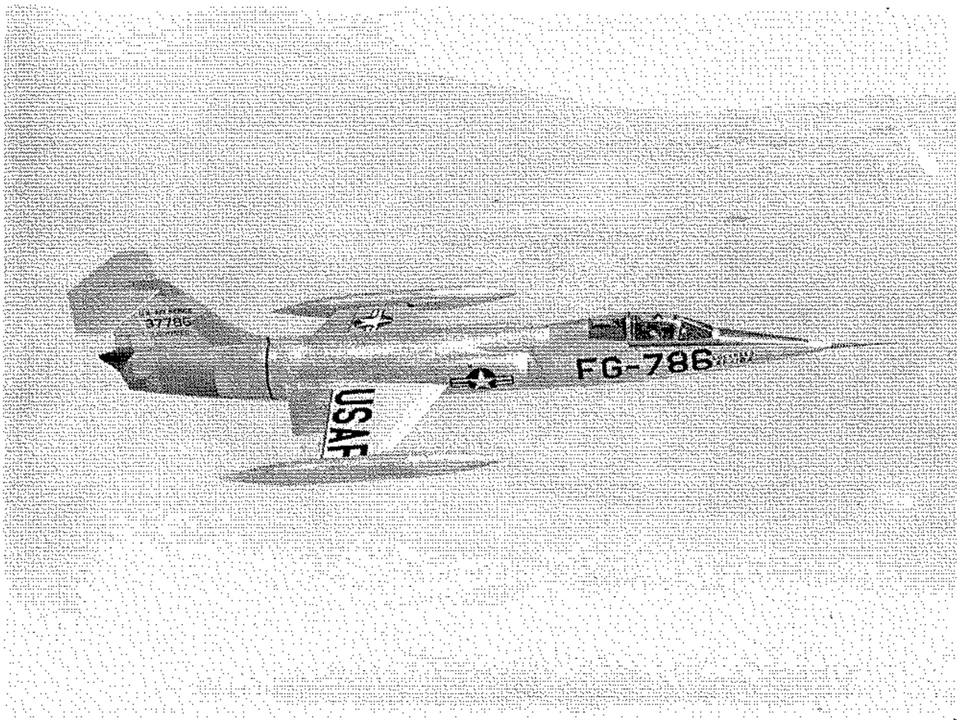
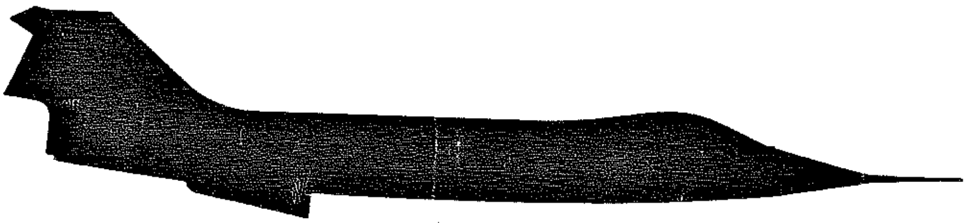
The SURE Project



Lecture – 1/10



THE SURE PROJECT

Lockheed
-California Company

LOCKHEED REPORT CA/ME 2383

REPRINTED APRIL 1981

SURE MOTTO

KNOWLEDGE
+
EXPERIENCE
+
LUCK

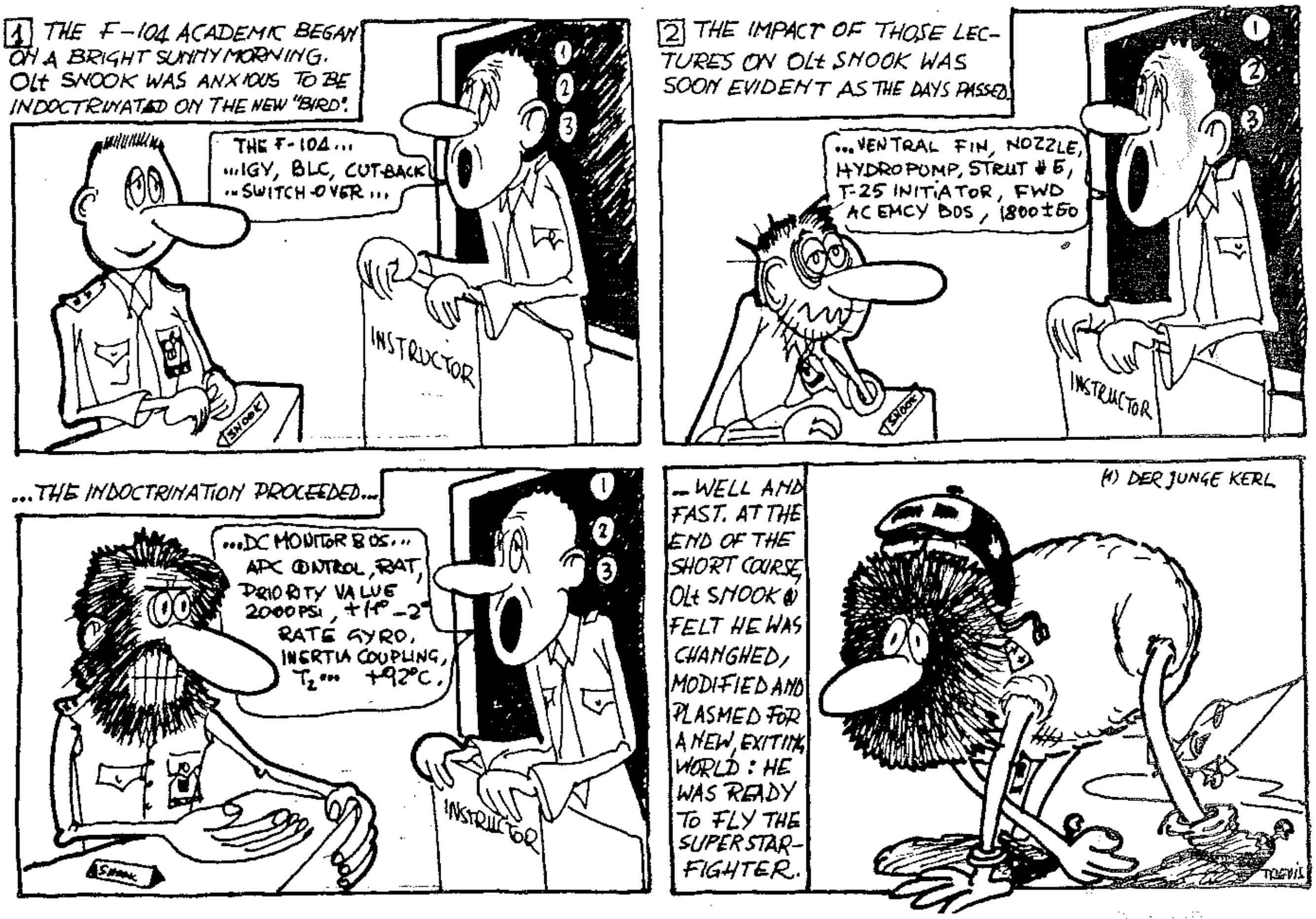
=

MISSION EFFECTIVENESS
WITH
FLIGHT SAFETY

What does SURE mean to you? We hope you are becoming aware that SURE is synonymous with the deep interest that Lockheed Aircraft has in your flight operation, maintainability, and effectiveness with the F-104 Starfighter.

The SURE motto expresses the three ingredients any fighter pilot needs for absolute success in accomplishing his mission. During my flying career, I have always been able to depend on my knowledge and experience. Lady Luck, however, is a fickle mistress and cannot be depended upon. Sometimes she smiles on you and other times, when you need her most - she's off smiling on someone else. Therefore, the purpose of these lectures is to increase your knowledge and then with your growing experience, you will have less need for that undependable creature - Mistress Luck.

Since there is only one sure way to gain technical knowledge - hard study - I hope to pass on to you, through these lectures, a postgraduate study on the F-104. Only by continual study and flight experience will you be able to exploit the vast reservoir of performance that exists in this classic fighter aircraft.



LOCKHEED-CALIFORNIA COMPANY

A DIVISION OF LOCKHEED AIRCRAFT CORPORATION

BURBANK, CALIFORNIA 91503

July 1967

Greetings and Salutations to the Royal Order of Starfighters:

Since 1961, when I first realized the need for direct pilot support, Lockheed Aircraft Corporation has generously funded a company-sponsored support program. Originally, it was the Operational and Engineering Reliability Team (OERT). In 1963, we renamed it the Starfighter Utilization and Reliability Effort Team.

From 1963 until now, G. L. "Snake" Reaves has been the manager of this project. In his efforts, he has traveled around the world numerous times to visit and directly brief you on the latest information about operation of the F-104. Those of you who have talked to him know that he is a staunch advocate of the professional fighter pilot. In his earnest desire to help you, he wrote the first SURE Project Book in 1966, which contained lectures 1 through 4. Now, once again, "Snake" and "Pete" have collaborated to bring you lectures 5 and 6.

Even though you may have to study this information at great length, I feel that the knowledge to be gained from these lectures is what you need to know in order to most effectively operate and fly the greatest all-around aerial weapon in the Free World.

Sincerely yours,

LOCKHEED-CALIFORNIA COMPANY

Tony LeVier

A. W. LeVier
Director of Flying Operations

"Snake"

APPRECIATION

On behalf of the family we wish to express gratitude for your kindness evidenced in thought and deed, and for your attendance at the memorial service.

Ode To The Sky

Long ago, I gazed into the sky
And wondered, "What therein did lie?"
So, up I flew with questing mind
And perused the firmament to find
What God reveals to those who dare
To scale the steeps of Heaven's lair.
For years I searched to now relate
His creations which there await.
For there in the sky, you will find:
—The shouting of the wind
—The majesty of the cloud
—The uplift of the thermal
—The brilliance of the Sun
—The velvet of the Moon
—The twinkle of the star
—The crackle of the lightning
—The rumble of the thunder
—The pelting of the rain
—The tempest of the storm
—The solace of the heights
—The current of the jetstream
—The curl of the contrail
and
—The caprice of the pilot's rainbow
But greater than these, will be the discovery
That there in the sky, you will find—yourself!

—Glenn Reaves
July 1980

In Loving Memory of
Glenn "Snake" Reaves

July 5, 1926
Oklahoma City, Oklahoma

October 11, 1984
Granada Hills, California

Memorial Service
Wednesday, 2:00 P.M.
October 17, 1984
Kingdom Hall of Jehovah's Witnesses
13262 Bradley Avenue
Sylmar, California

Officiating
Mr. Ron Cooper

Graveside Service
Wednesday, 3:00 P.M.
October 17, 1984
Forest Lawn
6300 Forest Lawn Drive
Hollywood Hills, Los Angeles, California


TO LOCK
RELEASE
To all
fans in the world
Happy landings!

LOCKHEED - CALIFORNIA COMPANY

A DIVISION OF LOCKHEED CORPORATION

BURBANK, CALIFORNIA 91520

January, 1981

GREETING AND SALUTATIONS TO THE ROYAL ORDER OF STARFIGHTERS:

It is fitting and proper that this final SURE lecture from G. L. "Snake" Reaves contains his personal insights and techniques concerning the art of flying. Those of you who have read his previous lectures realize that he is a unique source of information concerning the F-104. Those lectures are:

LECTURE NO.	TITLE	LOCKHEED REPORT	DATE
1	Analysis of the F-104 Aircraft Limitations and Operating Restrictions	CA/ME/2301	June, 1966
2	Investigation of F-104 Pitch-Up and Spin Modes	CA/ME/2301	June, 1966
3	A Critique of Selected F-104 Emergency Operating Procedures	CA/ME/2301	June, 1966
4	A Test Pilot's Review of F-104 Accidents	CA/ME/2301	June, 1966
5	Theoretical and Practical Aspects of Subsonic and Supersonic Airflow Affects on the F-104	CA/ME2383	July, 1967
6	The Energy Maneuverability Concept and Recommended Air Combat Tactics for the F-104	CA/ME2383	July, 1967

January, 1981

LECTURE NO.	TITLE	LOCKHEED REPORT	DATE
7	F-104 Flight Profile Optimization for the Intercept Problem	CA/GME3044	Dec., 1969
8	Go For The Odds	No Number	Mar., 1970
9	A Test Pilot's Comments on Emergency Procedures	No Number	Jan., 1978

Even though "Snake" is ending his lecture efforts for the SURE Project, we at ADP (Advanced Development Projects), who designed and built the XF-104, are still concerned about the operational problems of all the Starfighter Units - worldwide. Therefore, if you have a problem or need assistance, please contact us.

Sincerely yours,

LOCKHEED-CALIFORNIA COMPANY

Ben R. Rich

B. R. Rich,
Vice President and General Manager
ADP

STARFIGHTER
UTILIZATION
RELIABILITY
EFFORT

LECTURE
1

ANALYSIS
OF THE
F-104
AIRCRAFT LIMITATIONS
AND
OPERATING RESTRICTIONS

Written By

G. L. "Snake" Reaves - Lockheed Test Pilot

Cartoons By

P. P. "Pete" Trevisan - FIAT Test Pilot

K

References

1. Lockheed Report No. 12313, "XF-104 Aileron Roll Characteristics", dated May 20, 1957.

2. Lockheed Report No. 11698, "Analysis of the Roll Performance of the F-104", dated December 26, 1956.

3. Lockheed Report No. 13039, "Flight Test Results of F-104A Roll Performance", dated November 22, 1958.

4. Air Force Specification No. 1815-B, "Specification for Flying Qualities of Piloted Airplanes", dated June 1, 1948.

5. Air Force Specification MIL-F-8785(ASG), "Flying Qualities of Piloted Airplanes", dated September 1, 1954.

6. Lockheed Report No. 13372, "Airload Survey and Structural Demonstration Test Results, Including Comparison with Design Loads - Model F-104A", dated November 11, 1958.

7. Aeronautical Engineering Review, "Airplane Design Implications of the Inertia Coupling Problem", issue of September, 1957.

8. "Mechanics, Heat and Sound", by Francis Weston Sears, Professor of Physics, Massachusetts Institute of Technology, dated 1950.

9. NASA Publication No. TM X-137 "Flight Behavior of the X-2 Research Airplane at Mach Numbers to 3.20 and Pressure Altitudes to 119,800 feet", by Richard E. Day and Donald Reisert.

10. Lockheed Report No. 15805, "Summary Flutter Report of the F-104G (MAP)".

11. Lockheed Report No. 15872, "Stability and Control Flight Test of F-104G".

12. Lockheed Report No. 15868, "Determination of Operational Flight Limits - F-104G".

13. Air Force Specification MIL-A-8870(ASG), "Airplane Strength and Rigidity - Vibration, Flutter and Divergence", dated 18 May 1960.

FOREWORD

One of the many challenges that must be faced with newly designed aircraft is the discovery and establishment of aircraft limitations and operating restrictions. From the moment of the first flight of the experimental or prototype model, the never ending search is begun. Although the designer does his best to exhaustively search out the limits, sometimes the aircraft reaches the user with not all of the exact limitations known and listed. Often times some limitations are placed on the aircraft that are not only not understood by the user but appear in all respects to be so prohibitive as to compromise the mission capability of the aircraft. My main purpose of this lecture is to explain the why's of the limitations on the F-104:

- Why they are there -
- Why they should be observed -
- Why an understanding of them will yield greater mission effectiveness -

The history of aircraft limitations shows a very definite trend. Looking back to when the Wright Brothers fulfilled their first contract with the U.S. Government, we find that they produced an aircraft that would -

(1) Fly at least 40 miles an hour.
(2) Stay aloft at least 1 hour.
(3) Carry two passengers.

When we compare the extremely simple and limited flight profile of this aircraft to our modern military craft, it is obvious that the trend is for more limitations and restrictions as greater performance is achieved. We have now reached the point where we are confronted with a complete section of the handbook that is stuffed with tables of limitations and overflowing with restriction numbers. Since it is impossible to memorize these hundreds of limitations, we are forced to study the reasons behind the limitations so that we can intelligently fly the bird to its maximum and still play the game of fly safe.

Again going back to the Wright Brothers, and following the entire history of aviation development, we note that there has been established only two basic limitations to any aircraft. They are -

(1) Airframe and Engine strength.
(2) The ability to retain control of the airplane.

However, from these two basic criteria comes the tables and numbers in section V of our Handbook. In this section we are faced with -

(1) Prohibited Maneuvers.
(2) Maneuver Limitations.
(3) Control Restrictions.
(4) Velocity Limitations.
(5) Acceleration Limitations.
(6) Configuration Restrictions.
(7) Take-off and Landing Limitations.
(8) Loading Limitations.
(9) Bomb Release Limitations.
(10) Jettison Limitations.

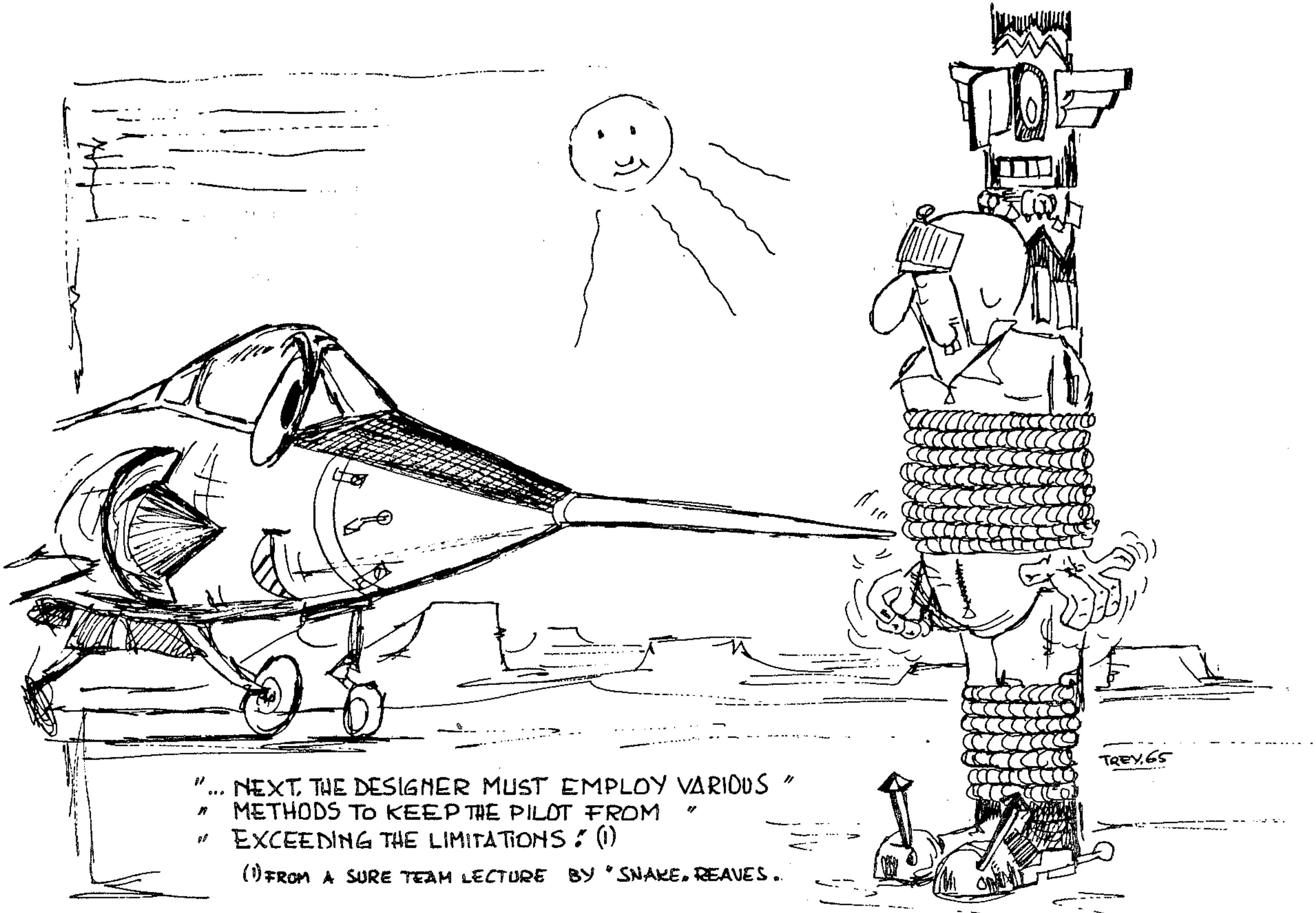
And on and on. The manner in which these factors are found follows a tried and proven method. First, computer studies and wind tunnel tests are carried out in conjunction with static loading tests to help point the way for a flight test program to obtain data that will determine the dynamic limitations. In the computer static loading and wind tunnel phase, the effects of the aircraft design are studied, or more precisely the effect of size, shape, weight and C. G. vs. computed air loads.

Here we are looking for the relationship of -

(1)	Size:	Maneuverability and Performance.
(2)	Shape:	Aerodynamic parameters - Lift, Drag, Stability, Inertia.
(3)	Weight:	Strength parameters.
(4)	C. G.:	Stability and Control.

During the programmed flight test phase, the analysis of the data determines the operating boundaries, aircraft restrictions and optimum operating procedures.

Next, the designer must employ various methods to keep the pilot from exceeding the limitations. These methods take the form of control restrictions, stall-warning devices, warning lights, instrument-markings and cockpit placards. Also, the handbook lists prohibited maneuvers, engine limitations and airspeed and "g" limitations. Taking into account the limitation of the Handbook itself however, all that the pilot knows is what he's been told <u>not</u> to do but not <u>why</u> he shouldn't do it. From this lecture I hope you will learn why we put the restrictions and limitations in your pilot's handbook.

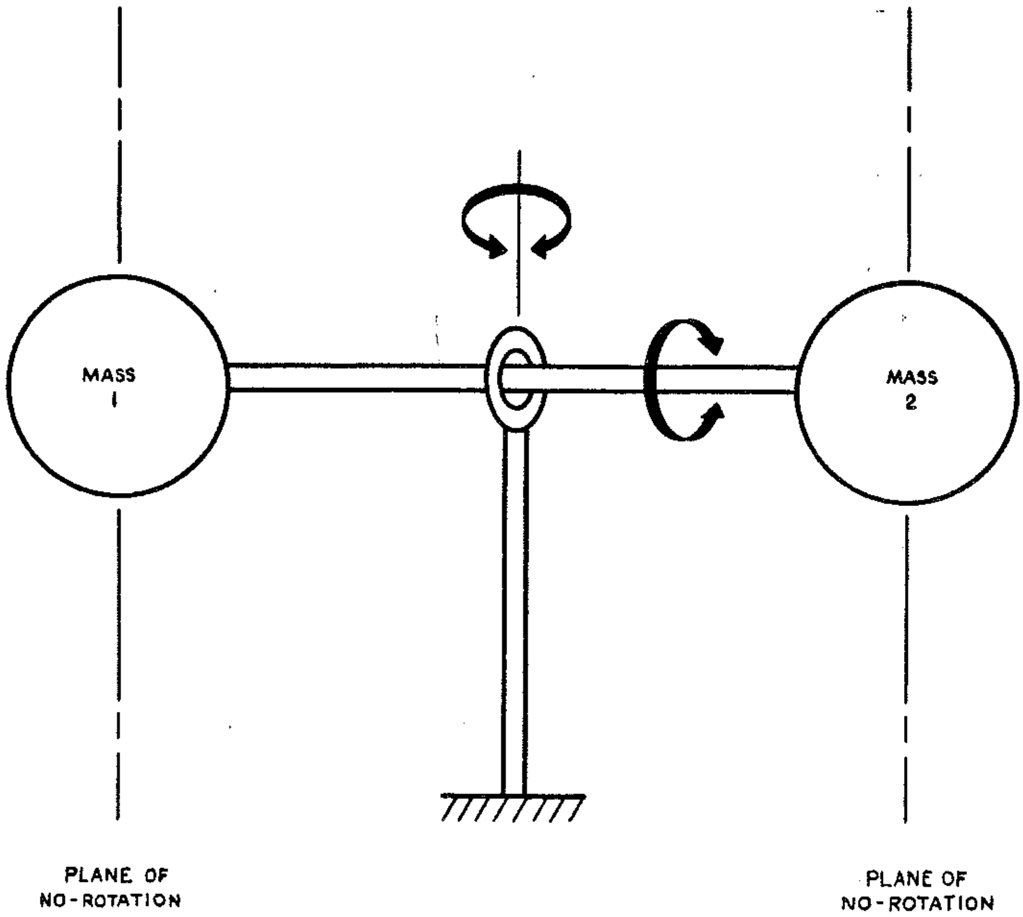

"... NEXT, THE DESIGNER MUST EMPLOY VARIOUS "
" METHODS TO KEEP THE PILOT FROM "
" EXCEEDING THE LIMITATIONS." (1)
(1) FROM A SURE TEAM LECTURE BY "SNAKE" REAVES.
TREY, 65

AILERON ROLL LIMITATIONS

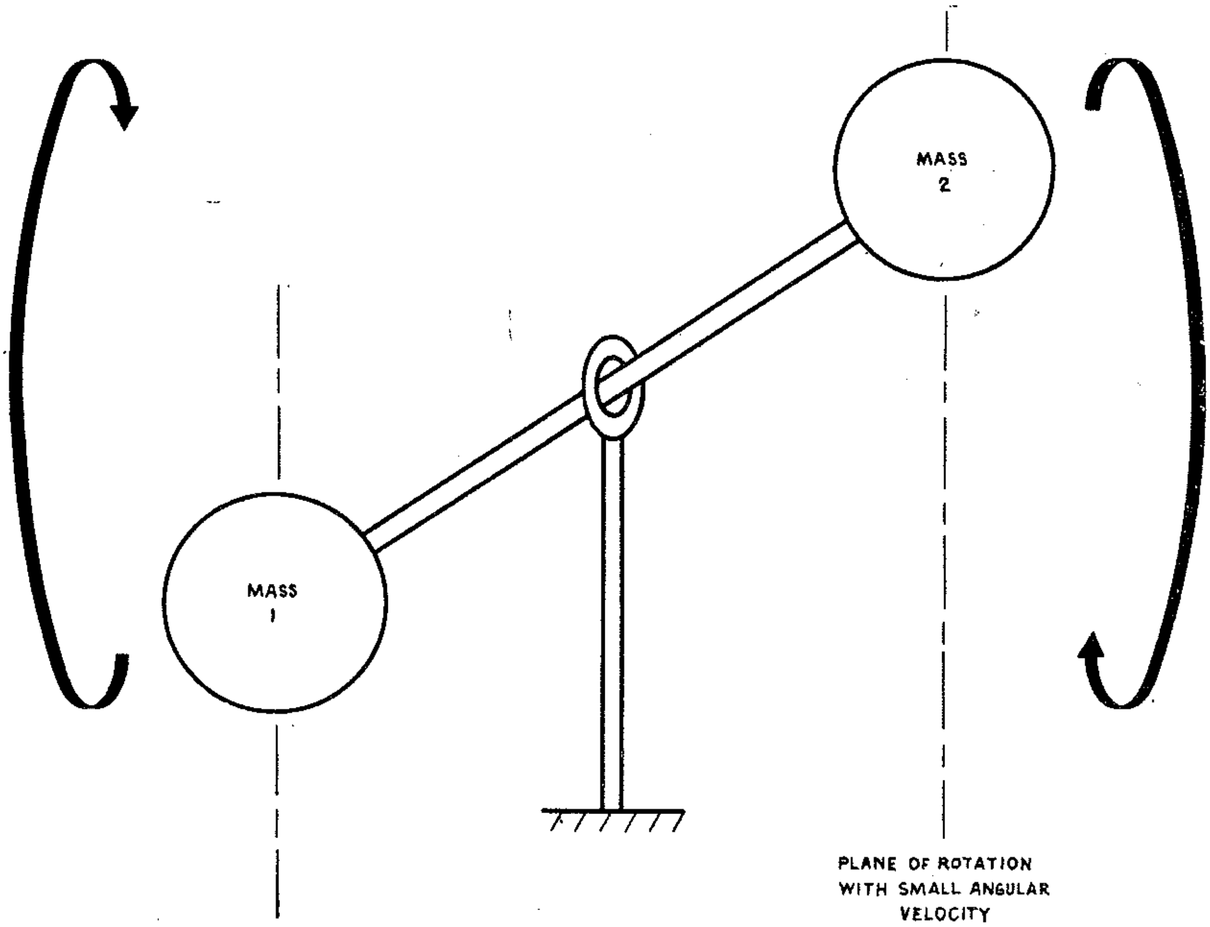
The aileron roll limits of the F-104 are the result of two considerations:

1. Structural loads as a result of rolling.
2. Inertia coupling tendencies affecting ability to retain control of the airplane.

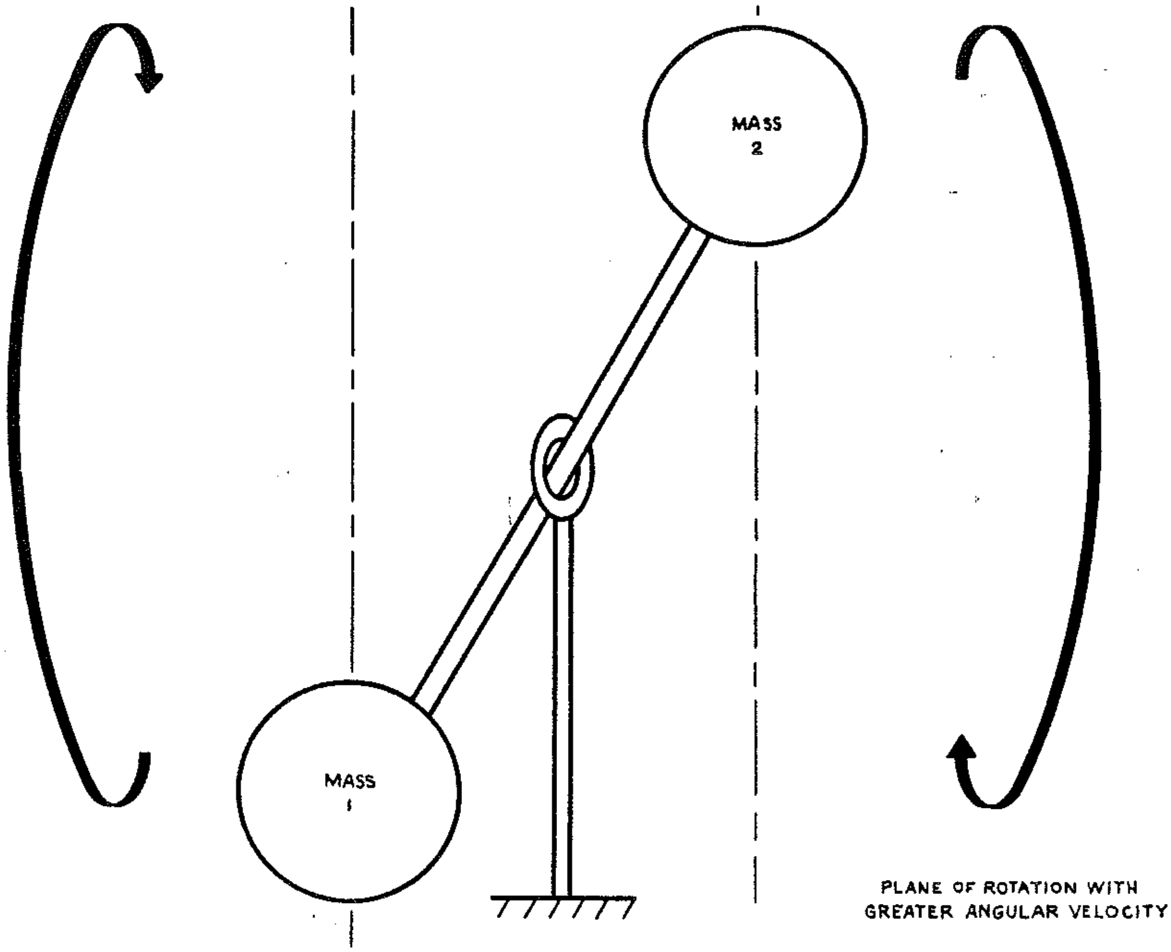
Without a doubt, the limitation of full deflection rolls to 360 degrees is the most confusing, and I suspect the most exceeded of all the restrictions. There is good reason for the confusion and considering the ease with which the aircraft does aileron rolls, the restriction can be exceeded without any premeditation. The limitation in the handbook unfortunately sheds no light on the reason for the restriction but simply makes the statement - "In order to avoid inertia coupling and high structural loads approaching limit values, aileron rolls are subject to the following restrictions." And then further confusion is compounded by the inputs of "g" factors, damper operation and the amount of stick deflection during the roll. Since there is only one approach to enlighten the aspects of this restriction, I shall now explain to you inertia coupling and how it applies to the F-104. But before I get involved with the theoretical aspects, you might rightly wonder, "How bad is inertia coupling - can it cause the loss of an aircraft? Or does it just result in a wild ride and a few pulled rivets?" The answer can be found in the accident report of the loss of the Bell X-2 Rocket Ship and USAF Test Pilot Capt. Milburn Apt. In 1956 at Edwards Air Force Base, Capt. Apt was launched in the X-2 from a modified B-50. Confounding the predictions of the engineers, he flew a perfect profile <u>and</u> the rocket motor burned a few critical seconds longer than expected. These were the ingredients that added up to disaster. Attaining a greater speed (Mach 3.2) and altitude (119,800 feet) than planned for, Apt was literally "running out of airspace" and unknown to him - out of directional stability. Seeing that he was over the geographical point of his profile where he should turn to return to the dry lake - Apt actuated the controls to turn and the craft went divergent with the resulting loss of control. Accident investigation listed the cause as a greater loss in directional stability than planned for, which yielded inertia coupling. Now let's take a close look at inertia coupling. Our first consideration will be with the application of the laws of motion to such a system as I have depicted below.



This system shows two balls of equal concentrated mass connected together by an essentially weightless rod that is pinned at the mid-point but the balls have freedom of movement as shown. If an initial force is applied to set the balls in rotation, it is obvious that the planes of rotation must move toward the pinned mid-point of the rod as shown.



If a greater force is now applied to the balls it should be clear that not only will the balls achieve a greater angular velocity but of necessity must rotate in two planes that are yet even closer to the pinned mid-point of the rod as shown.

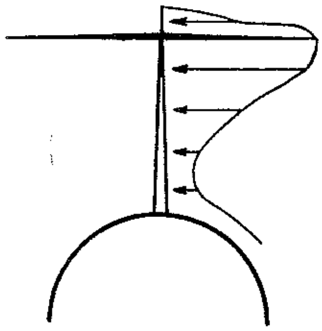


The main concept of this system should now be clear. As the angular velocity of the end points is increased, the planes of rotation seek the point of maximum radius of rotation of the masses which is the mid-point of the system. From Newton's laws of motion, inertia is defined as that property of matter because of which a force must be exerted on a body in order to accelerate it. Therefore, our system has shown its resultant motion when the inertia of the masses is accelerated in circular rotation. Now let's apply this concept to the F-104.

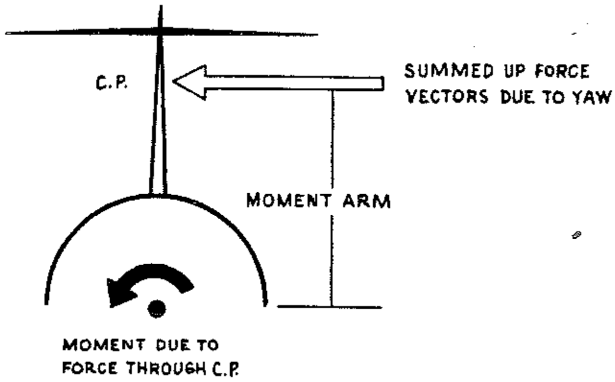
A close look at the configuration of the F-104 will disclose the design characteristics that have an implication in the inertia coupling problem. The first impression is the concentrated mass along the fuselage center axis with the short wing span. This obviously gives high inertia in pitch and yaw and low inertia in roll. Another pronounced feature is the swept vertical tail with the horizontal stabilizer mounted on top. In the initial phase of designing the F-104, Kelly Johnson decided on the high T-tail for important benefits in supersonic flight.

1. It gives good pitch stability and is highly effective for supersonic maneuvering.
2. The rearward mounting gives considerable saving in interference drag.

Of course, the disadvantages of a high tail position are that some way has to be found to dampen the large amount of positive dihedral effect and in slow speed flight the high tail position contributes to pitch-up. Kelly drooped the wings with 10° of cathedral and this gives normal side-slip reaction. In order to visualize positive dihedral effect, we have to look at the pressure profile on the tail in yawed flight.

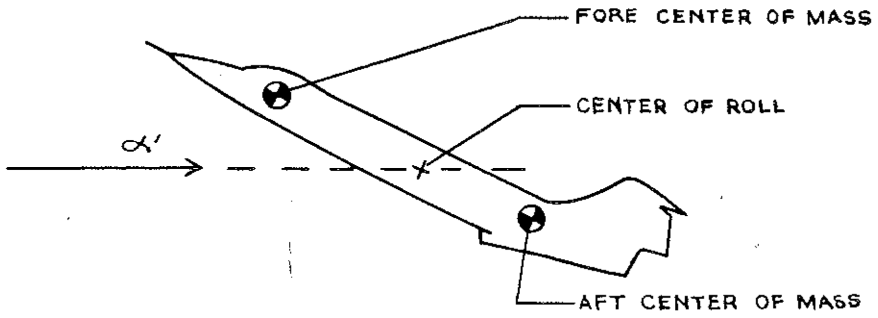


Assuming the aircraft is in a right yaw, the tail develops a pressure pattern as shown. If the pattern is summed up, the yawed condition can be shown as one total force vector acting through a calculated center of pressure. With this situation, the effect of the tail is to not only return the aircraft to straight-line flight but will also generate a rolling moment around the longitudinal axis in the direction of the initial yaw.



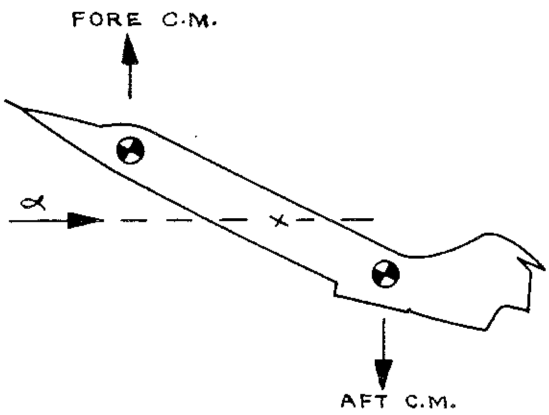
These conditions are exactly what you are familiar with for a left side-slip. You first push in right rudder and then you must come in with left aileron to counter-act the positive dihedral effect and maintain the side-slip.

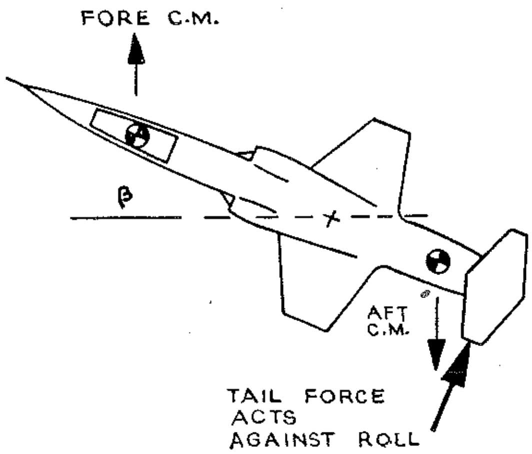
At this point all the basic factors that contribute to inertia coupling have been examined. With these factors in mind, Lockheed initiated a study analysis of the roll performance of the F-104A that was completed in December of 1956. The results showed close comparison with the theoretical predictions. The analogy of the aircraft to our rotating ball system can be shown with a center of roll point acting as the hinged mid-point and by computing a fore and aft center of mass, we are now in business. The only important difference is that we now have a completely dynamic system.



The study analysis investigated three conditions of roll entry -- positive "g", one "g", and negative "g". Applying the foregoing principles of motion the conditions are:

1. Positive "g" entry -- left roll;

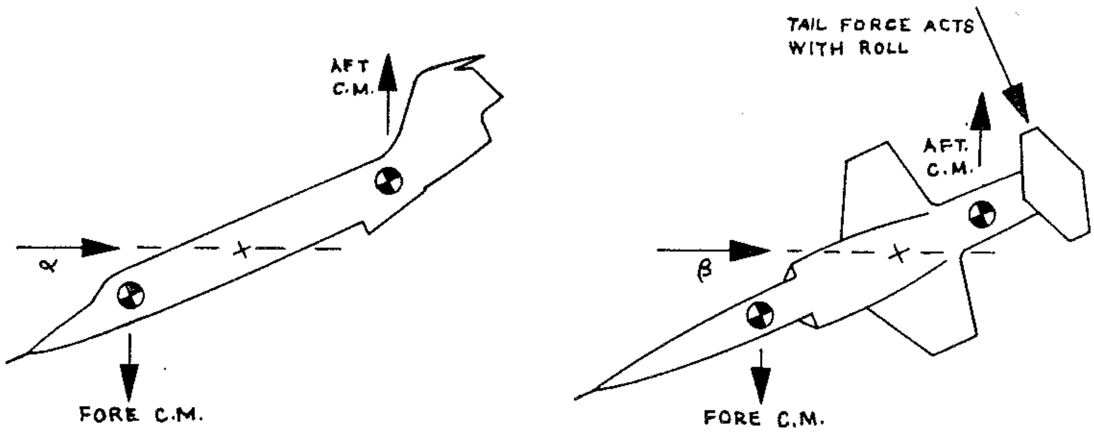




As these drawings show, we have the displacement of the aircraft end-points with the fore c.m. up and the aft c.m. down as positive "g" is applied just prior to the roll. A check of our force that has been induced on the tail, by the yaw, shows that the force is acting as predicted and trying to bring the aircraft back to straight line flight and due to the direction in which it is acting, it is generating a roll moment around the fuselage axis to the right. Since this moment is in direct opposition to the left roll of the aircraft, then it is a roll-damping moment. The magnitude of this roll-damping moment is a direct function of angle of attack at the time the roll is initiated.

2. One "g" entry -- left roll; this roll entry is more or less the nominal type of entry -- neither positive nor negative "g" loads are imposed. Also this entry gives the least amount of displacement of the fore c.m. and aft c.m. with negligible tail factor effect during the roll.

3. Negative "g" entry -- left roll;



As these drawings show, we have the displacement of the aircraft end-points with the fore c.m. down and the aft c.m. up as negative "g" is applied just prior to the roll. A check of our force that has been induced on the tail, by the yaw, shows that the force is acting as predicted and trying to bring the aircraft back to straight line flight <u>and</u> due to the direction in which it is acting, it is generating a roll moment around the fuselage axis <u>to the left</u>. Since this moment is in the same direction as the left roll of the aircraft, it is a roll-augmenting moment. The magnitude of this roll-augmenting moment is a function of the angle of attack at the time the roll is initiated. If we remember the mass balls example and the fact that whenever a greater force was exerted that accelerated their angular velocity, the balls were forced to rotate with greater radii around the hinged mid-point, inertia coupling is now fully explained. As the tail factor increases the roll rate, since it is acting in the same direction as the initial roll, the fore and aft center of masses <u>must</u> rotate in larger circles. As the end points are displaced in larger circles -- this increases the yaw and increases the tail force, which increases the angular velocity, which increases the radii of rotation, which increases the yaw -- until the whole ball of wax is rotating in a common vertical plane that unfortunately is 90° to the flight path. Hence, inertia coupling.

With this spectre of inertia coupling staring our intrepid engineers in the face, they decided on a computer study that would utilize the equations of motion in order to investigate this problem thoroughly before launching a flight test program. A basic F-104A configuration was established, which at this time was without ventral fin and with all dampers inoperative and $\pm 20^{\circ}$ of available aileron. This information was tabbed into an IBM 701 computer along with the following conditions:

1. Speed - Mach 1.6
2. Altitude - 40,000 feet
3. Zero "g" roll entry
4. Full 20° of aileron input

The decoding of the computer's answer told a most interesting story. Completely substantiating the study analysis, the computer predicted that:

1. The airplane would develop a large amount of augmenting side-slip.
2. A peak roll rate of 460 degrees per second would be rapidly established after the ailerons were deflected -- at Mach 1.6!
3. Even if the ailerons were reversed at the end of one revolution, the large amount of augmenting side-slip would provide sufficient rolling moment to counteract the reverse rolling moment of the ailerons. The airplane would be in a condition of autorotation. And --
4. Both normal limit load factor and limit side loads would be exceeded in the maneuver. The aircraft would break up!

Before the smoke had cleared from this little bomb, the engineers had rapidly retreated to the drawing boards and slip-sticks. After some wind tunnel tests, a new configuration began to emerge which included:

1. A ventral fin to augment static directional stability at maximum speed.
2. Reduction of maximum aileron travel in the clean configuration to limit the peak roll rate to 150 degrees per second. This level of peak roll rate is adequate and full lateral control is retained at the stall in take-off and landing by the use of a variable aileron stop permitting full aileron travel in the landing configuration.
3. Detailed modifications to the yaw and pitch dampers to utilize the full inherent damping capability of these devices in rolling maneuvers.

With this configuration, the computer analysis showed safe and adequate rolling performance at all speeds and altitudes, including the foregoing conditions that predicted the other aircraft configuration would break up. We were now ready to launch upon the flight test program and consultation with the USAF outlined the roll requirements with respect to handling qualities and structural integrity as set forth in MIL-SPEC F-8785 and MIL-SPEC J-5702. On the basis of these specifications, the following criteria were established for purposes of demonstrating safe and adequate rolling performance.

1. The airplane must demonstrate a peak roll rate of 150 degrees per second in a level flight condition at an altitude of 40,000 feet. Reductions in peak roll rate at higher altitudes or higher "g" entry conditions are acceptable. At the placard design speed of 750 knots the airplane must demonstrate a peak roll rate of 50 degrees per second.
2. The airplane must demonstrate the capability of achieving 100 degrees of bank angle in one second at an altitude of 20,000 feet in a one "g" roll. Reductions in this requirement at higher altitudes or higher "g" entry conditions are acceptable.
3. For purposes of demonstrating safety in rolling maneuvers, the airplane must demonstrate 360 degree rolls. Reversing the aileron to accomplish a check must not be initiated until the airplane has accomplished a full 360 degrees of bank angle.
4. Limit loads must not be exceeded for a range of entry conditions from zero "g's" to 2/3 maximum "g's".
5. The airplane must demonstrate reasonable handling characteristics to the pilot for a range of entry conditions from level flight to 2/3 maximum "g's".

With the configuration firmly established and the test requirements set, the flight test program now got under way. Between NASA and Lockheed pilots, more than 220 full and partial deflection aileron rolls were conducted at roll entry conditions of zero "g", 1 "g" and 2/3 maximum "g". The effect of multiple revolution rolls was not evaluated because of the unacceptable increase in test span and flights that would have been required. In addition the USAF Systems Project Office did not think there was any tactical use for extended rolling maneuvers. Based upon the pilot's comments and analysis of the data, the following conclusions were reached:

1. The F-104 would not experience inertia coupling in 360 degree rolls entered from 1/2 "g" and above at any speed and altitude within the design envelope.
2. Roll-augmenting side-slips and increasing peak roll rate attest to a small degree of inertia coupling at 40,000 feet as roll maneuvers are entered from initial load factors of 1/2 "g" and less.

3. Tail loads did not exceed 50% of design limit under any test condition.
4. All rolls were promptly terminated upon neutralization or slight reversal of ailerons; no autorotative tendencies were evident.
5. A 65% aileron stop will permit an acceptable level of roll performance and in conjunction with the recommended maneuvering placard will provide freedom from excessive roll or inertia coupling as required by military specification.
6. With 65% aileron stops, the military requirement of one second to roll 100 degrees is essentially met over the entire speed range tested at the maximum applicable altitude of 20, 000 feet.
7. Peak roll rates using 65% aileron stops are maintained above 140 degrees/second for the one "g" entry case throughout the entire operating speed range at 40, 000 feet.
8. There was no noticeable difference in rolling performance between rolls with dampers on or off in any flight condition tested. With dampers on, however, pitch and yaw transients during roll recovery were better damped.

The final consideration before establishing the roll limitations was the possible build-up of structural loads during rolling. During aileron rolls, airloads on the empennage are experienced due to roll-rate and side-slip. The magnitude of these loads varies with airplane angle of attack or load factor during the roll, generally increasing as the angle of attack or load factor is increased. As explained before, with increasing angle of attack, side-slip due to rolling increases. The side-slip generated during rolls at angles of attack in excess of 3 degrees is nearly always a roll-damping side-slip and tends to decrease the roll rate; therefore, the increase in loads is primarily due to the side-slip excursion.

In case of rolls conducted at angles of attack below 3 degrees, the side-slip generated due to rolling is roll augmenting (as explained before) resulting in significant increases in roll rate. In this condition, tail loads increase more rapidly due to the higher roll rates acting in conjunction with the induced side-slip.

These were the factors that dictated the limits presented in the flight manuals. Regardless of the model of F-104, the restrictions are primarily:

1. Wing Flaps retracted:
   - A. Entry load factor of 1/2 "g" and greater--- full deflection rolls are limited to 360 degrees. Below one "g" with pitch or yaw stability augmenters inoperative, full deflection 360 degree rolls are prohibited.
   - B. Entry load factor less than 1/2 "g" -- full deflection 360 degree rolls are prohibited. All rolls below 1/2 "g" load factor must be executed with extreme caution.
2. Take-off flaps extended:
   - A. Rolls are limited to 360 degrees.

B. Either the pitch or yaw stability augmenter must be operative for all rolling maneuvers.
C. Aileron rolls are prohibited for entry load factors of less than one "g".

The reason for the limitations being divided into flaps up and flaps in take-off is that with flaps in the take-off position, the angle of attack is lower than that for the flaps up configuration. This further increases the inertia coupling tendencies at low load factor entry. Therefore, rolls are prohibited at load factors less than one "g".

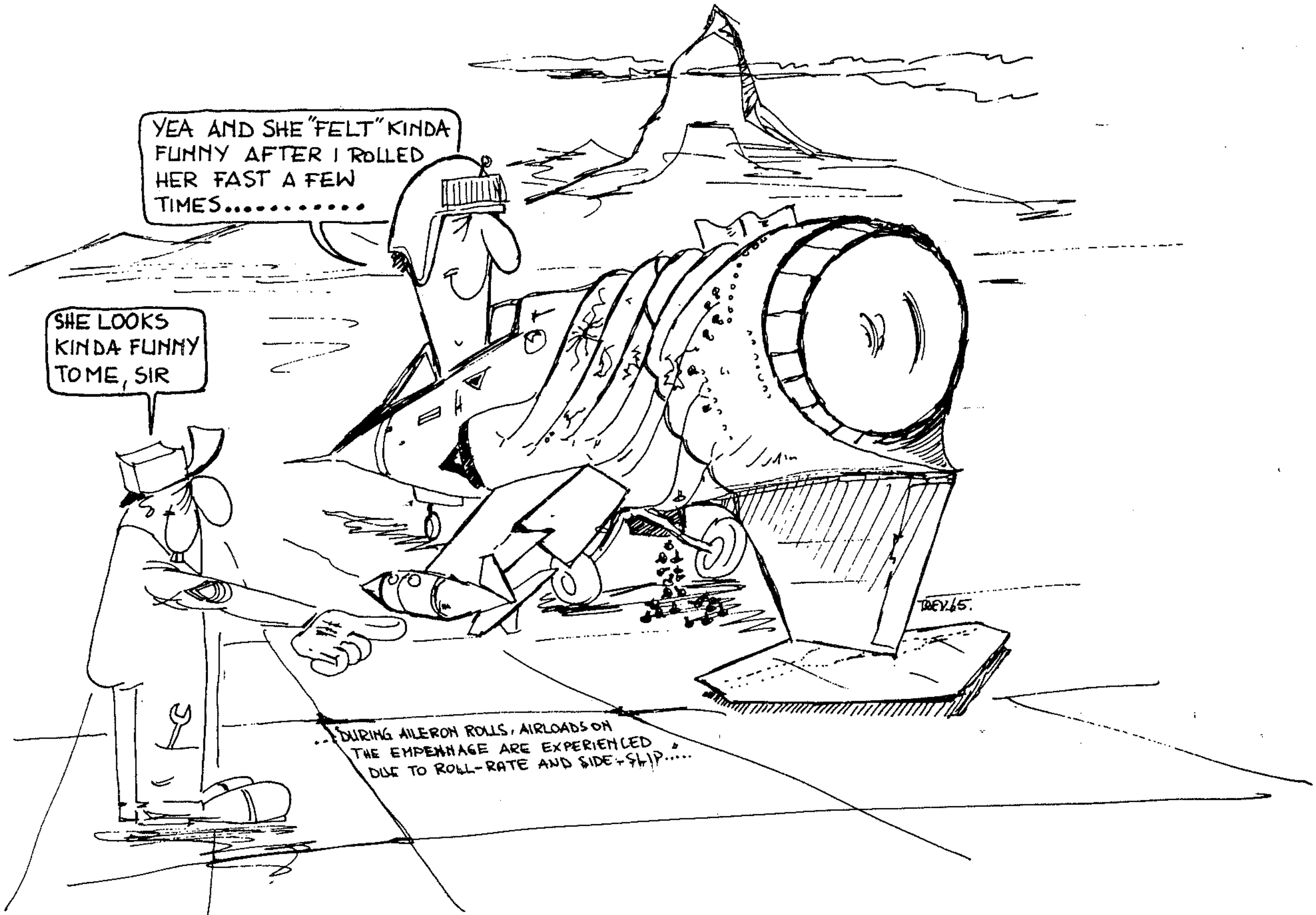
Pilot comments are very interesting in that it was pointed out that the high initial roll acceleration of the F-104 made it necessary -- when using large aileron throws -- to securely brace himself in the cockpit in order to be able to apply the desired abrupt aileron input. That is, the airplane would tend to "roll-away" from the laterally advancing control stick. Another important consideration in low "g" entry rolls is that by the time the aircraft has rolled 90 degrees, the pilot is sensing a build-up of negative "g's" due to the outside rolling. This sensing of negative "g's" causes an instinctive pull-back on the stick which helps in the roll recovery.

A final result of our roll analysis came from the five-degree-of-freedom computer studies that were conducted in conjunction with the flight investigation. Flight data were used continually to revise and improve the computer's accuracy, as demonstrated by the ability to match closely the records of actual test maneuvers. The interesting predictions were:

1. With either pitch or yaw damper inoperative, roll maneuvers may continue safely through three successive revolutions (1080°) without adverse effects at any operational speed or altitude, provided entry load factor is 1/2 "g" or more.

2. At entry load factors of zero "g", 360 degree rolls in certain cases can be satisfactorily performed. Above 40,000 feet, however, there is a likelihood of autorotation or critical loads being encountered with either or both dampers inoperative.

I must, of course, warn you that these predictions are based on computer studies and have not been confirmed by data from flight tests.


YEA AND SHE "FELT" KINDA FUNNY AFTER I ROLLED HER FAST A FEW TIMES............
SHE LOOKS KINDA FUNNY TO ME, SIR
...DURING AILERON ROLLS, AIRLOADS ON THE EMPENNAGE ARE EXPERIENCED DUE TO ROLL-RATE AND SIDE-SLIP.....
TREV.65.

Aileron Restriction

There is another aspect of aileron restriction that must be explained. On the F-104A, B, C, D, and F aircraft the maximum available aileron travel is ± 15 degrees per aileron. On all models subsequent, the maximum available aileron travel is ± 20 degrees per aileron. Strangely enough, we have to go back to the early design of the tip tanks to understand this difference in aileron travel. In the very early studies of supersonic stability with the unvaned tip tanks, it was found that aileron reversal occurred at very low Mach numbers because the forward center of pressure on the unvaned tip tank body led to a low divergence speed. Further design tests led to an arrangement of eyebrow vane and inboard and outboard aft vanes -- which satisfied both the flutter stability and rolling power requirements.

Another important parameter which was investigated for the tip tanks was the size of the aft vanes. Tip tanks with symmetric horizontal stabilization vanes of a semi-span of 16.5 inches caused aileron reversal at about 700 knots EAS. Analysis of the downwash created by wing twist and aileron deflection along with computations based on computer analysis, indicated the reversal problem could be eliminated by increasing the span of the inboard vane. Subsequently the inboard vane was enlarged to a span of 30 inches. But while this alleviated the aileron reversal the longer span decreased the roll effectiveness at normal landing speeds. In a full rudder sideslip at the engine speed of 80% for landing with land flaps, it was found that 10 degrees of aileron was required to maintain the flight path at landing lift coefficients with 30-inch vanes on the tip tanks. Therefore, the aileron travel limit was extended to provide a deflection of 20 degrees, with the gear down, which gives adequate lateral control during sideslip with the 30-inch vane tanks.

Airspeed Limitations

The airspeed limits of the airplane with and without the various external stores were determined considering the following variables:

1. Airframe design speed.
2. Engine limits.
3. Airplane stability and control.
4. Airframe flutter limits.
5. External store limits.
6. Practicability.

Even though the airframe design speed extends out to the Mach 2.5 region, other limitations take priority in the high Mach area. We are all familiar with the compressor limit on the engine but perhaps the stability and control problem is not as well understood. Many pilots have inadvertently shot past the Mach 2.0 limit and upon consideration of the manner in which the excess thrust pushed the aircraft there, they honestly wondered about the validity of the Mach 2.0 restriction. This can only be understood by a study of the directional stability limitations at high Mach.

The static directional stability of an aircraft varies with Mach number -- increasing up to Mach 1.0 and then decreasing as speed is increased. Depending upon the design of the aircraft, the static directional stability decays, with increasing Mach, until the aircraft is in an area of neutral or negative stability. Entry into an area of neutral or negative stability can result in sideslip angles of sufficient magnitude to cause structural failure. When the airplane is at a condition of neutral stability, there is no tendency, once disturbed, to return to the initial trim condition. If the airplane enters a negative stability area, the aerodynamic forces will increase the sideslip angle until structural failure occurs.

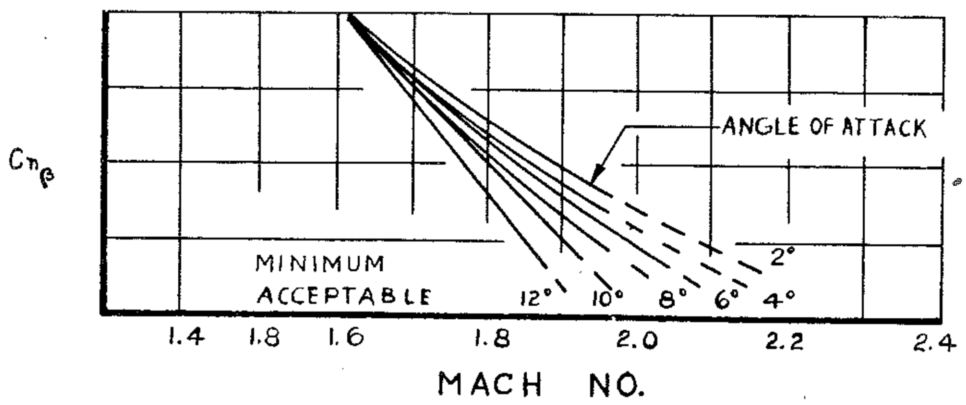
The other factor of static directional stability is that, at a given speed, the level of stability varies with airplane angle of attack. The level of stability of the F-104 was determined from flight test data by displacing the aircraft with a rudder kick at the desired flight condition. The ensuing oscillation was then analyzed to obtain a quantitative measure of the stability level. After obtaining a measure of the stability level trend with both Mach and angle of attack, a further analysis was made to set operating limits for normal tactical use of the airplane.

Inasmuch as the stability level varies with angle of attack and Mach number and the pilot does not have an angle of attack presentation, the complexity of setting limits increases. Because of this, limits are given in the manual in terms of Mach number and load factor. The load factor limit represents the angle of attack effects. This results in complexity in that, at a given Mach number and load factor, the angle of attack will be different as altitude is changed, i.e., as altitude is increased, the angle of attack will be increased. For example, with an assumed gross weight of 17,500 lb., at Mach 2.0 and 3 g's at 40,000 feet, the angle of attack would be approximately 6 degrees, but at 60,000 feet the angle of attack would be about 16° at Mach 2.0 and 3 g's. In order to provide limits then, an altitude consideration must be employed. Therefore, in the manual, an altitude of 40,000 feet was selected as a break point; i.e., for altitudes up to 40,000 feet, one set of g limits apply and above 40,000 feet another set are to be used.

In setting actual values used in the manual, the following considerations were used:

1. Minimum acceptable level of static directional stability.
2. Rate of decay of stability with angle of attack and Mach number.

At speeds above Mach 1.7, the static directional stability decreases very rapidly as the angle of attack increases. This decay in stability is shown in our representative sketch.



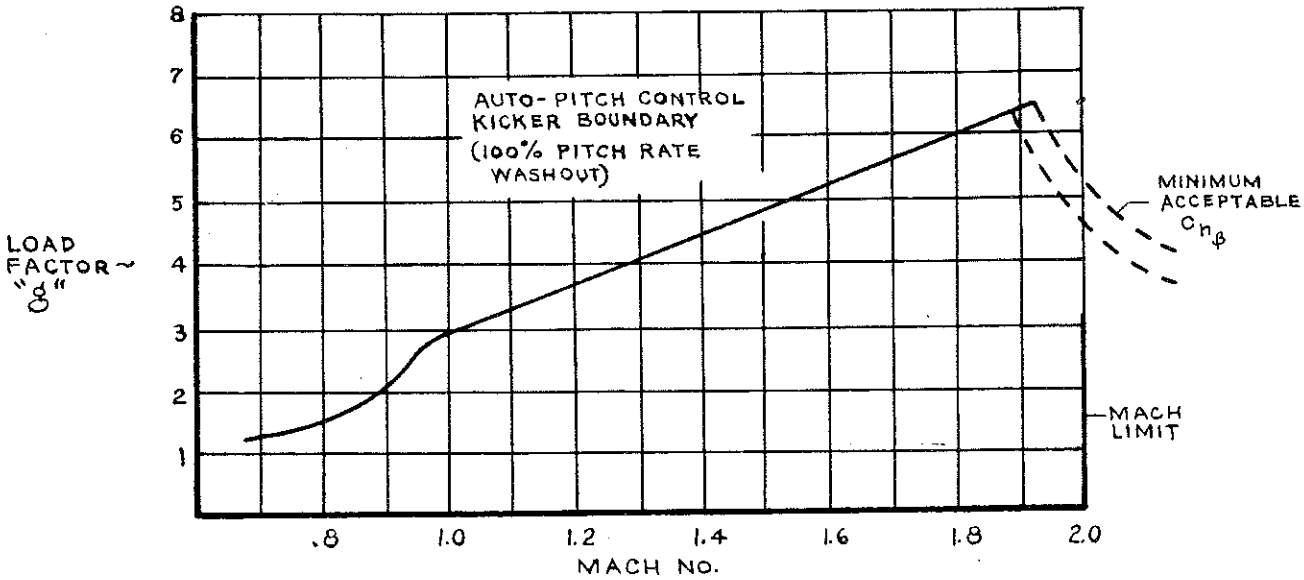
As you can see, any small overspeed at high angles of attack could easily result in entry into an unacceptable stability level area or into an unstable area. However, if we compare the APC boundary and static directional stability, a very simple guide is presented for observing the limitations and flying the bird to its maximum. The following plot shows that if the stick kicker boundary is used as a limit for symmetrical maneuvering up to Mach 1.9, you will be within all directional stability limits. Above Mach 1.9, the airplane maneuverability will have to be reduced slightly to retain an adequate level of directional stability.

In relation to airframe flutter limits in airspeed limitations, a comprehensive investigation of the wing and empennage was accomplished. The analyses of the wing included the effects of a wide range of external stores which the airplane is capable of carrying. Inasmuch as the centers of gravity of the tip and pylon stores are all within proper limits, all configurations are flutter safe within the design speed limitations of the airframe <u>except</u> the configuration involving empty tip tanks and the pylon tanks containing more than residual fuel. This configuration is limited to 500 KTS. IAS but is definitely a malfunction since it is not supposed to be possible with the proper operation of the fuel system.

Airspeed limitations for various external stores are based on the following considerations:

1. Strength limit of the store.
2. Possibility of flutter inducement due to the aerodynamic shape of the store.
3. Heat limit of the store.
4. Combination of airframe and store result in reduced directional and/or lateral stability factor.
5. Maximum speed at which the store was carried during flight tests.

SYMMETRICAL MANEUVERING CAPABILITY
NO EXTERNAL STORES ~ 19100 LBS
40,000 FEET
FLAPS UP



Acceleration Limitations

The maximum allowable acceleration limits are those loads which if exceeded can result in damage and structural deformation of the airplane. Again there is great complexity in presenting the limits due to the interacting variables. Since it is impossible to list the "g" limitations for all possible tactical maneuvers, the load factors had to be divided by fuel weights, Mach numbers, altitudes, symmetrical and unsymmetrical maneuvers.

The effect of airplane weight was simplified by presenting load factors for two weight conditions. The break points selected were 5500 lb. of fuel and 4000 lb. of fuel with the gun installed. These fuel loadings represent the maximum airplane weight at which the maximum listed load factor may be used for that particular configuration.

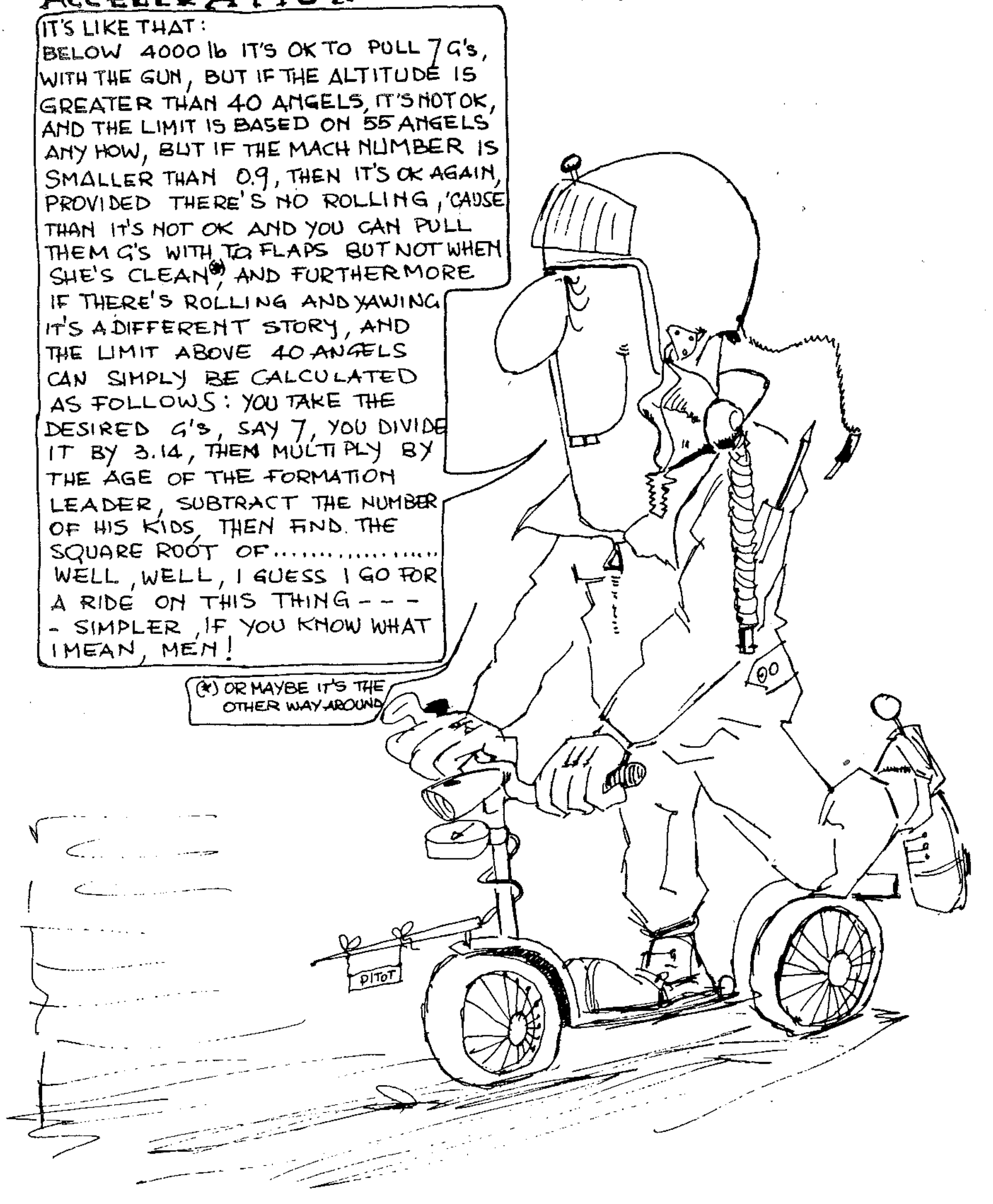
Mach number limits for "g" loads are those limits to maintain directional stability as discussed previously.

Altitude effect is simplified by presenting two ranges, "up to 40,000 feet" and "above 40,000 feet". The limit for altitudes up to 40,000 feet is based on the airplane capability <u>at</u> 40,000 feet; for altitudes above 40,000 feet, the limit is based on the airplane capability <u>at</u> 55,000 feet.

Maneuvers are divided into those that result in symmetrical loading of the structure and maneuvers that result in asymmetric loadings of the structure. Any maneuver wherein only pitching is involved, such as a steady turn or wings level pull-up, results in symmetrical loading of the structure and higher "g" loads may be imposed before reaching structural limits. Any maneuver involving rolling and yawing with "g" loads results in asymmetric loading of the structure and is more critical, and unpredictable as to the stresses on the aircraft.

The limits listed in the manual were determined by inflight measurement of loads at critical speeds and by static load tests performed on the ground.

ACCELERATION LIMITATIONS



Stores Jettison Limits

The external stores jettison limits were determined from the results of wind tunnel tests and inflight jettison of the stores during test programs. Factors that were recorded and considered were:

1. Airflow effects upon the store at separation.
2. Jettison cartridge capability.
3. Ballistics of the store upon release.
4. Airplane response and trim changes.

A question asked many times is -- what is the reason for not having a manual release system for external stores? Well, in the early F-104A test program, we had manual handles for release of external stores at the tip and pylon stations. Unfortunately, one of the releases malfunctioned on a test flight and the released tip tank wiped out the tail. In the investigation we came upon the cold hard fact that the pressure from the bow wave of the aircraft will hold manually released stores so close to the fuselage that in all likelihood you will encounter damage. Therefore, we designed cartridge-ejection systems with safety features like the auto-drop circuitry. So our answer to manual release is that with any appreciable Mach number, a manual release of a store would knock you out of the sky with more accuracy than would a MIG on your tail.

The relatively low (subsonic) airspeed requirement for jettison of launcher rails, pylon racks, and all non-aerodynamic shapes is due to the absolute unpredictability of their flight path after jettison.

TAKE-OFF FLAP RESTRICTION

In our search for more maneuver capability in the F-104, we investigated the loads and the limitations on the aircraft for three conditions of flight: First: Lowering the flaps and, Second: For maneuvering with the flaps extended and, Third: For raising the flaps. Our computations and flight test results soon showed that the second and third consideration could be listed together, and therefore, the limitations are listed for two regimes of flight: (1) During flap extension and (2) Flaps extended or retracting. The following table lists the restrictions as they apply to the various models.

MAXIMUM ALLOWABLE AIRSPEED LIMITS

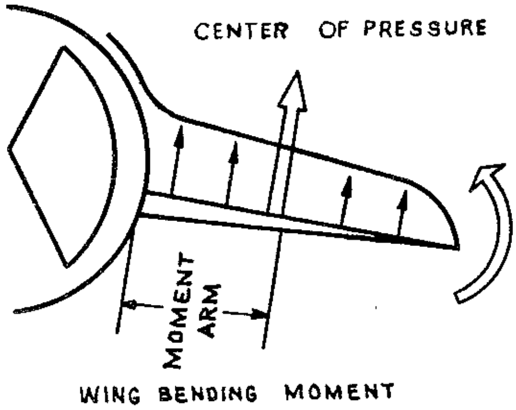
Model	During Flap Extension	Flaps Extended or Retracting
F-104A	450 Knots IAS or Mach 0.80. There is no Mach limitation if 330 knots IAS is not exceeded.	450 Knots IAS or Mach 0.80. There is no Mach limitation if 350 knots IAS is not exceeded.
F-104B	(Same as above)	(Same as above)
F-104C	(Same as above)	(Same as above)
F-104D	(Same as above)	(Same as above)
F-104F	370 Knots IAS or Mach 0.84. There is no Mach limitation if 290 knots IAS is not exceeded.	370 Knots IAS or Mach 0.84. There is no Mach limitation if 350 knots IAS is not exceeded.
CF-104	450 Knots IAS or Mach 0.85. There is no Mach limitation if 330 knots IAS is not exceeded.	520 Knots IAS or Mach 0.85. There is no Mach limitation if 360 knots IAS is not exceeded.
CF-104D	450 Knots IAS or Mach 0.80. There is no Mach limitation if 330 knots IAS is not exceeded.	450 Knots IAS or Mach 0.80. There is no Mach limitation if 360 knots IAS is not exceeded.
F-104G	450 Knots IAS or Mach 0.85. There is no Mach limitation if 330 knots IAS is not exceeded.	520 Knots IAS or Mach 0.85. There is no Mach limitation if 360 knots IAS is not exceeded.

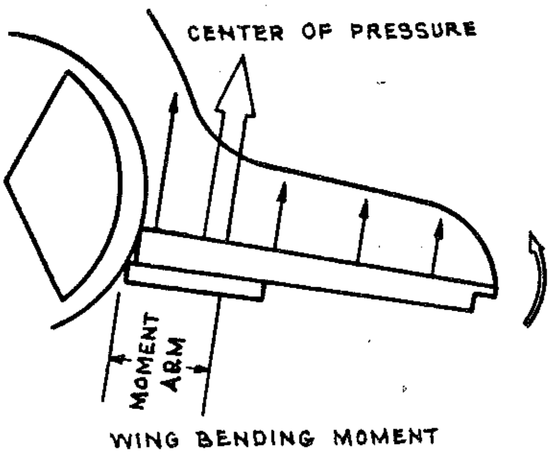
MAXIMUM ALLOWABLE AIRSPEED LIMITS (CONT'D)

Model	During Flap Extension	Flaps Extended or Retracting
TF-104G	450 Knots IAS or Mach 0.80. There is no Mach limitation if 330 knots IAS is not exceeded.	450 Knots IAS or Mach 0.80. There is no Mach limitation if 360 knots IAS is not exceeded.
F-104J	370 Knots IAS or Mach 0.84. There is no Mach limitation if 290 knots IAS is not exceeded.	500 Knots IAS or Mach 0.84. There is no Mach limitation if 350 knots IAS is not exceeded.
F-104D/J	370 Knots IAS or Mach 0.80. There is no Mach limitation if 290 knots IAS is not exceeded.	450 Knots IAS or Mach 0.80. There is no Mach limitation if 350 knots IAS is not exceeded.

In order to analyze reason out of what appears to be chaos in this table, I will first explain the airspeed limitations. For the F-104F, F-104J, and F-104D/J, the limitation of During Flap Extension is at 370 knots IAS because these aircraft have not incorporated the latest ECPs and Service Bulletins to raise the limitation of the flap driving mechanism. The other models have incorporated the latest changes and, therefore, have the 450 knots IAS limitation of During Flap Extension. Also, in the particular case of the F-104F, the limitation of 370 knots IAS for the Flaps Extended or Retracting is because this aircraft releases the $\pm 6^{\circ}$ rudder deflection to full throw with take-off flaps. Therefore, the possibility of full rudder deflection at an airspeed that would exceed the allowable fin root bending moment yields the lowest limit for this regime of flight. For the models of F-104A, B, C, D, and CF-104D, TF-104G, and F-104D/J, the limitation of 450 knots IAS for Flaps Extended or Retracting is actually not due to any limitation on the flaps. The limitation is actually due to aft fuselage bending moments caused by tail loads with maneuvering "gs" at these speeds. The models of CF-104, F-104G and F-104J were strengthened in the aft fuselage section and therefore the 520 and 500 knot IAS limitation for Flaps Extended or Retracting is actually due to flap strength.

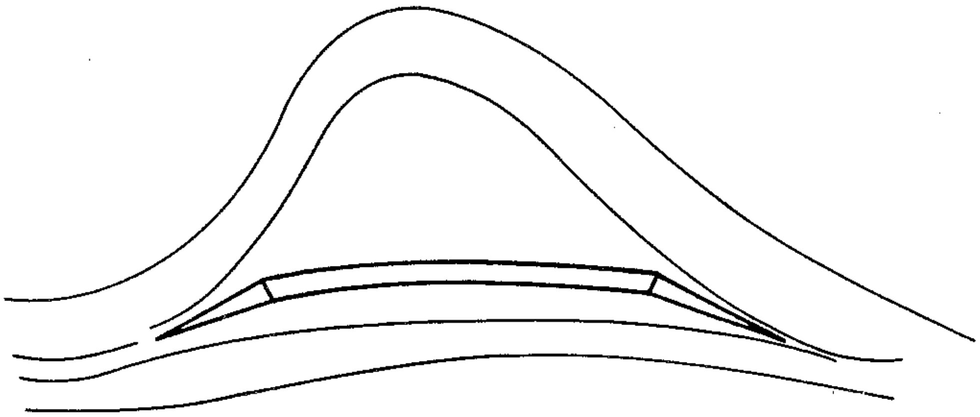
In the analysis of wing strength and flap strength, the following sketch shows the relation of wing bending moment for flaps Up and flaps in Take-off position.



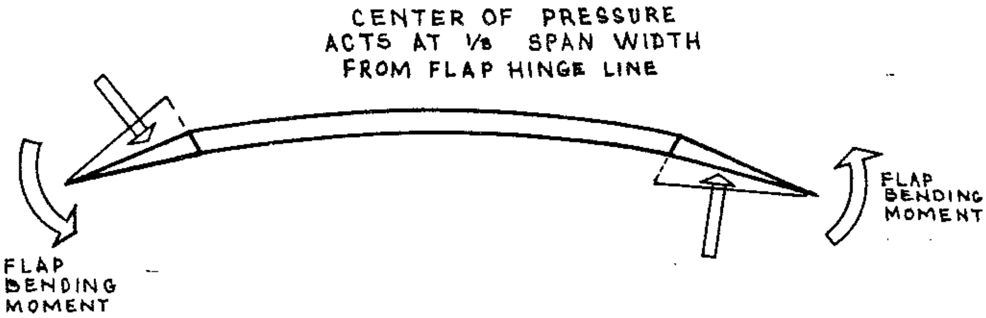


These sketches show that the pressure profile developed by positive angle of attack yields a center of pressure force that flexes the wing and causes a wing bending moment. This pressure profile changes shape with the flaps in take-off position and the center of pressure point moves inboard so that even though a greater force is developed, the wing bending moment is actually less. By instrumenting the flaps and flying unsymmetrical load maneuvers, the basic speed limitation of the flaps was established.

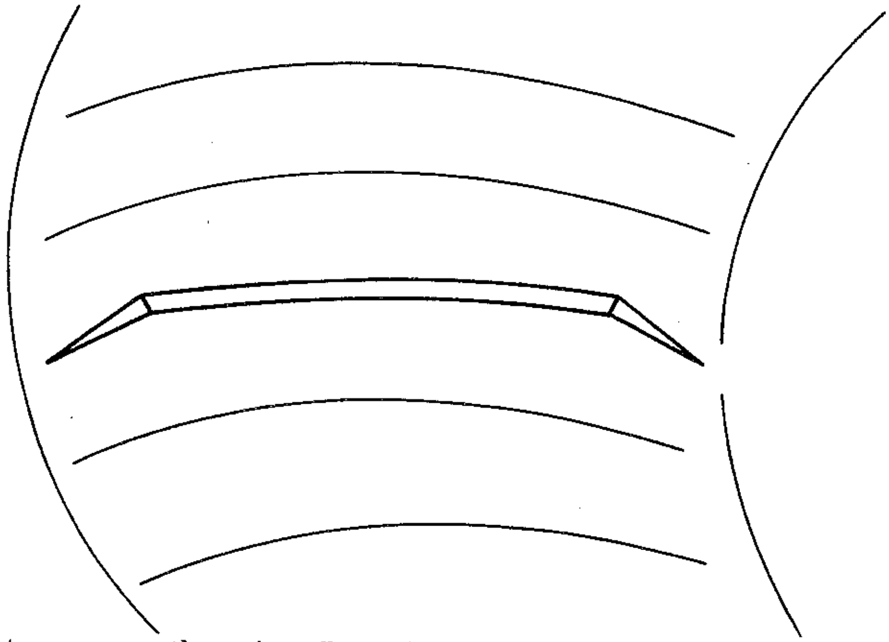
And now an explanation of the Mach Number effects will disclose the reason for the 0.80 to 0.85 Mach limitation. Airspeeds alone, as you know, build up pressure on any airfoil that is deflected into the slipstream. At a relatively low altitude, the pressure profile over the wing can be shown thusly --



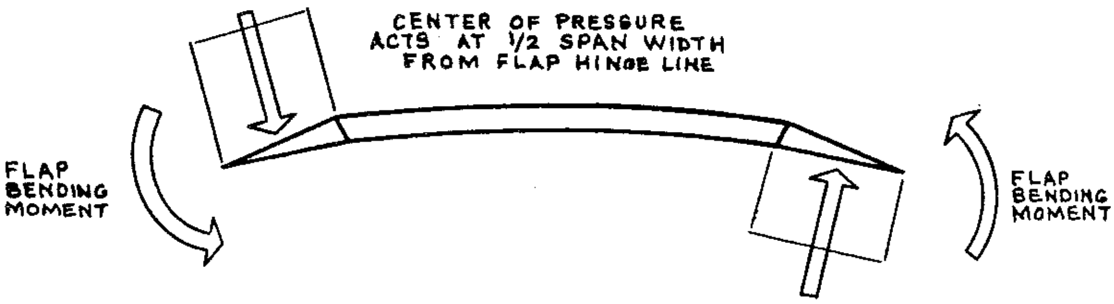
If we examine the airflow just over the flaps, the airflow pattern is shaped like a triangle. For instance, the pattern over the leading and trailing edge flaps has a triangular shaped stress load as shown.



With this airflow pattern, the moment load on the flap hinge is low. However, at higher altitudes, the airflow pattern changes shape due to the compressibility effects and now can be shown thusly --



The pattern over the wing flaps has changed drastically and now is in the shape of a square.



This great change in airflow pattern means a doubling of the hinge moment load between Mach 0.85 and Mach 0.95. Therefore, the Mach limitation reflects the rapid build-up of compressibility effects.

In-flight failures of the flaps have occurred when the Mach limitation was exceeded. They have exhibited a predominate trait of the leading edge flaps failing first and apparently failing due to a down load failure.

At extreme altitudes, the density factor of the air becomes so low that if certain airspeeds are not exceeded, there is no Mach limitation.

POWERED RUDDER RESTRICTION

The restriction of the powered rudder to $\pm$ 6 degrees with the landing gear retracted can be very critical in some regimes of flight, so a fuller understanding of this restriction will definitely be helpful. To be specific, the restriction is invaluable in preventing overloads at high speeds but can be frustratingly prohibitive in recovering from extreme maneuvers -- like spinning.

The reason for the restriction has an excellent basis for normal flying of the aircraft. To preclude an unintentional rudder input at a speed that would exceed the fin root bending moment, it was mandatory for a limiter to be installed. Again, this was not an easy problem for us. The requirement for full rudder throw on take-offs and landings was obviously one parameter to be met. But the limit for climb, acceleration, cruise, maneuvering and let-down had to cover a great portion of the performance envelope. Also, the limit allowable fin bending moment is not a constant, but, is a variable dependent both on stabilizer unsymmetrical bending and vertical load on the horizontal stabilizer. Therefore, to cover the large area of performance, the powered rudder is limited to $\pm$ 6 degrees with the landing gear up. This will give you adequate control with structural safety for normal regimes of flight. However, if you are planning on those high altitude missions or flight into any area that could possibly result in a spin, you should give some thought to the restriction. (See SURE Lecture II "Investigation of F-104 Pitch-Up and Spin Modes".)

SPEED BRAKE RESTRICTION

The restriction of Mach 1.6 for fully extended speed brakes on the F-104A, B, C and D is not for a strength limitation, but due to a sudden degradation of directional stability. In the flight test program on stability and control of these aircraft, it was discovered that the opening of the speed brakes to their maximum of 60 degrees generated a shock wave around the aft fuselage that greatly blanked the rudder, thereby lowering directional stability. Further tests showed that a speed brake extension of 52° in conjunction with the larger tail gives a demonstrated capability at Mach 2.0. Therefore, there is no restriction listed in the manuals for aircraft from the F-104F and up.

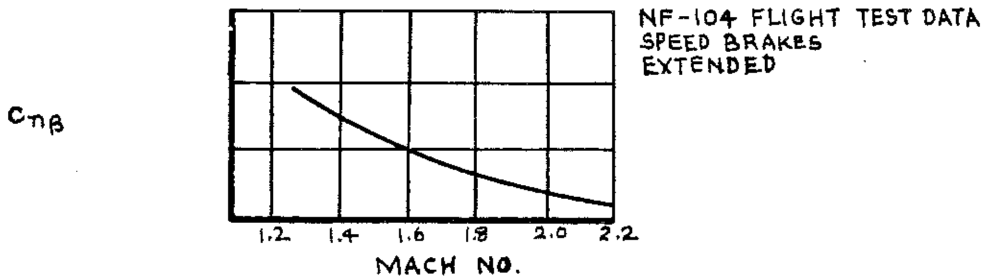
However, the natural question arises -- what to do if an inadvertent overspeed occurs and you must slow down very quickly. In considering all models, our recommendations are:

1. Throttle -- immediately to idle; this should decrease the airspeed instantly. Slight lateral oscillations may be encountered that are a primary result of engine air inlet duct spillage.
2. Upon airspeed decreasing to Mach restriction -- Speed brakes -- full open; you should be prepared for sudden forward deceleration.

If you are not decelerating fast enough with throttle in idle and you want to extend the speed brakes over their restriction, you must consider the following:

1. The decay of directional stability will be proportional to your angle of attack, therefore, you should be in straight and level flight to extend the speed brakes.
2. Consideration should be given to opening the speed brakes only partially. Since they are designed to open in 4 seconds or less, you will be on the conservative side by assuming they open in 3 seconds. Then, by mentally counting during the extension, you can stop them at 1/3 open, 2/3 open, and full open. Actually, you will probably be slightly under the calculated positions and therefore on the safe side.

The latest tests that have been flown by the NF-104A with 52 degrees of extension and the large tail have shown safe operation at Mach 2.2 as depicted by their flight test curve.

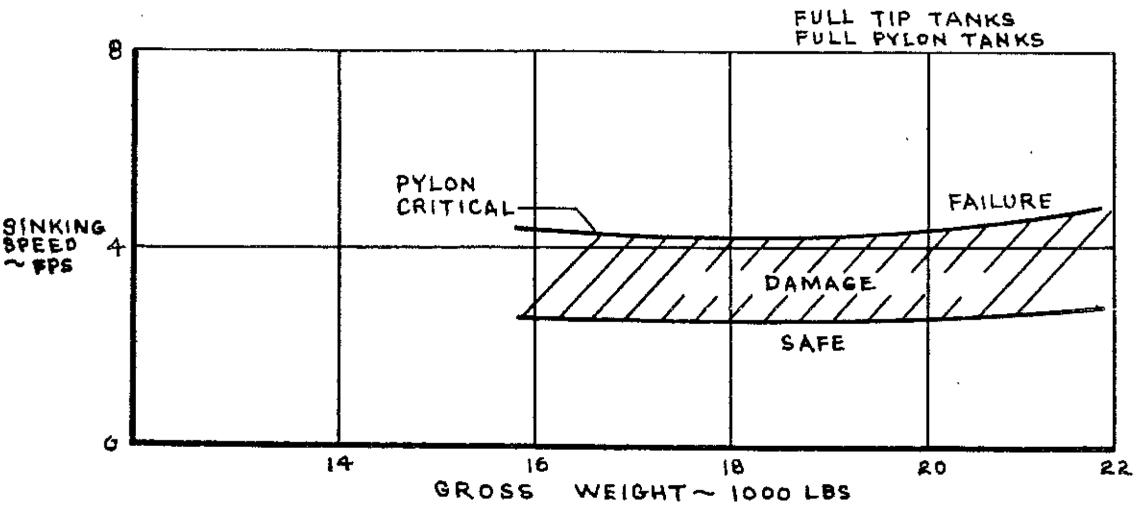


Center of Gravity and Weight Limitations

These two limitations are covered in the manual with one sentence devoted to each. But I want to take this opportunity to enlighten you on some critical points that you might bump into in regard to Center-of-Gravity and weight.

It was determined in tests for static longitudinal stability that on landings with heavy fuel loads or stores combinations where the C. G. was forward 2% MAC, that using land flaps greatly reduced flare capability. This was due to the increased down moment which reduced the amount of available effective stabilizer at flare. So in section VI of the applicable manuals, there is a recommendation to use only take-off flaps when landing with a fuselage-mounted store and a table with recommended airspeeds. The use of take-off flaps results in reduced stabilizer requirements providing sufficient control to land. The effectiveness of the stabilizer was demonstrated with take-off flaps at forward centers of gravity during the course of tests to determine the nose wheel lift-off speed. During these tests, adequate stabilizer effectiveness was shown at C. G. locations as far forward as -5% MAC. At these forward C. G. locations, the stabilizer is capable of rotating the aircraft to take-off attitude at take-off airspeeds and consequently below the speeds normally used in a landing. So the problem you are faced with on landings with forward C. G. 's is one of high approach speeds due to take-off flaps and the heavy weight. And now there is another factor you must consider if it is a landing with full pylon tanks. If you touch down at too high a sink rate there is a possibility that the pylons will fail and you will be dragging the loaded tank down the runway.

A look at our plot of permissible sinking rate with full tips and pylons shows a desired sink rate of not more than 132 feet/min., which is a very soft landing!



PERMISSABLE SINKING SPEED AT LANDING

There have been many landings with full pylon tanks that were made with no failure at all. However, due to the high speeds necessary for safe final approach, you should consider the following in your planning:

1. Runway approach and length.
2. Day, night or low visibility on approach.
3. Barriers available.
4. Experience level.

Obviously, then the handbook recommendation to jettison the full pylon tanks is very reasonable.

RAM AIR TURBINE EXTENSION LIMITS

The recommended minimum airspeeds for RAT extension above 30,000 feet is solely to assure that the aircraft is relatively straight and level. This will insure a stall-free duct flow at these high altitudes.

The recommended maximum airspeed of 550 knots IAS below 30,000 feet is because of propellor aerodynamics. Sonic tip-stall and shaft torque stress are some of the factors determining the limiting airspeeds.

You will notice in Section III of the handbook, we recommend only take-off flaps for any cross-wind landing with the RAT extended. In our flight tests, we discovered that the RAT will spoil the BLC effect on the right wing with LAND flaps and this gives a right roll. If you are landing with a gusty left cross-wind you can see you are really compounding your difficulties. Our recommendation -- stick with TAKE-OFF flaps.*

* See SURE Lecture - "A Test Pilot's Review Of F-104 Accidents"