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Evolution of Modern Air-Transport Powerplants

D. J. JORDAN* AND H. S. CRIM†
Pratt & Whitney Aircraft, East Hartford, Conn.

The advance in the performance and economics of aircraft powerplants is a significant aspect of our technical history and points the way toward expansion of air transport. In the 1935–1964 period, aircraft engine cruise power has increased twentyfold, weight/horsepower ratio has improved by a factor of 5, and fuel consumption per pound of thrust horsepower of jet engines now approaches that of the best piston engines at twice the flight speed. With these gains have come substantial decreases in powerplant initial and maintenance costs and in-flight shutdown rates, and a great jump in engine earning capacity. Further, the turbofan engine compares most favorably with land and sea propulsion systems in initial, direct operating, and maintenance costs. Advances in engine technology and reliability over the past 30 years indicate the feasibility of attaining the supersonic transport goals, but only after a development program of great magnitude has been established. More immediately promising is an expansion in the air-cargo area, using present technology.

A THOROUGH discussion of the modern air-transport engine is so broad that this paper can uncover only particular highlights of the subject, which is concerned with an unusual and relatively fundamental device in the history of technical progress. An attempt is made to describe some significant and interesting aspects of the characteristics and evolution of the modern gas-turbine engines that power our larger transports.

To establish a perspective in which to view the aircraft and engines, which are today so commonplace, we shall look first at the brief and dramatic chronicle of transport aircraft powerplants, beginning with scheduled commercial operation in the early 1930's.

Figure 1 illustrates various improvements in aircraft engines in the 1935–1964 period. Figure 1a shows the growth in cruise power requirements of transport aircraft over the past 30 years. For the purpose of this comparison, the DC-3 aircraft was used for the initial point and the large turbofan-powered transport of today as the final point. It can be seen that the cruise horsepower has increased by a factor of 20 in this 30-year period, making it possible today to propel a 300,000-lb aircraft through the air at a speed of 550 mph. This increase has been so great that it is interesting to compare the present transport aircraft with other major transport vehicles. For example, the thrust horsepower of a modern airliner at cruise is 150% of a Mariner class cargo ship and is 10 times that of a fast passenger train.

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* Chief Engineer, Advanced Engines.

† Senior Project Engineer, Advanced Engine Analysis.

Since the beginning of the air-transport era, the powerplant weight vs cruise horsepower has improved markedly, taking a major stride with the introduction of the turbine engine. Figure 1b shows the trend and illustrates the fact that the modern fan provides more than three times as much thrust horsepower per pound of installed weight as the reciprocating engine.

The trend in efficiency of air-transport powerplants is somewhat difficult to define, since the usual parameter of Specific Fuel Consumption (SFC) in terms of lb/thrust horsepower hour does not give credit for the higher cruising speed of modern powerplants.

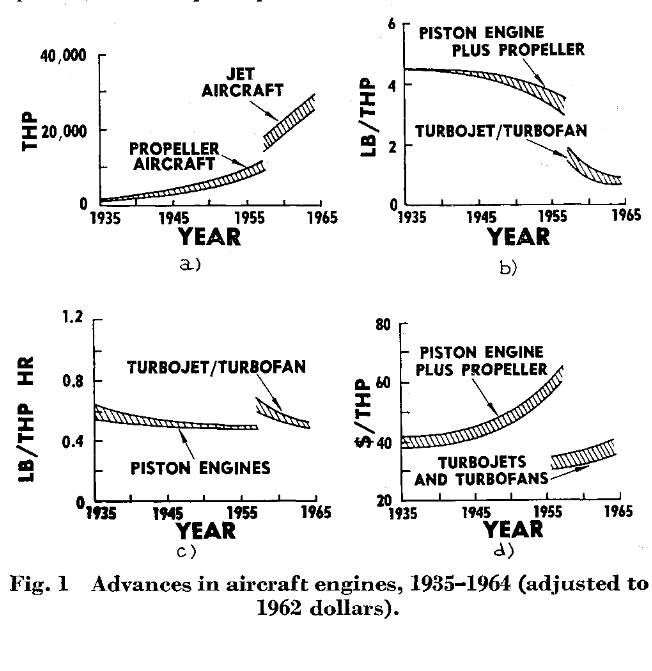

Fig. 1 Advances in aircraft engines, 1935–1964 (adjusted to 1962 dollars).

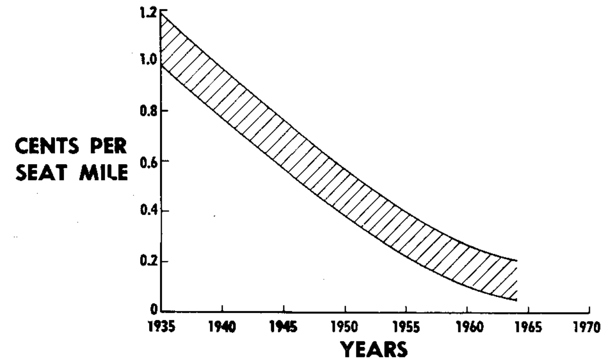

Fig. 2 Decline in the cost of powerplant maintenance, 1935–1964 (adjusted to 1962 dollars).

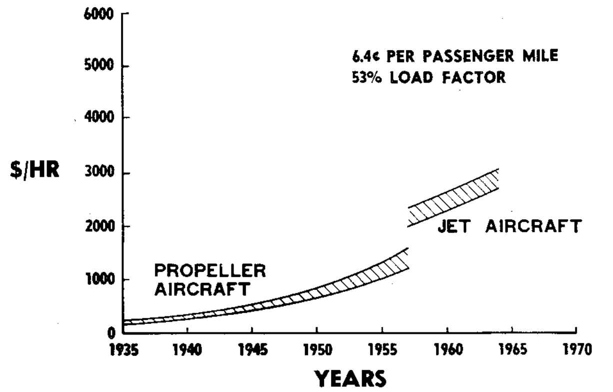

Fig. 4 Comparison of gross earning potential of piston engines and gas turbine engines, 1935–1964.

Nevertheless, as shown on Fig. 1c, the modern turbofan is approaching the best of the complex reciprocating powerplant cycles in SFC and is providing this performance at twice the cruising speed. From the discussion, it is apparent that the air-transport powerplant has made phenomenal technical strides in a few decades.

These technical accomplishments are of fundamental importance, but since air transport must compete on an economic basis, there are equally important cost considerations that must be taken into account. Figure 1d shows the initial cost of transport powerplants vs time. For the purpose of this presentation all costs were converted in today's dollars, and the comparison was made for the entire propulsion system, including the propeller and gear in the case of the reciprocating powerplants. With the introduction of the jet engine, the initial cost of the powerplant has come down markedly despite the increase in performance capabilities.

Powerplant costs are, of course, made up of both the initial cost and the maintenance cost. Powerplant maintenance and overhaul costs are difficult to disentangle and are therefore presented as a band of data in Fig. 2. The data clearly indicate that the hourly maintenance cost of a modern turbofan is only a small portion of that of an early reciprocating engine.

Reliability, another crucial powerplant characteristic, is measured in many ways by different people, and widespread agreement as to its true measure is difficult to attain. However, in an attempt to illustrate long-term trends, it is useful to show the decrease in in-flight shutdown rate over the years. As shown in Fig. 3, the change has been quite pronounced, having been reduced by a factor of 7 since 1950. It should be realized, however, that the large, high-speed modern aircraft must achieve a much higher level of reliability as compared to the small, low-speed aircraft of the past to hold the line from a cost standpoint. Figure 4 shows a measure of the loss in revenue per hour caused by a discrepancy preventing the use of the airplane. A single leaky valve or stuck solenoid can delay a 707 or DC-8 just as long as it does a DC-3, but the loss per hour to the operator is many times greater. Thus, if it had not been possible to develop greatly improved reliability into large, high-performance aircraft powerplants, the whole concept of the modern jet aircraft would have become economically impractical.

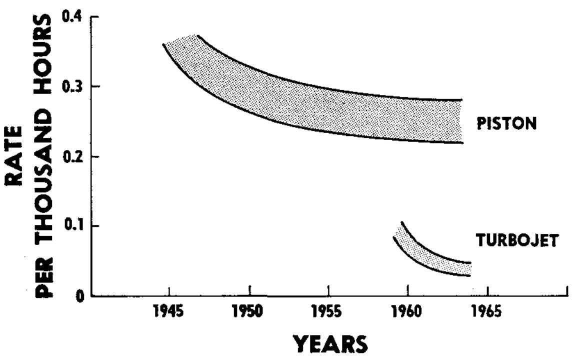

Fig. 3 Historical trend of in-flight shutdown rate of powerplants in transport aircraft, 1945–1964.

While on the subject of transport powerplants, it is of interest to consider land and sea vehicles briefly. A large cargo ship, such as a Mariner type, cruising at a speed of 20 knots, requires about 14,000 thrust hp, and a passenger train at 60 mph requires approximately 2000 thrust hp. These compare with the 20,000 thrust hp required for a modern jet. The approximate installed thrust specific fuel consumption of the different propulsion systems is shown on Table 1. There is relatively little spread between the values, although the speed of vehicles varies from 30 to 600 mph. The relative economics of the competing transportation systems is much too complex to discuss here, and even the propulsion system costs are difficult to present on a truly comparative basis. However, to give a rough feel for the current situation, Table 1 includes the best information readily available. It is seen that the initial cost of an aircraft gas turbine is very competitive with other systems, including a diesel truck engine. The maintenance cost is an even more nebulous quantity to pin down accurately, but the table shows some best estimates. Here again the transport aircraft powerplant is remarkably competitive.

Reflecting on the events of the last 30 years in the field of aircraft propulsion, one cannot help but be impressed by the great technical strides that have been made in so short a time (few other major mechanical devices have had such a dynamic and constructive history) and an understanding of the factors that made this progress possible is of value. The first factor to be considered is money. Aircraft powerplants traditionally were developed as part of a primary military weapon and, as such, received government support for engineering and development. A rough estimate of the total government expenditure for aircraft powerplant develop-

Table 1 Economic comparison of four propulsion systems[a]

Type	Installed sfc, lb/thrust, hp-hr	Initial cost, $/max hp	Maintenance cost, mils/hr/ cruise hp
DC8/707 aircraft			
JT3D turbofan	0.52	20	2–2.5
Mariner class cargo ship			
steam turbine	0.62	160	0.6–1.0
Railroad diesel locomotive	0.50	80	2–2.5
Truck V-8 diesel engine	0.48	25	5–6

[a] Cost is total installed cost including, in the aircraft, nacelle, reverser, engine, and, in others, transmission, propeller, etc.

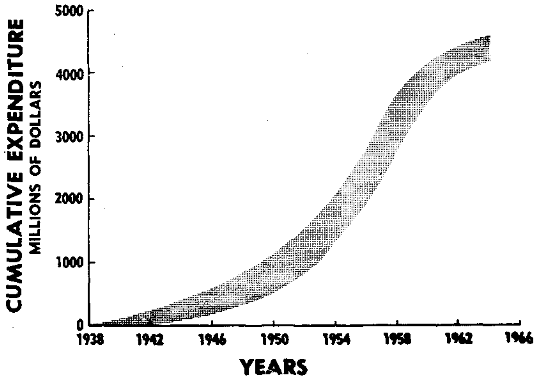

Fig. 5 Total U.S. governmental expenditure for military aircraft engine engineering and development, 1938–1964 (estimated).

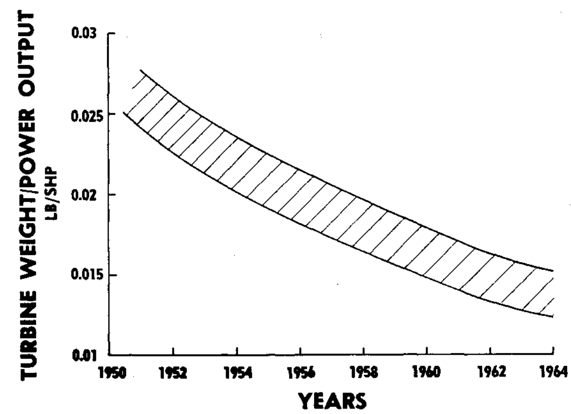

Fig. 7 Reduction in specific weight of the turbine from the JT3.

ment in the United States is shown on Fig. 5. As of this date, over four billion dollars have been spent, not including funds for procurement of prototype engines for flight test or for facilities, so the true amount is probably significantly higher than five billion.

When confronted with such tremendous expenditures one naturally conjectures whether the money was spent wisely. So-called modern management techniques are the vogue today, and in the development business, there are two conditions which, when applicable, are of great significance in determining "management" efficiency. The first is the presence of a truly competitive environment in which competing efforts may be compared on actual performance (as opposed to comparison of promises to perform); and the second is the expenditure of the available funds on hardware that can be tested and evaluated rather than on paper studies and planning exercises. It can be said that both of these conditions were applicable to the management of the aircraft powerplant development process and that they did indeed exist. The aircraft powerplant grew up in a healthy, rough-and-tumble environment. Competition, the most powerful and effective management tool we have, was established and maintained throughout. In the United States alone over 50 different turbine-type aircraft powerplants have been designed and carried to the point of actual test demonstration. Of these, only about half of the designs saw limited production and only approximately one-third reached reasonably large production and service use. Possibly some of the failures should never have been started; however, with full appreciation of the frailties of mankind, we must conclude that those who must judge cannot pick out all the failures in advance, and the very existence of many of these competing "failures"

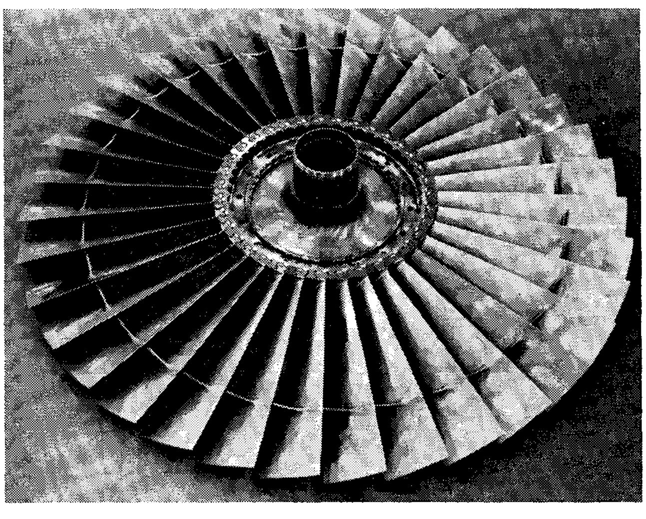

Fig. 6 Fan rotor from a JT3D engine.

contributed important stimulus to the eventual success of other engines. In fact, in retrospect, one might propose that the history of aircraft powerplant development represents an outstanding example of the results achievable by the competitive free-enterprise system of supporting and managing major technological programs.

The advancement in over-all performance of the powerplant is, of course, the result of advances in each of its many components. On a turbofan, such as the JT3D, the fan stages that operate with supersonic flow at the tip, transonic flow at midspan, and subsonic flow at the root represent a high point of sophisticated aerodynamic and structural design as applied to rotating machines. The fan stage, shown in Fig. 6, handles 466 lb/sec of air at a pressure ratio of 1.33 and weighs 148 lb. Comparable compressor stages of conventional design would weigh 540 lb to do the same job. Such progress came from the use of a new material, titanium, which made possible higher tip speeds; advanced aerodynamics, which pointed the way toward efficiency at supersonic speeds; and advanced structural techniques, which overcame the serious hurdles of flutter and vibration.

In the turbine area, the specific weight of the turbine has decreased with time, as shown on Fig. 7, mostly as a result of shorter chords for a given loading. The short chords are made possible by better understanding of the complex vibration modes encountered over the range of operating conditions. With regard to turbine inlet temperature, there is little reason for commercial subsonic powerplants to move up into the range where air-cooled blades would be required. Even with the most advanced, high bypass ratio turbofan, air cooling is not needed to give optimum performance. Figure 8 shows the relationship between turbine inlet temperature and minimum specific fuel consumption for turbojet and turbofan engines. When these characteristics are integrated into an over-all subsonic commercial airplane problem, including hot-day takeoff requirements, we find that air cooling

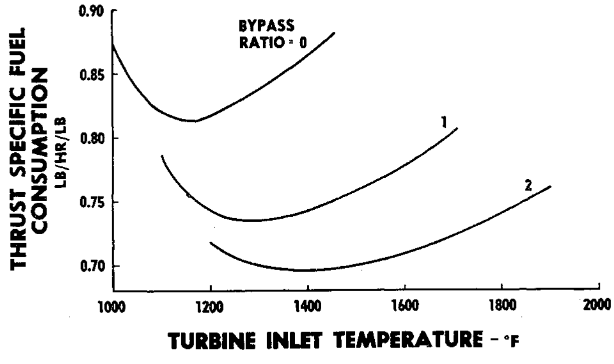

Fig. 8 Typical turbofan cycle performance at altitude cruise conditions.

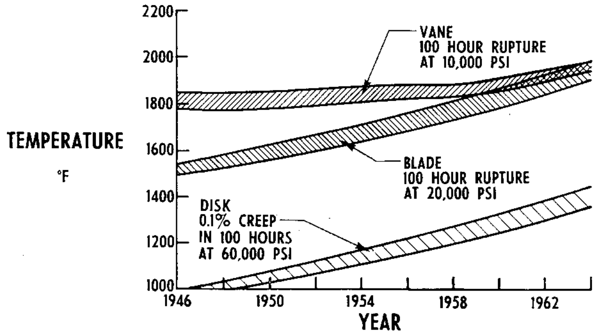

Fig. 9 Advances in turbine blade, disk, and vane material.

of the turbine is not required or desirable unless the engine is essentially too small for the job. In such a case, blade cooling provides an acceptable but not optimum solution.

Although the subsonic transport aircraft does not create a strong demand for increasing turbine inlet temperature greatly above today's levels, the supersonic transport presents a different situation. Here the thermodynamic considerations of the powerplant and aircraft system dictate that temperatures several hundred degrees higher than now in commercial use are desired for maximum cycle efficiency. It is apparent that the ability to develop blade, vane, and disk materials with adequate lift at higher temperatures, together with suitable cooling techniques, will be a major factor in determining the economics of the supersonic transport aircraft. In Fig. 9, the trend of allowable temperature for these classes of materials over the years is indicated. Significant advances have been made in blade and disk materials, but progress in vane materials has been slow. In Fig. 10, the past trend of operating temperature in military and commercial service is shown. The improvement has been gradual but steady over the years. Because of the great value to advanced military powerplants, as well as to the supersonic transport, a major effort throughout the industry is directed toward development of these higher-temperature materials.

The mechanical components, that is, the bearings, seals, pump, etc., are the unheralded heroes of the successful powerplant, although they are only noticed when they give trouble. Approximately a decade ago, antifriction bearings had a dubious reputation for reliability. One in ten was expected to fail prematurely, and no designs were available which would, even on paper, meet the load, speed, and temperature requirements of a modern turbofan engine. Shaft seals were similarly undeveloped, and one of the major feasibility questions of the high-compression ratio engine was the shaft-sealing problem. Over the past fifteen years, great effort has been expended in this field. Over 350,000 hr of component testing have been accomplished on 80 separate bearing and seal test stands at Pratt & Whitney Aircraft alone. The improvement in the performance of antifriction bearings and carbon seals has been greater than might have been anticipated. Figure 11 shows the improvement in antifriction bearing performance with time. At present, the antifriction bearing has been completely accepted as a reliable component. The technology produced in the course of aircraft bearing development has spread into other fields and resulted in a general upgrading of the art.

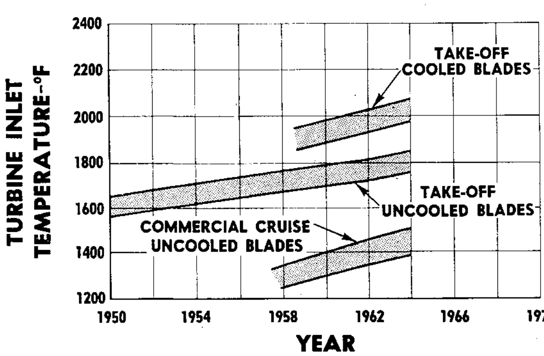

Fig. 10 Past trend in turbine inlet temperature.

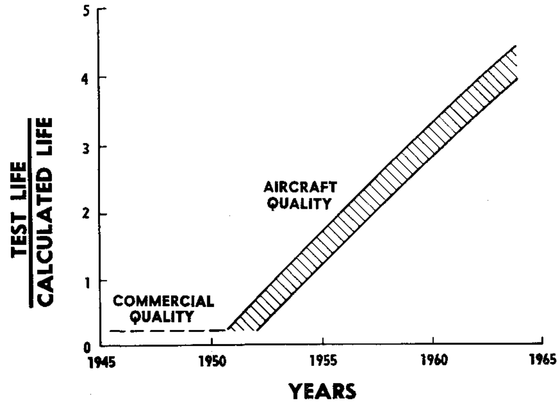

Fig. 11 Improvement in the life of the gas turbine engine main bearing since 1945.

A similar situation exists as a result of the development of carbon shaft seals for the aircraft gas turbine. A modern shaft seal operating at a face speed of over 300 fps in a 900°F environment and at a pressure difference of 120 psi is expected to have a life of many thousands of hours. Such a seal provides complete isolation of the bearing compartments from dirt and other contamination, and in contrast to the labyrinth-type noncontact seal, eliminates the performance loss associated with labyrinth bleed flow. Performance such as this is the result of many thousands of hours of painstaking testing, ranging from the initial material evaluation to environmental testing of the complete seal assembly.

In summary, we have come a long way in a short time. However, the aircraft powerplant is no longer at the frontier of our weapon development programs. Military development support has diminished, and the initiation of new military airframe and engine projects has virtually stopped. In the air-transport field there are, however, many opportunities for further technical progress and expansion of the role of air transport. Of great potential significance are the supersonic transport and the air-cargo or air-logistics area.

The supersonic transport represents a major step in technical progress. To achieve the required performance, the powerplant must operate continuously at turbine inlet temperatures above those now used for takeoff. The supersonic transport propulsion system, with the increased complexity of the variable inlet and exhaust system, must provide reliability even beyond that of our present equipment. The data from Fig. 4 are replotted on Fig. 12, and a point added to

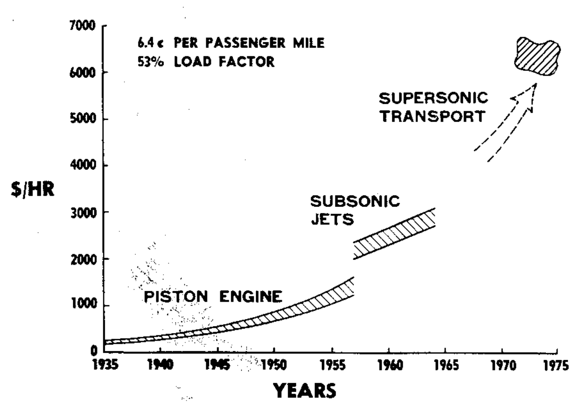

Fig. 12 Gross earning potential (expressed in dollars per operating hour) for transport aircraft powerplants.

Table 2 Comparison of direct operating costs for cargo transport aircraft

Case	Transport	
	Current	Future
Takeoff gross weight	300,000 lb	600,000 lb
Maximum payload	80,000 lb	160,000 lb
Engine	JT3D	Advanced turbofan
Direct operating cost (based on 2000 hr/year utilization)	5.3¢/ton mile	4.4¢/ton mile

show the earning potential of the supersonic transport. The inference is clear: we cannot tolerate mechanical delays. The necessary degree of reliability will be achieved only by hard and painstaking work. In the case of the supersonic transport, the required performance and reliability can be obtained, but only if the nature and scope of the problem is recognized, and a development program of sufficient magnitude is undertaken at an early date.

The air-cargo area appears to be in a very different phase. The potential of air cargo and its impact on the air-transport industry is generally recognized. Here, however, there is at hand the powerplant technology required to do the job. It becomes daily more apparent that the large turbofan-powered aircraft is a practical, successful, economical device and may well be one of the fundamental machines invented by mankind. Furthermore, there are no obvious limits in the size of turbine-type powerplants, and it would be possible to build even larger and more economical aircraft in the future. By way of illustration, the relative direct operating cost of a current cargo jet and a possible new aircraft powered by new, large turbofan engines are compared in Table 2. The new

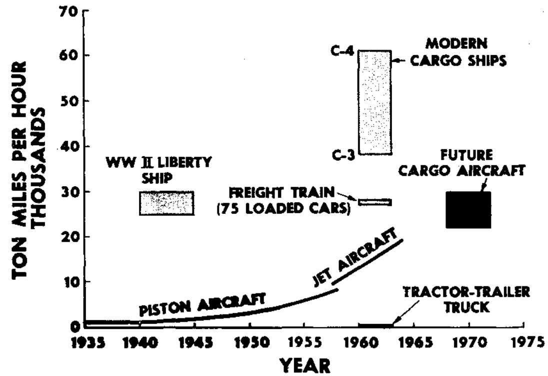

Fig. 13 Growth of productivity in various modes of transportation (based on typical air-cargo density of 8 lb/ft^3).

aircraft is conceived to be twice the gross weight and payload of our largest transports today and would be powered by engines substantially lighter and more efficient than present powerplants. Direct operating costs for such a machine are conjectured to be on the order of 15% lower than current transports, and the productivity, expressed in ton-miles per hour capability, would put the airplane in the range of other general cargo transportation for the first time. In Fig. 13 this productivity growth is shown in relation to air transports over past decades, and the comparable load-carrying ability of rail and ship transports is indicated for a representative cargo density of 8 lb/ft^3. It appears, then, that the long-awaited expansion of air cargo can and will become a reality, owing to today's technology, and that the growth will be timed by the dissemination and acceptance of what the air transport industry can now offer.