THE AMAZING CONSOLIDATED PBY CATALINA

An analysis of its long range performance

1. The Question of Range

The Consolidated PBY Catalina flying boat was already famous before the Second World War. Although fewer and fewer of its veteran builders, flight crew, technicians and passengers are alive today, Catalina's reputation is as strong as ever.
A few specimen have survived and are still maintained in flying order. Designed as a patrol bomber for the US Navy in 1934, it was built in great numbers, some 4000, and earned lasting fame during war time service. In use by all allied forces, it saw action over all seven seas. It was prized for its flying characteristics, ruggedness, dependability, versatility and remarkable load-carrying capacity, but most of all for its amazing operating range.

Catalina landing

Its capacity to fly long and far had already been demonstrated by formation flights to USN bases when the aircraft were first delivered in 1935. Soon non-stop coast-to-coast flights, flights to Hawaii and to the Canal Zone (5300 km, 28 hours) were no exception. During the war the Catalina played different roles, but it must have flown tens of thousands of patrolling and escorting missions; twelve to fifteen hours at a stretch, each flight covering 3000 km or more. Daring and heroïc rescue missions were undertaken over great distances, for example from Australia to Corregidor and back (7500 miles); evacuating personnel of the Dutch East Indies to Australia, etc.

Catalina was also a peaceful vehicle for exploration and a carrier of passengers and cargo. Guba II, the private Model 28-3 owned by the American Museum of Natural History, circled the globe at its largest diameter after spending eleven months on expedition with Richard Archbold in the most inaccessable parts of Dutch New Guinea (1938/39). In 1939 a flying boat Model 28-4 was used by the American Export lines to carry a crew of six and a ton of freight across the Atlantic (6400 km). For several years during the war Australian Quantas operated with converted Catalinas the longest regular non-stop passenger service between Perth and Colombo (5600 km, 27 hours).

How was this exceptional range achieved? Did the Cat have special wings? Were there any aerodynamic secrets? Did its slow cruising speed have anything to do with it? In the following pages the design of the famous airplane is analyzed with respect to these questions. By comparing Catalina to three other, equally famous, wartime aircraft - Dakota, Skymaster and Liberator - the decisive design factors which gave the aircraft its exceptional performance are identified. Or was it not exceptional, but was it merely up to the highest standards of its time?

2. Method to find an Answer

Catalina, Dakota, Skymaster and Liberator (the latter in its C-87 transport role) are analyzed in their role of unarmed military transport. As the author has no access to authentic data like pilot's notes, instruction manuals or flight records, his analysis is based on figures available in general aviation literature.

For each aircraft the structural efficiency is determined, that is the ratio between loading capacity and total weight.

Assuming that the propulsion characteristics of the four aircraft are very similar, the calculated differences in range can be attributed to either aerodynamical or structural causes.

Finally attention is paid to the relation payload-range and the practical matter of cruising speed.[1]

3. Weights

It is important to be clear on the matter of airplane weights. References state many sorts of 'weight' and different sources will give a confusing variety of figures for even a single type of aircraft.

Therefore, in order to compare Catalina, Dakota, Skymaster and Liberator, a single source of information was used: *Jane's 'Fighting Aircraft of WWII'*. Unfortunately, this reference does not give an explicit definition of terms, such as 'Weight Loaded' and 'Weight Empty'. (When is a plane empty indeed?) However, it may be assumed that Jane's editor will have used these terms at least in a consistent manner, so that a comparison of aircraft of the same period may be undertaken with some confidence. In this paper:

'Weight Loaded' is taken to mean the normal maximum weight for which the airplane has been designed to take off and is indicated by **Wmax**.

'Weight Empty' is indicated by **Wmin**. The difference between the two quantities is called '**Loading Capacity'**.

This capacity may or may not be fully utilized for carrying the **'Total Load'** of the airplane. See Fig.1

Total Load <= Loading Capacity. .

[1] Written in 1993, this analysis should have employed SI units, with 'mass' instead of 'weight', 'newton' rather than 'kg', 'joules' for 'kgm' and 'kW' for 'hp'. Somehow these new-fangled units seemed to fit the subject badly and the temptation to stay with the old ones has proven just too big.

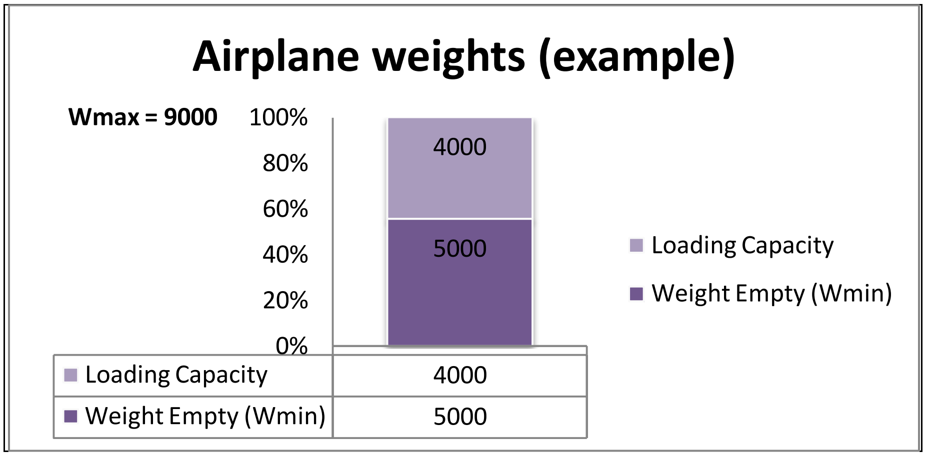


Fig.1 Definition of Weights and Loading Capacity

The **Loading Capacity** will be used to transport the **Total Load**, which will consist of different types of Loads, of which the **Fuel Load** is of special interest to this analysis.

Total Load = **Non-Fuel Load** plus **Fuel Load**

Non – Fuel Load

Operational Load ('O')	*Pay Load ('P')*
oil; parts; equipment; crew + bagage	Passengers + bagage; mail; freight

Fig.2 Different types of Load

The exact composition of the Total Load varies according to the purpose of the flight and the distance to be covered.
Certain 'Loading Patterns' may thus be recognized, such as the:

1. *'not-full' or 'short distance' pattern*, in which the aircraft takes off with a Total Load smaller than its Loading Capacity:
    - *Total Load* < *Loading Capacity;*
2. *'full-load' pattern*, in which the plane is loaded to capacity with Fuel, Pay Load and Operational Load:
    - *Total Load* = *Loading Capacity*.

In this case Pay Load and Fuel Load have a see-saw relationship: more Pay Load can only be taken by reducing the Fuel Load and consequently shortening the range of the aircraft.

3. '*maximum or long range*' *pattern*, which is a special case of the full-load pattern, with maximum Fuel Load and no Pay Load.

    - *Total Load = Loading Capacity; Pay Load = nihil*.

If the Operational Load is not stated explicitly for a certain flight we assume it in our calculations to be five percent of Wmax, irrespective of the Loading Pattern.

The Loading Patterns are illustrated in Fig.3.

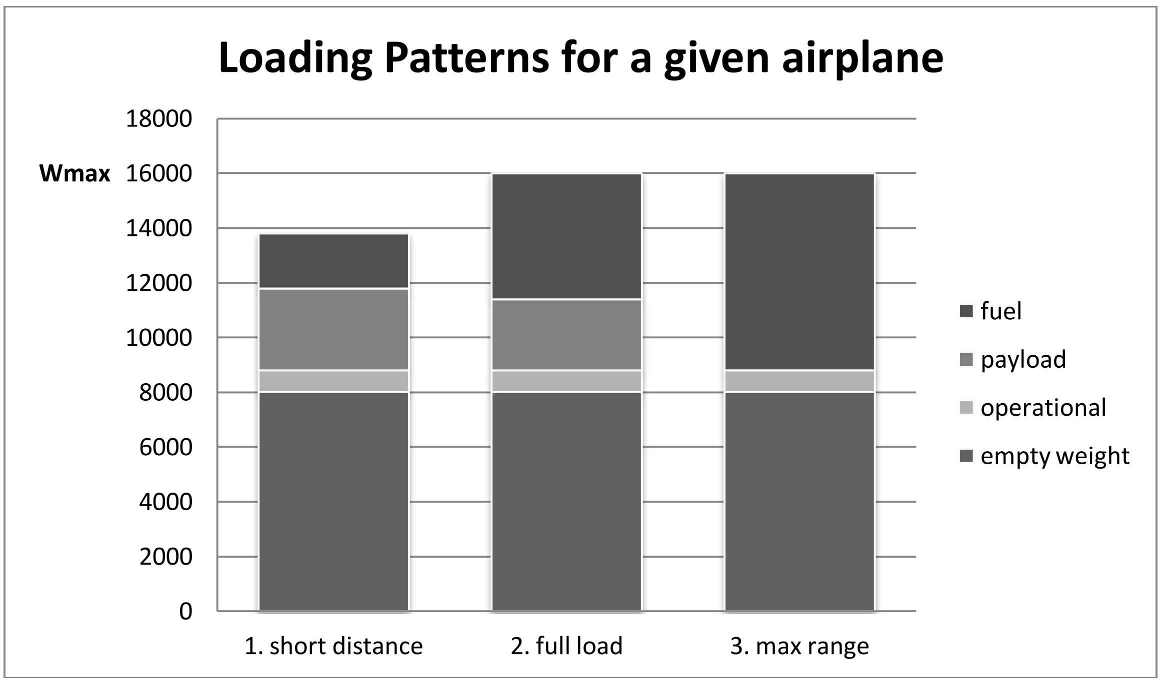


Fig.3 Loading Patterns (example)

The third Loading Pattern for 'maximum-range' is to be considered an exceptional case, in which the aircraft may be equiped with additional, non-standard fuel tanks in order to carry the maximum amount of fuel. The extra fuel reduces to zero the amount of Pay Load that can be carried, because the loading capacity of the airplane cannot be exceeded. (No overload conditions are being considered).
As a starting point for our analysis however, we use the data for certain long distance flights that is to be found in Jane's and that is reproduced in Table 3. These flights are made with the second Loading Pattern. Attention will be given to the fact that during flight the weight of a powered aircraft decreases.

We shall call:

W_0: starting weight (W_0 < or = Wmax, see Fig.3)

W_1: landing weight

As no bombs are dropped or other heavy weights are put overboard during flight, the difference in weight accounts for the fuel consumed:

$W_0 - W_1$ = Fuel Used during flight, or:

$W_1 = W_0$ - Fuel Used

It is good practice to terminate the flight before the fuel tanks are completely empty and the total Fuel Load has been exhausted.

For instance:

Fuel Used = 0.9 x Fuel Load, in which case:

$W_1 = W_0$ - 0.9 x Fuel Load

4. Construction Efficiency

The 'construction' or 'structural' efficiency of an aircraft may be defined as:

ncon = Loading Capacity / Wmax [1]

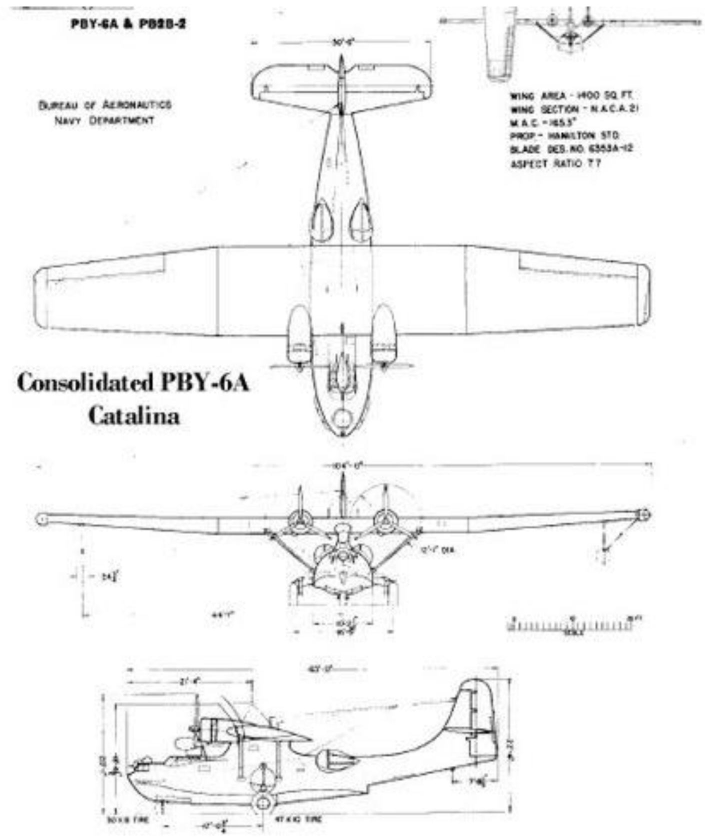
In words: the construction efficiency is the ratio of the total load an airplane can carry to its fully loaded weight. It is an important parameter for comparing airplane designs.

For most airplanes: ncon < 0.5

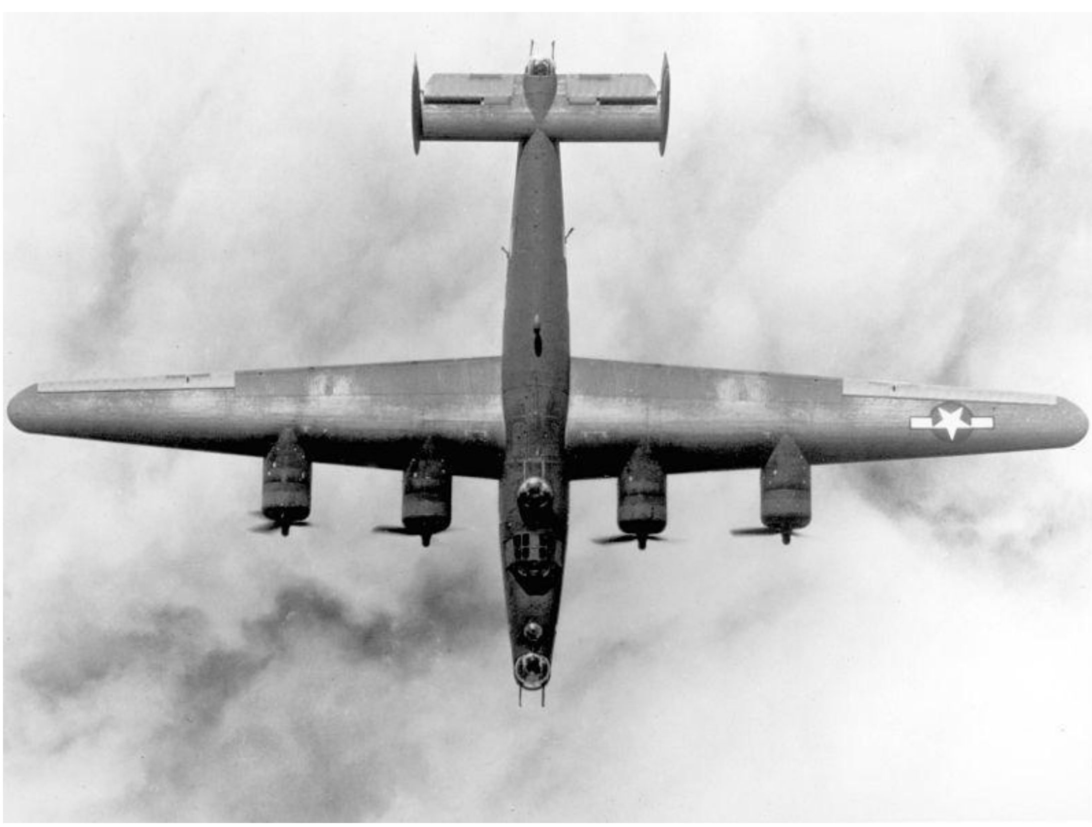
If ncon = 0.5 the airplane can lift a load equal to its own weight.

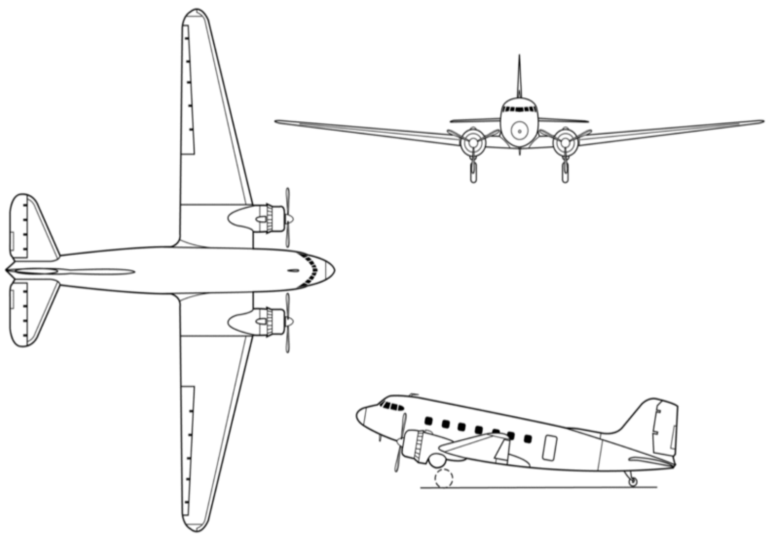
If ncon > 0.5 the airplane can lift a load greater than its own weight.

5. The aircraft



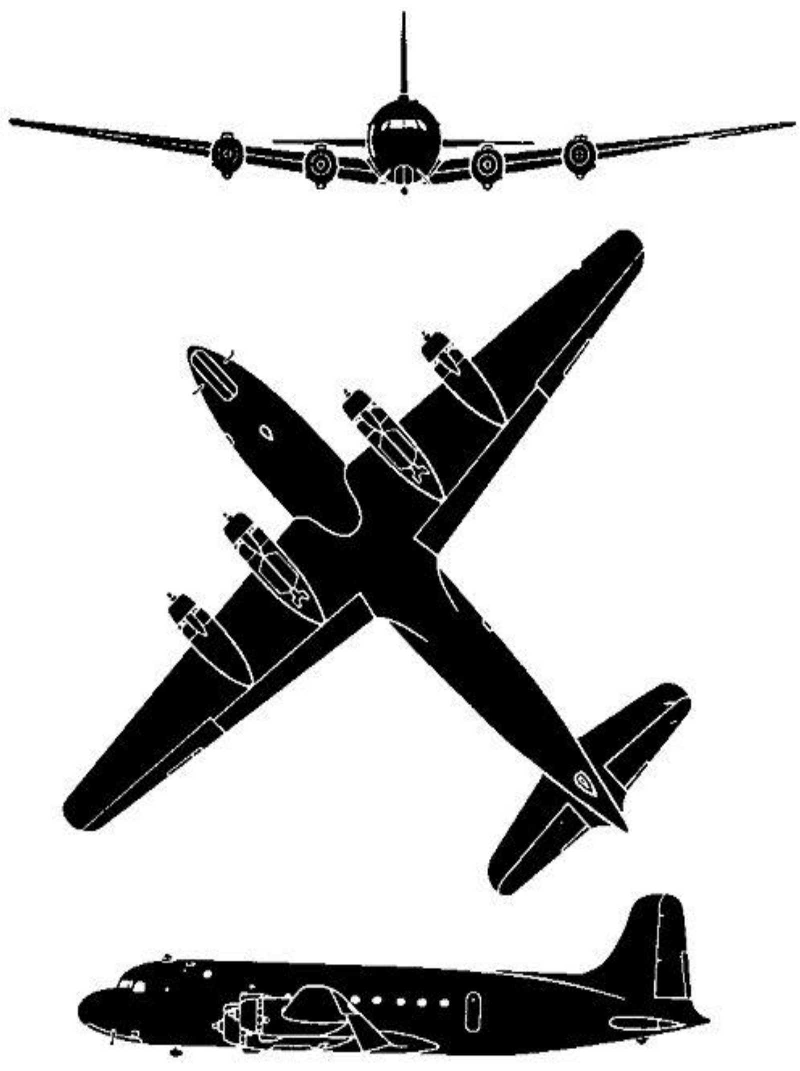
C-87 Liberator





Douglas C-47 Dakota

Douglas C-54A Skymaster



6. Wing characteristics and Weights

Some important wing characteristics of the four aircraft are given in Table 1.
The aspect ratio AR has been calculated with the formula:

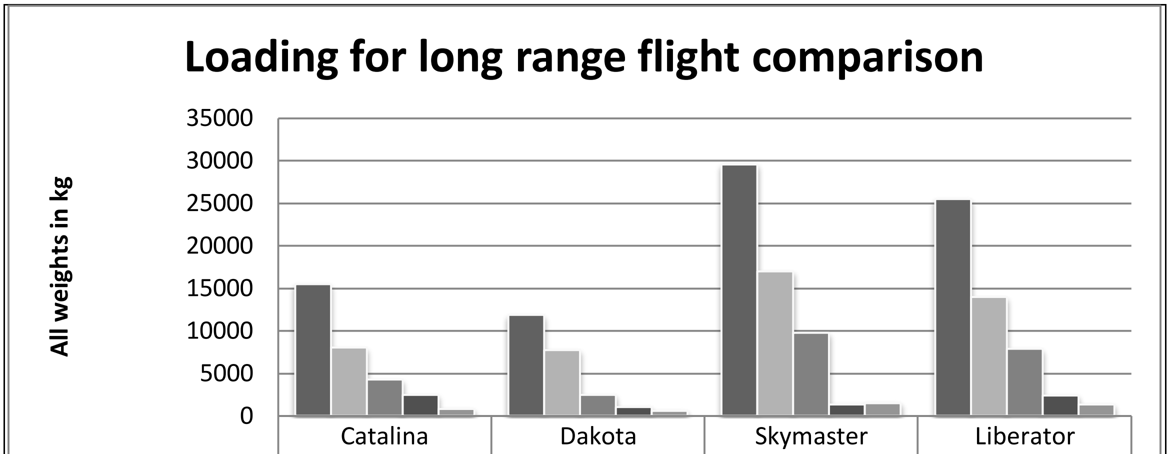
AR = (span x span) / Wing Area [2]

	First Flight	Span m	Wing Area m2	AR
Catalina	1935	31.7	130.0	7.7
Dakota	1935	29.0	91.7	9.2
Skymaster C-54A	1942	36.0	135.8	9.5
Liberator C-87	1939	33.5	97.4	11.5
	Jane's			[2]

Table 1. Wing Characteristics

Note the large wing area and low aspect ratio of Catalina, as opposed to those of Liberator's. Note also the almost identical aspect ratio's of the Douglas machines. (The aspect ratio partly partly determines the so-called 'induced drag' while flying.)
A first conclusion may be that Catalina's wing is of conservative design, which is confirmed by its wing loading factor (see Table 2). It should be remembered that this flying boat was designed in 1934 by Consolidated as the latest member of a family of Navy patrol boats, which had been sesqui- and biplanes. A large wing area, important for a short takeoff, had traditionally formed part of the Navy specifications. Comparing Dakota to Catalina, Dakota belonged to the first airplanes of a new generation: it was revolutionary, certainly in its aerodynamic design and its wing construction, which could be traced to Jack Northrop's Alpha. However, it still had lots of puppy fat, and so it could be outstripped in some respects by Catalina, the product of more than seven years of flying boat construction and refinement.

The weights (loads) of the four airplanes are shown graphically in Fig.5. Shown are Weight Empty (Wmin), Operational Load and the Fuel Load corresponding to the long range flight data of Table 3. The height of each column represents Weight Max.
All weights and loads are expressed in kg.
In Fig. 5a the same weight distribution is shown for each aircraft, in %%.



	Catalina	Dakota	Skymaster	Liberator
Wmax	15460	11820	29550	25460
Wmin	7980	7730	16960	13930
Fuel Load	4230	2475	9750	7840
Payload	2450	1015	1340	2390
Operational Load	800	600	1500	1300

Fig.5 Weights and Fuel Loads for actual Long Distance Flights (based on Jane's, see Table 3 below)

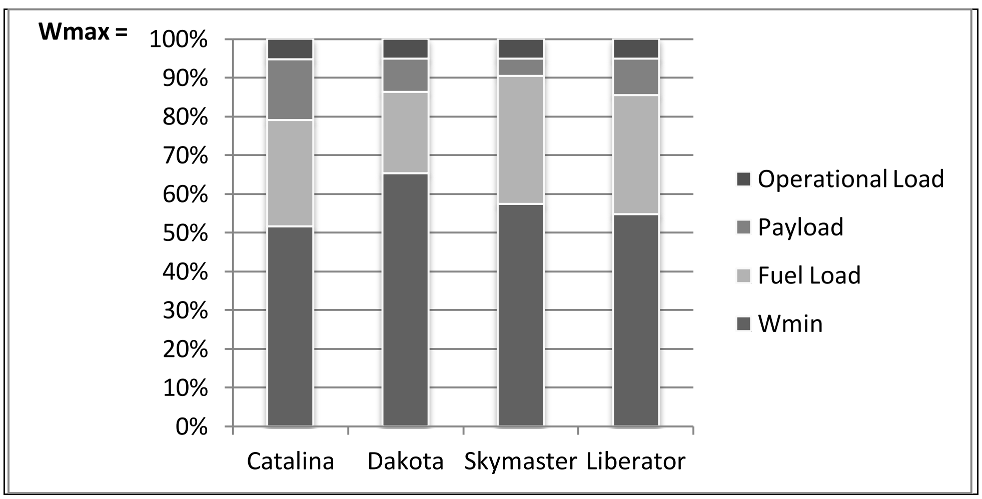


Fig.5a Relative Weights and Fuel Loads for Long Distance Flight (based on Jane's)

Weights and wing area being known, two important design parameters may be calculated for each aircraft: wing loading and structural efficiency [eq.1].

(1 $lbs/ft^2 = 0.454\ kg/ft^2 = 0.454 / 0.3048^2\ kg/m^2 = 4.9\ kg/m^2$)

	First Flight	Max Wing Load kg/m2	ncon	AR
Dakota	1935	127	0.35	9.2
Skymaster C-54A	1942	220	0.43	9.5
Liberator C-87	1939	260	0.45	11.5
Catalina	1935	117	0.48	7.7

[1]

Table 2. Wing load and structural efficiency

Note the general increase in wing loading in later years and the remarkable high wing loading of Liberator, the prototype of which flew already in 1939. Of even more interest is the structural efficiency, where Catalina takes a definite lead. This aircraft is capable of lifting a load almost equal to its own weight.
Dakota comes last, its Loading Capacity being only about one third of its fully loaded weight. Some reasons for the lightness of Catalina compared to the others can be guessed at:

1. the use of integral fuel tanks (according to Creed a 385 kg weight saving);
2. the use of a semi-cantilever wing construction, which gives a high strength to weight ratio at the cost of some extra parasite drag;
3. the use of fabric on certain parts of wing and elevator;
4. the intrinsic lightness of two engines versus four;
5. the absence of certain provisions, like landing flaps, a cabin heating system and armouring(?);
6. the overall excellent structural design.

In the pure flying boat no-wheels version Catalina saved furthermore on retractable landing gear. On the other hand its hull design had to be heavier than comparable landplanes in order to make possible landings in open sea.

7. Analysis of Long range flight data given by Jane’s

Among the data given by Jane's is the long range performance of each aircraft, except for Dakota. The aircraft are loaded to what we have called 'Loading Pattern 2'. (see Fig.3 and Table 3). This loading pattern allows the transport of a considerable payload over a long distance. Table 3 shows the data, with the airplanes in order of distance flown. Dakota's Fuel Load has been estimated.

	Jane's							
	Load Cap kg	Fuel Load kg	fuel %%of Wmax f	Range km	Est. PayL. kg	Work Perf’d tonkm	Tonkm per kg fuel	
Dak C-47	4090	2475	(21%)*	2600	1015	2639	1.2	
Cat PBY-5	7480	4230	(27%)	4990 +->	2450	12226	3.2	<!!
Lib C-87	11520	7840	(31%)	5313	2390	12698	1.8	
Sky C-54A	12590	9750	(33%)	6280	1340	8415	1.0	

Table 3. Jane’s Long range flights with a certain Fuel Load

In Table 3 the Pay Load (not having been specified by Jane's) is estimated according to the following rules:

Operational Load = 0.05 x Wmax[2)], resulting in:

Estimated Pay Load = Loading Capacity - Fuel Load - 0.05 x Wmax

In the calculation of ‘Work Performed’ it is assumed that each aircraft takes off at maximum Weight Loaded and lands after 90 per cent of its Fuel Load has been consumed.

There is, however, more to comparing aircraft performance than this table shows. The given data is in itself not very satisfactory, as the planes each carry a different proportion of fuel. What range would be obtained if all planes were fueled up to the same extent, or to their maximum? Secondly, long range flying is not just a matter of filling up the fuel tanks; there is also the problem of finding the most economical airspeed and engine settings and then maintaining these during the entire flight. How were the flying conditions? These questions remain open. What remains is the robust reputation of the Catalina as a true patrol boat and the outstanding figure of Work Performed per kg fuel shown in above table.

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[2] The assumption that the Operational Load equals five percent of Wmax may be unfavourable for the four engine craft.

8. Theoretical range according to Bréguet

Bréguet's equation for range is given by von Mises [p.463]:

Range in km: $R = 270 \times [c_L / c_D] \times [\eta_{prop} / c] \times [\ln (w_0/w_1)]$ [3]

in which:

- c_L / c_D is indicator of the 'aerodynamic quality'
- η_{prop} is the propeller efficiency
- c is the fuel consumption in kg per bhp hr
- w_0 is the starting weight of the aircraft
- w_1 is the landing weight of the aircraft.

Bréguet takes a very theoretical view of a long distance flight: he takes no notice of wind or weather. Such trivial matters as initial climb or final descent are also discarded. What remains in his analysis is a body (the aircraft) which moves against an opposing force (drag). This requires a certain amount of work to be performed by the engines, which consume the fuel that is carried by the aircraft. When (nearly) all the fuel has been used, the plane lands; the distance covered is called the range. The equation uses constant values; the logarithmic term takes the fact into account that as the plane flies, its weight gradually decreases. Successive kilograms of fuel therefore propel an airplane which is ever getting lighter and less opposed to moving in the air.

No attention is given however to possible changes in c_L / c_D ratio during flight, or to changes in propeller efficiency or fuel consumption. The formula is remarkable for the absence of any dimensioned quantities, except fuel consumption. The three factors between square brackets may all be called 'efficiencies' or 'qualities':

1.	the quality of aerodynamics:	c_L / c_D	
2.	the quality of propulsion:	η_{prop} / c	
3.	the weight ratio,	w_0/w_1 ,	which depends in the end on
the quality of structure:		n_{con}	

No absolute quantities like size, weight, wing area, wing load, span, speed or power enter into the equation (apart from c), and consequently the formula allows the possibility of analyzing any existing aircraft. It also sets design goals for a long range aircraft of any size or weight-class or speed-class.

The airplane designer merely(!) has to marry light structure to excellent aerodynamic form and find a matching efficient power plant plus propeller(s). Also, he should take

care that the optimum values of the 'qualities' 1. and 2. occur at the same operating conditions.
By the same token, the equation shows that it is apparently valid for airplanes of totally different categories to be compared with respect to range (e.g. Lindbergh's 'Spirit of St. Louis' to Dornier's Do-X). A comparison such as we have in mind between four craft of more or less the same time period is thus certainly valid.

The pilot of course will have a rather different (and somewhat gloomier) view of Bréguet's formula. Apart from the fact that it pays no attention to such practical matters as *the influence of head or tail winds*, it obliges him to perform a rather impossible task:

- for maximum range, the engine has to be kept running at minimum fuel consumption,
- while constantly flying at the best c_L / c_D ratio, meaning reducing the airspeed continually as his plane gets lighter and lighter.

Of course this is impractical and so the Bréguet form will yield an unrealistic large range if maximum values for c_L / c_D and η_{prop} / c are substituted. The result may be considered however as an upper bound, of which maybe 75 % can be reached under quiet atmospheric conditions in practical flight.

9. Average c_L / c_D ratio during long range flight

As in our situation the starting and landing weights are known, Bréguet's equation may be used to calculate the average c_L / c_D ratio that was apparently achieved during the long range flights of Table 3.

For this purpose, and for all calculations that follow, we shall assume that the 'quality of propulsion' η_{prop} / c has the same value for all four aircraft. As all four planes use engines of the same family (14 cylinder Pratt and Whitney radial engines of approximately 1200 hp) and constant speed propellers, it seems reasonable to assume that all four planes operate at roughly the same propeller efficiency and specific fuel consumption.
The following values have been chosen:

$\eta_{prop} = 0.85$; $c = 0.23$ kg fuel per bhphr; giving: $\eta_{prop} / c = 3.7$ for all.

In this way the 'quality of propulsion' is placed 'hors concours'and the equation for determining $(c_L / c_D)av$ becomes:

$$(c_L / c_D)_{av} = \text{Range in km} / [270 \times 3.7 \times \ln (W0 / W1] \qquad [4]$$

We further assume that each aircraft takes off at maximum Weight Loaded and lands after 90 per cent of its Fuel Load has been consumed:

W0 = Wmax; W1 = Wmax - 0.9 x Fuel Load

The calculation of the average 'aerodynamic quality' during thelong range flights described in Table 3 is summarized in Table 4.

	Range km	Start Weight kg (W0)	End Weight kg (W1)	W0 / W1	ln W0 / W1	CL / CD av	
Dakota	2600	11820	9570	1.23	.21	12.4	
Liberator	5313	25460	18330	1.387	.327	16.1	note [3]
Catalina	4990	15460	11620	1.33	.284	17.6	
Skymaster	6280	29550	20750	1.422	.352	17.8	
	<-------Jane's------>					[4]	

Table 4. Average value CL / CD during long range flight (nprop / c = 3.7)

------------- further deliberations omitted out of consideration for the reader

14. Conclusions

For conclusions on specific details of Catalina see:

on wing design: page 8, earlier

on wing loading and structural efficiency: see page 10 eearlier

on cost per tonmile: Table 3.

on apparent average Cl/Cd during the recorded flights: see Table 4.

In general:

1. Table 3 shows that Catalina has the larger maximum Work Performed per kg Fuel, because of its greater structural efficiency **ncon**. It can carry more fuel and payload per pound of starting weight, due to the lightness of its construction.
2. Catalina - a two engine, relatively light aeroplane - operates in the same range class as its four engined competitors, which were designed some five years later.

[3]) The values of all L/D come out too high; apparently one should be careful when combining theoretical formulas with practical data. For the definitive performance data of historical airplanes see the monumental work of Loftin:

LOFTIN, Laurence K.: "Quest for Performance"The Evolution of Modern Aircraft / NASA SP-468 / internet, National Aeronautics and Space Adm.: Washington 1985 US

A remarkable success for Isaac 'Mac' Laddon and his team, who built a simple but sturdy, very efficient airplane.

3. Table 4 shows that all planes except the Dokata flew at much the same Cl/Cd value. This is surprising, knowing the great deal of design effort that went into the special wing of the Liberator. It should be pointed out however that the analysis up to this point (Table 4) does not take into account the operating speeds of the aircraft. Further analysis will show that all machines, except PBY, were able to fly at a higher Cd/Cl, if the cruising speed was lowered. Their actual speeds were chosen for sake of safety or economy well above their optimum aerodynamic speed. The Catalina, however, cruised in daily practice at a speed close to its economical optimum, in contrast to the other three planes. Having been assigned to patrol the oceans for submarines, its engines were apparently set in such a way that they could be run for a long period of time at extremely low output ratings, without damaging critical parts.
4. *The Cat flew slow but far*. The argument can also be turned around: Catalina flew near its most economical speed.[4] The others, for commercial or military reasons, chose to cruise considerably faster, thereby sacrificing some of their range and economy. If needed they could extend their range by going slower. Catalina could not.

Summing up: Catalina, product of seven years of continuous flying boat evolution at the Consolidated Aircraft Co., was extremely well constructed, light, with an excellent aerodynamical shape, beautifully mounted (simple) light, high wing, cruising near its best speed - from a point of view of long range: these factors were enough to give her a reputation which lasts to the present.

References

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1993 Arnhem NL ; 2014 Newport Beach CA

[4]) In fact it flew at about 100 knots. At that speed it could outmaneuver its main Atlantic opponent: the German Fw-200 Condor. By making tight turns it escaped enemy attacks.

Friends of the Catalina - Holland 2014

http://www.catalina-pby.nl/

For a fascinating article about another beautifully restored PBY Catalina, see the May issue of Sport Aviation:

http://www.sportaviationonline.org/sportaviation/may_2014#pg60