Some Development Aspects of the YF-12A Interceptor Aircraft

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In this paper, problems encountered in the development and testing of the Lockheed-USAF Mach 3+ interceptor aircraft are discussed. The application of high-strength titanium alloys, some system development aspects, and a number of aerodynamic and thermodynamic problems are briefly reviewed. Flight tests at very high speeds and altitudes involved development of new escape systems, cooling, and navigation equipment among many others.

I. Introduction

In the early 1960's, the Advanced Development Projects Group, the "Skunk Works," of Lockheed, was given the task of development of an advanced interceptor. This aircraft was to have a continuous cruising speed above Mach 3.0, at altitudes over 80,000 ft. It was to incorporate a Pratt and Whitney turbo-ramjet power plant and the Hughes ASG-18 GAR-19 fire control and missile system (Figs. 1–3). The engine had never been flown previously, and was, and is, a very advanced concept in all respects.

The Hughes system, involving advanced doppler radar and many other features, was undergoing tests, along with the GAR-9 missile, on a B-58 test bed. It is interesting to survey the status of design and equipment availability for the continuous cruising speed at the conditions noted at the time of conception of the YF-12A (see Fig. 4).

Although there was a considerable amount of experience with the aluminum fighter aircraft at Mach numbers of approximately 2, these aircraft had very short durations of only a few minutes at such speeds, and neither the temperature nor the altitude factors gave much help or experience required for the design of Mach 3 aircraft.

The North American B-70 was in its design stages. It was expected that a large amount of fallout would result from this program and the NASA tests on the X-15. Both of these conditions did not apply however, the YF-12A rapidly passed the development status and took different paths than followed for the B-70. The X-15 with its very short duration of flight, even though at high Mach numbers and altitudes, did not encounter the problems of air breathing power plant inlet design, ejectors, or steady-state temperature conditions (Fig. 5). In fact, in terms of cooling of the cockpit, the problem turned out to be at least seven times as hard on the YF-12A because of the steady-state heat flux, than it was for the X-15. It is also true that, in the whole series of research aircraft from the X-1 through the latest types beyond the X-15, there are no power plant problems even remotely resembling those we encountered on the YF-12A. Most of the high-speed X-series aircraft were either rocket powered, or followed conventional design, current at the same time on military fighter aircraft.

We considered various advanced materials, particularly steels and new titanium alloys for a considerable period before deciding on the most modern of the titanium alloys. In studying the B-70 honeycomb approach, it was evident very shortly that the Skunk Works was not smart enough to make use of steel honeycomb with its very involved and precise tooling and difficulties in quality control. We decided to use the unconventional alloys of titanium in a construction which was open for inspection and construction. When one speaks of titanium, it should be realized that approximately 93% of the structural weight of the YF-12A is built of advanced alloys of this material. Certainly, our whole industry had used titanium in its lower strength and, particularly, in its annealed conditions for certain applications on many aircraft, including our jet transports, (where it is used for rip stoppers as well as certain hot areas in the engine installations). There is, however, a vast difference in using materials with ultimate strengths of 120,000 lb/in.^{2} and those of up to 200,000 lb/in.^{2}, which we finally used on the YF-12A and its follow-on aircraft. Lockheed had worked with titanium on a research basis since 1949. We attempted to attain high strength-weight ratios, good ductility, and relatively cheap structures, which did not develop very rapidly, however.

In the field of equipment, there was an amazing lack of high-temperature electronic gear, particularly in the areas of wires, plugs, transducers, etc. Many vendors told us they had transducers good for 1000°F operating temperatures, but when we tested the gear we found it had mainly been

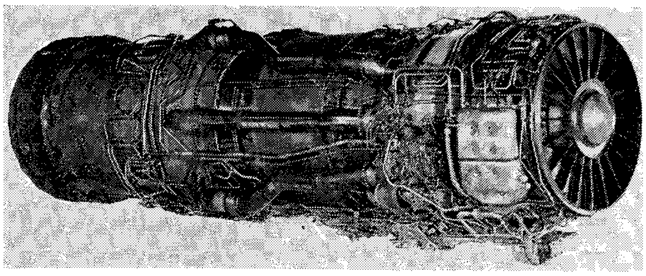

Fig. 1 Pratt and Whitney J-58 turbo-ramjet engine.

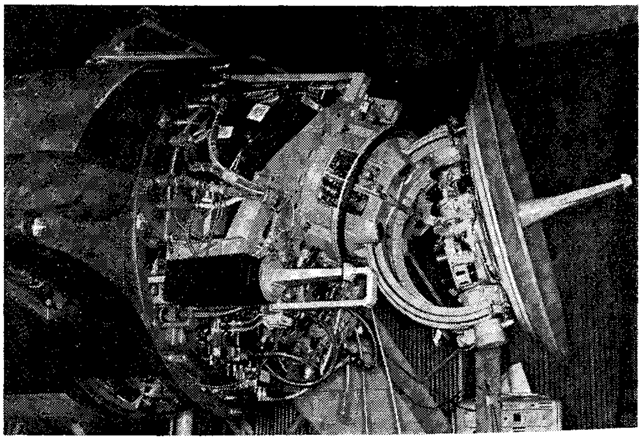

Fig. 2 Hughes ASG-18 radar.

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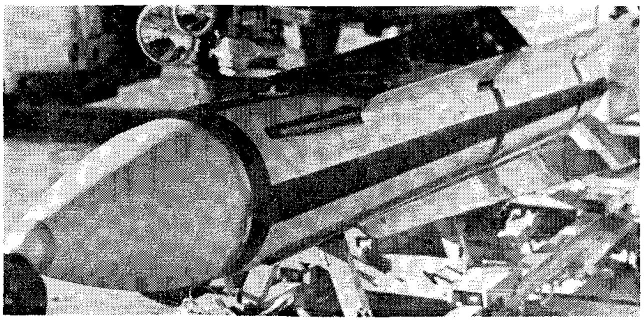

Fig. 3 Hughes GAR-9 missile.

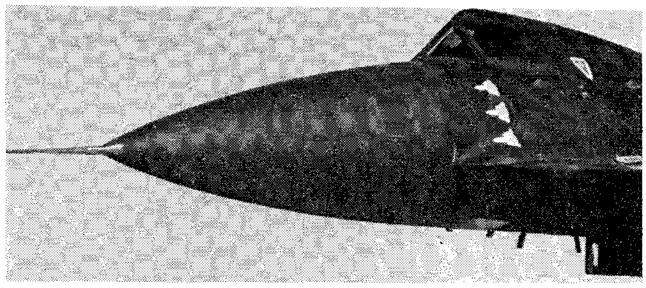

Fig. 6 High-temperature plastic radome.

designed for rocket testing and its life span was very short. Essentially because of the temperature lag, the inside of the unit seldom got hot.

There were no hydraulic fluid or pumps that could take operating temperatures continuously of approximately 600°F. There were no hydraulic seals, suitable for such an environment. The navigation problem was particularly important in that at such high speeds, which we were designing for, it was absolutely mandatory to depend on automatic navigation, which we chose to be of the inertial type. The cooling for the electrical black boxes, armament, and cockpit led us into a new area of design.

Starting with bleed air from the engine at a temperature between 1300°F and 1400°F, it was necessary to develop equipment such as the turbine units, as well as heat exchangers for both air-to-air and air-to-fuel types, that would provide cooling air to the cockpit at −30°F to maintain the temperature between 30° to 100°F maximum. There were no escape parachutes, drag chutes, rocket-eject propellants, and similar equipment available that could take the range of temperature, altitudes, and speeds which would develop after continuous thermal soaking at high speeds and altitudes. There were no control cables that would take the required number of cycles safely. So we had to have special ones made of elgiloy, the material used for watch springs. There was no fuel available that could take the continuous high temperatures, particularly, having the characteristics of low vapor pressures at high temperatures and low coking characteristics to prevent clogging of the engine fuel system.

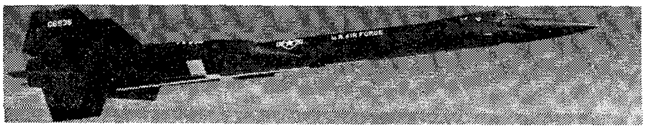

Fig. 4 Lockheed YF-12A.

The use of plastic for radomes (Fig. 6) at these temperatures required the development of new materials and new processes for their construction. A whole host of antennas had to be developed for high-temperature and high-altitude operations in air density only slightly greater than 1% of the sea level values. It is said truly that everything on the aircraft from rivets and fluids, up through materials, and power plants had to be invented from scratch.

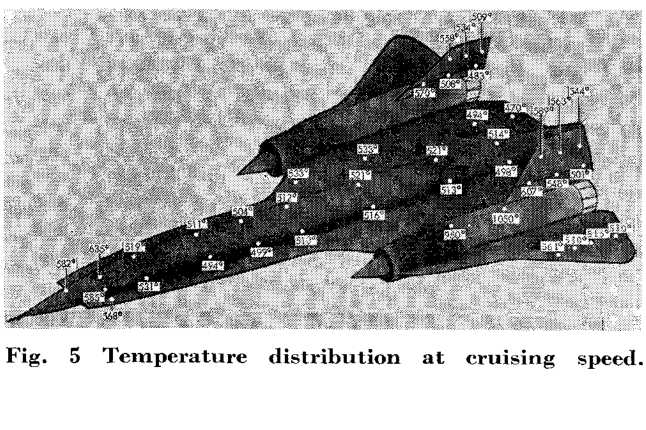

Fig. 5 Temperature distribution at cruising speed.

II. Design Effort

It is rather amazing that with all these problems to be solved, that using the so-called, "Skunk Works" approach, the number of engineers in the design effort at ADP was considerably less than 200 at its peak. These were very experienced personnel who performed well in producing the advanced weapon system. A similar system was followed by Pratt and Whitney in the design of the J-58 engine and their performance, as well as that of Hughes, was remarkably good. We could do such a job only by having the closest possible liaison among our associates and vendors. They responded uniformly with the greatest dedication in taking on the problems outlined previously.

The Skunk Works' system provides for minimum paper work, but does require good documentation on all important developments. It can be assured that one does not develop an aircraft like the YF-12A on the "back of an envelope," a term sometimes used in a derogatory sense regarding our operation. The fact is, that in such a large program, our operating techniques were investigated many times by various groups of Government-technical, contractual, and audit types, and we were given excellent marks for performance, and, in the discipline, we were able to maintain in our various systems and controls.

A few interesting items in the design effort will be discussed here briefly. We made ample use of full scale mockups and test rigs. Figures 7–9 show such test gear. The whole fuel system from the refueling probe into the engine fuel control and afterburner boost pump was represented and run for hundreds of hours simulating fuels at various temperatures and altitudes up to 100,000 ft. The fuselage angle could be simulated up to 35° inclination as well as for the dive conditions, and the complete fuel gauging system, refueling, and dump systems were represented accurately. When it is understood that the fuel temperature and pressure of final injection to the engines takes place at a temperature of 600°F and a pressure of 130 psia, the fuel characteristics as well as the purging system and pumping system required a very considerable amount of development.

Obtaining satisfactory grease for high-temperature bearings turned out to be extremely difficult. We evaluated dozens of different types. Two of the best for high-temperature use froze up the grease guns at normal temperatures.

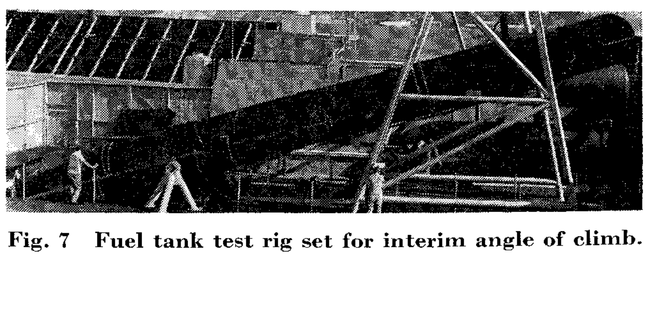

Fig. 7 Fuel tank test rig set for interim angle of climb.

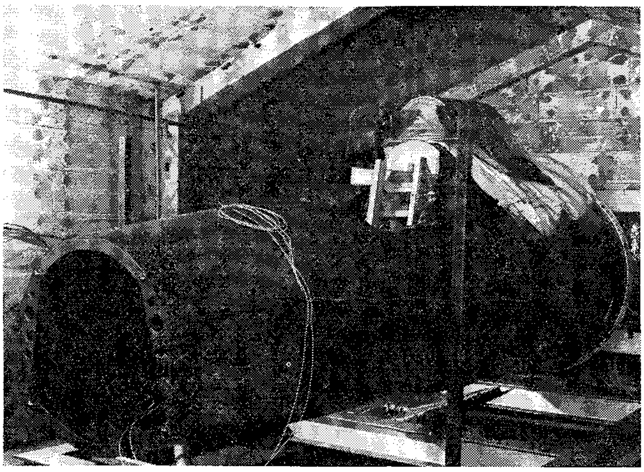

Fig. 8 Cockpit in oven.

A full-scale hydraulic system was also mocked up and operated many hundreds of hours.

When the author first wrote to various vendors to get hydraulic oils, as well as other gear, one enterprising firm sent us a free sample of a fluid good for operation at 600°F. Opening the package, we noticed it was enclosed in a canvas bag. It was a white powder at normal room temperatures and up to 200°F! Not being desirous of thawing out the system with a blow torch every time we had a flight, we did not use this material. The petroleum based fluid which we did use was an initial development at Pennsylvania State College, in which we placed a considerable number of additives to get proper lubricity. We finally arrived at a suitable specification and were able to get a supply of material which has given us excellent results to date. We must say that the original cost of something like \$130/gallon led us to spend another 50 cents to ship the material in 1-gallon cans, to avoid the risk of destroying larger containers in service.

We had need for a complete cockpit installation which could be tested at high temperatures, so we built the forward fuselage (Fig. 8), which was of interest to us also from a structural point of view. This section of the aircraft makes use of the minimum gauge materials, includes, of course, the windshield glass, and has many pieces of double curved structure. This gave us an opportunity to check our production methods, which was indeed fortunate. We found of the first 6000 pieces we fabricated of the Beta B-120 titanium, we lost 95%. With the help of Titanium Metals Corporation, we attacked the problem vigorously, investigating such factors as hydrogen embrittlement, heat treat procedures, forming methods and design for production. We solved these problems, but at considerable cost.

We were very concerned about the method of building the wing box, with particular reference to the difference of heating rate between the thin outer skin and the heavy spars. We built a section approximately 4 ft wide × 6 ft long and subjected it to the temperature flux which would be encountered during typical climb and acceleration maneuvers. We had taken the usual steps to provide the smoothest possible external surface. On the first test using heat lamps to develop the proper heat flux rate—as well as we were able to—the skin curled up like a dish rag. It was therefore necessary to provide a means for allowing the skin temperatures to climb exactly with the Mach number, and yet not to wrinkle in a manner that would provide low strength and high drag. This was done by using chord-wise corrugations and a few tricks with how we attach the wing surface to the spars. We have had no difficulties because of the time difference in heating up of various aircraft components which vary from a few seconds for the thin skins to an hour for the landing gear.

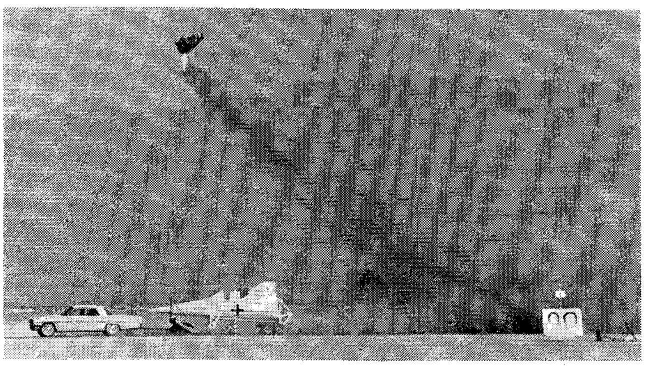

Fig. 9 Escape system—car towing rig for low-speed escape test.

Fig. 10 Pressure suit.

We were very concerned about temperatures for the tires during long missions. Here, Air Force programs sponsored by Wright Field, gave us a good lead in tire design. When we retracted the wheels into the fuselage fuel tank area, we were able to provide enough insulation and radiant cooling so that tire temperatures in flight have not been a problem.

We set for ourselves a very high goal in providing crew escape systems. We were determined to develop a system

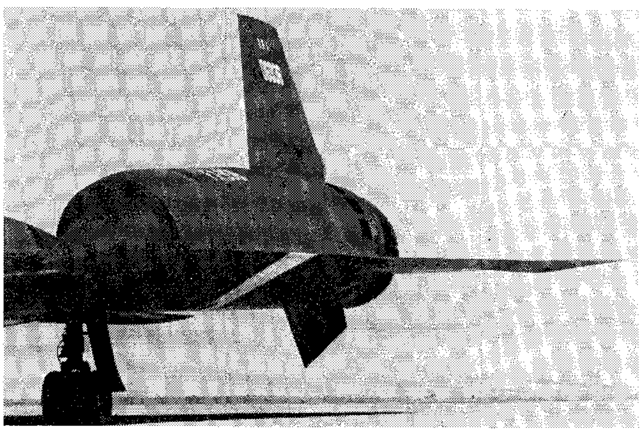

Fig. 11 YF-12A inlet.

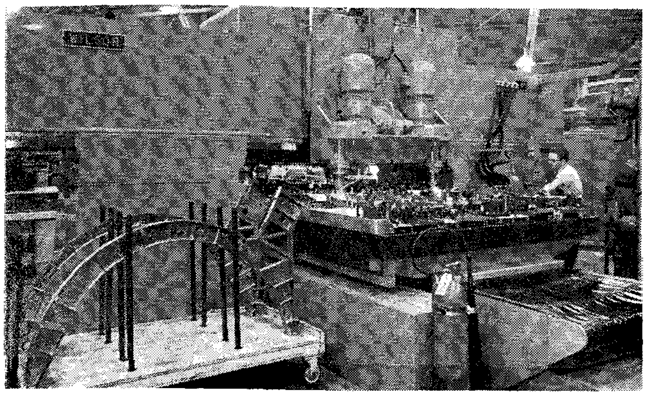

Fig. 12 Machining nacelle ring on numerical control profiler.

good for escape at zero velocity on the ground and through the complete flight spectrum, having speeds above Mach 3 at 100,000 ft. Figure 9 shows some early testing of the cockpit. You will note it is being towed by an automobile. We did achieve our design goals, but it took several years of constant improvement of parachute design, the seat itself, the rocket ejectors, and every element of the escape system, including substantial work on all aspects of personal equipment.

We have never been convinced that a capsule ejection is required for anything other than high velocity re-entry from outer space. Our escape system in a very important sense really provides a capsule, which is the pressure suit, which is surely capable of meeting the speeds and temperatures likely to be encountered in the near future of manned aircraft (see Fig. 10). The area of such escape system which needs more work at the present time, has to do with water recovery, particularly in high waves, but in this regard excellent progress is being made to date.

III. Aerodynamic Testing

Obviously, very sophisticated wind-tunnel testing was required in the design of the YF-12A. Besides the usual lift, drag, and stability testing, very careful measurements transonically had to be made. The testing of the inlet and the ejector, took by far, the most effort (Fig. 11). Millions of test points were taken to develop the internal compression inlets. Basic to the concept of the YF-12A was to get the inlet away from the wing and fuselage effects within the limits of the shock patterns developed by the fuselage nose, and to get the ejector to work in a field where we had a chance of minimizing base drag.

Early designs involving engines buried in the fuselage were discarded for these reasons. We faced the problem of high, offset thrust, and drag during engine failure or blow out. It was decided to account for this by using a stability augmentation system that in a few milliseconds would provide the proper rudder angle to compensate for any duct or engine

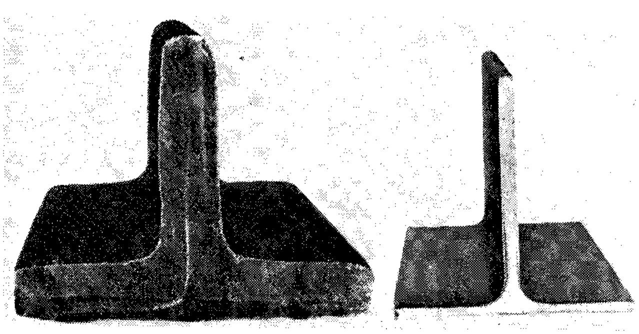

Fig. 13 Titanium extrusion as received, and machined part cut from it.

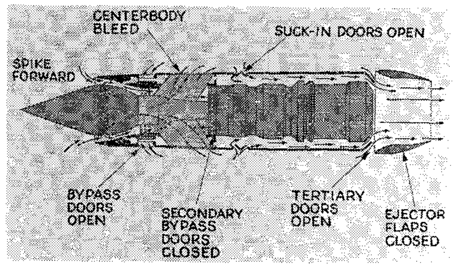

Fig. 14 Nacelle airflow—takeoff speed.

blow out. This device has been so successful that it was several years after the initial flights before the pilot knew which engine would blow during an inlet unstart. It is absolutely impossible to depend on manual reaction to account for such disturbances, but the stability augmentation system designed to our requirements by Minneapolis-Honeywell has been extremely good.

Tests of the ejector, which is of the blow-in door type, were run in several facilities, including the Pratt and Whitney wind tunnel. We made a fundamental error in not providing for the presence of the wing, fuselage, and vertical tail, which affected the ejector performance. This was particularly true in the transonic speed range. As soon as aerodynamic data were available, NASA modified the X-15 flight simulator which was used to very good effect to study the flight characteristics of the aircraft in advance of its first flight. The simulator, in fact, gave conservative results in terms of emergency conditions, as the pilot was not subjected to the various accelerations and vibrations, which developed and which assist him in taking proper corrective action. The device was very useful in development of the stability augmentation and control system.

IV. Construction Phase

Tooling for the type of construction used in the YF-12A was quite straightforward, except that, fabrication tools were a much higher percentage of the over-all cost of tooling than they normally would be for aluminum structures. In an effort to save weight, the basic structure contained many small pieces, which in aluminum could have been combined readily to reduce the parts count. Hot forming of the B-120 alloy was very expensive and slow, but an excellent product was obtained in the end.

We found that the machinability of titanium was of great importance to our over-all cost, as the rate of metal removal from the high-strength titanium alloys was initially 5% of what could be done on aluminum parts. Likewise, it was necessary to invent new drills, cutting machinery, powerheads for profilers, and cutting lubricants to increase the rate of metal removal. We were not able to obtain die forgings to final dimensions, or extrusions in the finished form. On certain large rings, which were cut on tape controlled profilers (Fig. 12) approximately 90% of the forging weight had to be removed by machining. Figure 13 shows typical early extrusions as received from the mill, and as finally machined.

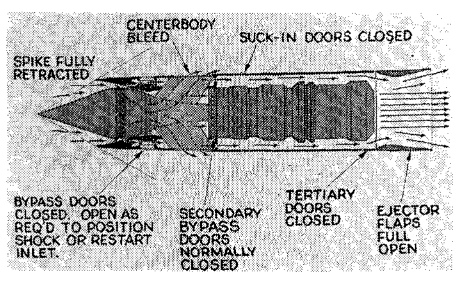

Fig. 15 Nacelle airflow—cruising speed.

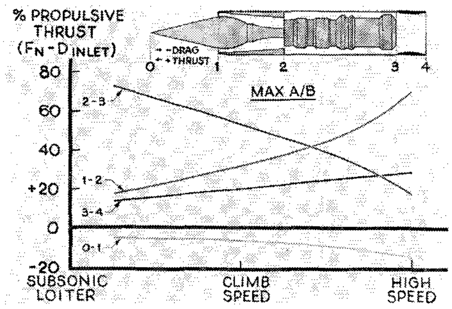

Fig. 16 Thrust and drag distribution vs Mo.

When you consider the miles of extrusions required for an aircraft the size of the YF-12A, it is obvious that every effort had to be made to improve titanium machining, not only at Lockheed, but with all of our vendors who did approximately 60% of such work. We set up training classes for machinists, a complete research facility for developing tools and procedures, and issued research contracts to competent outside vendors to develop improved equipment. This was very successful in all its phases. We were able to improve the rate of metal removal from three to ten times the industry average rate at the conclusion of the program, and we increased drill life from 10 holes/grind to an average of over 119.

There is still a great deal to do since titanium construction is still very expensive compared to dural in aircraft. Very careful records were kept of all processes of making titanium parts. In fact, it is possible to trace back the construction of all parts to the output at the rolling mills. These data include strength information on the parts, the direction of grain in the sheet metal used, and such factors as the critical bend radius, at which the coupon sample would break. We found it more important to make what is described as a notch bend test on the material sample, than it was to try to correlate ductility with elongation factors.

One of the hardest items we had to construct was titanium rivets. This was basically because of inability in the early days to obtain pure enough samples of materials in wire form. Initially, the cost of titanium fasteners, such as bolts of different types, were extremely high, but today with their greater use in other aircraft, the price has been reduced considerably.

V. Flight Test Phase

After completion of very thorough structural tests, the flight test phase was undertaken. Great difficulty existed in obtaining instrumentation satisfactory for measuring pressures and air velocity over the speed-altitude spectrum. This is particularly true of conditions in the engine air inlet and ejector. This necessitated the development of water cooled instrumentation packages, which were quite clumsy, but did provide a means for making the millions of pressure measurements required through the development tests. The greatest problem encountered in flight had to do with the transonic speed region, where it was extremely difficult to correlate the results from wind-tunnel tests and flight tests. The next greatest problem had to do with the development of the air inlet control system, which involved scheduling the air inlet spike position, and various bypass door arrangements, to maintain the optimum shock position on the cowl, and minimum drag. Operating forces as high as 14 tons can develop on the spike. This requires massive hydraulic power and extremely fast sensing of the various design parameters to restart the inlet.

Figures 14 and 15 show the air flow patterns in the nacelle in the takeoff and cruising speed conditions. Effective bleeding of the boundary layer, both on the outside of the inlet and the spike itself, must be done with minimum drag and carefully balanced to obtain optimum stability of the air flow pattern.

Figure 16 plots the net thrust and drag of the complete nacelle installation. It is most interesting to note that, at high speed, the thrust developed by the engine, which shows up on the engine mounts, is only 17% of the propelling force of the aircraft. The remainder of the thrust is provided by the pressure distribution integrated around the inlet and the ejector for the complete nacelle. Note that the inlet alone provides 70% of the thrust, the spike is 14%, and the ejector pushes with 27% to make up the total thrust for the aircraft. Our good friends at Pratt and Whitney do not like us to say, that at high speeds, their engine is only a flow inducer, and that after all, it is the nacelle pushing the airplane!

The aircraft showed itself to have excellent flight characteristics throughout its speed range, particularly on takeoff and landing. Visibility was good, but the pilots initially complained of a very high glare flying at high altitudes. The use of nonreflective coatings on instruments, and other areas, definitely helped this condition. We looked with great interest on the test program to see whether we would ever reach an altitude where there was no clear air turbulence at all. Unfortunately, this situation does not exist, although the frequency of encountering turbulence, and the load factors therefrom, are substantially less at high altitudes than at low altitudes under 50,000 ft.

The sonic boom experiences encountered provided a shotgun pattern of ground pressures, which showed the computed values to be good, but variations therefrom, particularly in the transonic region, to be about ±200% from the theoretical value. During the initial test stages, an unforeseen problem cropped up, and this was how to get the airplane down! If power was retarded too quickly, and a high rate of descent established, it was possible for the engine case to cool much faster than the compressor disk, which resulted in rubbing of the compressor blades on the case. The testing of the military equipment is classified and cannot be discussed in this paper.

VI. Conclusions

As a result of our experience on the YF-12A, the following conclusions are noted: 1) It was proven again, that it is absolutely impossible to foresee all problems in advance, when making large steps forward in the speed altitude regime. We need prototype programs now, more than ever, since the beginning of manned flights, in our view. 2) There was, and still is, a lack of an industrial base to produce Mach 3+ aircraft. In fact, the nineteen requirements, which we outlined in our panel discussion on Advanced Precepts of Aircraft Technology at the AIAA Aircraft and Technology Meeting in 1965, still apply, almost unchanged. 3) Good agreement exists between properly run wind-tunnel tests, engine stand tests, and flight tests, after the problems of instrumentation were solved. 4) There is a completely new breakdown in the cost of manufacturing a Mach 3+ aircraft considering material, parts fabrication, tooling assembly and testing, from what we encountered in low-speed aircraft (under Mach 2.2). 5) There are great opportunities for cost reduction in building titanium aircraft from the procedure used to build the YF-12A, but inflation is rapidly eroding these potential savings in terms of actual dollar costs per aircraft. 6) Improved machining methods, forging and extrusion presses are vitally needed for high production of either steel or titanium aircraft. 7) The sonic boom is quite unpredictable with ground pressure varying greatly from flight to flight and from day to day, particularly in the transonic region.