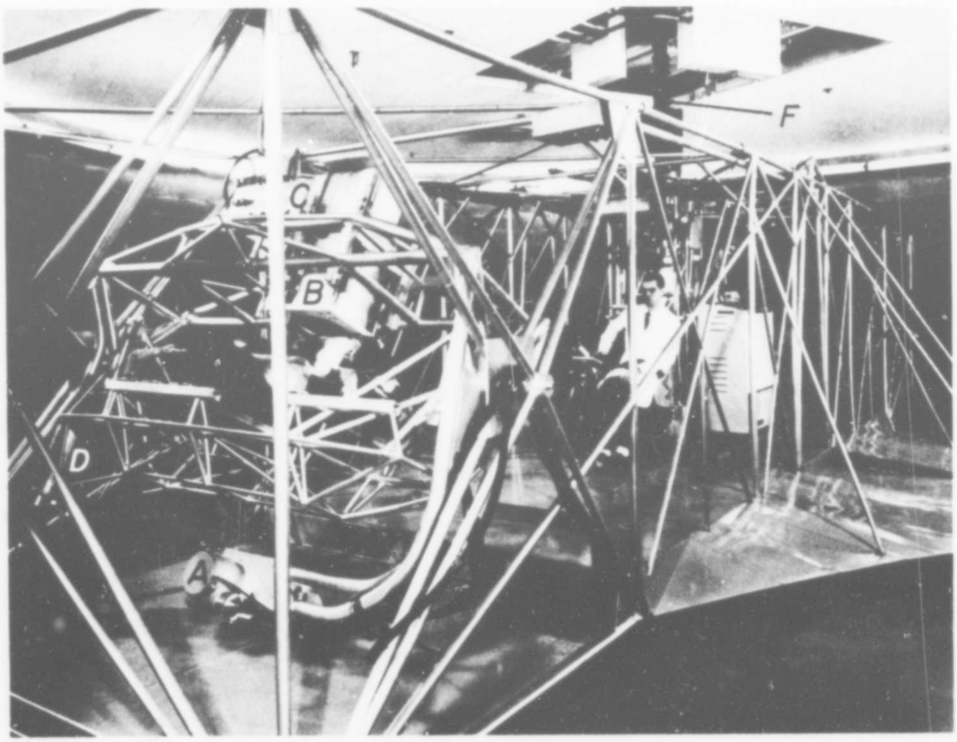

Fig.39 Mayo Clinic Centrifuge, Section of Physiology, Mayo Foundation and Mayo Clinic, Rochester, Minnesota, USA

APPENDIX

Index to Facilities and Equipment