THE HISTORY OF THE DYNAMIC FLIGHT SIMULATOR

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INTRODUCTION

This is a history of one of the world's greatest man-rated centrifuges and a tribute to those who were farsighted enough over 50 years ago to specify the performance and physical requirements for a device, which has continued to meet the research and training, needs of our nation's ever advancing military aircraft. The unique capabilities of this device, which resulted from these requirements, are described herein along with specific references to the benefits, which they provided. Also described, are the many modifications and improvements to these capabilities, which were made over the years. Further details are provided which show how these capabilities enabled this unique centrifuge to be converted into the world's first pilot-controlled total G-force Dynamic Flight Simulator (DFS).. To emphasize the importance of this conversion and to show evidence of the potential value of this device, a detailed description of a few of the DFS's most dramatic programs is provided, each of which has been recognized as having the potential for preventing the loss of many aircraft and their crew.

A tribute is also paid to the many scientists who, recognizing the extraordinary capabilities of this device, developed and obtained the funding for the many research and training programs which used these capabilities, directed their implementation and operation, and published the results of their findings. Also, to the engineers and technicians who were responsible for the computer programming and safe operation of each program, and for the design, construction, and installation of the hardware and instrumentation which each required.

Finally, recognizing that the DFS is currently inactive and its future in doubt, some ideas are presented which describe its potential use for both training and research programs regarding problems facing the aircrew of our nation's military, commercial, and general aviation aircraft.

CHAPTER I

THE DFS'S ORIGINAL FEATURES AND LOCATION DETERMINED

In the years immediately preceding and during World War II, the "blackout" problem encountered by Navy pilots due to the accelerations produced by their aircraft during air combat and dive bombing maneuvers, became sufficiently serious as to be of great concern to aviation physiologists. In order to study the problem and to develop methods of protecting the pilots during these maneuvers, human centrifuges were built both in this country and abroad. By the year 1945, seven such centrifuges were in operation. Table I shows a list of these centrifuges, the year in which they became operational, the agency that operated them, their location, and their physical characteristics.

TABLE I

YEAR	AGENCY	LOCATION	RADIUS (ft)	MAX G	G/SEC
1935	USAAF	Dayton,OH	10	20	--
1935	GAF	Forschunginstituten, Germany	19	20	2
1940	RCAF	Toronto, Canada	11.5	20	6
1942	Mayo Clinic	Rochester, MN	10	15	2
1942	Japanese Army	Tachikawa, Japan	10	15	2
1943*	USAAF	Dayton, OH.	20	20	2
1944	USC	Los Angeles, CA.	23	20	2
1945	NAS	Pensacola, FL.	20	20	2

* Replaced the earlier USAAF 10 ft. centrifuge.

All of these centrifuges were built under the duress of war and, because there was an urgency to put them to use, they were all designed to be put in operation in the shortest possible time. Consequently, all of the centrifuges were relatively small, varying in radius from 10 to 23 ft.. Also, they accelerated very slowly, so that the time history of the G forces developed on them were not directly comparable to that which the aircraft exerted on the pilots during dive-bombing and air combat maneuvers. The scope of the knowledge of acceleration physiology was greatly enlarged by the use of these machines, however, and the early G-suits used by fighter and dive-bomber pilots were developed on them.

As early as 1944, the Aviation Medicine Branch of the Military Requirements Division of the Bureau of Aeronautics, realized the inadequacy of these centrifuges, and began drawing up specifications for a high performance centrifuge which would more nearly simulate the stresses experienced by combat pilots of both current and future aircraft. Of particular concern, were pilot problems anticipated with the Bell Aircraft Company's new jet propelled X-I aircraft, which was projected to fly at altitudes above 80,000 ft. and at speeds near the speed of sound.

To implement this project, Dr. Ralph Christy, Dr. Lysle Peterson, and Capt. Ashton Grabiel of the Aviation Medicine Branch, visited all of the centrifuges on this continent and spent time in the field with fighter and bomber squadrons in order to define more clearly the specifications for the new centrifuge. These groups were later joined by Dr. E.T. Baldes and Dr. Earl Woods of the Mayo Clinic, Dr. William Franks of the Canadian A.F., two engineering consultants; a Prof. Murray and a Mr. Peggs, association unknown, and from the Special Devices Center, Commodore Adams and his deputy, Harry Schroeder, who was to actually direct the project.

Finally, after many meetings and discussions, the group proposed the construction of a high performance centrifuge to be developed under the direction of the Special Devices Center of the Office of Naval Research. The specifications of performance were planned to give aviation medicine personnel a research tool, which would exceed any existing device in performance and versatility, and would be capable of simulating the stressed applied to the pilots of all current and future aircraft. The original features of this new Navy centrifuge are shown in Table II.

TABLE II
ORIGINAL FEATURES OF THE NAVY CENTRIFUGE

- Controllable Dual Gimbal System
- 10 G/Sec. G-Onset Rate
- 50 Ft. Arm Radius
- 40 G Capability
- Environmentally Controlled Gondola
    1. Vacuum; 0 to 60.000 Ft. Simulated Altitude
    2. Temperature, 40 deg. F. to 110 deg. F.
- Independent Power Supply involving two 1500 kw. generators.

During a telephone conversation in March, 1991, Dr. Lysle Peterson, who had championed the need for the controllable dual gimbal system, stated that the 50 ft. arm radius and the 40 G capability were the two most controversial features of the new centrifuge. This controversy was not so much because these features were not deemed desirable, but whether their worth justified the increased costs involved in implementing them. Dr. Peterson future stated that the 50 ft. arm length was chosen more to reduce the G-gradient effect, a major defect of short arm centrifuges, than the Coriolis acceleration effect, although the reduction of both of these effects was deemed highly desirable. In effect the 50 ft. arm reduces the G-gradient by 60 % and the Coriolis accelerations by 33% over those developed on a 20 ft. centrifuge. It also enables the centrifuge to produce a more accurate G and to provide more usable gondola space.

The 40 G capability may seem excessive because very few programs require operation above 15 G (with the possible exception of the Iron Maiden program which will be discussed later), the capability permits the required 1.5X structural load testing of all gondola installations designed to operate up to 15G., prior to manned runs. Also, the structural capability of the arm and gondola designed to support a payload of 1000 lb. (originally 400 lb.) at 40G, enables the centrifuge to support a typical 2500 lb. cockpit at 15G.

The independent power supply provided by the two 1500 kw generators, enables the centrifuge to be operated at high rates of G-onset without dimming lights or causing other undesirable effects in the surrounding community. This has been a major concern in the planning of other high performance centrifuges.

Perhaps the most valuable feature of this centrifuge was its controllable dual gimbal system. It was designed primarily to keep the subject aligned with the resultant G vector during rapid onset/offset G profiles, and to thereby minimize any tumbling sensations. The high tangential accelerations developed by the centrifuge during these profiles would not only be disorienting to the subject as they are in non-gimbaled centrifuges, but would depart from the required aircraft G environment and could result in unrealistic physiological effects. While this was the original purpose of the system according to Dr. Peterson, this capability has enabled the centrifuge to expand into areas unattainable by non-gimbaled centrifuges. These include:

* The ability to generated multi-directional G-profiles for simulating the G environment of both controlled and uncontrolled flight conditions such as aircraft catapulting, post stall and spin gyrations, automatic interceptor attacks, etc.
* The ability to produce realistic angular motion cueing to the centrifuge pilot during his control of the centrifuge when used as the force and motion base for a total G-force Dynamic Flight Simulator.
* The ability to generate the somato-gravic and somato-gyral illusions associated with spatially disorienting maneuvers for either training or research purposes.

After deciding on the basic requirements for the futuristic centrifuge, the next step was to decide where it should be located. Dr. Grabiel felt that it should be located at the Naval Air Station in Pensacola, Fl. because it would compliment the mission of that Station. The construction engineers pointed out, however, that a device of that magnitude would have to be constructed in a soil containing a solid rock foundation, and that the sandy bottomland, which exists at both Pensacola and the Naval Air Material Center, Philadelphia, Pa., which had also been considered, could not support such a massive structure. The rocky foundation at the recently acquired Naval Air Modification Unit (NAMU), Johnsville, (Warminster), Pa. was found to be satisfactory in all respects. Consequently the NAMU site was selected for the location of the new human centrifuge. NAMU had been acquired from the Brewster Aeronautical Corporation by the Navy in 1944. Its mission at that time involved the conversion and modification of Navy aircraft prior to delivery to combat units in the fleet.

This selection of NAMU as the site for the new centrifuge was undoubtedly the major factor in the Navy’s decision to announce in May 1947, the proposed expenditure of 100 million dollars for further development of facilities there. With the expenditure of the gigantic sum, it was projected that NAMU, eventually to be called the Naval Air Development Center (NADC), and even later to be called the Naval Air Warfare Center (NAWC), would be virtually equivalent to the Army’s great Wright Field installation, and would become one of the Navy’s greatest shore establishments.

This announcement appeared to settle permanently the question in the minds of the local residents who were concerned about the future of the great aircraft plant and flying field built originally by the Brewster Aircraft Company and later taken over during the war by the Navy. There had been many rumors at the time that large private industries of various natures had sought to purchase the property, and again that the Navy would retain it, but only as a secondary installation, little more than a storage plant. This announcement, therefore, was seen as being of tremendous importance to the future of the entire region.

The actual construction of the buildings to house the centrifuge and the power plant was started in June 1947, and completed in July 1950. The building was basically cylindrical in shape with massive steel reinforced concrete walls. At the center of the 124 ft. diameter, 11,000 sq. ft. operating floor was a 180 ton, 4000 horsepower, 600 volt, DC motor which was capable of attaining a power output of 16,000 horsepower for a short period. This motor, which was built by the General Electric Company, was directly attached to the centrifuge arm and was mounted through 18 feet of reinforced concrete on a solid bedrock foundation The power supply for this motor was obtained from two 1500 kilowatt generators driven by a 4200 horsepower synchronous motor. This motor-generator set and its associated control system were located in a powerhouse adjacent to the centrifuge building and connected to the main centrifuge motor by a bus tunnel. The power to drive the motor-generator set was obtained from a sub-station, which was a part of the regular power distribution network of the NADC.

The centrifuge contract itself was awarded to the Mckiernan & Terry Corporation of Harrison, N. J., with Mr. Hans Hansen, who contributed much to the fine details of the centrifuge design, the project engineer. The centrifuge construction and installation occurred concurrently with the building construction and was in full operation in July 1950, albeit without the gondola and gimbal system. The construction of the gondola was more difficult to fabricate because of the high vacuum requirement. The centrifuge continued to operate for the next two years with swinging carriages attached under the arm at the 20 and 37.5 Ft. locations until the gondola was finally installed in 1952, with the centrifuge dedication occurring shortly thereafter. Scientists who had been using the swinging carriages for their experiments were at first reluctant to move their programs into the unknown world of the dual gimbaled gondola. However, once they made the move, they were able recognize the benefits which it provided and they never went back to the swinging carriages.

CHAPTER III

EARLY CENTRIFUGE PROGRAMS

In order to study all aspects of the effects of acceleration on man, the Aviation Medical Acceleration Laboratory (AMAL), was staffed with professional and technical personnel, both civilian and military, in the fields of medicine, physiology, psychology, human factors, biochemistry, biophysics, and engineering. The Laboratory was officially designated as an associate laboratory of the University of Pennsylvania's School of Medicine, and many of the staff members had faculty status with it's graduate school. The Laboratory was also equipped with a medical library, shop facilities, clerical offices, an animal house, and a small animal centrifuge.

Without citing each of the many worthwhile human and animal experiments that were conducted on the centrifuge during the first ten years of its existence, the following is a list of some of those programs:

* Regularly scheduled pilot training programs;
* The measurement of cerebral metabolism, cerebral blood flow, and arterial blood pressure in both humans and monkeys during centrifugation.
* The determination of human tolerances to various G-profiles in both the upright and supine positions;
* The evaluation of various anti-blackout suits;
* The dynamic simulation of low altitude flight of the A2F aircraft;
* Human tolerance measurements to positive-G at 5 to 10 G/sec.;
* Human tolerances to exposures of 15 transverse G;
* The effect of temperature on human tolerance to positive G;
* The effect of acceleration forces on a pilot during a simulated automatic interceptor attack;
* The increasing resistance to blackout by progressive backing tilting to the supine position;
* Human tolerance to positive G as determined by physiologic end-points;
* Arterial blood pressure response to abrupt positive acceleration;
* Acceleration problems associated with projected research aircraft;
* The measurement of a pilot's ability to carry out such required tasks as: performing optical sightings, actuating cockpit controls, and activating emergency escape devices when under G, when seated in both the upright and partial supine positions.
* Air-to-air tracking in the TV-2 aircraft during closed-loop centrifuge operation;

Over 100 professional papers were written and published on these experiments during the first decade of the centrifuge's existence, many in the Journal of Aviation Medicine and in ASTIA.

Although names are purposely omitted in this treatise for fear of missing any, it would seem inappropriate to include in this list of early centrifuge programs, two that gained those involved a major taste of fame, without mentioning their names. The first was the "Iron Maiden" program in which the civilian psychologist, Flannagan Gray, submerged in the water capsule of his design, endured the world record run of 32 G for 10 sec., answering lights perfectly throughout the run. He suffered slight frontal sinus pain during maximum G and a little blood was observed the next day on first blowing his nose, but no lasting effects. Commander Gil Webb, who was the attending doctor, and Carter Collins, a civilian scientist, also rode the "Iron Maiden", but not to the level that

Gray had attained. Gray actually wanted to go to the 40 G limit of the centrifuge, but the Iron Maiden would not fit into the gondola of the centrifuge at that time, and was mounted on the arm at the 40 ft. section facing outboard, thereby limiting him to the 32 G level in the negative prone position. A special facemask was provided with a hose inserted through the top of the Maiden for the subjects to breath through before the run began. At the end of a count down, a valve on the breathing hose was remotely closed and the G-run began. The subjects, therefore, had to hold their breath during the entire duration of the run, which for Gray, was well over a minute. This apparently was not a problem for Gray, however, because he had been a competitive swimmer. Communication from the subject during the G-run was provided by a finger-operated key inside the Maiden. In the case of an emergency, the centrifuge was quickly brought to a stop, after which a large valve located at the bottom of the Maiden was opened, immediately dumping the water from the Maiden onto the centrifuge chamber floor. After removing the clamps which secured the upper half of the Maiden to the lower half, the upper half was removed by an overhead crane. Although this procedure was practiced often during trial runs, it was used only once during actual subject run, and that was due to the monitoring doctor misinterpreting a signal from the subject.

The second program that gained the participant a degree of fame, was the historic 24 hour 2 G run that the civilian physiologist, Dr. Carl Clark endured. His stated purpose for performing the run was to show that if man could endure such a stress for that length of time, he could therefore travel to the moon or beyond faster than that predicted by other methods by accelerating at 2 G for half the distance, and then decelerating at 2 G for the remaining half. Except for some initial problems in regaining his balance after the run, he suffered no lasting effects. .

During the term of these early experiments, the major method of centrifuge control was provided by mechanical cams. These cams were large masonite discs, designed and cut in-house to simultaneously control the speed of the centrifuge and the directional position of the subject in the gondola with respect to the resultant G vector. Three cams were required for each G profile. Although it was possible to extend the “time at peak” for each G profile when using these cams, they were otherwise found to be quite inflexible--requiring extensive effort in computing, designing, and cutting them.

THE X-15 PROGRAMS

A turning point in the evolution of the centrifuge came during the first X-15 in the spring of 1957. The specific question to be answered here was whether or not the test pilot could tolerate the accelerations of the magnitude anticipated during the aircraft's reentry into the atmosphere with the pitch damper inoperative. The program was run and the accelerations were found to be near the physiological tolerance limit of the test pilot. In this program, the pilot flew as a passenger and the question remained as to whether he could have maintained control of his aircraft under these conditions. The complexity of this simulation, however, required an equally complex cam pattern, which required the use of an analogue computer. It then became obvious that, if the centrifuge were controlled "on line" by an analogue computer, it would be possible to place the pilot in the control loop of the centrifuge and the cockpit instruments, thereby creating a complete dynamic flight simulator. (This simulator would be similar to those, which were used in pilot training and in advanced aircraft design, but would include the addition of acceleration to the simulation.) The analogue computer was used during these early years because the digital computers, at that time, could not perform the many calculations necessary at the speed required for on-line closed-loop operations.

The first real test of this concept came during the second X-15 program in December, 1957. In this program, it was proposed to study not only the pilot's performance, but the performance of the control system and the instruments as an integrated entity. For this initial closed-loop simulation program, 153 runs were conducted in which the pilot experienced all of the accelerations he would have experienced, including those which were self induced, had he been in actual flight. Some of the participants in this program included such well-known aviators as Chuck Yeager, Scott Crossfield, Joe Walker (who had recently set the highest flying altitude record), and Neill Armstrong. It should be pointed out that this crucial program involved the cooperative efforts of the US Navy, the US Air Force, the National Advisory Committee for Aeronautics (NACA), and the North American Aviation Corporation. In addition to the Aviation Medical Acceleration Laboratory, the US Navy participation included the Aeronautical Computer Laboratory and the Aeronautical Instruments Laboratory of the Naval Air Development Center. The success of this program, which not only provided valuable training for the test pilots involved, but also provoked the redesign of a major part of the X-15 control system. It further paved the way for additional X-15 studies and for the many space vehicle programs, which were to follow.

THE SPACE PROGRAMS

The centrifuge gained perhaps its greatest fame as the facility used to train the early astronauts. In support of the national space program, the centrifuge was used in eleven major programs from April 1959, to Nov. 1964. This included six Mercury programs, two Dyna-Soar programs, two Gemini programs, and one Apollo program. A total of 1165 manned runs were performed on the seven original Mercury astronauts, the nine Gemini astronauts, and the fifteen Apollo astronauts. Most of these astronauts, whose names are listed below, were later to gain international fame through their many journeys into space.

Their centrifuge runs were not closed-loop in the sense that the second X-15 runs were, in that the astronauts did not have control of the centrifuge, but they were to perform certain critical tasks during the runs. The G- profiles basically consisted of the accelerations produced by the rockets during the three phase boost period, and the decelerations developed on the capsule during the re-entry period. The maximum accelerations were about 9G during the third phase of the boost period, and about 8 G during the re-entry period. Both of these peak G's had a relatively slow rate of onset. A pad abort profile, however, which was introduced at the decision of the program director and which often caught the astronaut by surprise, had a very fast rate of onset and reached a peak of about 10 G. In order to withstand these G's, the astronauts were positioned in the supine positions, and the very early ones had their own form fitted couches. o The seven astronauts who participated in the six centrifuge Mercury training programs from August 1959 to July 1963 included: M. Scott Carpenter, Donald K.(Deke) Slayton, L. Gordon Cooper, Walter M. Shirra, Alan B. Sheppard, Virgil I. (Gus) Grissom, and John H. Glenn.

The nine astronauts who participated in the two Gemini training programs in July 1963 and Nov. 1964 included: James A. McDivitt, Frank Borman, Thomas P. Stafford, James A. Lovell Jr., Neil K. Armstrong, John W. Young, Edward H. White, Charles Conrad Jr., and See.

The fifteen astronauts who participated in the one Apollo program in Nov. 1964, included: Roger B. Chafee, Charles A. Bassett II, Edwin E. Aldrin Jr., Walter Cunningham, Allan L. Bean, William A. Anders, David R. Scott, Donn F. Eisele, Russell L. Schweichart, Stegal, Michael Collins, Richard F. Gordon Jr., Eugene A. Cernan, Clifton C. Williams, and Richard Truly.

For those questioning why the current group of astronauts does not have to undergo similar acceleration training, they are not subjected to the high accelerations experienced by the astronauts during the re-entry period. The maximum accelerations produced by those early space capsules.

It should be noted here that there were a lot of unknowns in those early days of the space program, and those who were responsible for detailing a plan which was primarily concerned with the safety of the astronauts, should be commended for such a plan that proved its worth by the successful and safe number of moon landings. The plan covered approximately nine years during which it specified the many manned and unmanned tests to be performed, the training for both the astronauts and the ground support personnel, and the many technical problems which had to be solved. If more of America's problems were attacked with the same thoroughness and with less regard for the time required, a similar degree of success could most likely be achieved.

CHAPTER IV

THE CENTRIFUGE MODERNIZATION PROGRAM

In projecting the expected extent of the centrifuge's participation in the nation's manned space program and in the advanced research associated with high performance aircraft, the Bureau of Aeronautics and later the Bureau of Naval Weapons in 1958 sponsored a modernization program to meet the new performance requirements and the increased utilization of the facility. Because of its previous experience in the construction of the original centrifuge, the McKiernan and Terry Corporation was hired as the prime contractor for the construction of the new arm, the gimbal ring, and the gondola. The project engineer, Mr. Robert Ruppert, was notably responsible not only for the design of the new arm and gimbal support structure, but for the new gondola itself, which had been only conceptually described in the specifications. The specific features of this program, which were accomplished on a modular basis resulting in only four months down- time for the heavily loaded centrifuge schedule, include the following:

1. New Centrifuge Control Center --A new centrifuge control center was established in an area exterior to and directly adjacent to the main centrifuge door. It replaced the control center which had originally been located in a blister cell in the ceiling of the centrifuge chamber. This new center, which had its own air conditioning supply, housed a new centrifuge control console with its associated electronic and monitoring equipment, an environmental control console, and a new centrifuge control computer. These items were either non-existent or separated in the previous arrangement. This new center improved capabilities in the operation of the centrifuge in the following areas:

(a) System Performance--The direct control of the gain and damping parameters of all three drive motors permitted performance optimization as required. The centrifuge performance was also greatly improved by installing an electronic device, which balanced the current output of the two main generators, which control the torque of the 4000 hp. main centrifuge motor. These currents had previously become unbalanced during rapid rates of G-set, resulting in reduced performance.

(b) Safety-- A special interlocking system was installed which prevented the start-up or continued operation of the centrifuge when a fault occurs anywhere throughout the control system, including the computer itself. Each interlock had sufficient back-up capacity to make the entire operation both machine-proof and man-proof as well.

(c) Monitoring-- All operational meters including those of the powerhouse equipment were displayed at the control console. Visual contact of the centrifuge and the gondola subject were provided by television.

(d) Perhaps one of the most valuable innovations of the new system was the fault-finding panel. This panel displayed the functional position of all of the major interlocking relays in the entire control system, thus providing fast pinpointing of fault areas.

(e) Mode Control-- Individual control was made available for each axis in either manual or remote (computer) control.

(f) Synchronization and Energization. Special control and display features were provided for and, in fact, required precise synchronization between the command and follow-up signals before energization. This permitted smooth energization and thus prevented undue jarring of the gondola subject, which was typical of the original system.

(g) Limit Selection-- All limit selections were easily adjustable on the console or the computer. These included accelerations in all three axes, the position and velocity of both gimbals, error limits on all drive systems, command limits as generated by the computer, etc.

(h) Compatibility for Analogue Computer Control -- Permanent wiring of controls and interlock circuitry was provided between the computer and the centrifuge control console.

(i) New Centrifuge Control Computer -- A new general purpose analogue computer (EAI 231R) was installed directly adjacent to the new centrifuge control console. This computer, which was used in all centrifuge programs for over 20 years, performed such on-line computations as coordinate conversions, drive motor compensations, G-profile generation, on-line data analysis, and the aeronautical and centrifuge control algorithm equations involved during the many dynamic flight simulation programs. The arrangement of locating the computer adjacent to the centrifuge control console provided a number of technical and operational advantages over the previous situation in which the computer was located in another building over 1000 yds. away. Among these were:

(1) The shortness of the signal lines from the computer to the control circuitry minimized the possibility of interference to the motor drive signals. In this new arrangement, the computer actually functioned as a part of the centrifuge control circuit and was interlocked with it.

(2) The proximity the centrifuge control and centrifuge consoles enabled the operators of both consoles to be in direct communication resulting in increased operational efficiency. Additionally, each operator was immediately available to support the other in the location and correction of faults, which may occur in either system.

2. A New and Larger Gondola ---The new gondola was a 10 ft. sphere compared to the former 10 ft. by 6 ft. oblate spheroid gondola which made it capable of accommodating larger installations. More importantly, however, it was constructed in such a manner that both its upper and lower hemispherical caps could easily be removed, thereby permitting the installation of certain types of cockpits or space vehicles which the original gondola could not accommodate. Also, the limited door size of that gondola necessitated that all gondola installations had to be mantled and dismantled piece-by-piece, thereby consuming valuable centrifuge running time.

3. An Interchangeable Capsule Concept --- This new spherical gondola, with its removable upper and lower hemispherical caps, was actually designed to facilitate the easy removal and insertion of a complete gondola installation which included such items as the seat, the instrument panel, the hand and foot controls, the wiring, and all of the support structure. This interchangeable capsule concept would therefore minimize the downtime between programs and thus increase the availability of the centrifuge for more and larger programs.

Four gondola ground installation fixtures, which were portable replicas of the gondola structural segment, were originally obtained. These fixtures were to be uses in the area adjacent to the centrifuge chamber or at remote locations to be used in the prefabrication of gondola installations. A number of gondola crossbars, universal fittings, bushings, etc. were provided to facilitate the fabrication. The fixtures were provided with casters to facilitate their movement to and from the installation area and the centrifuge chamber. A monorail was installed in the ceiling of the centrifuge chamber for handling the gondola caps and the installations in that area.

Ideally, this concept envisioned further conservation of centrifuge operational time, by having all tasks not requiring the actual running of the centrifuge, performed in the mock-up fixture remote from the centrifuge gondola. If a second computer were available, the complete programming and checkout of each new centrifuge program could be completed in this fixture, including the pre- and post-dynamic subject testing and training.

4. A New and Stronger Centrifuge Arm and Gimbal Ring -- The use of the relatively new Armco 17-4 PH stainless steel with its high strength to weight ratio in the construction of the new arm and gimbal ring enabled them to support a larger payload, a larger gondola, a larger gimbal ring, and additional gondola sliprings and rotary joints with little depreciation (less than 10%) in the centrifuge performance due to its increased moment of inertia. The maximum payload of the new gondola was increased to 1000 lb. at 40G compared to the 400 lb. at 40G limitation of the previous gondola.

5. I*ncreased Slipring Capacity* --- Sliprings at the first and second axes of the gondola were increased from 23 to 124, including the increase of coaxial rings from 4 to 19 in order to transmit more data to and from the gondola. Specifically, the new slipring complement of the gondola included, in addition to the 19 coaxial rings: 15 (1 amp. individually shielded) physiological rings; 48 (5 amp. pair shielded) instrument and control rings; 26 (1 amp. pair shielded) instrument and control rings; and 16 (35 amp.) power rings. Additional slipring requirements for the gondola were to be satisfied by utilizing multiplexing techniques on the coaxial circuits, which would increase their capacity by some sevenfold. A new upper hub slipring stack was also installed which provided 144 circuits (an increase of 44 over the original stack). This stack thus provided 124 circuits to the gondola and 20 circuits to the hub area only.

6. Increased Number of Rotary Joints -- Two independent 3 in. conduits for vacuum or conditioned air were connected from the upper hub rotary joint to two 2 in. conduits on the centrifuge and thence to two new 2 in. rotary joints on each axis of the gondola. The stationary end of the upper hub rotary joint was connected via a 4 in. conduit and various automatic and manual control valves to the air conditioning and vacuum supply rooms. A previously installed 1/2 in. rotary joint in the lower hub area was connected through two rotary joints, one on each axis of the gondola, to supply compressed air for the subject’s anti-G suits. Additional 3/4 in. rotary joints were also installed on each axis of the gondola to convey hydraulic fluids at pressures up to 3000 lbs. to the gondola.

7. Increased Rotational Movement of the Outer Gimbal -- The new outer or roll gimbal was designed to permit 360 degrees continuous rotation which was the same as both the original and new inner or pitch gimbal. The previous roll gimbal had been limited to 90 degrees of rotation.

8. New Wiring and Jack Panels -- In addition to the new wiring and conduits that were provided on the arm between the hub and the gondola slipring stacks, new wiring and jack panels were installed on the stationary side of the upper slipring stacks. The jack panels were located at the instrumentation station on the upper floor, which was the nucleus of all signals being transmitted to and from the gondola.

9. New Intercommunication System -- A new intercommunication system was designed and installed to facilitate the programming of signals between various stations such as the gondola, the instrumentation station, the computer, remote or local, the gondola-loading platform, and a Bell Telephone central station.

10. New Circuit Breakers in the Main Generator Circuit -- Two new circuit breakers were installed in series with the original contactors in the main generator circuit. These circuit breakers, which will primarily operate only during emergency conditions, were installed to absorb large generator currents that may occur under short circuit conditions. The main contactors, which were not capable of absorbing such large currents, were retained for normal usage. This arrangement was made to significantly increase the lifetime of the contactors.

11. New Lower Bearing in the Main Accelerator Motor -- The lower bearing in the main accelerator motor was replaced due to excessive wear. Also, the main motor shaft

was realigned and the bearing support structure tightened. Additionally, an extensive study conducted on the main accelerator motor foundation found it to be in excellent condition.

12. New Environmental Control Console -- A new environmental control console was installed in the centrifuge control room to enable either vacuum or air-conditioning to the gondola to be remotely controlled and computer programmed if desired.

13. Vacuum Caps for the New Gondola --The hemispherical caps provided under the basic contract were not structurally capable of withstanding stresses, which would occur during high altitude testing. A second set of caps was subsequently obtained which were capable of withstanding the stresses incurred during a simulated 100,000 ft. high altitude testing. This surpassed the structural capability of the original oblate spheroid gondola, which was structurally limited to simulating a 60,000 ft. high altitude test. The first set of hemispherical caps were retained, however, and have been used almost exclusively in every program since because of their lighter weight compared to the vacuum caps.

14. New Centrifuge Building Annex -- Increased facilities were provided by the addition of a large three-story annex to the original centrifuge building. This annex was completed in July 1965, and primarily provided space adjacent to the centrifuge chamber for the following support functions:

(a) The fabrication, instrumentation, testing, checkout, and storage of gondola inserts in the ground installation fixtures.

(b) Medical and psychological examination and processing, static testing, performance and medical monitoring, briefing and debriefing, suiting and instrumenting the gondola subject.

The increased operational efficiency and performance capabilities of this new modernized centrifuge were clearly demonstrated in November and December 1964, when 199 runs were completed ahead of schedule in a NASA sponsored Gemini Space program. This program, which used the new controls and in-house computer equipment only, provided the dynamic simulation of a normal launch profile and five abort-reentry pilot controlled profiles for the nine Gemini astronauts. Also, a 3 degree-of-freedom flight profile was realistically simulated which included a fully activated instrument panel.

CHAPTER V

FURTHER IMPROVEMENTS TO THE CENTRIFUGE'S CAPABILITIES

Further improvements to the capabilities of this giant centrifuge have continuously been made over the past 35 years following technological advancements in centrifuge related areas. Some of these include:

1. Digital computers have replaced the analogue computers in both the centrifuge control and the data analyses areas
2. A multi-colored visual display system which provides the centrifuge subject through virtual image optics, a 48 X 32 deg. forward windscreen field-of-view in real time. The system is a Redifusion SP-2 with some of its supporting struts resized to carry the weight of the 400 lb. display unit under a load of 15g.
3. A multipurpose cockpit gondola insert with adjustable down vision, panel width, pilot eye-to-panel and ejection seat dimensions that enable it to be reconfigured to simulate virtually any cockpit while adhering to military specifications. It contains active flight instruments, a programmable GEC A-7 head-up display with a 14X9 deg. field-of-view, and an adjustable McFadden hydraulic three-axis (stick and rudder) control system.
4. A hydraulic driven oscillating platform, which provided the capability of including the effect of buffet in any dynamic simulation study. Since the oscillations, which were involved in either the buffet or turbulence, studies were generally 5 hz. or higher, they did not excite the arm which had a natural frequency of about 2-3 hz.. This platform was essential to the successful 'Clear Air Turbulence" program which will be discussed below.
5. A large array of performance and physiological monitoring consoles which were strategically located in an area adjacent to the loading platform.
6. An attractive subject ready room with a newly constructed viewing window to the centrifuge chamber.
7. A realistic centrifuge control algorithm has been which was essential to the use of the centrifuge a "Total G-Force Dynamic Flight Simulator".

The development of this control algorithm came about during early attempts to use the centrifuge as a motion base for closed-loop (pilot in control) flight simulation studies. It was discovered, not unexpectedly, that in controlling the centrifuge to accurately reproduce the simulated aircraft's acceleration both in magnitude and direction, the centrifuge pilot was exposed to angular motions of the gimbals, which were totally unrelated to those of the simulated aircraft, and which often caused pilot induced oscillations (PIO'S) to occur.

In an attempt to resolve or at least minimize this problem, a series of tests were performed on the centrifuge to develop a human perceptual model, which could then be used as a basis for determining how to modify the control of the centrifuge during closed-loop studies. The initial tests, which involved four centrifuged experienced subjects, were run in May 1974, and included 212 manned runs. In these tests, the subjects were trained to use their control stick to indicate their perception of the vertical when exposed to two types of angular motion in a totally darkened gondola. The first type of angular motion was termed pure angular, in which the subject was exposed to angular motion about his pitch and roll axes while experiencing no variation in the direction of the acceleration vector with respect to his body. The acceleration vector therefore, although varying in magnitude, rotated with the subject's z-axis. The second type of angular motion was termed pure vector, in which the subject was exposed to the angular rotation of a resultant acceleration vector about his pitch and roll axes while remaining in an upright position.

As a result of these studies, which showed that all of the subjects responses were remarkably repeatable and similar, transfer functions were developed which mathematically described the subjects’ responses to both pure angular and pure vector rotations about their pitch and roll axes. In general, the measured perceptual responses to a pure angular rotation were close to being a rate response, while the responses to a pure vector rotation were a delayed proportional response.

The second series of tests, which involved the same four subjects, was run in April and May 1975, and included 445 manned runs. In these tests, the subjects were first required to verify the results obtained the previous year, and then to respond to a series of combined pure angular and pure vector rotations about both their pitch and roll axes. The results, which even amazed the investigators, showed over and over again that the subjects’ responses were in agreement, both in amplitude and phase, with those obtained by adding the individual responses predicted by the above derived transfer functions for each of the angular motions involved.

The remarkable conclusion from these tests is therefore that pure vector rotations, properly phased and amplified can be used to counteract undesired angular motions or to be used in place of them if needed. This then became the basis for designing a centrifuge control algorithm which provided realistic aircraft angular motion sensations to the centrifuge pilot during closed-loop simulation studies with little sacrifice to his acceleration environment This was dramatically illustrated during one closed-loop program in when a subject pilot, who had been making various roll left maneuvers into G in his simulated aircraft, cried out when he made what he considered to be an impossible roll right maneuver. He knew beforehand that the roll gimbal only rolled to the left, and yet he realistically perceived that he had actually rolled to the right. ;

CHAPTER VI

A FEW OF THE MORE SIGNIFICANT CENTRIFUGE PROGRAMS

It is recognized that any attempt to single out just a few of the hundreds of worthwhile programs that have been conducted on the centrifuge during the past 50 years, will omit many that others may justifiably feel were equally if not more significant. For the sake of brevity, however, this treatise will limit itself to those programs, which the lay reader may easily relate to.

To many, this centrifuge is most renown as the device that was used to train the early astronauts. As significant and important as that effort was, however, the centrifuge has been used in many other programs that have directly impacted the safety of the thousands of military, commercial, and general aviation pilots of this country. It has often been said ," If it can be shown that a device has saved just one multi-million dollar aircraft and its crew, the cost of building and operating that device is more than justified." With this in mind therefore, the following programs are presented, each of which, it is felt, meets the above criteria and each of which required the unique characteristics of this centrifuge.

1. CLEAR AIR TURBULENCE SIMULATION OF THE 720-B

This FAA sponsored program involved over 100 transport pilots from various air carriers and 6 USAF Boeing C-135 pilots. The FAA stated that this centrifuge was specifically chosen for the study because it could not only simulate the high frequency accelerations (7 hz.) due to the flexing of the aircraft fuselage during turbulence penetration, but also the long term accelerations associated with flight path changes. This latter effect was a serious omission in a previous study that had been conducted on a vertical oscillator at the Ames Research Laboratory in 1964. Long-term accelerations had to be immediately washout on that device because of its limited oscillation travel.

This program, which began operation in May 1966, lasted for about a year, during which there were 155 manned operating days.

The prime purposes of the program were:

(a) To study the control and stability characteristics of jet transports during severe turbulence penetration;

(b) To evaluate the soundness of presently published pilot control techniques;

(c) To provide training for those pilots which participated and to identify possible revisions which should be made in pilot training programs.

To perform the study, the centrifuge engineers and technicians constructed a mock-up of a Boeing 720-B cockpit, which included the pilot's seat, a functional instrument panel, and a variable force control column. The cockpit was attached to a hydraulic driven oscillating platform, which was then mounted to the center structural segment of the gondola.

While performing simulated maneuvers, including descending and climbing turns, the test subjects experienced three severe turbulence profiles during an approximately 30 min. flight.

"I can recall no other single event that has been more valuable to me as a pilot," said Capt. H. E. Tatman, United Airlines test pilot, after completing the centrifuge runs. "The simulation of turbulence encountered is extremely realistic in the centrifuge. The Boeing 720 cockpit is adequate, and the control forces, the response and stability of the capsule are all remarkably representative of the actual aircraft."

Tatman cited two major benefits from his participation in the study:" Verification of the soundness of presently published severe turbulence penetration techniques and the confidence gained by applying these techniques and maintaining control of the simulated aircraft throughout the severe turbulence penetration."

The general consensus of all the participants was that the study would contribute significantly in determining the proper pilot techniques, which should be used while flying jet transports in turbulence. The pilot procedures recommended to the test subjects for this study emphasized that they maintain a flat, level attitude as much as possible with a minimum of power or trim changes performed while experiencing turbulence. Only when gross, sustained changes in airspeed or altitude are experienced is the pilot advised to change power or trim settings. By applying these techniques during their centrifuge runs, none of the subject pilots lost control of his simulated aircraft.

"The most immediately productive area for improvement in coping with turbulence has been, and still is, in pilot knowledge and training," said Capt. John B. Clark, American Airlines, who has contributed significantly to research into jet transport operations in turbulent air. He further stated, "Misinterpretations of the cues available to the pilot in heavy turbulence can lead to divergent pitch oscillations." Referring to the FAA simulations, Clark said, "It is my belief that they are learning a lot about the human reaction to the elements."

2. NIGHT CATAPULT LAUNCHINGS OF THE A-7 AIRCRAFT 'PHASE I'

The Phase I results of this Bureau of Medicine and Surgery research project, conducted on the centrifuge from Nov. 13 to Dec. 10, 1970, were reported in the January 1973, issue of The Journal of Aviation Medicine. The purpose of this open-loop study was to determine the disorienting effects of catapult launchings on a pilot's ability to properly perceive the attitude of his aircraft, particularly during night launchings. It had been reported that there had been incidences, especially regarding the Navy's A-7 aircraft, where a pilot, following a night catapult take-off from the deck of a carrier and without any signs of a problem, had nosed his aircraft down and flown into the water.

71 manned runs were made during this Phase I part of the study, which involved 12 male subjects, 6 of which were Navy pilots who had experienced aircraft catapult launchings in the preceding six months period, and 6 were Navy enlisted men with catapult experience.

To generate the fast onset Gx linear accelerations on the subject as required by this study, the subject's normal orientation in the gondola had to be modified. By initially placing the roll gimbal in the 90-degree position, and then installing the subject's seat in the gondola in an upright facing forward position, the pitch gimbal became a yaw gimbal. In this position, the subject was exposed to the rapid onset and offset accelerations generated by the tangential accelerations of the arm in combination with the radial accelerations. To maintain the accelerations through the subject's plus x-axis only, the roll gimbal remained fixed at its 90 degree position while the yaw gimbal was rotated through 180 degrees as the centrifuge arm accelerated and decelerated, to keep the subject aligned with the resultant vector of the two accelerations. For this study, the subjects were exposed to approximate square-wave 4Gx acceleration for 3 sec., which was generated during only a 180-degree rotation of the centrifuge arm. The high performance of both the yaw gimbal and the arm as well as the 50 ft. length of the arm were major factors in enabling the centrifuge to generate an extremely realistic linear Gx acceleration on the subject, even to the surprise of many of our nation's best scientists.

All 12 subjects underwent 4 sessions in which data were collected. The sessions lasted for 5 min. each, and exactly 120 sec. into the session the subject was exposed to the simulated catapult launch accelerations. To assure that the subjects were not unduly startled by the rapid accelerations, a 5-sec. countdown preceded the accelerations. The subject's task was to keep a continuously moving target projected on a curved screen in front of him at eye level before, during, and after exposure to the accelerations. The results showed that subjective eye level changed by exposure to the accelerations, and that, in some individuals, the change persisted for more than 1 min. after the simulated launch was completed.

These results, which showed the effects of rotated acceleration vectors on human spatial orientation, are related to certain aircraft losses that have been reported following catapult launchings at night. The explanation here is that the large 76-degree tilt back effect that a pilot experiences during a 4 Gx catapult launch, continues for almost a minute after the pilot has left the deck of the carrier. Concerned with climbing to steeply and stalling his aircraft and without any visible horizon to guide him, he responds to his basic senses and noses his aircraft down and collides with the water. This study, therefore, provided the basis for the cause of those accidents and pointed for the need to make pilots aware of these illusions during their training.

3. NIGHT CATAPULT LAUNCHINGS OF THE A-7 AIRCRAFT 'PHASE II'

The Phase II part of this catapult program was a closed-loop (pilot-controlled) study and was run from March 9 to May 9 1973. In this study, which involved 142 manned runs, an actual A-7 cockpit was obtained from a damaged aircraft, and, after being fully instrumented and provided with support structure, was installed in the gondola with the pilot seat oriented in the same manner as it was in the Phase I study. The subject pilots were then required to actually fly their aircraft after exposure to the catapult accelerations. This study basically confirmed the results predicted by the Phase I study, that, lacking any visible knowledge of his aircraft's attitude, the pilots nosed their aircraft down shortly after the catapult launchings.

The important fact to be gained from both Phases of this study therefore, is that, especially during a night catapult take-off, a pilot must not rely on what could be a very strong somato-gravic illusion regarding his aircraft's orientation, but to rely only on the orientation information provided by his flight instruments, especially the attitude indicator.

4. DYNAMIC SPIN SIMULATION OF THE F-4B AIRCRAFT 'PHASE I'

With the operational necessity, especially during air-combat, for a pilot to fly his high-performance aircraft close to its stability limits, the possibility is increased that he will encounter spin, become incapacitated or disoriented, and lose control of his aircraft. Statistical records at the time showed that of all aircraft accidents, stall/spin accidents were responsible for the highest percentage of human fatalities, with the percentage of aircraft loss close to 100%. Since training and practice in controlling an actual aircraft during a spin situation were prohibited because of the danger and cost involved, pilots were forced to recognize, react to, and recover from their first encounter with stall/spin conditions without previous trial or experience. Since the alternative to actual flight experience would be a ground-based simulator which was capable of producing the dynamic force field, an out-the-window view, and other response characteristics of an aircraft in a stall/spin status, the Navy initiated this feasibility study to determine if a centrifuge could effectively be used as such a simulator.

This Phase I part of the study was run from Aug.24 to Oct. 27 1967, and involved

138 manned dynamic runs. It was basically an open-loop feasibility study designed primarily to assess the centrifuge's ability to realistically reproduce the forces a pilot would encounter when his aircraft flies, goes into stall and post-stall gyrations, spins, and pulls out of the spin in recovery.

To perform the study, an actual F-4B cockpit from a damaged aircraft was obtained and configured to mount within the 10 ft. spherical gondola of the centrifuge. All of the original flight instruments, switches, levers, and other peripheral components of the cockpit were retained and activated where necessary to ensure a realistic environment for the subject pilots. As in the actual aircraft, an artificial feel system was designed in the simulated aircraft controls to provide the pilot a feedback of the forces being developed on his aircraft's control surfaces.

Data from actual spin test flights performed on an F4-B at the Naval Air Test Center (NATC), Patuxent River, Md. were used as the basis for the dynamic spin simulation. The spin of the F-4B was being investigated from various spin entry conditions such as level-flight, stalls, accelerated turns and reversals, and vertical and inverted climbs. The resultant spins were both to the right and to the left. Spin reversals were often encountered during the recovery from the spin.

Recorded data from these flights that were used in the simulation study included; Gx, Gy, Gz, (accelerations taken at the pilot's seat), p, q, r, (body angular velocities), alpha, (angle of attack), IAS (Indicated air speed), altitude, attitudes (angles of roll, pitch, and yaw), positions of the aileron-spoilers, stabilator, and rudder, forces on the stick and rudder petals, and positions of the stick and rudder. Also recorded and used for the visual outside-world presentation to the centrifuge subjects were motion pictures taken by a camera that had been mounted over the right shoulder of the pilot and focused to record both the flight-instrument response and a view out of the window. Because of the dual function of these black and white films, the out-the-window display had very poor quality; nevertheless, it was sufficient to use as a visual reference for the centrifuge subjects.

The subjects selected for this study were eight Navy pilots from NADC and three test pilots from NATC who had flown actual spin flights in the F-4. Six of these pilots had extensive experience in flying attack and fighter aircraft; and of these, three had considerable F-4 experience. Five pilots recalled spin experience; three had encountered unintentional spins; and two were versed in intentional spins of the F-4.

The spin progression of the F-4B can be defined as occurring in two stages; incipient and fully developed. The incipient spin is the initial stage during which irregular oscillations occur about all three axes. The fully developed stage is attained when equilibrium conditions are reached and the oscillations are stabilized about all three axes. Recovery from the fully developed stage is often more difficult that from the earlier stage.

The experimental program consisted of having the pilots experience the simulated spins and then evaluate them. Four representative spins were selected from the NATC data. In general, each pilot was scheduled to make four static and eight dynamic runs (four in a fog condition and four with the visual display). By reversing the direction of the pertinent signals, the possibility was created for any one spin to be either a left- or a right-turn spin. When proper care was taken to shield against visual clues to the subject, the yaw effect of the centrifuge's motion was minimal if at all noticeable. In spins to the left, the centrifuge yaw motion and the aircraft yaw motion are aligned; however, in spins to the right, they are opposed. In spite of this fact, the control of the total acceleration was such that none of the pilots perceived this difference sufficiently to comment on it, either in written or verbal communication.

A projector was mounted inside the cockpit. The films were projected on a mirror situated behind and above the pilot and focused on a screen placed in front of the cockpit. The enlargement was of a size to compare with the field of view as seen by the original flight pilots. The time relationship of the out-the-window display of the flight-control instruments and of the motion sensations was very critical.

Results-- Five of the pilots rated the spin simulation without the visual display as excellent, and six rated it as good When the visual display was added, the pilots who had classified the simulation as good subsequently rated it a qualified excellent, asking for improved film quality.

Regarding the control stick, the pilots were told that the stick had no influence on the problem, but they were given the freedom to use it if they so desired. Under static conditions, the pilots made few meaningful stick inputs. Under dynamic conditions, however, there was a significant reaction. Those pilots, who were versed in high performance aircraft recovery techniques, responded by either voluntarily putting in proper signals, or requesting to do so. Pilots uncertain about recovery techniques either wiped out the cockpit or just gripped the stick and hung on. Thus the dynamic simulation was sufficiently realistic to excite a positive reaction in the evaluating subjects.

The activation of the control mechanism by the centrifuge pilots during the spin maneuver was found to be in close agreement with the action taken by the aircraft pilot in recovering from the same spin. This adds credence to the realism of the simulation and supports the concept that training in a realistic simulator is beneficial.

This open-loop simulation study basically substantiated the concept of using this centrifuge as a dynamic simulator for aircraft spin maneuvers and recovery. The desirability of a spin simulator which includes activated instruments, a dynamic force field, an out-the-window visual display, and a realistic environment was clearly demonstrated.

5. DYNAMIC SPIN SIMULATION OF THE F-4B AIRCRAFT ‘PHASE II‘

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This Phase II part of the F-4B Spin Program was closed-loop (pilot controlled) and was run during January, February, and March 1970, with a total of 200 manned dynamic runs. The purpose of this program was two-fold. The first was to determine if a closed-loop dynamic spin simulator using the proper aero dynamical data was feasible and could make a positive contribution to the training and experience of pilots who must fly high performance aircraft. The second purpose was to determine the relative values of the various components of the total simulation and to what degree are they essential for a aerodynamic equations of the F-4B aircraft.

As in the actual aircraft, the control stick was fitted with an artificial feel system. The force on its longitudinal axis was provided by a hydraulic actuator, which was controlled by a load cell transducer, which sensed the variation in aircraft speed, dynamic pressure, and G force. The less complex lateral stick and rudder petal controls were simulated using springs with appropriate constants.

The visual display for the spin simulation was the result of an in-house effort. The nucleus of the display system was a separate attitude indicator, which was driven by the same signals that drove the attitude indicator in the instrument panel. The upper hemisphere of this eightball was painted to physically resemble the sky with various cloud formations while the lower hemisphere was painted with a typical landscape as seen from an aircraft flying at roughly an altitude of 25,000ft. A small 1-inch square portion of the painted eightball was illuminated by a special light source and the reflected image of this small area was enlarged through a remote-controlled zoom lens so that it engulfed a screen directly over the instrument panel. Using altitude as the control signal for the zoom lens, size variation of the display corresponded to the real world. A Fresnel lens, placed in front of the screen, not only enlarged the picture for the simulator pilot, but also added a feeling of depth to it.

23 USN pilots, 5 USMC pilots,1 USAF pilot, and 5 engineers rode the spin simulator although only eleven participated in the formal phase of the program. The others, although they did not have the required flight experience in the F-4 aircraft to meet the needs of the program, had special interest and responsibilities in problems dealing with spin. To evaluate the effects of motion on the simulation, three different modes of motion were provided for each of the participating eleven pilots: a static mode, in which the centrifuge wasn't energized corresponding to a fixed-base simulator; a gimbals only mode in which only the gimbals were energized; and the fully dynamic mode which encompassed the long term multi-directional accelerations provided by the arm and gimbals.

After a brief indoctrination period, each pilot made a series of six experimental runs in a random sequence in which the presence or absence of the visual display was a variable as well as the modes of motion. Each pilot experienced one run with the visual display and one without for all three modes of motion. The subject's task during these runs was to recover from a spin, which he had deliberately initiated. His recovery was to follow at least three complete turns of spin, and was to be accomplished by the use of anti-spin controls dependent on the direction of the spin, followed by recovery controls when the yaw rate went to zero. The recovery control was very time dependent -- too soon the spin wraps up tighter, too late it reverses.

At the end of these runs, the pilots were allowed optional runs, when time permitted, in which they could try alternate methods of spin recovery techniques including the use of trim rather than stick and direct neutralization of controls. Other optional runs included; high G spin encounters, spin reversals, inverted spins, and sustained high G. The engineers were especially interested in the effect of changing the aerodynamic coefficients and derivatives.

Although there were many recommendations regarding ways to improve the quality of the spin simulations such as adding buffet, wing rock, and noise, the spins produced were quite realistic and favorably accepted by the evaluating pilots. They encountered spin reversals and difficulties in recovery when improper recovery procedures were followed.

Aircraft did "crash" on occasion; however, unlike the real world, a simple "reset" resulted in a new aircraft ready for flight.

The greatest compliment given to the simulation was the eagerness of both knowledgeable engineers and pilots to try theories and ideas, which they had been holding in abeyance due to the lack of a suitable simulator and to the necessity of solving the very complex multi-looped equations in real time.

The analysis of the data obtained in this spin study revealed that a closed loop dynamic spin simulator using a centrifuge as the motion base and the proper aerodynamic data was feasible and could make a positive contribution to the training and experience of pilots who must fly high performance aircraft. A dynamic visual display was deemed a necessity, and the long-time accelerations provided by the centrifuge as highly desirable. The accelerations not only furnished the longitudinal G stress resulting from the spin but also the stresses and strains of the flying task similar to those present in real flight. Flying the simulator with full motion committed the pilots to being more involved in the task than they were when flying in the static mode.

The success of this F-4 spin program was recognized by the Naval Air Systems Command in their decision to proceed with a spin study on the F-14, a high performance aircraft currently being developed at that time. It was projected that such a program would help to anticipate spin problems of that aircraft and would develop methods of solving them. The problems and their solutions would involve the basic aerodynamics, the variable coefficients, and the man-in-the-loop interactions in a fully dynamic environment.

6. F-14 DEPARTURE/SPIN PROGRAM

In early January 1979, the Commander, Naval Air Systems Command, established an Executive Review Group (ERG) to conduct an independent, objective review of the recent loss of eight F-14/TF30-P-412A/414 aircraft due to controlled flight departure and spin entry following an engine stall.

With the knowledge that the F-14 would be in their operating inventory for at least another 20 years, the ERG Group had to take into consideration the costs of long- range improvements and the long-range consequences of near-term actions.

After a thorough study of the accidents, the Group concluded that the basic cause of most of the accidents stemmed from a quite pervasive Fleet tendency to fly the aircraft during ACM flight out to the limits of its envelope, where engine stalls and aircraft departures were not uncommon and from which prompt recovery was the usual experience.

Occasionally, however, the Group found that a combination of aircraft mission, aircraft configuration, aircraft attitude, engine behavior, and consequent pilot reaction would lead to departures and flat spins, from which only one recovery had resulted at that time, even though indications were that others may have been possible. The problem therefore, that faced the Group, was to reduce the likelihood of these departure/spin-prone combinations from occurring, and to increase the opportunity for recovery, should flat spins occur.

Among the recommendations of the Group included:

* An evaluation of the planned improvements to the underpowered TF30 engine to ascertain whether they would reduce the incidence of engine stalls;

* A study of the flight control system, and the response of the aircraft to flight control inputs;

* A determination of the probable nature of the pre-spin departure, the spin itself, and the influence of engine stall and pilot control actions;

* The identification of the aircraft configuration at the time of the accident. Those elements that would have tended to exacerbate the departures included the addition of external tanks and the absence of maneuver slats. In addition, if the roll Stability Augmentation System (SAS) had been switched on during high angle of attack maneuvers, the differential tail would have introduced increased pro-departure yawing moments when high roll rates were encountered.

* The possibility of placing restrictions on the maximum angle-of-attack to which the aircraft could be flown, or to restrict the lateral control inputs without changing the angle-of -attack limits or both..

A major concern of the group, however, was the extent to which each pilot was able to function, both physically and mentally, under the stress of both the pre-spin and spin conditions, the kind of actions which he took, and the status of his restraint system. A review of the accidents revealed that in some cases the pilots had actually ejected prematurely. This may have been contributed to the fact that very few F-14 pilots had had any experience, real or simulated, with the force characteristics of flat, nose-low, or inverted spins, and consequently would not have been prepared for the debilitating and disorienting stresses, which would occur. These effects could have been further aggravated by the pilot’s uncertainty as to which way the flat spin was occurring, by his contradictory cockpit displays at high yaw rates, and by his real concern as to whether his restraint system would prevent his forward or upward motion as the negative and/or longitudinal G increased. Forward motion would have further added to his distress by reducing his options for applying recovery controls, and by making ejection harder to accomplish.

In order to overcome these problems imposed by the G forces in a spin, or their effect on a pilot, the ERG Group recommended that F-14 pilots undergo regular training in a spin simulator. Such a simulator should represent the complete spectrum of disorienting motions characteristic of all F-14 configurations, from departure to erect or inverted spin recovery, with proper representation of the effects of alternative recovery controls including throttles, the view through the cockpit window, and the operation of the cockpit instruments, under flat and nose-low spin conditions. The design of this simulator and the need for aerodynamic data inputs would have to be coordinated with other activities by NASA, the Navy, and GAC to reduce duplication of effort.

It was envisioned that this R&D spin simulator, which should be developed utilizing NADC technology, would be used for departures, spins, and recoveries for the F-14 and other aircraft, assessment of loads on the crew and the incapacitating effects of spins, evaluation of alternative crew restraint and other safety systems, development of spin-proof cockpit presentations, evaluation of pilot workload and responsibilities in spins, and development of specifications for a Fleet general purpose spin simulator.

Following this recognition of a need for a dynamic spin simulator, and at the request of NAVAIRDEVCEN, a departed flight/spin flight fidelity evaluation of the DFS was conducted on 13-14 March 1985. The multi-purpose cockpit was configured to represent that of the F-14 aircraft. The McFadden stick and rudder control loader systems were programmed to give realistic feel simulation for the pitch and roll control functions. A computer generated out-the-window real world display was provided by a Rediffusion Simulation, Inc. SP-2 system. The visual scene was generated on a 19-inch cathode ray tube, which was then reflected to the pilot to provide a 48 deg. by 32 deg. field-of-view. The sideslip and yaw rate were accurately represented by the display and provided the pilot a good representation of the actual motion that occurs in the F-14 during departures. An automatic locking restraint harness and a stick position indicator, both developed by engineers at NADC, were included in the installation for evaluation. Also included was a spin direction arrow and yaw rate indicator, developed at the Navy's Pacific Missile Test Center, Naval Air Station, Pt. Mugu, CA

One of the purposes of the program was to determine the yaw rate at which F-14 pilots would be able to recover their aircraft after it had entered a fully developed flat spin. This was addressed by having pilots perform spins at various yaw rates up to 155 deg./sec. (-5g), and then assessing the effectiveness of their control inputs by measuring the time elapsed and the altitude lost before the aircraft was brought under control.

Seventeen pilots participated in the study. Eleven were fleet F-14 pilots, two were spin instructors in the Rockwell International T-2, and the remaining four were test pilots from the Naval Air Test Center, NASA-Dryden, and Grumman Aerospace Corp.

The automatic locking restraint system was unanimously praised by the pilots because it allowed them freedom of movement, desirable during many phases of flight such as air combat maneuvering, until the aircraft senses 0.8g eyeballs out, at which time the harness locks automatically. They, in fact, recommended that it be immediately incorporated in fleet aircraft. Following an NADC proposal, therefore, such a system was subsequently designed to be incorporated in a new common ejection seat scheduled for the F-14D, the Navy/McDonnell Douglas F/18, the Navy British Aerospace/McDonnell Douglas T-45, and the Navy/Grumman A-6F.

While the spin direction arrow did not have any well-defined impact on aiding pilots in recovery from developed spins, the pilots felt that the yaw rate readout gave valid trend information. When measured against altitude remaining, it aided them in reaching a decision on whether to continue recovery attempts or eject. This display, which results from a software change, has now been incorporated in both the F-14A and the F-14D aircraft.

The study showed that pilots were not incapacitated by the high eyeballs-out G forces and that they were able to hold full anti-spin controls even under -5g. In addition, the DFS provided an excellent vehicle for evaluating new developments safely during out-of-control conditions. While there were some technical criticisms of the study, mainly with regard to the inadequacies of the aerodynamic data used in the computer software part of the simulation and which were recommended to be updated for future programs, the force and motion phases of the simulation provided by the centrifuge as well as the visual system and cockpit controls and instrument displays were deemed very satisfactory.

Further, the pilots who participated in the study, felt that the training was invaluable and that as many F-14 pilots as possible should be exposed to the spin training.

CHAPTER VII

POTENTIAL FUTURE PROGRAMS FOR THE CENTRIFUGE

It should be noted, that although the centrifuge has been inactive for almost three years, it is still physically operational and uniquely capable of serving the needs of the military, commercial, and general aviation aircraft authorities. When NAWC moved to Patuxant River, Md. in 1996, the operation of the centrifuge was placed in the capable hands of the Veridian Corp.(formerly Veda Inc.).who operated it efficiently for about 3 years, mostly on Navy programs. Unfortunately, with the large distance between the facility and its sponsors and the obvious commitment of the Navy to its new facility in California for its training requirements, the funding available for the operation of this centrifuge was insufficient There were concerns expressed, however, by some members of the Navy when the decision was made by Veridian to stop operation.

Regarding its future, there have been newspaper articles published that recommend it be relegated to the status of a museum. However, another Company, familiar with its potential, would like to reopen it if they could get the go-ahead from Washington.

While updating is needed in certain areas, this centrifuge, with its unmatched capabilities and realistic control algorithm, is uniquely capable of providing an entire class of training methodology that is available in no other U.S. facility, such as:

* Pilot-in-the-loop, high acceleration maneuvers, with high onset rates.
* High angle of attack departures/flat spins with sustained negative Gx
* G-LOC exposure and recovery.
* Pressure breathing to combat G.
* Altered states of awareness (AWA)
* Familiarization with various aircrew equipment when failures occur.
* Emergency procedures under environmental stress.
* G tolerance following exposure to negative G.(push pull maneuvers)
* Aircraft catapulting.
* Spatial Disorienting Maneuvers.

Pilot controlled dynamic simulations of these potentially hazardous flight situations could provide, in addition to pilot training under safe conditions, the evaluation of new cockpit instruments and displays, new restraint systems, new pilot procedures, etc.

In the area of spatial disorientation, the late Kent Gillingham stated: “Despite continuing efforts to educate pilots about spatial disorientation and the real hazard it represents, the fraction of fatal aircraft mishaps caused by or contributed to by spatial disorientation remains fairly constant at about 10%. A pilot’s ability to cope with the effects of disorientation on his control inputs to his aircraft comes through effective flight instruction, proper physiological training, and experience in controlling his vehicle in an environment of conflicting orientation cues“.