THE GENESIS OF AN EXPERIMENT

or

The Framework of Experimental Development

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Abstract

Every experiment, when performed for the first time, is done in order to further develop a science, or technology to enhance military or civilian equipment. This paper shows that experiments into unknown territory always use the same fundamental steps, regardless of if or how they are named. When these experiments are repeated as student work, sometimes these steps are only implied. Instruction delivered by computer simulation frequently ignores most of these steps.

I. INTRODUCTION

While computer simulations of experimental processes can be valuable because they save time and allow greater progress in limited class time, both professors and students must recognize and understand the essential steps of an experiment as detailed below. Class discussion should explore these steps at the beginning of a course.

The seven essential steps of any experiment are:

a.) PROBLEM: Recognizing a need to either find answers to a new situation or further develop a field of study.

b.) DESIGN: The experimental apparatus and procedure visualized to accomplish the desired result whether using standard instruments and apparatus or something entirely new.

c.) DATA: The records which document the experimental procedure. These may be written, recorded, photographed, or researched from old records; whether quantitative or subjective.

d.) INTERPRETATION: Selecting, sorting, filtering, and reducing the mass of raw experimental data to expose consistent results.

e.) DECISION: Determining the next step to resolve the original problem, or determining if the experimental results are acceptable.

f.) IMPLEMENTATION: Redesigning the test apparatus or modifying the experimental approach as required to test the newly formulated experimental hypothesis.

g.) REPORT: Publishing the experimental results in the required format, whether as a formally published scientific journal article, a student lab report or a report document prepared for the sponsoring agency.

Most faculty do not recognize these names or terms since they are not standardized. Whether named or not, these same steps are always present in any new original work, as will be shown. Most undergraduate work, even if it uses real physical experiments, fails to show students this essential seven step framework.

Both undergraduate and graduate students are trained to do original work; as are two year associates, who work as lab technicians and four year technologists. They are not needed strictly for repetitive work. Their job description includes developing job-related tools.

I will illustrate this process with a few projects from my own experience in the aerospace industry. Each is broken down into the seven steps to show that these basic steps are always there even though I didn’t recognize them myself, at the time.

My experiences are typical: Aerospace engineers compete by developing proposals for new work. When a contract is awarded we went to work on challenges which frequently had never been done before. Many engineers have had similar careers.

The experiments ranged from miniaturized replications in the lab using traditional laboratory equipment, to *in situ*, in-flight tests on full sized aircraft/spacecraft, when we couldn’t replicate required conditions in a lab or wind tunnel. (and in a few cases, because the environment was in outer space).

II. AIRCRAFT DEVELOPMENT TESTING (1942-1946)

Back in this era, the state of the art for aerodynamic calculations was such that the calculations of top speed, rate of climb, and ceiling of a new design could only be estimated to within about 2 or 3% of the actual test results. However, no calculations could give much information on how the controls felt or responded, or the stall and spin characteristics. Today this situation has not greatly improved.

The then newly minted Chance Vought F4U-1 "Corsair" fighter was the first fighter to actually reach an effective 400 mph air speed. While performing up to expectations the Corsiar had some very nasty stall and spin characteristics.

Data for "leading edge technology" environments usually does not come from conventional instruments. In fact even today, needed data may not yet exist as it often escapes conventional instrumentation.

The first six production Corsairs were test flown briefly, before delivery to the Navy. Five of the six were sent back to Vought for extensive testing. The sixth wound up in Chesepeake Bay. So we had five Corsiars back for testing only a few weeks after delivery: One was for performance measurements, one for powerplant testing, and a third for high speed dive tests. A fourth was for maneuver and spin tests, the last was for durability testing and it flew more or less continually. Each airplane had different instruments for its specific tests which were constantly changed and upgraded.

1. Corsair (F4U-1) PERFORMANCE TESTS - (1942 - 1947)

Tests were made for maximum speed, rate of climb, peak and critical altitude, stall speed and characteristics, spin and spin recovery, landing speed, takeoff speed/distance, roll rate, maximum safe dive speed, high g (acceleration) dive pullouts, control forces, and others. In fact tests continued for five years as problems emerged and were resolved and new design features were added to improve performance.

We found that pilots, however skilled and experienced, were challenged to their limits just in flying the designated flight patterns and in reaching and holding the desired conditions. Hence we needed Step-by-Step automatic recording equipment, which was then developed and used.

As a new-hire in the Chance Vought Aerodynamics Dept.[1], I spent my first two weeks plotting performance curves from ongoing tests from the XF4U-1 and the XTBU-1 torpedo bomber. Later, on loan to the Flight Test Instrumentation department, there was a rush of instrument calibrations for the five new test aircraft, (the Corsairs). All this while keeping the instruments in the XF4U-1, the XTBU-1 and Mr. Sikorsky's VS-300, the first true Helicopter, ‘flight ready’. By January 1947, this department grew to ten engineers and technicians. Here are a notable few of our experimental test programs.

The need for accurate recording became evident early on in an assignment to take a Corsair about fifty miles from the Stratford, CT factory to East Hartford, CT to fly a measured three mile speed course along the Connecticut River.

The flight plan was to maintain 100% power (2700 rpm @ 53” Hg manifold pressure) while flying at 300 feet altitude. This was done to stabilize the engine and oil temperatures while flying at about 300 miles per hour in the dense low altitude air. In addition to maintaining the flight plan parameters the test pilot, Boone Guyton, also read and recorded 18 cylinder head and 18 cylinder base temperatures along with a few others. He would check outside conditions, then duck his head down to read the cylinder temperatures on three cylinders, come up and look around and then write the data on his knee pad. This was dangerous business at best even, though he had carefully trimmed the controls. In this case he flew past East Hartford and never saw it. Next, he saw only unfamiliar territory so he finally landed at the first airport he saw which was in Haverhill, Mass., some 100 miles too far!

As a result of this flight, and other inadequate measurement situations, we soon developed a “Photo Observer”. This was a closed aluminum box which contained duplicate set of flight instruments and other meters used to monitor special test data. These instruments usually paralleled those the test pilot used. A special single-frame motion picture camera was used to record readings on the whole group of duplicate instruments which was lit by sealed beam auto headlight bulbs.

A Veeder-Root counter in the Photo Observer was synched with a similar counter on the pilot's instrument panel. They were incremented after each single frame picture. The pilot would fly the desired flight plan and record his counter reading to log his progress. This system worked well once nonreflecting coatings were applied to the instruments cover glass.

[1] a division of United Aircraft Corporation

As another immediate result of the aborted speed test flight above, we searched and found a recording potentiometer for the engine temperature thermocouples. This Brown Recorder was a vacuum tube servo-driven self-adjusting slide wire in a modified Wheatstone Bridge circuit and mounted in a large case. It would adjust to an individual thermocouple then hesitate while its stamp wheel inked itself and stamped a small **x** on the moving chart paper. Then it would automatically self switch to the next thermocouple in sequence. This device had been developed for central station powerplant recording and, like many other devices, it did not "take kindly" to the sudden accelerations and rapid temperature, pressure, and attitude changes in a fighter flight regime.

A solenoid was added to a commercial rubber stamp[2], to advance it one digit at a time, for printing sequence numbers on the moving chart. The sequence numbers matched those in the Photo Observer and on the pilot's panel. Once adjusted, calibrated and debugged, this apparatus produced reliable data.

Many test flights combined tests for instrumentation development with aircraft performance tests. In wartime, flight time, test costs and hazards, were too precious to allow things to be done one at a time. Even using these unorthodox methods each test can be broken down to the seven essential steps, as will be shown..

The science of aerodynamics had not yet discovered that at speeds near Mach 1, the center of lift in the wing would quickly move aft (about six inches in a Corsair). This made the 13,000 lb. aircraft abruptly very nose heavy. This aircraft, like others of this era, had no power boosted controls, or even ejection seats.

As a result, no WW II fighter airplane could safely dive to its terminal velocity, e.g. its maximum speed. Earlier in the 30s, bi-planes with fixed landing gear had enough drag so that they would only reach roughly twice their level flight speed when diving straight down. This was well below Mach 1, the speed of sound. Mach's experiments, which used artillery shells, showed no pressure shift aft as he measured the shell drag while it was in a trajectory.

All WW II fighters, US, Allied or enemy, were streamlined monoplanes with retractable landing gear and closely cowled engines or radiators so they shared a common problem: In a dive, any one of them could reach a speed where they either come apart or become so nose heavy, that they could not recover from it. The steepest prolonged survivable dive, was around 15° !

Consider the massive power gravity exerts on a diving aircraft:

$$1 \text{ hp} = 550 \text{ ft lbs/sec.}$$

$$550 \text{ ft /sec} = 375 \text{ mph}$$

$$\therefore 2000 \text{ lbs of thrust at } 375 \text{ mph} = 2000 \text{ hp!}$$

A Grumman F6F Hellcat needed 2000 lbs of thrust to overcome its total drag at its top level speed of 375 mph. A dive straight down adds the weight of the aircraft to its propeller thrust.

[2] The kind that uses belts with ten digits each

In a dive, as the speed increases, and the center of lift shifts aft, the weight of the aircraft (13,000 lbs.), is added to the thrust from the propeller. At 375 miles per hour, the aircraft will be driven by a total thrust of nearly 15,000 lbs. As a WW2 fighter approaches Mach 1 it may become too nose heavy to pull out of the dive, or it may come apart due to the violent vibrations. Engineers and test pilots in Chance Vought and other aircraft factories around the world, were kept busy finding out just where the boundary between safety and destruction really was. No U.S. wind tunnel was available that could produce supersonic or even Mach 1 speeds.

After WW II, captured German documents showed that they too had done high speed aerodynamic experiments, by using a nozzle on a pressurized tank which produced a blast of air around Mach 1. The plume of Mach 1 air was about three or four inches in diameter, so tests had to use a tiny model.

Selected Corsair performance tests are described below:

2. CRITICAL ALTITUDE TESTS - (1942)

a.) PROBLEM: Find how closely the Corsair met its critical altitude specification. Note that critical altitude is the highest altitude at which full engine power can be produced. In 1942 the early R-2800 B was rated as 2000 horsepower @ 53” Hg manifold pressure and 2700 rpm. This 2800 cubic inch, 18 cylinder engine was state of the art. It could exceed its rated 53” manifold pressure on its main supercharger and so take-off used slightly reduced throttle. At around 7000 feet, full throttle would no longer produce 53” pressure, so the second stage supercharger blower was engaged at low blower setting and the throttle eased to 53 in. At about 15,000 feet, 53” required full throttle again so the second stage blower was shifted to high blower setting. There were clutches and various gear ratios to accomplish this. The pilot operated blower speed controls for no, low, or high auxiliary blower. It was desired to find these three altitude points and especially high blower critical altitude which was the highest that full power could be held and also the highest speed that could be reached in level flight. This was expected to be about 403 mph.

b.) DESIGN: Since this was one of the first performance tests, no recording equipment had yet been developed. The test pilot would fly straight and level at successive 100 foot altitude increments to collect data.

c.) DATA: The test pilot started below the expected critical altitude and climbed to where the 53” manifold pressure could no longer be reached. During each run he manually recorded this data on his knee data board: engine RPM, manifold pressure, cylinder head temp (hottest cylinder), airspeed, altitude, and outside free air temperature. The latter was used to correct the indicated airspeed, IAS, to standard conditions at that pressure/altitude. He also checked oil pressure and oil temp frequently to see if they were changing. Multiple test flights were required.

d.) INTERPRETATION: All pilot recorded data had to be manually corrected for instrument calibrations to produce accurate readings. Air speed then had to be corrected for standard air temperature at that altitude. This required a corrected temperature reading because the air would compress and increase temperature in front of the small, stub pencil size, air temperature bulb. The correction factor was taken from with US Navy and Bureau of Standards temperature rise corrections to get the true air temp and then the calibrated airspeed corrected for the standard temp at that altitude. This data factor was adjusted for each data run, a table was built, the data was hand plotted. Data, though scattered, could be interpreted to show the true critical altitude.

e.) DECISION: To optimize the ram air inlet pressure, various refinements of supercharger inlet air duct opening contours were tried to get marginal improvements in ram air pressure. Separate tests were run with all sorts of total head and static air pressure tubes in the ducts, and connected to special instrumentation by pneumatic selector switches.

f.) IMPLEMENTATION: Subtle duct shape changes were made and tested in flight until an optimum shape was found and put into production.

g.) REPORT: Our tests found that the true critical altitude was 22,500 ft, which met the critical altitude spec. As a result, the Corsair actually exceeded 400 mph in level flight!

The tests continually got more elaborate as the instrumentation, the recording devices, and test techniques were refined.

3. STALL TESTS / Corsair F4U-1 - (1943)

a.) PROBLEM: Identify the cause and take steps to prevent or correct the Corsair's potentially lethal tendency to stall quickly, and without warning on a simulated carrier deck landing approach. It would flip over on its back and dive into a potentially fatal crash into the stern wake of the carrier if the pilot got two or three knots below the desired landing speed. Fortunately this tendency was found before actual carrier landings were attempted. This problem caused long delays in carrier acceptance and the early Corsairs went to shore-based outfits such as the famed "Black Sheep" squadron.

b.) DESIGN: Flying at a safe altitude, the test pilot would repeat the entrance to a stall. Gunsight Aiming Point Cameras (GSAP) were installed high on the leading edge of the vertical tail. Equipped with wide angle lenses, cameras were aimed at the upper surface of each wing, which was covered in a grid of six inch squares each marked with a five inch tuft of bright yellow yarn. The tufts were attached with squares of “duct tape”.

c.) DATA: The stalls were repeated over and over and motion pictures from the GSAP cameras clearly showed that the stall started at the root of the gull section of the left wing. The affected area was conspicuous because the yarn would stand up and lash violently in a stalled area. These yarn stall detectors are still used today even on new space shuttle designs.

d.) INTERPRETATION: When synchronized motion pictures of the right and left wings were projected side-by-side, the unsymmetrical stall was clearly shown. Enlarged prints of sequential stall progression were used to pinpoint the problem.

e.) DECISION: It was soon determined that the desired cure would be to induce a stall on the right wing because the unsymmetrical rotating vortex from the propeller, which was still delivering power, would strike the root of the left side gull wing at a higher angle of attack than the right wing.

f.) IMPLEMENTATION: A small wood block spanning about 10 inches, with a sharp leading edge, was attached to the right wing leading edge outboard of the gun ports but still inboard of the aileron. In successive tests the position up or down and the leading edge radius of the block were varied Step-by-Step. Finally a satisfactory straight ahead stall was achieved and this small wood block was installed on all of the 10,000 or so Corsairs produced over the next decade.

g.) REPORT: While I was completely involved as a new Flight Test Instrumentation Engineer, I never did see the final report, since it was classified SECRET. But the Navy Bureau of Aeronautics was satisfied.

4. GEAR LUBE & BEARING DESIGN - CHANCE VOUGHT XF5U-1 Flying Wing - (1946)

a.) PROBLEM: This experimental aircraft had six gear boxes which had bearing failures at a fraction of their design power of 1700 hp/engine.

b.) DESIGN: The bearings were mostly pressure-lubricated, plain bronze sleeve bearings with clearances and oil supply ports designed from handbook information. A theoretical analysis based on oil film wedge principals and rubbing velocity was used. This bearing-by-bearing analysis took six months or more. Oil ports were opened up in order to prevent pressure losses due to increased flow. One small bearing, the size of the smallest joint of your little finger, carried a load of 800 lbs. @ 22,000 rpm!. Sixteen of these bearings were used in the planet pinions in each engine's reduction gear. We opened up these bearings from 0.001 to 0.004" clearance, to increase their oil flow and hence survival rate.

c.) DATA: Oil temperatures, flow rates, and pressures etc. were measured at various power settings. This was done progressively, one gear box at a time.

d.) INTERPRETATION: Basically, did a bearing type survive or fail under test conditions? Oil-out vs. oil-in temperatures were closely watched and if the temperature rise was reasonable the tests continued.

e.) DECISION: The final design evolved as bearing types were progressively passed after clearances were opened up and oil supply pressure and flow was increased.

f.) IMPLEMENTATION: Parts were machined, bearings were honed to new clearances and a final complete test rig for two engines and six gear boxes was set up and tested satisfactorily.

g.) REPORT: Detailed reports were submitted to the program manager and ultimately to the Navy. The whole system passed 150 hours of prescribed power and speed with no problem. For example, the small planet pinion bearings mentioned above still showed final hone marks after 150 hours because the hydrodynamic oil film had kept the parts separated by a few tenths of thousandths of an inch. The airplane was never flown because jet propulsion took over.

***Historical irony** ... About 20 years later, in 1966, Aeronautics and Space magazine ran a feature article describing modern and vintage vertical take off (VTOL) and short take off and landing (STOL) aircraft that had been proposed or built. Twenty odd types were shown, yet only autogyros (STOL) and helicopters (VTOL) had actually flown successfully. The ancestor of the XF5U -1 Flying Wing was the dynamically similar but much lighter V-173. It flew successfully and met its design goals, yet neither of these aircraft were mentioned in the article. The Flying Wing was designed as a 500 mph STOL fighter, which probably would have been useful even now in today's military!*

4. IN-FLIGHT PILOT SKILL MEASUREMENTS - (1947-48)

a.) PROBLEM: The Aeromedical Division of the newly formed US Air Force, wanted to be able to measure a pilot's in-flight skill level both qualitatively and quantitatively, and simultaneously find the effectiveness of cockpit instrumentation. Several arrangements of controls and instruments were to be tested under varying flight conditions in order to define optimum cockpit industrial design.

b.) DESIGN: An Air Force C-47 (the military DC-3) was modified by our team at Link Aviation, Inc.. We devised recording apparatus for up to 10 variables, and switching apparatus to route transducer data to designated recorders. Transducers measured control forces, grip strength, etc.. Several complete cockpit instrumentation layouts were drawn up and built. Since we used analog, vacuum tube computer systems, then the state of the art, transducers were typically built up from aneroid capsules driving low torque precision potentiometers especially calibrated for their task.

c.) DATA: The C-47 was flown on many missions using strip-chart data recording.. For example, how well could a group of pilots in turn hold a steady rate of climb and steady direction under various conditions: clear, cloudy, stormy, day, night, etc. In some cases a pint of blood was taken just before or during flight to see how the pilot's skill was affected. There were many many variations.

d.) INTERPRETATION: Relocating some instruments made a big difference in pilot skill recordings. The usual primary flight arrangement of Airspeed, Turn and Bank, and Rate of Climb was confirmed as best. However, pilot abilities to fly blind-flying cross-pointer, left and right of the course of the localizer radio beam and above and below a glide path radio beam, varied widely. No conclusions were made before the aircraft and its apparatus was sent on to Wright-Patterson Air Base in Dayton, OH.

e.) DECISION: A base-line cockpit arrangement was adopted, but true standardization remains elusive. Before Link was cut off from the exchange of information we found that vertical bar graph presentations were best for presenting data, but only simulated versions were available then. Today, bar graph instruments are widespread, even used in light aircraft.

f.) IMPLEMENTATION: Various cockpit instrument layouts (arrangements) were standardized by the USAF. A flurry of proposals for servo-driven vertical bar graph instruments were solicited. I was involved later at Sperry Gyroscope and still later at Norden, and even share a patent for a Sperry cathode ray presentation instrument.

g.) REPORT: As in many classified government projects, only the actual report writer ever sees the report, and in my case, I left Link for greener pastures in 1948, before this program was finalized.

5. FLIGHT SIMULATORS - (1947-48)

Also while at Link, we designed the first *aircraft-specific* Flight Simulator, (as opposed the traditional Link Trainer which was used for instrument flight navigation training).

a.) PROBLEM: The Air Force was having great difficulty in transitioning pilots from propeller driven conventional landing gear (tail wheel) fighter trainers to the first operational jet powered fighter, the Lockheed F-80. To make the transition a bit more difficult, the F-80 had a newly designed tricycle landing gear with nose wheel steering. We wanted to build a simulator that acted and felt like an F-80 while the pilot was still safely on the ground.

b.) DESIGN: A partial airframe mockup was built and fitted with a complete F-80 cockpit including instruments and a blackout cockpit cover. Control forces were simulated with servo controlled spring loaded actuators. The instruments had normal dial faces which were servo driven to simulate selected flight regime. The entire cockpit instrument cluster was controlled with servomechanisms driven by vacuum tube circuits[3] using 10-turn precision potentiometers for input and output signals. Each instrument simulation computer cluster was built on a separate chassis, and fastened to pull out slides, so that each panel could be quickly changed out with the next test arrangement. Each was designed and calibrated to test part of the elaborate control scheme.

c.) DATA: Subjective “feel” data and charted “control response” data were recorded during a long development and testing phase. Control response feedback could be softened or stiffened by dialing in, (loading) pre-determined response ratios into potentiometers which determined control feel.

d.) INTERPRETATION: A major problem developed when the few experienced F-80 pilots we tested did not agree with how an F-80 responded. It was possible to tune the inputs until an individual pilot was satisfied that "Yes, now it feels like an F-80!" but some of their feedback pressure calibrations varied over a nearly ten to one range! Part of this was due to simulating the various center of gravity conditions and the pilot's setting of the simulated trim tabs.

e.) DECISION: Since diversity of pilot opinion was part of what the Air Force Aeromedical Laboratory wanted to explore and quantify, they were pleased. We altered the simulator to make dial-in changes easier and then put it in a long test and/or modification program.

[3] This was before the era of “OP-amps” (operational amplifiers)

f.) IMPLEMENTATION The unit was cleaned up and smoothed out for delivery but, as far as I know, never duplicated. While not officially called a “simulator,” it indeed was. Simulators of increasing complexity have since been built to study the handling of hypothetical (unbuilt) aircraft. I am proud to say that our pioneering efforts on the F-80 simulator, warts and all, has now become a standard part of aircraft and space vehicle development programs.

g.) REPORT: Many reports were rumored to have been written using test data from our flight simulator. However military security concerns kept them highly classified, sometimes secret, and I never did get to see them before I left Link in June, 1948.

6. AIRCRAFT ENGINE CONDITION ANALYSIS - (1948 - 1955)

The Sperry Aircraft Engine Analyzer was a CRT “scope” which showed individual spark plug condition in the final generation of 18 and 28 cylinder reciprocating engines. These were used on multi-engine aircraft such as the Lockheed Constellation, Douglas DC-7, C-124, Boeing B-50, C-97, B-377, and Convair B-36.

John Lindberg, a Pan American Airlines engineer[4], came up with the Engine Analyzer[5] concept. Shortly after joining Sperry as a project engineer, just as the first Lockheed Constellation analyzers were installed, I took over new analyzer versions and installations in other types of aircraft.

a.) PROBLEM: To find and match various ignition patterns to identify specific problems such as a short circuited spark plug or an incorrectly set magneto, then produce a specific operator's manual for each engine type.

b.) DESIGN: Determine the best installation location and circuit configuration. Capture test traces showing frequently occurring problems for trainees to study.

c.) DATA: Specific CRT traces were recorded for selected problems as they developed over a long period of operation. These patterns closely resemble a human heart electrocardiograph patterns but varied according to built-in conditions and occasional operational surprises.

d.) INTERPRETATION: We found that a new engine usually needed some minor tune-up for subtle differences between various cylinders and/or magnetos. Operator's manuals were built up around optimum conditions with variations, e.g. showing how minor differences in spark plug electrode gap affected the traces. We found that each airline Flight Engineer and Crew Chief needed to be shown that problems he added while we were away from his aircraft, could be quickly interpreted and cured. We promised a steak dinner with all the trimmings to anyone who could build in a problem that we could not identify. We never lost, but fed them the dinners anyway and made trusted allies as a result.

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4 No relationship to the famous Trans-Atlantic aviator, Charles Lindbergh

5 We avoided abbreviating this to “EA” because of conflicting use in commercial aviation

e.) DECISION: Each airline crew chief or USAF project engineer for a specific aircraft soon came "on board" and usually found specific features he wanted in the analyzers installed in his aircraft. Pratt and Whitney fought us all the way until we uncovered a consistent problem in the 28 cylinder R-4360 "Wasp Major". It turned out that all seven of the dual magnetos had slightly different cams to account for the different spark timing between the four master connecting rods and the various link rods. Somewhere in the production drawings, the part numbers for two cams had been interchanged. Thus, one specific cylinder was as much as 5 or 6 degrees in advance of its correct timing. That cylinder was almost always the first to fail. When we finally convinced a B-50 crew chief to swap the two cams the engine was noticeably smoother and that specific cylinder no longer ran hot. The full acceptance and resulting modifications took nearly a year.

f.) IMPLEMENTATION: Fleet-by-fleet, the analyzer installations were made both for the USAF and the airlines. The clincher for the USAF came when finally a B-36 completed 400 hours of flight with no engine shut downs or cylinder changes or failures. It was the first B-36 to have a complete Engine Analyzer installation. No other B-36 made it to 400 hours without multiple cylinder or engine failures and changes.

g.) REPORT: In the final version of the B-50D and B-36E aircraft, the analyzers were installed immediately after delivery and the USAF ordered its base commanders, not to fly those aircraft until the analyzers were installed and operational, and their crews had graduated from Engine Analyzer classes.

Historical note*: After about five years this instrument became widely accepted, the piston-engine fleets were replaced with turbojet aircraft, such as Boeing B-52, B-707 and Douglas DC-8.*

Although in 1963, I developed a concept for an analog jet-turbine engine analyzer using different principles, it enjoyed no wide-spread acceptance because digital computers were gaining acceptance, and engine manufacturers insisted on digital monitoring devices, even though the tools to interpret their digital data format were not yet developed. This was published it in ASEE Conference Event 3626 (1998),

7. DETERMINING CAUSES OF PROPELLER FAILURES - (1950 - 51)

a.) PROBLEM: There was an in-flight failure of a propeller blade on a passenger-carrying Eastern Airlines Lockheed Constellation. The blade snapped off, penetrated the fuselage, and killed the flight steward. At the same moment, the other two blades and the engine nose section tore off and, fortunately flew the other way. The damaged aircraft then made a successful emergency landing. Eastern Airlines, Curtiss Wright Propeller Division, and the Civil Aeronautics Authority wanted to know the cause of the failure as soon as possible.

b.) DESIGN: The Curtiss Propeller Corp. at Caldwell Field in NJ had just finished rebuilding a suitable test cell. They installed a rebuilt Curtiss Wright R-3350 BD 18 cylinder, 2500 horsepower engine in the cell. This particular engine was the same model as that in the Constellation and thus had the same dynamic characteristics even though it had been built from rejected parts and was not suitable for flight.

A production model of the same Curtiss Electric hollow blade steel propeller was mounted on it and equipped with strain gauges cemented to each blade both at the root and about 3 feet in from the tip. These were connected to signal amplifiers and data recorders through a large multi-channel slip-ring set.

The plan was to deliberately misfire each cylinder at various speeds and power settings, to find resonant conditions and to record stress increases at resonance. We suspected that, even though relay controls were designed to short out spark plugs on selected cylinders, perhaps the cylinders were firing anyhow due to insulation break-downs in the ignition harnesses.

At this point I was one of two engineers at Sperry Gyroscope who were experienced in using their Aircraft Engine Analyzer. Sperry sent us to monitor whether cylinders were firing or misfiring as planned. The analyzer was hooked into the test setup and tested to Curtiss' satisfaction.

c.) DATA: In the early days we had trouble in obtaining good strain gauge readings because the signals were typically only a few millivolts. After installing polished silver collector rings and multiple brushes we got useful data.

The propeller test was run over a range of rpms from below to above the failure point and data was recorded. The strip chart recorder showed the cyclic propeller blade vibration frequency and the stress level. At normal climb power and rpm, certain cylinders, if deliberately misfired, would cause dangerous strong resonant vibrations in the propeller.

Our data showed that when No. 6 cylinder misfired, the blade tip stress tripled. Further, the same condition increased the blade root stress by a factor of six! Just after this data was recorded and verified, the test engine had a catastrophic failure, while under close scrutiny, causing considerable excitement and chagrin.

d.) INTERPRETATION: After careful correlation and data reduction to plots of strain vs. speed at various cylinder conditions the results were very clear: **Avoid this critical RPM at all costs!**

e.) DECISION: Specific instructions were sent out to all EAL[6] Constellation pilots, co-pilots and flight engineers to avoid this RPM by at least ±50 RPM. Meticulous propeller inspections were made to determine blade condition. Engine analyzers were required on all aircraft and firm instructions issued that no Constellations were to be flown without functioning analyzers and trained flight crews.

f.) IMPLEMENTATION: The Engine Analyzer installations were accelerated to the point that the Air Force had to accept delayed delivery of their analyzers. Airline EA use was considered a primary safety measure[7]..

g.) REPORT: Curtiss Propeller Division did what they could to reduce unfavorable publicity and distributed our test report in several levels of detail to all concerned. The Curtiss pro-

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6 Eastern Airline

7 At that time Air Force aircraft operated about one tenth the hours per year of a typical civilian airliner

propellers were ultimately replaced by propeller design which used solid aluminum blades**.**

8. WHERE VALID DATA IS PREJUDICIALLY REJECTED - (1952)

History gives us many examples where perfectly valid data seemingly leads to an unreasonable result. An outright rejection of engine analyzer data that was contrary to expectations, happened frequently while I was training customers on the Sperry Aircraft Engine Analyzer.

A little background will help clarify these situations: As the rated power output was constantly being increased for both the Wright R-3350 18 cylinder engine and the Pratt and Whitney R-4360 28 cylinder engine, certain characteristic failure modes began to appear. All high-power aircraft engines used hollow exhaust valves which were about two thirds filled with sodium. This metal would melt and slosh up and down inside the hollow valve stems and dissipate more heat up through the valve guides than solid steel valve stems. This practice was proven in the late 1920's. However, as engines and their valves became larger and rotating speed and combustion pressures increased, valve failures became more serious.

Cylinder detonation (from whatever cause) stressed these valves and caused them to fail. The usual failure was that the perimeter weld around the head of the valve would crack and the sodium would leak out. Then the valve head would turn white hot, which aggravated the detonation. Next, the whole valve head would break off the stem, and combustion would cease in that cylinder. The soft valve head “ingot” would cool off and become a hard hammer-like metal chunk which was batted back and forth between the piston and the cylinder head. Meanwhile, the engine running on now 17 or 27 cylinders, would soldier on sometimes with no apparent loss of power or smoothness.

The flight engineer’s only clue came from the Engine Analyzer which clearly showed both spark plugs in the cylinder with the failed valve were completely short circuited because they had been smashed down by the chunk of decapitated valve head. By this time we had "autopsied" a few of these failures from Pan Am aircraft, with the complete cooperation of their service and engineering staff. They pioneered the Engine Analyzer and they were justifiably proud of its diagnostic abilities.

The resulting complete engine failure mode scenario was now apparent: The still-pounding steel valve head chunk, about the size of a tennis ball, would progressively batter the inside of the cylinder head and the top of the piston. The piston top would be forced downward over the wrist pin and begin to lose fragments from its under side. These fragments would collect in the sump of that row of cylinders and eventually one or more fragments would get into the oil scavenger pump and wreck it.

While the engine “oil-in” pump was still delivering oil to the engine, from 1/4 to 1/2 of the oil was no longer being sent back to the oil cooler and reservoir. In two hours or less after the failure, the reservoir emptied out, because the oil was blown out the breather. With no oil in the engine it would rapidly overheat and seize up.

The inertia of a 600 lb. propeller would tear the nose right off of the R-3350 engine because its steel crankcase could withstand this huge rotational force. The residual thrust of the still-spinning propeller would pull it forward, as it and its reduction gears sheared off the crank-case.

That type of failure was bad enough in the Wright R-3350, but the P&W R-4360 engine failures were still worse! The massive torsional jolt from an engine seizure would rip the aluminum crankcase right out of the engine mounts and the whole engine, propeller and all its accessories would fly out forward. If the engine was mounted on the trailing edge of the wing, in a pusher configuration al la the B-36, it would smash forward into the wing and sometimes just hang there. In either case, with the early Engine Analyzer detection of a failed valve, the flight engineer had as much as two hours to shut down before catastrophe. But he had to have an Engine Analyzer, use it periodically, believe and respond to what it told him.

9. FAILED VALVE EXPERIMENT - (1952 - 1953)

a.) PROBLEM: To get a newly introduced Flight Engineer to believe and act on what he saw.

b.) DESIGN: In this case a new trial Engine Analyzer installation was made in a Northwest Airlines Boeing 377, "Stratoliner". These transports had evolved from the WW II Boeing B-29 but they, like the B-50, used the new P&W R-4360 which delivered up to 3500 horsepower

We at Sperry had a fully qualified and experienced field service representative, Russ Aveny, who flew back and forth from Chicago to Seattle, WA on this aircraft. He would show each flight engineer, captain and co-pilot what the analyzer could do and train the flight engineer in proper procedures.

One night coming East he encountered a truculent flight engineer and a few hours out of Seattle he also encountered the now dreaded double short circuit pattern on the Engine Analyzer cathode ray tube screen. Of course, Russ described what it meant and told the flight engineer that if he shut down that engine right now, all it would involve was cylinder and piston change, or that if he waited, a total engine failure and engine tearout would ensue, (and possible a fatal crash).

This flight engineer flatly refused to believe the indication as did the Captain. Russ protested heatedly and was ordered to get out of the cockpit and told to stay out.

c.) DATA: In this case the double shorted spark plugs were clearly shown and identified.

d.) INTERPRETATION: The disbelief masked the fact this result had been seen before in more than one case. The interpretation came from early failed engines that had been shut down and inspected.

e.) DECISION: In this case the decision was to do nothing and Aveny retreated to the lower deck bar and lounge which was a feature of the Boeing 377. He was justifiably frightened because by this time Pan Am had lost a few Boeings over the Pacific without a trace and we at Sperry suspected that this type of failure was a contributing factor. These events, the Pan Am crashes, were attributed to propeller blade failures, but no one was really sure about the cause.

Russ was nursing a drink when the aircraft shuddered a bit and then flew on with a slightly different sound. He rushed back to the cockpit deck and burst in, because in those days, (before hijacking), there was no lock on the door to the flight deck.

When he arrived the flight engineer was standing on the left side, peering out an inspection window with a flashlight and looking at #1 engine (left outboard) and then #2 (left inboard) which were both droning on peacefully. By the time the Flight Engineer crossed over to the right side to look out that inspection window, Russ was looking over his shoulder. The #3 engine (right inboard) was completely missing right back to the firewall, with a few hoses and cables dangling down.

The engine and propeller were later found half buried in the parade ground of an abandoned US Army base in western Minnesota. A careful teardown showed the conditions described above but in a now wrecked engine and propeller, which had torn off the aircraft in mid-air.

f) IMPLEMENTATION: Northwest Airlines immediately ordered a rush delivery of engine analyzers for its fleet.

g) REPORT: Admittedly, this was a “bass-ackward” experiment but Northwest became "true believers".

10. HUMAN HEART CONDITION ANALYSIS - (1952 - 1953)

HUMAN HEART DIAGNOSTIC INSTRUMENTATION: This was my graduate thesis subject at Polytechnic Institute of Brooklyn in 1953.

a.) PROBLEM: Study the available range of contemporary cardiac diagnostic instrumentation such as the electrocardiogram. Determine if any new and/or improved diagnosis of congenital conditions could be made. This came from a challenging article in the monthly magazine, "Electronics"[8], which I found while searching for a suitable thesis project.

b.) DESIGN: First I studied the unfamiliar medical nomenclature and technical jargon to understand appropriate medical literature. With the help of local doctors and a chance meeting with one of the pioneers of open heart surgery, Dr. Robert P. Glover[9], I was passed off from one heart specialist to another. As a result I was built up a reasonably comprehensive body of heart literature. Next, we attempted to build a table of the 26 known congenital heart conditions against the various known diagnostic techniques.

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[8] a monthly publication from McGraw-Hill, publisher

[9] From the cardiology team of Bailey, Glover and O’Neill

Each instrument type such as the armcuff blood pressure monitor, sphygmomanometer, and the electrocardiograph were tabulated listed as capable of identifying each specific condition positively, or partially in conjunction with another method, or able to rule out a specific heart condition, but not identify what problem was present. At this time, many recognized and named heart problems could only be positively identified by an autopsy! My table was the center of heated debates between doctors when I could get one or more to peruse it. Obviously, better diagnostic tools or instruments were needed.

c.) DATA: My son Russell, then six years old, had been diagnosed with a heart murmur but many causes were known to cause murmurs. Dr. William Dock, of Kings County Medical Center, agreed to perform a series of noninvasive tests on Russell, including a unique experimental Tricardiograph which Dr. Dock was developing. I was also tested on this unit as a baseline. This device would chart the body's slightest movement when lying supine and supported on one-degree-of-freedom “swing seats” under the head/shoulder blades, buttocks and heels. The strip chart record also traced simultaneous electrocardiograph records from arm, leg, and two other places on the body. It also showed a synchronous slit kymograph trace[10] which showed synchronized pictures of the heart when fully expanded and completely contracted. Last, it showed the recorded audio heartbeat sounds from a microphone on the patient’s chest.

Dr. Dock's charts showed that my son Russell had a hole in his ventricular septum. This hole in the wall between the left and right ventricles which leaked a stream of blood causing a heart murmur. Dr. Dock said, "Don't worry about it." The hole was about 1/4 inch in diameter and would gradually grow closed and not cause any distress. He was correct and Russell went on to become captain of his high school cross-country team. He later joined the Coast Guard and careful exams showed no heart murmur.

This, and many other measurement types gave subjective data. Only rarely could a data chart be scaled and quantified as with a modern electrocardiograph.

d.) INTERPRETATION: Interpretations vary from doctor to doctor and instrument to instrument. Some positive information could then be deduced from invasive tests such as catheter tubes inserted into veins to measure pressures and percentages of oxygen in the blood, etc. I hoped that with a decade of experience on all types of instrumental measurement of fluids, gases, sounds, and forces, I could devise a new, more reliable test that would be less invasive.

e.) DECISION: I proposed building a dynamically similar, analog scale model of the human heart and circulatory system. By using flexible rubber molds of autopsied human hearts, both normal hearts and models with various known congenital faults, and pumping a viscous, blood-like fluid through this simplified circulatory system, to observe the resulting pressure patterns . The simulated heart pumping action would come not from simulated heart muscles, but by imbedding the heart model in chamber where the surrounding fluid pressure caused pumping. The pressure in the chamber fluid is driven by a pulsating input from a motorized, cam-driven external bellows.

[10] An modified X-ray camera with a narrow-slot oscillating shutter

It seemed feasible to match flow rates by varying cam shapes and stroke timing so that flow sounds and pressure waves, etc. could be quantitatively measured and matched to normal hearts. Then molded “faulty hearts” would be substituted to learn how to match external sounds and pressure variance to known heart fault conditions. Our work would create an analog dynamically similar model of the human heart and circulation system, and could be used to provide enhanced stethoscope training for cardiologists in all phases of their careers.

f.) IMPLEMENTATION: The model was never built because it exceeded my available time and limited financial resources. The doctors lost interest in my proposal, because it was for a masters thesis, not a sponsored, revenue producing, Ph.D. program. Nonetheless, my thesis grew out of this study.

g.) REPORT: My thesis documented this study and it gained me a nomination to Sigma-Xi. I was told a few years later that it was the first[11] medical-engineering thesis, and was used as a reference for Ph.D. studies, but I never got any feedback. My department head and thesis advisor, Professor Ernst Midgette, left Poly, moved and later died and I never heard any more about it.

III. EXPERIMENTS IN OUTER SPACE

11. WS-107A MISSILE NOSE CONE ATTITUDE CONTROL (1956 - 58)

a.) PROBLEM: To design and build a gyro-stabilized platform to control cold gas vernier rockets, which aim stabilize and spin at the final entrance attitude (angle) of an ICBM warhead. The rocket thrust points the capsule to its preset reentrance angle as it comes back into the atmosphere.

b.) DESIGN: Norden's White Plains, NY division, a descendent of the original WW II Norden Bombsight group in Brooklyn, NY, designed a state of the art three-axis gyro stable platform. The platform’s absolute angle of reference is set before liftoff. The platform must hold its attitude angle extremely closely during liftoff, acceleration to orbital velocity, orbital insertion and nose cone separation, despite all the violent shock, vibration and acceleration of launch. Then the gyro platform control system contacts control small compressed nitrogen rockets which orient the nose cone at the required angle so that it holds its planned course without wandering during reentry.

Sperry left for Phoenix, AZ and I transferred to Norden, in Milford, CT. I collected and oversaw transmission of design information from White Plains to Milford where the production versions were manufactured. No one at Norden believed that I had never worked on a gyro device. Since I had spent 8 1/2 years at Sperry Gyroscope, they thought I *had* to be a gyro expert.

No matter, this was a precision mechanical design, manufacturing and testing project. A large three-axis test platform had to be designed, built, and fitted to the missile platform. The flight

[11] for Brooklyn Polytechnique Institute

device had to be extensively vibration, shock and spin tested, and still maintain its contract angular accuracy.

c.) DATA: All contract requirements were met in extensive tests and none of the environmental tests caused the preset angles to fall below specifications. The final test of an actual missile launch was performed at Cape Canaveral. The USAF Missile Command told us to build the remaining gyro platforms and not ask questions about performance.

d.) INTERPRETATION: Our only conclusion was that the performance was satisfactory but since we did not have "need to know" in this then top secret missile project we were not told anything.

Quite by chance, about 15 years later at an American Society for Engineering Education National Conference at Rensselear Polytechnic, I got the answers. A group of us profs were sitting around during a break and swapping stories of what we had done before teaching. I regaled the group with some of my background and finished by telling part of this ICBM story and pointed out that we never heard the performance data. One of the men started to rise up out of his chair, pointed to me and said, "You S.O.B., you hit our island!!!" He went on to say that he had been a radar technician for the USAF on Ascension Island in the South Atlantic, about 5500 miles down range from Cape Canaveral.

Our first missile hit dead on, its dummy warhead fell within about half the allowed C.E.P.[12], and he had to quickly dive into a rain-filled slit trench which had never been used before. A dummy warhead makes a sizable crater when it impacts at a very high Mach number. The implication is that all components on the missile and the nose cone worked well within spec.

e.) DECISION: The USAF ordered Norden to build the rest of the procurement without changes.

f.) IMPLEMENTATION: A year of very precise machining and testing followed with no suggested or allowed changes.

g.) REPORT: All Norden could do was to report the conclusion of the contract. We never saw Avco's final report to the USAF and I have never since seen any of the team that I worked with to tell them of my unexpected report of the actual missile test 15 years after the fact.

12. ULTRA-PRECISE DYNAMIC ANGLE MEASUREMENT (1960)

a.) PROBLEM: The USAF and NASA both needed to measure the dynamic attitude angles of moving satellites very precisely, in order to detect orbital irregularities resulting from minuscule earth gravitational anomalies. At first measurement was required to 0.001 degree and later to one second of arc (or 1/3600 degree). Results were required in digital format.

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[12] Circular Error of Probability

b.) DESIGN: Now, as section head for engine instruments in the Norden Div. of United Aircraft, I had inherited engineers and shop technicians who were used to designing and manufacturing ultra-precise mechanical devices. A rotating toothed wheel of 6.3662” (2π in.) diameter was machined with rectangular teeth of 0.010 inch wide and equal gap width between teeth. This machined part was built on our best, most precise, rotary table and jig borer. The tooth cutter used was a modified Schick Injector razor blade which was a very precise 0.010 in. thick. Every other tooth was cut in the first pass; then the intermediate teeth were cut later to avoid distortion. The teeth were cut shaper fashion. The toothed wheel floated on an air bearing to remove any chance of vibration interference. It was driven with a thin flat belt and its external teeth faced a segment of matching fixed teeth and movable segment which was attached to either the azimuth or elevation axis of an optical telescope. Colorado Research Inc. built the digital electronics, which at that time used all solid state logic built from hundreds of discrete transistors.

The perceived problem was how to calibrate this special encoder and its electronics, both statically and then dynamically. The U.S. Bureau of Standards notified us that they did not know of any device that could produce a certifiable calibration.

To build such a calibration standard, we had purchased a ground and polished large glass prism with 12 non-uniform facets. Then two vertical shafts, 100 feet apart, were dug down to bed rock in the middle of factory floor. A pier was built up in each shaft to make a stable platform, insulated from the factory vibrations. The prism was mounted on a horizontal turntable attached to a vertical shaft which could be rotated at typical satellite angular speeds. The drive train, which rotated this vertical shaft was mechanically linked to spin our “Microgon” transducer and the test prism was all mounted on the first pier.

A collated light source and a slit-masked photocell readout were mounted on the other pier. The photocell on the telescope saw a very brief flash from each prism reflecting this light source as the prism rotated. Although the prism facets were only nominally 30° apart, each complete revolution of the prism was always precisely 360 degrees.

c.) DATA: At operational speeds, our Microgon, (as it was named), would record the angular variation of each facet as it reflected the light back, but each revolution consistently totaled 360°, ±0.0003°.

The next step was to track some stars whose angular separation were known precisely from repeated historic astronomical observation. The Microgon was mounted on a fixed platform so that its field of view swept by the stars at the earth's rotational speed. The angular spacing between stars agreed with accepted astronomical data. Then the measurements were repeated with the Microgon moving at simulated satellite angular velocities. Its field of view "swept" by these same stars and again the angular separation measurement agreed with astronomical data.

d.) INTERPRETATION: This part was relatively straight forward because the data was in simple sets and was consistent.

e.) DECISION: We finished drawings for a version of the Microgon which could accurately measure to one second of arc and got ready to manufacture copies of each unit.

f.) IMPLEMENTATION: Copies were built and delivered to Colorado Research, Inc., the prime contractor, and the design rights were sold to them for further manufacture.

g.) REPORT: As in many classified products, the prime contractor submitted reports to the USAF and NASA, which we never saw.

By now, we have shown that all experiments, however diversified they may be, can be subdivided into these seven essential steps. After compiling this record of my own experiences I'm quite sure that they are not unique. Many practicing engineers have experienced the same sort of thing because we were trained to do this kind of work. I sincerely hope that school curricula can be modified to allow the young men and women to realize that, behind all the wonderful computer simulations, are real world physical elements that must be recognized, especially when they are involved in break-through work.

The United States continues to be a world research leader but has already lost and continues to lose more of its technological superiority. We are becoming more and more a second rate manufacturing nation as more of our technical work is sent overseas, to boost corporate profits.

THIS WE ALLOW AT OUR PERIL AS A FREE NATION!

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Professor Richardson received his BSME Aero from the University of New Hampshire in 1942, and an MME from Brooklyn Polytechnic in 1953. He is a registered Professional Engineer in Connecticut, and held various management and technical positions in the aerospace industry from 1942-1969. He holds patents in special instrumentation.

He taught Rotating Electrical Machinery from 1969 until he retired in 1980. Wrote three text-books in electrical machinery including the only fully detailed laboratory operations manual published since WW II. The text itself is also published in French and Spanish. He has consulted for the Association of American Railroads since retirement.

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