

NASA Technical Memorandum 102311
AIAA-89-2142

Aeronautical Applications of High-Temperature Superconductors

(NASA-TM-102311) AERONAUTICAL APPLICATIONS
OF HIGH-TEMPERATURE SUPERCONDUCTORS (NASA.
Lewis Research Center) 15 p CSCL 21E

N89-26008

Unclas
G3/07 0222718

George E. Turney and Roger W. Luidens
Lewis Research Center
Cleveland, Ohio

and

Kenneth Uherka and John Hull
Argonne National Laboratory
Argonne, Illinois

Prepared for the
Aircraft Design, Systems and Operations Conference
cosponsored by the AIAA, AHS and ASEE
Seattle, Washington, July 31—August 2, 1989

NASA

AERONAUTICAL APPLICATIONS OF HIGH-TEMPERATURE SUPERCONDUCTORS

George E. Turney and Roger W. Luidens
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135

and

Kenneth Uherka and John Hull
Argonne National Laboratory
Argonne, Illinois 60439

SUMMARY

The successful development of high-temperature superconductors (HTS) could have a major impact on future aeronautical propulsion and aeronautical flight vehicle systems. A preliminary examination of the potential application of HTS for aeronautics indicates that significant benefits may be realized through the development and implementation of these newly discovered materials. Applications of high-temperature superconductors (currently substantiated at 95 K) have been envisioned for several classes of aeronautical systems, including subsonic and supersonic transports, hypersonic aircraft, V/STOL aircraft, rotorcraft, and solar, microwave and laser powered aircraft.

In this paper, we shall introduce and describe particular applications and potential benefits of high-temperature superconductors as related to aeronautics and/or aeronautical systems.

INTRODUCTION

The recent discovery of high-temperature superconductors (HTS) has created a stir of excitement in the scientific community. The potential benefits which may be provided through application of these newly discovered superconducting materials (ceramic perovskite structures) are now being explored by investigators. Studies have been initiated to assess the potential advantage of HTS in a number of areas, including: electrical power transmission and storage, communications, computer systems, medical diagnostic equipment, and ground transportation systems (magnetically levitated high-speed trains).

Despite the acclaims and projections made for these newly discovered superconducting materials, it is generally agreed that a significant effort will be required before these materials can be developed to a state where they can be successfully used in practical applications. For example, problems associated with the physical and chemical stability of these materials must be addressed and solved. Also, methods must be developed for fabricating these materials into relatively strong, useful shapes (wires, films, etc.) for specific uses and/or applications. Nevertheless, the feeling of many researchers seems to be that most or all of the currently recognized problems with HTS can be resolved through applied research efforts (ref. 1). Based on this premise, HTS likely, in time, will find a way into a number of specific

applications. In this paper, we shall look into the potential application of high-temperature superconductors in relation to aeronautics and/or aeronautical systems.

HTS RESEARCH AND DEVELOPMENT

Critical Temperature

In general, it appears that the successful development of HTS technology could have far-reaching benefits in the field of aeronautics. The real benefits, however, will depend on several factors—some of which are not well known at this time. For example, the critical temperature (T_c) of high-temperature superconductors most certainly will influence the projected benefits which may be realized—particularly for some proposed applications related to aeronautics. (Critical temperature, T_c , is defined as the upper temperature limit at which a material exhibits superconducting properties.) At the present time, critical temperatures of, or near, 95 K (171 °R) have been well substantiated. And several researchers² have reported (in a popular technical magazine) evidence of superconductivity at temperatures near 300 K (540 °R).

Obviously, the higher the critical temperature, the smaller the cooling requirement will be. And this is especially important in aircraft systems because coolant for maintaining the T_c must be carried on board. There are, however, applications in aeronautics where the need to carry coolant on board may not be an overriding concern. In supersonic and/or hypersonic aircraft, where the fuel may be cryogenic (liquid methane or liquid hydrogen), the fuel may be used as a heat sink to maintain the superconducting materials at or below the critical temperature. Likewise, for aircraft flight missions which are short duration, the coolant requirements may be relatively small and of a lesser significance. Then, too, in aero applications where superconducting motors and generators are proposed, the predicted high efficiencies of these components could reduce the cooling requirements to a more reasonable and manageable level.

Materials

Before high-temperature superconductors can be successfully used in practical applications, specific processes and techniques will need to be developed for fabricating these materials into useful shapes. The inherently brittle nature of these ceramic based materials poses a problem which will need to be addressed.

Superconducting wires and ribbons which exhibit both strength and flexibility will be required for fabrication of superconducting components, such as electrical power transmission lines, motors, and generators. For aero applications, in particular, these components must be lightweight and must offer advantages over conventional electrical components.

Motors/Generators

Preliminary estimates indicate that HTS motors and generators could have a significant weight advantage over conventional electric motors and generators. This estimated weight advantage may be realized in practice, however, only if the HTS materials have the strength necessary to withstand the loads generated. The possible need for large supporting structures to withstand the high torques could also diminish the estimated weight advantage of HTS motors and generators.

The efficiencies of large HTS electric motors (induction-type) and generators have been estimated to be extremely high, i.e., in the neighborhood of 99.9 percent. Essentially all of the energy resulting from inefficiencies shows up as heat generation. Thus, with a 99.9 percent motor efficiency rating, 0.1 percent of the power input to the motor is transformed into heat. This heat generation rate, although only a small part of the motor power, results in a significant cooling requirement. The penalty imposed by the cooling requirement will depend largely on the critical temperature (T_c) of the superconducting material. If the critical temperature is relatively high, say 300 K (540 °R), then ambient temperature air (or slightly precooled air) may be used for cooling. The penalty associated with using ambient air as a coolant is estimated to be small. However, if the critical temperature is near 95 K (171 °R), some other cooling scheme, such as use of liquid nitrogen, may be required. And this could impose a more significant penalty. For example, it can be shown that the amount of liquid nitrogen coolant that must be vaporized to cool a 100 HP HTS motor (of 99.9 percent efficiency) is about 3.0 lb/hr.

AERO APPLICATIONS OF HTS

Mag-Lev Aircraft Launch Systems

The principles of electromagnetic (EM) propulsion and levitation, enhanced through the use of the new high- T_c superconducting (HTS) materials, can provide the foundation for airports of the future. The technology for EM Airports is a blend of that used in magnetically levitated (MAGLEV) trains and in certain EM mass driver concepts.

Aircraft launching can be accomplished through magnetic levitation and low "g" acceleration by means of either linear synchronous (d-c field windings) or linear induction (a-c) motors. Since superconducting magnets are only able to tolerate d-c currents without energy loss, linear synchronous motors (similar to those developed for MAGLEV trains) offer significant advantages. The most straightforward approach for aircraft launch is to attach the aircraft (via quick-disconnect cables) to an EM shuttle vehicle that rides on linear stator tracks. One configuration, for example, uses the operating principle of a squirrel-cage-motor, except that instead of the stator being in circular form with the rotor revolving within it, the stator is unrolled and laid out flat with the moving shuttle vehicle becoming a linear rotor. For aircraft launching, the linear EM propulsion track is located below the airfield surface, with only the top portion of the accelerating shuttle car and its aircraft cable connections protruding slightly above the surface level.

An alternative to the EM catapult system described above is the application of EM fields directly to the underbody of the aircraft itself and omitting the track shuttle vehicle. This approach would be more analogous to the levitation/propulsion systems under development for MAGLEV trains. However, the EM shuttle/catapult approach offers several advantages which include: the magnetic fields can be applied over a larger surface area than would be available on the airplane itself, location of the EM field (rotor) windings in the shuttle vehicle results in reduced aircraft weight, and the airplane passengers could be more easily shielded from effects of the magnetic fields.

In all likelihood, the most probable near-term application of aircraft EM launch will be aboard naval carriers. Figure 1 depicts a mag-lev aircraft launch system operating from a naval carrier. A mag-lev launch system such as shown here could be a welcomed replacement for the noisy steam catapult launchers on present-day carriers.

HTS Electric Motors For Propulsion

The proposed use of electric motors for powered flight has been studied by a number of investigators (refs. 3 and 4, for example). For the most part, these studies indicated that electric motors did not offer a distinct advantage over conventional aircraft engines (recips. and/or turboshafts). Electric motor weight and the inefficiency associated with conversion of mechanical shaft power to electrical power were considered to be major drawbacks.

Whereas conventional electric motors typically have power-to-weight ratios that are relatively low (0.5 to 1.0 hp/lb), estimates for HTS motors indicate that much higher power-to-weight ratios are possible, e.g., 15 hp/lb. Likewise, the projected efficiencies of HTS motors are expected to be far better than conventional electric motors. These projected improvements, taken together, may significantly improve the attractiveness of electric motors for aircraft propulsion and/or particular powered flight applications.

Figure 2 shows the progression of specific shaft power as a function of time for both electric motors and gas turbine engines. The values shown for the gas turbine with transmission are indicative of systems used for rotorcraft, where the transmission represents a significant part (~40 percent) of the overall propulsion system weight. As indicated in figure 2, present-day gas turbine engines of this type have about twice the specific shaft power of conventional electric motors. Future projections for these systems are shown on the far right side of figure 2. With advanced technology, the specific shaft power of the gas turbine system could increase in the future to a value near 2.5 hp/lb. And the specific shaft power of electric motors, with HTS technology (currently with T_c of 95 °R), may reach a value of about 15 hp/lb. An improvement of this magnitude, i.e., a fifteen-fold change in specific shaft power, could revolutionize the thinking regarding electric motors for aero propulsion and aero applications.

Lightweight HTS motors and generators may, in some cases, offer advantages over conventional aero propulsion systems. In the paragraphs which follow, HTS electric motors and generators are considered as a means of supplying propulsive power for specific types of aircraft. The types of aircraft to be considered here are: helicopters, subsonic transports, supersonic/hypersonic and solar powered aircraft.

Helicopters. - Most commonly, the propulsion system for conventional helicopters consists of a turboshaft engine and a shaft speed reduction system (transmission). Because of the large reduction in shaft speed required between the turboshaft engine and the rotor system, the transmissions for rotorcraft are normally large, heavy and generate considerable noise. Typically, the weight of the transmission system for helicopters represents approximately 40 percent of the total weight of the gas generator and transmission system. A conventional rotorcraft propulsion system with onboard fuel is depicted in figure 3(a).

A conceptual propulsion system for rotorcraft which uses a HTS generator/motor is shown in figure 3(b). In this conceptual system, the turboshaft engine drives a HTS generator which, in turn, supplies electrical power to a HTS motor. The HTS motor, in turn, drives the helicopter rotor. The HTS generator/motor system just described is currently being studied by Pratt and Whitney under a NASA-Lewis sponsored contract.

The potential advantage of this conceptual system (fig. 3(b)) is that the heavyweight gearbox is eliminated from the propulsion system. But, as indicated in fig. 3(b), a HTS generator/motor system is added in place of the heavy gearbox. Nevertheless, a net weight advantage may be realized by this exchange if the specific shaft power of the generator/motor system is relatively high. For example, if we assume the specific shaft power of the conventional rotorcraft propulsion system to be 1.25 hp/lb, and also assume the transmission weight to be 40 percent of the total propulsion system weight, we can then estimate the potential improvement which may result. By using a specific shaft power of 15 hp/lb for the HTS generator/motor system, it can be shown that the total weight of a rotorcraft propulsion system can be reduced by nearly 25 percent. That is, the weight of the total propulsion system shown in figure 3(b) is nearly 25 percent less than the conventional system shown in figure 3(a). This is obviously a substantial improvement. Other more subtle advantages of the system shown in figure 3(b) are elimination of gearbox noise and vibration and a possible improvement in the rotorcraft weight distribution.

Figure 3(c) depicts a more advanced conceptual propulsion system for rotorcraft which uses HTS technology. In this conceptual system, microwave power is beamed to a rectenna (a rectifying antenna) on board the rotorcraft. The rectenna, in turn, converts microwave energy directly to electrical energy which then powers an HTS electric motor. The HTS motor, in turn, drives the helicopter rotor. High temperature superconductors are projected to offer significant weight reductions for both the electric motor and the rectenna.

The advantages of the system shown in figure 3(c) are rather apparent. This conceptual system carries no onboard fuel and the propulsion system consists only of a rectenna and an HTS electric motor. A rotorcraft powered by the conceptual system shown in figure 3(c) could be a valuable resource for long duration surveillance activities, such as for specific naval operations at sea.

Subsonic transports. - HTS motors and generators may be used to advance and improve the propulsion systems of subsonic transport aircraft. A conceptual application of HTS motors and generators to a subsonic transport propulsion system is shown in figure 4. A collection of several separate applications of HTS is included here. In this system, gas turbine engines mounted below the aircraft wings are used to drive HTS electric generators.

The generators, in turn, supply electric power to systems and subsystems on board the aircraft. In effect, the aircraft shown in figure 4 is an all-electric powered aircraft. In this aircraft, a major portion of the electric power generated is used by HTS motors located at the rear of the fuselage. These HTS motors drive propulsors (propellers or fans) which provides thrust to the aircraft. A minor portion of the electric power is used for other subsystems. These include: winglet propellers or "proplets" (powered by small HTS motors) to counter the drag produced by wing-tip vorticies, and suction devices (driven by HTS motors) to promote a laminar boundary layer and thereby reduce drag on the wing surfaces.

The major advantage of the conceptual propulsion system shown in figure 4 is that the turboshaft engines and propulsors need not be colocated on the aircraft. By locating the propulsors at the rear of the fuselage, aircraft cabin noise can be reduced. This arrangement may also improve the aircraft balance and/or weight distribution. And, finally, the total drag of the aircraft may be significantly reduced through use of "proplets" and laminar boundary layer control.

Again, the critical temperature of the HTS materials needed in this application is of major importance. Mostly likely, an all-electric propulsion system such as shown in figure 4 would be advantageous only if superconductors with relatively high critical temperatures (>95 K) were available.

Supersonic/hypersonic aircraft. - High-speed supersonic and hypersonic aircraft are again being strongly advocated for some civil and military missions. In the high-speed flight regime (Mach 3 and above) cryogenic fuels (liquid methane and liquid hydrogen) appear to be especially attractive because of their heat sink capacity. Cryo fuels may be used to cool high-temperature components on both the vehicle and propulsion system. Specific examples are: the leading edge of wings, the leading fuselage structure and the engine inlet cowl/lip structures.

Most of the proposed propulsion systems for high-speed flight, say to Mach 6 or so, are "composite" engine systems. These systems consist, usually, of a low by-pass turbofan engine for flight speeds up to about Mach 3 and a ramjet engine for speeds above Mach 3. A conceptual turbofan engine which uses HTS technology and which may offer superior performance for flight speeds up to Mach 3 is shown in figure 5. The key feature of this engine is the all-electric, tip-powered fan. The engine fan is effectively the rotor of an electric motor and the fan shroud contains the stator windings which surround the fan and/or rotor.

It appears that high-temperature superconductors may be the enhancing or enabling technology for this type of conceptual all-electric tip powered turbofan system. And cryogenic hydrogen may provide the cooling needed to maintain the HTS materials at or below their critical temperature, even for T_c values of or near 95 K.

Solar powered aircraft. - A solar powered civil aircraft is illustrated in figure 6. A manned aircraft of this type has already been flown across the English Channel. The basic performance of the aircraft shown in figure 6 may be improved by use of a superconducting electric motor and generator, and energy storage coils. The storage coils would be used to supply power for

nighttime operation and would be recharged during the day. This type of airplane could be used for weather observations and predictions, and for communication. The airplane may fly for months at a time and hence the critical temperature of the HTS is extremely important.

A solar powered airplane can fly using existing technology for electric drive motors and storage batteries. A future system based on room-temperature HTS would be enhancing and may provide a low-cost means of surveillance for civil needs.

The same airplane system described above may also be applicable for military missions as illustrated in figure 7. Such an aircraft may be advantageous for long duration survey/reconnaissance activities such as those connected with naval operations at sea.

Aircraft secondary electric power systems. Current subsonic transport aircraft use three different types of secondary power; namely, hydraulic, pneumatic and electric. As indicated in figure 8, secondary power is used to activate control surfaces and other systems (flaps, spoilers, slats, landing gear, etc.) on the aircraft.

It has already been shown in reference 5 that an all-electric secondary power system (which uses conventional conductors) can provide significant benefits over the currently used multiple power system. Reference 5 indicates, for example, that a conventional (copper-wire) all-electric secondary power system could produce nearly a 10 percent reduction in the mission fuel requirement of a subsonic transport aircraft. The benefit cited in reference 5 may be improved further if an all-electric HTS secondary system is used. Indications are that mission fuel could be cut an additional three percentage points with an all-electric HTS secondary power system. This additional reduction in mission fuel is the result of lighter weight and higher efficiency HTS motors.

In this particular application, however, critical temperature of the HTS material is especially important. If cooling of the superconducting materials is required, the potential benefits of HTS for secondary all-electric power could be reduced or lost. Thus, for this application, a room temperature superconductor may be both desirable and necessary to achieve the gains just cited.

Magnetic Bearings

Significant benefits may be realized through the use of magnetic bearings in aero propulsion systems. Preliminary estimates by Pratt and Whitney indicate that the exclusive use of conventional-type magnetic bearings in turbofan engines could provide as much as a 6 percent reduction in engine weight and a 3 percent improvement in thrust specific fuel consumption (TSFC) for a subsonic high BPR turbofan. These estimated improvements come about from: (1) the ability to operate a turbofan engine at higher rotor speeds, (2) reduced rotor tip clearance resulting from tighter bearing clearance, (3) significantly lower friction and heat generation, and (4) reduced engine nacelle size resulting from smaller bearing compartments.

Magnetic bearings made of HTS materials should be significantly smaller and lighter than conventional mag bearings. As depicted in figure 9, the HTS magnetic bearings have smaller coils, contain no iron and are stiffer than conventional mag bearings. Estimates indicate that these bearings could provide an additional improvement in fan performance over that projected for conventional mag bearings.

Magnetic Braking

The high-conductivity plasma created upon entry of a hypersonic aircraft (or spacecraft) into the atmosphere can potentially be used as the working plasma of a MHD braking system. A vehicle flying at high speed through the atmosphere may raise the local stagnation temperature high enough that the air becomes ionized and hence an electrical conductor. In principle, a strong magnetic field generated by HTS could be used to deflect the plasma formed and thereby decelerate the vehicle through an imposed reaction force.

Magnetic braking could minimize the need for heat shields of the type used on the shuttle spacecraft. Magnetic braking may also permit the deceleration of a spacecraft to begin at a more distant point in the trajectory, thereby reducing the peak reaction forces on the spacecraft. Figure 10 depicts a spacecraft entering the atmosphere and being decelerated by aerodynamic drag forces (upper left) and magnetic braking forces (lower right).

CONCLUDING REMARKS

The successful development of high-temperature superconductors could have a major impact on future aero propulsion and aero flight vehicle systems. A number of conceptual aero applications of HTS have been identified and described herein. The next step in the study of HTS applications for aeronautics is to quantify the potential advantages in terms of performance, weight and cost. In general, it is believed that aero applications of HTS will be more sensitive to critical temperature than most other applications. This is because the cooling system weight must be carried on-board the aircraft and, as such, may compromise the payload and/or range of the aircraft.

Finally, the technologies that must be developed for the most attractive applications of HTS need to be identified and the appropriate research should be initiated.

REFERENCES

1. Lemonick, Michael E., "Superconductors"--Cover Story of Time Magazine, May 11, 1987.
2. Fisher, Arthur, "Superconductivity"--Popular Science Magazine, April, 1988.
3. Galbraith, A.D., "Electric Propulsion for High Performance Light Aircraft" AIAA/SAE/ASME 15th Joint Propulsion Conference, June 18-20, 1979.

4. Kirchen, P.T., "Practical Feasibility Assessment of Electric Power Propulsion in Small Helicopters Using Lithium-Hydrogen Battery Technology" Hughes Helicopters Inc., December, 1981.
5. Hoffman, A.C., Hansen, I.C., Beach, R.F., Plencner, R.M., Dengler, R.P., Jefferies, K.S., Frye, R.J., "Advanced Secondary Power System for Transport Aircraft", NASA Technical Paper 2463, May, 1985.

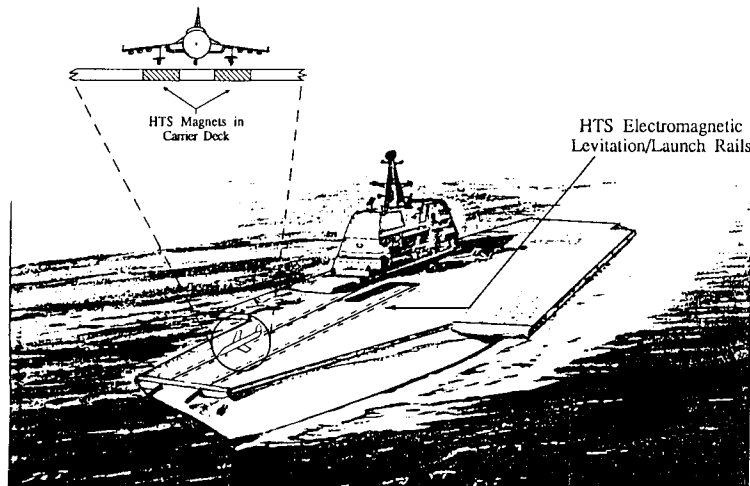


FIGURE I - ELECTROMAGNETIC LEVITATION / LAUNCH OF AIRCRAFT FROM NAVAL CARRIER

ORIGINAL PAGE
BLACK AND WHITE PHOTOGRAPH

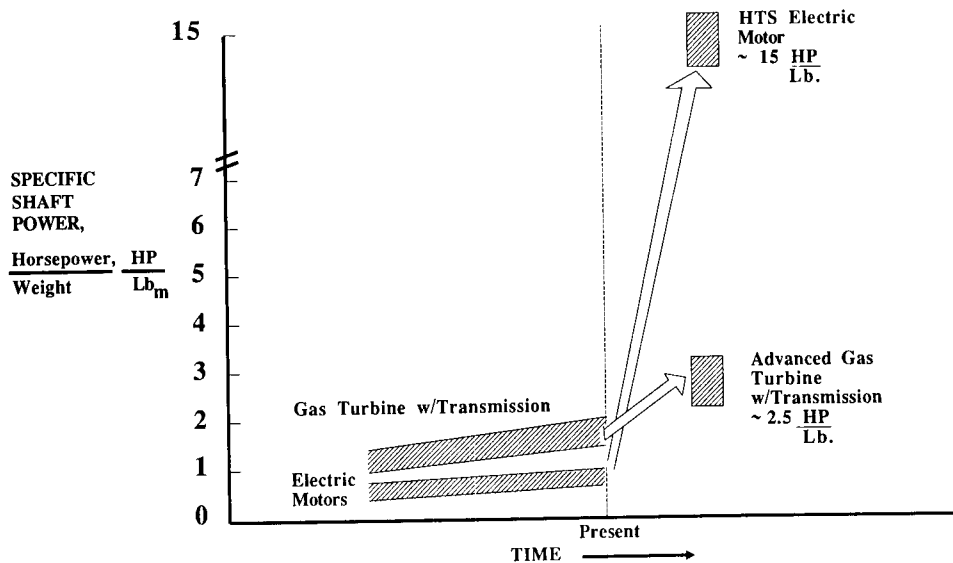
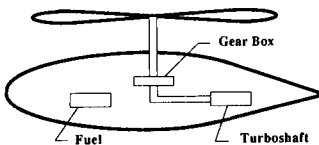


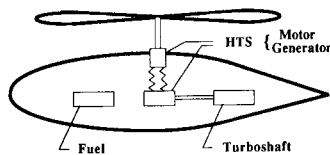
FIGURE 2 - ELECTRIC MOTORS FOR AERO PROPULSION

SYSTEMS

A. CONVENTIONAL



B. SUPERCONDUCTING - MOTOR / GENERATOR



C. SUPERCONDUCTING - BEAM POWER

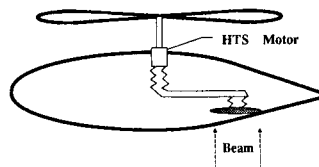


FIGURE 3 - ROTORCRAFT DRIVE SYSTEMS USING SUPERCONDUCTORS

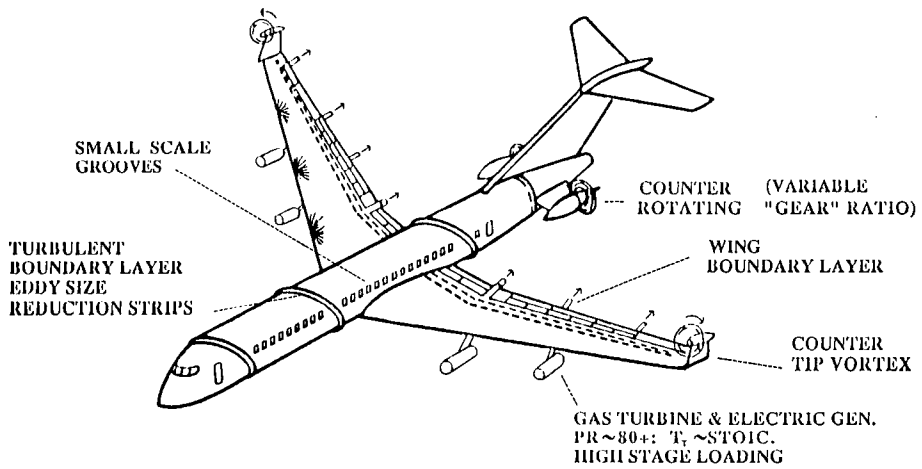


FIGURE 4 - SUBSONIC TRANSPORT OF THE FUTURE
 Aircraft BLC: Separate Superconducting Generators, Motors

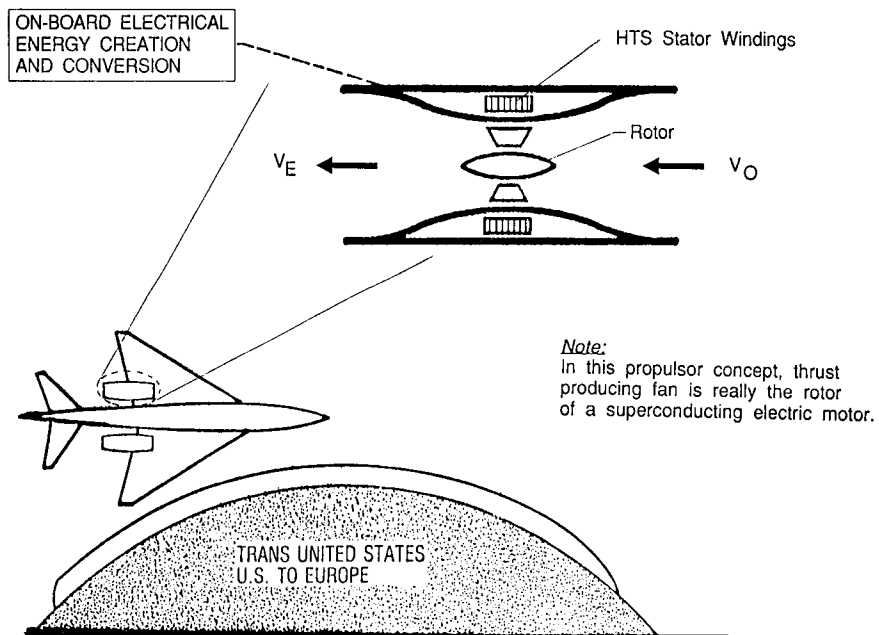


FIGURE 5 - HTS ELECTRIC MOTOR OPERATING AS A PROPULSOR

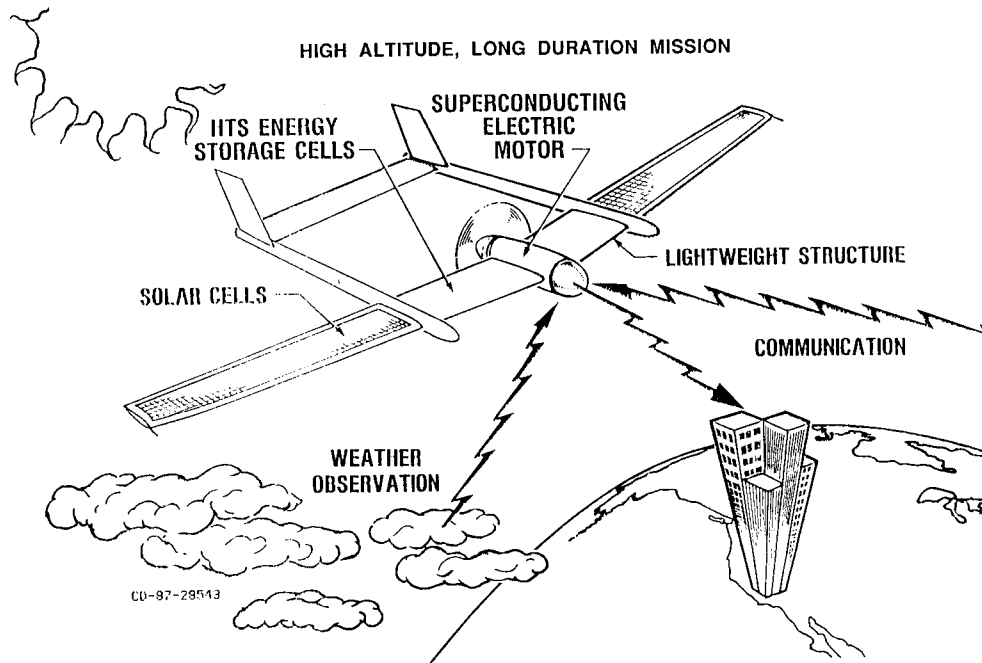


FIGURE 6 - SOLAR POWERED AIRCRAFT WITH SUPERCONDUCTING TECHNOLOGY

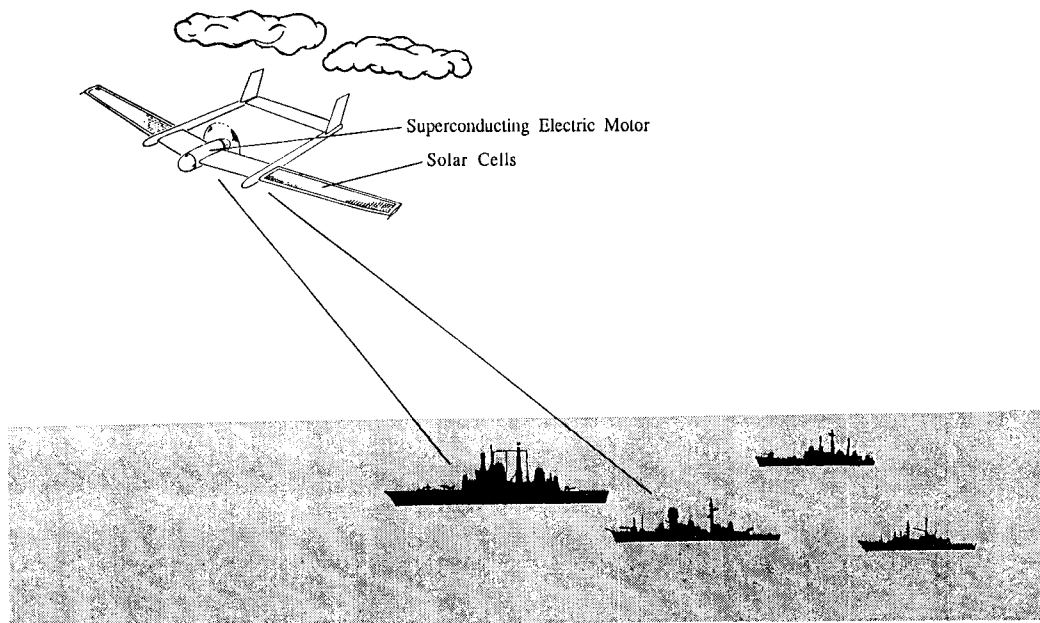
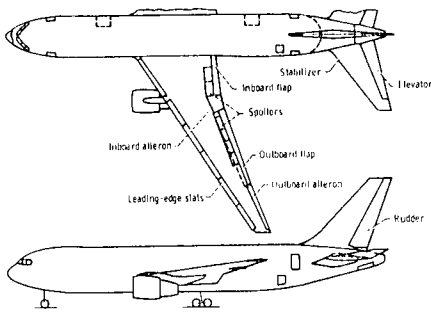


FIGURE 7 - ULTRA-LIGHT SURVEY / RECONNAISSANCE AIRCRAFT FOR NAVAL OPERATIONS

(Aircraft Powered by Superconducting Electric Motor and Solar Cells)



- Current transport A/C use three types of secondary power (hydraulic, pneumatic and electric).
- Studies indicate that an all-electric secondary power system using HTS has significant advantages.

FIGURE 8 - HTS FOR SECONDARY POWER SYSTEM OF TRANSPORT AIRCRAFT

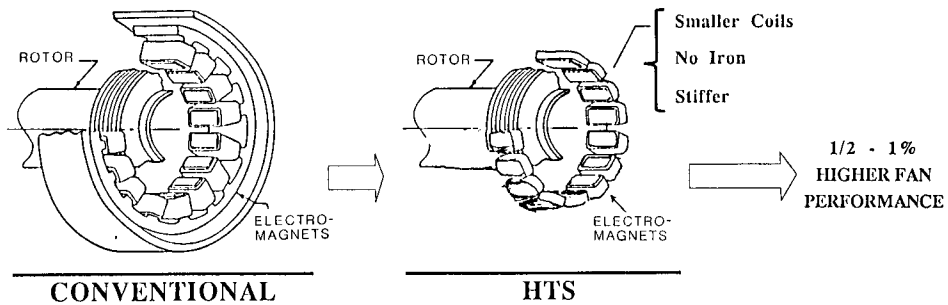


FIGURE 9 - HTS MAGNETIC BEARING

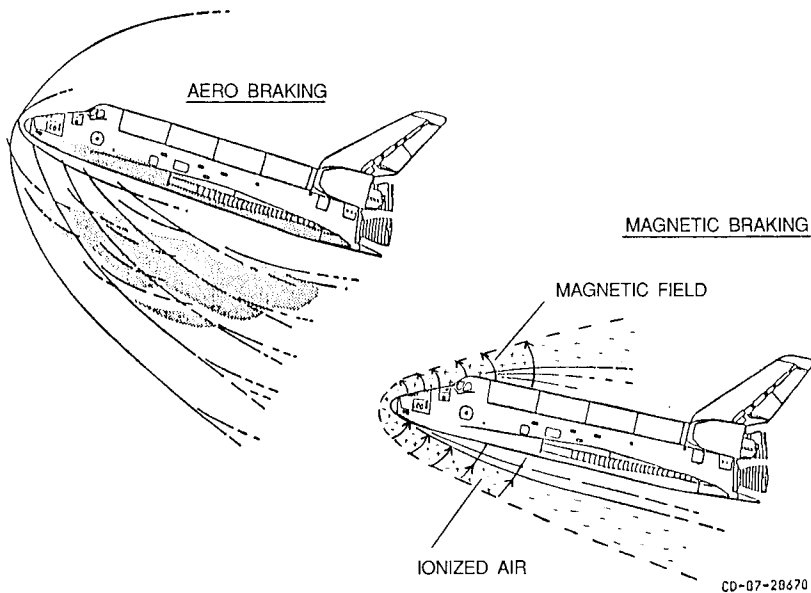


FIGURE 10 - MAGNETIC BRAKING WITH HTS

1. Report No. NASA TM-102311 AIAA-89-2142		2. Government Accession No.		3. Recipient's Catalog No.	
4. Title and Subtitle Aeronautical Applications of High-Temperature Superconductors				5. Report Date	
				6. Performing Organization Code	
7. Author(s) George E. Turney, Roger W. Luidens, Kenneth Uherka, and John Hull				8. Performing Organization Report No. E-4951	
				10. Work Unit No. 505-69-61	
9. Performing Organization Name and Address National Aeronautics and Space Administration Lewis Research Center Cleveland, Ohio 44135-3191				11. Contract or Grant No.	
				13. Type of Report and Period Covered Technical Memorandum	
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546-0001				14. Sponsoring Agency Code	
15. Supplementary Notes Prepared for the Aircraft Design, Systems and Operations Conference cosponsored by the AIAA, AHS, and ASEE, Seattle, Washington, July 31-August 2, 1989. George E. Turney and Roger W. Luidens, NASA Lewis Research Center; Kenneth Uherka and John Hull, Argonne National Laboratory, 9700 So. Cass Ave., Argonne, Illinois 60439.					
16. Abstract The successful development of high-temperature superconductors (HTS) could have a major impact on future aeronautical propulsion and aeronautical flight vehicle systems. A preliminary examination of the potential application of HTS for aeronautics indicates that significant benefits may be realized through the development and implementation of these newly discovered materials. Applications of high-temperature superconductors (currently substantiated at 95 K) have been envisioned for several classes of aeronautical systems, including subsonic and supersonic transports, hypersonic aircraft, V/STOL aircraft, rotorcraft, and solar, microwave and laser powered aircraft. In this paper, we shall introduce and describe particular applications and potential benefits of high-temperature superconductors as related to aeronautics and/or aeronautical systems.					
17. Key Words (Suggested by Author(s)) Aeronautics High-temperature superconductors Propulsion			18. Distribution Statement Unclassified - Unlimited Subject Category 07		
19. Security Classif. (of this report) Unclassified		20. Security Classif. (of this page) Unclassified		21. No of pages 14	22. Price* A03