Technology for Design of Transport Aircraft

Lecture Notes for MIT Courses

Sem. 1.61 Freshman Seminar in Air Transportation

and

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A) Measures of Performance

The common measures of performance for a transport aircraft are listed below:

1. Cruise Performance - Payload (passengers) versus Range (s. miles)
2. Cost Performance - ($/block hour, $/available seat mile)
3. Runway Performance - takeoff and landing distances (feet)
4. Speed Performance - max. cruise speed (mph)
5. Noise Performance - noise footprint size, or peak noise (PNdb)

For a long range transport aircraft, the designer maximizes cruise and cost performance subject to constraints specified for takeoff and landing, speed, and noise performance. If the designer optimizes takeoff and landing performance as for STOL or VTOL transport aircraft, then cruise performance will be less than optimal, and these aircraft will only perform well over short cruise ranges. Introduction of noise constraints into the design of transport aircraft requires good knowledge of the noise generation characteristics of engines and other propulsive devices as a function of size and technology, and like all constraints will cause less than optimal cruise and takeoff and landing performance.

The designer's problem is to create an aircraft design which is matched to some design mission stated in terms of desired or required levels of these measures of performance.

Here we shall discuss the design parameters which determine cruise performance for a conventional subsonic jet transport, and fix other design considerations. We shall assume the aircraft burns climb fuel to reach cruising altitude, and ask ourselves how far the aircraft can carry a given payload at cruising altitude. This simple analysis brings out the major factors in establishing the cruise performance. We shall see how the current state of aeronautical technology determines the current size of transport aircraft,(and therefore its operating cost) and how different sizes of transport are needed to provide the cost optimal vehicle for different given payload-range objectives.

B) Technology

We have three areas of aeronautical technology, aerodynamics, structures, and propulsion, which keep improving, and which cause newer aircraft to be superior as time goes on. In discussing cruise performance, we will use a single measure for the level of technology in each area.

Areas of Technology	Measure of Technology Level	
1. Aerodynamics	V(L/D)	= speed x (lift/drag ratio in cruise)
2. Structures	W_E/W_G	= empty weight fraction
		= (operating empty weight/gross weight)
3. Propulsion	SFC	= Cruise specific fuel consumption (lbs. of fuel per hour/lbs. of thrust)

B.1 Aerodynamics Technology

The lift/drag ratio, L/D, in cruise for present subsonic aircraft is a number like 16-17, i.e. for every 16 lbs of weight, there is a requirement for 1 lb. of thrust. The steady state forces on the aircraft are shown in Figure 1. The aircraft weight W_G equals the lift L. Dividing the lift by the L/D ratio gives the drag D, which requires an equal thrust, T.

While L/D ratios of up to 40 can be obtained for sailplanes at low speeds by using large span, high aspect ratio wings and good airfoil sections, the objective for transport aircraft turns out to be the maximization of the product of speed and L/D, i.e. to achieve good L/D values at higher speeds. This objective must be compromised by aerodynamic requirements for takeoff and landing performance which demand a larger wing area than otherwise would be used for cruise.

A plot of values of V(L/D) is given by Figure 2 which shows the

Figure 1 STEADY STATE FORCES IN CRUISE

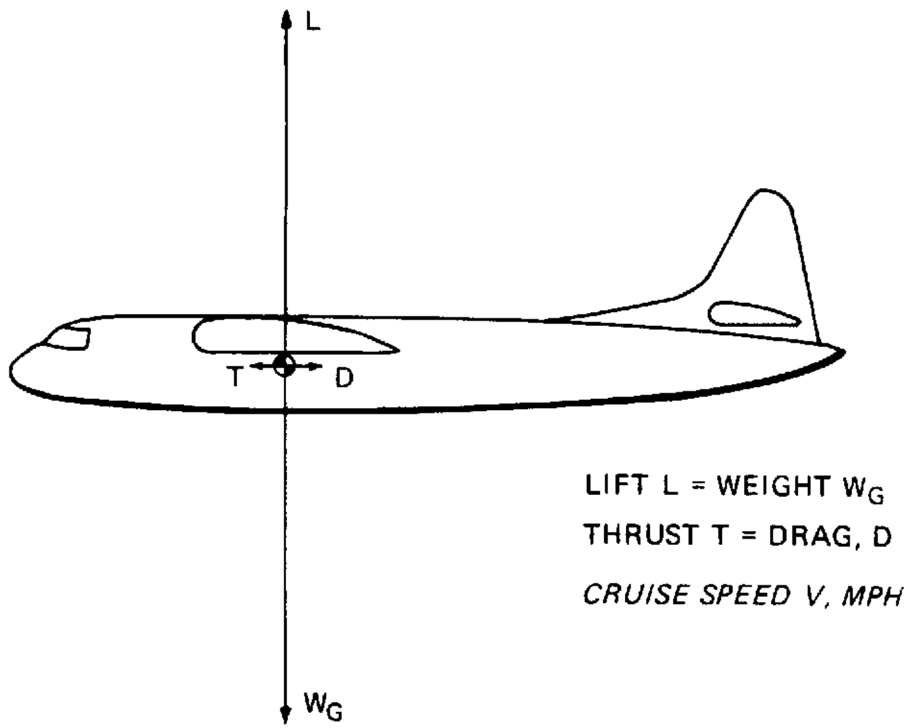
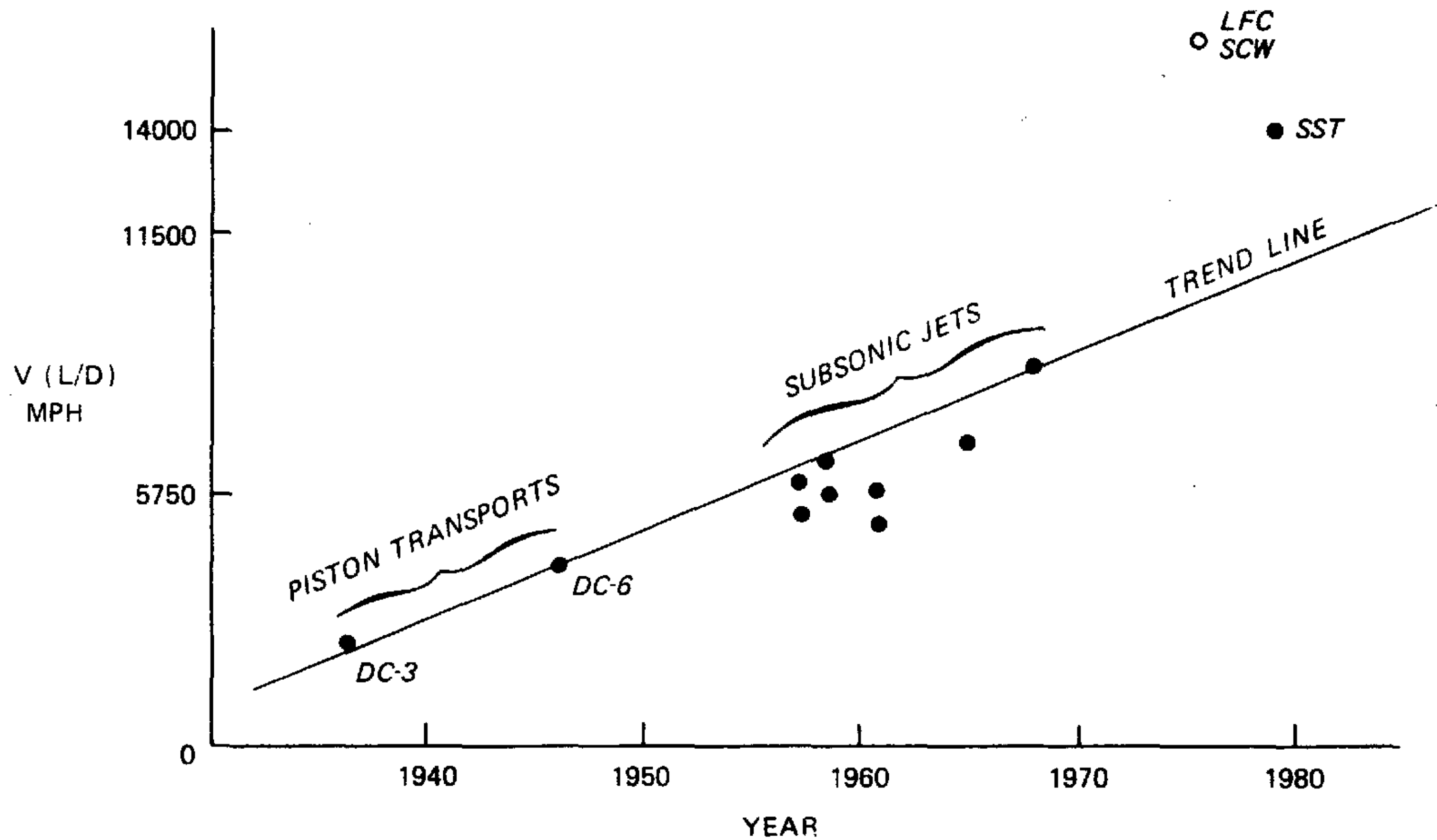


Figure 2 TREND OF V(L/D) FOR TRANSPORT AIRCRAFT



steady improvement for transport aircraft over the past 35 years. These improvements have been developments like laminar flow airfoils, thinner wings, swept wings, higher wing loadings in cruise because of better high lift devices, etc. The supercritical wing section (SCW) and perhaps laminar flow control (LFC) wing are developments which have promise of continuing improvement.

Notice that although the SST has L/D values of only 8, its speed on the order of 1800 mph gives very high values for V(L/D).

B.2 Structures Technology

Here we use the "empty weight fraction" as a measure of structures technology although it contains other than the weight of the aircraft structure.

We shall use the following, non-standard breakdown of the weight of a transport aircraft:

We define W_G = takeoff gross weight

W_{Gi} = initial cruise weight

W_{Gf} = final cruise weight

The total fuel load is divided into:

W_F = total fuel weight

W_{FC} = fuel burn in climb

W_{FB} = fuel burn in cruise

W_{FR} = weight of fuel reserve

Then $W_{Gi} = W_G - W_{FC}$

$$W_{Gf} = W_G = W_{FC} - W_{FB} = W_{Gi} - W_{FB}$$

For simplicity, we shall ignore fuel burn in descent, and range during climb, and shall be computing only range in cruise. We shall assume that $W_{FC} = W_{FR} = 5\%$ of W_G.

We define the operating weight empty, W_E, as made up of:

$$W_E = W_S + W_{FE} + W_{PP} + (W_{FR})$$

where W_S = weight of aircraft structure

W_{FE} = weight of furnishings and equipment (pilots, seats, galley, toilets, radios, etc.)

W_{PP} = weight of power plant

W_{FR} = weight of reserve fuel.

Notice that for convenience, we include the reserve fuel in the "operating weight empty" although that is not standard practice.

We define the useful load, W_U, as the difference between the initial cruise weight, W_{Gi} and W_E

$$W_U = W_{Gi} - W_E = W_G - W_{FC} - W_E$$

The useful load will consist of some combination of payload, W_P and fuel burn in cruise W_{FB}. We are going to examine the effects of range requirements on the payload fraction, W_P/W_G, which can be achieved. As range is increased, more of the useful load must be devoted to fuel, thereby decreasing the payload fraction.

Typical values of the "empty weight fraction" (without reserve fuel) for current aircraft are given by Table 1. Notice that the empty weight fraction is roughly 50%, and that lower values are obtained for long haul, large size aircraft, where emphasis is placed upon achieving a low value, and where some economy of scale

TABLE 1. Typical Values of Basic Empty Weight/Max Gross Weight

Passenger Aircraft	Empty Weight Fraction	Max. Gross Weight	Range
747	.491	710.	5,790
DC-10-30	.474	555.	5,400
L-1011	.550	426.	2,878
DC-8-63	.437	350.	4,500
707-320B	.423	327.	6,160
727-200D	.552	175.	1,543
Trident-3B	.554	150.	2,430
Mercure	.557	114.6	1,100
DC-9-40	.488	114.0	1,192
737-200B	.538	109.0	2,135
BAC-111-475	.532	97.5	1,682
F-28-2000	.557	65.0	1,301
VFW 614	.656	41.0	1,553
VAK-40	.570	36.4	807
Falcon 20T	.607	29.1	641
DHC-6	.560	12.5	745
Concorde SST	.44	385.	4,020
S-61 helicopter	.62	19.00	275
Freighters			
747F	.428	775.0	2,880
CSA	.425	764.5	3,500
707-320C	.402	332.0	3,925
L100-30 (C130)	.468	155.0	2,800
		x 10^3 lbs.	St Miles

(Source: Jane's 1971-72)

may occur for fixed equipment like radios, galley, etc.

The major portion of the empty weight fraction is the structures weight, W_S, which is usually 30% of the gross weight. A diagram of the value of the "structures weight fraction" is shown by Figure 3. Since the construction of the DC-3 there has been very few basic changes in structural technology. However, there is considerable promise currently of new developments which use composite materials, and different construction techniques to provide extremely light weight and rigid structures. These are expensive now, but future development work may reduce their costs.

B.3 Propulsion

The specific fuel consumption is given in terms of rate of fuel burned per lb. of thrust for the engine. Here we want the cruise SFC values at cruise altitude and speed. For the early jets, SFC had a value of roughly 1.0 in cruise, which meant that a 10,000 lb. thrust engine would consume 10,000 lbs. of fuel in one hour. For present fan engines, SFC is roughly 0.6, so that only 6,000 lbs of fuel per hour would be consumed by current engines.

Another common measure of propulsion technology is the thrust to weight ratio of the engines, but here we have made it a part of the operating weight fraction as a measure for structures technology.

The most remarkable improvement over the last decade has been the improvement in cruise SFC for the engines used by subsonic transport aircraft. This is illustrated in Table 2 and Figure 4 which show the almost 50% reduction in fuel consumption by current

Table 2. Specific Fuel Consumption for Current Transport Engines

		Takeoff Conditions Static		Cruise Conditions		
Engine	Bypass Ratio	Thrust (lbs)	SFC	Mach	Altitude	SFC [9]
JT3-C	0	13,500	0.77	.69	35000	0.92
CONWAY	0.6	20,400	0.62	.83	36000	0.84
SPEY	1.0	9,850	0.54	.78	32000	0.76
JT8-D	1.03	14,000	0.57	.80	35000	0.83
JT3-D	1.4	18,000	0.52	.90	35000	0.835
TFE-731	2.55	3,500	0.49	.80	40000	0.82
M-45	2.8	7,760	0.45	.65	20000	0.72
CF-6-6	6.25	40,000	0.34	.85	35000	0.63
ASTAFAN	6,5	1,5622	0.38	.53	20000	0.63

Figure 3 TREND FOR STRUCTURES WEIGHT FRACTION FOR TRANSPORT AIRCRAFT

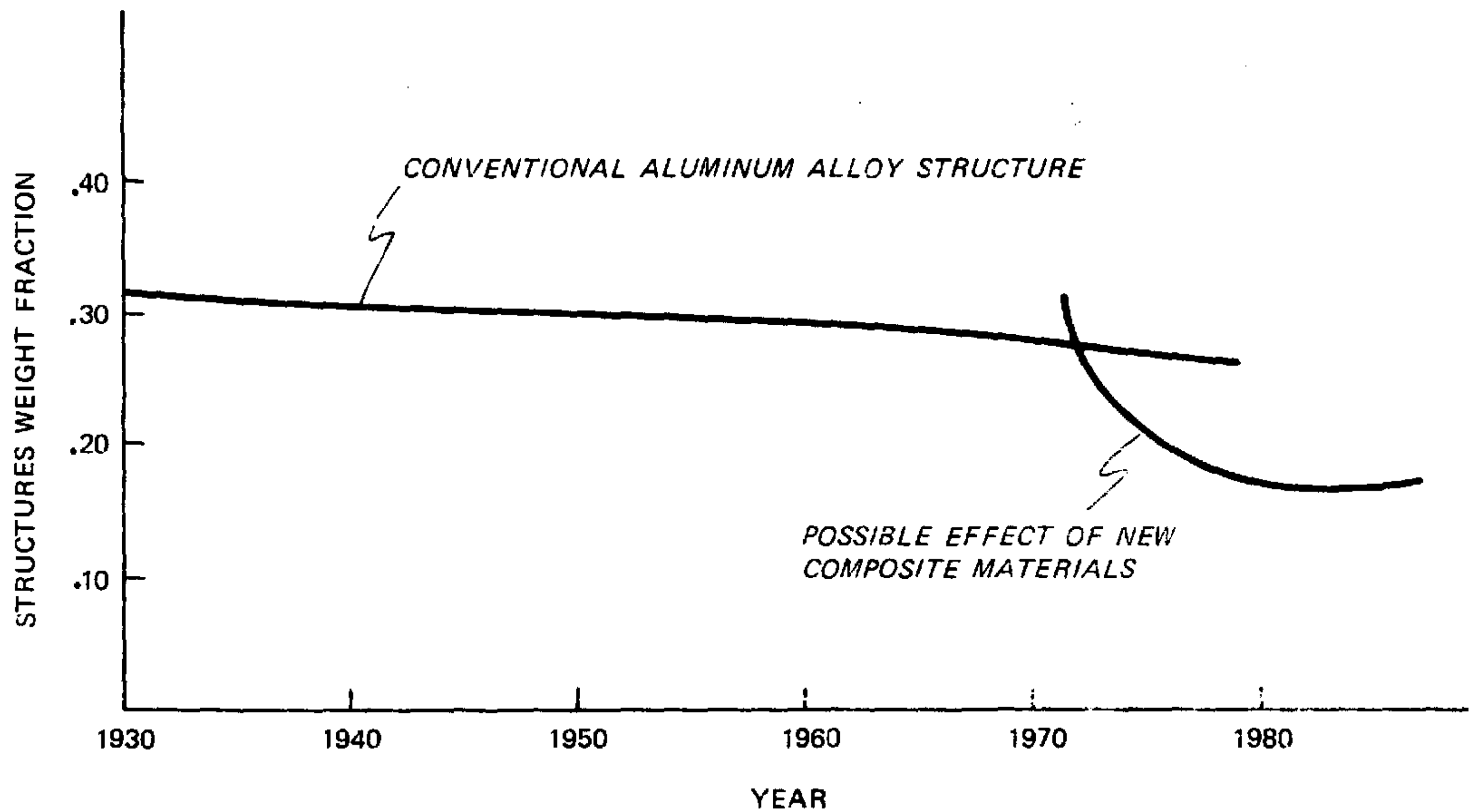


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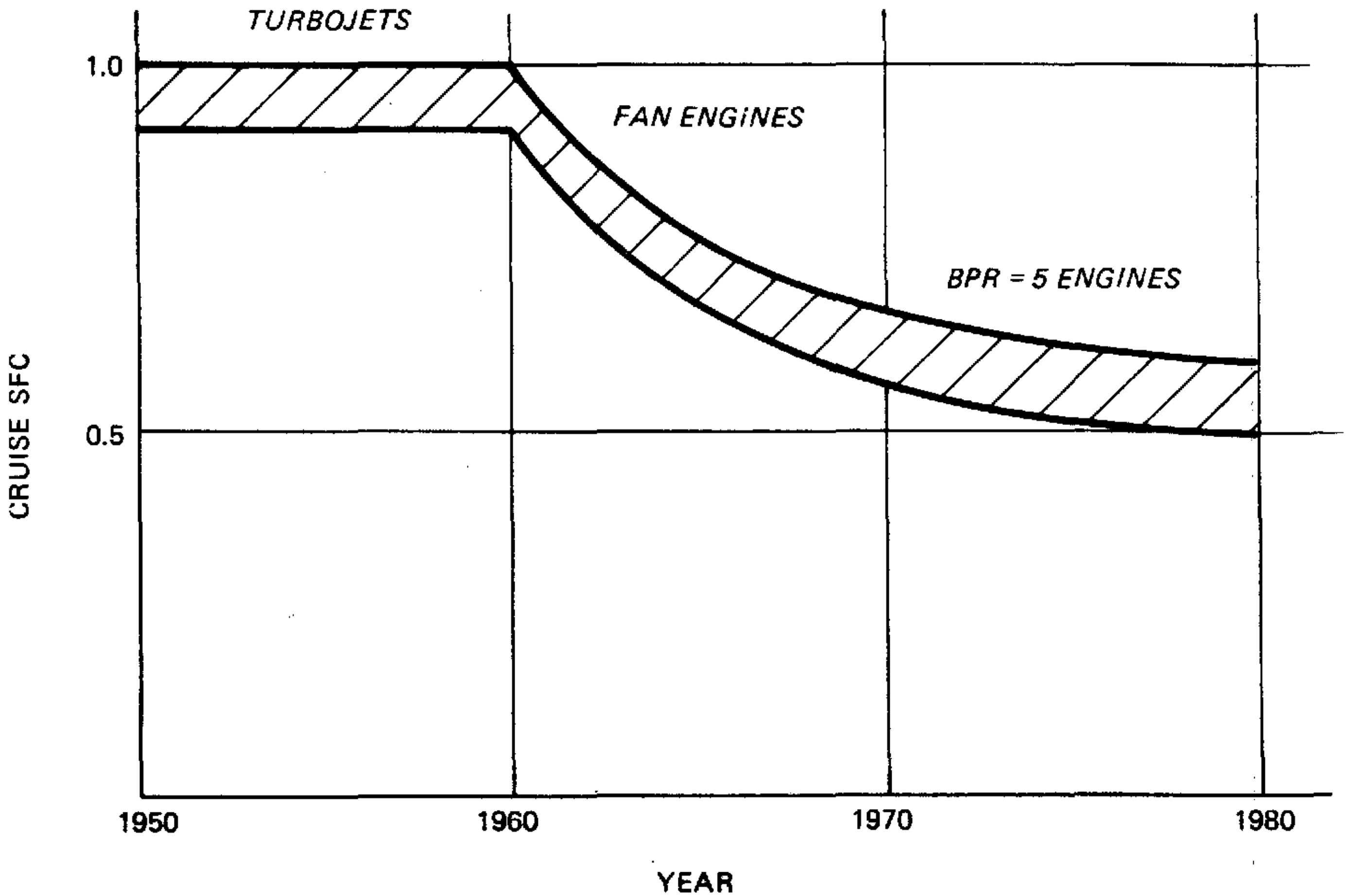
Figure 4 TRENDS IN PROPULSION — SFC



high bypass ratio fan engines over the initial pure jet engines. This improvement is due to better propulsive efficiencies from the fan, improved component efficiencies for engine components like compressors, turbines, combustors, etc., and higher cycle temperatures due to improved materials and technology in the design and construction of the turbine blades.

C) Determination of Range-Payload Performance

C.1 Short Range Aircraft

Where the fuel burn, W_{FB} is a small fraction of W_G, we can assume that W_G remains constant during cruise, or $W_{Gi} \approx W_{Gf} \approx W_G$.

If we define R = cruising range (s. miles)

m = mileage factor, (s. miles per lb. of fuel)

$$\text{Then} \quad R = m \cdot W_{FB} \qquad (1)$$

We can express m in terms of V, T, and SFC

$$m = \frac{V}{T(SFC)} = \frac{\text{s. miles/hr}}{\text{lbs of fuel/hr}} = \frac{\text{s. miles}}{\text{lb. fuel}}$$

But from Figure 1, $\frac{T}{W_G} = \frac{D}{L}$, or $T = \frac{W_G}{(L/D)}$

$$\therefore \qquad m = \frac{V}{SFC} \cdot \frac{(L/D)}{W_G}$$

Substituting m in (1)

$$R = \frac{V(L/D)}{SFC} \cdot \left[\frac{W_{FB}}{W_G}\right] = r \cdot \left[\frac{W_{FB}}{W_G}\right]$$

where r is called "specific range" (s. miles)

and $\frac{W_{FB}}{W_G}$ is called "fuel burn fraction"

Note: r has the dimensions of s. miles

e.g. if L/D = 16, SFC = 0.6 lbs. of fuel/hr. per lb. of thrust

V = 550 mph

Then $r = \frac{550 \times 16}{0.6} = 14,700$ s. miles

We shall use these assumed values in later examples.

a) <u>If no payload is carried</u>, then $W_P = 0$, $W_U = W_{FB} = W_{Gi} - W_E$,

then the maximum cruise range, R_{max}

$$R_{max} = r\left[\frac{W_{FB}}{W_G}\right] = r \cdot \left[\frac{W_U}{W_G}\right] = r \cdot \left[\frac{W_{Gi} - W_E}{W_{Gi}}\right] \qquad (3)$$

$$= r.(1 - \frac{W_E}{W_{G_i}})$$

So, our structures technology parameter is a strong determinant of the maximum range for a fuelled aircraft. If the "empty weight fraction" can be reduced, it increases the "fuel fraction", or "useful load fraction", and thereby the maximum range

b) If payload is carried, then $W_{FB} = W_{Gi} - W_E - W_P \quad W_G - W_E - W_P$

and for any given payload

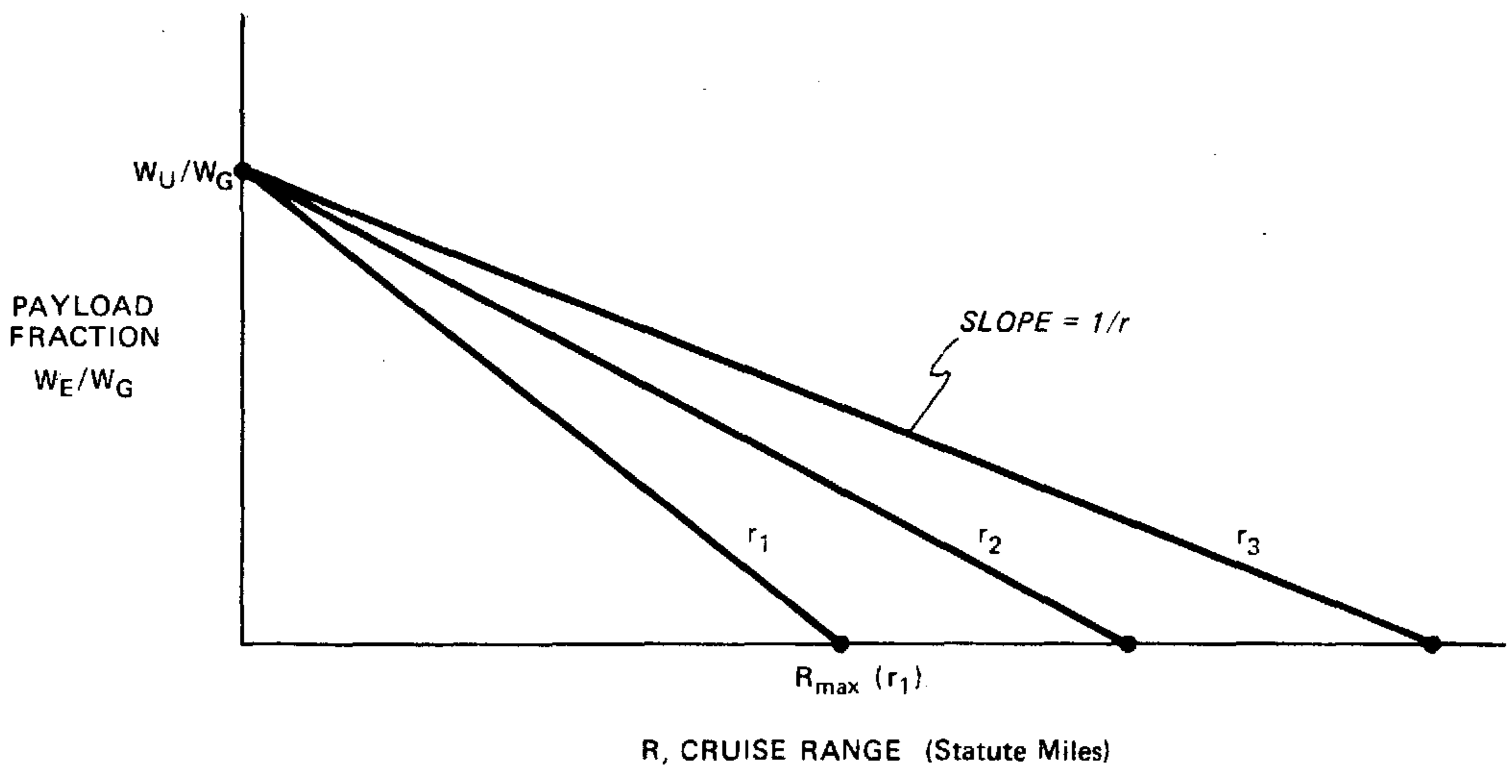
$$R = r\left[\frac{W_{FB}}{W_G}\right] \approx r\left[\frac{(W_G - W_E - W_P)}{W_G}\right]$$

$$= R_{max} - r \cdot \left[\frac{W_P}{W_G}\right] \qquad \text{from (3)}$$

where $\frac{W_P}{W_G}$ is called the "payload fraction".

We can plot the payload fraction against R in Figure 5

Figure 5 PAYLOAD FRACTION versus RANGE



where $$\frac{W_P}{W_G} = \frac{1}{r} \cdot (R_{max} - R) \qquad (5)$$

At $R = 0$, $$\frac{W_P}{W_G} = \frac{R_{max}}{r} = \frac{W_U}{W_G}$$ from equation (3)

For this short range case the variation of payload fraction is linear in R, decreasing to zero at R_{max}. As r is improved, the payload fraction at any range improves, and R_{max} increases. As $\frac{W_E}{W_G}$ is decreased, $\frac{W_U}{W_G}$ is increased which gives higher payload fractions for all ranges.

This simple analysis has been for the short range case where W_G may be considered as remaining constant over the cruise, or the fuel burn fraction is small for the short range mission.

C.2 Long Range Aircraft

For a long range aircraft, the change in W_g during the flight cannot be ignored (W_g = instantaneous gross weight)

e.g. a B-707-300 on a NY to Paris trip

W_{G_i} out of NY $\approx$ 315000 lbs

W_{G_f} at Paris $\approx$ 230000 lbs

so final weight is 2/3 of initial weight.

Equation 2 still applies over a small increment of cruise so we resort to the calculus which produces a different, more precise formula called the "Breguet Range Equation". Equation (2) becomes

$$dR = \frac{r}{W_g} \cdot d\,W_{FB}$$

where dR = increment of range

$d\,W_{FB} = -d\,W_g$ = increment of fuel burn

= decrease in W_g

$$\therefore \quad dR = r \cdot \left[\frac{-dW_g}{W_g}\right]$$

If the value of W_g at start of cruise is W_{gi}, at end of cruise is W_{gf}, then we have to integrate from W_{gi} to W_{gf} to get the exact formula for R

$$R = r \cdot \int_{W_{Gi}}^{W_{Gf}} \frac{-dW_g}{W_g} = r \int_{W_{G_f}}^{W_{Gi}} \frac{dW_g}{W_g} = r.\ln\left[\frac{W_{Gi}}{W_{G_f}}\right] \qquad (2a)$$

If we compare to Equation (2) we see that the specific range is now modified by a logarithmic expression involving the initial and final cruise gross weights;

i.e. $\frac{W_{FB}}{W_G} \approx \frac{W_{FB}}{W_{Gf}}$ is now replaced by $\ln\left[\frac{W_{Gf} + W_{FB}}{W_{Gf}}\right] = \ln\left[1 + \frac{W_{FB}}{W_{Gf}}\right]$

a) <u>If no payload is carried</u>, then $W_P = 0$, $W_U = W_{FB} = W_{Gi} - W_E$ then the maximum range becomes,

$$R_{max} = r.\ln\left[\frac{W_{Gi}}{W_{Gf}}\right] = r\ \ln\left[\frac{W_{Gi}}{W_E}\right] = r\ \ln\left[\frac{1}{W_E/W_{Gi}}\right] \qquad (3a)$$

As before, if W_E/W_{Gi} is reduced, R_{max} will be increased. However since W_g now decreases as fuel is burned, R_{max} is greater in (3a) than from the sample case (3).

For example if r = 14,700 as before, and $\frac{W_{FC}}{W_G} = .05$, and we assume $\frac{W_E}{W_G} = 0.60$, $\frac{W_E}{W_{Gi}} = \frac{0.60}{0.95} = 0.632$

or $\frac{W_{FB}}{W_G} = 0.35$, $\frac{W_{FB}}{W_{Gi}} = \frac{0.35}{0.45} = 0.370$

From (3), $R_{max} = 14,700 \times (0.37) = 5450$ s. miles in cruise

From (3a), $R_{max} = 14,700 \ln \frac{1}{0.632} = 14,700 \ln (1.58) = 6770$ s. miles

The correct formula makes a 1320 s. mile difference in R_{max}!

b) <u>If payload is carried</u>, then $W_{FB} = W_{Gi} - W_E - W_P$, and the payload

becomes $R = r.\ln \left[\frac{W_{Gi}}{W_{Gf}} \right] = r.\ \ln \left[\frac{W_{Gi}}{W_E + W_P} \right] = r.\ln \left[\frac{1}{W_E/W_{Gi} + W_P/W_{Gi}} \right]$

If we unlog this expression

$$\frac{W_E}{W_{Gi}} + \frac{W_P}{W_{Gi}} = e^{-R/r}$$

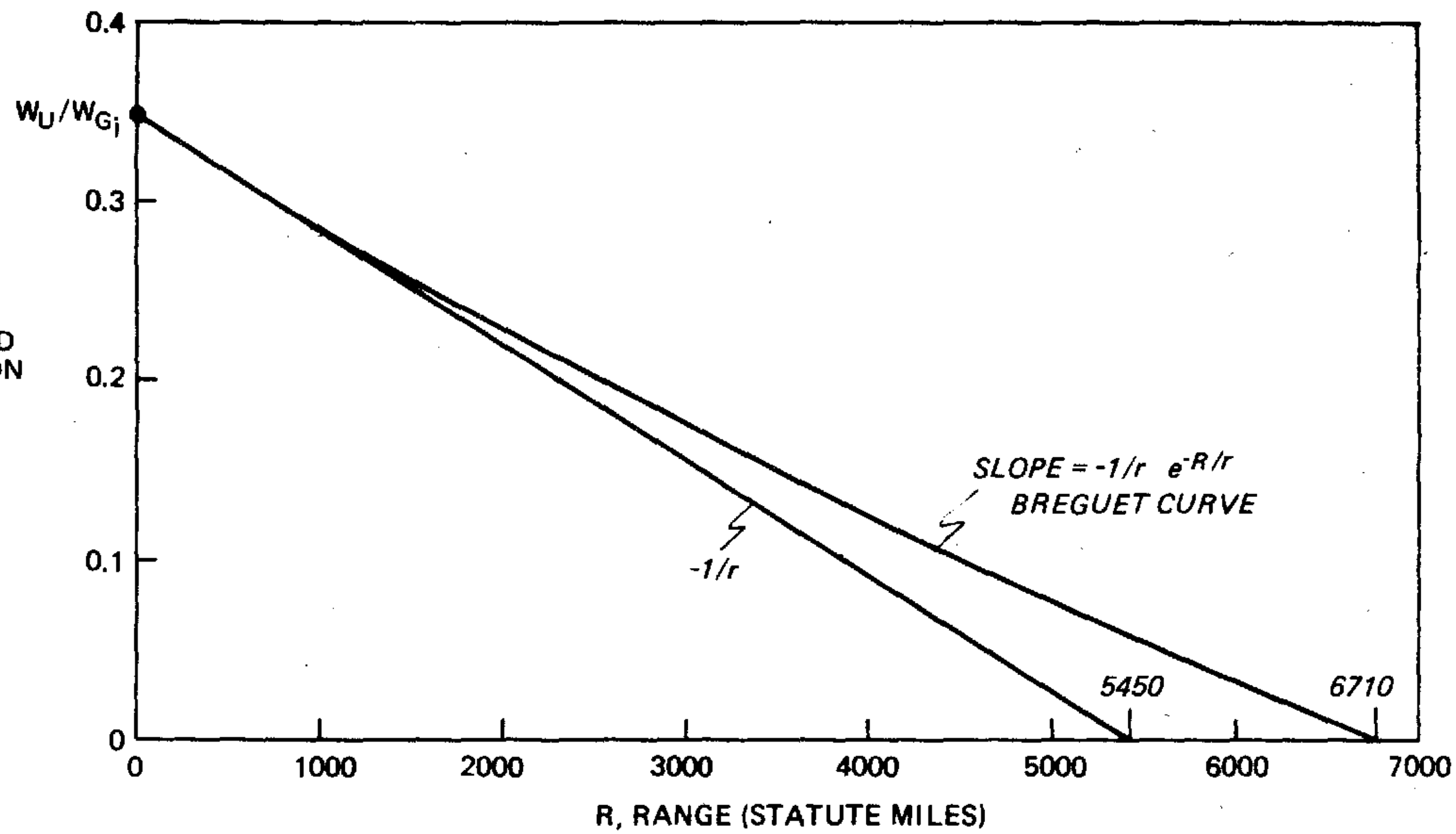
or payload fraction, $\frac{W_P}{W_{Gi}} = e^{-R/r} - \frac{W_E}{W_{Gi}}$ 4(a)

At $R = 0$, $\frac{W_P}{W_{Gi}} = 1 - \frac{W_E}{W_{Gi}} = \frac{W_U}{W_{Gi}}$ as before for short range case

At $R = R_{max}$, $\frac{W_P}{W_{Gi}} = 0$

As shown in Figure 6, the payload fraction curve is now a shallow exponential. Near maximum range, the payload fraction becomes very small, and very sensitive to errors in estimating technology measures.

Figure 6 PAYLOAD FRACTION versus RANGE



D. Weight-Range Diagram

We can now show the weight breakdown versus design range for a conventional subsonic jet at a given level of aircraft technology. From Figure 7, we see that the payload fraction is strongly dependent on design range.

For a long range aircraft, the payload fraction will be very small, and aircraft payload-range performance will be very sensitive to the values of r and W_E/W_G which can be achieved. For example, if W_P/W_G is 10% for some design range, then every lb. saved in empty weight converts directly to payload, and saves 10 lbs. in design gross weight.

However, for a short range aircraft where W_P/W_G may be 33%, then every lb. saved in empty weight still converts directly to payload, but saves only 3 lbs. in design gross weight.

Therefore, a critical decision in the design of any transport aircraft is the choice of the full payload-design range point. Once this is selected, we have a good idea of the required aircraft gross weight for a given level of aircraft technology, and consequently, as we shall see, its probable purchase cost and operating cost.

For our example technology, we can compute payload fractions at design ranges from 6000 to 500 s. miles. Table 3 gives the result of applying equation (3a), and quotes typical gross weights for a 50,000 lb. and 100,000 lb. payload, or roughly a 250 and 500 passenger vehicle.

Figure 7 WEIGHT BREAKDOWN versus RANGE

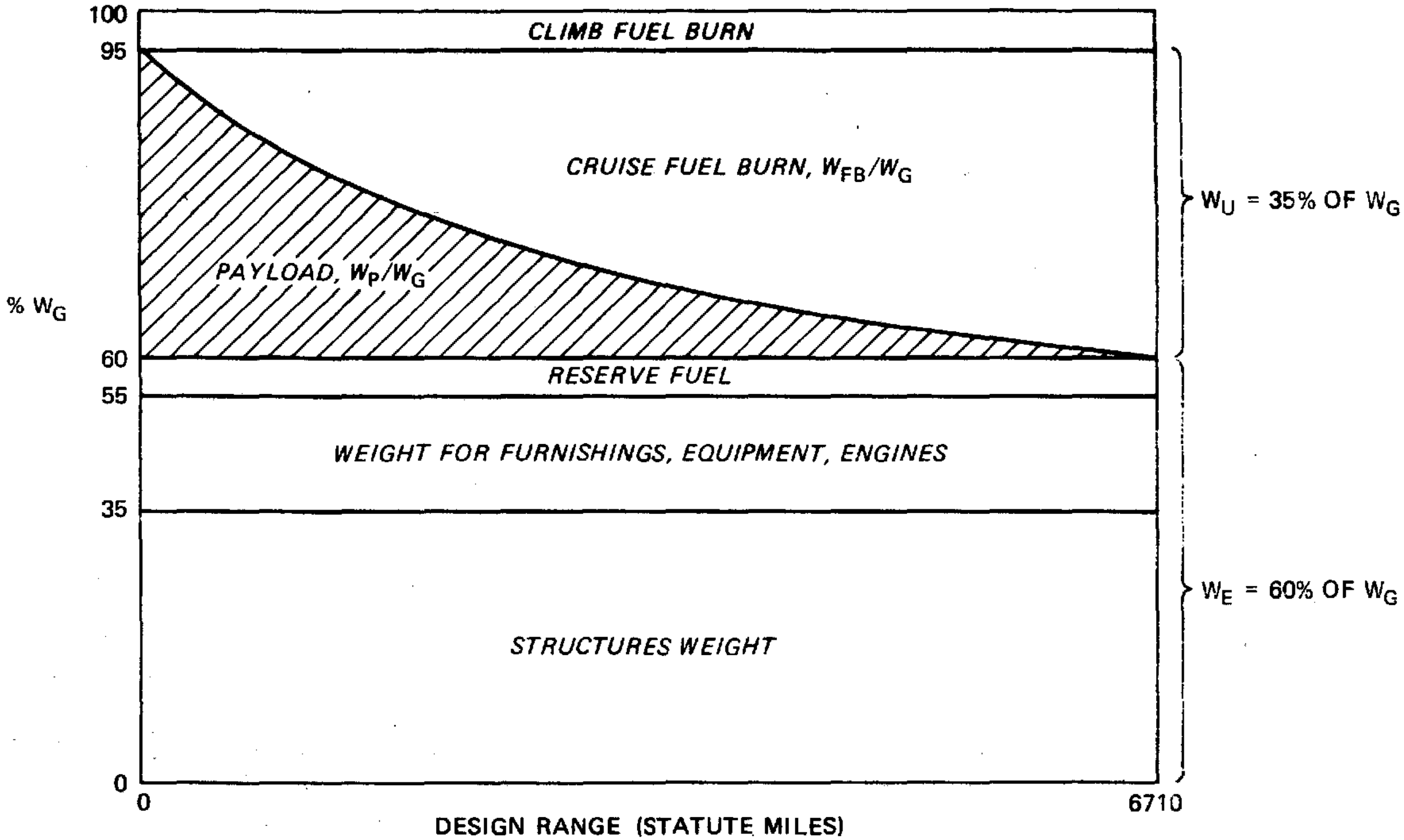


TABLE 3. SIZING TRANSPORT AIRCRAFT

Cruise Design Range (s. miles)	Payload Fraction (W_P/W_G)	W_G/W_P (lbs. per payload)	Gross Weight 250 pax or 50,000 lbs.	Gross Weight 500 pax or 100,000 lb
6000	.04	25	1.25×10^6	2.5×10^6
5000	.075	13.3	666,000	1.33×10^6
4000	.122	8.20	410,000	820,000
3000	.177	5.65	282,000	565,000
2000	.230	4.35	217,500	435,000
1000	.284	3.52	176,000	352,000
500	.317	3.15	158,000	315,000

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E) Payload-Range Diagrams

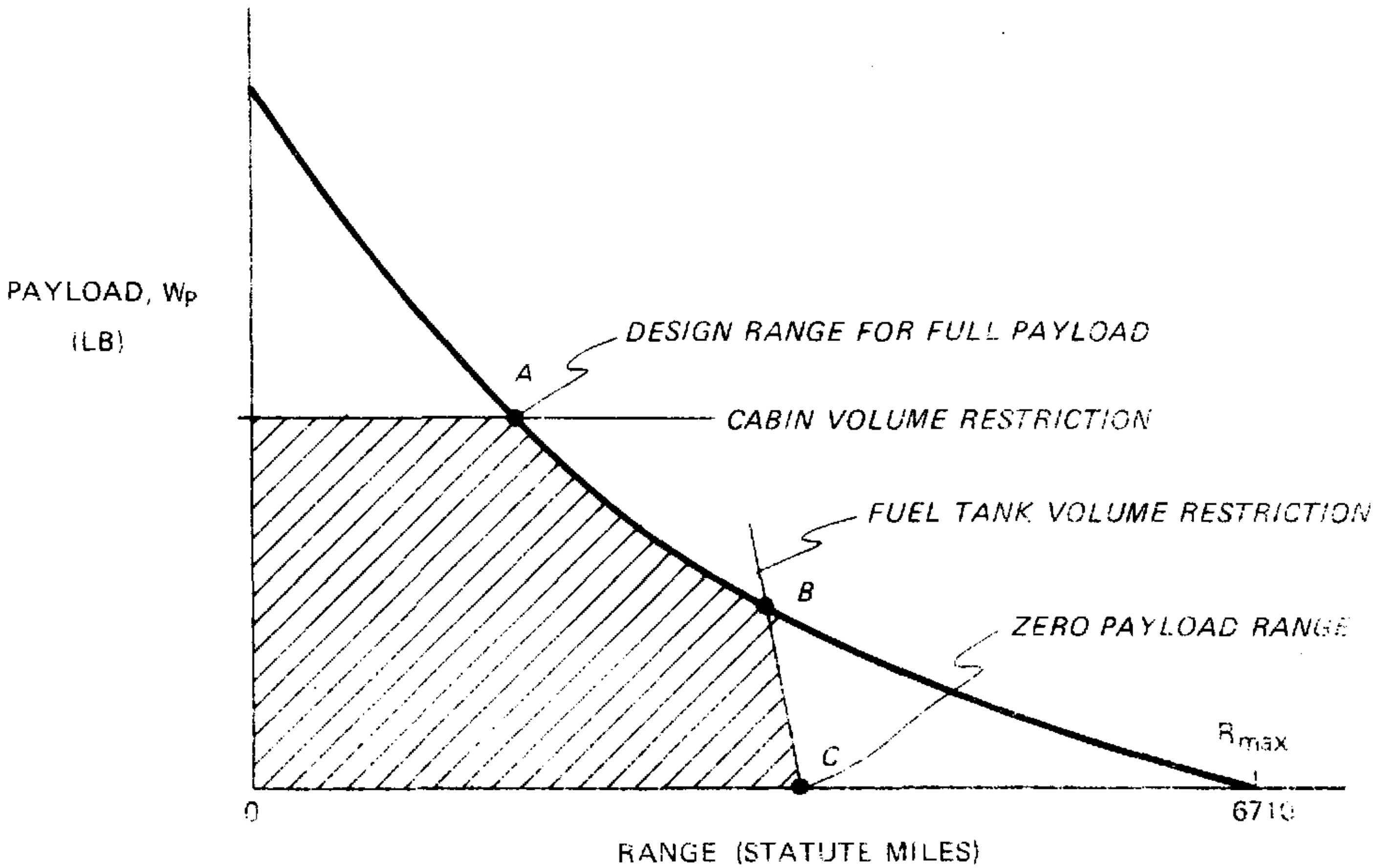
Having chosen the design range point for a given payload weight, there are two volume decisions which subsequently must be made. First, a fuselage volume must be selected to comfortably house a number of passengers corresponding to the payload, or a cargo load of a given density, or container configuration. Secondly, a fuel tank volume must be selected.

The fuselage volume restriction prevents the addition of passengers or cargo on trips of shorter than design range where the fuel load can be reduced. The fuel volume restriction prevents extending the ranges on trips where less than full payload is being carried. These volume restrictions are shown in Figure 8.

Point A is the design range for full payload. Point B is a point where the fuel tanks are completely filled and a reduced payload is carried. Along the lone AB the aircraft operates at full gross weight, and trades off payload and fuel load. Point C is the zero payload range, and the aircraft takeoff weight is reduced from the maximum gross weight as we move along the line BC. Any payload-range point inside the shaded area can be handled by the aircraft by operating at reduced gross weights.

By choosing different volumes, the designer establishes points A and B, and can provide quite different range-payload performance for transport aircraft of constant gross weight as exemplified by the exponential curve which is now dimensional on Y-axis.

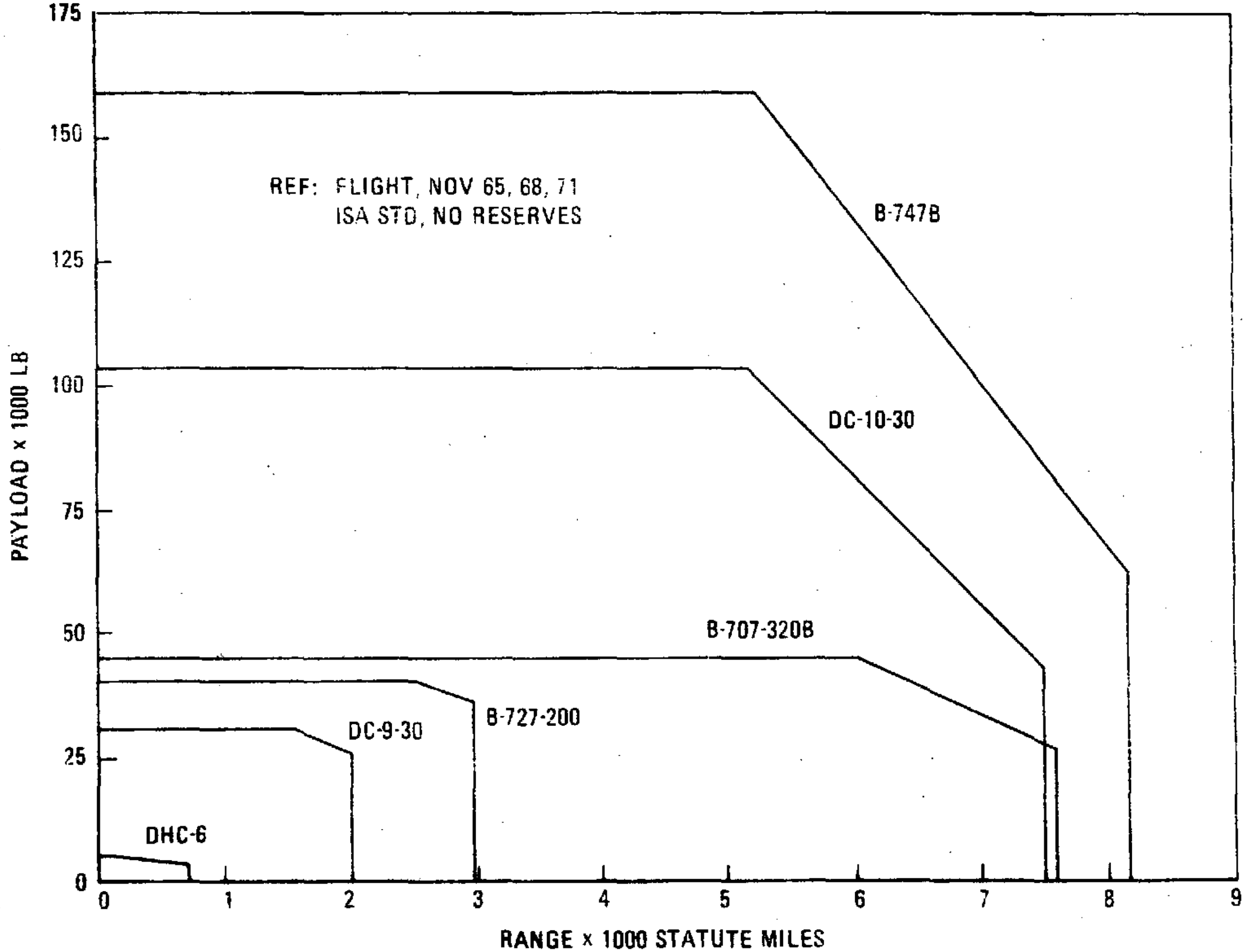
Figure 8 VOLUME RESTRICTIONS ON RANGE-PAYLOAD PERFORMANCE



We now have derived one of the two basic diagrams describing transport aircraft performance. It is called the "payload-range" diagram. Payload-range diagrams for various current jet transports are shown in Figure 9. Since smaller aircraft are cheaper to own and operate, airlines buy several kinds of aircraft even at a given level of technology to match their fleet capabilities to their traffic loads on routes of varying distances. Traffic load points should be kept near the outer boundaries of the range-payload diagrams for profitability. This will be shown later using the second basic diagram, the direct operating cost-range curve.

As technology improves, a smaller gross weight airplane can be constructed to provide the same payload-range capability at lower costs. For long range aircraft, these technology improvements can provide spectacular changes in gross weight. For example, if the present cruise engines of SFC = 0.60 did not exist, a transport aircraft of the general size of the B-747 (i.e. the second aircraft in Table 3, Range = 4000 miles, Payload = 100,000 lbs) would increase in gross weight from 820,000 lbs to 1.67 million lbs. if the cruise SFC were only 0.8. One can safely say that the C-5A, B-747, DC-10, L-1011, etc. would not have been built if it were not for the development of this better engine technology. The construction of new engines of smaller thrust will similarly cause new smaller transports to be built in future years to replace the present DC-9 and B-727.

Figure 9 PAYLOAD-RANGE DIAGRAMS FOR CURRENT TRANSPORT AIRCRAFT



F) Direct Operating Cost

F.1 Effects of Size and Range on Operating Cost

We shall now discuss the second basic diagram describing transport aircraft performance, the direct operating cost curve, or DOC curve. The direct operating costs are made up of crew, fuel, maintenance, and depreciation costs directly associated with operating the aircraft. A fuller discussion of total airline costs is the subject of a separate lecture. In this section we shall make some observations on the effects of aircraft size and range (as determined by technology) on these operating costs.

We shall use a single cost measure, FC_{HR}, the flight operating costs per block hour to show the effects of size as measured by the gross weight, W_G, and range as measured by the full payload-design range. Figure 10 shows a typical result of FTL computer design studies for CTOL jet transports. For a level of technology described as 1970 technology, it shows a linear variation of hourly costs with gross weight (or payload size) for a given design range. However, there is also a variation with design range, so that a set of linear rays far out from a zero weight point of 100 \$/block hour. The hourly costs for current transport aircraft are shown in Figure 10. The rays correspond to a level of technology used in the DC-10 and B-747 aircraft, and good agreement is shown for those aircraft.

The positive intercept at zero gross weight causes an economy of scale as aircraft size is increased for a given design range. We will show this by introducing another basic cost measure, FC_{SHR}, the flight operating cost per seat hour. The variation of FC_{SHR} as payload is increased (shown for a design range of 1000 s. miles) is given by Figure 11(a). Obviously, there is a significant economy of scale as payload increases from 50 passengers (5.40 \$/seat hour) to 200 passengers (3.64 \$/seat hour). Note that the gains are not significant after that size, but there clearly are benefits from introducing

Figure 10 OPERATING COSTS PER BLOCK HOUR versus GROSS WEIGHT AND RANGE

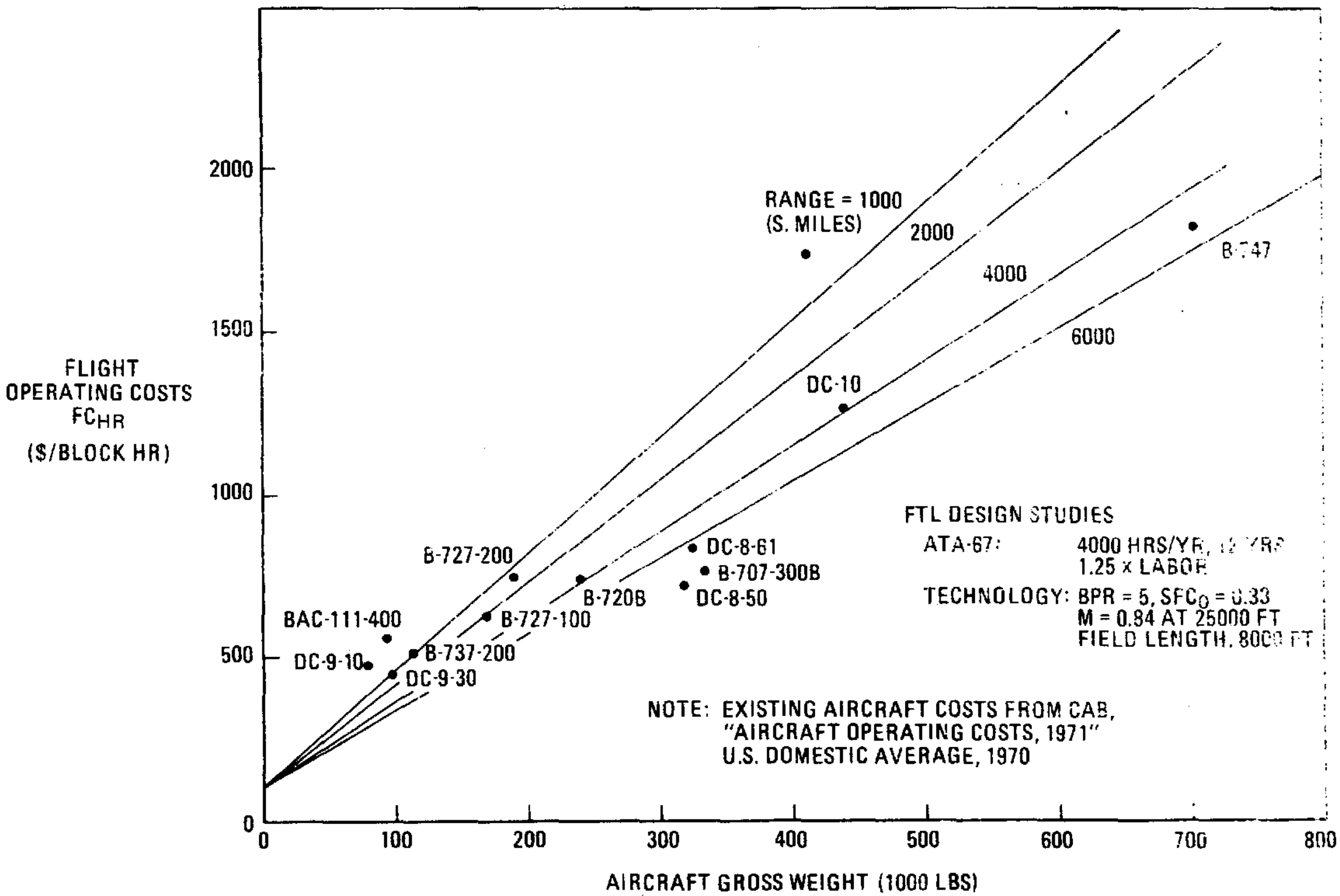


Figure 11 EFFECT OF PAYLOAD SIZE ON FLIGHT COSTS PER SEAT HOUR

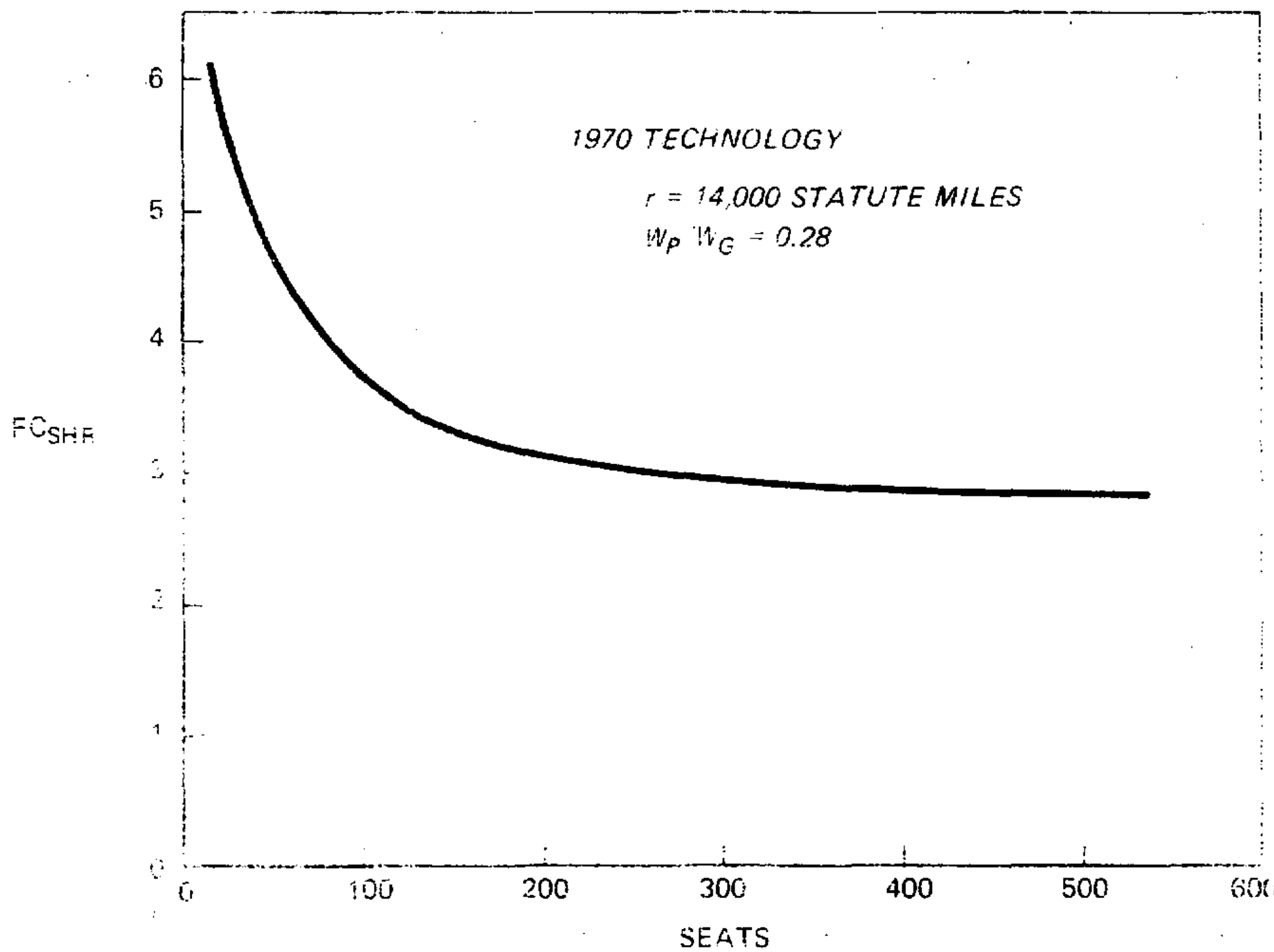


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Figure 11a EFFECT OF PAYLOAD SIZE ON FLIGHT COSTS PER SEAT HOUR

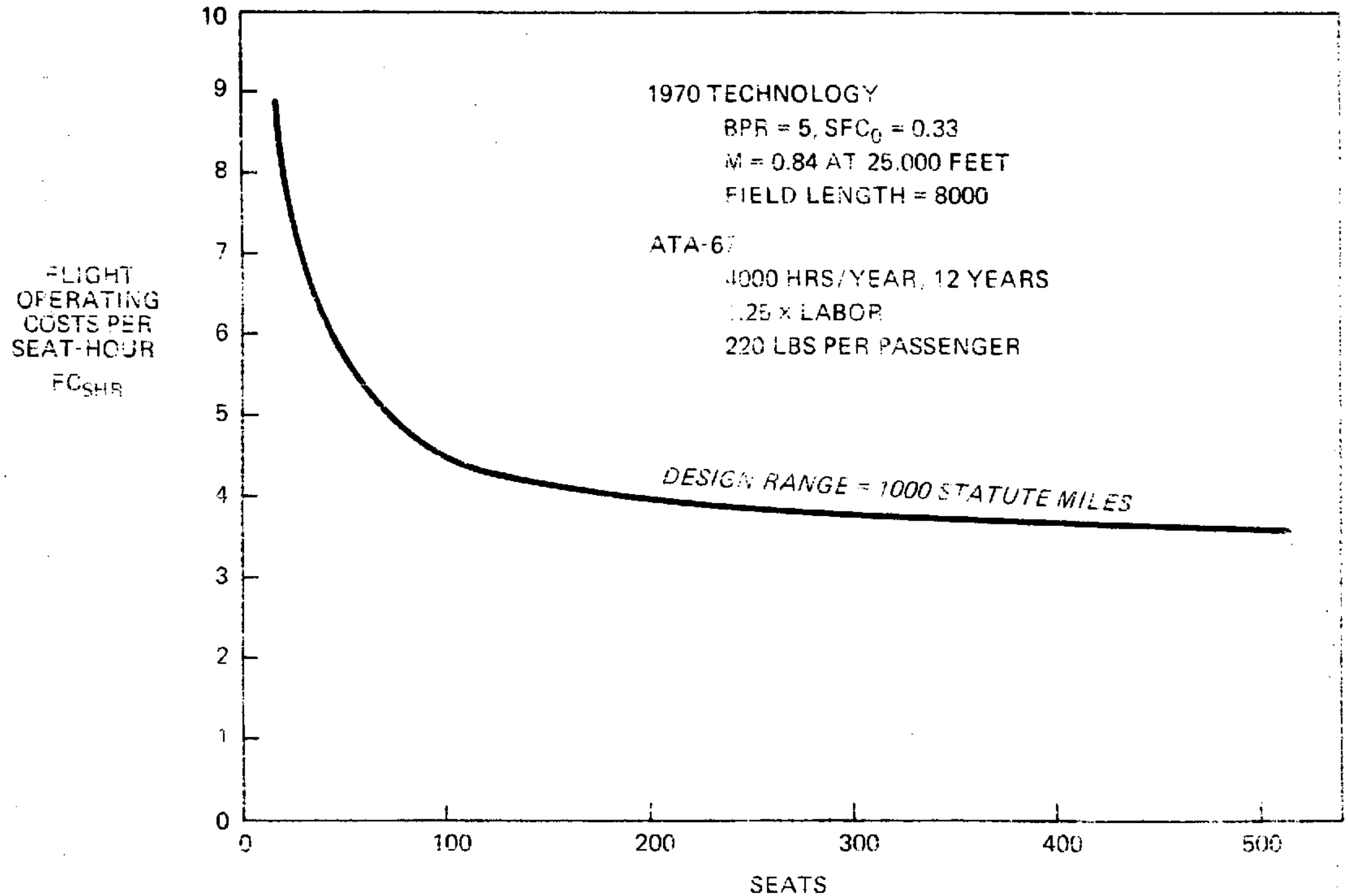
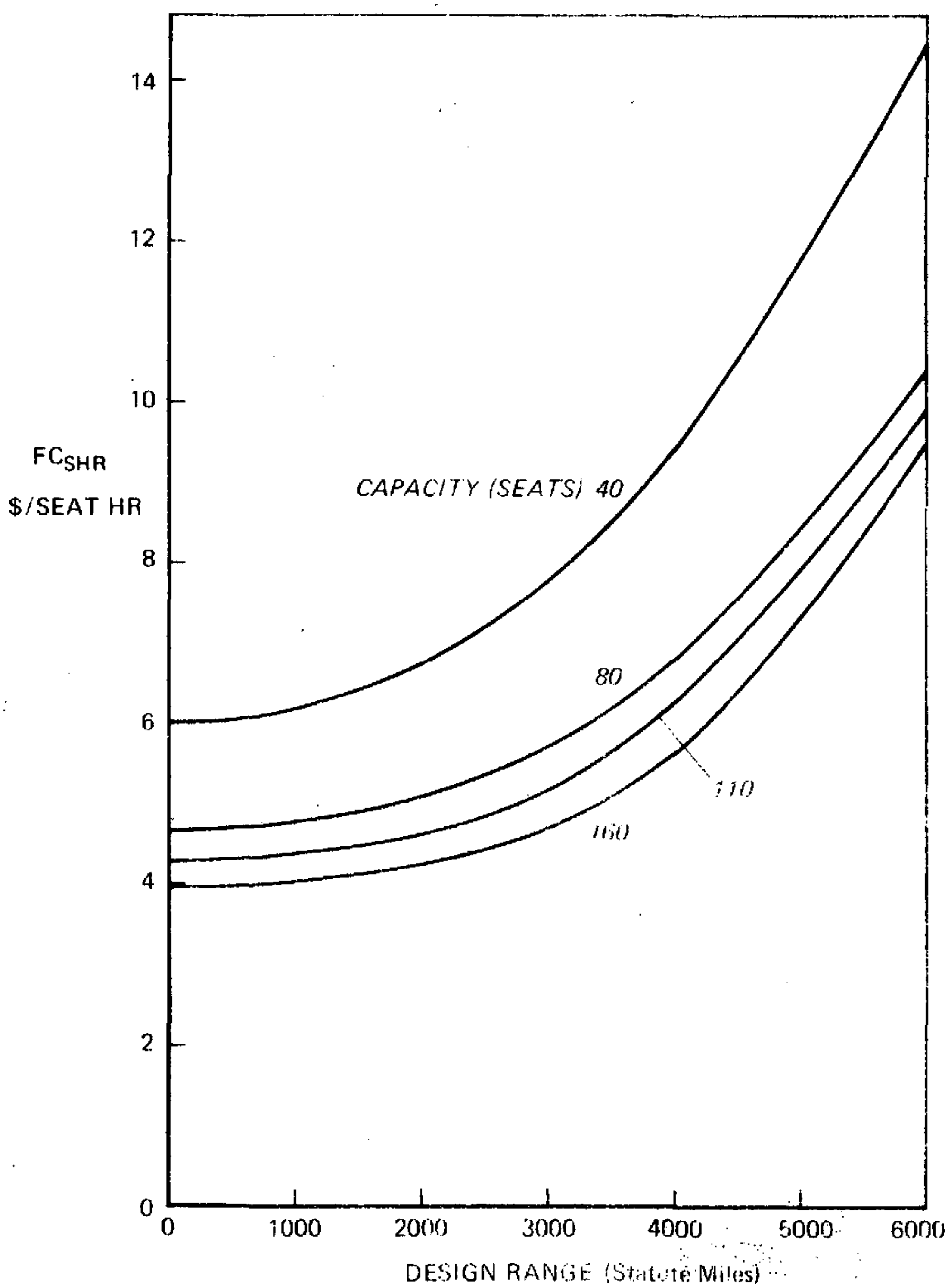


Figure 11b EFFECT OF DESIGN RANGE ON FLIGHT COSTS PER SEAT HOUR



larger size aircraft whenever traffic loads warrant their usage.

The variation of FC_{SHR} with design range at constant payload is shown by Figure 11(b). Here as range is increased, there is an exponential growth in FC_{SHR}, so that for a given payload size, there are benefits from using the shortest design range vehicle which will perform the task. Figure 11(b) shows the effect of size and range simultaneously, (a crossplot of the 1000 mile design range points actually produce Figure 11(a).) Notice that a smaller, but lesser design range vehicle can be cheaper than a larger, but longer design range vehicle. The cheapest vehicle is the one designed for exactly the payload and range of the transportation task to be performed. Using a larger vehicle is cheaper per seat, but not cheaper per passenger.

F.2 Derivation of DOC Direct Operating Costs ($/available seat mile)

For a given aircraft, we can compute the operating cost per hour, FC_{HR}. From this basic cost measure, we can derive the DOC curve in terms of cents per available seat mile versus range. We shall now show this derivation.

First, we must know the variation of block time with range. This is shown in Figure 12 as a linear form, where the slope of the curve is inversely proportional to cruise speed, V_{CR} and the zero distance intercept accounts for taxi time, takeoff and landing times, circling the airport for landing and takeoff, and any delays due to ATC congestion. This curve can be obtained by plotting scheduled times versus trip distance, and Figure 12 shows a typical result.

Figure 12 BLOCK TIMES FOR DOMESTIC SERVICE

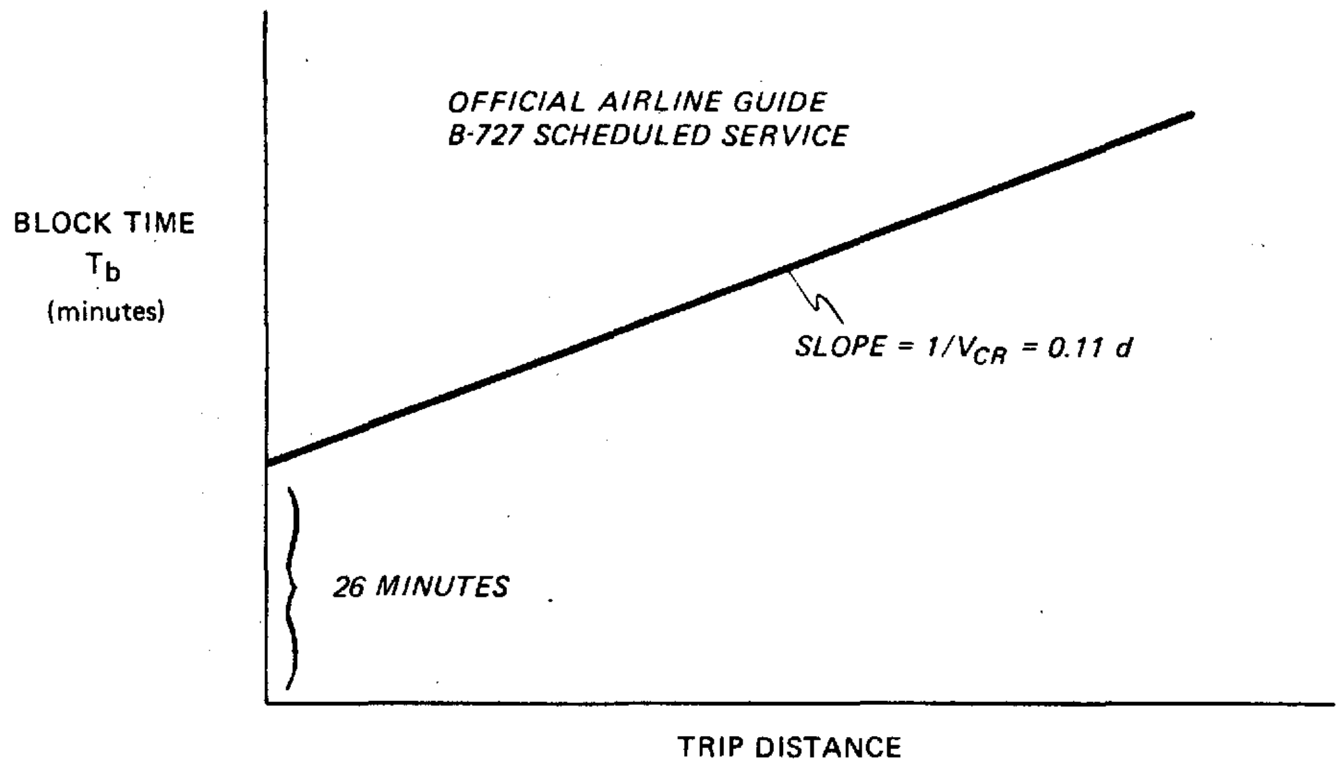


Figure 13 BLOCK SPEED VARIATION WITH TRIP DISTANCE

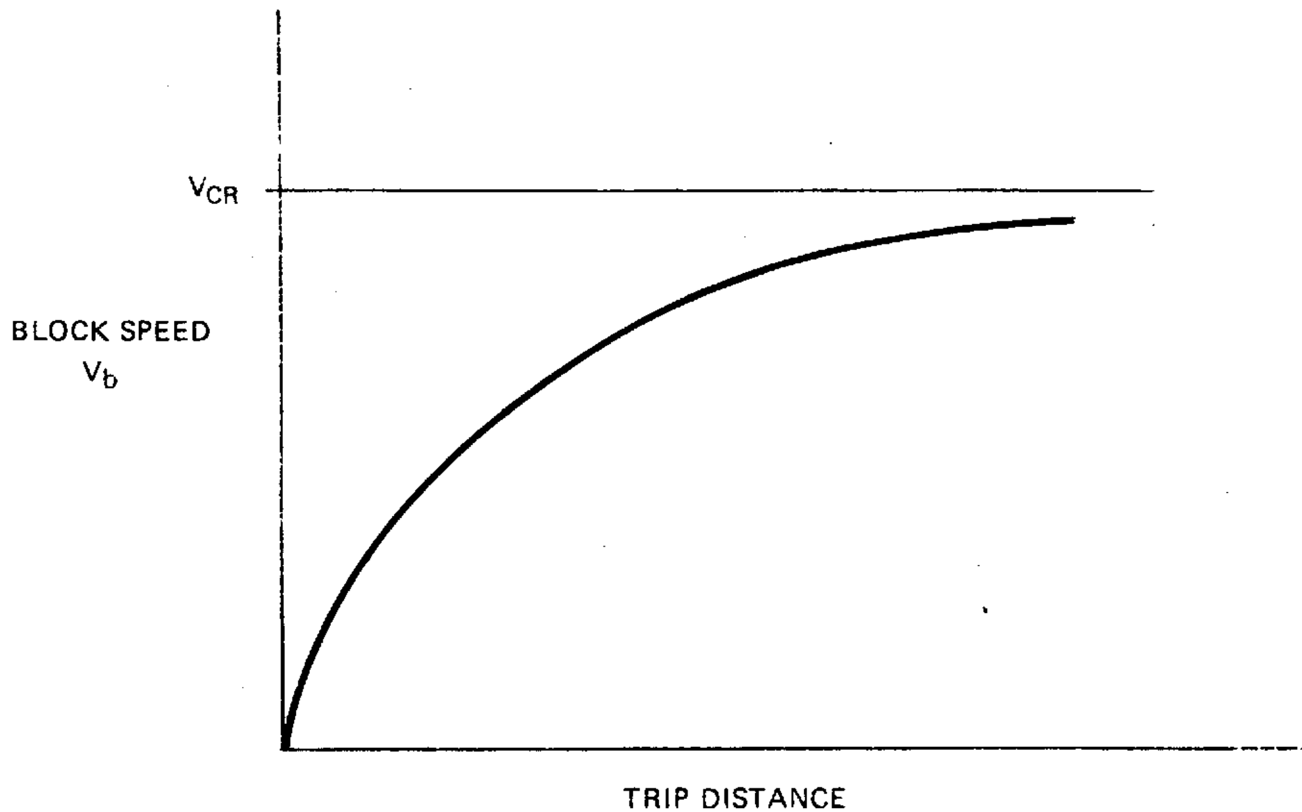
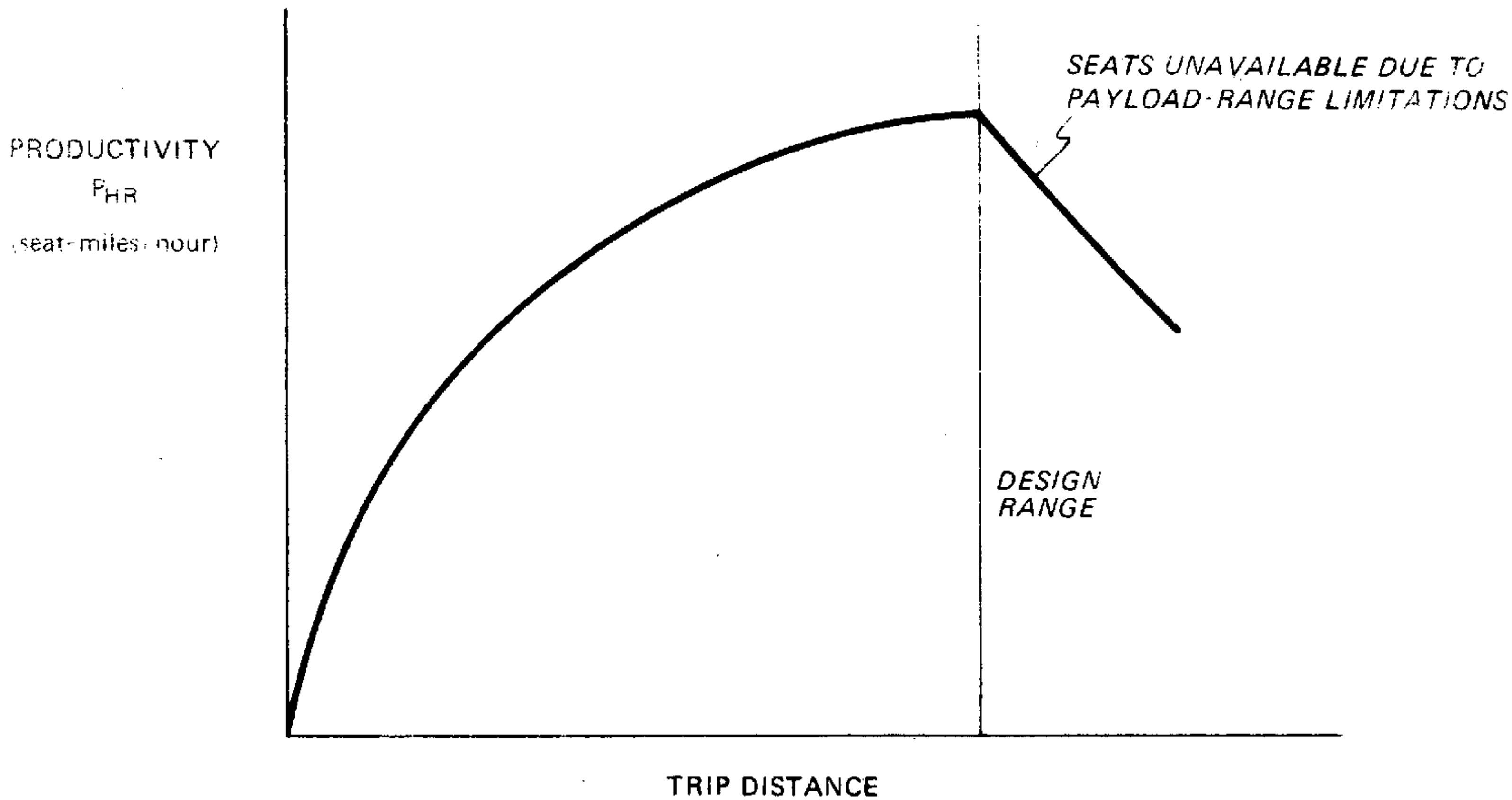


Figure 14 VARIATION OF PRODUCTIVITY WITH TRIP DISTANCE



If we compute block speed, V_b, as trip distance divided by block time, we get the asymptotic curve shown in Figure 13 where at longer ranges, the blockspeed begins to approach the cruise speed.

If we define P_{HR} = productivity per hour in terms of seat-miles per hour where S_a = available seats for a given trip, then a curve shown in Figure 14 is obtained. It is proportional to the V_b curve up to the full payload design range point where the number of available seats begins to be reduced causing the aircraft pooductivity to decrease after that point.

Now if we divide the hourly cost by the hourly productivity, we obtain the second basic diagram for transport aircraft, the DOC curve (Direct Operating Cost).

$$DOC = \frac{FC_{HR}}{P_{HR}} = \frac{\$ \text{ /hour}}{\text{seat miles/hour}} = \$\text{/available seat mile}$$

Since FC_{HR} is a constant, this curve is the inverse of the P_{HR} curve and produces the form shown in Figure 15, where DOC is high for short trips, decreases towards the design range point, and increases thereafter.

If we consider different payloads and ranges for the DOC curve, we see that a 50 seat vehicle is more expensive than a 100 seat vehicle, and a vehicle designed for 1000 miles will be dheaper than one designed for 2000 miles as stated previously.

Figure 15 VARIATION OF DOC WITH TRIP DISTANCE

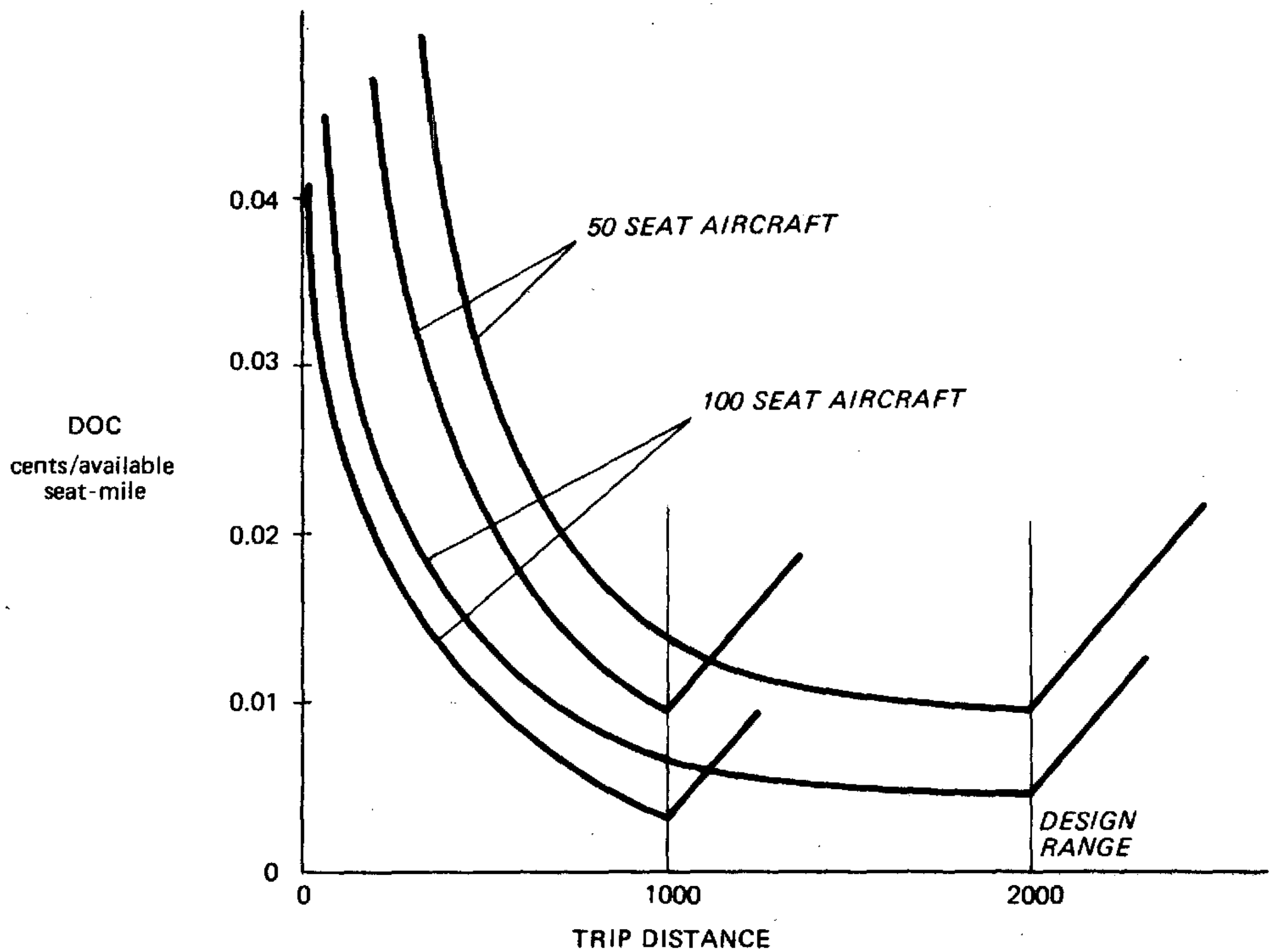


Figure 16 VARIATION OF FLIGHT TRIP COST WITH TRIP DISTANCE

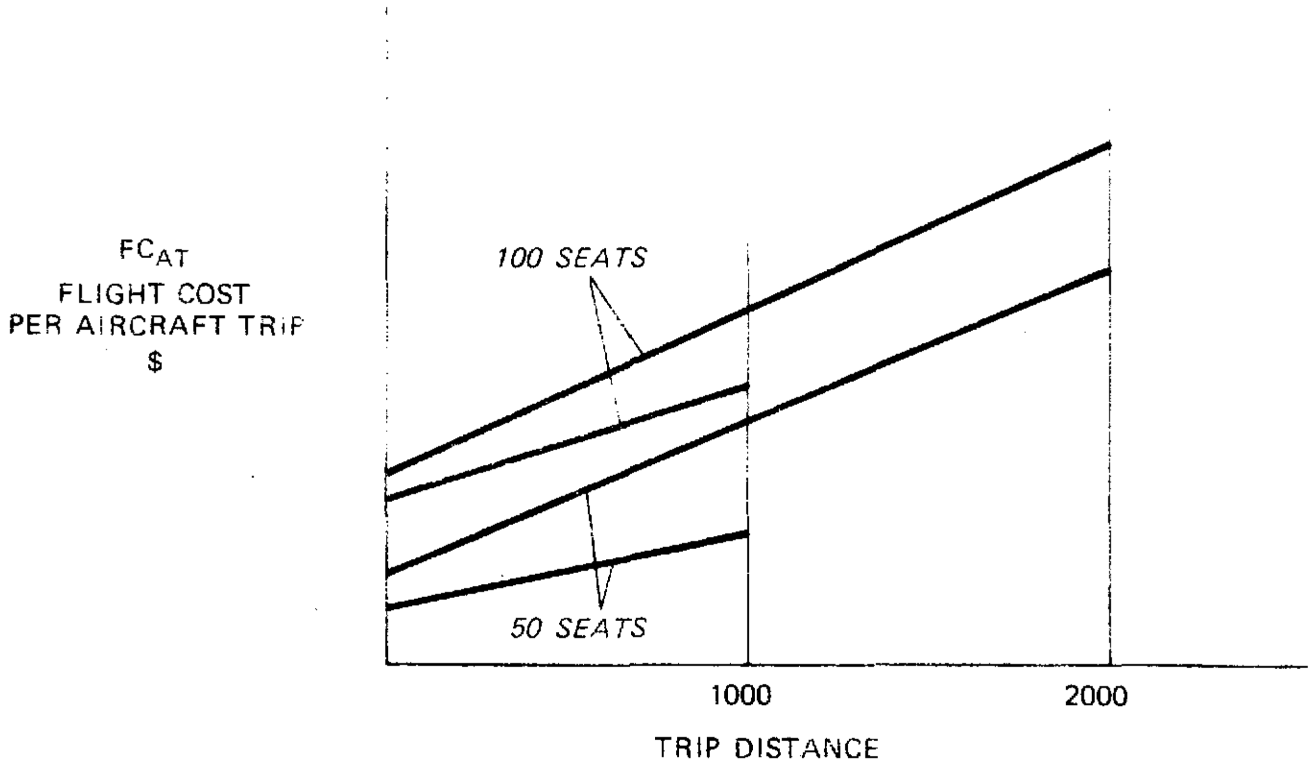
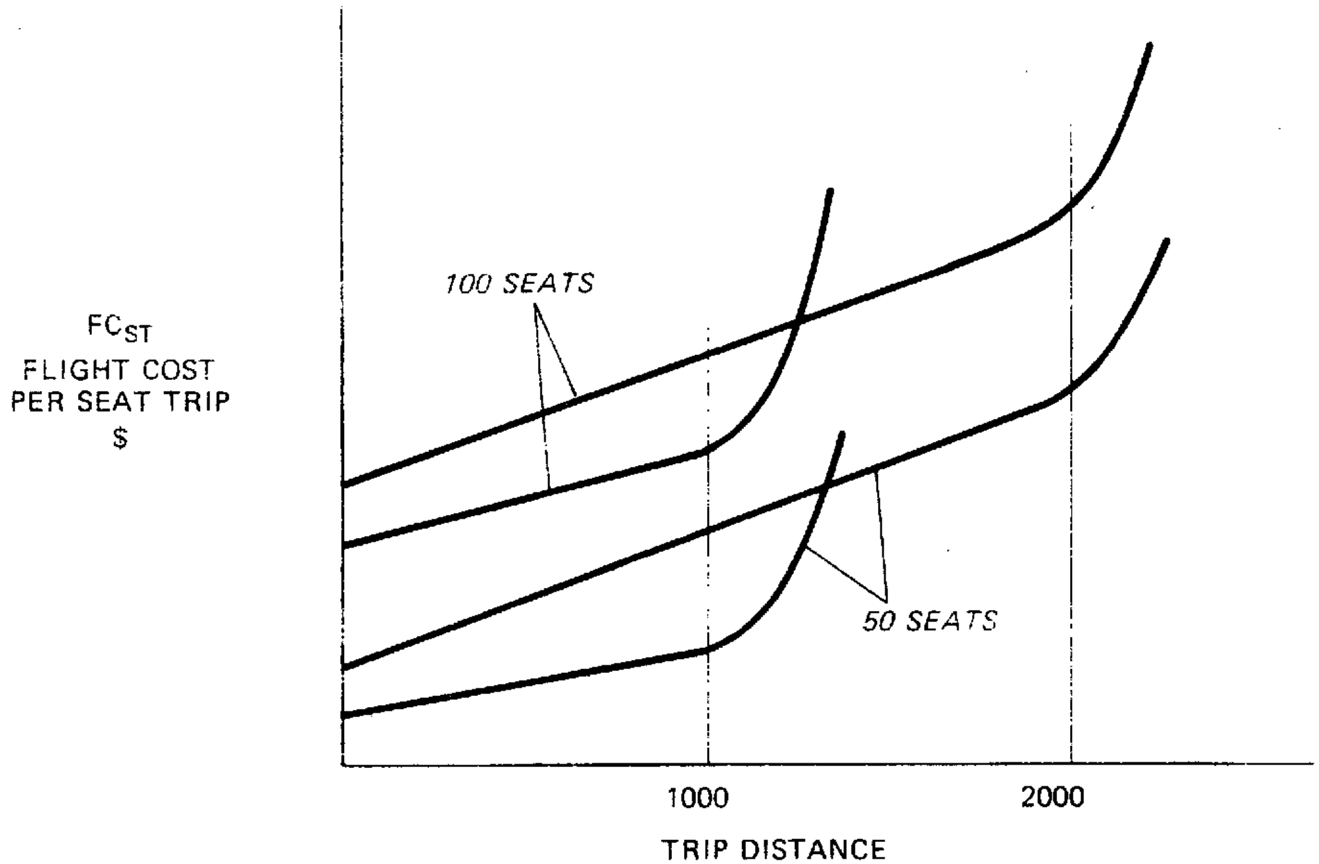


Figure 17 VARIATION OF FLIGHT TRIP COST/SEAT WITH TRIP DISTANCE



These curves may cross so that a smaller, shorter range vehicle is cheaper at certain ranges than a larger, longer range vehicle.

Because of this hyperbolic shape, it is easier to work with trip cost measures which have a linear form with distance since they are proportional to block time. We define two trip cost measures here:

FC_{AT} = flight cost per airplane trip = $c_1 + c_2 d \approx FC_{HR} \cdot T_b$

where c_1 and c_2 are know cost coefficients

FC_{ST} = flight cost per seat trip = $\frac{FC_{AT}}{S_a}$

where S_a = available seats

The form of EC_{AT} and FC_{ST} with distance is shown in Figures 16 and 17. After design range, where S_a is decreasing FC_{ST} becomes non-linear.

Generally, these trip cost measures are easier to understand and more useful than the DOC curve with its hyperbolic shape. One needs only to compute c_1 and c_2 for a given airplane and cruise schedule, and know the variation of available seats with trip distances

It must be emphasized that because of the strong variation in DOC with trip distance, any value quoted for DOC is meaningless unless accompanied by a value for trip distance. This point is often forgotten by economists, laymen, and inexperienced systems analysts.

G) Profitable Load Diagrams

The two basic diagrams, range-payload and DOC, may be combined to form a "profitable load" diagram of certain major assumptions are made:

1) It is necessary to assume a variation of revenue yield with distance. While a fare formula may be known, yield for a given route is an average net contribution in terms of dollars per passenger computed by taking into account the mix of standard and discount fares, sales commissions, taxes, and perhaps short term, variable indirect operating costs per passenger arising from ticketing, reservations, passenger handling, etc. Here we assume Y is linear with trip distance.

2) It is necessary to assume a variation of total costs, TC with distance, or to ignore allocation of overhead costs and produce a short term profit (or contribution to overhead) diagram. Here we shall assume that short term total operating seats per seat trip, TC_{ST} have the same linear form as the flight costs, FC_{ST}.

The usual relationship of Y and TC_{ST} is shown on Figure 18 where the linear forms cross at some short range. The result is a hyperbolic form for breakeven load decreasing to very low values at design range as shown in Figure 10. As with DOC, any value quoted for breakeven load factor must be accompanied

Figure 18 VARIATION OF TOTAL COSTS AND YIELD WITH TRIP DISTANCE

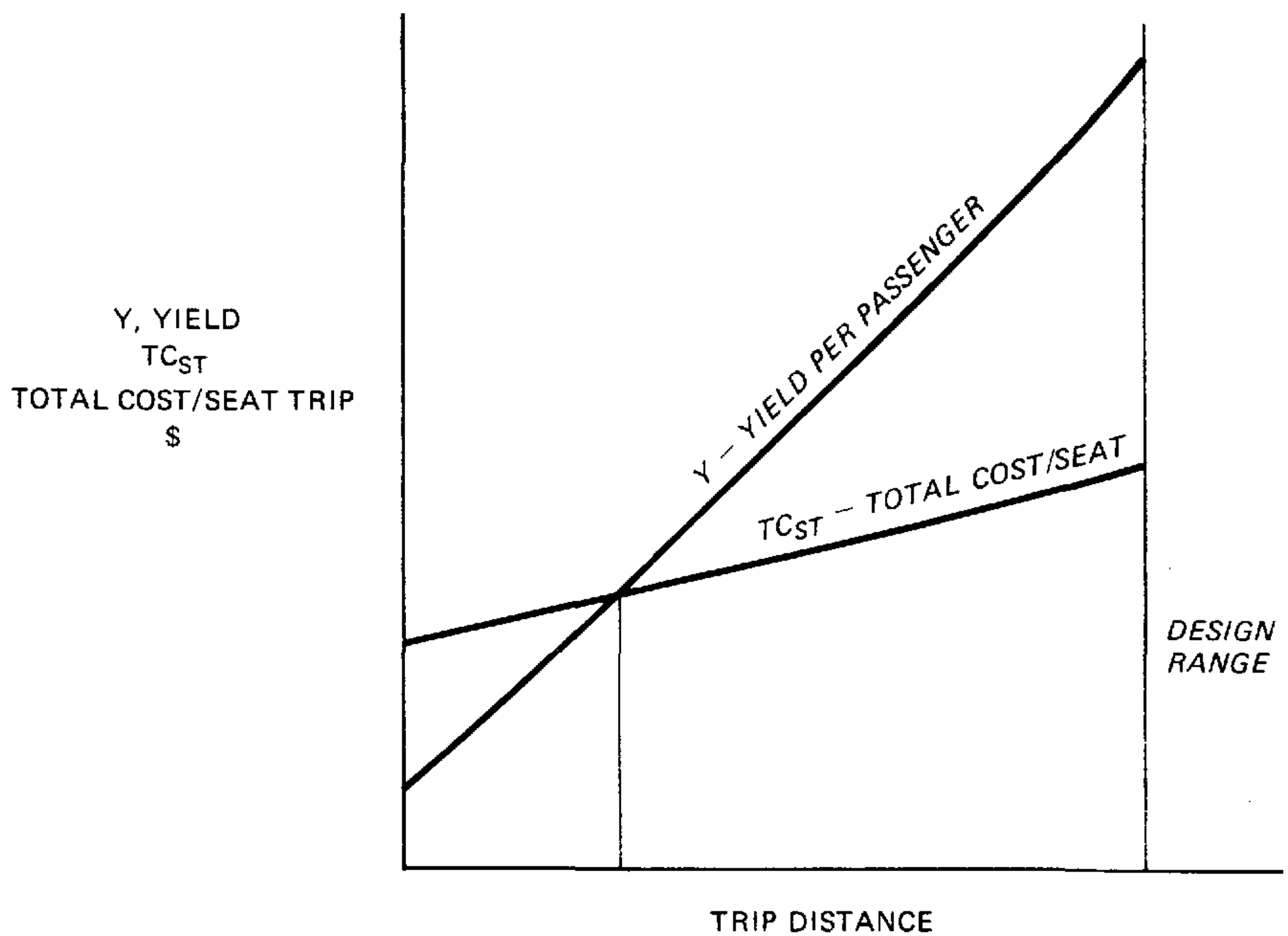


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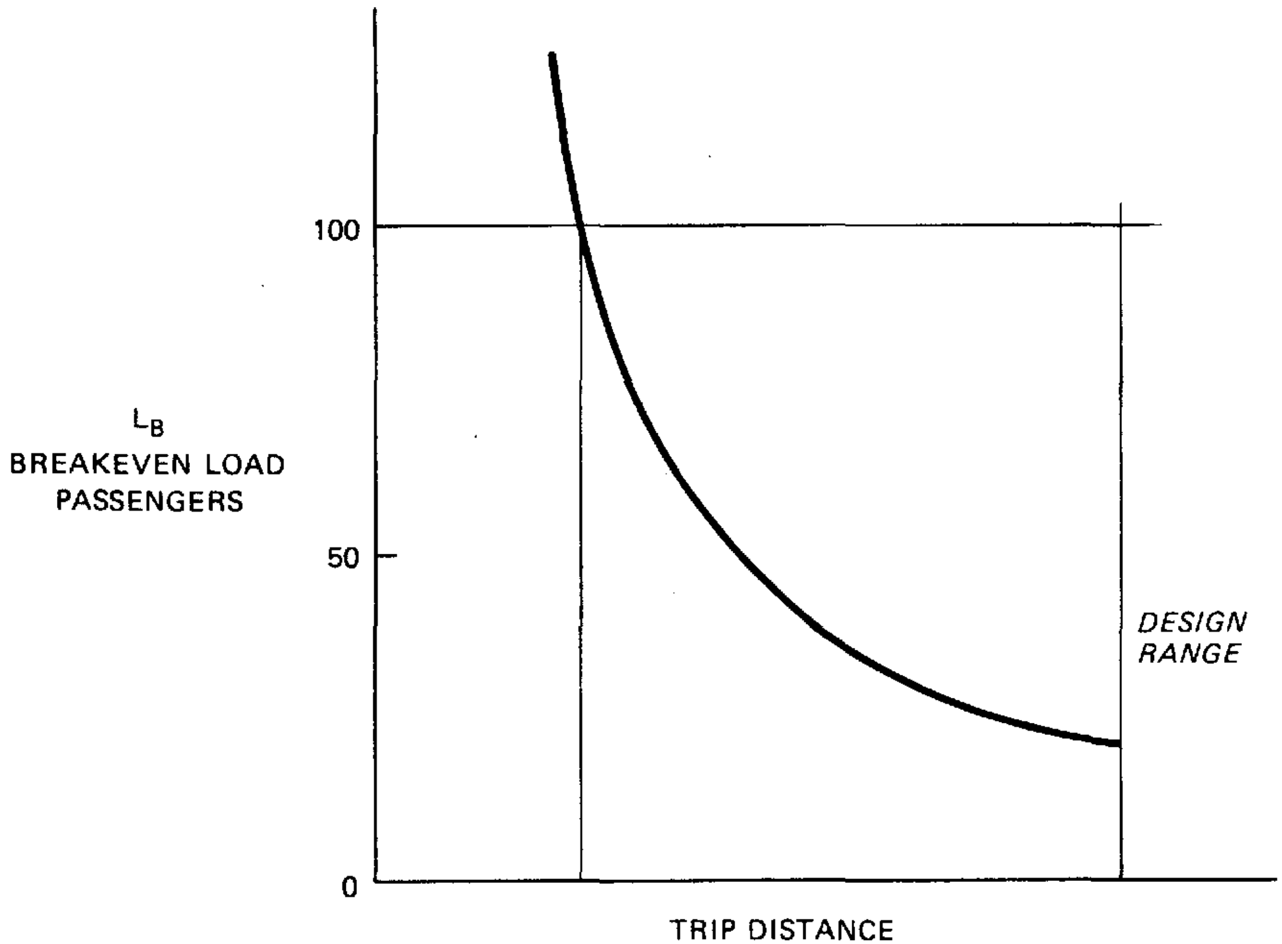
Figure 19 TYPICAL VARIATION OF BREAKEVEN LOAD WITH DISTANCE



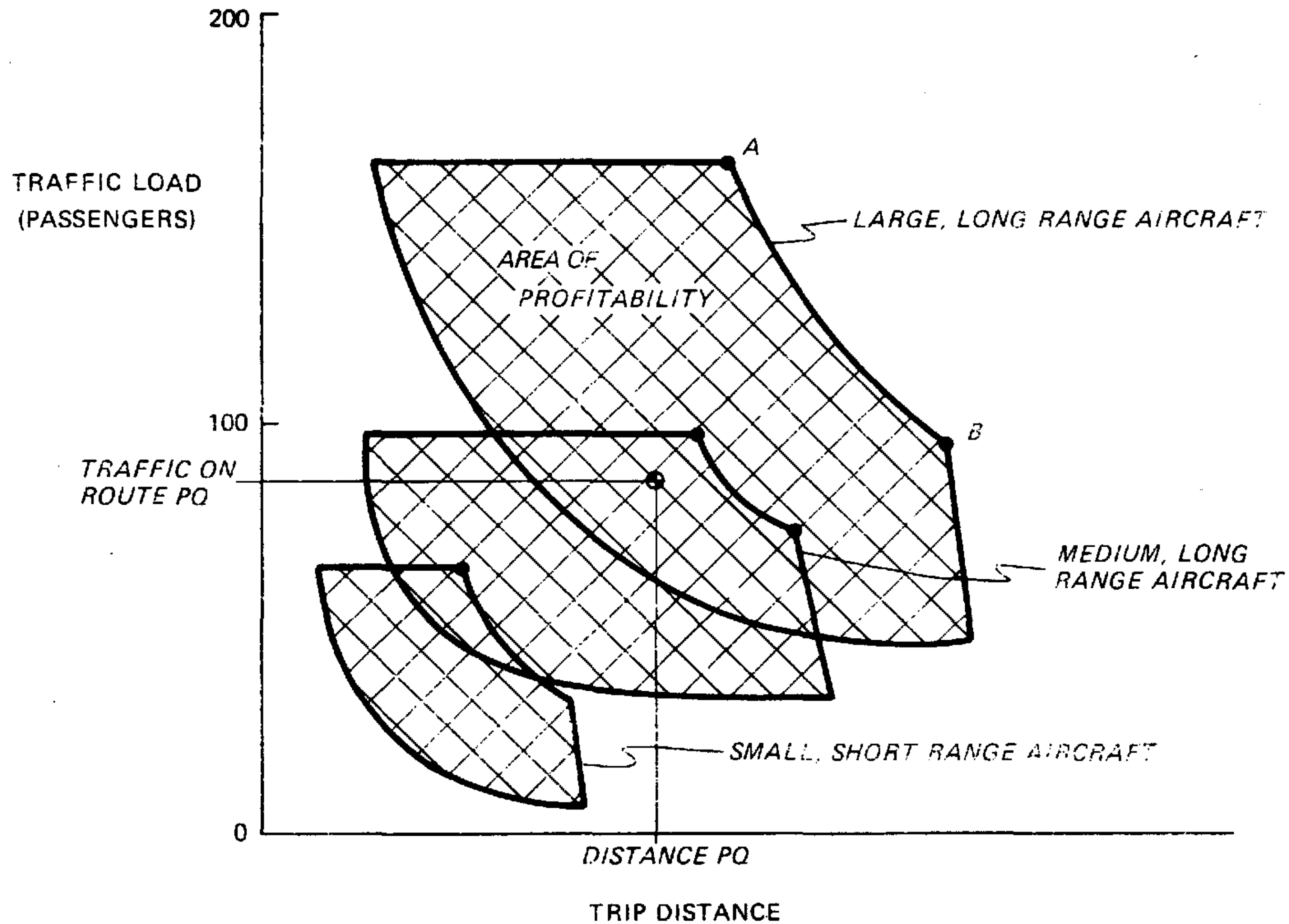
by a quoted value for trip distance.

The payload-range and breakeven load curves can now be combined to form a "profitable" load diagram as shown in Figure 20. The shaded areas represent points where a "profit" can be made using the aircraft to carry a given load over this trip distance. If the areas overlap, it is preferable to choose an aircraft where the point lies close to the upper boundary of payload-range limits since it is more profitable. E.g., choose the medium range aircraft for point PQ in Figure 20.

Notice that the profitable load diagram cannot be uniquely associated with a particular aircraft because of its assumptions. It must be associated with an airline and a set of routes since the indirect costs are specific to the airline, and the yield values are specific to a set of routes or city pairs. Thus when profitable load diagrams are shown, these additional data should be quoted.

Notice also that the hyperbolic form of the breakeven load curve is due to the differing slopes of the yield and total cost curves with trip distance. If yields, or fares were proportional to cost over distance, then the breakeven load would be constant with trip distance. Recent fare changes have moved fares much into line with costs by raising the zero distance intercept for coach fares

Figure 20 **PROFITABLE LOAD DIAGRAMS**



from \$6.00 to \$12.00. This provides much lower breakeven loads for shorter distance trips.

H) The Price of Transport Aircraft

As mentioned earlier, the purchase price and therefore depreciation costs are proportional to aircraft size. To demonstrate this Figure 21 shows a plot of current prices against aircraft operating empty weight. A good fit is given by the curve,

$$P_a = 1.9 \times 10^6 + 66.W_E \qquad \$$$

where P_a = fully equipped market price

W_E = basic operating weight empty

This correlation does not mean that W_E is the causative factor in determining the price which a manufacturer will decide to establish for his new product. Competition from existing aircraft, the expected size of the production run, etc. are factors which he considers closely. It is merely interesting to note the correlation with empty weight.

Notice also, that the DHC-6, a simple STOL transport from Canada, and the YAK-40, a new entry in world markets from Russia, are well below the minimum price for conventional transport aircraft from the Western world.

A set of data on prices for current new and used jet transports taken from the weekly editions of Esso's "Aviation News Digest" is given by Table 4. There is considerable variation in unit prices which may be due to various amounts of aircraft spares included with the purchase.

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Figure 21 THE PRICE OF CURRENT TRANSPORT AIRCRAFT

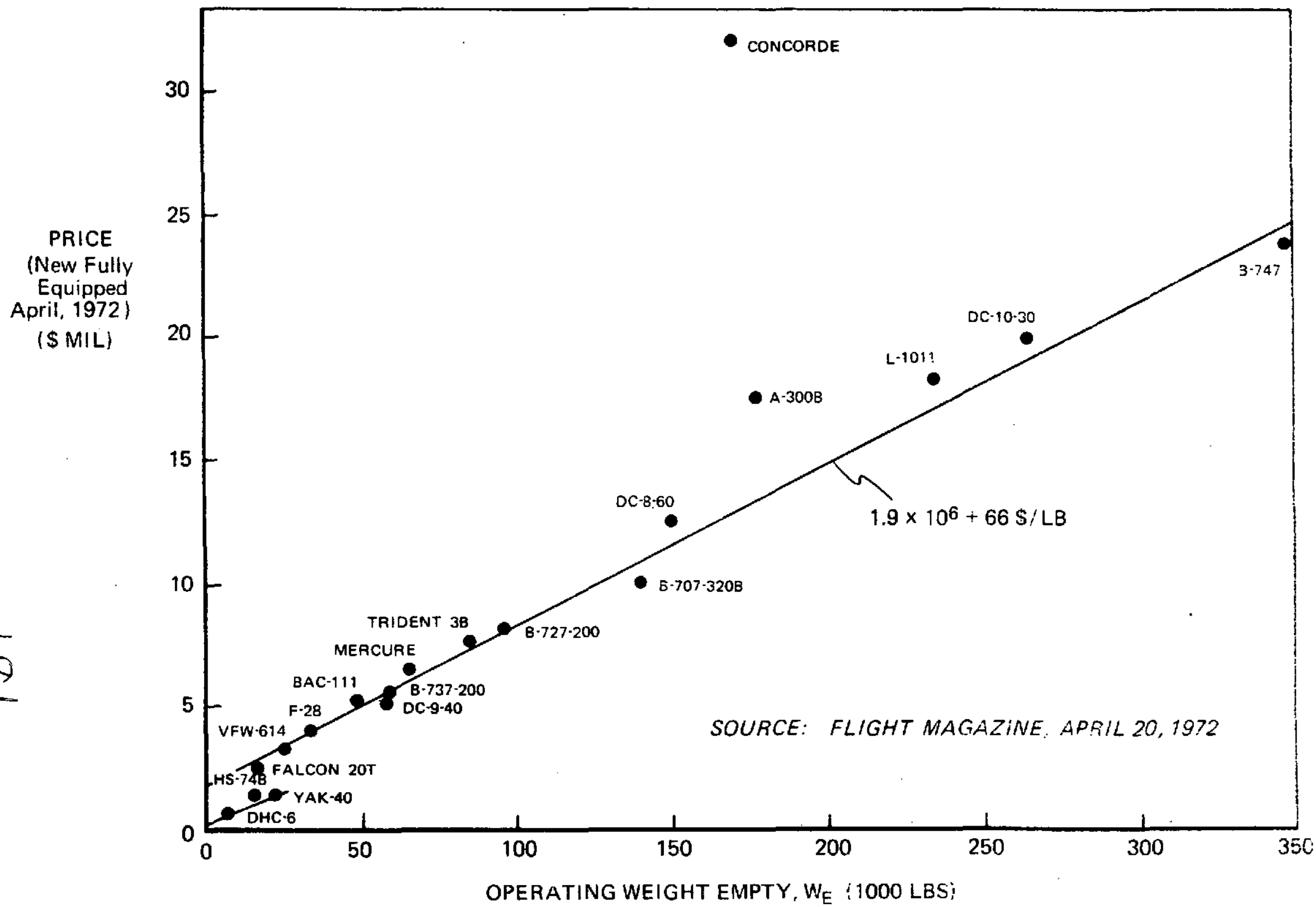

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Table 4. ACQUISITION PRICES FOR NEW LONG-RANGE TRANSPORT AIRCRAFT

SERIES	Month of Purchase	Airline Purchaser	Aircraft	Number Purchased	Total Price (Millions of $)	Price/Aircraft (Millions of $)
B-747	April 1972	World Airways	B-747C	3	100.00	33.33
	November 1971	Japan Airlines Ltd.	B-747	7	209.80	29.97
	October 1971	Delta Airlines	B-747	1	25.40	25.40
	August 1971	Alitalia	B-747	1	26.00	26.00
	July 1971	Qantas Airways	B-747	1	28.30	28.30
	May 1971	South African Airways	B-747B	2	48.00	24.00
	February 1971	British Overseas Airways Corp.	B-747	4	108.00	27.00
DC-10	May 1972	Continental Airlines	DC-10	4	83.00	20.72
	April 1972	Iberia	DC-10	3	72.80	24.27
	March 1972	Martinair	DC-10F	1	23.00	23.00
	March 1972	Laker Airways	DC-10	2	47.30	23.65
	January 1972	Trans-International Airlines	DC-10 (cargo)	3	57.00	19.00
	December 1971	Scandinavian Airlines System	DC-10-30	2	58.00	29.00
	October 1971	Western Airlines	DC-10-10	4	85.00	21.25
	August 1971	Alitalia	DC-10	4	97.00	24.25
	April 1971	World Airways	DC-10	3	72.00	24.00
	February 1971	National Airlines	DC-10	2	35.00	17.50
	February 1971	Finnair	DC-10-30	2	48.00	24.00
L-1011	November 1971	Court Line Aviation	L-1011	2	48.00	24.00
	January 1971	Pacific Southwest Airlines	L-1011	2	30.00	15.00
A300B	November 1971	Air France	A300B-2	6	75.00	12.50
B707	May 1971	Cathay Pacific Airways	B707-320B	1	8.60	8.60
DC-8	July 1971	Air Congo	DC-8-63	1	14.50	14.50
	June 1971	Scandinavian Airlines System	DC-8-63	1	11.46	11.46
	March 1971	World Airways	DC-8 Super 63	3	40.00	13.33

Source: Weekly editions of Esso's "Aviation News Digest", January 1, 1971 through May 1, 1972.

Table 4 (cont.) ACQUISITION PRICES FOR NEW MEDIUM AND SHORT-RANGE TRANSPORT AIRCRAFT

SERIES	Month of Purchase	Airline Purchaser	Aircraft	Number Purchased	Total Price (Millions of $)	Price/Aircraft (Millions of $)
B-727	May 1972	Continental Airlines	B-727-200	15	119.00	7.93
	April 1972	Ansett Transport of Australia	B-727-200	4	38.80	9.58
	April 1972	Trans Australia Airlines	B-727-200	4	40.15	10.04
	April 1972	Iberia	B-727-200	16	140.30	8.77
	April 1972	Condor Flugdienst	B-727-200	3	30.00	10.00
	April 1972	Delta Airlines	B-727-200	14	100.00	7.14
	March 1972	Western Airlines	B-727-200	2	15.00	7.50
	February 1972	Eastern Airlines	B-727-200	15	115.00	7.67
	October 1971	Western Airlines	B-727-200	3	22.50	7.50
	May 1971	Tunis Air	B-727-200	1	9.70	9.70
	April 1971	Ansett Transport of Australia	B-727-200	6	69.75	11.63
DC-9	April 1972	United States Navy	DC-9	5	25.30	5.06
	April 1972	Yugoslovenski Aero Transport	DC-9-30	6	30.00	5.00
	October 1971	Iberia	DC-9	11	67.50	6.14
	August 1971	Alitalia	DC-9	1	5.50	5.50
	June 1971	Austrian Airlines	DC-9	8	38.00	4.75
	February 1971	Scandinavian Airlines System	DC-9	5	27.30	5.46
BAC-111	January 1971	Fiji Airways	BAC-111-475	1	3.60	3.60
B-737	April 1972	Pacific Western Airlines	B-737-200	2	10.90	5.45
	April 1972	Malaysian Airlines System	B-737-200	18	112.00	6.24
	November 1971	Pacific Western Airlines	B-737	1	5.00	5.00
	October 1971	Saudi Arabian Airlines	B-737	5	37.30	7.46
	October 1971	Malaysian Airlines	B-737	6	41.50	6.92
	August 1971	Air Algerie	B-737-200	1	7.00	7.00
	August 1971	Braathens SAFE	B-737	1	4.30	4.30
	August 1971	Southwest Airlines	B-737	1	5.00	5.00
	April 1971	National Airways Corp	B-737-200	1	4.50	4.50
	March 1971	Pacific Southwest Airlines	B-737-200	1	4.70	4.70
Mercure	February 1971	Air Inter	Mercure	10	80.00	8.00

Source: Weekly editions of Esso's "Aviation News Digest", January 1, 1971 through May 1, 1972

Table 4 (cont.) **ACQUISITION PRICES FOR USED TRANSPORT AIRCRAFT**

SERIES	Month of Purchase	Airline Purchaser	Aircraft Seller	Aircraft	Number Purchased	Total Price (Millions of $)	Price/Aircraft (Millions of $)
B-707	April 1972	China Airlines	Continental Airlines	B-707-324C	1	6.20	6.20
	Decem 1971	Transavia Holland	American Airlines	B-707-123B	1	3.60	3.60
	Novem 1971	Trans American Airways	Braniff International	B-707-320C	1	4.85	4.85
	Oct 1971	Cathay Pacific Airways	Northwest Airlines	B-707-320B	2	10.00	5.00
	August 1971	Varig Airlines	American Airlines	B-707-320C	1	2.40	2.40
	July 1971	BEA Airtours	Britist Overseas Airways Cor.	B-707-436	7	10.30	1.47
DC-8	April 1972	Japan Airlines Ltd.	Eastern Airlines	DC-8-61	3	20.40	6.80
	Novem 1971	Intersuede Aviation AB	Eastern Airlines	DC-8-51	2	6.00	3.00
	Oct 1971	Air Jamaica	McDonnell Douglas Corp	DC-8-51	1	2.90	2.90
	Oct 1971	Icelandic	Seaboard Airlines	DC-8-63F	1	10.80	10.80
	July 1971	Air New Zealand	United Airlines	DC-8-52	2	3.70	1.85
B-727	Decem 1971	Braniff International	Boeing Allegheny Frontier Grant Aviation	B-727	13	87.30	6.71
	Sept 1971	Aerovias Nacionales(Colombia)	Boeing Corp	B-727-24C	3	9.18	3.08
DC-9	April 1972	Air Canada	Continental Airlines	DC-9	3	6.00	2.00
	Jan 1971	Finnair	McDonnell Douglas Corp	DC-9	8	22.30	2.79
BAC-111	March 1972	Allegheny Airlines	Braniff International	BAC-111	11	14.50	1.32
B-737	May 1971	National Airways Corp	Aloha Airlines	B-737	1	3.80	3.80
Caravelle	Decem 1971	Sterling Airways	United Airlines	Aerospatiale Caravelles	13	6.80	0.52

Source: Weekly editions of Esso's "Aviation News Digest", January 1, 1971 through May 1, 1972

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