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THE PROMISE OF ADVANCED TECHNOLOGY FOR FUTURE AIR TRANSPORTS

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ABSTRACT

Aviation is viewed as a growth industry with technological advances continuing well into the 21st Century. While growth constraints to air transportation such as economics, energy, and congestion are very real, technical improvements in dependability, efficiency, and speed will tend to counteract them. Certain NASA activities which impact long-haul (greater than 500 miles) and far-term air transports (1990's and beyond) are discussed. The keys to improved dependability are congestion relief and all-weather operations. Progress in all-weather 4-D navigation and wake vortex attenuation research is discussed and the concept of time-based metering of aircraft is recommended for increased emphasis. The far-term advances in aircraft efficiency are shown to be skin-friction reduction and advanced configuration types. The promise of very large aircraft - possibly all-wing aircraft - is discussed, as is an advanced concept for an aerial relay transportation system. Very significant technological developments are identified that can improve supersonic transport performance and reduce noise. The hypersonic transport is proposed as the ultimate step in air transportation in the atmosphere. Progress in the key technology areas of propulsion and structures is reviewed. Finally, the impact of alternate fuels on future air transports is considered and shown not to be a growth constraint.

INTRODUCTION

Air transportation is one of the most remarkable technological developments of the 20th Century. In the past 50 years, we have progressed from 100 miles per hour open-cockpit mail planes to 1,300 miles per hour supersonic jets. A 30-hour transcontinental air mail service (fig. 1), with six pilot changes enroute has become a 5-hour nonstop flight. The supersonic Concorde has reduced trans-Atlantic flight times an order of magnitude since Lindbergh's flight in 1927. Today's domestic airline system is an extensive network of 58,000 city pairs served by 13,000 daily flights carrying more than 500,000 people and 8,000 tons of mail and freight daily. Air transportation has provided unprecedented mobility to hundreds of millions of people and has opened up vast new areas of economic development and trade. The safety of air transportation rivals the safest of transportation modes, and passenger comfort and service has improved dramatically - all, while the traveler's cost has declined an average of 2 percent per year in constant dollars.

Now, what is the outlook for the future? Is air transportation a mature industry? Is it plagued with obsolescence in the near future such as the railroads experienced? The constraints to the growth of air transportation are very real. The major ones are economics, energy, and airport congestion. The effects of the first two slowed air transportation growth dramatically in the United States in the mid-1970's. It was little consolation that the congestion problem was minimized as a result. All indications are that we are emerging now from the slump of the 1970's. Traffic demand is up and the need to replace worn and obsolescent aircraft is building. While current projections for aviation growth are more modest than those of the early 1970's, they indicate a doubling of operations within 15 years. An industry will survive only as long as it provides a superior service. Aviation is no exception. It is this writer's view that aviation is a growth industry with very exciting technological advances continuing to appear on the horizon. The purpose of this paper is to discuss some of the emerging technologies in aviation at the NASA Langley Research Center and how they might relate to future air transports. The emphasis will be on long-haul (greater than 500 miles) and on the very far term (1990's and beyond).

Before discussing advanced technology trends, however, it is important to concentrate for a moment on the question of economics. New technology must be economically viable and one measure of this is its effect on direct operating costs (DOC). Figure 2, taken from a Boeing estimate (Ref. 1), shows the effect of technology improvements on DOC for a commercial subsonic transport. In order for advanced aircraft to be a viable investment, their DOC's may have to be 25 percent less than replaced aircraft. The leverage of drag reduction and a reduction in flight time due to air traffic control is seen to be large and will therefore receive considerable emphasis in the discussion to follow.

The future directions in aircraft technology that form an outline for this paper include: (1) the need to improve the *dependability* of air transportation - the keys being congestion relief and all-weather operations, (2) continued advances in aircraft *efficiency* to meet the constraints of energy and economics, and (3) exploitation of increased *speed*, since basically speed is the most important benefit offered to the customer by air travel.

DEPENDABILITY

Moving traffic under instrument flight rules (IFR) is a serious problem in aviation. The number of major-hub airports having reached IFR capacity today with present air traffic control (ATC) systems is 14 (Ref. 2). With aircraft operations projected to double by the mid-1990's, this number will grow to 24. The prospect for new airports is bleak. With the exception of small, private fields, no new airports have been built since 1970 because of cost and other factors. Some airports are disappearing and are referred to as "endangered species." It is clear that maximum use must be made of our existing airports. There are many ways to optimize airport capacity, including the use of large aircraft. The discussion to follow considers only landing operations on a single runway.

Time-Based Metering

In order to maximize landing operations on a runway, it is necessary to provide a continuous supply of closely spaced aircraft to the initiation point of final approach. All aircraft types will have to be sequenced so that they arrive at a particular point at an assigned time. This concept of time-based metering (fig. 3) can be utilized all the way from departure to landing, if required, so that an airplane doesn't take off until it has an assigned landing slot at its destination. It is most important, of course, in the terminal area and the approach to the terminal area. The essential elements of the time-based metering system are shown in figure 3. They include a precision 4-D (space and time) navigation system, air traffic time sequencing, and air/ground/air communications data link.

The FAA has an extensive program in developing an advanced ATC system. The planned ATC system components affecting time-based metering include the microwave landing system (MLS), increased analysis capability in the automatic radar terminal system, digital data links such as the discrete address beacon system (DABS), and other elements such as collision avoidance and weather detection. The addition of automated metering and spacing (M&S) to the ATC is vital for traffic time sequencing.

The Navstar global positioning satellite (GPS) illustrated in figure 3 is an exciting possibility for upgrading navigation information over the ground-based distance measuring equipment (DME). A constellation of 24 satellites, 8 in each of three 12-hour, 10,900-n. mi. orbits, allows passive reception to determine position, velocity, and time. The projected accuracies are impressive: position, 30 feet; velocity, 0.5 ft/sec; and time, 20 nanosec. Results from tests conducted last fall with a simulated system were better than the projected values. These accuracies suggest the possible use of the GPS also in the terminal area for low-visibility approaches (CAT I) at airports that do not have sophisticated landing systems (Ref. 3).

NASA has been concentrating its research on the airborne side. Aircraft requirements for 4-D navigation include not only precise aircraft navigation/computational capability, but also thrust and flight-path control with time and position. The NASA research aircraft shown in figure 4 is being used to develop both manual and automatic 4-D navigational techniques. (Another paper in this conference by, J. P. Reeder, describes other NASA research with this aircraft.) The aircraft is a B-737 modified to be flown both from the forward flight deck with conventional controls and the aft research flight deck using a fly-by-wire, triply redundant digital computer system. From the aft flight deck, the airplane can be flown with advanced electronic displays and pilot selectable automatic navigation, guidance, and control systems in simulated CAT III weather operations.

Flight tests have been conducted on the operation of the 4-D RNAV system in the aircraft with the navigational system updated by dual DME (Ref. 4). The flights were about 1-1/2 hours duration with take-offs and landings in a tracking radar environment. They included climbs, descents, turns, and speed changes. All operations except take-off were automatic. The navigational accuracy demonstrated in these tests is shown in figure 5. Arrival errors of ±3 seconds were achieved, compared with ±20 seconds for the current manual mode. This accuracy obtainable with the NASA experimental 4-D navigational system and existing DME navigation aid is very encouraging. If this single aircraft performance could be extended to all aircraft types with automatic traffic sequencing control, it would result in a 20-percent increase in runway capacity for a mix of 20-percent heavy aircraft under 3-, 4-, and 5-mile separation restrictions. If this distance can be reduced to 2 miles, runway capacity is doubled. Note that without improved arrival accuracy, decreasing separation distance to 2 miles only increases capacity by 35 percent.

Wake Vortex Problem

The current restriction on separation distance is due to the wake vortex hazard. As shown in figure 6, this hazard can extend a distance of 6 miles for a Learjet type aircraft following a B-747. Also shown in the figure is the progress being made by NASA in vortex attenuation research. By altering the spanwise loading (retracting outboard flaps), systems of vortices can be generated that will interact in such a manner to produce early dissipation of the vortex core. The use of spoilers to alter the load distribution as well as to generate turbulence reduces separation distance even further. Flight tests of the spoilers have been conducted at altitude, and this summer it is planned to land aircraft behind a B-747 with spoiler deflection. Addition of a vortex producing fin on the wing has shown promise in ground facilities of reducing the vortex strength with perhaps less performance penalty to the generating aircraft. (A paper by R. E. Dunham and D. J. Morris in this conference gives additional details of this research.) While much additional work needs to be done before these devices are operationally acceptable, the results to date are extremely encouraging.

All-Weather Operations

As previously stated, weather is the basic enemy in efficient air traffic control. Time-based metering with automatic control and/or manual control with advanced displays will function in zero visibility. Severe storms, however, present serious problems, particularly in the terminal area. The only safe solution to a severe storm is to avoid it. Recent research in severe storm prediction indicates that there is promise for substantially improving the warning given enroute and in the terminal area. Computational fluid mechanics has now advanced to the point that the small-scale atmospheric gravity waves which set up the conditions for severe storms can be simulated over fairly large volumes of the atmosphere. These 100- to 200-n. mi. waves which "drive the storm development" are not included in current large-scale prediction models because of lack of computer capacity. Recent storm simulations run on the NASA-Langley STAR computer including these effects are shown in figure 7. An improvement in warning time from 1-1/2 hours to 7 hours for comparable sizes of the warning area is obtained. The model is presently being evaluated to determine its potential for predicting both storm location and time to a higher degree of accuracy. Much work remains to be done, but it is hopeful that the future will see weather forecasting accurate enough to allow the full utilization of time-based metering ATC.

EFFICIENCY

Energy consumption for commercial aviation has tripled in the past 10 years and is expected to at least double again by the 1990's. Fuel prices escalated with the OPEC oil embargo of 1973 and continue to rise. Forecasts through 1989 project a 7-percent annual rise in fuel costs exclusive of possible increases in domestic fuel taxes. Clearly, energy is a serious growth constraint to aviation, and all future aircraft designs must be even more energy efficient. NASA has an extensive R&D program to improve aircraft efficiency with a goal of a 50-percent reduction in fuel burned. This program involves all the aeronautical disciplines and is documented well in the literature. The discussion to follow is restricted to long-term drag reduction concepts and advanced aircraft configurations.

Skin-Friction Reduction

Nearly 70 percent of the fuel burned on a transcontinental trip is consumed during cruise. Cruise drag is more important than any other single parameter in its effect on fuel consumption. Figure 8 shows the contribution of each drag element to the total cruise drag of a modern subsonic wide-body jet transport. In the near term, most of the drag reduction opportunities indicated for induced drag and pressure drag will be realized. The drag reduction frontier for the far term is in the area of skin friction, which currently makes up 50 percent of the cruise drag. While skin-friction reduction offers high payoff, it is also very difficult to achieve.

Maintenance of a laminar boundary layer on a surface can reduce skin friction by as much as 90 percent. Very smooth surfaces and controlled pressure gradients can delay the transition to turbulent flow and produce significant regions of "natural" laminar flow on an aircraft wing. The laminar flow airfoils of the late 1930's and early 1940's are examples of this concept, and research in natural laminar flow is continuing today. Maintenance of laminar flow over large portions of a surface has only been obtained by active means. The technique of removing a small amount of air from the boundary layer through very thin slots in the airplane surface was verified in flight tests by the U.S. Air Force on the X-21 back in 1964. The principal difficulties in laminar flow control (LFC) through suction are indicated in figure 9. They include the high manufacturing cost of smooth, slotted, or porous surfaces; surface contamination and maintenance; suction system design; and the compatibility of slotted suction surfaces with advanced supercritical airfoil shapes.

There has been a void in LFC research since the X-21 program. The area is now receiving accelerated research attention under the NASA aircraft energy efficiency (ACEE) program. Emphasis is on the development of a practical, reliable, and maintainable system for LFC. Recent progress has been significant. Concepts for preventing leading-edge contamination from bugs have been demonstrated and suction surfaces and primary structural concepts have been defined. A major thrust of the effort is the design of new LFC airfoils. A significant challenge is to marry boundary-layer control and supercritical airfoil technology. A recently designed LFC airfoil is shown in figure 10. The upper surface is designed to achieve shockless supercritical flow at the design cruise point ($M = 0.8$). The unusual lower surface is dictated by a need for reasonable thickness (13.5 percent), a small radius nose section to stabilize the boundary layer and reduce suction requirements, and fore and aft camber to achieve the required lift (section lift coefficient of 0.6). No test data are available for such airfoil shapes, particularly with boundary-layer control. A complex wind-tunnel test is therefore planned in the low-turbulence NASA Ames 12-Foot Pressure Wind Tunnel in order to determine aerodynamic performance and suction requirements. The airfoil will be tested in the swept condition and will require a special tunnel liner to achieve the desired free-stream simulation (fig. 10). The wing will have at least a 7-foot chord and will contain over 200 slots in the upper and lower surfaces. In order to test the LFC airfoil at nearly full-scale Reynolds numbers and under actual flight conditions, a section of an LFC wing will be "gloved" on the wing of an existing aircraft and flight tested sometime in 1981. Far-term plans, not as yet approved, include flight test of a complete LFC wing on an LFC demonstrator aircraft. This program, when carried to completion, will determine for the first time the operational feasibility of LFC on passenger jet transports. Its progress should be followed with interest.

On areas of an aircraft where it is difficult to maintain laminar flow - for example, the fuselage - it may be possible to reduce turbulent skin friction by means of special surface treatment or devices to break up the large eddies in the turbulent boundary layer. Several of these concepts are under research investigation at the NASA Langley Research Center (Ref. 5). One such concept is illustrated in figure 11. It uses transverse surface waviness in an attempt to produce periodic partial relaminarization and, hence, a lower average skin friction. Figure 11 gives a comparison of the local skin friction for a low-velocity flow over a wavy wall with that of a flat plate. Both theoretical and experimental values show about a 20-percent reduction in local skin friction. Note the rather gentle waviness of the wall used to achieve this reduction. Despite this, however, the wall has a pressure drag that is in excess of the skin-friction reduction. Therein lies the research state of the art for turbulent drag reduction. There are several known concepts to reduce local skin friction, but to date this cannot be done with a net decrease in drag. The researchers are optimistic that, for the case of the wavy wall, optimized surface contours can produce a reasonable (10-20 percent) net drag reduction, even when the small additional surface area is included.

Advanced Configurations

Long-Range LFC Aircraft.- Application of LFC to the wings and empennage of a "conventional type" aircraft such as that shown in figure 9 can probably reduce total drag by 30 percent (Ref. 6). It is interesting to consider an airplane that takes maximum benefit of LFC. Such an airplane would operate at long ranges and high altitudes. The concept shown in figure 12 has been evolved over a period of many years by Werner Pfenninger of NASA Langley Research Center, who is well-known for his work in LFC. The aircraft has a gross weight of 880,000 pounds and a 450-foot wing span. A high-aspect-ratio wing (over 16) and "tip feathers" are required to reduce induced drag compatible with reduced skin friction. Wing weight penalties are minimized by strut bracing. LFC is applied to the wings, struts, external fuel nacelles, engine nacelles, and the empennage. The resultant lift-drag ratio (L/D) is estimated to approach 50. The calculated performance is much better than that of conventional airplanes - a 30-percent payload fraction at a range of 11,000 n. miles. It should be emphasized that although considerable analysis has been performed on this aircraft, to date there are no experimental data available on this configuration.

Distributed Load Aircraft.- The favorable effect of increased size on aircraft productivity is well known and is illustrated by the outstanding efficiency of the current wide-body jets. Large size also reduces runway congestion. With future aircraft seeking continued improvements in efficiency, it is natural to consider very large aircraft types. There are interesting trends, however, when considering increases in size. One stems from the familiar square-cube law for scaled aircraft, which leads to the result that stress tends to increase as the linear dimensions. Figure 13, adapted from unpublished work of T. A. Toll of NASA Langley Research Center shows the rapid decrease in payload fraction for a 500,000-pound aircraft scaled up in all dimensions (constant geometry aircraft) to 2-1/2 million pounds. The parameters held constant in figure 13 include cruise Mach number, range, thrust-to-weight ratio at take-off, wing loading, wing geometry, and fuselage fineness ratio. For this simplified analysis, a fivefold increase in size results in a 30-percent reduction in payload fraction. In addition, the fuselage volume exceeds volume required and the payload density decreases by a factor of 4.

The obvious answer to the inefficiency of scaled constant geometry aircraft is to size the total volume to meet the payload requirements. This is the case for the constant payload density curve in figure 13. Payload density is defined here as payload weight divided by usable aircraft volume. It is assumed that available volume in either the fuselage or the wing can be used to contain payload. As gross weight increases, an increasing fraction of the payload can be carried in the wing, with the result that the fuselage decreases in size as indicated schematically in the figure and finally vanishes at a gross weight of about 4.5 million pounds for a payload density of 20 pounds per cubic foot.

The payload fractions of these aircraft remain relatively constant. These higher efficiencies over scaled conventional aircraft are due to decreased fuselage size and distributed loading. In the extreme of an all-wing aircraft, the payload is distributed along the wing span and the weight is largely balanced by the local lift. Structural efficiency is improved by at least 20 percent as a result of reduced bending moments (the square-cube law no longer applies). The aerodynamic advantage of an all-wing aircraft is 25 to 30 percent due to the elimination of fuselage and tail drag and a decrease in the friction drag of the wing, which is operating at a higher Reynolds number. Distributed loading can also remove the structural restriction on aspect ratio, and an all-wing aircraft may be better suited to LFC - both leading to further increases in aerodynamic efficiency.

The analysis in figure 13 is for a constant wing loading of 140 pounds per square foot. This is a maximum set by landing and take-off conditions. If wing loading is reduced to 80 pounds per square foot, the aircraft having a payload density of 20 pounds per cubic foot becomes an all-wing aircraft at a gross weight less than 3 million pounds - a size of more practical interest. The practicality of the all-wing aircraft is also a strong function of payload density. The high payload density of liquid natural gas, for example, favors the all-wing aircraft. The lower density payloads do not, because of the poorer volumetric efficiency of a wing compared to a fuselage. This is illustrated in figure 13, where for a payload density of 5 pounds per cubic foot, some fuselage volume continues to be necessary well beyond the limits of the chart.

It is obvious that the trends with aircraft size discussed above are oversimplified. However, the discussion does highlight the need for careful attention to structural weight in the design of very large airplanes and the importance of advanced materials. It appears that distributed loading is very promising in reducing structural weight and increasing aerodynamic efficiency. Because of this promise, NASA has been studying the application of distributed loading to very large freighters for the past 4 years. These studies were conducted both in-house and under contract with industry and emphasized economics.

Figure 14 presents an evaluation of several advanced design concepts studied (Ref. 7) with DOC's normalized to a conventional B-747-type freighter. Assumptions made in the figure include use of intermodal containers, 12 hours per day utilization, 85-percent load factor, container payload density of 10 pounds per cubic foot, and a fuel price of 37¢ per gallon. Several points can be made. First, a fuselage-loaded, advanced technology freighter shows a 30-percent savings in DOC at a gross weight of about 1 million pounds. Second, distributed loading in the form of a twin-fuselage design reduces DOC some 40 percent at a gross weight of about 1.5 million pounds. One factor in this low DOC was the assumption that the existing fuselage from the 747 could be used, resulting in low initial costs. Further work is warranted on twin-fuselage designs. Third, an unswept all-wing aircraft or spanloader with a gross weight of 1.67 million pounds is roughly comparable with the low-cost twin-fuselage design. The spanloader was handicapped at this low gross weight because of the low-aspect-ratio, thick wing dictated by cargo container requirements and a low drag-rise Mach number (M = 0.68). Fourth, the very large, swept-wing spanloader looks very attractive with DOC savings of over 50 percent. The large gross weight of 2.83 million pounds allows higher aspect ratio, a thinner wing, and a higher cruise Mach number (M = 0.8) for improved productivity. The design and construction of an all-wing aircraft also appear to be simpler with fewer parts and lower initial cost. For the gross weights studied, no minimum in DOC was reached for the spanloaders. A 3-million pound swept-wing spanloader studied by The Boeing Company is compared with a B-747-F in figure 15. The wing span of the spanloader is over 2-1/2 times that of the B-747-F and the ratio of payload-to-gross weight approaches 0.5, compared with 0.32 for the B-747-F.

These NASA studies indicate that the distributed load concept is promising for very large aircraft but also highlight the near void in wind-tunnel data needed in design tradeoffs. Research work in very thick airfoils has now started. Other areas requiring research include wing-tip devices, aeroelasticity, propulsion integration, integrated controls, and handling qualities. The spanloader in figure 15 employs 24 landing gears. An air cushion landing gear has obvious attraction here.

Aerial Relay Transportation System.- While the cargo market is expanding rapidly and may support the need for 3-million pound aircraft, it is unlikely that very large aircraft will have a sufficient passenger market because of schedule frequency demands by the customer. An interesting concept for passenger transportation, however, has been proposed by A. C. Kyser of NASA Langley Research Center. It is called the aerial relay transportation system (ARTS), and it is illustrated in figure 16. The system consists of large, continuously flying, multiple-module "liners" that operate in conjunction with smaller short-range "feeders." The liners would operate along a network of prescribed paths, never landing except for periodic maintenance or emergencies. The large liners are configured as strings of identical tip-coupled modules, in order to allow emergency landings at existing airports. The feeder aircraft would carry passengers, cargo, fuel, and replacement crews from the ground to the liner, and back. The transfer of payload between feeder and liner takes place at cruise altitude and speed, as the liner proceeds along its route. Since a given liner carries passengers between a variety of origins and destinations, it serves as a flying airport. The single liner route shown in figure 16 is suggested as an initial route. Networks covering the entire United States have been studied, and the concept could readily be extended to foreign travel. The time-based metering concept discussed earlier in this paper becomes a must for ARTS.

The possible benefits of such a transportation system are numerous. They include (1) relief of airport congestion, by serving local airports directly; (2) outstanding aircraft efficiency; (3) improved passenger comfort; and (4) reduced door-to-door trip time. Very limited study to date indicates possible gains in all these areas, but extensive research will be required to confirm these benefits and preclude serious obstacles. To illustrate the possibilities in one area - that of aircraft efficiency - it should be pointed out that the liner can be specialized for cruise while the feeder is specialized for take-off, climb, and landing. The liner takes advantage of distributed loading and LFC, both of which are enhanced by continuous flight. Tip coupling of the span-loaded modules makes possible a very large span, which gives high aerodynamic efficiency, together with very low structural weight. The possible fuel efficiency of ARTS is shown in figure 17. Calculations indicate that a five-module liner with LFC might have an L/D of 100, resulting in a fuel efficiency of nearly 700 seat miles per gallon. If the fuel used by the conventional feeder (L/D = 18) is added to that used by the liner, the combined system efficiency, as a function of trip length, is as shown. Although the magnitude of these numbers is debatable, the possibilities are indeed impressive and ARTS deserves further study.

SPEED

Today's emphasis on energy and aircraft efficiency tends to totally eclipse the benefit that aviation offers over other forms of transportation - that of speed. It was reduced trip time that allowed air transportation to supplant the railroads and ships in hauling passengers. There is ample evidence that travel between countries is directly proportional to the speed of that travel. The world really does shrink as travel time decreases, and with this shrinkage comes a far greater intermingling of people and a greater hope for world trade and peace. Figure 18 illustrates the opportunities for reduced trip time when considering $M = 2.7$ supersonic transports (SST) and $M = 6$ hypersonic transports (HST). The savings are most dramatic, of course, for the longer routes. Flight times from Los Angeles to Sidney are reduced by a factor of nearly 3 for the SST and over 5 for the HST. The capability to travel nearly anywhere in the world in under 3 hours is an exciting goal.

Another benefit of speed that strongly affects economics is productivity. Since 1960, U.S. scheduled airline revenue passenger miles has increased by a factor of more than 4 while the number of aircraft has increased only about 20 percent. Half of this increase in productivity was due to size and the other half to increased speed. The technical opportunities in size were discussed in the previous section; this section will treat technical developments in supersonic and hypersonic transports.

Supersonic Transports

With nine supersonic Concordes now operating in scheduled service throughout much of the world, the SST is hardly a far-term "frontier" vehicle which is the subject of this paper. However, despite the fact that the Concorde is a technically superb machine, it represents 1960 technology and its economic and environmental viability has yet to be established in today's market. Since 1972, NASA has been engaged in an R&D program to expand our technology base and find solutions to the problems that led to the cancellation of the U.S. SST program in 1971. Essentially, these factors were poor economics, noise, and pollution. Impressive progress has been made in identifying solutions to these problems. Although it will not be discussed further here, the problem of pollution seems to be fairly well resolved. Studies have shown that there is minimal ozone reduction from operations of advanced supersonic transports. Indeed, they may even increase the ozone level. The discussion to follow will address some significant advances in propulsion, aerodynamics, and noise reduction.

Variable-cycle engines can vary their airflow capacity to match the wide variation in requirements with Mach number. At cruise, they act like a turbojet and, during subsonic operation and at take-off, they act like a turbofan. As shown in figure 19, this results in significant improvements over the GE 4/J6 turbojet, which was to be used with the 1971 U.S. SST. Engine weight is down by 25 percent and, most significantly, subsonic specific fuel consumption (SFC) is down by as much as 35 percent. Supersonic SFC is also reduced because of reduced cooling flows and improved component efficiencies.

Figure 20 shows the advantages of aerodynamic blending on L/D. Although this NASA technology has been available since the mid-1960's, industry rejected the approach because of difficult structural design and emergency egress problems. Recent emphasis on efficiency, however, has caused the manufacturers to take another look and it now appears that the concept is feasible. Wing-body blending, along with some slight modifications in wing planform improve L/D some 20-25 percent over the 1971 U.S. SST configuration.

A real technical breakthrough in noise reduction appears possible with the so-called coannular nozzle shown in figure 21. Results from static tests of variable-cycle nozzle models have shown that an inherent reduction in jet noise occurs when a relatively hot, high-velocity jet stream surrounds a cooler, lower velocity jet core. Forward velocity model tests have also been conducted in the wind tunnel at speeds of 230 miles per hour. The results in figure 21 shown an 8-dB reduction in noise relative to single-flow nozzles in static tests and a 7-dB reduction at 230 miles per hour (Ref. 8). It remains now to verify this reduction in forward flight at larger scale. Such tests will be conducted in the near future.

Another very promising development in noise reduction is the use of advanced operational procedures. In contrast to a subsonic jet which has the engine, inlet, and nozzle all fixed, the supersonic jet has a significant degree of variability. If this variability is properly utilized, important noise reductions may occur (fig. 21). For example, during take-off, if an auto-throttle procedure is used whereby the throttle is increased about 15 percent from brake release until the altitude where the maximum sideline noise normally occurs, the aircraft can reach that condition at a higher velocity and/or altitude with no increase in sideline noise. If the flaps are also automated, the combination of reduced flap settings and increased velocity results in an increase of L/D from 7 to more than 10. This improved aerodynamic efficiency allows a throttle cutback that could result in noise reductions of 5 to 7 dB over the community (Ref. 9). During landing, the use of decelerating approaches and increased glide slopes could reduce noise by 4 or 5 dB. The most important point here is that a supersonic transport does not have to and should not take off and land with the same rules as its subsonic counterpart.

The progress in noise reduction described above is extremely encouraging and probably will allow the design of a supersonic transport that will have noise levels equal to or less than FAR-36 noise standards. Possibilities for range improvement as a result of the advances in propulsion and aerodynamics shown in figures 19 and 20 as well as in the other disciplines of structures and controls, are equally exciting. A 2,500-n. mi. range increase over the 1971 U.S. SST may be possible for an all-supersonic mission (fig. 22). The improved subsonic SFC of the variable-cycle engine essentially removes the penalty for subsonic legs experienced by the 1971 design. This estimated performance would greatly improve economics by permitting a capability to serve some of the important trans-Pacific routes as well as efficient operation on the shorter range, high-density North Atlantic routes. This is the good news. The bad news is that the existing NASA R&D program to develop these technologies falls far short of a near-term technology readiness date. With the present level of effort, the U.S. supersonic transport is indeed a far-term future vehicle.

Hypersonic Transports

The ultimate step in long-range, fast transportation within the atmosphere is probably the HST with a cruise capability of $M = 6$ to 8. Little decrease in block times is obtained above $M = 8$. The HST would cruise at very high altitudes (greater than 100,000 ft) and offer the potential of low sonic-boom levels (less than 1 lb per sq ft), possibly acceptable for overland operation. It is obvious that the HST requires significant advances in hypersonic technology. The key areas shown in figure 23 include the development of hypersonic air-breathing propulsion systems, long-life structures that will sustain the 1,500° F environment, and efficient aerodynamic configurations intimately integrated with the propulsion system. All these areas are receiving research attention at the NASA Langley Research Center. Particular emphasis is on the pacing propulsion system.

It has been recognized since the early 1960's that a hydrogen-fueled supersonic combustion ramjet (scramjet) is the only realistic propulsion choice for vehicles cruising at $M = 6.0$ or above. The performance of hydrogen-fueled scramjets at $M = 7$ is comparable with that of JP-fueled turbojets at $M = 3$. Figure 24 shows an advanced scramjet concept that has been under development at Langley since 1970. It is highly integrated with the airframe - the vehicle forebody acting as a precompression surface for the inlet and the afterbody acting as the nozzle. Three generations of inlet improvements have been incorporated into the fixed-geometry inlet, which has excellent starting, mass-capture, and pressure-recovery characteristics over the range $M = 3$ to 8. Direct-connect tests of combustor components have verified the concept of swept fuel-injection struts using a mix of normal and parallel fuel injection to control heat release. The design minimizes combustor length, wetted area, and thus, cooling requirements. A complete subscale, boilerplate-type single-engine module is presently undergoing tests in the Langley Mach 7 scramjet test facility shown in figure 25. Performance data should be available later this year on the performance of the inlet and combuster. Off-design tests are also underway at $M = 4$. Since the scramjet cannot operate at low speeds, some form of take-off and acceleration propulsion system such as the variable-cycle engine described earlier must be used. The integration of multiple propulsion systems will be challenging.

The hydrogen fuel is used to cool the scramjet structure. Studies indicate that there may be sufficient heat sink in the hydrogen fuel to cool both the engine structure and the airframe. Figure 26 shows the potential of cooling a shielded aluminum airframe to speeds of at least $M = 8$, and an unshielded advanced boron-aluminum airframe to nearly $M = 7$. Actively cooled structures may be the only method of achieving the 50,000-hour structural life required for civil transports. Cooled structures are also extremely attractive for airline operation because they reduce maintenance, inspection, and aircraft turnaround time.

The development of an HST is indeed challenging, but the scramjet and actively cooled structures offer interesting possibilities for practical hypersonic cruise flight. It may well be that the hypersonic vehicle will first see application with the military. Without military interest and support, the HST is well into the 21st Century.

CONCLUDING REMARKS

In concluding this paper, it is appropriate to consider the question of alternate fuels. The supply of oil-derived fuel available to aviation in the future will be severely limited and any look at far-term vehicles must include considerations for alternate fuels. Synthetic fuel options include synthetic aviation kerosene (Syn Jet-A) from coal or oil shale, liquid methane (LCH_4) from coal, and liquid hydrogen (LH_2) from coal, nuclear, thermal, or organic energy sources. To date, most aviation systems studies have centered on LH_2. The necessity for LH_2 in the HST has been discussed and hydrogen SST's have also been studied briefly at NASA Langley and under contract. Major emphasis has been on subsonic aircraft, their fuel systems, and airport requirements. Liquid hydrogen appears particularly suited to long range and large size aircraft because of energy and volume requirements. Using the fuel to cool the aircraft surface presents interesting possibilities for achieving laminar flow conditions.

A current study by the Lockheed-California Company under contract to NASA Langley Research Center includes consideration of engines, feed systems, and fuel containment for a 400-passenger 5,500-n. mi. range subsonic aircraft (fig. 27). The results of the study showed that an LH_2 aircraft has an 18-percent lower onboard energy consumption (Btu per seat mile) than a Jet-A fueled aircraft. If LH_2 were derived from coal at an efficiency of 49 percent and Syn Jet-A at 54 percent (Ref. 10), the total energy savings of the LH_2 aircraft would be 9 percent. Distribution of hydrogen from the point of manufacture to airports, however, may pose problems, and the cost of LH_2 from coal is projected to be about 20-percent higher than that of Syn Jet-A from coal (Ref. 10). The projected cost of LCH_4 from coal is about 25-percent less than Syn Jet-A and may provide a very attractive alternative to LH_2. More study is planned on LCH_4 aircraft as well as the safety aspects of both LH_2 and LCH_4 in the air transportation systems.

The most important point to be made here is that the future of air transportation is not dependent either on oil reserves or fossil fuel resources. Very viable options are available to the aircraft designer regardless of the actions taken by the nation in establishing its major energy position. Aviation will not drive that decision. It is the writer's opinion that if the nation turns to coal, Syn Jet-A will become the aviation fuel of the future because of the minimum impact of its introduction. However, when solar or non-fossil energy sources become the standard, LH_2 must and can be very effectively used. This may very well come sooner than we can accurately project today.

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Some conclusions are suggested from the discussions in this paper:

1. Aviation is still very much a growth industry with exciting technological advancements emerging.

2. Growth constraints in the areas of economics, energy, and congestion are very real and require technological assistance in their solutions.

3. Air travel needs improvements in dependability. Delays due to weather and congestion are unacceptable and will continue to increase into the 1990's because of traffic growth.

4. Technical advances in all-weather 4-D navigation and wake vortex attenuation offer promise of increasing the capacity of our existing airports. Upgrading our ATC to allow time-based metering of aircraft is necessary in the far term.

5. The problem of increasing the energy efficiency of aircraft is being worked very hard in all technical disciplines with benefits already appearing on derivative aircraft. In the far term, aerodynamic advances in skin-friction reduction may offer large improvements in efficiency.

6. Very large aircraft are attractive for increased productivity and congestion relief. Their configurations, however, may be radically different from today's aircraft in order to take advantage of distributed loading and LFC. Tip-coupled, all-wing aircraft optimized for cruise offer an interesting far-term concept for extreme efficiency.

7. Improving the speed of air transportation is receiving little interest today because of the energy situation, and this probably will not change until the nation establishes a sound energy policy.

8. Technological improvements have been identified that can greatly increase the performance, economics, and environmental acceptability of supersonic transports. The level of R&D activity, however, is insufficient to establish technical readiness in the near term.

9. The HST, which will cruise at $M = 6$ to 8, offers the promise of travel to most points of interest in the world in less than 3 hours. The HST is truly a frontier vehicle and will require much technical innovation. Developments in scramjet propulsion and active cooling are attractive for attaining practical hypersonic cruise flight.

10. Far-term vehicles must consider the use of alternate fuels. Fortunately, the long-haul vehicle is adaptable to either Syn Jet-A, LCH_4, or LH_2. Liquid hydrogen is a viable choice if the nation decides to pursue a non-fossil energy economy.

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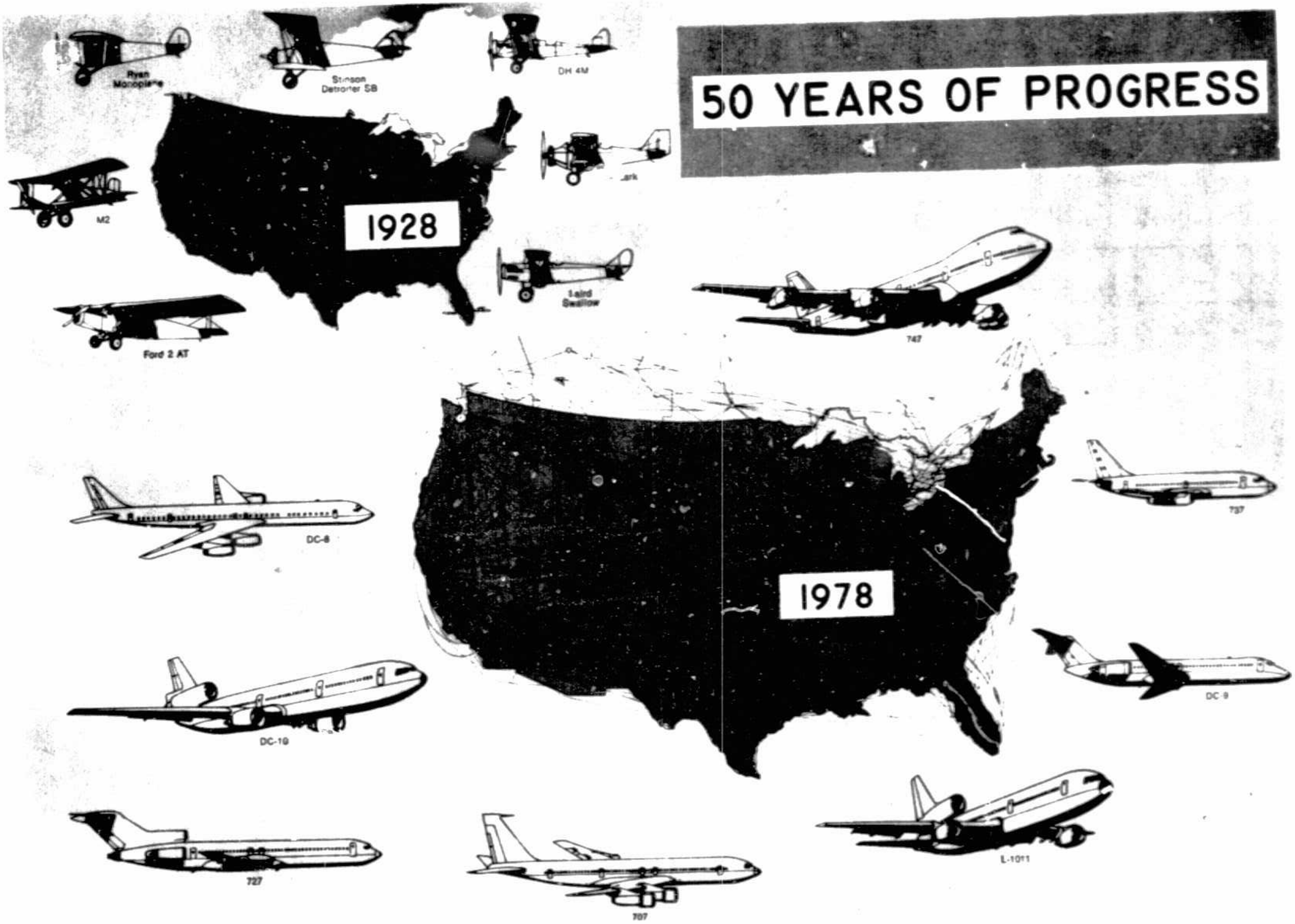

Figure 1. - Fifty years of progress.

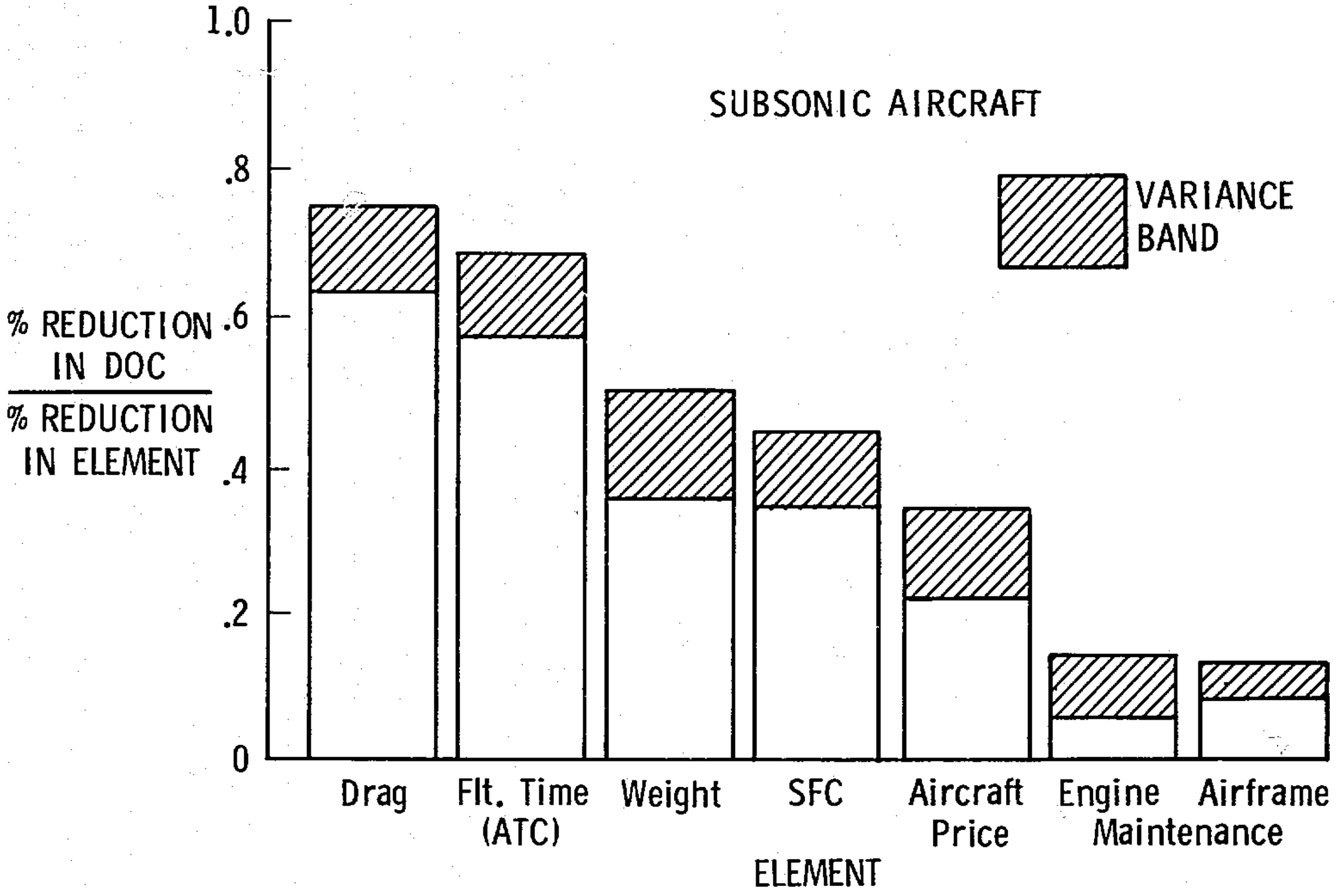

Figure 2. - Effect of technology on direct operating costs.

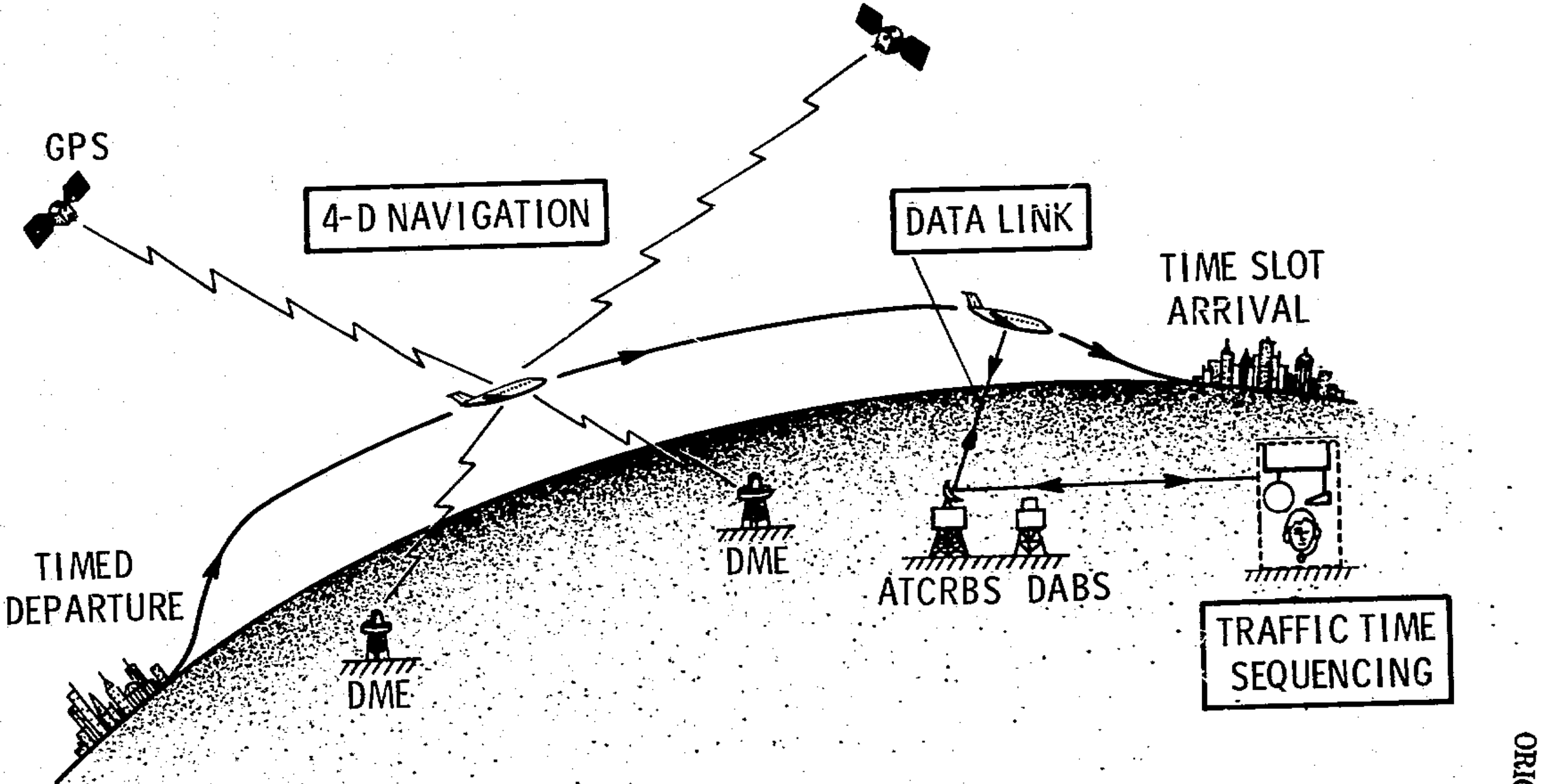

Figure 3. - Time-based metering.

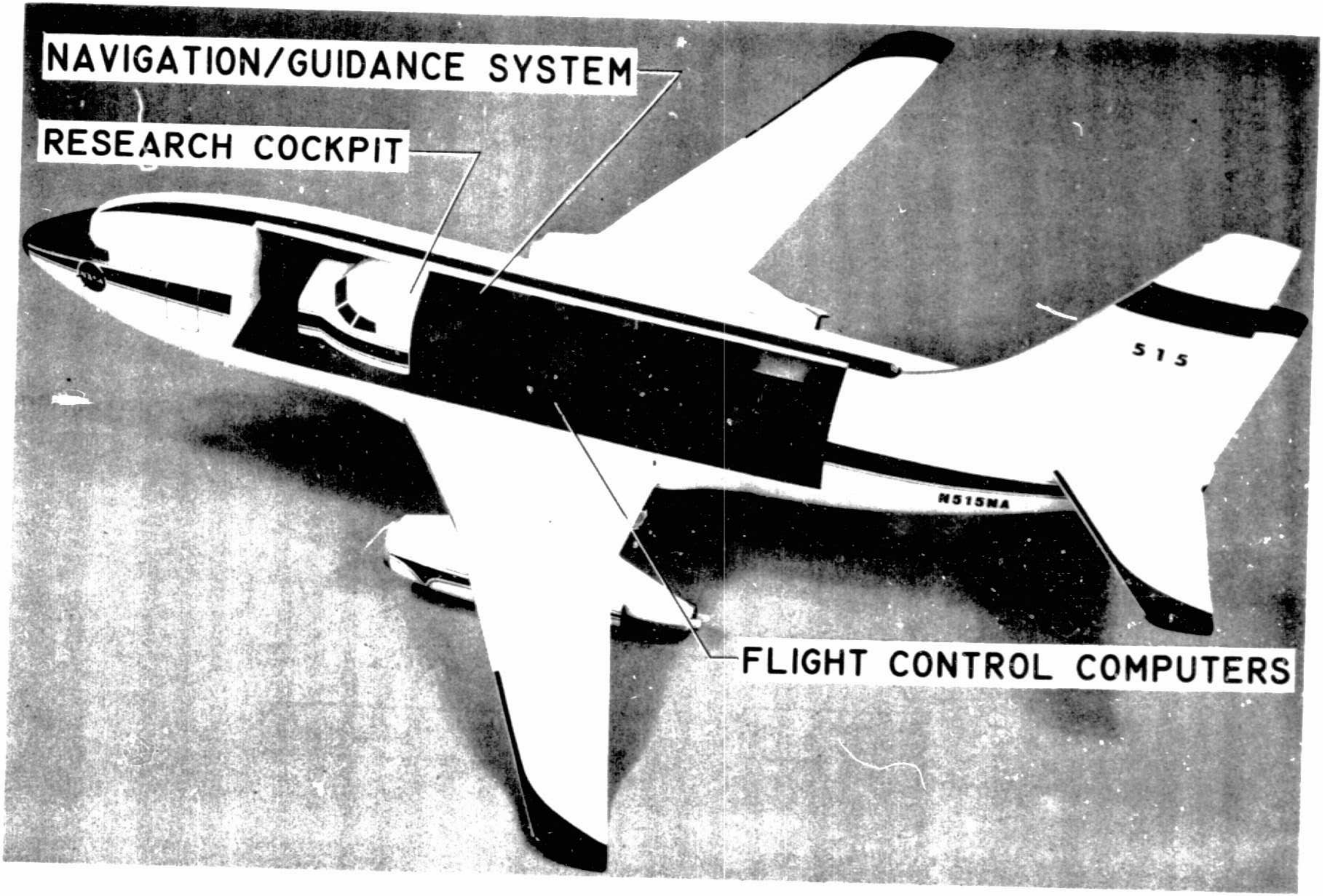

Figure 4. - Terminal-area research aircraft.

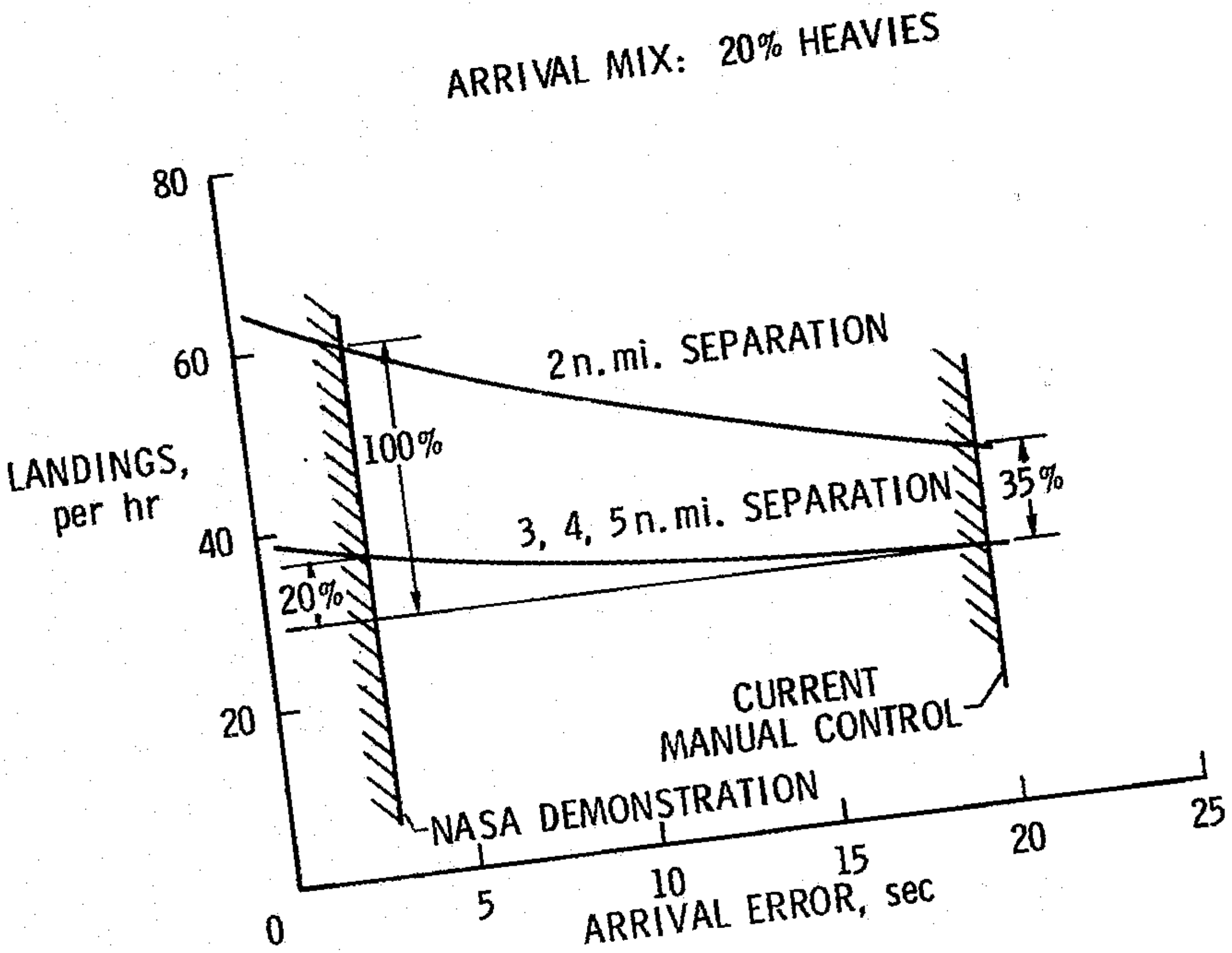

Figure 5. - Improvement in runway capacity.

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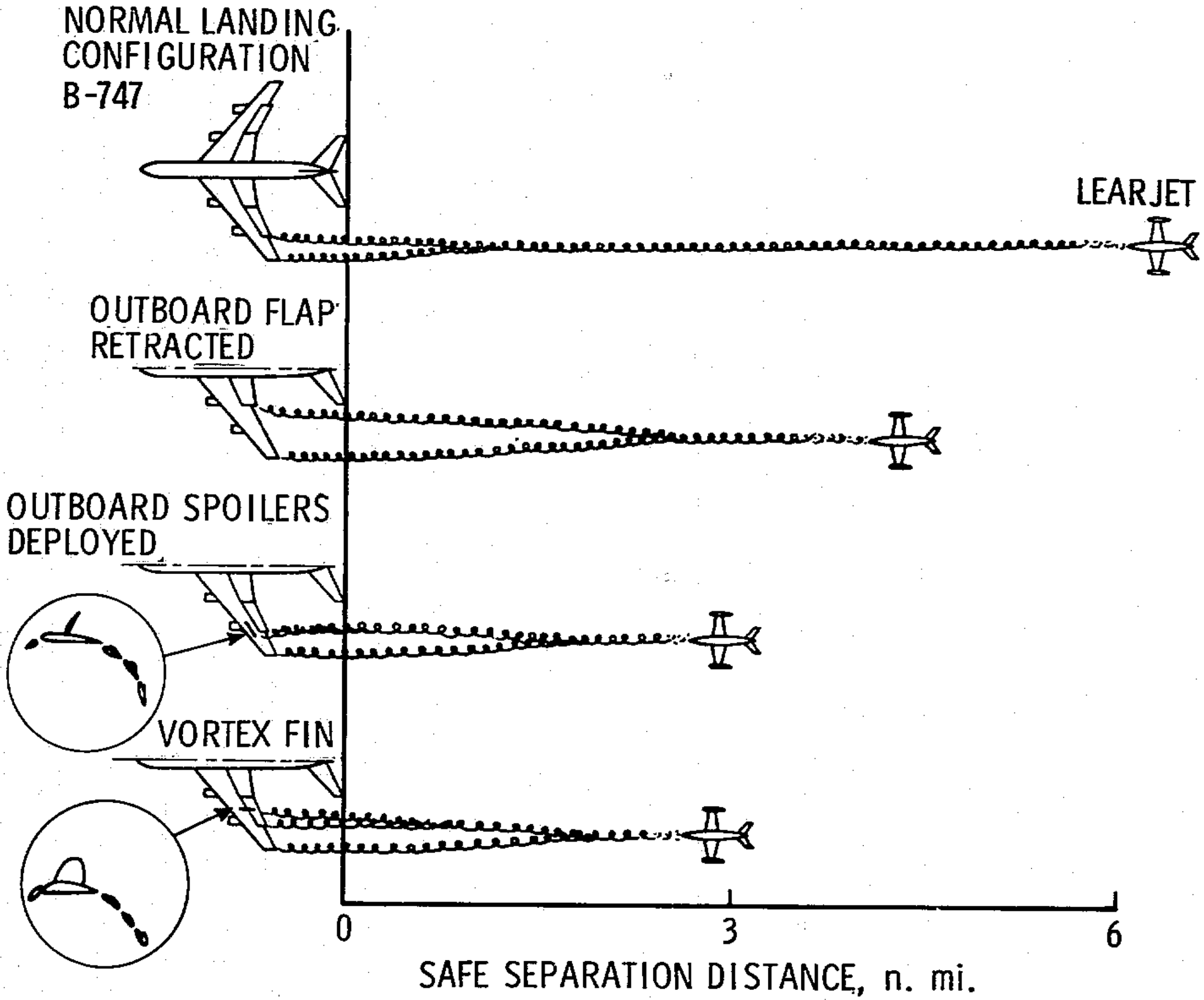


Figure 6. - Wake vortex attenuation research.

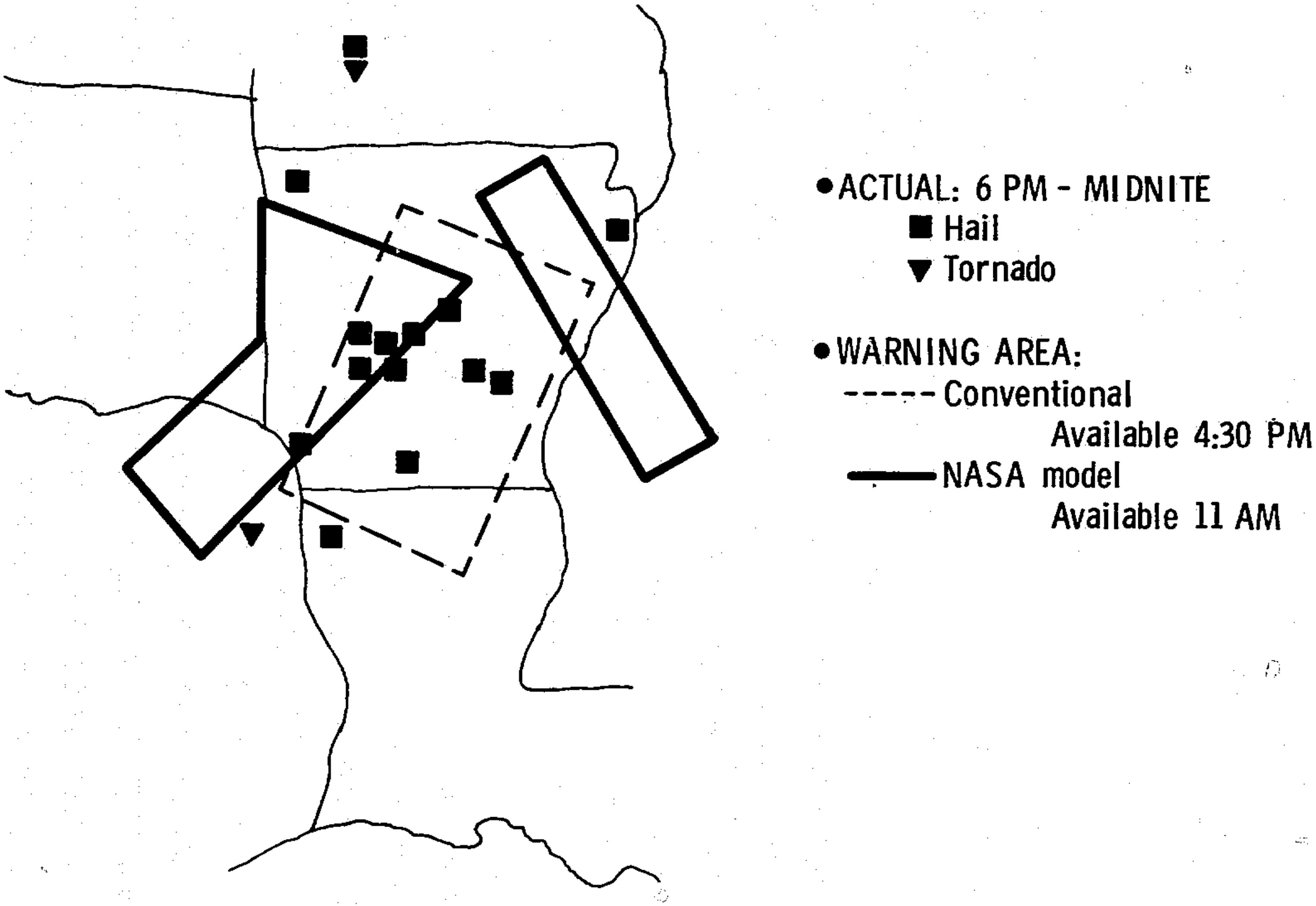


Figure 7. - Progress in severe storm forecasting research.

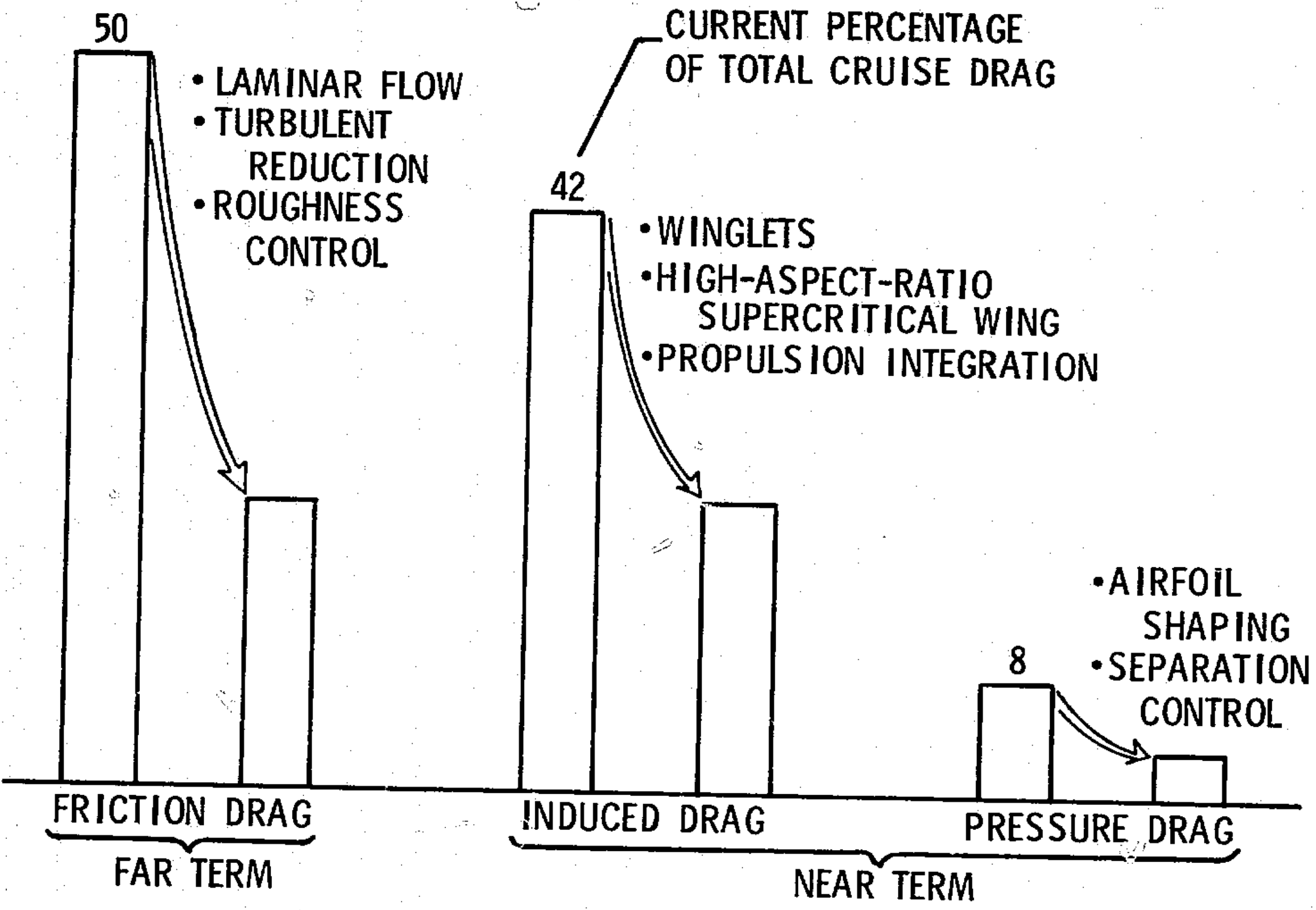


Figure 8. - Opportunities for subsonic drag reduction.

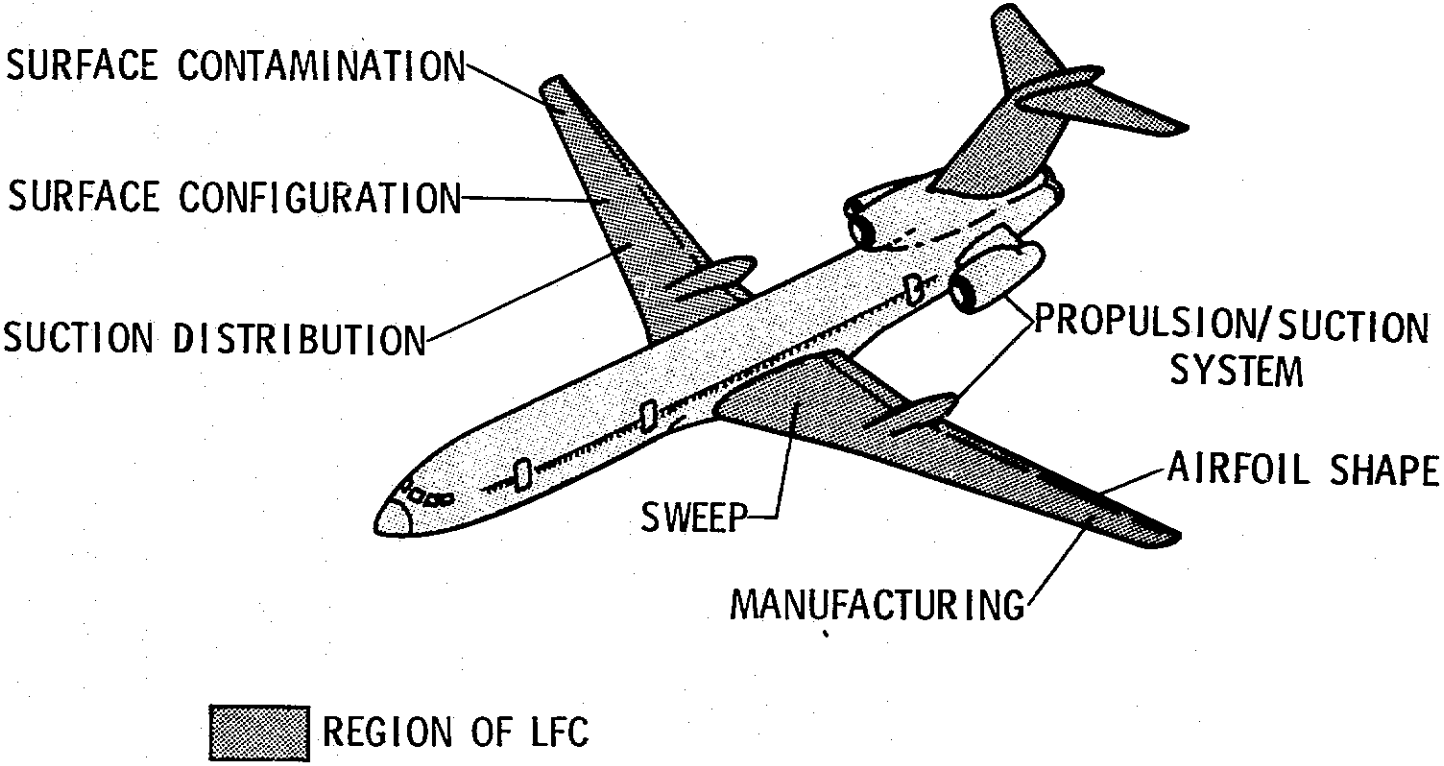
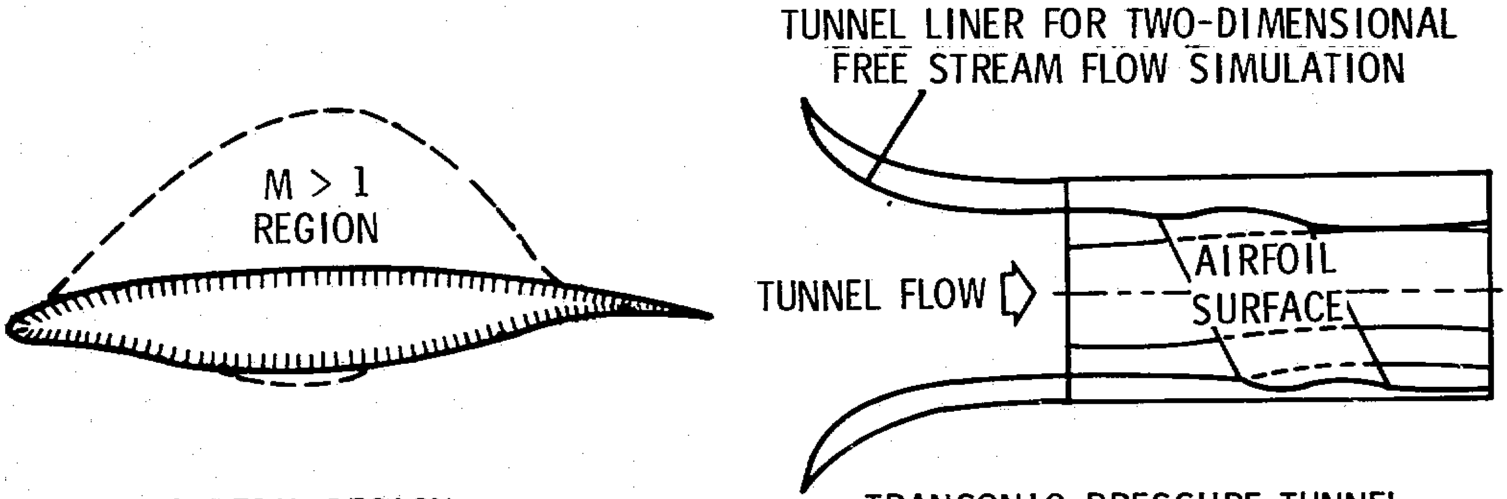


Figure 9. - Key laminar flow control technology.



AIRFOIL DESIGN

TRANSONIC PRESSURE TUNNEL TEST SETUP

Figure 10. - Laminar flow control airfoil wind-tunnel tests.

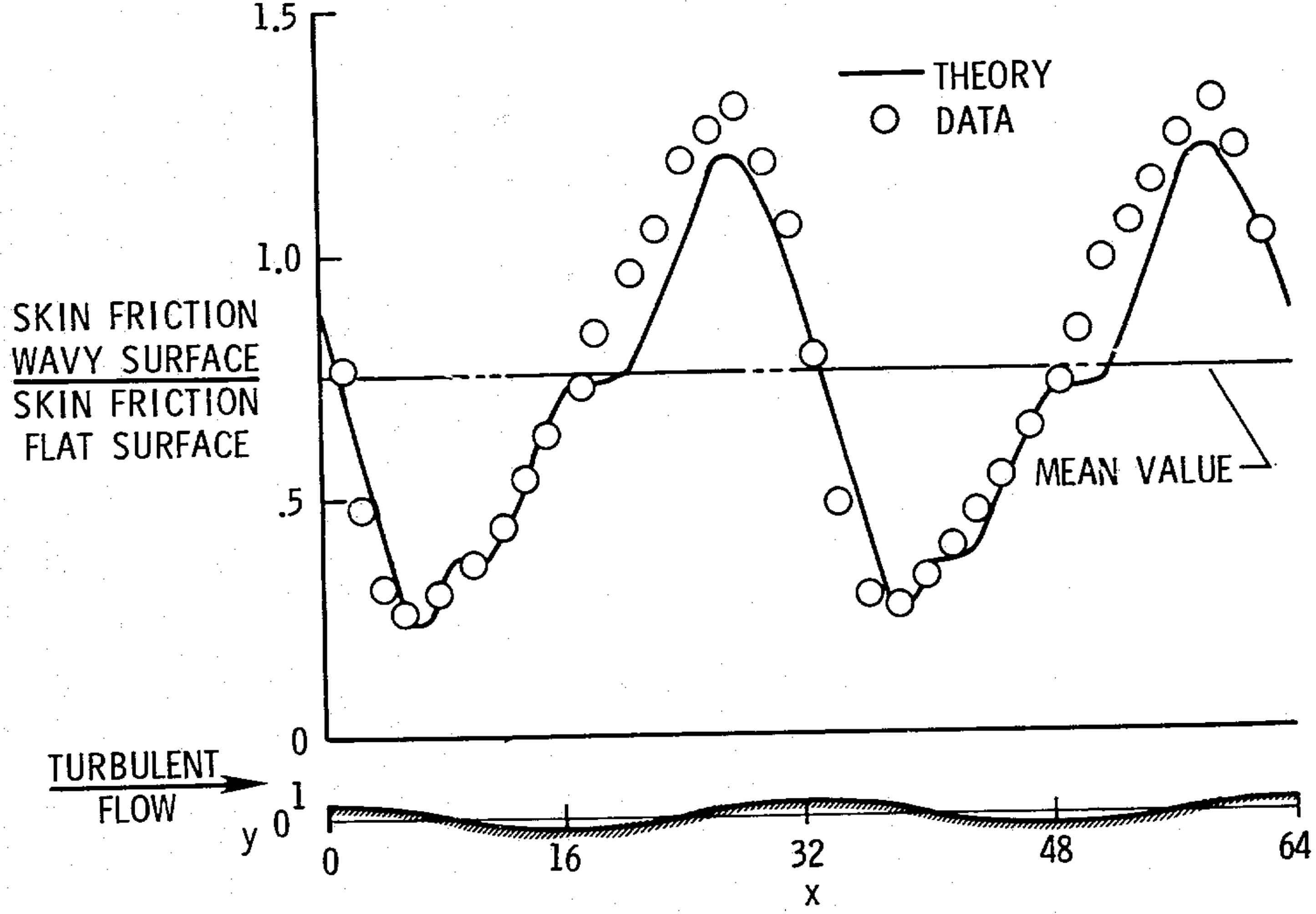


Figure 11. - Turbulent skin-friction reduction over wavy surface.

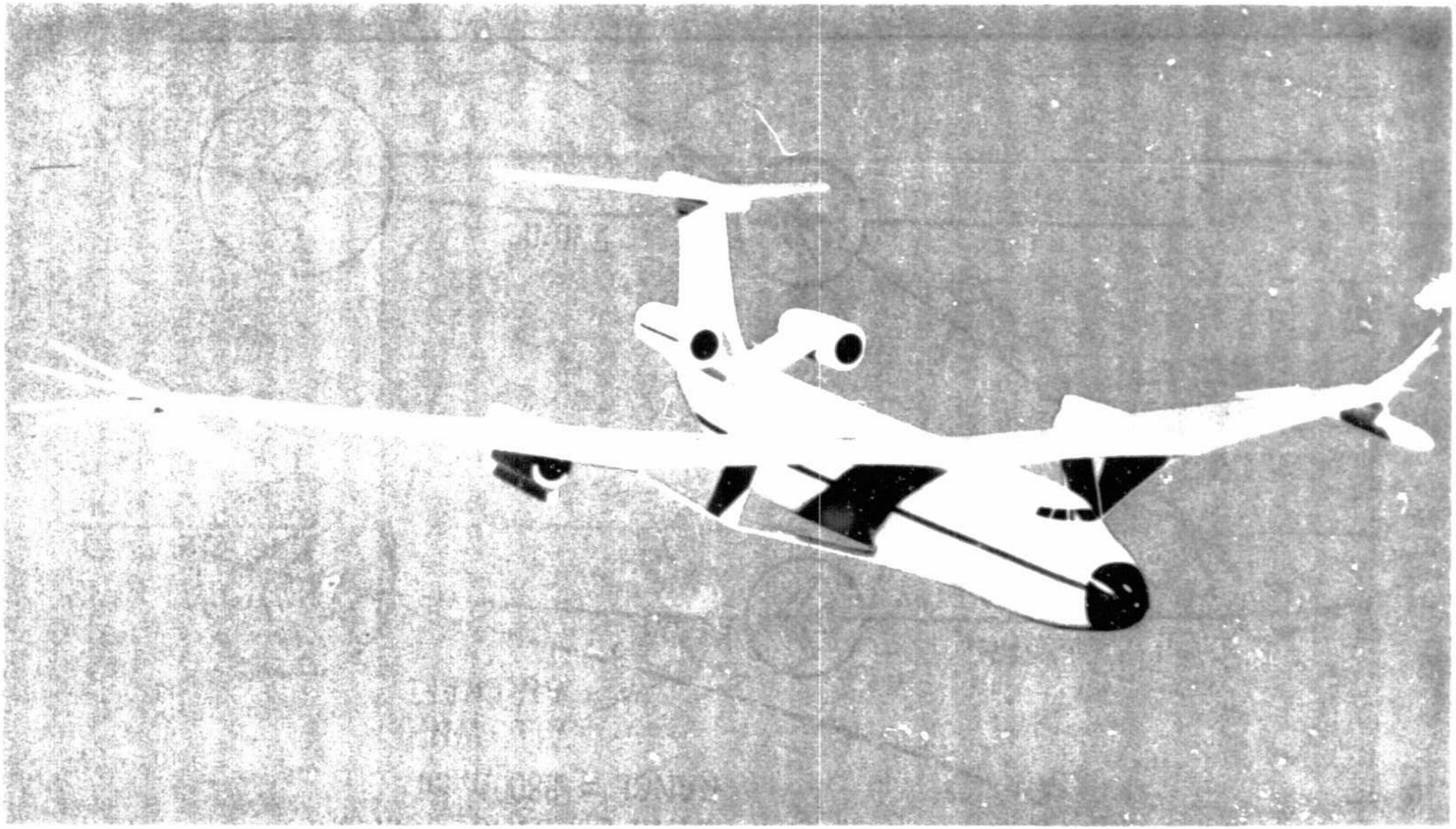


Figure 12. - Long-range laminar flow control airplane.

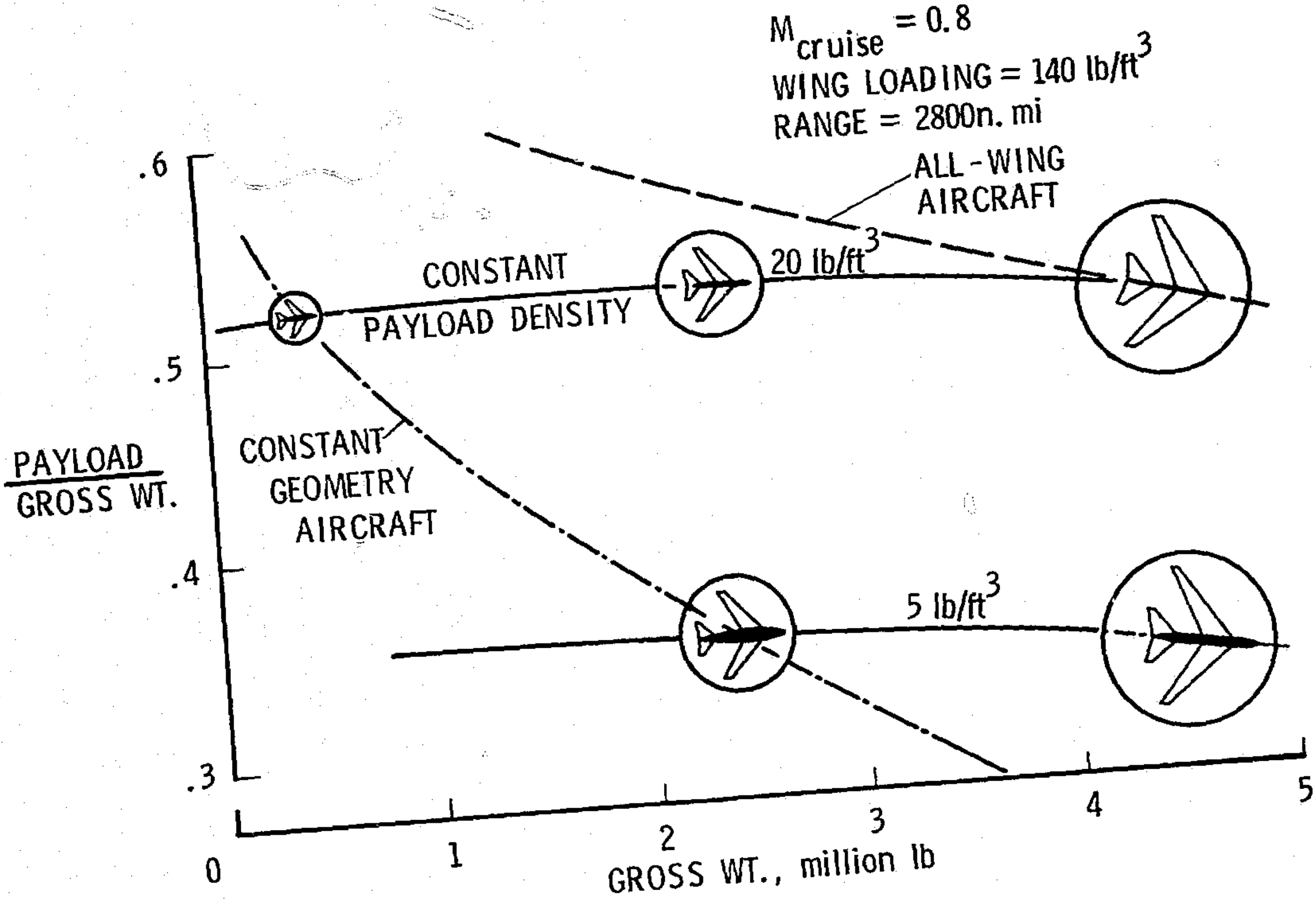


Figure 13. - Aircraft scaling.

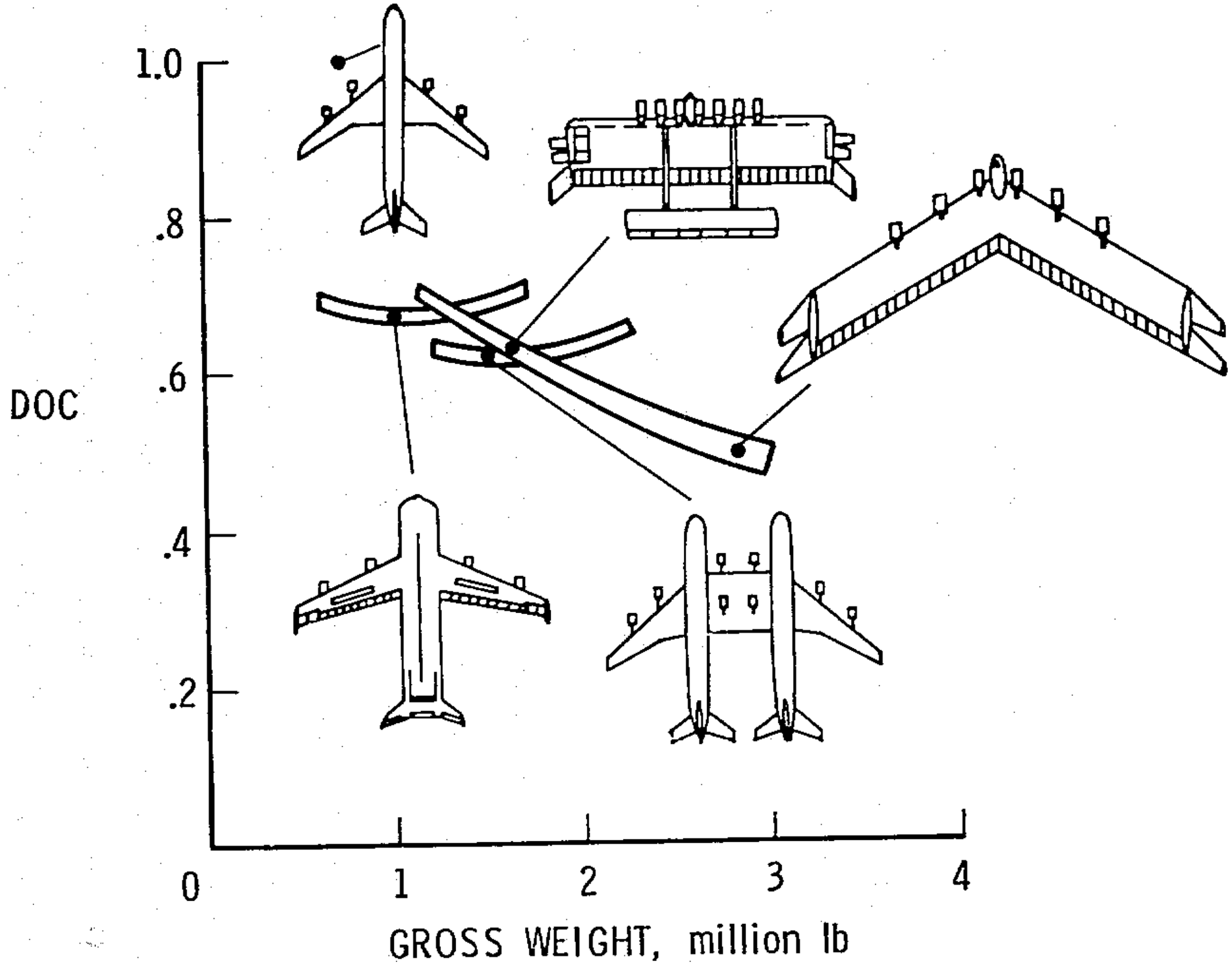


Figure 14. - Economic evaluation of advanced cargo designs.

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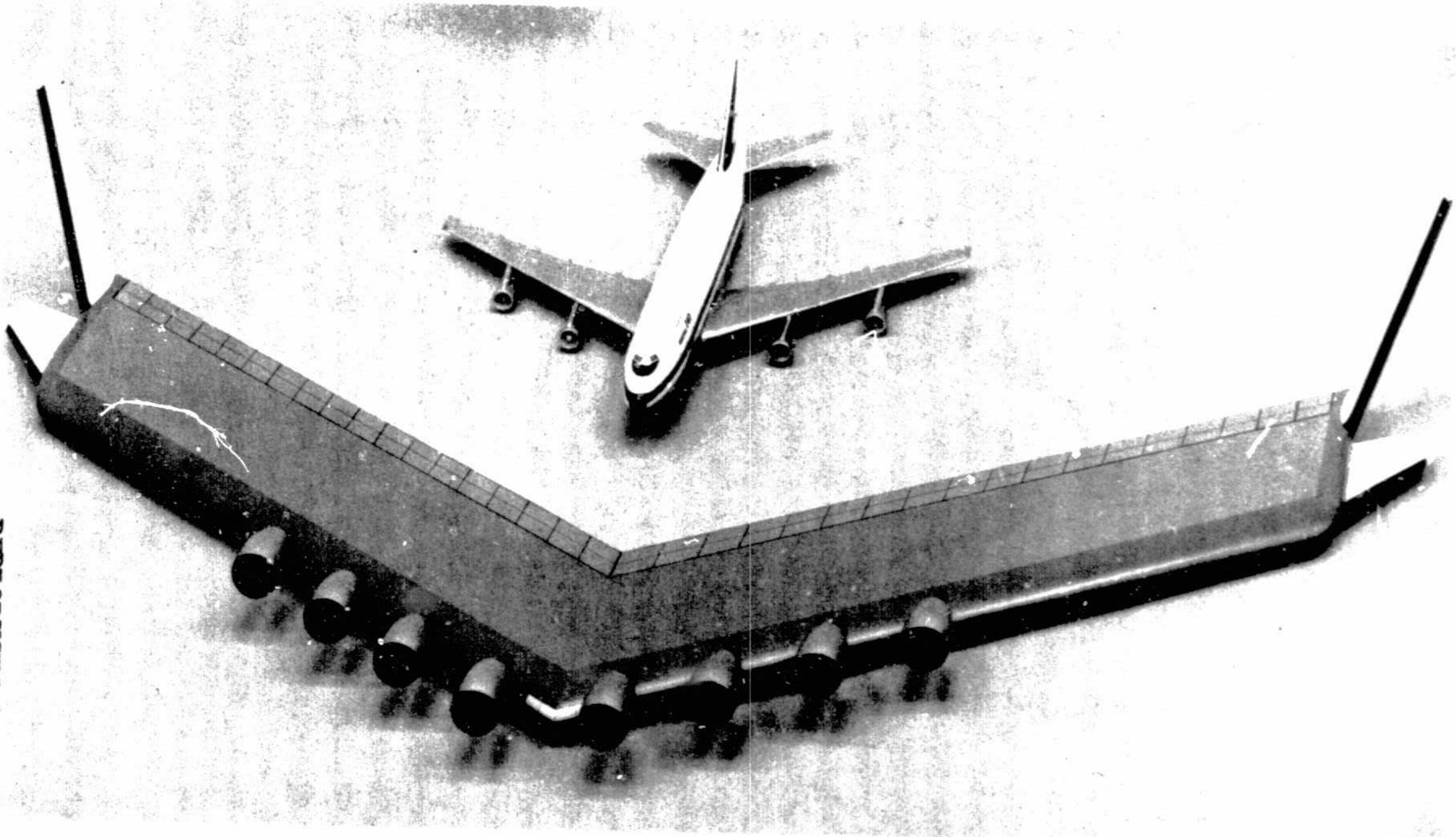


Figure 15. - Distributed load freighter (NASA-Boeing study).

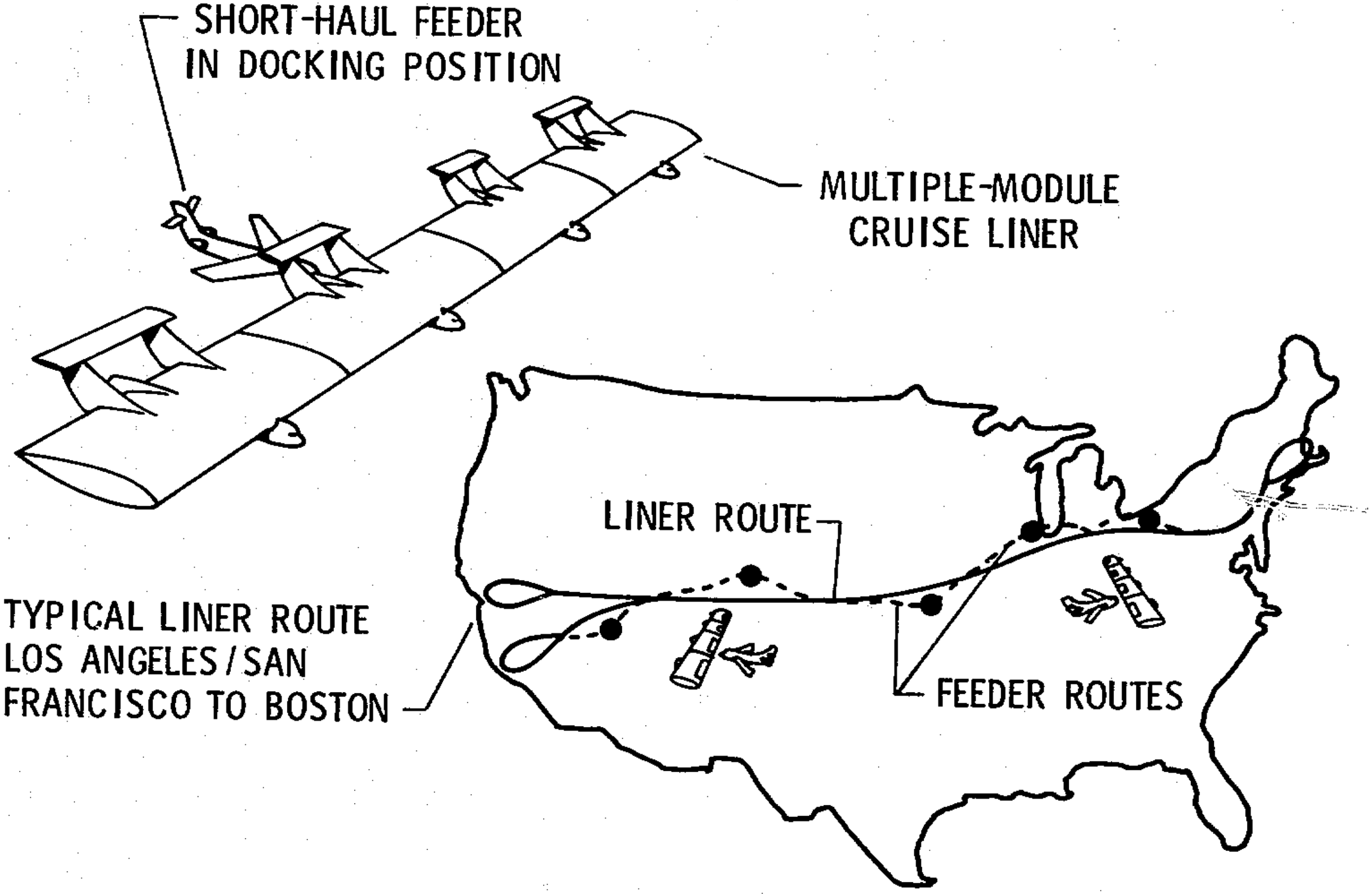


Figure 16. - Aerial relay transportation system concept.

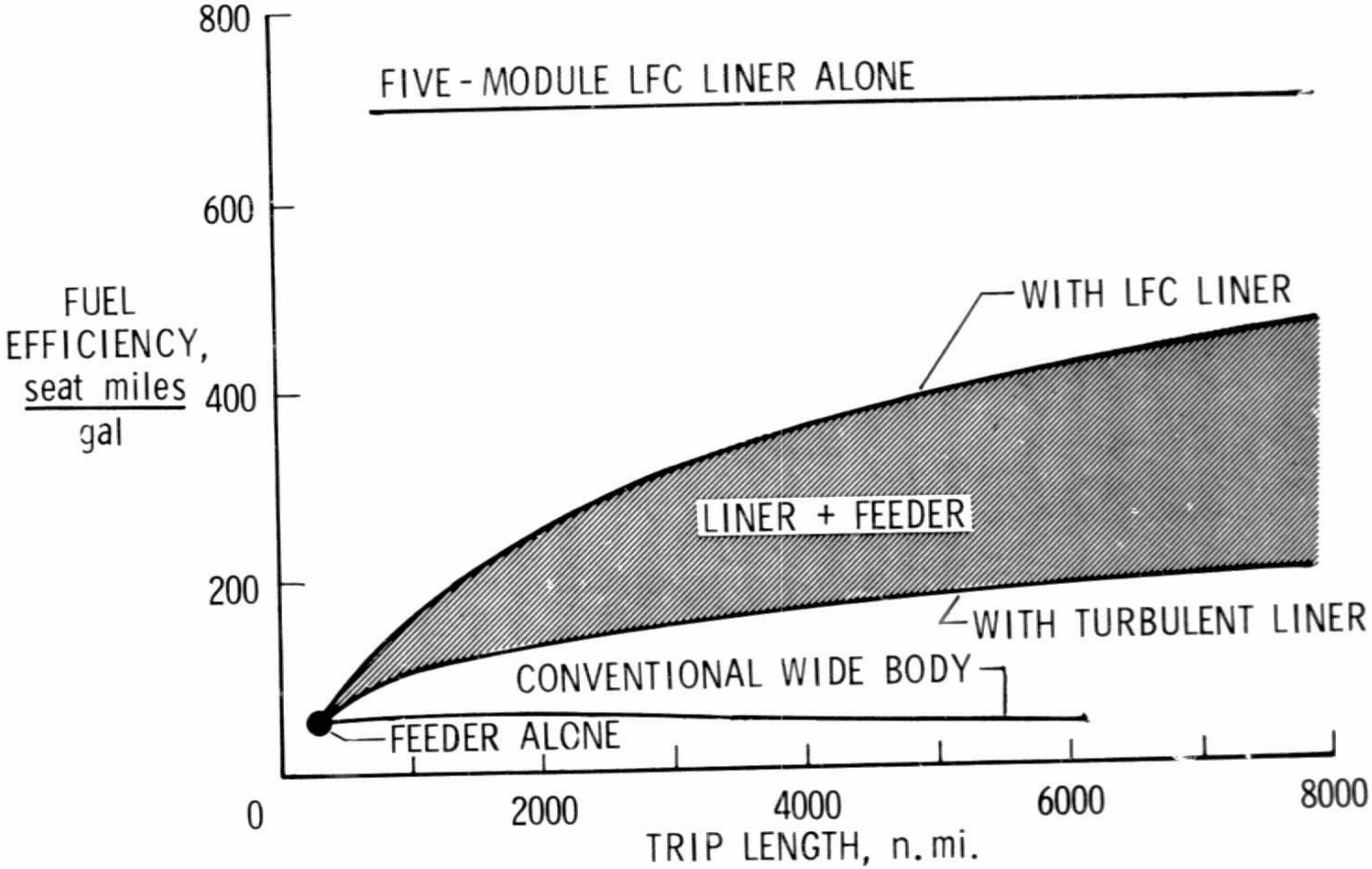


Figure 17. - Potential fuel efficiency for ARTS.

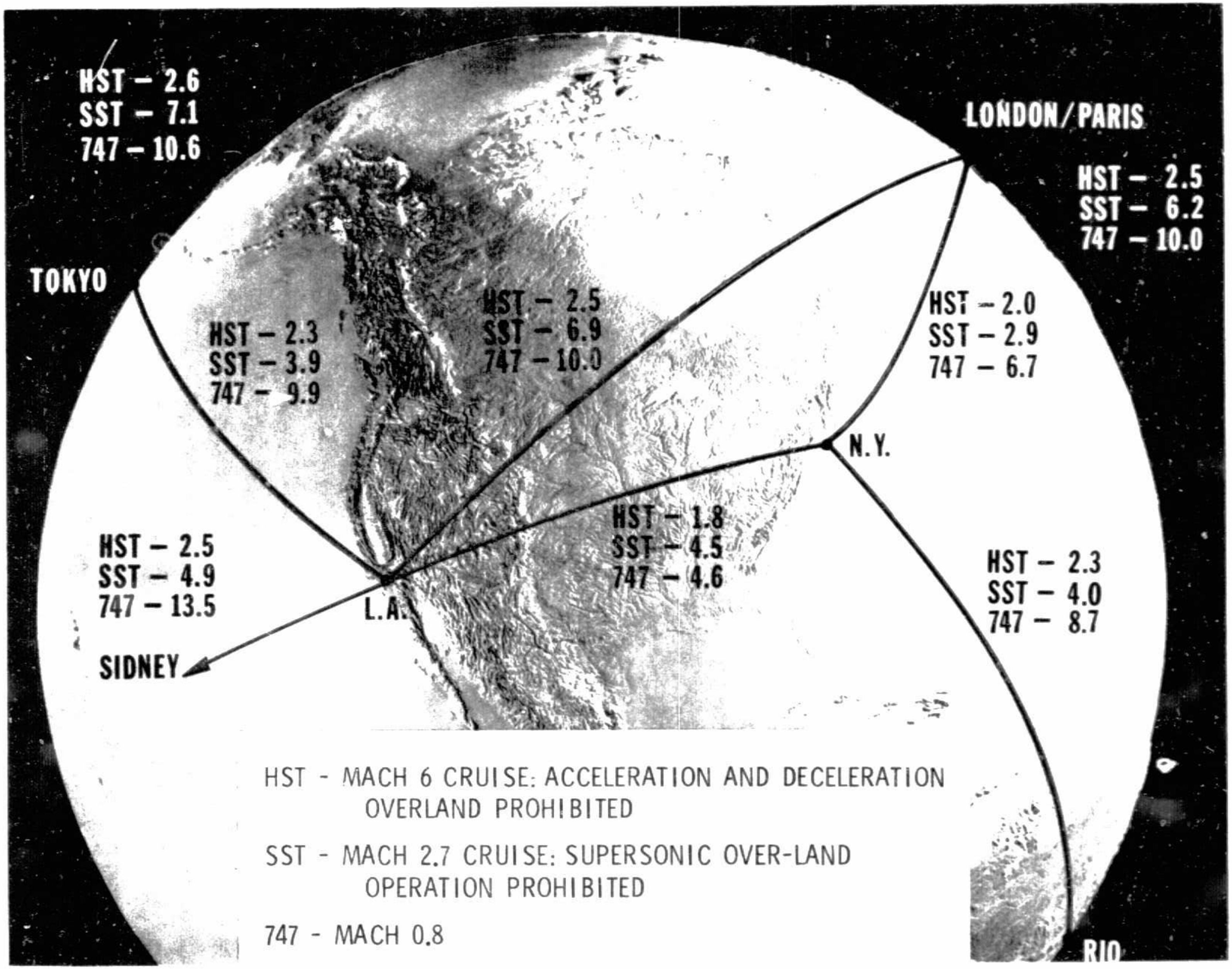


Figure 18. - Transport nonstop trip-time comparison (hours).

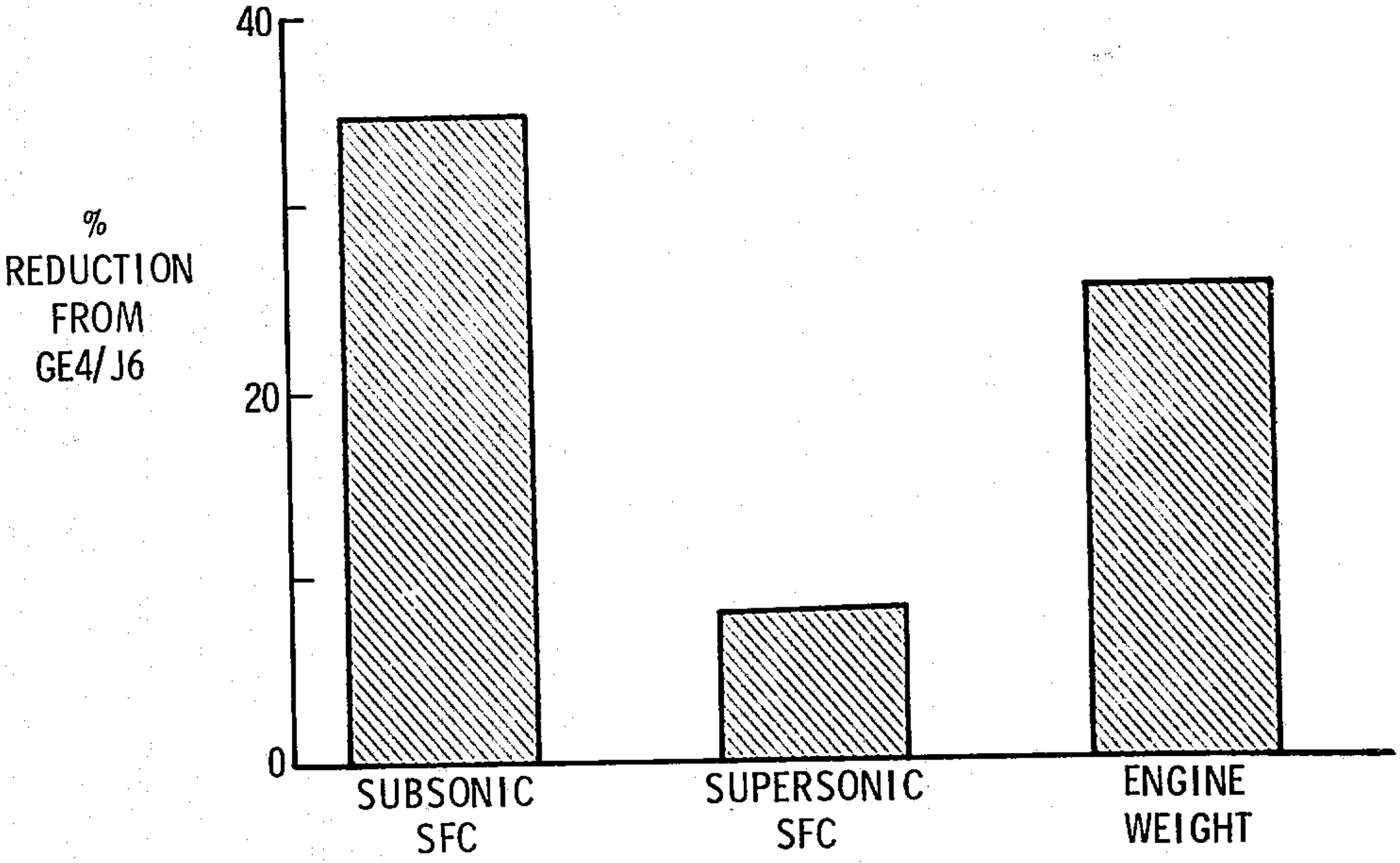


Figure 19. - Improvements with variable-cycle engines.

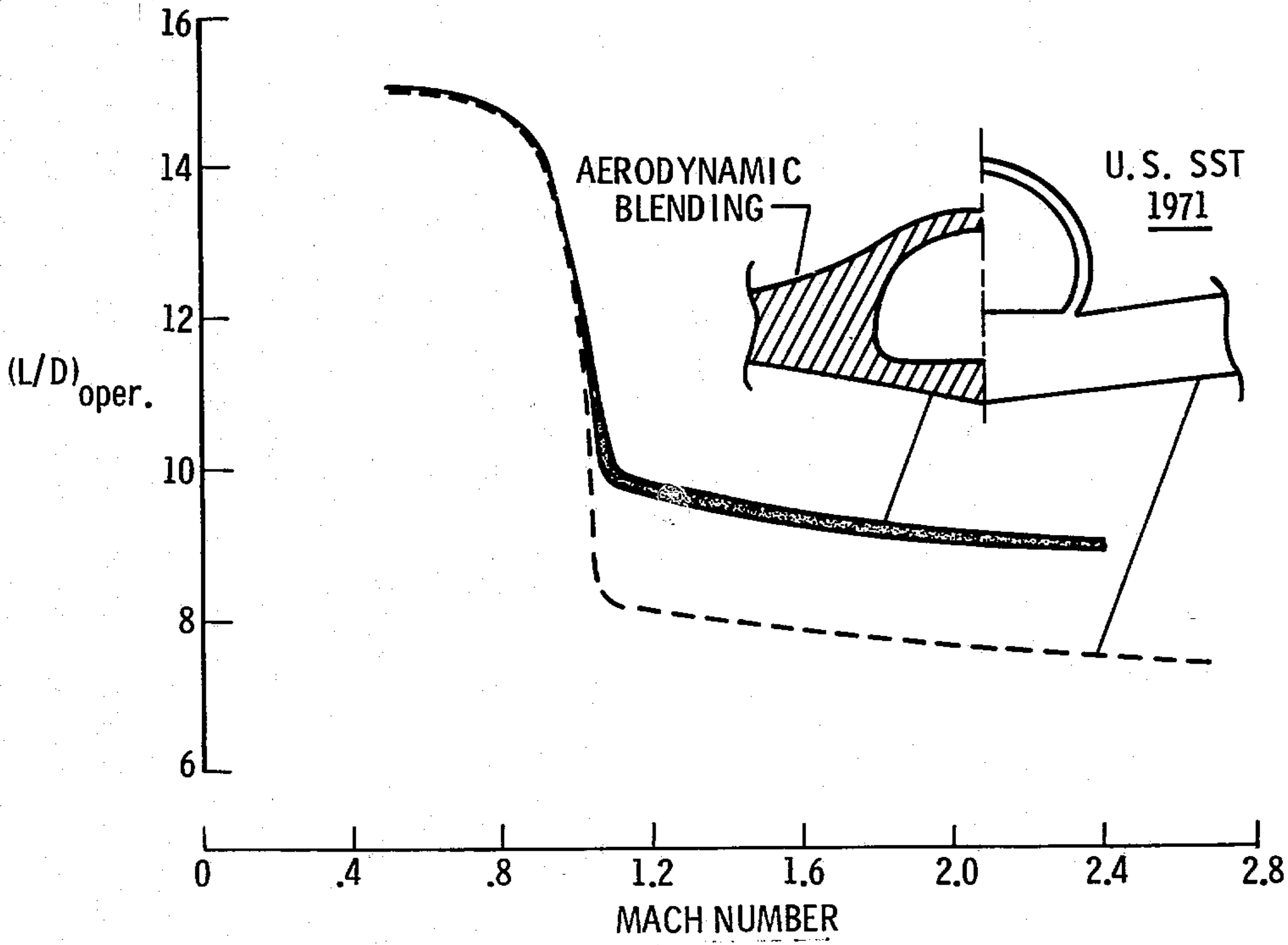


Figure 20. - Advantages of aerodynamic blending.

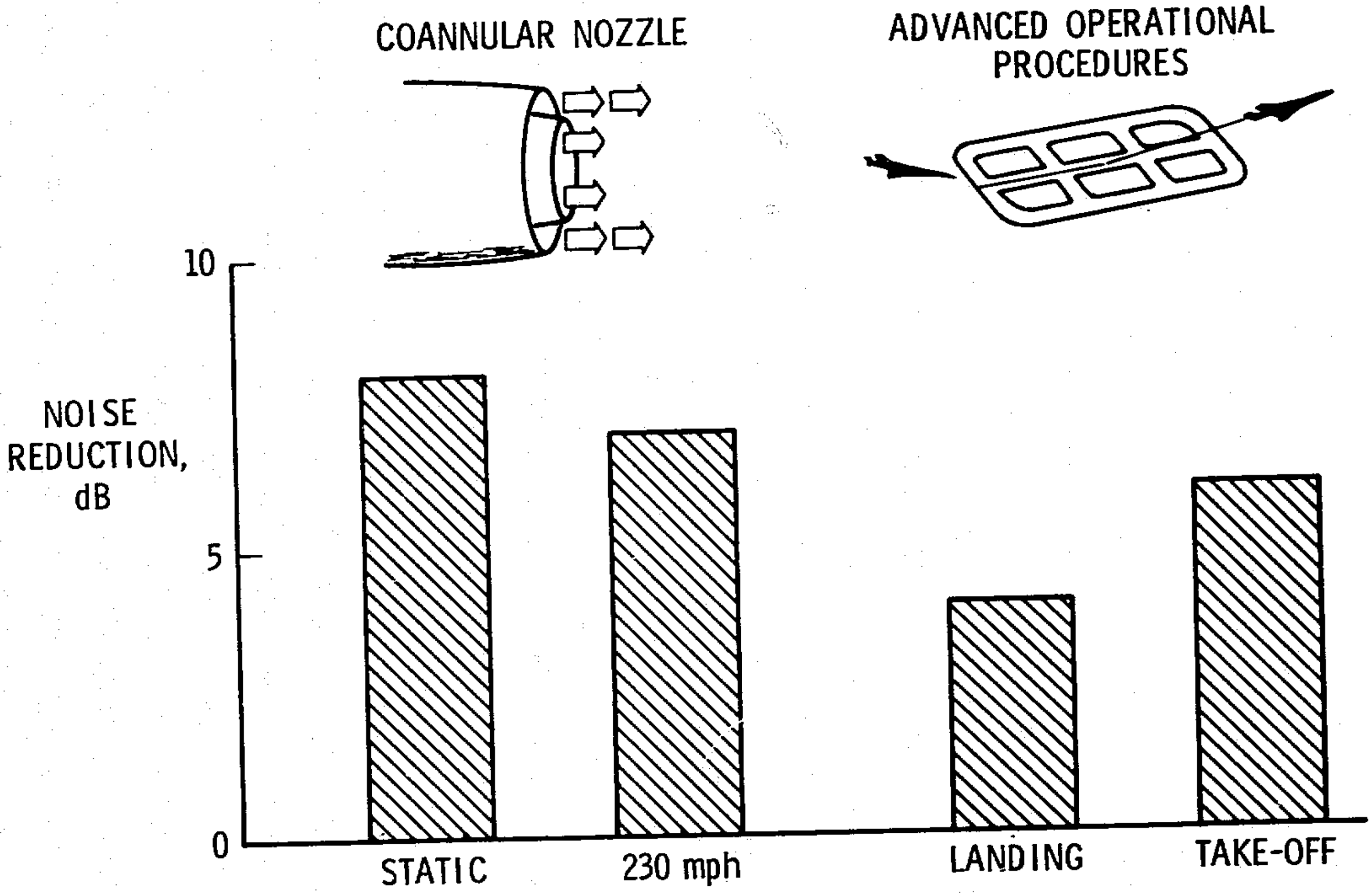


Figure 21. - Promising noise improvements for supersonic transports.

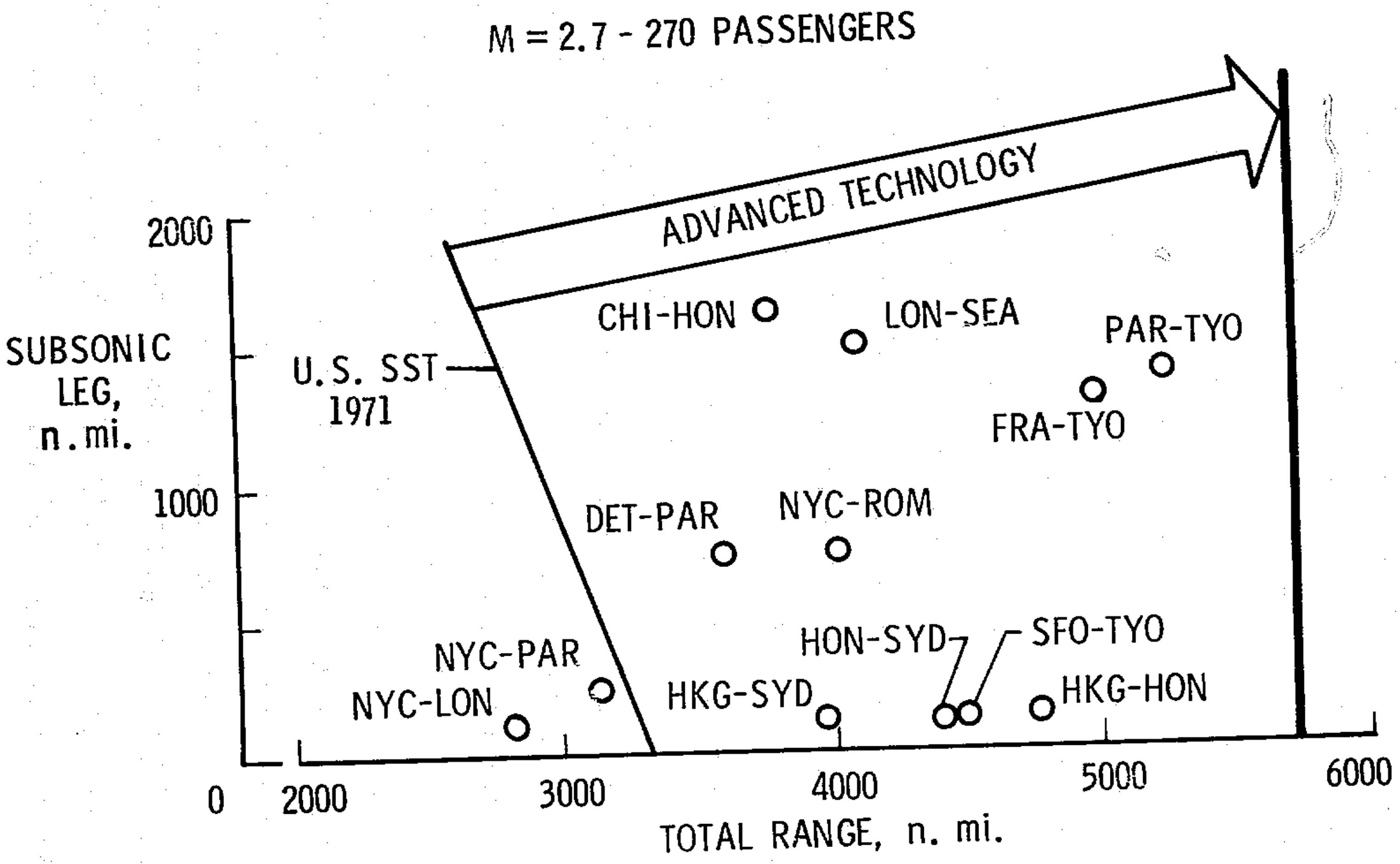


Figure 22. - Possible range improvements for supersonic transports.

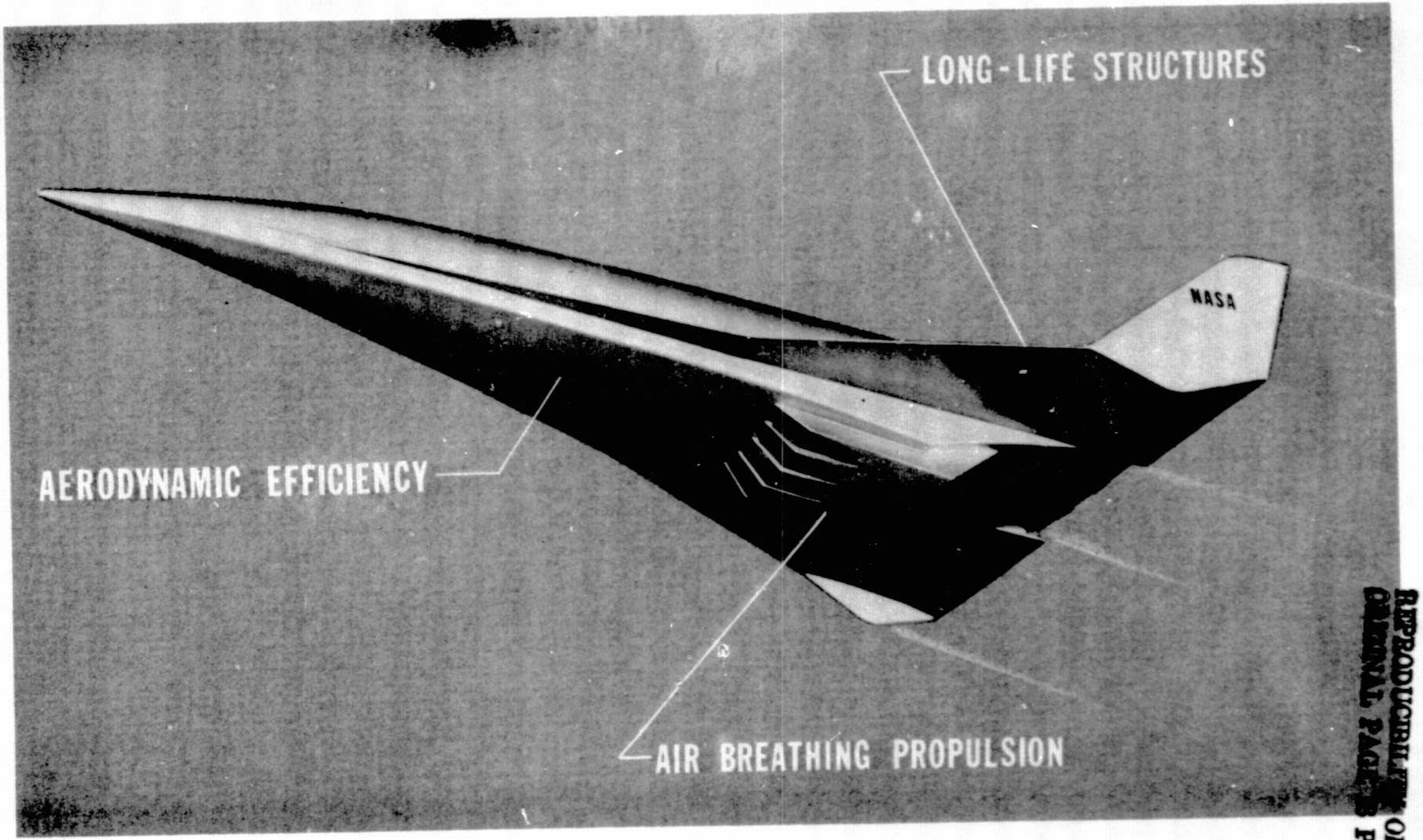


Figure 23. - Key hypersonic technologies.

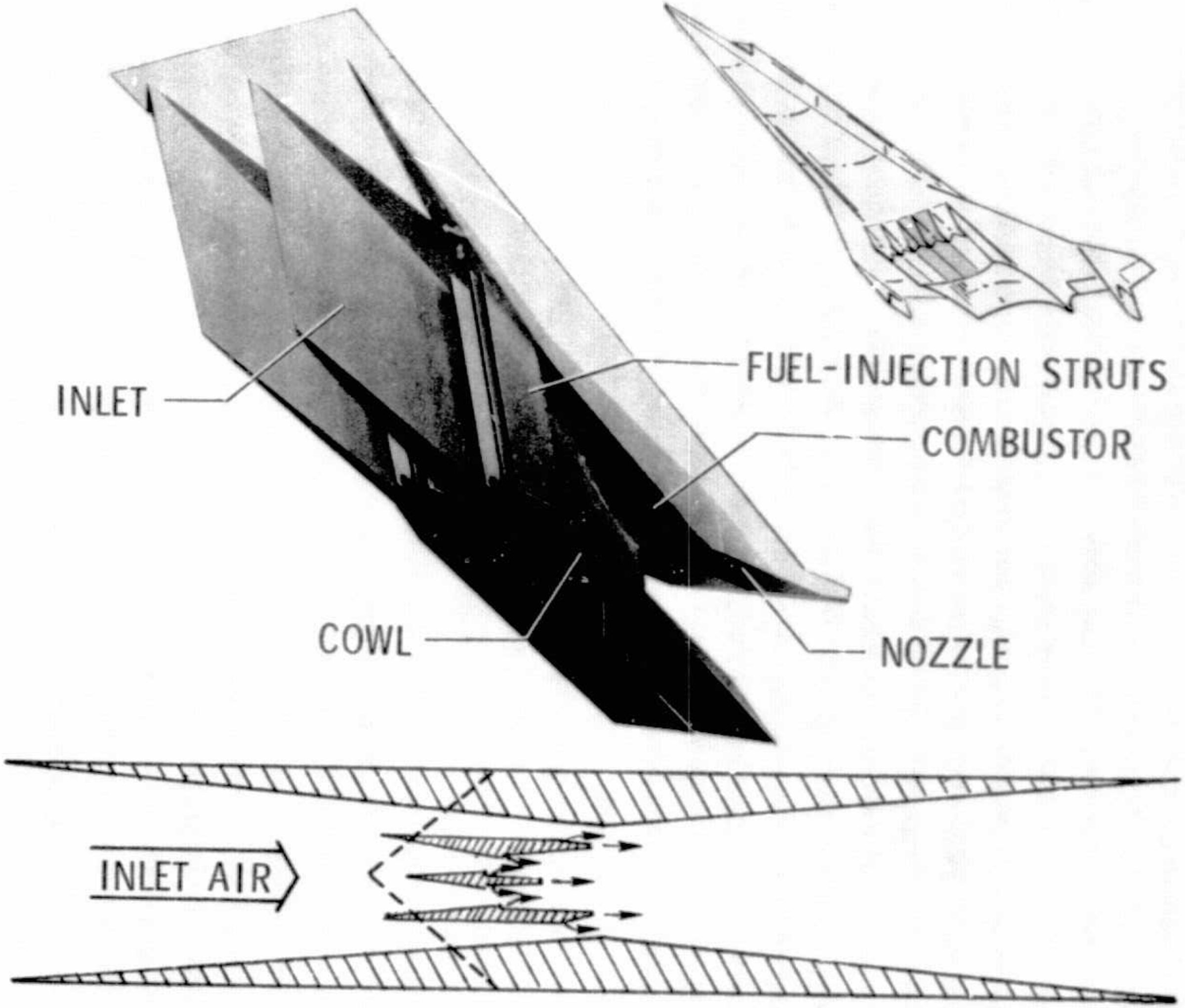


Figure 24. - Airframe-integrated supersonic combustion ramjet.

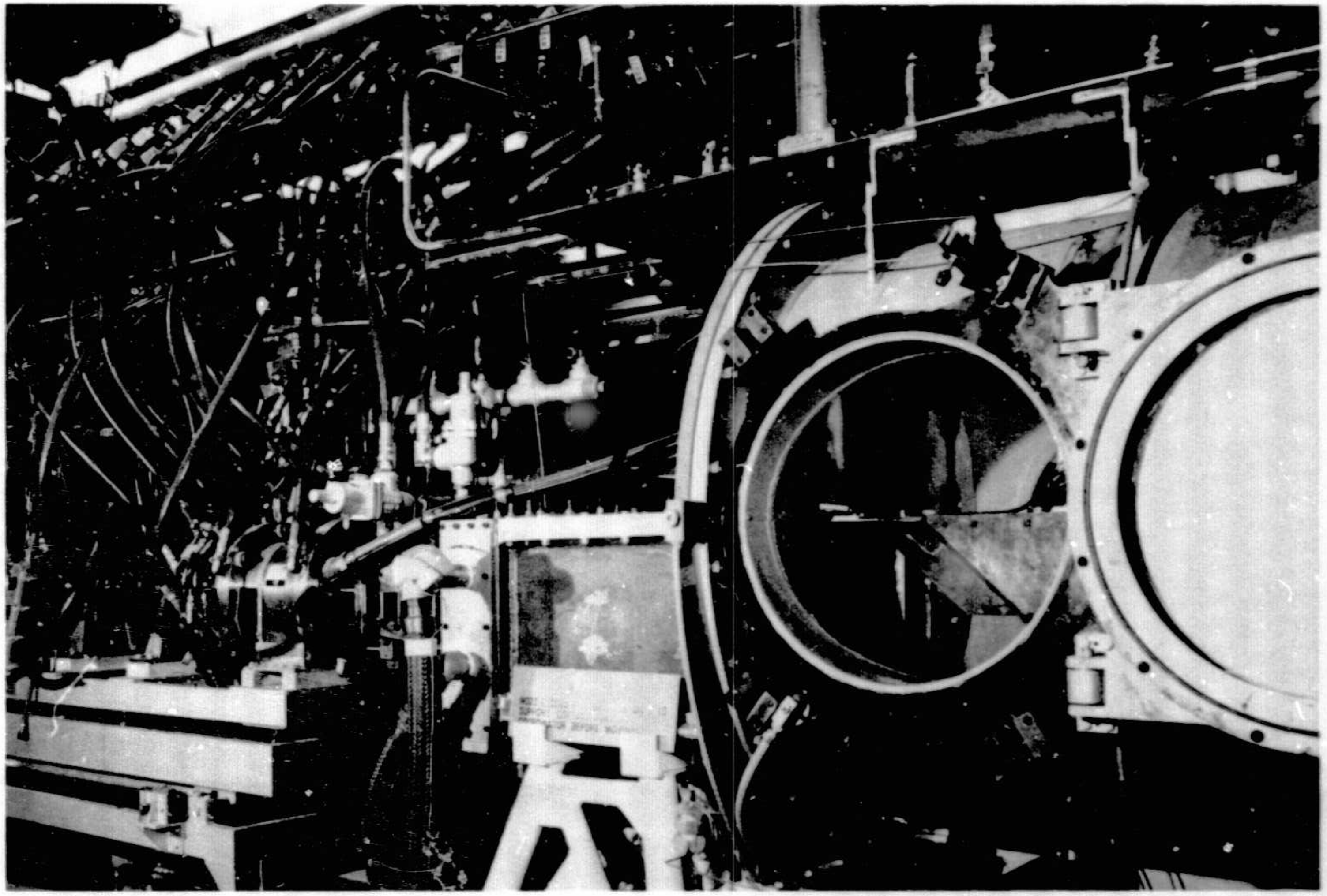


Figure 25. - Test of scramjet in Langley M = 7 test facility.

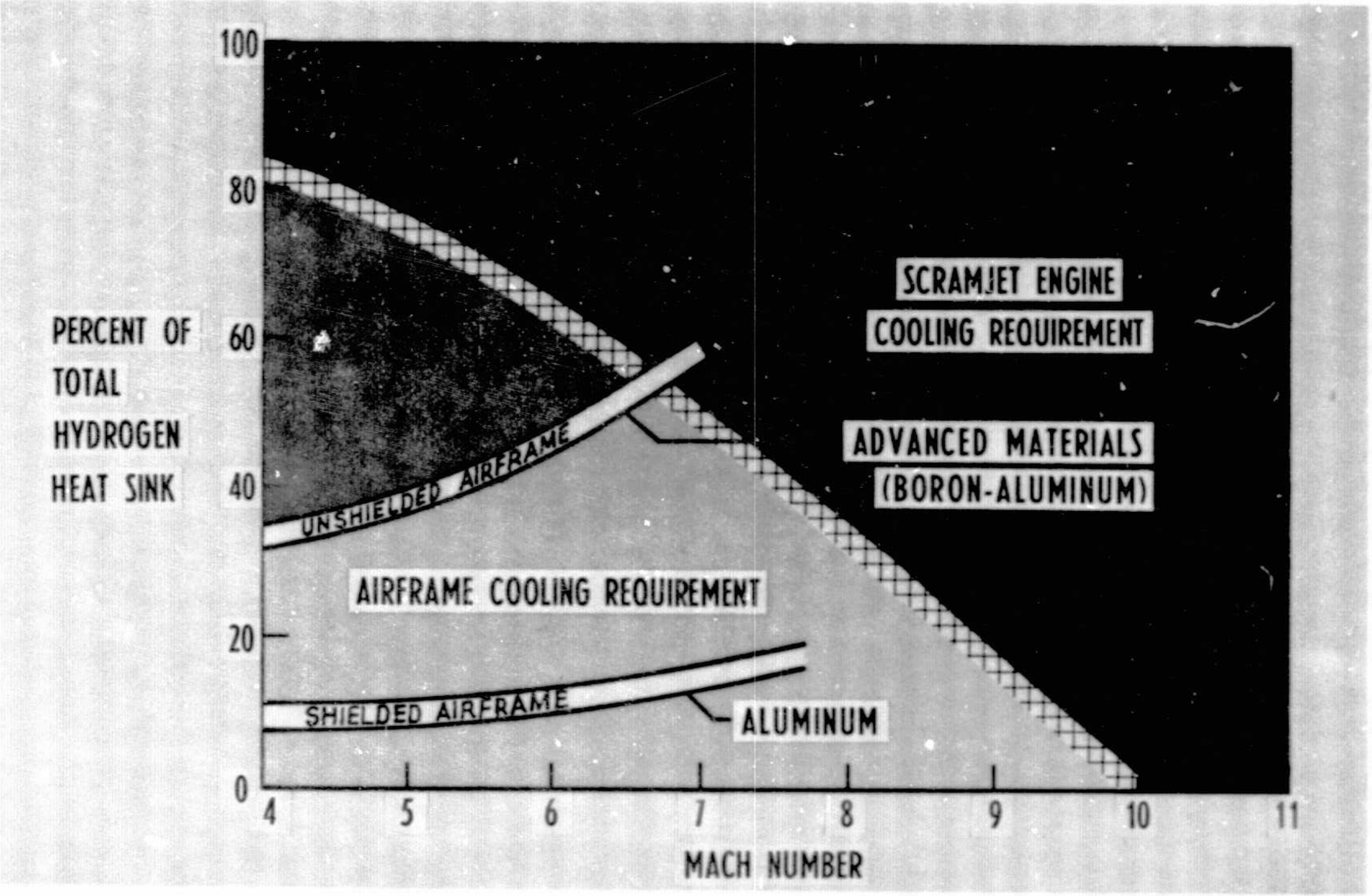
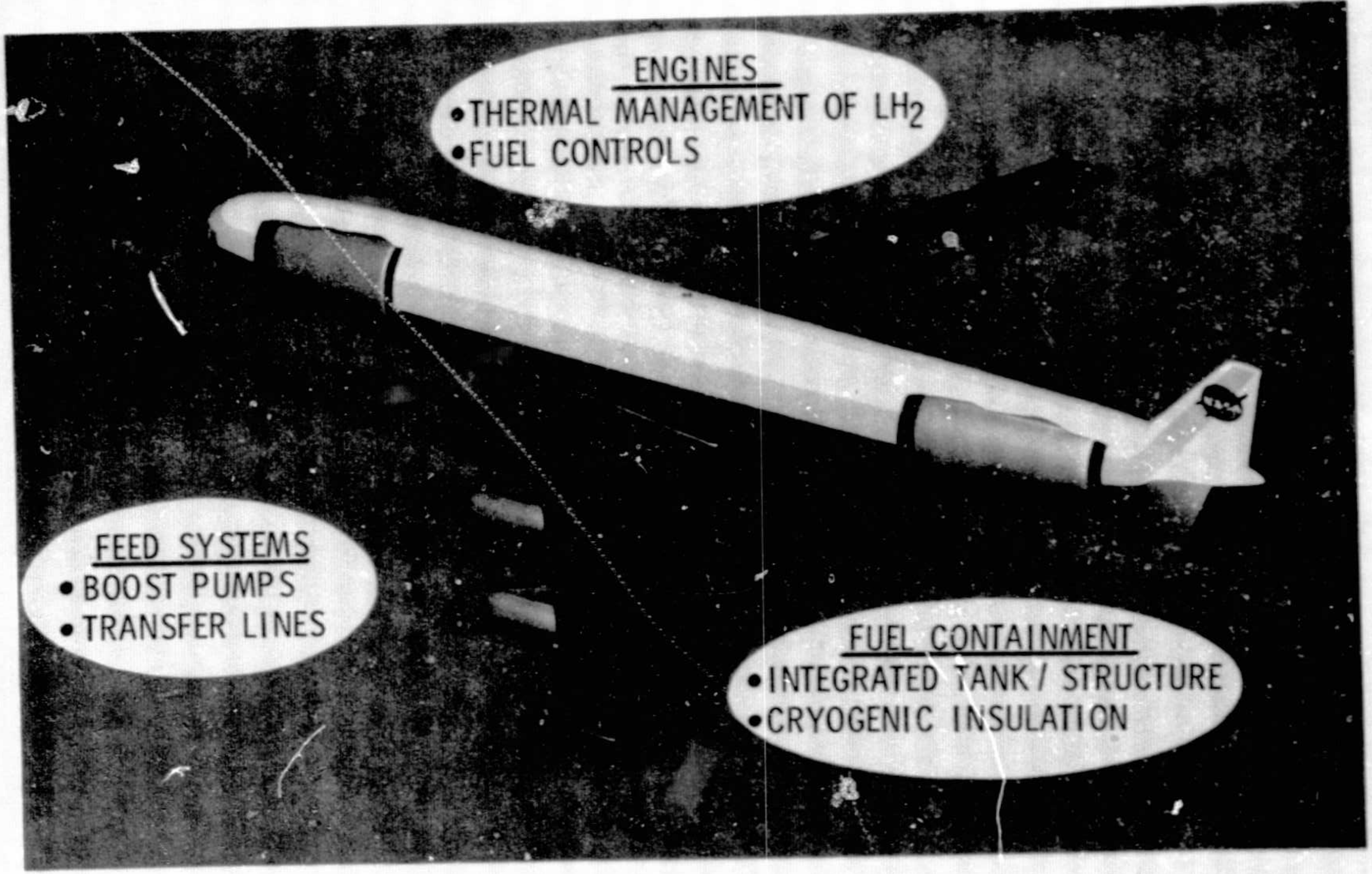


Figure 26. - Engine and airframe cooling requirements.



HIGHLIGHTS

18 % ON-BOARD ENERGY SAVING OVER JET-A

9 % TOTAL ENERGY SAVING OVER SYNTHETIC JET-A DERIVED FROM COAL

Figure 27. - Liquid hydrogen aircraft fuel system study.

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15. Supplementary Notes

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16. Abstract

Aviation is viewed as a growth industry with technological advances continuing well into the 21st Century. While growth constraints to air transportation such as economics, energy, and congestion are very real, technical improvements in dependability, efficiency, and speed will tend to counteract them. Certain NASA activities which impact long-haul (greater than 500 miles) and far-term air transports (1990's and beyond) are discussed. The keys to improved dependability are congestion relief and all-weather operations. Progress in all-weather 4-D navigation and wake vortex attentuation research is discussed and the concept of time-based metering of aircraft is recommended for increased emphasis. The far-term advances in aircraft efficiency are shown to be skin-friction reduction and advanced configuration types. The promise of very large aircraft - possibly all-wing aircraft - is discussed, as is an advanced concept for an aerial relay transportation system. Very significant technological developments are identified that can improve supersonic transport performance and reduce noise. The hypersonic transport is proposed as the ultimate step in air transportation in the atmosphere. Progress in the key technology areas of propulsion and structures is reviewed. Finally, the impact of alternate fuels on future air transports is considered and shown not to be a growth constraint.

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