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PROPULSION TEST FACILITIES REQUIREMENTS FOR THE FUTURE

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Abstract

The advent of the C-5A and SST-type aircraft, with their attendant large subsonic and supersonic propulsion systems has brought the need for improved altitude simulation testing capabilities into sharp focus. A rationale to support the trend toward even larger aircraft and engines and identification of the time period wherein they will probably evolve is discussed. The evolution of advanced propulsion test units for component development in supersonic combustion ramjets, the development or evolution toward large bypass ratio engines and hybrid power plants, coupled with the methods which one might use to perform their normal development evolution, will be described.

I. Introduction

There seems little doubt that the greatest contributor to the successful development of sophisticated aeronautical vehicles is the timely availability of adequate ground test facilities. The advent of the C-5A and SST-type aircraft with their attendant large, subsonic and supersonic propulsion systems has brought the need for improved altitude simulation testing facilities into sharp focus. For a significant period of time, there was minimum airbreathing propulsion development as well as minimum planning for test facilities to accommodate this type of development requirement. However, within the past four to five years there has been an extremely large resurgence of interest in a development of airbreathing propulsion systems.

The bringing about of such significant focus on ground test facilities has generally been caused by the very rapid developments that have occurred in this area of flight propulsion, and the need for test of the system. The impórtance of the development test type ground facilities is even more sharply brought into focus since they often double as the research facilities in which new concepts are first born and then evaluated. Unfortunately, the lead time required for designing and building simulated ground test facilities, the procurement of necessary equipment and then its actual construction is often comparable to that of the lead time required for the design and development of the initial engine development hardware. Much discussion has been carried on by many authors regarding the development of a well-defined philosophy for planning and development of aeronautical test facilities. All of which boils down, however, to the need to have actual development requirements and an early enough time phase to solve the difficult problem of gaining support for making the capital expenditures.

II. Engine Growth and Aircraft Size

The revolutionary trends in air transport have begun to be shaped by the economic forces and have in fact been acting directly on commercial aircraft for several decades. With the advent of a steady evolution in aircraft material and methods of detailed structural analysis, the maximum transport aircraft size has been pushed up routinely. If one assumes a continuation of the rate of progress as has been typical in the recent past of these technological areas, one can develop a curve which shows a steady improvement in operating cost (Fig. 1).[1] One can

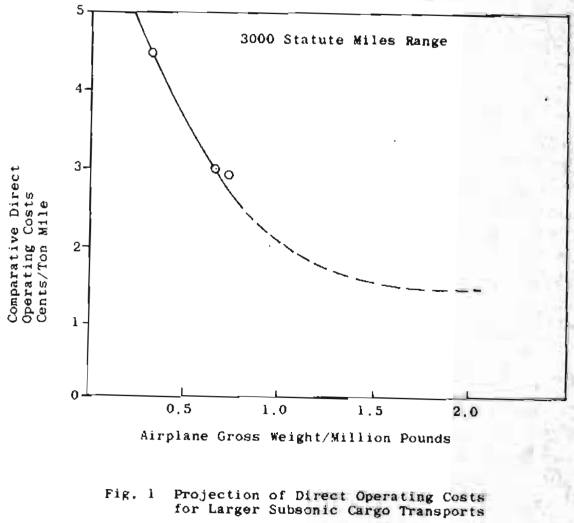

Fig. 1 Projection of Direct Operating Costs for Larger Subsonic Cargo Transports

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then expect this increasing size to eventually develop a flight weight of around one million pounds. Predictions by R. J. Smelt indicate this limit is unquestionably conservative and if one assumes a truly revolutionary change in structural materials occurring, the total flight weight of the aircraft could increase to over five million pounds. Forecasts from industry, in fact, for subsonic aircraft include the projections based on these kinds of assumptions (Fig. 2) which in-

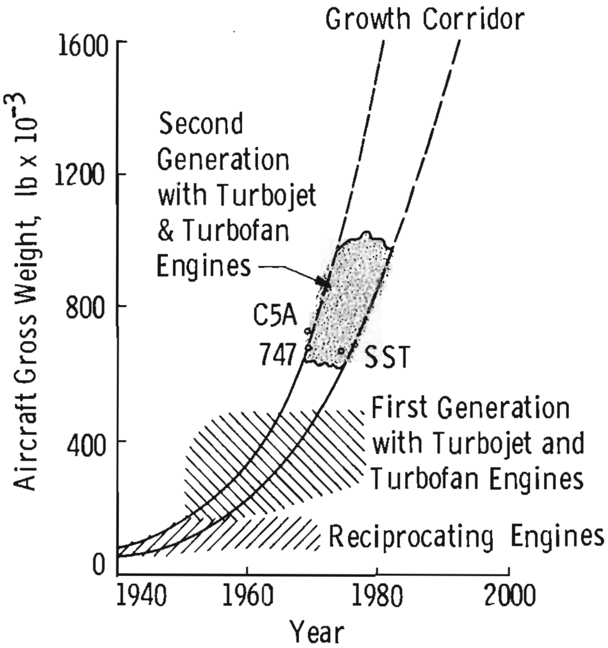

Fig. 2 Aircraft Growth Trends

clude gross weights to 900,000 pounds by 1975 and to 1,500,000 pounds by 1990. Aircraft of these sizes can be developed with technology available today.

It is not adequate to project that future aircraft and associated propulsion systems will be larger simply because technology trends predict the growth. Undoubtedly, technology trends predict "what could be built" but take no account of "what is required." A variety of trend analyses in related subjects have been derived from the many trend papers presented by various experts.

The parameter "ton-miles" appears to be an accepted standard for discussing transportation requirements and will, therefore, be used to examine aircraft capability. The product of payload and range is used in Fig. 1 to depict subsonic aircraft capability trends. It is noted that the growth curve sustains a rate of about 15 percent. The improvements in capabilities of individual aircraft or specie have occurred at a rate of about five percent. It is also possible to relate aircraft capability in ton-miles with aircraft gross weight, as illustrated in Fig. 3b. This projection is based upon a variety of existing

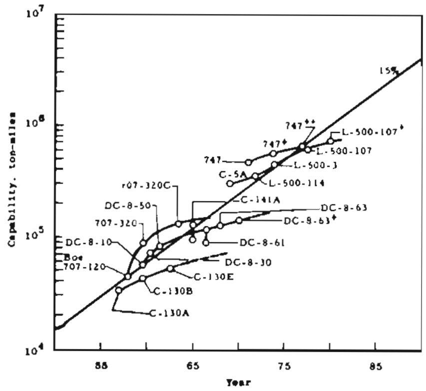

Figure 3a.
Large Subsonic Aircraft Capability Trends

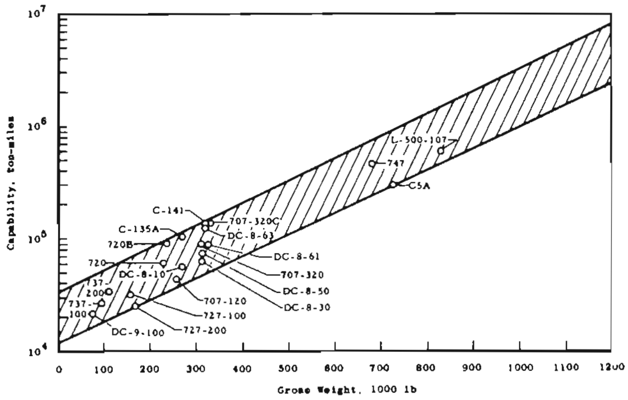

Figure 3b. Transport Aircraft Capability

and proposed subsonic transport aircraft, and represents a wide range of such performance parameters as specific fuel consumption, engine bypass ratio, lift-to-drag, etc.

The aircraft thrust requirement is a complex function of many variables but shows a surprisingly good historical correlation with gross weight, as illustrated in Fig. 4

The subsonic aircraft trend is typified by the cross-hatched strip, but it is expected that aircraft improvements will permit a closer approach to the upper

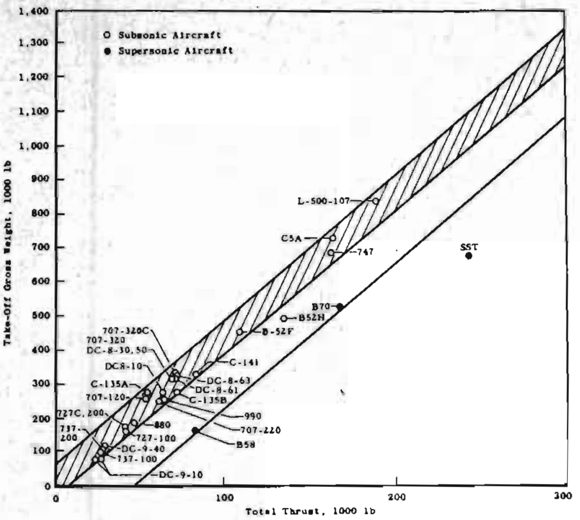

Figure 4 Large Aircraft Thrust Loading

boundary. The supersonic aircraft curve is lacking data points, but may be expected to generally follow the same slope with some displacement.

A recent survey of the aircraft and engine industries confirmed that an optimum configuration for large, future, long-range transports will be four engines - the fewest number for safety while providing the desired operational economy. Reduction in the number of engines results in impressive performance improvements, better reliability and less maintenance cost. Integration of Figs. 3a and 3b with the assumption of four engines on an aircraft permits construction of a growth curve of subsonic engine thrust with time (Fig. 5). Interpretation of the "bands"

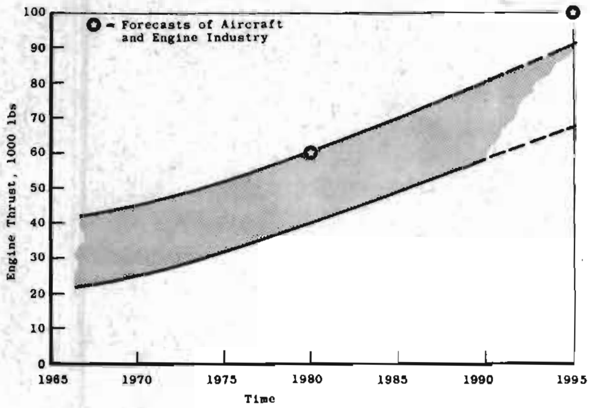

Figure 5 Engine Growth Predictions

of the previous curves results in a rather wide envelope, but even the upper curve of this band could be too conservative. A recent survey of the aircraft and engine industries indicates that turbofan engines in the 60,000 lb thrust class will evolve for 900,000 lb high-subsonic speed transports in the 1980 time period.

Forecasts for the 1995 time period show 1.5 million lb subsonic transports with engines approaching the 100,000 lb thrust class.

A sustained growth picture for supersonic transports is not so clear, due to the uncertainties of the traffic requirements, the solution of the noise problem, and the general public acceptance. There are, however, speculations by the engine manufacturers that even the first generation SST may utilize 75,000 lb thrust engines. It is not expected that further large scale growth will occur in the near time period, for it will take some time to amortize the larger R&D costs. However, based upon this analysis and some appraisals of industrial and military experts, it is estimated that improvements in the present supersonic aircraft could result in engine growth on the order of 10 - 15 percent after 1975.

There is every indication that the present trend toward turbofan engines for large subsonic transport aircraft will continue. These engines will continue to be popular because of certain innate operational advantages, e.g., low specific fuel consumption. Present engines under development have bypass ratios of 5 and 8.

It is probable that transports will progress toward cruise at higher subsonic Mach numbers, perhaps above Mach 0.90 with aerodynamic improvements. Bypass ratio is related to engine thrust and airflow in one manner as shown in Fig. 6. Based upon this relation and the engine growth predictions of Fig. 4, the resulting air-

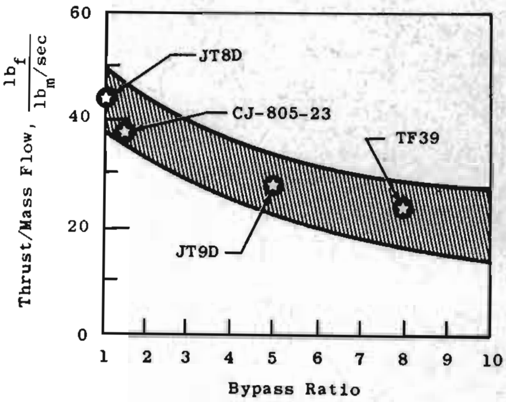

Figure 6. Relative Engine Airflow as a Function of By-pass Ratio

flow requirements for a 60,000 lb thrust subsonic engine were interpreted and are depicted on Fig. 7. It is suggested that

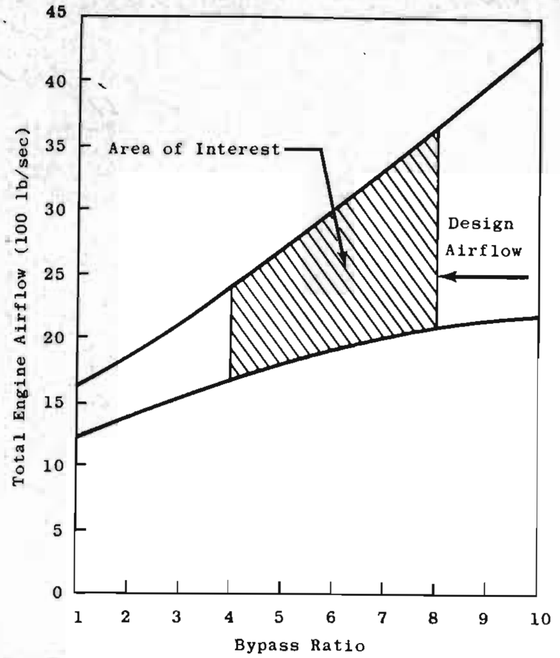

Fig. 7 Airflow Requirements for a 60,000 lb Thrust Subsonic Engine

2500 lb/sec be accepted as typical for purposes of engine definition. Such an engine would be about 10 ft in diameter.

III. Large Subsonic Engines

Figure 8[2] shows the trend of sub-

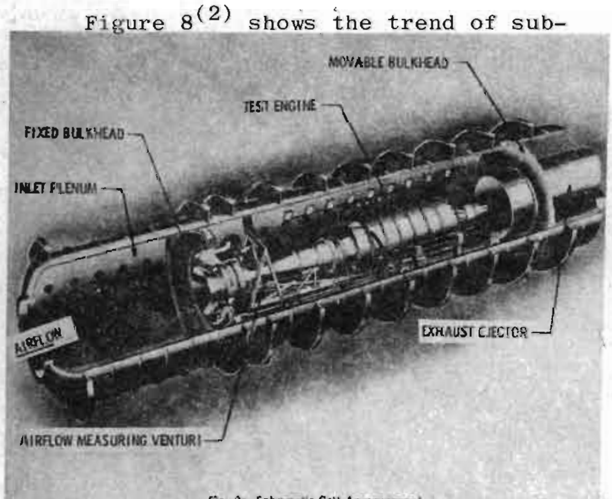

Fig. 8a Schematic Cell Arrangement

sonic engines over the past 20 years relating to the requirement for sea level static engine airflow. This problem, which is probably one of the most important ground facility parameters, has been precipitated due to the shift from the straight turbojet engine to high bypass turbofan engines with apparent increasingly higher bypass ratios to come in the future. It becomes apparent that this parameter will continue to grow in view of the fact that there will be a continued requirement for increased thrust and the constant requirement for lower flight specific fuel consumption. Even the most optimistic engine designer readily admits that he is dealing with an art as well as a science and that analytical techniques are only sufficient to produce pieces of hardware with which he can then begin to experiment and refine.

A complete cycle of engine developmental testing starts with a test of engine components and terminates with a program of evaluation and improvement aboard the aircraft on which the engine is to be used. But assuming that modest facilities can provide the component development requirements, the testing load of the engine composed of "developed" components then must be accomplished in a simulated environment in at least three distinct ways, each requiring a different capability and each providing data proportional to the simulation provided. The most complete facility test environment is provided in integrated systems tests where the entire propulsion systems and any surrounding or influencing aerodynamic surfaces are exposed to duplicated flight conditions. Much engine development and integration can and has been accomplished in lesser facilities than would be required via other modes of testing. The most economical and used technique is that of direct connect testing as illustrated in Figs. 8a and 8b. The former figure shows a schematic cell arrangement for direct connect testing, while Fig. 8b

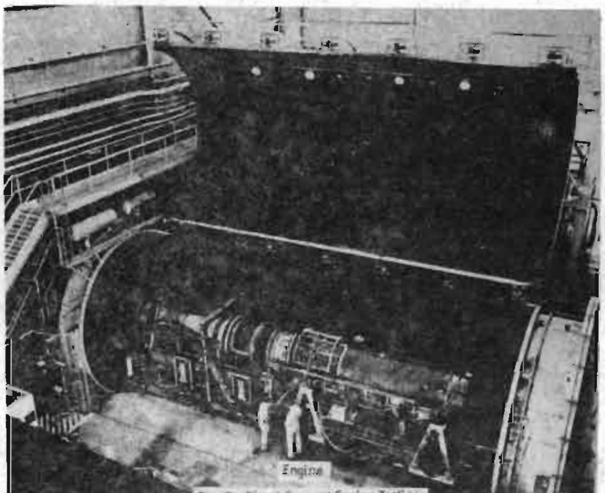

Fig. 8b Direct Connect Engine Testing

shows an engine installed for an actual engine test installation. In this mode, the flight conditions are simulated by connecting the engine minus inlet to an air supply system which produces a condition of flow expected from the aerodynamic inlet or air induction system. The engine exhaust nozzle is exposed to the correct altitude density.

The free jet test mode, as illustrated in Fig. 9, is a compromise between the first two modes and provides the

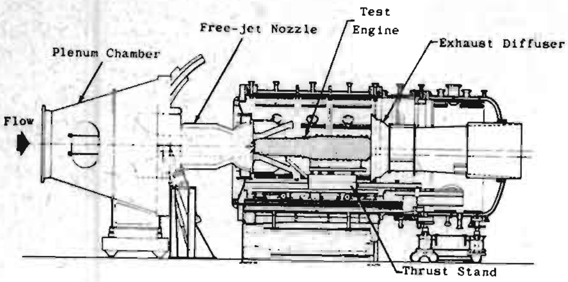

Figure 9 Schematic of Free-jet Test Mode

correct velocity and angularity in the flow approaching the inlet. Such test conditions are adequate for evaluation of the complete internal aerodynamics, mechanical problems of the engine if there is no upstream disturbance or perturbation, e.g., a pod-mounted engine with no shock interference. The test conditions are not adequate, however, to permit determination of engine external aerodynamic parameters (in stalled drag) and the effect of flow distortion. The free jet test facility is more expensive than the direct connect facility since it requires about twice the airflow, a nozzle, and a larger test cell. Also, the exhausters in the test facility must have twice the capacity to provide altitude simulation at the engine exit. There are, of course, compromises between the free jet and direct connect test modes wherein the inlet flow condition may be duplicated at any chosen point. It is also possible to simulate some flow distortion with properly positioned screens and vanes in the flow. However, the most economical and fundamental of the engine test modes is the direct connect and it is this basic capability that one very likely must face as a result of the increased air flow demands imposed by significant engine growth probabilities.

Aside from the engine-airframe integration problem, the modern supersonic (or subsonic) turbojet presents a formidable array of interrelated problems which require solution.

Some of the engine operating limits are depicted on a typical engine performance envelope in Fig. 10. It is noted that several of the severe problems which require investigation are located around the extremities of the envelope. Problems related to high pressure-high temperature lie along the right side of the flight envelope. Proof of sustained operation is required to demonstrate structural integrity of mechanical components and adequacy of lubrication, cooling, and other auxiliary systems. Problems relating to aerodynamic performance and combustion processes predominate along the left and upper portions of the

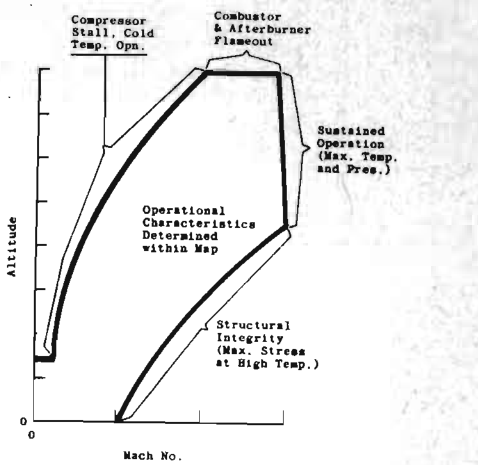

Figure 10 Engine Performance Envelope and Key Test Areas

envelope. In these regions, the performance of compressors becomes marginal, and the initiation and propagation of the combustion process are very sensitive. However, it is absolutely necessary to identify engine limitations that may exist throughout the entire operating envelope. Deficiencies must be eliminated if critical, or recognized as acceptable operational limitations if not critical. Therefore, test capability through the entire operating regime is required.

Propulsion systems are very sensitive to variations in operating conditions and susceptible to compressor stall and/or combustor flame out. To circumvent this possibility, the engine designer has incorporated many controllable components in his engine, thus allowing engine configuration to adapt to new operating conditions during flight. However, these variables are all interdependent and must be changed in a precisely controlled sequence. Figure 11 gives some indication of the parameters of interest.

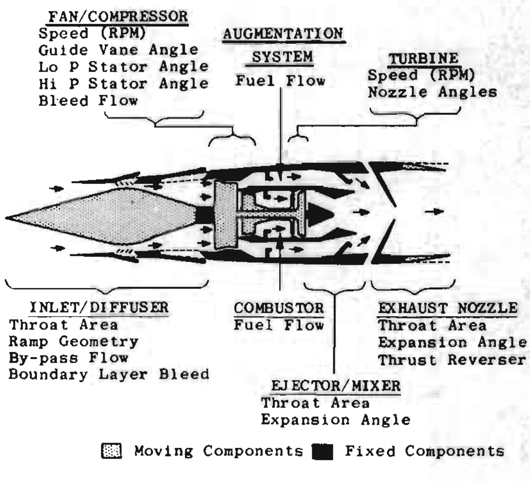

Figure 11 Advanced Turbine Engine Variable Parameters

In addition to and related to the 18 or more engine variables, there are a number of variables which the engine experiences in the flight environment. It is usually a change in one or more of the flight variables that propagates a sequence of events among the engine variables. A necessary engine adjustment may be brought about by any one or combination of the following:

- Acceleration or deceleration
- Ascent or descent
- Variation in angle of attack or yaw, flow distortion, etc.
- Atmospheric variation, e.g., clear air turbulence
- Hot air ingestion (rocket firing)

One has only to consider the many possible combinations of engine component variables and flight variables to obtain some feeling of the magnitude of experimental data required to solve this matching problem. Proper control and variation of the engine parameters through an engine control system can mean the difference in a "good" and "bad" engine. For example, great care must be taken to prevent compressor stall when the pilot shoves the throttle open. In addition, it is still necessary to integrate the engine components; determine heat and structural loads; assure design performance, reliability and endurance; verify various off-design operations; and evaluate transients, e.g., altitude restart.

The growth in engine size beyond the TF 39 (41,000 lbs SLS thrust), JT 9D (42,000 lbs SLS thrust) and the GE 4 (63,000 lbs SLS thrust) can be realized with existing technology. The primary justification for larger engines will be the propulsion demands of larger aircraft and the desire to retain the four-engine configuration which appears to be optimum for large, long-range aircraft. All large operational transports have had no more than four engines since the introduction of the DC-4 in 1938.

However, if one carries this rationale further, engines in the 60,000 lbs thrust class would be required for the 900,000 lbs subsonic transport forecast by 1975 and an engine rated at approximately 95,000 lbs thrust would be required for the 1,500,000 lbs aircraft predicted by 1990.

Reviewing the requirements then as a result of these trends in subsonic engines and the provision of development of ground test facilities to provide the appropriate simulation of the environment of the propulsion system, it becomes readily apparent that these conditions require the handling of very large quantities of air as indicated in Fig. 12, and at less than atmospheric pressure and generally at reduced temperatures.

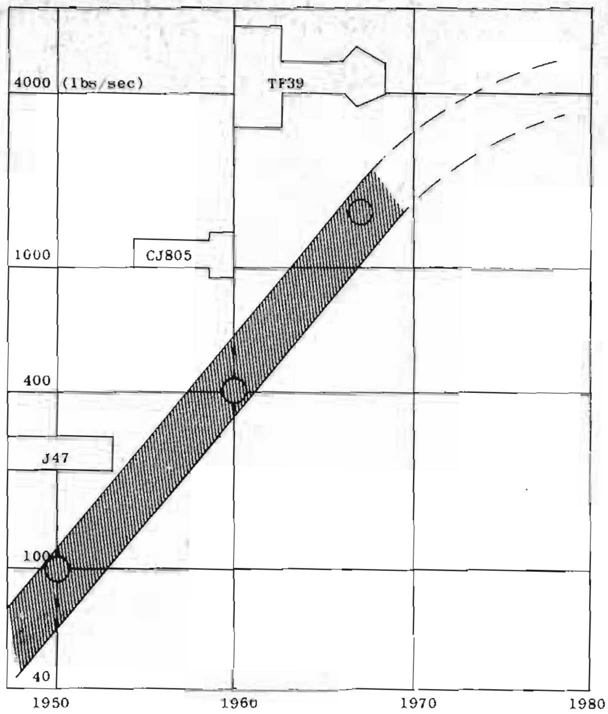

Fig. 12 Trend of Subsonic Engine Corrected Airflow

IV. Supersonic and Hypersonic Engines

If one looks at the development trends of the supersonic engine which are currently proposed for manned commercial aircraft, there are four general types of engines which have been considered: (a) afterburning turbojet, (b) dry turbojet, (c) duct burning fans, and (d) turbo ramjets. The trend is quite similar to that of the subsonic engine and indicates significant growth in discovering environmental test facility parameters. Since the engine thrust is directly related to airflow, one may view Fig. 13 also as the trend in thrust level. Although subsonic engines at altitude operate at lower temperature levels and pressures than at sea level static, engines in supersonic flight operate extended periods of time at inlet temperatures and pressure considerably above sea level static. It becomes obvious that altitude environmental simulation facilities must be provided which would allow a significant portion of the engine development cycle to be pursued at actual altitude maximum operating conditions. This, of course, means that the inlet air temperatures are significantly elevated and pressures are in the order of two or more atmospheres.

A myriad of problems has been recognized in this development cycle which include engine operational effects on inlet

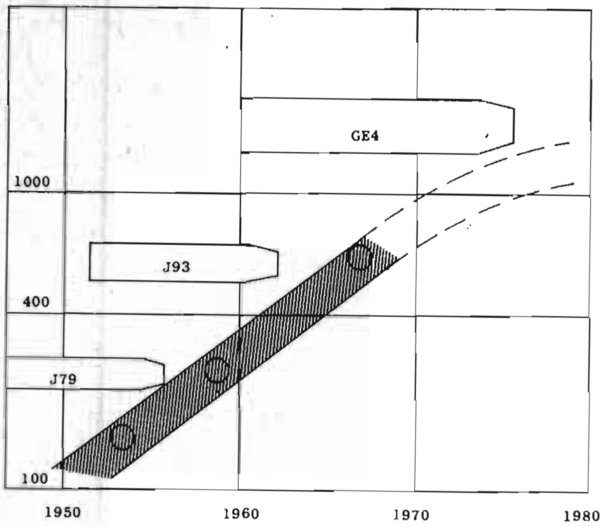

Fig. 13 Trend of Supersonic Engine Corrected Airflow (in lbs/sec)

unstart effect on the engine and the problems of inlet generated distortion effects on engine performance. If simulation of the mechanical and aerodynamic operation of the exhaust nozzle is required, then a further increase in required facilities results. If one goes further in the prediction of application of airbreathing propulsion systems into the hypersonic regime, it becomes apparent that airbreathing propulsion systems which fly from Mach 5 to near orbital velocities can be and have been considered by a number of engine manufacturers. The applications and missions in this vein are for recoverable space boosters and the hypersonic transport.

In the case of the hypersonic transport, cruise Mach numbers have been considered from the range of Mach 6 to 12. There are three propulsion systems which have been considered and these are:

a. A type turbo ramjet using cryogenic fuel for the Mach 0 - 6 cruise vehicle has been potentially attractive. For these types of engines, size studies have indicated a corrected airflow per engine of up to 1,000 or more pounds per second.

b. A second consideration for high Mach number cruise vehicles is the turbojet for take-off and climb and acceleration to low Mach numbers, the use of a convertible scramjet engine and then accelerating to higher Mach numbers. There again, the critical size of the turbojet engine falls into the flow levels of about 1,000 pounds per second.

c. As above, the turbo ramjets take off and climb in acceleration after which the ramjets take over. If one looks at the existing airbreathing engine test facilities, it becomes apparent that some future facility planning is required for larger high Mach number engine developments if current trends persist for military and commercial aircraft and lead times are properly considered for their development.

V. Conclusion

It becomes increasingly important to recognize that the pacing factor in engine development, be it subsonic, supersonic or hypersonic, continues to be the ability to duplicate under laboratory conditions adequate test environments. These airbreathing engines will operate across a very broad speed range and at constantly changing operating conditions, and they will be increasingly complex and require a companion complex and extensive developmental test program. An important consideration is that engines are strongly dependent upon ground testing for this development and economically the trade-offs have consistently proven that this must be done in test facilities.

The answer should be obvious to those who ask, "Why can't we just flight test?" Without the capability to precisely control and vary the environmental variables in the test facility, while at the same time heavily instrumenting the engine to monitor the engine variables, the task of integration and engine development is unduly expensive and time consuming. This is not meant to degrade the importance of flight testing in the aircraft evolution, for this is the ultimate and necessary evaluation. But experience has plainly shown that complicated propulsion systems cannot be "developed" in this manner. The same holds true in those instances where we are fortunate enough to have on hand an aircraft to serve as a flying test bed.

An excellent example of the utilization of a flying test bed, but also one which demonstrates that the flight envelope of the test bed aircraft is a sizable constraint, is shown in Fig. 14. The ex-

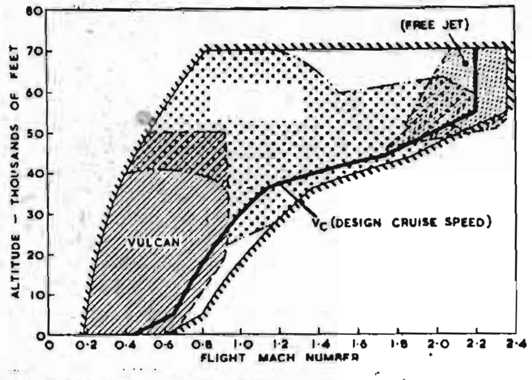

FIGURE 14 FLIGHT ENVELOPE - SCOPE OF TEST FACILITIES

tent to which the Concorde flight envelope could be tested by using the Vulcan is shown in this figure, and it depicts how the test cells of the NGTE Institute were utilized to then fulfill the balance of the design cruise portions of the envelope. It should be acknowledged that there are limitations in the usefulness of the "Single Engine Installation" in a ground test facility but this would apply also to the Vulcan flying test bed. Nevertheless, it is an excellent tool and one of considerable value which permits the exploration of the effects of aircraft attitude, engine and intake transient operation. It serves also as a good indicator of trouble areas and is a base line for correlation data between altitude test facility and a flight test bed.

In such cases, they may be used to supplement the facility test program, but the limitations are well defined. Testing is limited to the flight envelope of the test-bed aircraft; the test engine cannot be safely pushed to its operating limits; environmental control is limited and instrumentation is marginal. It is safe to conclude that <u>facility capability paces engine capability</u>.

The criteria for any engine development program are suitable performance and proven reliability. More than ever before the large aircraft of the future require that risks be minimized because of the hundreds of passengers and expensive equipment involved. A reliable engine can only be developed in a timely and economic manner by complete testing in a ground test facility throughout the operational envelope and with adequately simulated flight conditions.

The three major difficulties posed, then, to the airbreathing engine facility technology are that airbreathing engines require that flight conditions be duplicated closely in the facility, and repetitively; test times must be long enough to evaluate steady-state engine operation; and engine performance is affected by combustion dynamics which prevent sub-scale testing of most development engines.

When these factors are interpreted into facility requirements, it is increasingly clear as to why proper kinds of facilities are not only difficult to build but exceedingly expensive. The need for new methods of simulation such as combinations of components, direct connect and scale model testing must be investigated to relieve facility cost at least during the early technology phases. It seems readily apparent that both subsonic and supersonic engines will continue to grow in size, and beyond a doubt some altitude simulation facilities are required to develop these engines. Both aerodynamic development and verification of internal and inflight performance must be analyzed for the best economic balance between costs and risks compared to various levels of flight simulation.

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