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THE DYNAMIC ENVIRONMENT SIMULATOR - A MULTIENVIRONMENTAL MAN-RATED CENTRIFUGE

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13. ABSTRACT

The U.S. Air Force Dynamic Environment Simulator is a man-rated centrifuge with multiple environment simulation capabilities. This facility can generate combinations, either simultaneous or sequential, of acceleration, vibration, temperature, barometric pressure, gas composition, noise and related environmental stresses. Simulation of a broad variety of aerospace flight mission environments is now possible using this facility. The man rating of this facility was carried out in the last six months of 1969 and resulted in the first manned run in December of that year. Although presently programmed to meet Air Force data requirements for the design of planned and proposed aircraft systems, the Dynamic Environment Simulator represents a national research capability capable of supporting the requirements of many R&D programs including manned space flight, high speed surface transportation and other systems or functions where man is exposed to physical environmental stresses in combination.

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THE DYNAMIC ENVIRONMENT SIMULATOR - A MULTIENVIRONMENTAL MAN-RATED CENTRIFUGE

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ABSTRACT: The U.S. Air Force Dynamic Environment Simulator is a man-rated centrifuge with multiple environment simulation capabilities. This facility can generate combinations, either simultaneous or sequential, of acceleration, vibration, temperature, barometric pressure, gas composition, noise and related environmental stresses. Simulation of a broad variety of aerospace flight mission environments is now possible using this facility. The man rating of this facility was carried out in the last six months of 1969 and resulted in the first manned run in December of that year. Although presently programmed to meet Air Force data requirements for the design of planned and proposed aircraft systems, the Dynamic Environment Simulator represents a national research capability capable of supporting the requirements of many R&D programs including manned space flight, high speed surface transportation and other systems or functions where man is exposed to physical environmental stresses in combination.

KEY WORDS: Dynamic Environment Simulator, man-rated centrifuge, combined environmental stress, man-machine system, simulation research

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The ultimate effectiveness of aerospace systems can be measured only by criteria or parameters taken from the total man-machine system. With the increasing complexity of present and future aerospace systems, the need is manifest for ground simulation of environments. The interactions of multiple concurrent sequential stresses is yet undefined; and the requirement for repeated exposure to mission environments demands that a centrifuge designed for simulation research should be capable of producing vibration, gas composition, pressure, acoustic, thermal and acceleration variables which may occur in aerospace vehicles during normal flight and emergency periods. The necessity to man rate aerospace simulation facilities cannot be avoided even though incorporation of man rating procedures adds significantly to the cost and complexity of the facility. Safety, of course, is the paramount consideration, and the well established medical ethics of experimentation with normal human volunteers demands complete fail-safe capabilities. In addition, the design requirements for a safe man rated device include consideration of mechanical, life support, control, communications, structures, emergency systems and associated medical facilities.

In 1960, after 18 years of continuous operation, the United States Air Force human centrifuge facility at the Aerospace Medical Research Laboratory, Wright-Patterson Air Force Base, developed excessive vibration and deflections. A study of alternative courses of action was conducted and three options became evident: (1) structural reinforcement of the existing quasi-operational device, (2) replacement of the current machine with an "off-the-shelf" centrifuge, or (3) design and installation of a specific motion simulator clearly based upon Air Force requirements evolving from aerospace operational needs foreseeable over the next two decades. Comparison of estimated costs, time, and, above all, the ability to solve Air Force scientific requirements directed the selection of the third alternative course of action. To meet this need, a complex multimode human centrifuge has been constructed at the Aerospace Medical Research Laboratory, Wright-Patterson Air Force Base, to replace a single mode simple centrifuge. The new facility called the Dynamic Environment Simulator (DES) is capable of providing acceleration, vibration, gas composition, pressure, acoustic and thermal environments as they may actually occur in an aerospace vehicle during normal flight or during emergency and escape conditions.

Simulation of a broad variety of aerospace flight mission environments is now possible using this facility. The man rating of this facility was carried out in the last six months of 1969 and resulted in the first manned run in December of that year.

PRIMARY SUBSYSTEMS

The Dynamic Environment Simulator has been called many things. A schematic diagram of the major hardware assembly is seen in Figure 1. It is essentially a stiff arm human centrifuge and complex motion device with a multiple environment capability. The system includes the following major components or functions: (1) rotation capabilities, main arm, fork and cab axes; (2) vibration table; (3) power train; (4) hydraulics and bearing systems; (5) environmental control; (6) command and controls; (7) standard operating procedures and operator positions including the medical monitor's room, machine operating room and pit and (8) data acquisition systems. The subject is positioned in a 10 foot spherical chamber or cab located at the end of the main arm. The cab is hydraulic powered and can rotate at 150 rpm. The outer gimbal or fork which moves in a horizontal plane is used primarily for vector alignment, however, it is capable of reaching 30 rpm. The main arm length is 19-1/2 feet from the center of rotation to the center of the cab axis. The major structure can reach 56 revolutions per minute or 20G units at the cab. The main arm of the centrifuge with its two gimbals weighs about 170 tons. The structure is supported by externally pressurized "hydrostatic" bearings and rides on an oil film 0.005 of an inch thick on the thrust bearings. Similar radial bearings support the main shaft from all sides. This type of bearing was chosen because of its smooth operating characteristics and minimum friction. A solution of water and propolene glycol which is not only nonflammable but harmless to personnel coming into contact with it was chosen for the hydraulic fluid. The glycol fluid required special deaerators because of its capacity for retaining air bubbles.

The arm is driven by three electric motors acting through a common gear system. Together they deliver 330 horsepower. The main drive system is augmented by six flywheels deriving their power from small hydraulic motors. Energy is built up gradually in the flywheels over a period of 15 minutes or more and then transferred to the centrifuge by a set of aircraft disc brakes used as clutch. The flywheel drive adds about 15,000 horsepower for quick thrust during the brief period that it is in action. Although this capability is in place, it is not in use. The design calculations predict onset rates of 10G per second for the main arm using this "hi-drive system". The electric motors maintain the high velocity obtained by the rapid onset of acceleration from the flywheels.

In order to prevent large bearing forces due to unbalanced weight distribution, good main arm balance is essential. Conventional methods used for balancing centrifuges could not be used since they depend on measuring minute changes in length of the centrifuge arm under centrifugal force. The main arm of the Dynamic Environment Simulator is so stiff that its elongation under load cannot be measured. It was, therefore, necessary to develop a special method of balancing that makes use of small changes in the hydrostatic bearing pressures as the arm is rotated at low speeds. In spite of the large weight of the arm (over 300,000 lb), the balancing method, which utilizes a digital computer, is able to detect an imbalance of less than 100 lb in the capsule.

When immediate medical attention is necessary, the machine must be brought to a stop in minimum time. Even unforeseen events, such as power failures, must not interfere with emergency procedures. The centrifuge can be brought to a stop from rotations at its maximum speed of 56 rpm, corresponding to 20G, in 35 seconds, or at the rate of about 1-1/2 rpm per second, even if electrical power used for dynamic braking is not available. This is achieved by three emergency brakes that are engaged automatically upon loss of power, or manually by the operator of the machine. At the same time, the bearings can remain pressurized by means of fluid stored in accumulators which maintain the oil film between the bearings and the journal of the main arm so that rotation could be continued for as long as 70 seconds, or twice the shutdown time, without damage to the machine.

In combination with the motion of the arm, the two outer gimbals make possible complex rotary movements about the three axes of pitch, roll and yaw. The maximum acceleration force at some portions of the gondola when all three systems are operated at top speed is 85G. Forces due to gyroscopic precession would probably limit such three mode rotations but the limitations of the machine have neither been calculated nor demonstrated in these modes.

One of the most important features of the new centrifuge is the cab mounted shake table capable of vibrations in all six degrees of freedom. It has a maximum vertical translation of 12 inches and rotations of $\pm 30°$ and $\pm 19°$ in pitch and yaw respectively. Smaller displacements are obtained in yaw and the other two lateral translations. Peak shake table accelerations will be 15G with a combined payload and shake table weight of 1500 pounds.

To simulate the internal environment of aerospace systems, the capsule can be evacuated to an absolute pressure of about 3 pounds per square inch or approximately 45,000 feet. Over pressure of approximately 1 atmosphere is also possible. In addition, the equipment is in place to vary the temperature within the cab between 40 and 120°F and relative humidity from 10 to 95%. In practice, however, it is likely that thermal stress will be applied to the subject with the use of a small cab-type enclosure or thermally controlled clothing. For efficiency in programming experiments, interchangeable gondola or cab capsules or shells are provided, thus one experiment may be set up in advance while another is in progress on the DES. A separate signal patchbox is available so that the entire experiment instrumentation can be set up in the off line gondola and complete test checkout and nondynamic experimentation performed.

All motions of the Dynamic Environment Simulator are controlled by a digital computer which also monitors the status of the main subsystems and automatically initiates shutdown in case of malfunction or emergency. Emergency stops can be called for either by the medical monitor or the machine operator or the subject inside the capsule. The medical monitor is able to watch the subject by means of two closed circuit TV cameras and can also gauge the magnitude and direction of the G forces applied to the subject by means of a special display.

The standard operating procedures for the function of this device are built around three major operating areas. The operating areas are further composed of integrated teams. For example, in the medical monitor's room area, there are four stations: (1) test director, (2) medical monitor, (3) instrumentation, and (4) experimenter. Other areas are the machine operator's room and the pit.

The data acquisition and processing system provides for the collection, processing and display of experimental data. Approximately four hundred signal channels are available for either physiological signals, performance measures or power transmission. A hybrid data processing system composed primarily of an Adage Ambilog 200 system serves two functions: (1) The on line new real time processing of biomedical signals to be displayed to the medical monitor for medical monitoring of safety purposes. For example, EKG and respiration signals can be transformed into appropriate rates, heart and respiratory rates or rate of change of rate and displayed on a sequential time based display in front of the medical monitor. (2) The preprocessing of experimental data with the preparation of digital tape output of experimental data. At this point, it is readily seen that the system is designed with the concept of man rating safety and ease of function. It is necessary to formalize the safety concept and to provide a succinctly reviewable package describing the system and insuring that there are no omissions of safety requirements. This led to development of the man rating approach adopted for the DES.

MAN RATING THE SYSTEM

To satisfactorily resolve any unforeseen problems and meet the requirements for man rating a simulations facility, such as is described in the first part of this report, a man-machine team system philosophy was developed and utilized. A document which includes all subsets of the system was written and provides the backbone of the safety analysis. The document is intended to collect, analyze and collate all that material pertinent to man rating the DES. Safety considerations as applied to the DES operation are broken into three related considerations: subject safety, operator safety including all industrial/occupational safety and environmental health considerations and facility safety.

The man rating procedure includes: (1) a detailed review of the safety considerations designed into all subsystems by reviewing as-built drawings of the major subsystems; (2) a detailed safety analysis conducted using the "worst possible case" or "failure mode" method. The pertinent components of each subsystem are identified as potential failure sources. The nature of the failure of a system or component is specified and its consequences established. The policies, methods and procedures to prevent such failure are listed. Systems studied include: structures, power/electrical, hydraulics/bearings, electronics, communications/control, data handling and air conditioning. Selected structural, electrical, control and operational failure modes are listed. Safety considerations are also implicit in operating procedures as well as the physical facility. Typical medical emergencies are manually inserted to develop reaction capabilities of the operating team. An ideal communication system for this facility was developed and implemented. The emergency system includes two types of planned shutdown, emergency air, power and fire protection systems. The man rating study provides logical organization and continuing analysis to achieve absolute or fail-safe safety standards for the operation of a manned environment simulator. The organization of the collected analyses provides a compendium of system information in the form of drawing files, specific safety analysis, industrial safety surveys, operating and administrative procedures.

The operation of this facility requires a well integrated team of approximately 12 people. Specific functions include test director, machine operator, pit operator, floor monitor, computer operator, medical instrumentation, investigator and medical monitor. The machine analysis currently reviewed is limited to the following configuration of the DES: main arm - rotation up to 35 rpm (approximately 8G) at 0.5-1G per second onset rate; fork - position holding capability for simple centrifuge runs with simple rotation up to 30 rpm with arm and cab locked; cab - position holding capability for simple centrifuge runs simple rotation up to 90 rpm as a short radius centrifuge; shells - perform as wind shield only; and restraint - seat design rated to 12G and direction perpendicular to platform with 500 lb subject payload. Subject restraint is designed to function in motion at G levels described above.

The heart of the analysis is developed in a tabular format listing Structures and Functions. The format forces a recognition of a potential system fault and a documentation of preventive measures. Table 1 shows selected portions of the analysis.

DES RESEARCH PROGRAM

The DES is presently programmed to support Air Force research efforts in two technical areas: biodynamics and combined environmental stress. A summary of the work units that the DES is to support in the next five years has been prepared. Specific support will be given to the development of the B-1 and F-15 systems in particular.

Although programmed to meet Air Force data requirements for the design of planned and proposed aircraft systems, the Dynamic Environment Simulator represents a national research capability capable of supporting the requirements of many R&D programs including manned space flight, high speed surface transportation and other systems or functions where man is exposed to physical environmental stresses in combination.

EPILOGUE AND ACKNOWLEDGEMENTS

The development of a complex state-of-the-art facility such as the DES includes personnel as well as technical considerations. The DES cost 6.5 million dollars and six years to build. That it exists is tribute to the foresight and dedication of a large group of scientists and managers. All of the problems of advanced systems development: technical administration and fiscal were present, and ultimately resolved. The list of credits is long. Well over 200 people devoted significant amounts of personal effort and energy over prolonged periods. Of the authors, Mr. Cappel of the Franklin Institute Research Laboratories was the principle investigator and design engineer, M. McCally, M.D., Chief of the Environmental Medicine Division of the Aerospace Medical Research Laboratory was the Air Force project engineer and monitor and Captain Rogers, Chief of the Dynamic Simulations Branch, accepted the system from the contractor and set up the systems operation program including final system testing, man rating and operation. Alvin S. Hyde, M.D., Ph.D., 11457 Washington Plaza West, Reston, Virginia, wrote the initial specifications and began the program, with Colonel A. S. Swan. Laboratory Commanders, Colonels A. Karstens, J. Quashnock, R. Yerg and C. Kratochvil provided the vital administrative support. The Raytheon Corporation designed the controls and the major subsystems and now support the maintenance and operations activities. Subcontractors selected for the construction of major components and subsystems deserve the highest credit for the excellence of their workmanship, and include: B. G. Danis Company, Dayton, Ohio; Digital Equipment Corporation, Dayton, Ohio; Foremans, Dayton, Ohio; General Electric Company, Cincinnati, Ohio; Goodrich Company, Troy, Ohio; Helldoerfer-Castellini Incorporated, Dayton, Ohio; Honeywell, Dayton, Ohio; Hughes Bechtol Incorporated, Dayton, Ohio; Walter M. Litsey Incorporated, Dayton, Ohio; Muth Brothers, Dayton, Ohio; Mutual Electric Company, Dayton, Ohio; Ohio Valley Painting

Company, Dayton, Ohio; Ray' ieon Company, Wayland, Massachusetts; Stevens Company, Fairborn, Ohio; Tibbetts Plumbing and Heating Company, Dayton, Ohio; Timons, Butt and Head Incorporated, Dayton, Ohio; Wiley Company, Huntsville, Alabama and finally, Mrs. Carole Smith who prepared this report and many others during development of the DES.

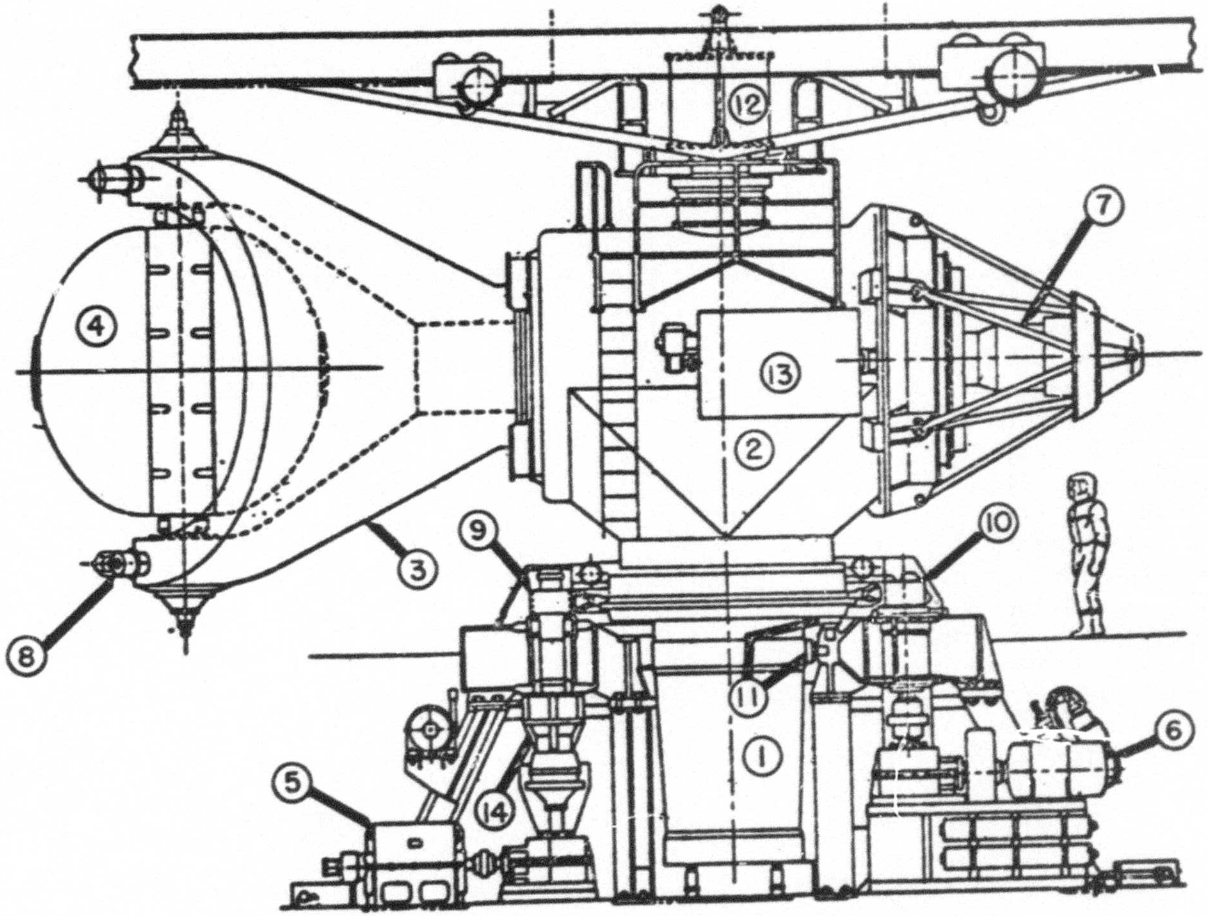

Figure 1. Dynamic Environment Simulator (Elevation)

1. Main Trunnion 2. Rotating Housing. 3. Fork Shaft and Fork. 4. Gondola. 5. Flywheel 6. Sustaining Drive Motor. 7. Fork Drive Motor 8. Gondola Drives 9. Accelleration Drive Pinion 10. Sustaining Drive Pinion 11. Thrust and Radial Hydrostatic Bearings. 12. Slip Ring Tower. 13. Motor Driven Counterweights 14. Multiple Disc Clutches

TABLE 1. FAILURE MODE ANALYSIS

STRUCTURES

SOURCE	FAILURE	CONSEQUENCES	PREVENTION	REFERENCES
building	inadvertent door opening during operation	damage to the machine or injury to the involved personnel	a. control of all doors is achieved with interlock system b. positive control of all areas during operation is achieved by strictly enforced standard operating procedure c. warning lights system d. warning buzzer system	a. see standard operating procedures b. see standard machine operation procedures
power distribution	exposed electrical lines or terminals	electrical shock	a. routine maintenance, surveys b. ground safety review	a. see maintenance procedures b. see consultation

TABLE 1 CONTINUED

SOURCE	FAILURE	CONSEQUENCES	PREVENTION	REFERENCES
hydraulic/fittings fracture anywhere in hydraulic supply to bearings - upstream of accumulators		loss of bearing	appropriate positioning of hydraulic accumulators assures hydraulic fluid source for duration sufficient to safely stop the machine	see test data and failure analysis
access to subject	access time greater than 1 minute	delay in medical diagnosis/treatment	a. standard operating procedures b. training c. emergency reaction plan	
	variables include: final cab position, magnitude and main arm velocity			

TABLE 1 CONTINUED

SOURCE	FAILURE	CONSEQUENCES	PREVENTION	REFERENCES
operations network	loss	test director goes to backup visual communication with machine operators/monitor with card system		