Development of the XB-70A Propulsion System

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The development of three major subsystems of the XB-70A propulsion system is reviewed. The use of a fuel system simulator in testing equipment and design principles is discussed. The importance of inlet-engine compatibility to the propulsion system is emphasized, and methods of testing the compatibility on the ground are illustrated. The cooperation of airframe and engine manufacturers in designing the engine installation is emphasized, and examples of engine configuration, engine mounts, engine heat shroud, electric thrust control actuator, and engine compartment cooling system development are given. The use of a ground test stand in demonstrating engine installation compatibility and installation problem solving is shown. Engine foreign object damage is stated to have new dimensions in sophisticated Mach 3 installations. Installation effects on engine air starts is shown to be a potential problem.

Introduction

The purpose of this paper is to review the development of the XB-70A propulsion system. This particular review has been pointed, where possible, at problems and solutions of especial interest to current designs of Mach 3 cruise airplanes. The development period started in 1956, during the competition for what was then designated WS110A, and continues to the present. We are proud of the part the XB-70A has had and will continue to have in the development of Mach 3 aircraft technology. The fact that the XB-70A exists, that it has flown, that it has already provided significant data from its brief flight test program, and that the feasibility and practicability of many new technical concepts have been demonstrated, is important. Although the original mission of the XB-70A was strictly military, its achievements have had, and will have, an influence on all commercial and military Mach 3 cruise aircraft.

For the purposes of this presentation, the propulsion system has been subdivided into three main categories: fuel system, inlet development and engine compatibility, and engine installation. Figure 1a shows the XB-70A in flight. Figure 1b shows the side by side arrangement of the six General Electric YJ93-GE-3 engines which power the XB-70. Figure 1c shows the inlets for the two air ducts, each of which supplies three engines.

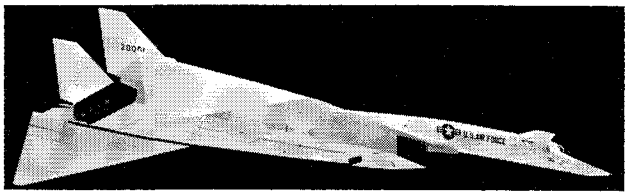

Fig. 1a XB-70A in flight.

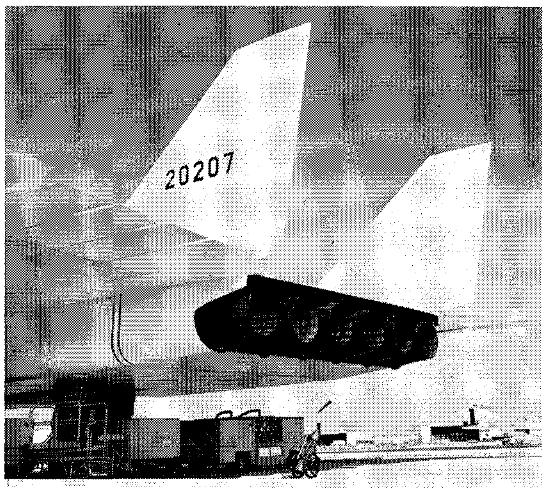

Fig. 1b General electric YJ93 engines.

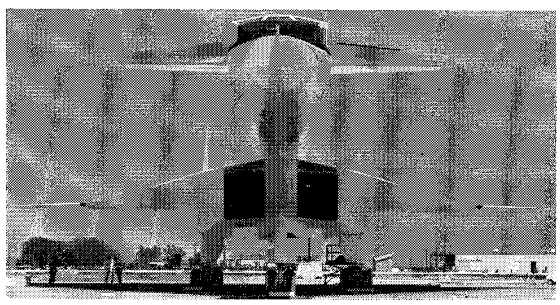

Fig. 1c Inlet air ducts.

Fuel System

Fuel system design for Mach 3 cruise demanded investigation of many potential problems. Those to be discussed here are autogenous ignition, fuel high-temperature stability, and heat-sink capabilities. From the outset of the XB-70A design, it was apparent that the use of JP-4 fuel would be prohibitive because of its high vapor pressure. Excessive boiloff or an unacceptable structural penalty would have been required to accommodate that fuel. The development of JP-6 fuel, with its lower vapor pressure and improved thermal stability, gave us the promise of a fuel adequate for the design mission requirements. There was still much to learn about the fuel, however, and tests were launched concurrently by North American Aviation (NAA) and General Electric (GE) to insure delivery of fuel to the engines which was compatible with engine requirements.

Autogenous Ignition

Calculations indicated that aerodynamic heating of the integral tanks would raise temperatures into the danger zone

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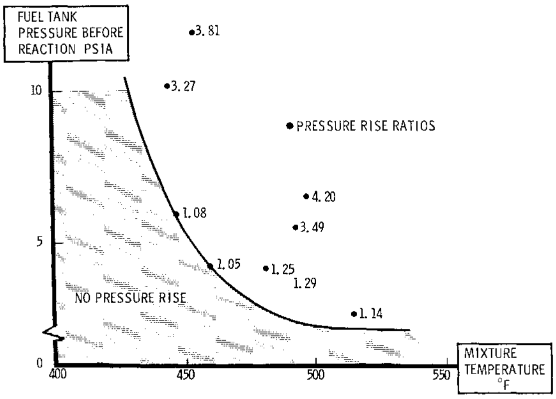

Fig. 2 1-cu-ft reaction chamber results.

of autoignition. Autogenous ignition temperature (AIT) data available for reduced pressure operation, such as is encountered at the intended cruise altitudes, were both scarce and suspiciously high. We soon found that test vessels of 1-liter size and greater, gave substantially lower AIT than that obtained with the initial test $\frac{1}{2}$-liter flask.

Figure 2 shows the results of tests, using a 1-ft^3 reaction chamber. These data posed two dilemmas for the fuel system. In order to stay in the region of very low or no pressure rise, it would be necessary to accommodate excessive boiloff. On the other hand, pressurizing the tank to prevent boiloff at the temperatures we would encounter would require prohibitively heavy structure to accept the attendant reaction pressure rise.

To increase our knowledge of the problems involved, a test rig using a 100- and a 500-gal tank was built. The reactions in these relatively large containers would, it was hoped, be more representative of the airplane fuel tanks. Figure 3 shows tank conditions during a simulated flight with a noninerted tank. The sharply decreasing oxygen content indicates that a reaction is taking place as tank and fuel temperatures increase during cruise. The attendant tank pressure rise is acceptable, which could lead to the conclusion that inerting of the vent space is not required. Figure 4 tells a different story, however. This shows the sharp reaction obtained during a simulated maximum rate descent. In view of these results and of those from a modified Setchkin apparatus, it was decided to take a dual approach to control autoignition. The method now in use on the airplane removes oxygen from the fuel during the refueling process; during flight, a liquid nitrogen system supplies inerting of the tank vent space to prevent air entry.

Heat Sink and Fuel Thermal Stability

It was apparent that air temperatures at Mach 3 would prevent its use as a cooling medium for the aircraft working and lubricating fluids. Consequently, the heat-sink potential of the large volume of fuel on board was investigated. Heat-sink capability is dependent on the temperature differential between bulk fuel temperature and the allowable temperature of the engine heat exchanger fuel discharge. A temperature limit of 300°F at the engine inlet, established early in the XB-70A development program, was based on the fuel thermal stability. At elevated temperatures, deposits form as a function of both time and temperature, and deposit buildup causes heat exchanger and fuel injector nozzle performance degradation. By withdrawing fuel as early in the flight as possible from those tanks most affected by aerodynamic heating, we kept bulk fuel temperatures as low as was practicable. Placement of the 13 airplane heat exchangers in the lines supplying the engines benefited the airplane fuel pumps by exposing them to lower temperature fuel, reduced boiling tendencies, and kept thermal stressing of the fuel low until just prior to use.

After system designs were finalized, fuel temperature cyclic testing was conducted to verify that JP-6 could withstand predicted thermal stressing without deleterious deposit buildup. During the aircraft fuel system development program, it was determined that the available fuel heat sink was inadequate at idle flow rates after bulk fuel had reached maximum temperature. Consequently, a fuel cooling water boiler was added in the heat exchanger system to provide supplementary heat sink.

Fuel System Simulator

Full-scale tests were conducted next, utilizing a simulator with airplane fuel system components and with the capability of simulating aerodynamic heating. The simulator is shown in Fig. 5. The position of the simulator was continuously variable in the pitch direction and could be fixed in three positions of roll. With the simulator, we were able to check out the oxygen removal system (in so doing, we learned 99 ways how not to do it); verify the size of structural cutouts; measure surge pressures at the level control valves (we found thin-wall tubing required beefup at the beaded ends, to prevent them from pulling out of the Wiggins couplings); make an available fuel check; verify system performance under normal and emergency operating conditions; and gather operating characteristics of the fuel tank pressurization, vent, and inerting systems. Figure 6 shows the results of a check on the ability of the fuel tank pressure control system to maintain positive pressure relative to ambient during a maximum rate descent to avoid drawing air into the vent space.

Flight Test

So far, airplane operation has permitted us to demonstrate the ability of the oxygen removal process to limit the ullage concentration to 5%. The automatic fuel sequencing control system which controls center of gravity location and minimizes aerodynamic heating of the fuel has performed satisfactorily. The tank inerting system and the heat exchanger system have performed as expected. As can be seen from the foregoing, a fairly high-confidence level in fuel system

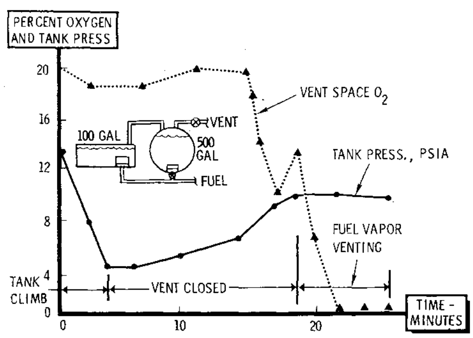

Fig. 3 100/500 gallon tanks noninerted heating test-simulated design mission.

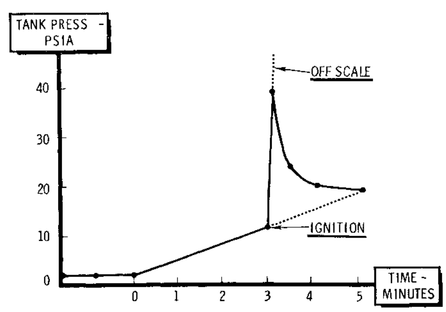

Fig. 4 100/500 gallon tanks noninerted heating test-maximum rate descent.

operation had been established prior to airplane completion, with adequate time allowed to introduce necessary changes that were indicated.

Inlet Development and Engine Compatibility

The importance of an efficient propulsion system to achieving long-range flight at any speed is well known. The Mach 3 propulsion system involves inlet design problems not encountered in lower speed aircraft. For a high Mach number airplane, the air induction system becomes a major component of the over-all propulsion system and the efficiency of the induction system compression process must be high if low specific fuel consumption (SFC) (and maximum range) is to be obtained.

Basic aerodynamic equations require that supersonic compression take place in a converging duct and that subsonic compression take place in a diverging duct. The goal of high total pressure recovery requires that the supersonic compression be accomplished through a series of weak oblique shocks. This compression occurs both on the external ramps of the inlet and, internally, in the converging portion of the duct. These aerodynamic requirements lead to the XB-70A inlet duct, a converging-diverging duct with a complex "X wave" structure of intersecting weak oblique shock waves in the supersonic diffuser (converging section) of the duct, forward of the duct throat, as shown in Fig. 7.

0.04 Scale Test

To achieve the desired inlet for the XB-70A, some 11,000 hr were spent in various wind tunnels with several different models. To start with, 0.04 scale models were used. Tests were run at NASA Ames, NAA, and NASA Lewis Laboratory. These early models served to improve performance through development of the basic geometry and to establish the configuration of the under-wing boundary-layer bleed gutter and compartmentation of the boundary-layer bleed-air system. With the addition of the fuselage forebody, it was possible to determine the effect of the airplane configuration and flight condition of inlet flow and performance.

One-Quarter Scale Test

Having gone as far as was believed practicable using small models, the next step was to build a $\frac{1}{4}$ scale model of one three-engine inlet. The use of a model as large as possible was desirable to permit using boundary-layer control (BLC) porous-panel bleed holes, as similar to full size as possible, and to measure accurately, BLC airflow in the four separate compartments. Use of this model permitted greater accuracy, and, in the test, produced near-full-scale Reynolds number.

One of the most significant objectives of this test was the validation of the control system parameters chosen to obtain high performance over the complete range of flight conditions. It is well known that high recovery of total pressure in the inlet takes place when the terminal normal shock wave is made to stand just aft of the throat in the region of the lowest supersonic Mach numbers in the duct. There are many normal or abnormal conditions, which can affect the shock position, and measures have to be taken not only to position the shock properly, but to reestablish the proper position if an inlet unstart is encountered. The throat height must be correctly scheduled as a function of the Mach number ahead of the duct. If the throat height becomes too small at a given Mach number, the inlet will unstart, regardless of the position of the normal shock aft of the duct throat. The converse of this is that, for a given throat height, if Mach number ahead of the duct decreases too much (resulting in excessive contraction), the inlet will unstart. Airplane maneuvers, such as turning, changing altitude, or changing speed, therefore can cause unstart unless the inlet geometry is properly shifted. Engine airflow transients downstream also can cause the normal shock to move from its intended position. The effects of off-design-point operation are highly significant and must receive close attention. These considerations are mentioned to emphasize the importance of choosing parameters that can satisfy the varying conditions of flight to maintain a high level of efficiency in the duct.

Another important use of this model, shown in Fig. 8, was to obtain the dynamic characteristics of the air induction system by introducing small disturbances and then measuring the dynamic response rates. We also were able to evaluate the inlet bypass system. The inlet bypass, of course, is the means for controlling shock position by diverting excess air captured by the inlet around the engines. Since the bypass is located just forward of the engine compressor faces, it was important to establish the level of distortion caused by bypass operation. The effects of engine-out on the inlet also were tested.

One-Third-Flow Scale Test

Meanwhile, considerable effort had been expended jointly by NAA and GE on developing mathematical models of both

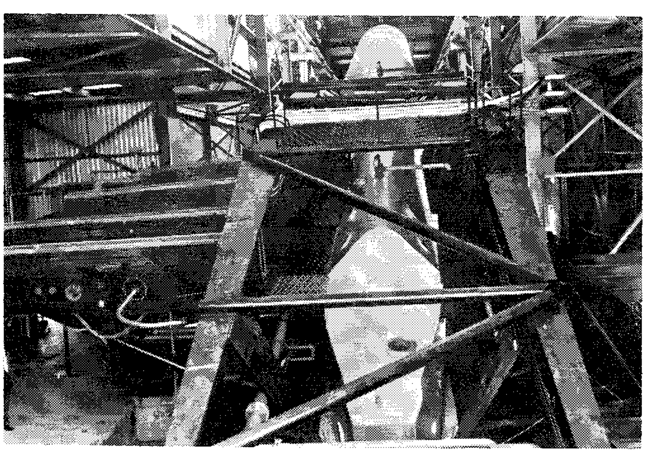

Fig. 5 Full-scale fuel system simulator.

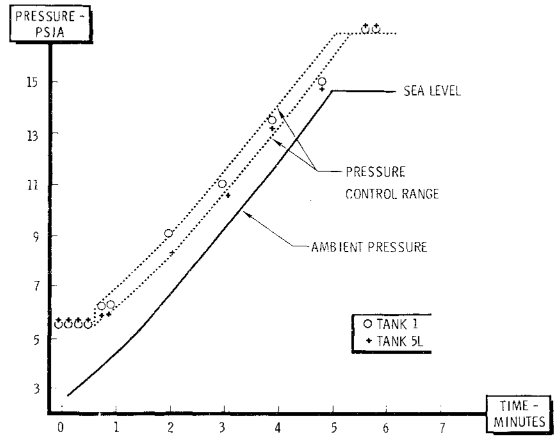

Fig. 6 Fuel system simulator tank pressure control for maximum rate of descent.

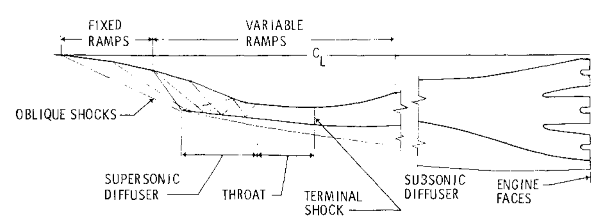

Fig. 7 XB-70A inlet system plan view.

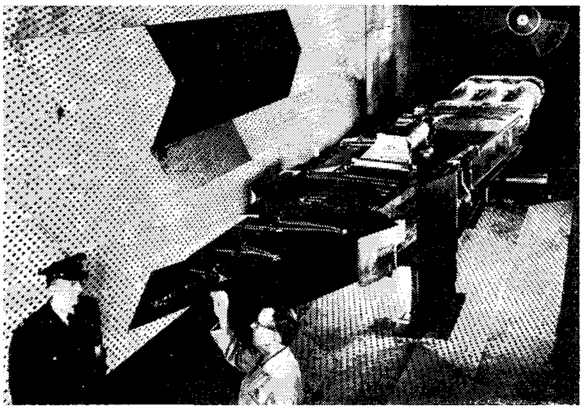

Fig. 8 Inlet model: 0.25 scale B-70 inlet model in AEDC 16- × 16-ft tunnel.

the inlet and the engine, to permit investigation of the mutual interaction of the inlet, inlet controls, engine, and engine controls under transient conditions. As mentioned earlier, engine airflow transients can cause displacement of the normal shock. The YJ93 engine was designed to be an essentially constant-speed, constant-airflow machine at high Mach numbers at NAA's request, in order to minimize engine airflow variations and the resultant effect on the inlet. Nevertheless, throttle lever variations by the pilot can result in airflow transients sufficient to cause inlet unstart if not corrected for by the inlet control system. This airflow variation occurs as the engine fuel flow changes in response to the request made, and airflow returns to constant only as the variable nozzles and stators slew from one position to another to accommodate the power change. In order to explore the obvious potentials of engine-inlet interaction further and to develop more confidence in the digital simulator program, it was decided to build a $\frac{1}{3}$-flow scale inlet to be operated in conjunction with one engine in the 16- × 16-ft supersonic leg of the propulsion wind tunnel at the Arnold Engineering Development Center (AEDC). In Fig. 9, the model, consisting of a stub wing, an inlet duct fixed-wedge splitter, variable position ramps, an inlet with subsonic diffuser modified to supply the air to a single engine, movable bypass doors, and the engine with its enclosure, is shown mounted in the tunnel.

During the first phase of the testing, an airflow meter was installed in place of the actual engine to provide an accurate measurement of inlet airflow. The inlet tests ranged from Mach 1.8 to 3.1. During this phase, data for inlet control signals were collected, as well as inlet characteristics information. The inlet control signal data obtained were adequate, rational with inlet aerodynamics, and presented no apparent problem for the airplane control signal schedules. The inlet performance data agreed with the previous model tests.

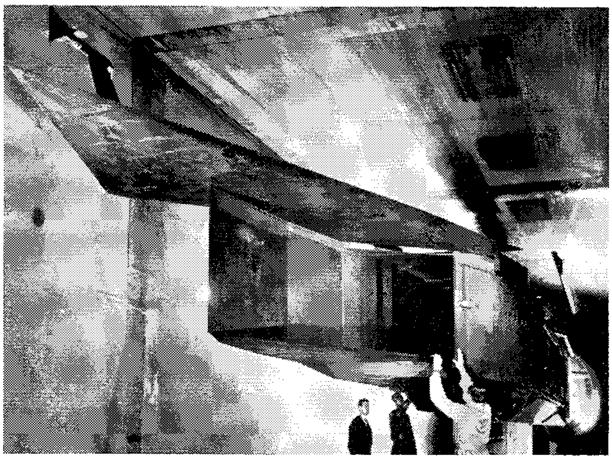

Fig. 9 One-third flow scale inlet model test at AEDC.

During the second phase of testing at AEDC, the inlet-engine propulsion system was tested between Mach 2.24 and 3.0. Some 343 hr of engine rotation time were accumulated, including 83.5 hr of engine burning—31 hr at military power and 10 hr in afterburning, the balance at lower power settings. The high ratio of rotating to burning time is indicative of the need to supply fuel to the engine continuously, while heating the tunnel and bringing it up to the desired operating condition. The fuel is used to cool the lubricating oil, hydraulic oil, and engine accessories, and it is not possible to windmill or soak at high temperatures in the absence of the heat-sink fuel. This same limitation carries over to the airplane, incidentally, where provisions must be made for limiting engine rotation in the event of a nonoperating engine. In the XB-70A, this necessitated that GE develop an aerodynamic braking device to control engine speed above Mach 2 adequately when shutdown is required.

In the test, in addition to steady-state data, we obtained good information on throttle transients at near peak pressure recovery; behavior during inlet unstarts, restarts, and duct buzz; stall and stall clearing following highly supercritical inlet operation; engine lights with inlet both started and unstarted; and inlet response to simulated A/B blowouts. Figure 10 shows engine airflow during A/B lights both with and without the inlet and illustrates the cushioning effect of the duct on the airflow transient. Testing did not bring to light any basic compatibility problems in the inlet-engine combination. The inlet was successfully controlled manually, indicating that manual control for the airplane would be satisfactory. We also found, inadvertently, that the YJ93 engine can be run backward with no noticeable aftereffects (caused by tunnel pressure dropping below exhauster pressure during tunnel pump-down). The engine also demonstrated a certain potential for underwater propulsion when it was accidentally flooded with water from the exhaust scavenge cooling system.

NAA was pleased with the test results. The dynamics of the engine and inlet were demonstrated to be compatible; the inlet control parameters proved satisfactory; we were able to more accurately define the mathematical model; and the engine performed admirably, considering the treatment it received (which included more than 100 compressor stalls at high Mach number, although these were mostly at extreme altitude, low absolute pressure conditions). Figure 11 illustrates how closely the mathematical model was able to predict inlet behavior during an unstart.

Prior to the test, there was some controversy over the value of attempting actual engine-inlet compatibility testing in a wind tunnel. We feel that the results demonstrate not only that it can be done but that it may be possible to perform many tests better in a wind tunnel than in an airplane, because one has control over conditions in the tunnel which are much more difficult to handle in a flight test program.

One-Tenth Scale Test

The final model test performed on the inlet system was the 0.1 scale. The model included both inlets (the forebody with canard and a portion of the wing) and depicted the final airplane configuration faithfully. The objectives of this test,

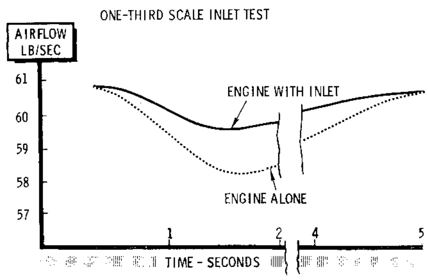

Fig. 10 Engine airflow during A/B light-off.

run at the Lewis Laboratory, were to more or less "proof test" the results of all other development and then make a final check on the interdependence of two inlets (such as effects of one duct unstart on the other duct and the effects of upstream variables on inlet performance and operation). The model is shown in Fig. 12.

Engine Installation

Concurrent design of the airframe and the engine provided the opportunity for interface integration to a degree never before attained. Usually engine design features for installation have been compromised among several users. In this case, the engine's only application was the XB-70A (the NAA F-108 was included for a short period), which provided much greater freedom in adapting the engine design for the best airframe-engine combination. For more detailed information on the engine installation, see Ref. 1.

Engine Configuration

The first step taken was to simplify the engine installation by mounting all aircraft accessories, not on engine pads, but on a separate gearbox that would be driven by a shaft from the engine. This not only simplified the engine installation, but also permitted the aircraft accessories a lower temperature environment than would have been available in the engine compartment. Design coordination among NAA, GE, and Sundstrand, the secondary power system subcontractor, evolved a power takeoff design that integrated bearing, lubrication, shear section, etc., requirements to produce what was felt to be the optimum configuration.

We think it noteworthy that, with the exception of a short bleed-air duct and some flight test instrumentation, all six engine buildups of the XB-70A are interchangeable among positions. This feature provides a significant reduction in the problems of logistics.

The next step was to move all engine accessories to the bottom of the compressor. This arrangement provided a minimum width engine (advantageous for the closely spaced six-pack arrangement of the XB-70A) and also then permitted GE to house these accessories in a honeycomb pod that improved fire safety and made a lower temperature environment possible. This pod served a useful purpose for NAA's electric thrust control system also, by providing, through the addition of an appendage, a fuel-cooled housing for the electric actuator. The complete engine installation package is shown in Fig. 13. This same NAA-GE cooperation was enjoyed on all facets of the installation design and development that will be mentioned in the following. The important point is that, although the XB-70/YJ93 situation favored such cooperation, in retrospect it appears that to have done otherwise would have resulted in costly compromises. The gospel we are attempting to spread is that Mach 3 cruise airplanes demand such integration of requirements in order to achieve a propulsion system adequate for the job to be done.

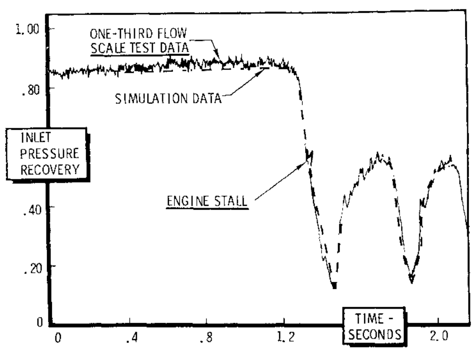

Fig. 11 Engine induced inlet unstart and buzz.

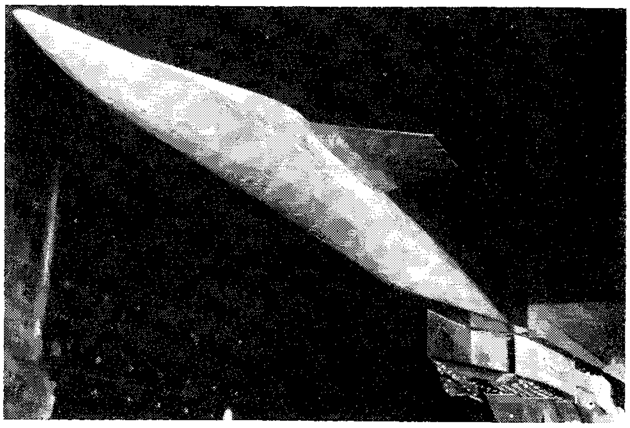

Fig. 12 One-tenth scale inlet model.

Engine Mounting

While working with GE, we conducted tradeoff studies of engine mounting arrangements, and finally settled on a system of six ball-ended links as being most advantageous to the installation. This type of mount makes it possible to transmit the loads from engine to airframe without inducing bending moments on either. To develop the links themselves, we ran bearing, lubrication, fatigue, and strength tests to finally arrive at a link made of René 41 tubing (which we had to machine ourselves), using silver-plated and dry-film-lubricated balls. These links were designed and tested to operate at 1200°F normally and at 1500°F for shorter periods in case of fire in the compartment. The links were tested successfully at Mach 3 conditions in the aft fuselage structural test section and were run at sea-level static conditions for 280 hr on the NAA propulsion test stand.

Engine Heat Shroud

The development of an engine-mounted shroud to protect the structure from engine heat from the combustors aft represented another significant item in the engine installation. Holding the airframe structure outside the shroud to an 800°F limit resulted in a substantial weight savings compared to an unshrouded configuration. Knowing the desired structural temperature level and using heat flux data provided by GE, we conducted tests on different candidate construction types. The selected configuration shown in Fig. 14, ended up as a $4\frac{1}{2}$-ft-diam. × 10-ft-long cylinder, with the $\frac{1}{4}$-in.-thick corrugated sandwich made of René 41 foil, 0.004-in. thick skins, and 0.003-in.-thick core. The shroud was gold-plated on the inside and coated black on the outside to reject a maximum of heat to the secondary airflow between the shroud and the engine. This structure is nominally designed to operate at 10 psi and 1100°F and also to contain a 2000°F fire for the required length of time.

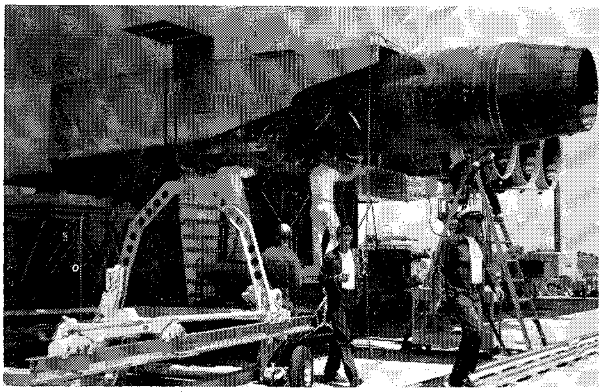

Fig. 13 Engine installation package.

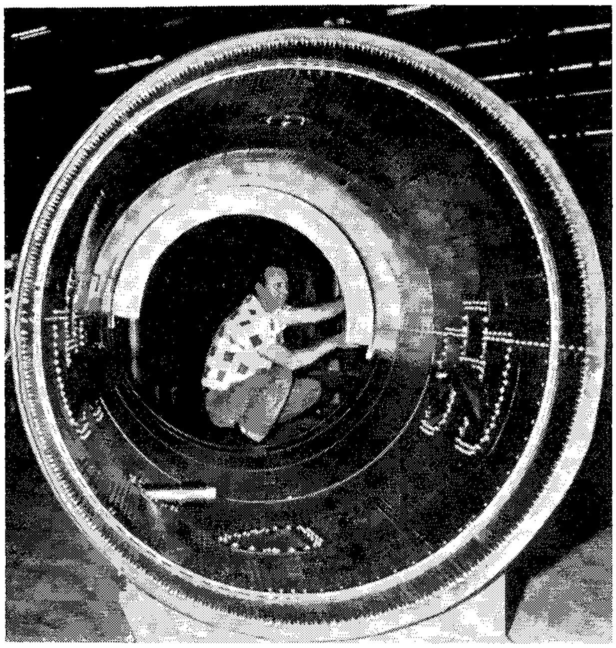

Fig. 14 Engine heat shroud.

A shroud was constructed early in the program to undergo testing of an engine primarily for mechanical integrity, although heat flux data were to be obtained also. After 95 hr of operation under conditions simulating up to Mach 3 flight at both GE and AEDC, a serious fatigue failure cropped up. Testing of a production shroud showed the shroud to be almost perfectly in tune with the engine vibration frequencies. After detuning by adding some circumferential stiffeners, the shroud was tested again at NAA and AEDC, and the stress levels were determined to have been reduced to a satisfactory level.

Engine Compartment Cooling

The engine compartment cooling system selected for the XB-70A is a relatively sophisticated three-regime (source) system, which switches from one regime to another during flight to select the most efficient source in order to create the least penalty on airplane performance. The pneumatic valves developed for this system by Whittaker Controls are shown in Fig. 15, installed in one of the engine compartments. As inlet duct pressure increases with Mach number, the valves modulate according to a temperature schedule to control the amount of air entering the engine compartment. The left valve shown includes the system control package that selects the appropriate air source. The valves handle 630°F "cooling" air, are powered by compressor bleed air, and include an override feature to shut the valves in event of compartment fire. Again, the need for integrating cooling system design with engine exhaust nozzle pumping and heat rejection characteristics emphasizes the importance of airframe and engine manufacture joint effort in the propulsion system design.

Engine Thrust Control

The development of an electrically powered throttle system, instead of using levers and cables, was another important feature of the propulsion system. The use of this system required the development of motors capable of operating in a 500°F ambient plus the development of confidence in the system reliability. Several sets of hardware were assigned to different test programs: the actuator qualification test, the GE engine development and qualification tests at Evandale and AEDC, the engine-inlet compatibility test at AEDC, and the NAA propulsion test stand. Prior to the first operation of the thrust control system in the airplane, some 1800 hr of operation had been accumulated, including about 600 hr of heated testing. Operation in the airplane has been very satisfactory; no problems or failures have been encountered.

Propulsion Test Stand

Mention has been made several times of the engine test stand at Santa Susana as a tool in developing many of the subsystems of the propulsion system. The primary value of the test stand, however, was in the compatibility testing of the engine and the secondary power generating subsystem (the aircraft accessories package driven from the engine by a shaft as mentioned previously). Although both the engine and the secondary power generating system (SPGS) package had undergone extensive development and qualification testing earlier, the Santa Susana program provided our first opportunity to operate the two together to uncover any interaction problems, as well as to test out the engine starting system that was integrated into one of the SPGS hydraulic pumps. The SPGS package tested consisted of a gearbox mounting with one 95 gal/min hydraulic pump/motor (the motor function serves as the engine starter), one 57 gal/min pump, and a 60 kv-a constant speed drive and alternator. Variable load devices for the hydraulic pumps and alternator were utilized. The package was hung in a compartment similar to that used on the aircraft and which included facilities for heating to Mach 3 conditions. The test stand is shown in Figs. 16 and 17. During this test, 244 hr of gearbox and accessories operation were accumulated, and 426 engine starts or motorings were made. Many problems were solved

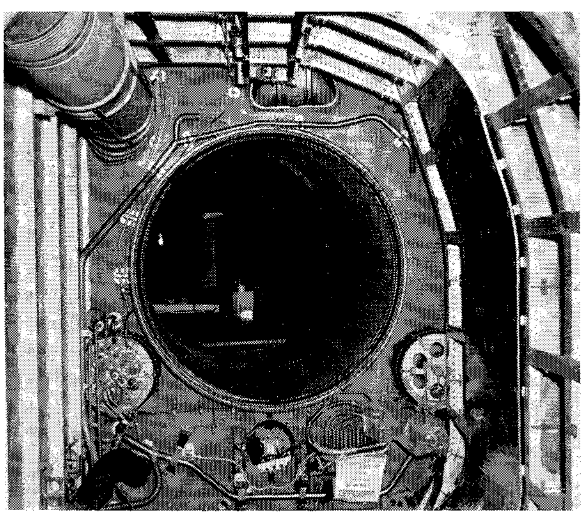

Fig. 15 Engine compartment number 6.

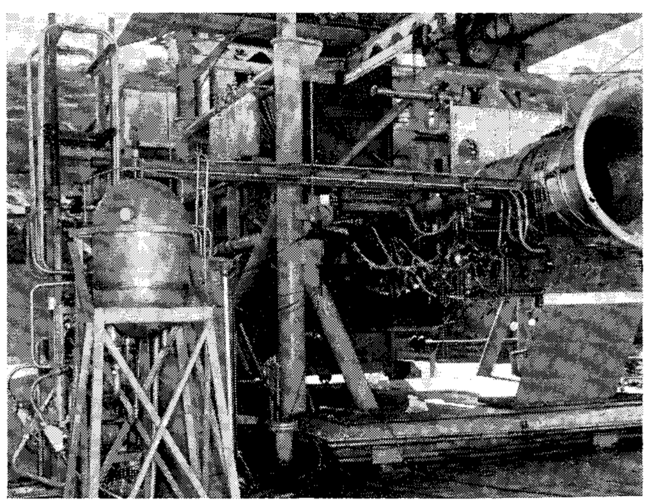

Fig. 16 North American Aviation test stand.

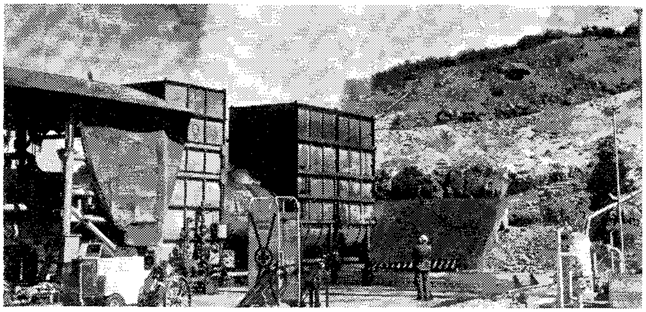

Fig. 17 North American Aviation engine test stand operation.

on this test stand which otherwise would have contributed to significant delays in the flight test program.

Foreign Object Damage

Finally, a few words about engine foreign object damage (FOD) prevention. Our experience in this field on the XB-70A could well be the subject of a paper itself. To sum up the results of our experience, however, we want to make two points. First, relatively complicated inlet systems required for Mach 3 aircraft add new dimensions to the FOD problem. It seems that nearly every step taken to increase the inlet efficiency adds a factor destined to increase the FOD potential. "Screen and clean" might be a succinct statement of the policy needed for FOD control. Suffice it to say that FOD on supersonic inlets is a bigger booby trap than we have experienced before, and nothing about the NAA experience in conquering the problem leads us to believe it was a problem peculiar to us.

The second point is that we have found an extreme lack of correlation between damage on the compressor stages observable from the inlet and those hidden downstream. (It is emphasized that we are speaking of damage initiated by objects as small as lockwire tangs to put it in the proper perspective.) It appears that in future engines it would be well to incorporate provisions for inspecting for FOD on downstream stages without requiring engine removal and disassembly.

To summarize this section, we have tried to give you a quick overview of the steps taken in developing the XB-70A propulsion system installation, progressing from laboratory tests, to component tests, to subsystem tests, to intersystem compatibility tests, and finally to the end result, the installed propulsion system (Fig. 18).

Fig. 18 XB-70A six engine A/B operation.

Engine Development

In such a limited program as we have in the XB-70, it is only natural that engine development continue into the flight test program. Through flight tests and further engine tests at AEDC, engine operation characteristics are being uncovered that were not known previously. For example, it was demonstrated that an installation capable of air starts at high altitude, high Mach number, may pose new problems of restart in the low-speed, low-altitude, region of the flight envelope. In the XB-70A we have found that SPGS drag has a significant effect on air starts.

Conclusions

This review of the XB-70 propulsion system development has pointed up several significant factors that we feel will be influential in the design of any high Mach cruise aircraft. Some of these factors are 1) development of the fuel system started with a 1-liter flask and progressed to a full-scale simulator, to provide both necessary design criteria and hardware capable of Mach 3 operation; 2) the ability to study inlet performance and engine-inlet compatibility, using a mathematical model and wind-tunnel tests, has been demonstrated; 3) the value of testing engine installation components in conjunction with the engine to solve installation problems prior to aircraft operation has been demonstrated; 4) foreign object damage on aircraft with sophisticated inlets presents new problems that must be coped with in inlet, engine installation, and engine design; 5) installation effects must be taken into account when engine air restart capability is being evaluated and demonstrated; and 6) the importance of close cooperation of airframe and engine manufacturers in developing all aspects of the propulsion system cannot be over-emphasized.

Reference

[1] Steele, E. S., "Meeting the challenge of the expanding performance spectrum: The XB-70A propulsion system," Society Automotive Engineers Paper 650841 (October 1965).