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HUMAN CENTRIFUGE SIMULATION OF MARS FLIGHT DYNAMICS

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ABSTRACT

Using a computer controlled gondola at the end of a fifty-foot arm of a giant human centrifuge as a dynamic flight simulator in a manned flight to Mars mission, one flight volunteer was exposed for 24 hours to sustained reactive acceleration forces at 2 g, twice the sustained acceleration forces of Earth gravity. Subjected to the biodynamic force field of a 2 g 24 hour flight to Mars simulation, the volunteer, Dr. Carl C. Clark, endured the required acceleration loads, and demonstrated that he could maintain sufficient consciousness, visual awareness and comprehension, cognitive capabilities and life support, physiological and psychological functions, and flight control capabilities in the Mars flight acceleration profile. Although data analyses for possible physiological and biophysical effects and defects in response to this sustained acceleration stress on one volunteer subject, this human centrifuge simulation of Mars flight dynamics provided design criteria for improving g-protection and life support systems, flight quality and comfort, biomedical instrumentation, communications and flight control, and centrifuge flight simulation operations. Modifications in the double-gimbaled gondola of the human centrifuge included improvements in acceleration restraint and life support systems, centrifuge control and pilot control interfaces, bioengineering and performance instrumentation, biomedical and psychological monitoring, and in-flight data presentation and recording. Additional pilots, astronauts, and volunteers were tested in a wide variety of acceleration tolerance evaluations conducted in the double-gimbaled gondola of the human centrifuge. Restrained in the gondola’s cockpit at the end of the human centrifuge’s arm, flight test personnel were exposed to combined acceleration force fields as their physiological and pilot performance capabilities were measured along x, y, and z centrifugal force axes for associated tolerance time-lines at different acceleration force levels, including through: 2 g, 3 g, 5 g, 7 g, 8 g, 9 g, 14 g, and higher. For the 2 g 24 hour human centrifuge simulation, the of the technical hypothesis was that the human pilot may tolerate continuous acceleration forces of two times Earth gravity by accelerating half way to Mars at 2 g, and decelerating at 2 g the rest of the way, mainlining a total flight time interval of 24-34 hours, flying a continuous 2 g acceleration force approach profile to Mars.

INTRODUCTION

The giant human centrifuge was used as a dynamic flight simulator to produce the physiological reactive forces which a human must tolerate within the cockpit of a spacecraft during exposure to the in-flight acceleration profile's dynamic loads during space flight missions. The human, restrained within the double-gimbaled 6 ft by 12 ft gondola at a 50-foot position along the axis of the rotating arm of the centrifuge, receives the resultant forces of the radial and angular accelerations, produced along the radial and angular axes; and the human is thereby exposed to the resultant force field levels to which he would be exposed in space flight. In the late 50's, this world largest human centrifuge, located at the Aviation Medical Acceleration Laboratory at the U.S. Naval Air Development Center, was modified for extensive space flight research, simulation, training, and effects of acceleration profiles on astronaut physiology, flight performance, and astronaut safety systems during flight operations, in a large number of space flight projects for NASA and the Department of Defense. (See Clark and Woodling, 1959; Chambers and Doerfel, 1959; Clark and Gray, 1959; Chambers and Eggleston, 1959; Chambers, 1960; Clark, 1960; Chambers and Nelson, 1961b; Chambers and Hitchock, 1963; Clark, 1963; Chambers, 1963; and DiGiovanni and Chambers, 1964) . Chambers and Nelson (1961a), Chambers, 1964; and Chambers, 1968 have formulated a series of acceleration force guidelines and standards, encompassing a large variety of acceleration G-levels and their combinations, ranging through 1 g to 26g. Many of these early guidelines were published in a book chapter by Chambers) titled: Human Operator Performance in Acceleration Environments, in Unusual Environments and Human Behavior (1963), and in a article titled: "The Psychology of Space Flight and Centrifuge Training, J. of the British Interplanetary Society (1968). Cope and Chambers (1961), Chambers and Nelson, (1963); Ross, Chambers, and Thompson (1963), and Ross and Chambers (1967), examined the effects of transverse acceleration on memory task performance at 1 G, 3G, 5G. 7G, 9G, and 14G. In these experiments, volunteers performed memory tasks in the centrifuge cockpit for 4 _ hours at 2Gx, and other g levels ranging to as high as 9Gx for 2 minutes and 18 seconds, and 14Gx for 2 minutes and 4 seconds. There were marked and somewhat consistent within-series decrements as functions of exposure times and increased G levels.

In acceleration physiology, acceleration a is measured as a multiple of g, the standard unit of acceleration due to gravity, and any force **F**, as a multiple of the standard weight, **W**, of the body upon which **F** is acting. However, because of the physiological importance of the position of the human body with respect to the acceleration force, the directional aspects of the acceleration quantity area considered differently from those in physics. (DiGiovanni & Chambers,, 1963) In acceleration physiology, the magnitudes of the vectors **g** and **W** are employed. The directions of the vectors **a** and **F** are independent and the fixed directions of the physical quantities, **g** and **W**. A single symbol represents the common ratio formed by normalizing **F** and a with respect to the standard gravitational values. Thus, physiological **G** is defined as a ratio of forces, or a ratio of accelerations: **G** = **a/g,** or **G** = **F/W.** Physiological **G** = the unit of reactive force causing displacement of the organs and fluids in the human body when the body is accelerated, where 1 **G** = force per unit mass due to acceleration of 1 **g**. The acceleration of Earth gravity is: g = 32.17 ft/sec 2 , or 980.6 cm/sec 2. Linear acceleration modes in g units are simulated on the human centrifuge by the radial acceleration of x, y, and z unit vectors through the human body, and angular acceleration modes about x, y, and z axes of heart motion, as operated by the computer-programmed and controlled combinations of forces from the rotating centrifuge arm and the gimbaled centrifuge gondola at the end of the centrifuge arm. The human's heart and body may then be evaluated for launch, space flight maneuvers, and reentry in response to exposures to many acceleration flight profiles and their resulting dynamic loads. Using radial and angular accelerations, the effects of the acceleration forces expected during launch and lift-off, many space flight maneuvers, reentry, and landing may be simulated, and the pilots and astronauts may be tested and trained dynamically, in their space craft configurations. Many flight simulation programs and projects with Mercury, Gemini, and Apollo astronauts, and flight volunteers, were conducted using this facility and its technology. The Project Director/Project Officer for many of these joint NASA-NADC-AMAL projects and programs was Dr. Randall Chambers, who directed joint Mercury-Centrifuge simulation, X-20- Centrifuge Simulation, Gemini-Centrifuge, and Apollo Manned Centrifuge projects, research and training programs.

Used as a space flight simulator, the rotating double gimbaled gondola at a 50 ft. position point along the axis of the rotating arm, produced the acceleration force conditions for testing human-machine interactions and biomedical performance in protective life support systems during manned flight stress simulation, human factors engineering of flight controls and displays, emergency and escape procedures during training, safety and flight abort profiles, acceleration profile familiarization during physiological and psychological performance, and communications and space flight procedures with pilots/astronauts performing piloting in combined environments of acceleration, atmospheric pressure, temperature control, medical monitoring and life support variations. (Chambers & Eggleston, 1959; Chambers, 1960; Clark, 1960; Chambers & Nelson, 1961b, Chambers, Kerr, Augerson & Morway, 1962; Chambers & Nelson, 1963; and Chambers, 1964 & 1968).

HUMAN CENTRIFUGE MARS SIMULATION.

The manned trip to Mars when it is closest to the Earth, about 35 million miles, with 20th century chemical propulsion in this early "sling shot era" of space exploration, involves about 10 minutes of acceleration above 0 g to attain the 25,000 mph (or 1139 g seconds) of earth escape speed and 6 months of coasting flight at 0 g and a few minutes of deceleration to Mars landing [See Zubrin, 1996, and 1999, his discussions of possible chemical propulsion flights to Mars.] The expected 21st century propulsion improvements, probably involving nuclear power, can provide a very desirable shortening of this flight time. The shorter flight time would greatly reduce the probability of exposure of the astronauts to a solar radiation storm, a significant danger of a six month coasting flight, and greatly reduce the weight and volume of needed en-route life support.

In 1957, Carl Clark was Centrifuge Training Officer for the X-15 pilots at the Aviation Medical Acceleration Laboratory (AMAL) of the U.S. Naval Air Development Center, Johnsville, also identified as in Warminster, Pennsylvania, a few miles north of Philadelphia. This human centrifuge, then the world’s largest, had been developed recently as a dynamic flight simulator of the above 1 g parts of the simulated X-15 flights. A full cockpit was provided within the gondola of the human centrifuge, with pilot seat and restraints, controls and displays, and instruments computer driven to show the status of the simulated flight while the centrifuge and cockpit “gondola” double gimbal system rotations provided an approximation of the linear and rotational accelerations for the particular instants during the flight time-lines. Pilot training emphasis was on pilot familiarization with the instruments and controls under dynamic condition, including simulated failures or malfunctions of system components [Clark and Woodling, 1959].

In effect, the pilots were flying the X-15 before it was built, within the limitations of earth bound simulation of free flight. This may be compared to the earlier rocket research aircraft, in which the pilot experienced the accelerations of flight for the first time when he first flew the aircraft. Mel Apt, test pilot for the X-2 rocket research aircraft, for example lost control when he ran into severe aircraft directional oscillations at high altitude due to inadequate directional control by aerodynamic control surfaces alone.. He was able to eject, but did not survive his first flight.

The X-15 pilots were very proud of their machine, and troubled by the human limitation in more extreme flight conditions. "The machines are almost ready for space flight, but the humans limit what we can do," they would report.

Carl Clark was interested in the early planning for a human Mars flight, but concerned with the six months of coasting flight before arrival. So with the approval of Dr. James Hardy, AMAL Research Director, and Navy management Captain Kirk Smith, he had his home reclining arm chair and a small electric stove installed in the centrifuge gondola, and on the weekend after Thanksgiving in 1957, became the first human, and perhaps still the only human, to experience 2 G for 24 hours [Clark, 1960]. If one accelerated in a straight line at 2 g for 12 hours, then decelerated at 2 g for 12 hours, one would not cover enough to get to Mars on its near approach of 35 million miles from the Earth.. But the principal was demonstrated that the human could tolerate long duration 2 G acceleration. Clark should have ridden at 2 G for 30 hours.

Unfortunately, the engines to provide this acceleration are not yet available. The challenge to the engineers was made to provide short duration manned flights to Mars, such as 2 G for 24 hours.

The earth’s gravitational acceleration of 1 g, or 32.2 feet per second squared, cannot now be provided to a test object for very many minutes without rotation. One g is an acceleration or increased speed of 22.0 miles per hour per second. If one’s motorcycle went from 0 to 66 mph in three seconds, one would experience 1 g of linear acceleration along the track, in addition to the 1 G of gravitational acceleration perpendicular to the track when not bouncing. If it were physically possible, 1 g in a straight line for a year would be about the speed of light. We distinguish the "displacement acceleration" by the unit g, and the "physiological effects acceleration" of displacement and gravitational acceleration by the unit G. If one is sitting at rest on the earth, one is experiencing 0 g of displacement, but indeed the body organs are being pulled down by gravitation, and one experiences 1 Gz. In most dynamic situations, it is desirable to speak of the x (vehicle displacement acceleration forward, or internal organs pushed toward the spine. or "eyeballs back"), y (vehicle right or eyeballs left), and z (vehicle up or eyeballs down) components of the linear accelerations, and similarly for the rotational accelerations (Clark and Hardy, 1961). In free flight one has six degrees of freedom, that is, any of the six linear and rotational accelerations can be varied by appropriate control. On the Johnsville Navy Human Centrifuge with a swinging arm with a gondola at the end with roll and pitch gimbals, with the subject’s head (where we primarily detect linear and angular accelerations) at the center of gimbal rotations, mechanical controls of changing arm speed and gimbal angles provides only an approximation of the free flight motions, but with centrifuge computer operator experience, translated into computer control, the most important physiological effects can be simulated.

To provide an acceleration experience on earth as if standing on a planet with 2 G of gravitational acceleration, or of a space ship linearly accelerating at 2 g, one can use a human centrifuge, ideally with a long arm to minimize the rotation effects. (The “gondola” of the Johnsville Human Centrifuge is at a 50 ft. radius of turn distance along the axis of the centrifuge’s rotating arm, which is driven by a direct drive 4000 horse power electric motor). One rotates the roll gimbal of the gondola to 60 degrees, and controls the arm to a constant rotational speed to provide 1.73 G of centrifugal acceleration. With the 1 G of gravitational acceleration perpendicular to the plane of arm rotation, one has a resultant physiological acceleration of 2 Gz ("eyeballs down") when standing up on the floor of the gondola. As far as Clark knew, no human had previously experienced 2 G for 24 hours, nor has he heard that this has been repeated or exceeded. The usual human centrifuge safety precautions of 1957 were taken, with continuous multi-lead electrocardiograms continuously viewed by a medical doctor, with two way voice communication with the doctor and centrifuge operator on duty .One can quite easily walk around with a person of similar weight on the back, so Clark knew he could walk around at 2 G in the gondola, and he did (Clark, 1963). Most of the time was spent in a reclining chair, with a back angle of about 50 degrees, listening to classical music on a radio. The experience was in no way uncomfortable except during the periods of determining the reaching threshold for head motions in this rotating environment. Calculations were made, using a slide rule, of speed and distance of simulated travel.

With an electric hot plate and coffee pot, a fried egg and coffee were made for breakfast, with milk and sandwiches for lunch. Lifting the half gallon of milk, now with contents weighing 8 pounds at 2 G, was a noticeable change. In talking, the increased weight of the jaw was also apparent, and lifting the arms or legs clearly required more effort. A motion picture camera viewing the subject in the reclining chair was turned on occasionally by the subject to document various activities.

The electrocardiogram did show occasional ectopic beats or premature ventricular contractions (PVC‘s), but not of sufficient frequency to be considered by the medical doctors as a basis for stopping the centrifuge. With a sphygmomanometer, Clark took his own blood pressure occasionally during the run. This remained in an acceptable "normal" range.

The most striking physiological decrement of the 2 G centrifuge environment was the potential nausea with head rotation, a centrifuge artifact that would not take place in linear flight. When rotating the head, even slowly at constant velocity in roll (a shoulder to shoulder rocking motion)), pitch ("yes"), or yaw ("no") in a rotating environment, a Coriolis acceleration develops in the vestibular canals, giving a false sense of body rotation. If the head motion is oscillating, the sense of false body rotation is also oscillating, and this quickly become nauseating. One can rotate the head in the plane of the centrifuge (or rotating room or rotating space station) rotation without nausea, but one learns to rotate the head out of this plane very slowly to be below the nausea threshold. There may be acclimatization effects, as suggested in the many "rotating room" experiments of Ashton Graybiel, Fred Guedry, and others at the Naval Medical Research Institute, Pensacola, Florida. In the human centrifuge, Clark made three experimental trials to determine the nausea threshold during the 2G run, indeed reaching nausea and reaching at a head rotation rate in worst angular direction of about ten degrees per second.

With a physiological acceleration above 1 G for more than brief periods when jumping or falling, the body is stressed beyond its primitive environmental conditions. Of particular concern is the altered blood distribution, particularly to the brain. The weight of the blood column along the resultant acceleration vector from the heart to the brain must be more than supported by cardiac blood pressure if blood is to reach the brain to maintain consciousness. Thus in spacecraft or military aircraft, reclining or supine seats are used to reduced the height of the heart to brain blood column along the resultant acceleration vector, and "anti-g" suits which compress the lower parts of the body to reduce blood pooling and maintain blood return to the heart, and pilot straining techniques are used. The Mercury spacecraft flight program had uncertain medical approval until Carter Collins showed, on the Johnsville centrifuge, that he remained conscious, while in the Mercury supine "contour couch" caste from polyurethane to his space-suited body shape, through a 28 Gx peak haversin wave form of an extreme emergency reentry from orbital speed.

But the consequence, in this 2 G experiment, of reduced blood flow to the brain over many hours, even when in the reclining chair, was uncertain. Clark was able to cook and eat, use a slide rule to calculate equivalent speeds, and converse cogently with the medical staff. He was able to sleep for a number of hours. But as the time dragged on, lying back and listening to classical music became the activity of choice - until the 24 hours was up, and the centrifuge stopped. Then he climbed out, with only a little unsteadiness, into the observation room. He felt surprisingly light, and with a big smile he gave a little jump to illustrate his feeling of less attachment to the Earth. Medical tests were ‘normal,’ and he returned home for a good dinner and a night’s sleep. However, on the next day, he was driving through town when a truck pulled out of a side street without stopping. He put on the brakes, but ticked the truck, without damage. He wondered if his reaction time was slower than usual. Otherwise, there was no apparent physiological decrement for experiencing 2 G for 24 hours. The experience is remembered some 47 years later with a sense of pleasure.

The implication of this experiment is that humans are ready for continuous 2 g space flight, accelerating half way and decelerating half way, for at least 24 hours, to greatly shorten flights to Mars, for example. As to "acceleration protection" at 2G, having the subjects in reclining chairs or "horizontal" couches will reduce blood pooling, but moderate periods of walking about appear acceptable. The engines for such a 2g flight are not yet available, and may not be for weight and cost and radiation levels. But the goal should remain with the engineers: how can we drastically reduce space flight times to distance objects?

DISCUSSION

This particular project, using acceleration protection at 2 G for 24 hours, accelerating half way and decelerating the other half way, suggests the possibility that slightly higher G’s could be sustained in acceleration approach profiles to Mars. Using this human centrifuge as a manned space flight simulator to expose the human volunteers and flight candidates, pilots and astronauts to a large variety of accelerations at higher G levels for much shorter duration exposure times, the effects of the acceleration dynamics of many aviation and space flight profiles and peak G's have been studied. Restrained in the gondola's cockpit at the end of the human centrifuge's arm, flight test personnel were exposed to combined acceleration force fields as their physiological and pilot tolerance time lines at different acceleration force levels, concentrating on those ranging between 2 to 15 G, and flight endurance times of a large variety of approaches ranging from 5 seconds at 15 peak G, and 4 hours and 30 minutes at 2G (Chambers, 1963; Chambers & Nelson, l963; Chambers, 1964, Ross & Chambers, 1967, and Chambers, 1968). Also, in The Psychology of Space Flight and Centrifuge Training, 1968, he formulated some of the basic principles and guidelines for the design and assessment of space flight training and simulation programs for pilots, astronauts, and flight crew members in acceleration force environments. He had served as the Project Director and/or Project Officer on many joint NASA-NADC-AMAL astronaut acceleration training and research programs: Mercury-Centrifuge Simulation, X-20-Centrifuge Simulations, Gemini-Centrifuge Simulations, Apollo Manned Centrifuge Program, and other NASA-NADC and contractor research and training projects. These acceleration training principles and guidelines are listed below: been slightly revised by the author and listed below.

Principle 1. Physiological Tolerance Limits
Principle 2. Performance Tolerance Limits
Principle 3. Predicting Performance Tolerance from Physiological Tolerance
Principle 4. Speed, accuracy and force of simple motor movements
Principle 5. G-Protection
Principle 6. Proper Body Position
Principle 7. Proper Body Support and Restraint
Principle 8. Visual Decrement
Principle 9. Air Pressure and Oxygen Content of Breathing Air
Principle 10. Vestibular Reactions.
Principle 11. Acceleration Sensation and Perception
Principle 12. Illusions, False Perception, and Motion Sickness
Principle 13. Hearing and Acoustics
Principle 14. Kinesthetic and Proprioceptive Senses
Principle 15. Time Perception and Temporal Events
Principle 16 Complex Psychomotor Skills
Principle 17. Cognition, Memory, and Reaction Time
Principle 18. Acceleration training and practice effects
Principle 19. Display Characteristics
Principle 20. Control Devices and Control Systems
Principle 21. Task Difficulty
Principle 22. Feedback Sensitivity
Principle 23. Higher Mental Processes, Alertness, Overload, and Fatigue
Principle 24. Emotional Processes
Principle 25. Characteristics of Performance Decrements and errors
Principle 26. Individual Differences in Physiological and Performance Capabilities
Principle 27. Effects of Combined Stresses

These acceleration principles may serve as useful guidelines for research, testing, training, and evaluating the effects of acceleration force levels on the physiological and performance reactions of human subjects during exposure to a large variety of human centrifuge simulations of space flights and their flight dynamic profiles.

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