Airframe Production

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In reviewing some of the factors which have influenced the production development of aircraft during the recent war, the paper focuses the analytical attention of engineers on to the very large technical and manufacturing resources employed: over forty per cent of the whole munition effort of the country. Some comparison is made between the experience of the United Kingdom and that of the U.S.A., the broad conclusion being drawn that technically production methods have been similar, that peak production (having in mind the relative populations), has been comparable, although American outputs have been much higher per man-hour. In some British factories where sufficient concentration has been possible, man-hours have also been comparable with those of the U.S.A. The paper gives some general indications of cost for various elements of aircraft production—e.g. engineering design, provision of manufacturing facilities, tooling, materials, etc.—and it discusses the relationship between the quantity made and the continual reduction of man-hours commonly experienced during the production period. The general problems are examined of meeting the Services' changing demands, of co-ordination of manufacturing through groups, and of material standardization and supply.

1. INTRODUCTION

The primary weapon of the 1939–45 war has been the aeroplane: its production in the quantity and quality which contributed so materially to victory probably constitutes the greatest co-ordinated industrial effort ever made; and this has mainly been an achievement of engineers. The resources utilized have been enormous—over forty per cent of the munitions industries effort—and have been provided at a great sacrifice to the nation as a whole. It is therefore wise that analytical attention be focused by engineers on the employment of these resources.

On a subject of such magnitude it is only possible to present, without exhaustive study, a number of factors which have influenced production. No attempt is made to write a production history of this phase of the war, and only the airframe is considered as typifying the majority of the factors encountered in the production of the complete aircraft: its engines, instruments, radio and radar, armament, etc. Many of the facts given in the paper have already been published in some form, but it is hoped that their presentation together may be of assistance. Primarily United Kingdom experience is considered, but occasional comparison is made with production in the United States of America: circumstances in the two countries have in many material particulars been dissimilar, and in a comparison of them and of their engineering consequences conclusions may possibly be drawn of value in maintaining future security and achieving efficient engineering production.

There has necessarily been difficulty in ascertaining figures or operating conditions with accuracy: this follows inherently from the normal fog of war, and particularly because those engaged have been tackling great problems as a matter of survival and without the opportunity to consider data from any viewpoint other than its usefulness in day-to-day control. Many official forms have been filled up, and might well repay digestion by engineers, but there is a risk that the basis on which many of the earlier ones have been drafted or executed has been too ambiguous to make them useful.

2. OBSERVATIONS

The analysis leads to the following observations:—

Achievement. There can be a great pride in this achievement of the aircraft and engineering industries of Britain; United Kingdom peak production per head of population has only been about one-fifth less than that of the U.S.A., and to obtain this British sacrifices have been higher in meeting their special difficulties so close to the actual fighting front.

Methods. General production methods are technically similar in Britain to those in the U.S.A. In both countries basic advances in production technique have been associated with the cheapening of tooling for blanking and forming operations, with progressive assembly and the splitting up of complete aircraft into large numbers of component sub-assemblies.

Man-hours. Much larger manufacturing units have been employed in the U.S.A. than in Britain (where the probability of enemy air attack was a factor against their adopsion): they have resulted relatively in very much higher output per man-hour.

In those British factories, however, where it has been possible to concentrate sufficiently and obtain a comparably high rate of production, indications are that overall efficiency has been as high as in the U.S.A., and costs have been lower. An important matter in Britain has been the effect of rapid change in achieving and maintaining a lead over the enemy in technical quality, but while—apart from this—the great average difference between U.S.A. and British output is capable of full explanation (in the light of repetition production experience) in this instance it is interesting as it apparently mainly arises from similar manual operations and not from fundamental differences in equipment.

Dispersal. A certain dispersal of manufacturing facilities, so long as a sufficiently large volume of specialized production has been concentrated in each, has been demonstrated not unduly to prejudice manufacturing efficiency. Dispersal generally, however, did result in relatively small-scale—or at least duplicated—production for reasons of bombing risk, and necessarily cost heavily in direct and indirect labour. Some of the very large factories in the U.S.A., however, apparently proved too big for optimum operation because of the wide area from which workers had to be drawn.

Time. The overall time of production development, determining the availability of aircraft for operational service and the period over which peak production continues, are major related factors influencing the scale of provision of production equipment.

Labour. British labour was largely paid on a piece-work basis; American on day work, and both resulted in high earnings. The American labour may have been more flexible, and, with very similar methods and equipment but larger units, produced more per man-hour.

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Expansion. During the war, floor space or equipment has always been adequate, and limitations were firstly in labour and then in raw materials. On the latter, experience showed that output of a raw material could be expanded, however, more quickly than a change in design to use other materials could be effected.

War Potential. While the type of weapon used in war may be expected to change, it is useful to consider the lessons of the 1939–45 war as to the maintenance of war potential. Apart from the obvious measures of reserving suitable facilities, e.g. large buildings on airfields, and of appreciating that war expansion can only occur on the foundation of a strong engineering industry, it is necessary that:—

(*a*) The aircraft industry builds up and maintains stronger design and experimental production teams, which necessitates better apprentice and educational facilities, and a stable outlook for the future.

(*b*) The aircraft production engineer, while maintaining close contact with the technique employed in other branches of engineering, should himself concentrate his development effort on manufacturing methods peculiar to aircraft.

(*c*) Production effort in time of peace on military aircraft should be especially concentrated upon the making of easily-distributed manufacturing information, including good drawings, material schedules, templates, jig references, gauges, etc., such that this may be quickly and easily assimilated as needed.

(*d*) There must be no restrictive labour trade practices that on the threat of war hinder the early stages of development and prevent the most efficient use of those employed in peace time as the nucleus of development for war; piece-work prices, where incentive systems are in use, must be fixed with specific and agreed reference to possible much-extended production.

3. THE PROBLEM OF AIRFRAME PRODUCTION

An aircraft, particularly a Service one, is a very complex engineering structure: excluding the production of the engine, propeller, armament, radio, radar, instruments, etc., the design and construction of the airframe and its equipment for flight is a major mechanical engineering problem. It requires for its successful solution a large team of research, design, and production engineers accustomed to working together, situated in a suitable environment, with great resources of equipment and of labour; furthermore, the whole enterprise absorbs much time. The problem is accentuated by the organic nature of aircraft, which are constantly in a state of rapid evolution. The art is a new one, and operational demands continually call for changes, with throughout emphasis on speed as to actual performance and availability for service operation.

Designs must thus be flexible, and their preparation is still an insufficiently exact science to make reliance for large-scale production on the first drawings other than hazardous. The Service aircraft is not "economic" in any generally accepted sense, and it carries out its function only because of strict attention to weight reduction and to the achievement of maximum performance—at the expense frequently of giving precise expression to the designer's wishes as to perfection of form without reference to difficulties of manufacture. Nevertheless, economics naturally enter largely as factors into effective production in war, and sound production engineering elements will by proper forethought, team work, and thorough co-ordination of engineering and production, be embodied in the design without spoiling performance.

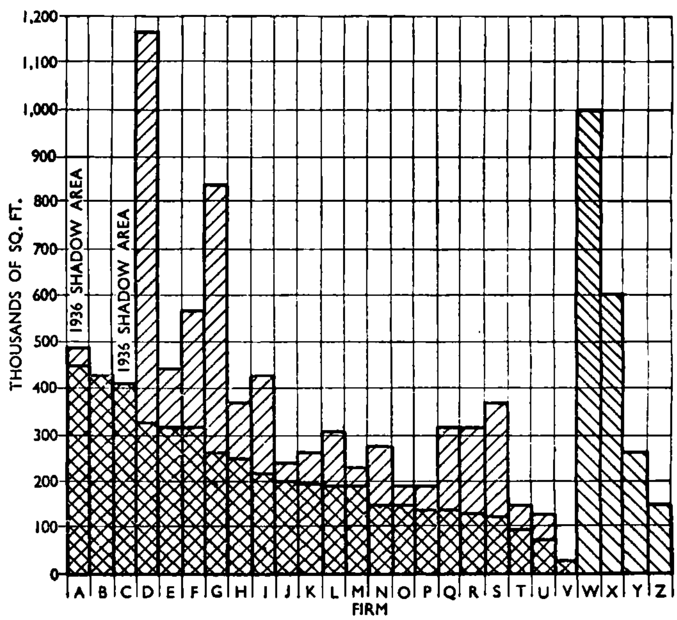
Form of Analysis. The analysis which follows will be made under the successive headings of: basis for expansion; general organization; preproduction work; production; production results.

4. BASIS FOR EXPANSION

Foundation. British and American war aircraft production has been based upon the foundation of sixteen to twenty established firms, who have produced all the effective aircraft designs and who have also controlled a large proportion of the productive effort.

Form of Construction. The war expansion came at a time when the manufacturing experience of the industry was largely on the small quantity production of designs in fabric and wood construction. This was due to the earlier conservative and cautious attitude of the Services; in 1935 aircraft such as the *Gauntlet* biplane fighter (with a top speed of 230 m.p.h.) and the *Hendon* bomber (with a bomb load of 1,500 lb. at 920 miles range) were passable by the day's standards, but they contrasted with all-metal monoplane construction in Germany. Such British aircraft have no inherent structural stiffness comparable with that of all-metal types, and, with their adjustments for rigging, presented none of the essential jigging problems for accuracy of incidence, correctness of main pick-up points, etc., of the latter; and fixed undercarriages, fixed pitch propellers, external bomb stowage, and manual gun operation were normal.

Early Expansion. Expansion commenced in 1935–6 with a definite planning of new "shadow" capacity. Prior to that the number of new aircraft ordered annually by the Government (from, say, 1928 to 1933) had varied between 450 to 850, averaging, say, 50 per month. The monthly delivery rate from 1936 to June 1938 was about 200 per month. In mid-1938 a further expansion scheme was commenced as a result of a rearmament vote of £500,000,000 to be spread over four years; the effect of this, at the middle of 1939, expressed in the approximate terms of airframe factories productive floor area, is illustrated in Fig. 1; then the intention was to produce about 12,000 aircraft by the middle of 1940.



Productive area existing at August 1938 of established airframe constructors.

Additional area being brought into production at middle of 1939.

Engineering firms turning over to aircraft with mainly new factories.

Fig. 1. Floor Area Expansion of Airframe Firms immediately prior to the War

Before 1938 the size of programmes was dictated by financial considerations; thereafter by industrial possibilities. When shortages first occurred they were not in floor space and equipment but in labour first and then in raw materials: throughout the war the theoretical capacity of airframe production measured by floor space or equipment has always been in excess of the actual output or programme.

"Pre-expansion" obsolete types (e.g. *Gauntlet*, *Gladiator*, *Fury*, *Hart*, *Wellesley*, and *Harrow* aircraft) had to be ordered for early expansion in order to absorb and create capacity, as new designs were not then ready. This policy of "stop-gap" orders continued later, notably with the *Battle*, and thus effective expansion was appreciably delayed until aircraft such as the *Hurricane* and the *Wellington* were ready. It should be noted that the main "heavy" bombers—*Stirling*, *Halifax*, and *Manchester* (later *Lancaster*)—were to a 1936 specification.

In 1935 the industry employed about 35,000 persons, of whom 18,000 were in eight works of 1,500 each or over and 8,700 in seven works, each employing between 1,000 and 1,500.

War Expansion. Compared with pre-war days, the industry as a whole expanded its employment about thirty times, the peak being reached about the end of 1943, and thereafter production was maintained although net labour losses were suffered. The main design firms on an average multiplied their own employment four times, individual cases varying from $2\frac{1}{2}$ to $8\frac{3}{4}$ times. These firms in 1936 employed about one-half of all aircraft employment, including engine manufacture, etc. By 1938 this proportion had dropped to 34 per cent, and by 1943 it had fallen again to one-half of the figure: this represented about 42 per cent of airframe effort. A similar number of principal contractors, not being design firms, were responsible for 18 per cent, and the remainder was contributed by the very large number of other contractors.

Expansion occurred by:—

(*a*) Increases at the basic aircraft firms: up to 1938 at their own premises and with their own capital; thereafter with Government resources, including their operating shadow factories, and by widespread dispersal into branch units (e.g. in early 1938 nineteen firms managed forty-five production units each employing over 100 workpeople, but in 1943 they managed 323).

(*b*) The utilization of new prime contractors operating partly in existing premises and partly in new Government buildings on the designs of the basic firms as "daughter" firms. The chief contributors here were the motor vehicle industry, with ultimately 30 per cent of the total airframe and engine employment; over three-quarters, however, being on the latter, and the electrical manufacturing industry with 7 per cent mainly on the former.

(*c*) The bringing in of a very large body of subcontractors, contributing about 40 per cent of the whole production, whereby 14,000 different engineering works—or six out of ten of the whole (excluding garages)—undertook aircraft work. The proportion of subcontracted work increased very rapidly from about 10 per cent in 1938 to 30 per cent by the middle of 1939, and then rose steadily to 35 per cent in 1940, 40 per cent in 1941 and to about 42 per cent for the remainder of the war. The final incidence of this work amongst industrial groups may be seen from Table 1.

TABLE 1. DISTRIBUTION OF CLOCK EMPLOYEES OR WAGE EARNERS ENGAGED ON M.A.P. WORK, 1943 AND 1944

Industrial group	Proportion of M.A.P. total labour force in each group, per cent	Proportion of group devoted to M.A.P. work, per cent
1. Engineering, boilermaking, etc.	25	22
2. Motor vehicles, cycles, and aircraft . . .	51	78
3. Miscellaneous metal goods, bolts, nuts, cutlery .	8	28
4. Electric cables, apparatus, lamps	7	42
5. Scientific instruments .	2	33
6. Non-ferrous metal manufacture . . .	4	50
7. Other industrial groups including railway carriage, heating, iron foundry, chemicals, etc. . .	3	5
Total	100	33

5. GENERAL ORGANIZATION

Central. The central procurement and organizing body in the United Kingdom has been initially the Air Ministry, and later the Ministry of Aircraft Production ("M.A.P."). Theirs has been the task of interpreting the technical operational requirements of the Service, of establishing production programmes, of maintaining an inspection system, of facilitating the supply and control of raw materials, and of providing liaison with other Government Departments. This organization has been characterized by the effective, close and friendly link between Services, Ministry, and industry. It has been particularly successful in maintaining a technical lead, without dissipating a dangerous amount of effort on new ideas.

Co-operation. British aircraft firms have long been accustomed to close technical co-operation on technical matters amongst themselves and with the Royal Aircraft Establishment, the National Physical Laboratory, etc. Important technical, production, and contract matters have been co-ordinated through the Society of British Aircraft Constructors.

Standardization. The Society of British Aircraft Constructors has particularly taken the lead on matters of standardization, and in 1939 initiated a scheme for the introduction of a range of standard aircraft parts and components. At that time, the industry was making fair use of the available National Engineering Standards, but there was a special demand for a new series comprising those specially designed aircraft parts for the supply of which aircraft firms had up till then used their own drawings and which, embodied in a series of National Engineering Standards, would simplify production and ease maintenance.

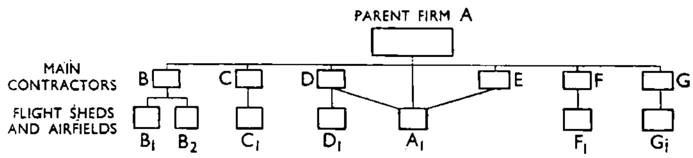
From a beginning on simple components, handwheels, pulleys, bulb holders, etc., the work has progressed until standard designs have been introduced to a degree for such major components as control columns, rudder bars, pilots' seats, and the complete aircraft electric wiring system. Standards are embodied in drawings in the "S.B.A.C. Standards Handbook". They are originated on the advice of the aircraft firms themselves, or on the suggestion from manufacturers who produce detail components, or from units of the Royal Air Force.

Up to now 3,000 items have been standardized without undue restriction on the designer or prejudice to aircraft performance. The Society realized that to issue standard drawings not backed by production facilities of the components concerned was to solve only a part of the standardization problem, so manufacturers were selected by the Society and their names incorporated on the drawings. In a number of cases where, as with plastic mouldings, tooling costs were high, the Society purchased these and amortized their cost over the quantity of components ordered: many hundreds of thousands of aircraft parts have been produced from such tools.

The Society has also introduced a uniform drawing office system, the use of which ensures easy interpretation of all reference numbers of the name of the firm responsible for the preparation of the drawing, the aircraft for which the drawing has been prepared, the section of the aircraft in which the part is located, and the details of the part itself.

Group System. During the course of the war there has developed in Britain the operation, under the auspices of the Ministry, of groups of prime contractors, each building as a co-ordinated whole the same aircraft design. This has resulted in substantial economies and greatly facilitated the employment of small units with rationalization of tooling procurement, press set-ups, machining, material purchase and subcontracting, and so securing to some degree the advantages of large-scale manufacture while at the same time retaining a decentralized layout relatively invulnerable to damage by air attack.

A diagrammatic arrangement of such a group engaged on heavy bomber production, with an indication of the number of airfields used and the number and location of the major subcontractors, is given in Fig. 2. In operating group or daughter-firm arrangements, experience showed that it was essential to have a proper time lag (generally at least 5 to 6 months) between early production at the daughter-firm and that of the parent



Regional distribution of major subcontractors supplying the foregoing main contractors thus :—

Region	B g	C g	D a	A h	E h	F g	G h
a—E. and W. Yorks .	—	—	3	3	1	2	1
b—N. Midlands . .	2	—	1	1	1	1	—
c—London and S.E. .	9	2	1	1	2	4	5
d—South . . .	—	—	1	1	1	3	—
e—South-west . .	2	1	—	—	1	1	—
f—Wales . . .	1	2	—	—	—	2	2
g—Midlands . .	11	9	5	5	5	8	5
h—North-west . .	6	1	7	7	10	2	5
i—Scotland . .	—	—	2	2	1	2	1

Fig. 2. Group Organization for Production of a Heavy Bomber

firm, in order to obtain reasonable stability and proving of manufacturing information. There is thus a heavy risk of the daughter-firm producing, owing to rapid obsolescence of the type, a small proportion of it: typical results, however, are shown in Table 2.

TABLE 2. PERCENTAGE OF WHOLE GROUP OUTPUT OF PARTICULAR AIRCRAFT PRODUCED BY EACH MEMBER

Type of Firm	Bomber	Bomber	Bomber	Naval	Fighter
"Parent" . .	25	59	24	44	35
1st "Daughter" .	35	19	47	31	55
2nd ,, .	17	17	29	25	12
3rd ,, .	13	3	—	—	—
4th ,, .	10	1	—	—	—
5th ,, .	—	1	—	—	—

Internal. Aircraft firms are commonly organized functionally so as to obtain the best possible co-ordination of design and production and to secure maximum economy of time and labour: for a fuller analysis of this, and on the subject-matter of the next section, see the recent paper by the author and Mr. Petter*. Basically cheap production results from designing for it initially, and improvements during the war indicate further possibilities in this direction.

6. PRE-PRODUCTION

Engineering Design and Development. A large engineering staff is required to design an airframe. The engineering man-hours required vary with the nature of the manufacturing drawings provided; for production the demand has been for the drawings to be as detailed as possible, necessitating extra time in the design offices in order to reduce later the time required in their interpretation; but the need for the earliest flying of the prototype, together with design staff shortage, has frequently meant that initial drawings have been "sketchy". Actual engineering man-hours, excluding clerical and similar services, have varied from about one to two hundred thousand on a fighter, up to half a million on the largest bomber; something of the order of an engineer's time for half a week has been required per pound of empty airframe. Typical figures are given in Table 3.

Engineering staffs in Britain have had as a maximum 200 to 250 draughtsmen, but generally 100 to 130, and typical examples and a rough overall average are given in Table 4. While some expansion has taken place during the war, this has been achieved with great difficulty and was obtained mainly by training apprentices and up-grading of juniors following the introduction of women—the latter now frequently amounting to 30 per cent of the total. Many of these are on clerical work, relieving draughtsmen for purely draughting work, but the dilution of actual draughtsmen has been very high: for the main firms, seniors have averaged about 36 per cent, detailers, etc., 22 per cent, juniors 27 per cent, and women 8 per cent. Even then airframe draughtsmen have probably represented 15 per cent of all mechanical engineering draughtsmen in the country during the war.

* MENSFORTH, E., and PETTER, W. E. W. 1944 Jl. Roy. Aeronautical Soc., vol. 48, p. 210.

TABLE 3. TYPICAL DESIGN ENGINEERING MAN-HOURS FOR AIRFRAMES

This table includes draughtsmen, stressmen, weightsmen, etc.

Type of aircraft	Weight of airframe empty, lb.	Design man-hours		Design man-hours, per lb. of airframe	
		To first proto-type flight	To com-pletion of pro-duction drawings	To first proto-type flight	To com-pletion of pro-duction drawings
Naval reconnaissance .	10,780	209,000	322,000	19·4	29·8
Heavy bomber .	34,230	440,000	490,000	12·8	14·3
Night fighter .	13,630	100,000	311,400	7·4	22·8
Heavy bomber .	39,010	346,000	593,000	8·9	15·2
Heavy bomber .	29,050	325,000	325,000	11·2	11·2
Trainer . .	4,250	25,000	75,000	5·9	17·7
S.S. fighter . .	8,200	92,000	180,000	11·2	21·9
Naval bomber reconnaissance .	9,350	201,600	—	21·6	—
Two-eng. fighter-bomber . .	14,690	200,000	400,000	13·6	27·2
Flying boat . .	37,450	197,000	242,000	5·3	6·4
Two-eng. fighter .	15,400	243,000	300,000	15·8	19·5

TABLE 4. TYPICAL ENGINEERING STAFFS

Summary of staff employed in drawing offices of certain aircraft design firms.

Typical firms	Total staff, excl. senior exec's	Air-craft d'men, all types	Stress weight loft-ing	Aero-dyna-mists, tech-nicians, and re-search	Tra-cers	All others, incl. train-ees*	Total jig and tool d'men
Fighter-bomber . A	437	190	54	15	12	166	35
Heavy bomber . B	428	245	33	5	51	94	67
Naval . C	369	168	66	15	5	115	45
S.S. fighter D	280	169	36	11	11	53	19
Naval . E	269	111	41	13	7	97	21
Heavy bomber . F	240	111	54	16	8	51	11
Trainer . G	225	132	23	6	5	59	20
Fighter . H	217	99	25	21	16	56	34
Flying boats I	113	57	15	12	6	23	5
Arithmetical average for 18 firms .	297	147	38	10	16	86	32
Per cent distribution .	100	49·4	12·8	3·4	5·4	29·0	—

* Includes all clerical staff, and those engaged on spare part lists, maintenance handbooks, etc.

There has been great labour stringency, and staffs have undoubtedly been too small; an increase in their size would have allowed of a substantial reduction in the development period. There is, however, an optimum size beyond which it is unnecessary to go, and an increase in total numbers of about 25 per cent—allowing the trained technical staff to be increased by 50–100 per cent—should be adequate with each design firm undertaking one major project at once.

American design staffs have grown enormously during the war and now range in size from about 1,000 up to 3,000. While the largest firm will tackle several major projects at one time, it is not felt that Britain should aim at such large sizes, as inefficiency may result with some of the best engineering brains spending the majority of their time on purely administrative work.

Prototype Manufacture and Flight Development. The effort required to design an aircraft is paralleled by that necessary to build the prototype: this requires the employment of a large proportion of skilled and experienced people accustomed to working very closely behind the issue of drawings and without many tool aids. There is a peak load on the experimental shop for a few months before completion of each prototype, and this peak can only be levelled out at the expense of overall timing of the project. The endeavour during the flight development period has been at the earliest possible stage to discover necessary changes in design so that these may be effected with a minimum of dislocation to production tooling. In order to obtain a maximum of flying in a short time it has recently become customary to order several prototype aircraft, to be followed closely by a number of "pre-production" aircraft.

Prototype design and construction has normally absorbed a minimum of 12 months up to 2–2½ years, according to circumstances and type, and the total time elapsing from the initiation of the design to the time squadrons received production operational aircraft has been from about 3 to 5 years. It is interesting to compare such times with those for other engineering projects, e.g. an aircraft carrier 3 years, destroyer 1½–2 years, electric main-line locomotive 1½–2 years, and large turbo-alternator 1–1½ years.

Number of Types. Although there has been much discussion on the elimination of other than a few types, this did not prove possible under changing war conditions, which called for continual modification. Also the practice of inviting several firms to design to one specification resulted in more than one promising design emerging and being allowed to continue as a valuable insurance against operational trouble by premature concentration on one type. As an example, had concentration been the policy the *Lancaster* would not have emerged from the *Manchester*. An analysis of types is given in Table 5.

TABLE 5. NUMBERS OF TYPES AND MARKS OF AIRCRAFT IN PRODUCTION

Of the 1943 types, 16 were put into production since 1940.

	In production in 1943		Produced actually during the war		
	Number of types	Number of prime production factories	Types	Marks	Proportion of whole production, per cent
Heavy bomber	3	13	5	14	15
Medium „	4	6	3	17	13
Fighter	7	12	10	51	33
General reconnaissance	3	6	4	7	2
Naval	7	8	8	16	7
Trainers, transports, and miscellaneous	8	9	18	29	30
	32	54	48	134	100

A study of U.S.A. types indicates a very similar variety with, of course, more emphasis on transports.

Means of Production. This may be considered as follows:—

Facilities. Much of the facilities utilized on airframe production have been of a general purpose type, e.g. buildings for detail work, machine tools, presses, etc. Specialized facilities have also been essential, however, e.g. a proportion of buildings of exceptionally large clear span and height, heat treatment equipment, rubber bolster presses, stretching machines, drop hammers, non-ferrous spot welders, routing machines, and spar milling machines.

Since September 1939, about 100,000 machine tools were supplied to all M.A.P. contractors, about 12 per cent of these being of American origin. Specialist equipment included fifty-six rubber bolster presses (one at 10,000 tons capacity, six at 8,000 tons, thirteen at 5,000 tons, and the remainder down to 500 tons), thirty-four stretching presses, and eighty-six drop hammers. In the provision of buildings considerable use was made of standardized units, where a total of over 1,300 such buildings was provided by M.A.P. with a superficial area of over 16 million sq. ft.; the smallest of these was 2,750 sq. ft., the largest group 330,000 sq. ft.

These buildings were ordered in advance on a stock basis, which was in fact turned over nine times with a maximum quarterly consumption at the rate of 7½ million sq. ft. per annum. Typical costs of providing new airframe factories in the early war years are given in Table 6. The use of underground production factories, in its contribution to the whole, was very small.

TABLE 6. COSTS OF TYPICAL FACTORIES ERECTED IN EARLY PART OF THE WAR FOR PRODUCTION OF AIRFRAMES AND COMPONENTS

Cost per sq. ft. (£).

Factory floor space, sq. ft.	Land	Building and services	Plant and equipment	A.R.P.
1,700,000	0·003	0·71	0·463	0·058
500,000	0·001	1·7	0·24	0·16
300,000	0·003	0·42	0·333	0·040
187,000	—	0·90	0·074	0·073
117,000	0·010	1·23	0·81	0·15
75,000	0·003	1·52	1·34	0·087
32,000	—	0·65	0·198	0·027

Size. The size of basic aircraft factory units in Britain averaged about 0·75 (from 0·5 to 2·4) million square feet, excluding branches and subcontractors; the average employment of each prime contracting unit was from about 3 to 15 thousand persons—including those, often under 100 in each and averaging only several hundred, situated in the many branch factories frequently converted from garages, etc. In comparison, U.S.A. units averaged about 2 (from 1 to 3·5) million square feet, with employment generally at least twenty and up to over forty thousand persons; recently the problems of concentrating so many people from a wide area proved in a few cases to be so great that apparently to some degree British practice was followed by establishing branch factories close to centres of population.

Floor area used has probably been typified by about 150 to 200 sq. ft. total per person employed. Its distribution has

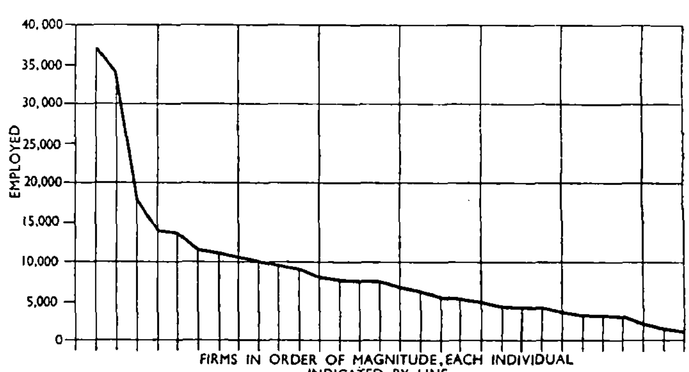


Fig. 3. Employment at the Main Firms producing Airframes at October 1944

probably varied as to stores about 12 to 16 per cent, detail fabrication 18 to 20 per cent, structural assembly and installation 20 to 25 per cent, erection and flight 15 to 25 per cent, and offices and services, etc., remainder.

Fig. 3 indicates graphically the peak employment of the main firms, and it will be seen that in a number of instances the figure shown includes several main contracting units.

TABLE 7. PRICE COMPONENTS OF AIRFRAMES, EXCLUDING EMBODIMENT LOAN ITEMS AND PROFIT

Figures show percentage of total cost.

Type	Materials and proprietary parts	Direct labour	Overheads*	Sub-contract	Total cost
Heavy bomber I	50·9	15·9	25·2	8·0	100·0
Heavy bomber II	39·5	11·3	26·8	22·4	100·0
Light bomber .	37·7	16·9	13·6	31·8	100·0
Naval T.S.R. .	30·9	14·5	26·8	27·8	100·0
Trainer . .	37·7	23·0	39·3	—	100·0
Heavy flying boat	36·8	29·4	33·8	—	100·0

* Indirect labour, services, management, and design charges, etc.

Distribution of Work. Typical distributions of the elements of cost of airframes are given in Table 7; tooling amortization is not included (see below).

Components normally made by the aircraft contractor will each absorb, typically: fuselage and engine installation 30–35 per cent; wing 40–45 per cent; aileron 2 per cent; flaps 1 per cent; tail unit 8 per cent; the remainder being on tanks, undercarriage, etc., and final erection and flight.

Tooling. Tooling is characterized by the large number, 5,000 to 10,000, of parts (other than standard machines details, etc.) requiring to be individually tooled but with relatively small-scale production; each of these parts will require an average of at least two tools. These details are then assembled into large and complex structural assemblies with tooling so that the work may be performed with unskilled labour and such that interchangeability results.

Some considerations influencing tooling are:—

Assembly Jig Construction. The main requirements are accessibility and stiffness to keep main "pick-up" points in correct relationship. Such points may be 20 feet or more apart, and temperature effects must be allowed for—frequently by inherent flexibility or relative freedom in service of one end (e.g. a wing tip).

Jig construction is variously based upon:—

(*a*) Iron castings special to the jig.
(*b*) Cast iron standardized units with special pick-ups only.
(*c*) Riveted or bolted mild steel structural sections.
(*d*) Electrically welded mild steel structures of conventional rolled sections, frequently made into box sections, or of tube.

Jigs may be either dependent upon the foundation for location of various sections or the whole may be a self-contained structure, on floor levelling pads or on a moving conveyor. All these methods have been employed during the war, but experience indicates that for most purposes self-contained welded structures are best.

Interchangeability. There has to be distinguished:—

(*a*) Component interchangeability: of wings, ailerons, power plants, etc., arising from transport considerations and from the convenience of being able to replace the whole when damaged with a minimum of labour and equipment. The difficulties arise here mainly from the large size of the units. In general, several similar assembly jigs are required for the quantity production of a particular component, and these have commonly been in a number of factories. Dimensional similarity of the product has been successfully obtained in Britain by a well-developed use of jig references or setting fixtures, which are stiff reproductions of the main pick-up points, occasionally but not necessarily coupled with the use of acceptance gauges.

Alternatively—particularly for large components—optical means of jig setting have been developed, with collimator equipment capable of detecting misalignment of 0·010 inch at 50 feet and lack of parallelism within six seconds of arc. Recently there has also been developed methods of setting jig references by means of optical triangulation with an accurate theodolite. In these matters British practice appears to have been in advance of American, but a development there is the provision of "tooling docks", up to about 70 feet long by 17 feet square, in which a system of bushed holes at specified centres is employed to locate crossheads fitted with micrometers, by which the co-ordinates of any jig pick-up point may be directly established relative to the axes.

(*b*) Detail interchangeability: an important matter affecting the total cost of tooling is the degree to which detail interchangeability is required. Earlier there was some loose thinking regarding this and attempts have been made to tool sized holes in mating structural parts, such that they assemble correctly for riveting. Because of material variations, absence of large tolerances in the rivet hole, inaccuracies impossible of correction in the short time available, and the "creep" of plating during riveting, these have, with certain exceptions, not been very successful, and general practice now is to drill or pierce holes in one part only, drilling to size through this into the mating parts; or alternatively to jig-drill through both when assembled together from tooling holes. On repair work in replacing detail parts—generally involving an assembly jig operation—drilling through from the mating part causes no difficulty. Parts such as cowlings have caused much difficulty in obtaining real interchangeability.

Tooling Expenditure. This has an important influence on the overall development time. A limit has been imposed by labour shortage to the amount of tooling completed in a given time, and a balance has had to be struck between saving unskilled and spending toolroom man-power; experience has shown that by the time the first production aeroplane of a new type flies the cumulative expenditure on toolmaking will be at least three times (and frequently more) that spent on actual manufacture. Tooling expenditure in Britain has varied between about £1,000,000 and £3,000,000 for both fighters and bombers; it has cost from 15 to 40 shillings per lb. of airframe required at peak production per month; its amortization has represented, with continuing production and relatively large quantities, up to 10 per cent of total cost (see Table 11).

In the expenditure of such a large sum it is desirable to have a budget allocation between classes of tools and sections of the aircraft. As an example of the former on a fighter, proportional costs were: main assembly and sub-assembly jigs, 25 per cent; machining fixtures, 16 per cent; press tools, 11 per cent; general detail tools, 45 per cent; and erection equipment, 3 per cent. Expenditure on press tools would probably have been a higher proportion for larger-scale production, for on one U.S. bomber over 13,000 press tools were provided. On a particular bomber, main assembly jigs cost 14 per cent; sub-assembly jigs, 32 per cent; and all detail tooling, including machining and press, 54 per cent. Tools vary in cost from about £10 each to, say, £3,000 for an assembly fixture, with an average of probably about £25.

Total tooling expenditure sponsored by M.A.P. (for all parts of an aircraft) in specialist tooling firms, or those not making aircraft or components, has been approximately (in *thousands of £*):—

	Jigs	Gauges, etc.	
1939	2,021	630	
1940	3,704	1,050	
1941	5,218	1,470	
1942	8,240	2,204	
1943	8,840	2,306	
Total	28,023	7,660	£35,683

It is believed that this figure may be doubled if those tools made in contractor's own tool rooms are included, and it then represents about £700 per aircraft produced during the war.

Proving of Tools. Early war experience showed the necessity for a careful system of proving tooling before release for quantity production, and tooling manufacture, and its checking, is best carried out in sub-assembly groups with detail tools and assembly fixture proved as a unit.

Manufacturing Information. Owing to the complexity of an aircraft, the issue of manufacturing information in the most economical way has been a matter requiring the closest attention, and many of the troubles in obtaining large-scale production have followed failings here. Drawings have often been incorrect, followed by a reliance on samples altered and proved in experimental manufacture but not used to correct the drawing. Great improvements have been obtained from the adoption of mould lofting to define principal dimensions, particularly those of curved surfaces, with direct draughting on to metal. By contact or photographic reproduction, working templates are then made economically and used directly in tooling; e.g. for router formers, blanking dies, and gauges, and for master forms faired in with plaster from which press tools, drill jigs, etc., are moulded.

Manufacturing Control: System. Manufacturing control methods used are similar to those in other engineering trades. During the war they have passed through the usual vicissitudes: from an early tendency to elaboration with the risk that the system would make itself master of production, to straightforward systems recognizing the necessity for simplicity and a strong and understanding human element.

Batch. Manufacturing has been on a batch system with, on established production, about one month's output in a unit batch; on detail, e.g. machines parts, press parts, etc., two or three months have been combined for a set-up.

Spares. Experience has enabled better forecasting of spares requirements to be made, and in the latter part of the war the manufacturer could normally look forward to spares—embracing on an airframe about 3,000 to 6,000 different items—being ordered in six monthly batches about 10 to 14 months ahead. These quantities were then commonly added on to manufacturing batches.

Work in Progress. Sound manufacturing control has required the maintaining of sufficient work in progress at all stages, necessitating a considerable proportion of total shop space being stores. This, coupled with "kit marshalling" of details a number of days ahead of assembly line requirements, has eliminated much detail progressing on a "shortage" basis which characterized the early war period.

Material Procurement: Organization. An important factor in production has been the organization of material procurement. There has been in Britain during the war a considerable amount of direct buying, or direct price control, by the Government, but the majority of their contracts have been placed through a relatively small number of firms who have carried the heavy responsibility of spreading the work. A typical aircraft has been divided as follows: "raw materials" bought at Government fixed prices, 12 per cent; "proprietary parts", e.g. wheels, tyres, undercarriages, etc., at Government controlled prices, 14 per cent; "embodiment loan" items, being direct Government purchases supplied free to the aircraft contractor for installation, e.g. engines, propellers, instruments, armaments, etc., 50 per cent; (Table 11) airframe construction (including subcontracting being on average 40 per cent), 24 per cent. Thus quantitive control of the purchases, and the last item, have directly concerned the airframe contractor.

The largest proportion of raw material on the airframe has been light alloy sheet, bar, tube, and extrusions; e.g. on a particular fighter these were 61 per cent of the total cost, the remainder being 8 per cent castings and forgings, 22 per cent rivets and miscellaneous proprietary parts, and 9 per cent other materials.

British material production and procurement has been coordinated by the Ministry of Aircraft Production, through controls that have successfully canalized particular types of material in bulk quantities to the most economical supplier, with resultant specialization and economy. Fundamentally, these controls have based supply on specific fabrication cycles relative to the aircraft programmes, instead of (as in the early days) on a panic system of priorities operating each month, and frequently putting into priority category more demands for manufacture than the industry as a whole was able to deliver. Fabrication periods have been from 3 to 6 months for a fighter, and 4 to 9 months for a bomber; the lower period being that achieved in steady full-scale production and the upper that allowed as a normal maximum by the controls.

Centralized control and manufactured specialization has been extended to many detail items, e.g. "A.G.S." parts (bolts, nuts, rivets, etc.), with the result of economy in production, with, for example, only length changes to make for long periods in automatic machine set-ups. To facilitate this control, material buying has generally been limited to the prime contractors, who have then supplied materials to their subcontractors as a free issue—with suitable arrangements for promoting economy in its use—in order to save double handling and transportation, etc. In the U.S.A. it is believed that subcontractors have generally bought direct from normal commercial sources.

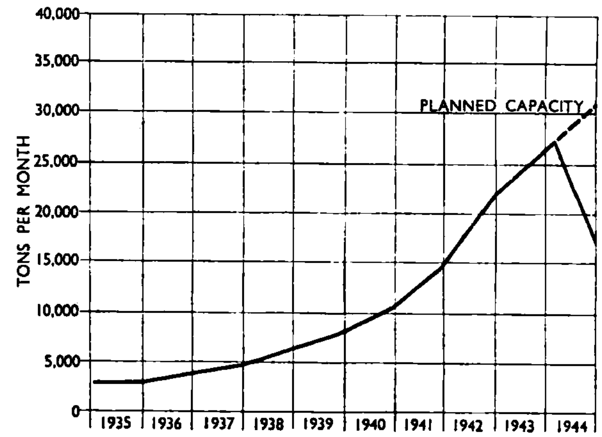


Fig. 4. Total Output of Fabricated Aluminium Alloys

	Average tons per quarter			
Distribution (M.A.P. only)				
Sheet and strips . .	12,000	14,000	21,000	25,000
Extrusions . . .	7,000	10,000	17,000	23,000
Castings . . .	4,000	5,000	8,000	10,000
Forgings . . .	3,500	4,500	7,500	11,000

Supply Position at the Outbreak of War. The major materials used on airframes were light metals: output in this industry during the pre-war period was very limited by comparison with the peak (some eleven times greater) which ultimately had to be achieved, as is shown in Fig. 4. At the outbreak of war, the airframe contractors found themselves faced with the position in which light metal supplies were very limited and where deliveries were offered as 9 to 10 months or more by the larger producers. Under such conditions spasmodic urging of individual requirements by the official organization then dealing with supply merely set back the promised date for the bulk of the materials and increased the liability for shortages; the relative strength of old-established and new firms in progressing power with the suppliers was an important factor in obtaining supplies, and buyers, realizing the supply difficulty, tended to over-order their forward requirements, thus creating artificially overloaded order books.

Expansion. In order to cope with the position, the control planned on the basis of the definite scheduling of requirements by aircraft contractors in direct relation with the aircraft programmes, which was based on an accurate bill of materials with agreed scrap allowances and agreed spares requirements. Suppliers were authorized to deliver only to the agreed schedule, and this involved the allocation and authorization of purchase orders by the control, which necessarily had a direct influence on the internal planning methods of aircraft contractors, and led to some uniformity of methods of material planning as between contractors and suppliers.

Initially to cover work in progress during the increasing programme, the expansion of materials output was required at a rate faster than the expansion of output of aircraft, thus making the creation of new capacity a formidable task. Early expansion was made largely by double or three shift working of seven days per week, but later expansion was by the provision of new capacity. In general, it proved easier to introduce new extrusion presses than rolling mills or heavy hammers; some extrusion presses were in fact brought into production on a three shift basis within nine months from ordering. The peak of capacity demanded crept steadily higher throughout the expansion period. Thus, for example, in March 1941 the peak annual output required for extrusions was planned at 5,600 tons, but by the end of the year this had increased to 7,600, by July 1942 to 8,600, and by April 1943 to 9,600.

Influence on Design. Throughout the country there has been a natural tendency for aircraft designers to be influenced by the short term delivery position of a particular category of materials. While the designer must bear in mind the availability of materials —certainly where imports, for example, might be the governing factor—major changes of policy should not be adopted without an appreciation of those arrangements which may have already been made by suppliers for expanding output. For example, at the end of 1941 a number of designers assumed that the forging position would be unlikely to permit of additional requirements of forgings, and they extended the use of high strength castings; as a result the high strength casting industry was overloaded at a time when the successful expansion of the forging industry would have been able to cope with the requirements for the new types. In general terms, experience shows that an extension of output in terms of plant and labour could be made effective in a shorter time than the period for which a new tendency in design in the use of materials becomes effective.

Standardization. This matter has already been touched upon in section 6. It has a major effect on material procurement and must necessarily emanate in the drawing office. Size and varieties of material have been successfully limited without prejudice to design, but the variations that may occur and the magnitude of the problem may be appreciated by observing the typical analyses given in Table 8. Many special light alloys of limited fields of application, and mainly sponsored by individual firms, were discontinued as soon as possible; but even then there remained fifty-nine specifications in twenty-one compositions of the wrought light alloys.

TABLE 8. TYPICAL MATERIALS' CONSUMPTION FOR NUMBER OF SEPARATE MATERIAL ITEMS, I.E. SIZES AND SPECIFICATIONS

Heavy bomber	Light alloy	Steel	Non-ferrous	Total
Raw materials:—				
Sheet	195	127	17	339
Bar	158	165	62	385
Tube	399	284	19	702
Extrusions	130	—	—	130
Castings	230	—	—	230
Forgings	173	54	23	250
Other items:—				
A.G.S. parts				1,277
Rivets (total used, all types)				496,000
Fabricated items not otherwise included				25,066

Modifications. The timely incorporation of modifications with a minimum dislocation of established production has presented many problems. In Britain this has generally been accomplished during production, some disturbance being accepted, but in the U.S.A. production has more often continued until the change has been instituted from the early operations, and the aircraft produced meanwhile, having to be altered later in separate "modification centres", necessarily absorbed additional labour and time.

The following are examples indicating the frequency with which essential and important modifications have actually been introduced into two types in large production; the figures, of course, exclude very many more minor changes, corrections to drawings, etc., which on particular types in their early production life would run to several hundred per week, or from fifteen to twenty thousand in total.

Monthly modifications average:—

	1942	1943	1944
Fighter	6·2	9·8	7·6
Heavy bomber	9·8	9·0	7·3

7. PRODUCTION

General. Production will be considered as to: machining, detail fabrication, structural assemblies, installation of equipment, aircraft erection, flight testing, and finishing. Generally, production methods may be analysed into those commonly employed in other industries, and into those special to aircraft and arising from difficulty of shape, from complexity of raw materials requiring care in heat treatment, mechanical handling and protection against corrosion, and from the relatively small quantities which necessitates economy in tooling. Each of these includes work for which the estimation of operation times can either be precise (e.g. from machining speeds and feeds), or require considerable judgement and data which were lacking in the early days of the war (e.g. assembly and installation).

The proportion of the total man-hours absorbed in the various phases of manufacture has averaged about: detail fabrication, 25 to 30 per cent; machining; 10 to 14 per cent; structural assembly, 30 to 35 per cent; installations, 15 to 20 per cent; and erection, 5 to 12 per cent.

For a detailed description of production methods peculiar to the airframe industry, reference should be made to the handbooks issued by the Ministry of Aircraft Production (January 1944) on Fabrication of Sheet Metal Details, which includes sections on router, press (mechanical and rubber), stretch forming, and drop hammer. The industry has also been fortunate in being well served with technical journals, in the files of which (e.g. *Aircraft Production*) will be found illustrated accounts of most of the specialized production methods.

Machining. For a particular bomber, machining was distributed as: drilling 20 per cent, milling and profiling 22 per cent, turning 53 per cent, and grinding and miscellaneous 5 per cent; this, of course, varies somewhat, however, with design and practice. The majority of machine tools used on airframes have been general purpose, but on engines and airscrews a much larger proportion of single-purpose tools have been employed. The airframe industry found itself, at the beginning of the war expansion, emerging—as it were—from the wood and fabric stage, and being poorly equipped with machine tools was able to obtain from the commencement the benefit of modern ones. Problems have mainly arisen from complexity of dimensions and form, from relatively unmachinable high-tensile steel parts (improved recently by the use of carbide-tipped and sometimes negative-rake tools); and from the time taken in machining light alloy parts (greatly speeded up by the early realization that high cutting speeds were necessary, e.g. 1,000 to 5,000 ft. per min.). One important special-purpose machine which has been developed is the heavy duty plano-miller for automatic contour milling of long extruded light alloy spars, etc.; these machines have achieved high outputs, e.g. 3 to 5 cu. in. of metal removed per h.p. per minute, and employ drives of 50 h.p. or so.

Fabrication : Blanking. Before the war-time expansion, the cutting of light alloy to shape was generally by shears, circle cutter, or nibbling, although some simple blanking tools were used; great economies resulted from the adoption of the high-speed router cutter (e.g. $\frac{3}{8}$ inch diameter running at 24,000 r.p.m.) with which several sheets are simultaneously accurately profiled, using only plywood, fibre, or mild steel templates, at feeds of about 20 inches per min. Originally conceived in the U.S.A., convenient forms of this machine were quickly developed in Britain. "Routering" enables "off-cuts", difficult to feed economically into press tools, to be utilized fully, and it is flexible because tooling is cheap. Normally it is associated with a "stack drilling" operation on several sheets at once through a mild steel jig using a floating bush on the drill—an operation which with proper care is accurate. With relatively few holes in a part (as several are drilled at each stroke), it compares favourably in operation time with ganged punching, and for normal quantities tool amortization is lower. For much larger quantities, particularly in the U.S.A., there has recently been an increasing use of blanking and piercing tools. Initially these were of classical type, and were inflexible in the event of design changes; but simplified types have now been developed, which are made, for example, from a steel sheet punch cut out to lines directly printed on to it by the mould·loft and zinc alloy sheet die. Punches have also been very successfully made from steel flexible rule sections bedded in impregnated hardwood bases (designed from printing trade practice). The production of these types of tools has been cheapened by the use of uniform bolster set-ups, and the employment of standard pre-machined sections such that skilled toolmaking labour is not required for their assembly.

Forming, etc.: (*a*) *General.* In the early war period much metal-forming in Britain was done by hand methods, often necessitating the employment of skilled sheet metal workers. The U.S.A. was increasingly adopting the drop hammer, which Britain has extensively also used, but we tended to avoid this where possible, as it was relatively slow and inaccurate, and employed drawing or stretching instead in cheap dies made of wood, cast iron, cast zinc alloy, or concrete. The ability to form large pieces from press tools, which are fairly cheap, has enabled the designer to use fewer parts—e.g. for internal stiffeners—and thus reduce operation times.

(*b*) *Rubber Platen Presses.* The greatest advance, however, has followed the development of the rubber platen press, used for general forming of a large variety of parts such as ribs, and such presses are operated in capacities from 400 to 10,000 tons—commonly 1,800 or 5,000 tons. For efficient employment of these expensive equipments, two or four (and in the U.S.A. occasionally six) feeder tables are normally used. These presses have the great merit of requiring no die—only a punch, frequently of compressed wood—and consequently there is no setting up. Properly fed, they have produced over 20,000 parts per week. On such a tool it is not normally possible to "lose" metal on convex curved flanges such that an accurate profile can be formed: while the best way on such a job—if quantities warrant it—is to use metal draw dies, and fairly satisfactory results have been commonly obtained on the rubber bolster with strip steel "slippers" and intensifier plates, although some hand correction is then generally necessary.

It has been found that the steady supply of normalized heat-treated blanks has been greatly facilitated by the use of refrigerated storage rooms, and the resultant uniformity of hardness has much improved the quality of pressings. For great accuracy—as on aerofoil rib contours—the use of a second press stroke after trimming and re-heat treatment has been found to be worth while to avoid correcting hand work later. The Ministry of Aircraft Production facilitated the provision of these presses by ordering in quantity a standard design capable of erection in one, two, or three units to give a range of capacities. Pressures from 0·35 to 1·5 tons per sq. in. of platen area are employed, according to the nature of the job and the hardness of the rubber pad.

Generally, in press work, care in design, e.g. on radii, has enabled the majority of detail forming work to be performed in the normalized condition, and thus avoiding distortion by later heat treatment; in the U.S.A. there appears until fairly recently to have been less success in this respect.

(*c*) *Stretching.* There have been developed for the forming of extruded sections a variety of special stretching processes, over open forms or in closed dies, and sometimes accompanied by simultaneous rolling operations. These processes have eliminated much work, which earlier was performed by panel beaters, sheet metal workers, and other hand trades. Standard sheet-stretching machines have been largely developed, but for extrusions and drawn sections machines have been evolved by aircraft constructors to suit their own conditions; they have comprised universal jaws capable of stretching parts within closed dies or such that a ram can form the part against an open die. Intermediate normalizing is necessary when work hardening occurs. Angle section fuselage formers have been reduced by such methods to 20 minutes from 7 hours by hand methods. A simple machine has been developed to form curved members of any required (e.g. "top hat" stringer) section from a flat strip or blank in a single operation: in this a former bar, curved to the required shape, is drawn through dies mounted in flexible holders so that the dies follow the former around which the metal strip is folded.

(*d*) "*Deburring*." The removal of burrs from detail parts has absorbed many man-hours as—in spite of limited success by rolling, by tumbling, and by the use of emery bands and buffs—much of the work has to be done by hand.

(*e*) *Drawing.* A great many of the sectional shapes required have been produced by rolling or drawing or a combination of the two; the early shortage of extrusion capacity led to a large increase in the demand for such sections. Considerable production economies have resulted from the adoption of pneumatic clamping heads on rolls, which reduce the time to introduce the strip from 10 minutes to 15 seconds, and then permit operating speeds of about 140 ft. per min. In some cases the section has been stretched before being parted off in the machine, so as to straighten it finally by work handling.

(*f*) *Protection of Surfaces.* Normal anti-corrosion treatment, requiring elaborate equipment (e.g. anodic baths), has been avoided wherever possible during the war—bearing in mind the short expectation of life of aircraft—because of the "bottlenecking" that it causes in the flow of parts. Painting of structural parts has commonly been performed at the detail stage by transporting them by conveyor for dipping; in the U.S.A., however, automatic sprays are more common, but without, it is believed, any compensating advantage for their complication.

Structural Joints : (*a*) *Riveting.* Structural joints and connexions have largely been riveted, with pneumatic hammer or squeeze. More blind rivets, closed by pulling a mandrel through their hollow centre and facilitating work in cramped places, have been employed in Britain than in the U.S.A. Explosive rivets have been little used, and automatic machines which punch the holes and then feed and close the rivet have been employed only to a limited extent. Simultaneous closing of several rivets by squeezing has been widely developed in the U.S.A. on straightforward assemblies such as spars. Automatic riveters have also been more widely adopted in the U.S.A. than in Britain as the centralized factory units have favoured their employment in large batteries, each machine set up for long periods for a single size and the whole fed from sub-assembly stations with tack bolted or clipped components.

(*b*) *Spot Welding.* Light alloy spot welding has been much developed, but in general for secondary structure only—such as cowlings—where it has effected savings and has improved external finish: the requirements of improved surface finish for boundary layer control at high speeds, however, point to a development of spot welding for primary structure. Reliable systems of cleaning for spot welding, using an acid dip, have been developed. Production welding of 8-gauge and 14 S.W.G. sheet, i.e. a total thickness of 0·24 inch, has been achieved in Britain by using condenser type welders. For manually fed machines, maximum rates of 20 to 40 welds per minute have been achieved, but more recently rates of up to 140 welds per minute (say, 12 ft. per min. at 1 inch pitch) have been reached on machines where the work is capable of being fed between wheel electrodes.

A typical cost comparison on a stressed wing door shows a total time of 2½ hours taken for the design when riveted, which is reduced to 1¼ hours when spot welded.

(*c*) *Cements.* Plastic cements for metal bonding are in course of active development, but have not yet seriously affected production. In glue form they have materially advanced the possibilities of wooden construction and have made important production economies in it. High-frequency induction heating of the joint has most recently greatly speeded up the setting time and reduced the number of assembly jigs required.

(*d*) *Electric Welding*. This has increasingly been employed on steel structural work, either simple arc or atomic arc, in place of gas; resistance flash welding has begun to be employed, e.g. in the connexion of tubes to end members in engine mountings and in the building up of hitherto forged undercarriage components.

Pipe Bending. Developments have occurred on pipe bending eliminating much of the work of the skilled coppersmith. In Britain these have generally included on the larger diameters (i.e. over about ⅜ inch) some rapid form of filling-springs, low-temperature fusible metal, or high-pressure oil; the tube is then bent over a form with a slipper or cam, or, alternatively, in a series of operations during a single stroke of a press in closed wood or fibre dies using a series of wedges to constrain the pipe. In the U.S.A., machines have been developed with very rapid semi-automatic operation, which use an internal supporting mandrel between the slipper and former, whereby excellent bends are obtained without any filling and which require only that in design a length of straight be left between curves.

Structural Assembly. This takes place in jigs with as much previous subassembly as possible. Installations have been made in the U.S.A. with the jigs on a moving conveyor to obtain series production, but experience indicates that there has not been any gain for the added risk and complexity, and it is believed that the latest trend in the U.S.A. was to abandon this. On fixed jigs various operations are generally allocated to specialized gangs, who progressively move from jig to jig. The time during which the unit is in the jig has an important bearing on cost, affects the number of jigs and floor space required, and is a considerable controllable element in fabrication time; these are comparable in Britain and the U.S.A. and vary from one shift up to six or eight for the largest units.

Installation. Many man-hours are spent in installing equipment and services into structural assemblies, and these have represented a fruitful field for economy. This has been attained by making a maximum of subassembly before installation, e.g. pipe runs into groups, wiring runs into harnesses (made up on pin boards); by giving the fullest access for working, e.g. by carrying out installation before components are joined together or by splitting a fighter fuselage longitudinally; and by the adoption of series flow with as much breaking-down of operations as possible. The use of some form of assembly line conveyor for this purpose is now general, varying from continuous mechanical conveyors to intermittently moved simple floor-trolleys. The rate of movement is in any case low, say one component per shift to one per hour, or 15 inches per minute, and experience shows that with a production rate of less than 250 aircraft per month the simple type, with from 6 to 20 stages per component (and from one to six days process time), gives practically all the saving that the mechanical conveyor would give and at considerably less capital cost. The feeding of material to assembly units is important, but while in the U.S.A. a number of installations have been made with overhead feeder conveyors, it is not thought that these have been justified as compared to simple racks, adjacent to the operation stations, to which the parts, suitably "kit-marshalled", are periodically fed.

Erection. Earlier erection included the fitting and testing of much equipment at a stage when there was necessarily the least accessibility; later work was carried as far as possible in the component stage, leaving final coupling and overall testing only for erection, thereby saving man-power and reducing the period when the aircraft—at its maximum value and being near an airfield—is most vulnerable. Experience has shown that erection is best performed with progressive movement with the aircraft on a bogie, conveyor, or its own wheels; in many cases it has been proven advantageous to keep it low, for easy access, with undercarriage retracted (except at one or more stations provided for undercarriage operation), and avoiding as much staging as possible. Erection times were commonly reduced to 1–1½ days for a fighter and 2½–3 days for a bomber.

Flight Testing. The amount of testing in the air has been greatly reduced in Britain during the war by thorough ground testing, and it averages only about 20 minutes on a fighter. Aircraft normally have all war equipment, e.g. guns, wireless sets, etc., fitted at the factory, as experience in the early days of the war showed this to be more economic than leaving this to the Service.

Finishing. Excellence of superficial finish, particularly on the aerofoil leading edges of high-speed aircraft, has become of great importance; primarily, development has been concentrated on obtaining good mechanical finish, with the profiles of internal ribs held to about 0·010 inch and covered with stretched or pressed skins made from the thickest permissible material. Heavy-gauge magnesium has attractions for this purpose, and a limited use has been made of it, but double curvature has had to be limited to avoid the necessity for hot working. Some production development work has also been carried out in heating skins before riveting, so that they tighten on cooling. Wooden construction with a relatively thick skin, as on the *Mosquito*, well finished with doped fabric, has proved very good. Rivets have normally been carefully countersunk, but some work has taken place on flush milling of the heads after closing. Primer, filler, and finishing spray coats of synthetic paint have recently been used, and these are dried with infra-red lamps, rubbed down wet between coats, and finally dull-polished.

Repair. Repair has been an important war task in Britain, necessitating the establishment of specialized factories and methods for the economical handling of aircraft. Aircraft have been returned into the air as quickly as possible by replacement of parts—sometimes on site, but about 50 per cent after transportation to a repair factory; damaged components lose their relation to a specific aircraft, being repaired by specialist subcontractors, and returned to a pool. On an average, aircraft have been repaired in a total time, from damage to completion, of six weeks. Extensively damaged aircraft and components have been systematically reduced to produce; and the parts have been used to feed repair shops, for spares, or for incorporation in new aircraft. Repair has saved much material, shipping, and man-hours; including spares used in repair the man-hours required to put an aircraft back into the air have averaged less than 25 per cent of those required to build a new one. Repair work has generally been executed by the main contractors or component subcontractors in separately established units under the general supervision of the Civilian Repair Organization.

8. PRODUCTION RESULTS

Expansion. The actual rate of expansion of the aircraft industries in Britain and the U.S.A. respectively is indicated in Figs. 5 and 6. It will be seen that consequent upon the early placing of orders by the British and French Governments in the U.S.A., and frequently including the payment for factory expansion, the latter were in a position to expand rapidly when later they entered the war.

British annual expansion factors have been:—

		Output	
Period	Employment	Weight	Numbers
1936–8	1·8	2·5	1·5
1938–9	2·0	2·9	2·7
1940	2·5	2·0	1·9
1941	1·6	1·5	1·3
1942	1·3	1·7	1·1
1943	1·1	1·4	1·1
1944	Fall	1·1	1·1

The weight of aircraft shown in Tables 4 and 5 is that of the empty airframe (i.e. less load, engine, propeller, etc.), and this is in fact a more useful criterion of the effort expended by the airframe manufacturer than the usually published British figure of net airframe structural weight. There has been added year by year to the weight of new aircraft a proper amount for spares and for repair effort, both of which (had they not been so used) would have produced more new aircraft—although in the latter case at an increased cost in importing raw material. By tempor-

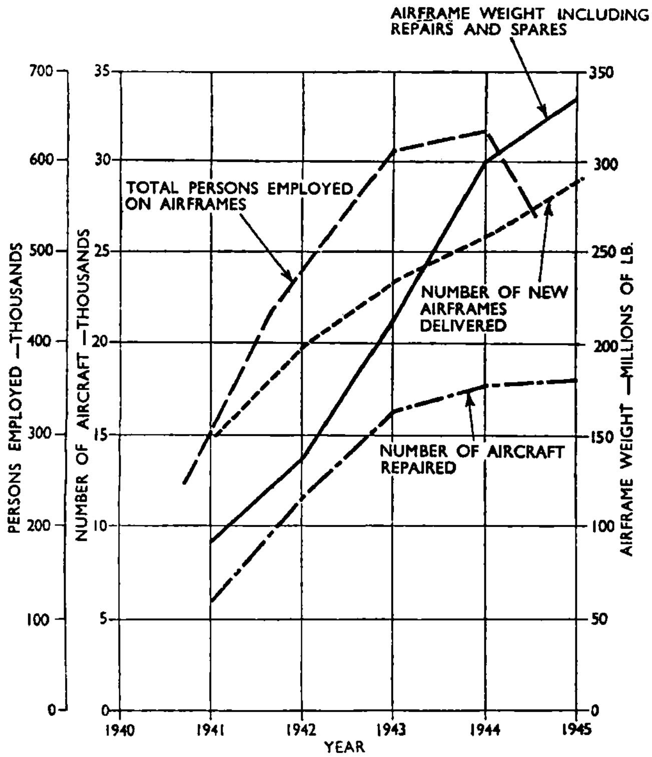


Fig. 5. British Annual Output and Employment

arily diverting spares supply to new aircraft, by reducing work in progress, by additionally and importantly achieving with success a quite phenomenal drive, and by continuous application to long hours of work, the industry expanded its output particularly rapidly after Dunkirk, monthly new aircraft deliveries being :—

May 1940	1,279
June 1940	1,591
July 1940	1,665

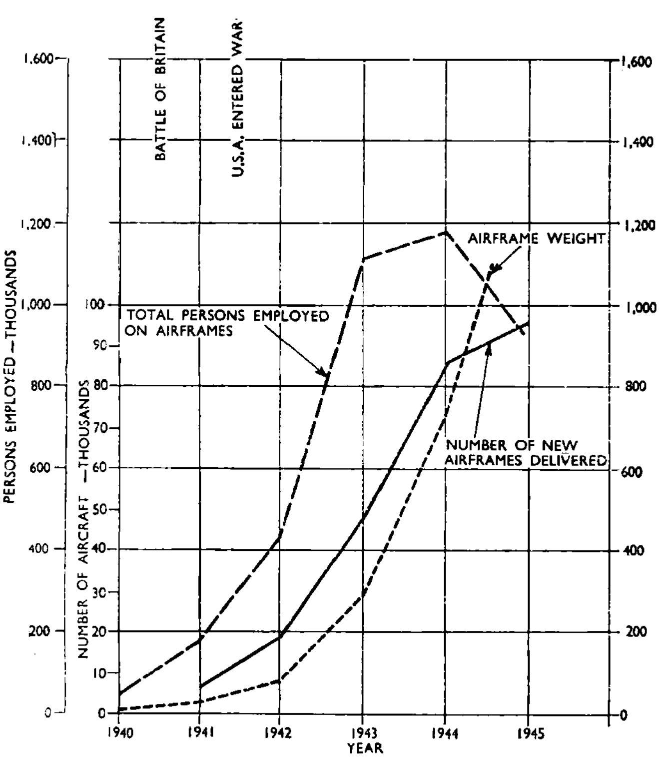


Fig. 6. American Annual Output and Employment

The changes in the type of aircraft called for as the war advanced is shown in Fig. 7.

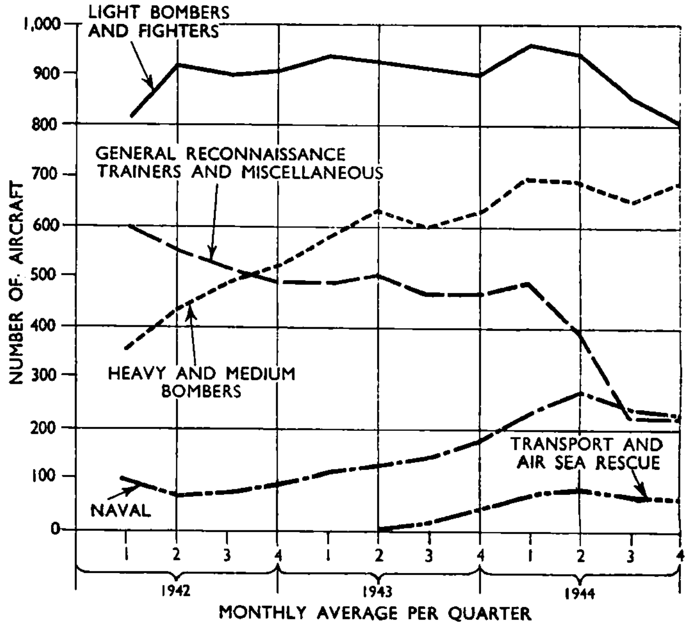


Fig. 7. New Aircraft Deliveries by Main Type Groups in the United Kingdom

A clear indication of the effective use of the production expansion is given by Fig. 8 showing the approximate weight of filled bombs produced in the U.K.

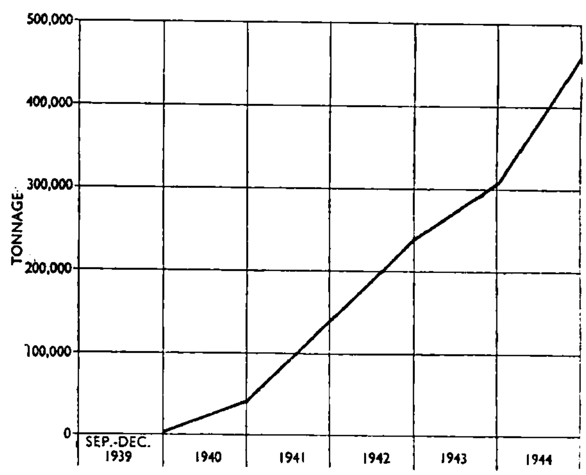


Fig. 8. Approximate Weight of Filled Bombs produced per annum in the United Kingdom

The total quantity of typical aircraft type produced is indicated by Table 9.

Table 9. Total Number of Certain Types of Aircraft Produced

Spitfire and *Seafire*	19,298	*Blenheim*	5,400
Hurricane	12,500	*Oxford*	5,000
Wellington	11,391	*Swordfish*	2,399
Anson	10,000	*Beaufort*	1,500
Lancaster	9,000	*Battle*	1,160
Mosquito	6,000	*Lysander*	1,171
Halifax	6,000	*Fulmar*	650
Beaufighter	5,400		

Proportional Population Comparison. If the British and U.S.A. actual annual outputs are compared at peak in terms of numbers and airframe weight it will be seen that they are 565 and 730 per million of population to 7·2 and 8·5 million pounds respectively. The British output was obtained under conditions of almost continuous bombing for a period, and intermittent attack over four years, and with necessarily small units. Also, almost continuously changes were made at very short notice—and frequently before tooling could be completed —in order to maintain the very highest fighting quality and give the forces quickly their latest needs as war circumstances dictated.

LABOUR

Women. The scale of aircraft production in both countries has been made possible by the large employment of women: over 40 per cent in Britain and 36 per cent in the U.S.A. The acceptance in the U.S.A. of equality of wage conditions for women operators has produced less difficulties than in Britain with its complicated wage rate agreements.

The rate at which women employment has built up in the U.K. is shown approximately by:—

Year	1938	1939	1940	1941	1942	1943	1944
Percentage of women employed	2–4	10	20	28	36	40	41

The proportion of part-time workers has not been large, although it was a useful contribution: in 1941 there were very few; in 1942 there was an average of about 30,000, and this grew steadily to a peak of 97,000 in 1944; these figures refer to all M.A.P. employment, and not only to airframes, i.e. to a total overall figure of about $1\frac{3}{4}$ millions.

Whilst the whole employment by M.A.P. was about 8 per cent of the nation's mobilized and gainfully employed man and woman power, M.A.P. was responsible for employing nearly 10 per cent of the women.

Data. Table 10 shows typical figures for working hours, absenteeism, and labour turnover in Britain towards the end of the war, with an approximate comparison for the U.S.A. They reflect the tight mobilization of man and woman power.

TABLE 10. BRITISH AND AMERICAN WORKING HOURS, ABSENTEEISM AND LABOUR TURNOVER

	Britain			U.S.A.
Average gross working week, hours . .	54			48
	Men	Women	Overall	
Percentage of time lost:—				
Involuntary . .	4·5	8·8	6·2	—
Avoidable . .	2·0	3·2	2·5	
	6·5	12·0	8·7	7

This overall figure varied up to about 12 per cent in the worst winter months for sickness, etc.

	Britain	U.S.A.
Average net week, hours . . .	49	$44\frac{1}{2}$

(The average for the industry increased from 47·4 in October 1938 to 51·4 in July 1943 and fell to 50·7 in July 1944 and to 48·8 in July 1945.)

	Britain	U.S.A.
Labour turnover per annum	Men—small Women—30 per cent	Men — varies greatly but up to 50 per cent Women — up to 80 per cent or 110 per cent

Remuneration. In Britain remuneration has been by piece-work, while in the U.S.A. day-work has been customary, and in both countries operational time study has been normal. Under the British system there was initially failure to appreciate that with long-continued production assembly and installation operation times automatically *progressively improve*, so that piece-work prices were with insufficient data in many cases fixed at too early a stage, which resulted in unreasonably high earnings not reflecting a proportionate real effort on the part of the operator. Such earnings have frequently meant that semi-skilled wages have, on continuing work, exceeded that of the skilled and experimental workers, etc., and of the staff. It must be borne in mind that throughout an overriding factor was rapid output and that on many "semi-hand" operations it was virtually impossible to start upon a new design in production with the full and desired degree of tooling at the outset. In general, work has been willing and enthusiastic in Britain as it has in the U.S.A. where, however, at least comparable results have been produced with day-work, also with high earnings: it is possible, however, that were production to continue as long in U.S.A. as it has done in Britain it would be increasingly difficult to obtain these results without some system of piece-work—a system which it would be difficult now to introduce into U.S.A. as earnings there are already so high that no margin is left.

Shift Working. Most work in Britain (after the hectic 1940–41 period) has been a simple day and night shift of six days per week; three-shift working has been infrequent, and has only been applied when machine tools were in short supply, and special processes, etc., were needed. Black-out and bombing have made night shift operation difficult, but nevertheless essential plant has been satisfactorily worked continuously, with total employment, however, much less than that of the day shift. Special rota systems have been worked but owing to their complication without general adoption; women in some districts have worked two day-time shifts, e.g. 6 a.m. to 2 p.m. and 2 p.m. to 10 p.m.; and with part-time workers, two have generally shared a day shift, e.g. 7 a.m. to 1 p.m. and 1 p.m. to 6 p.m. In the U.S.A., nominal three-shift working has been most common, with 8-hour shifts six days per week (the midnight shift effective as to $6\frac{1}{2}$ hours only): probably 60 per cent of employment has still been on the morning daylight shift, with at least 30 per cent on the afternoon shift, and only a small fraction on the night shift.

Works Committees. Works Committees in various forms have been greatly extended during the war, and have been of value in giving managements and workers a regular basis for meeting and discussing problems which otherwise, particularly under war conditions, could soon become matters of dispute.

EFFICIENCY

Criterion. The criterion of manufacturing efficiency should be the total employment required for a given output of aircraft. The latter—if it is assumed the proportions of various types are comparable—can be expressed in numbers or by weight; for this latter purpose the American definition of airframe weight has, as mentioned above, been employed.

Principles. It has been recognized for many years that with increasing production the unit labour cost of an airframe, as with other repetition products, will fall; in the U.S.A. it is generally stated that this fall will be fairly accurately represented by an exponential curve to the power 0·32, such that each time the quantity made is doubled the unit labour cost is reduced to 80 per cent of the previous figure. British figures show the same general trend within rough limits of 75 per cent to 85 per cent, as shown in typical examples in Fig. 9. It will be observed that when the same aircraft is made at various factories the man-hours required do fall fairly close to the curves at the same relative period of production development. It is also stated in the U.S.A. that with series production for a given aircraft the ultimate labour cost will tend to vary according to an "80 per cent curve", using peak rate of output instead of cumulative output as its basis; it is argued that this is reasonable because peak output normally determines the scale of tooling, and the total number of aircraft made. The size of the aircraft naturally also affects the labour cost; within reasonable limits and under otherwise similar conditions experience indicates that the basic man-hours for a given scale of production vary inversely as the cube roots of airframe weights (for a closer analysis of this see Wright, 1936*).

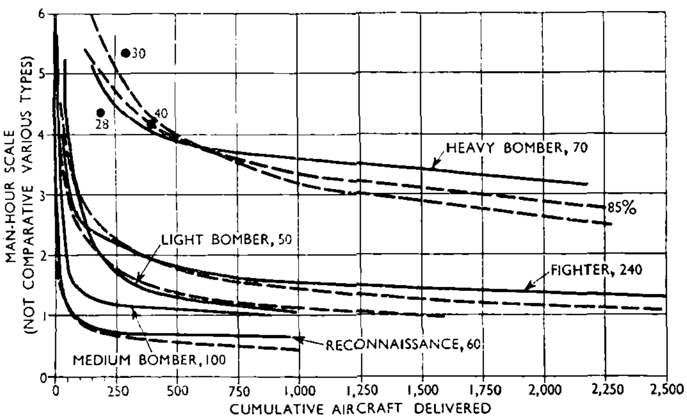


Fig. 9. Man-hour Reduction for Typical Aircraft Early Production

● Denotes man-hours of same heavy bomber at three other factories at position shown.
Numerals thus (40) indicate planned peak monthly production.
Dotted curves are theoretical 80 per cent reduction (or 85 per cent where marked).

The time taken to obtain "ultimate" man-hour figures on complete assemblies, and the resultant difficulty in fixing prime prices, may be seen by taking the actual figures on a bomber centre section:—

At start	1,014 hours taken
After 1 year	592 ,, ,,
,, 15 months	346 ,, ,,
,, 17 months	230 ,, ,,

Overall. The overall efficiency of British–U.S.A. production may be primarily compared by estimating the total employment (direct and indirect, i.e. all classes of manual workers and staff) per unit of output, making due allowance in this for repair work carried out in Britain. Estimation of total airframe employment on the data available is difficult; for the U.S.A. the figures given by Wright (1945)† have been taken, although earlier published figures were somewhat higher; these approximate to 35 to 37 per cent of the total figure of aircraft employment published by the U.S.A. Government. British figures used are 32 to 36 per cent of the similar total. As production in both countries was maintained, or even increased in the last stage of the war, with a substantial reduction in employment, there is the possibility of a further inaccuracy in relating at a particular time employment and output figures. Accepting, however, these estimates, it will be seen from the comparison below that there is a most significant difference—with U.S. unit production about 75 per cent higher than Britain.

	British				U.S.A.	
	Actual		Converted		Actual	
	1943	1944	1943	1944	1943	1944
Total employees per aircraft per annum	24	21	14	12	13	11
Pounds weight of airframe per month per employee	49	62	86	109	69	110

* Wright, T. P. 1936 *Jl. Aeronautical Sciences*, vol. 3, p. 122, "Factors Affecting Costs of Airplanes".
† Wright, T. P. 1945 Jl. Roy. Aeronautical Soc., vol. 49, p. 299, Wilbur Wright Lecture, "Aviation's Place in Civilization."

British average production per assembly unit has averaged about ten aircraft per week with a maximum of about sixty; whereas U.S.A. has approached sixty per week, with a maximum of 120. The relevant correction factor of an "80 per cent curve" (see above) calculated for this difference in production rate is approximately 1·75 times, showing an interesting theoretical agreement. The man-hour price paid for relatively small-scale production is clearly indicated. In considering this, however, it must be borne in mind that the explanation is not essentially by differences of methods but in the speed of working on assembly and other mainly manual jobs where the greater production rate permits more specialization and more rapid achievement of full dexterity. This has also been found in Britain: at two factories, producing the same aircraft with very similar equipment and tooling, the one at about fifteen per week and the other at fifty-five per week, the actual man-hours taken at the latter were about one-half that of the former; as the basic piece-work times allowed were similar, earnings were double—in fact, about 100 per cent on the old basis rate in the one case, and 200 per cent in the other.

Individual. Precise comparison of the actual labour absorption, in particular aircraft, is not easy between British aircraft or between British and U.S.A. The data are difficult to obtain, and there is the effect of modifications (frequently carried out in the U.S.A. in separate factories, not included normally in quoted man-hours, and sometimes responsible for an increase of at least 10 per cent) varying quantities of work in progress, changing subcontracting arrangements, etc.

In those relatively few cases where British production has been maintained for sufficiently long, at fifty to sixty per week on fighters or twenty to thirty per week on bombers, the evidence is that man-hour times have been of the same order as the best American, and costs have been lower; this is in spite of a large measure of detail and erection dispersal. British high labour times have arisen from the effect of the main bulk of production being in small units, and, to some degree, from necessary fluidity of design.

During the final stages of production development, when man-power stringency has been most severe, the output of individual factories has been usefully compared in the U.S.A. by assessing the pounds of airframe—including spares—produced per employee per day. For this purpose, staff, and direct and indirect employees, have been included, together with an addition for subcontracting (estimation of this being a source of possible fairly serious error in absolute values but not in relative comparisons over a period), and deduction for effort on experimental work, etc. The figures have then been corrected, using an 80 per cent curve to a standard rate of production of about 250 per month, and a standard airframe weight of 15,625 lb. (a reasonable magnitude and arithmetically convenient as its cube root is 25).

Results for all military operational types have shown similarity with variations a function of production efficiency, itself to some degree dependent on the design of the particular aircraft; for trainer types these notional output figures have been higher, as would be expected with the simpler construction and less equipment. Figures over all the main units varied at the end of 1943 from about 2 to 7 with an arithmetic mean of 4·6, showing a rising trend with an increase from 4·1 during the previous six months. Calculations on the same basis for British factories yield similar results with maxima of the same order.

Wages. In Britain, with direct piece-work, the labour cost of an aircraft drops as production continues and man-hours fall (and assuming that basic allowed times are not reduced consequent upon changes in practice or by agreement) only by the cost of living proportion of the wage, which is paid on a time basis. Wage rates have varied in Britain (base rates being for a 47-hour week) with nine increases since 1936, typically as given in Table 11, p. 37 (in each case showing a skilled fitter in the first column and a woman over twenty-one in the second).

Individual earnings have often been much higher, particularly in certain districts, where average bonus earnings of several hundred per cent have been obtained. It will be recalled, however, that the Select Committee on Public Expenditure in its

TABLE 11. BRITISH WAGE RATES FOR 47-HOUR WEEK

	1936		October 1938		July 1944	
	Man	Woman	Man	Woman	Man	Woman
	s. d.	*s. d.*	*s. d.*	*s. d.*	*s. d.*	*s. d.*
Base rate	43 0	29 0	45 0	30 0	65 0	37 0
Cost-of-living bonus	13 0	—	18 0	—	17 6	14 0
Total	56 0	29 0	63 0	30 0	82 6	51 0
Index	100	100	113	103	147	176
Average weekly earnings, motor and aircraft group			83 0	40 0	155 10	79 2

report of 26th May 1941 found that average earnings were not as high as was sometimes supposed, and for the highest grade of worker did not appear to be more than £7 per week. Typical cases taken in 1944 for average wage-rates per hour, including piece-work, overtime and extras, are:—

Grade of worker	Northern factory	Midlands factory	Southern factory
	s. d.	*s. d.*	*s. d.*
Skilled men	3 9·2	4 9·0	
Semi-skilled and unskilled labour	2 11·4	3 9·0	3 1·2
Boys and apprentices	1 5·5	1 8·0	1 0·4
Women and girls	1 0	1 11·1	1 6·4
Part-time women	1 5·75		
All classes	2 5·5	3 2·0	2 4·7

Average hourly earnings for a man may thus be taken as about 3*s.* and for a woman 1*s.* 9*d.*; an average of, say, 2*s.* 6*d.*

In the U.S.A. semi-skilled basic hourly rates for men and women, after training, appear to be at least 85 c. to $1, resulting in hourly earnings of probably $1.25, equivalent (at $4 to £1) to about 6*s.*; machinists' rates for a 40-hour week (with time-and-a-half for overtime) on the West Coast seem to go up to or over $1.75.

TABLE 12. TYPICAL DISTRIBUTION OF EMPLOYMENT BY PERCENTAGE

Firm	"Design" firms		"Shadow" firms	
	A, per cent	B, per cent	C, per cent	D, per cent
Wage earners directly on production:—				
Skilled	11·1	19·0	6·8	12·3
Semi-skilled	33·9	26·7	37·5	40·8
Unskilled	4·6	5·3	6·6	5·9
Other wage earners and staff:—				
Administration	5·3	4·7	10·3	6·0
Aircraft design	1·1	4·4	0·2	0·8
Experimental	1·3	1·7	—	—
Toolroom	3·3	4·6	2·8	2·2
Maintenance and general services	2·2	7·6	4·9	3·0
Foremen and chargehands	3·8	1·9	1·3	1·6
Inspection	7·1	6·0	9·5	9·6
Preproduction offices	2·8	2·4	3·9	1·3
Manufacturing control	4·0	7·5	3·1	2·6
Stores	7·9	5·0	6·5	8·3
General labouring, including watchmen	10·5	3·2	4·3	5·6
Canteens	1·1	—	2·3	—
Total	100	100	100	100
Approximate total of persons included	37,000	6,000	12,000	10,000

Indirect Labour. In assessing the overall results achieved in Britain and the U.S.A. on total airframe employment and on individual direct man-hours, it is useful to observe that the actual proportion of indirect (including staff) labour in Britain appears to be lower than in the U.S.A.—approximating to about 40 per cent and 50 per cent respectively. The reverse might have been expected as, with better centralization and after giving due weight to the effect of higher unit elements, indirect expense should, within certain optimum limits, be absolute and not proportional to direct. As would be expected from the large increase in the use of unskilled labour—which calls for elaboration of system and increase of inspection and supervision—and from the operation of governmental, economic, and labour controls in both countries, the war has tended to bring a disproportionate increase of indirect labour. A rough analysis of the distribution of employment in four U.K. factories is given in Table 12.

Production Expansion. A military aircraft, once conceived, is required at the earliest possible date in service, and relatively small numbers available quickly may be as valuable as larger quantities later. The larger the ultimate peak production the longer, within limit, has been the production development period and its expansion to the full rate: this is to be expected from the greater capital equipment, including jigs and tools, to be provided. Because of the relatively short useful life of an aircraft design, over-capitalization, with a short, if any, full utilization of peak resources, has occurred in some cases: a compromise has to be effected (frequently impossible under war conditions) such as to give early and bulk production at minimum capital cost. This is illustrated by considering the following two theoretical but typical cases (production figures are per month):—

Peak production		Production period to:—		Total aircraft available for service after, years			
		1st delivery	Peak production	1½	2	2½	3
(*a*)	75	12	24	45	350	785	1,230
(*b*)	200	18	33	1	50	520	1,675

The actual rate of development of production is shown in Fig. 10 for those factories engaged on the same fighter aircraft and shows the time taken to reach their first steady peak.

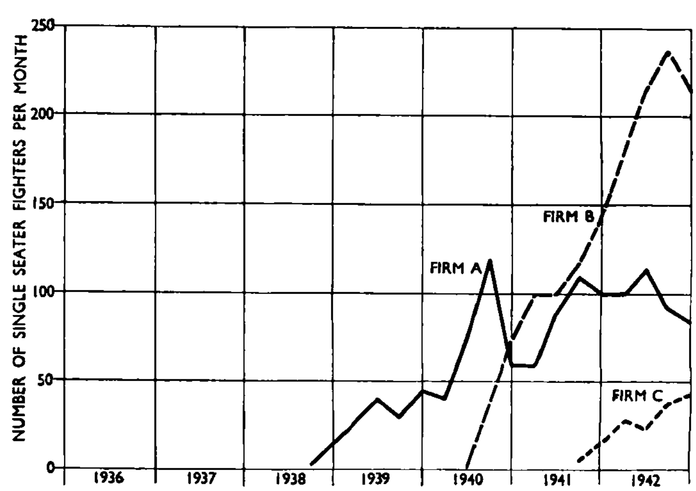


Fig. 10. Early Production of Single-seater Fighter at Three Factories

During the development of production the form of the man-hour reduction curve is important: where the same ultimate figure is reached then obviously the case which has followed a rapid reduction curve (e.g. 75 per cent) will also have commenced with a lower initial absorption, and would throughout have been more economical; even if it commenced at the same basis—with initially a rapid reduction and later a lower rate—it will have resulted in earlier delivery of aircraft. There are indications, not conclusive, that piece-work operated with goodwill has produced more rapid initial reductions than day-work.

Costs. Although basic wages and actual earnings have increased considerably during the war, and aircraft during their production life have always become more complicated, improvements in manufacturing technique have resulted in cost reduction, as is shown by Table 13, which gives typical indices of prime cost elements and of price during long production runs:—

TABLE 13. PRODUCTION COSTS

Type	Fighter		Fighter		Bomber	
Period of production	1941–4		1938–44		1939–43	
Cost indices, all equated to 100 at cumulative delivery of	1,400		9,750		2,300	
Cumulative delivery	150	600	200	4,000	150	1,200
Cost index						
For material	113	107		102	98	100
For labour, direct	116	109	163*	112	145	99
For subcontracting	116	96	71	95	80	97
Price index						
Excluding tools	118	103	104	104	109	99
For comparison at another contractors	100 (at 4,200th)		96 (at 1,600th)		1st—104 (at 1,300th) 2nd—99 (at 4,000th)	

* Including material.

Typical distribution of the main elements of costs in certain aircraft, are shown in Table 14.

TABLE 14. TYPICAL DISTRIBUTION OF MAIN ELEMENTS OF COST IN AIRCRAFT

	Air-frame, per cent	Jigs and tools, per cent	Total air-frame, per cent	Government issue: Engines, per cent	Government issue: Propellers, per cent	Government issue: Armament and wireless, per cent	Other including Government equipment, per cent	Total per cent
Naval reconnaissance	69·1	6·0	75·1	12·5	2·9	3·6	5·9	100
Medium bomber	60·3	3·5	63·8	24·4	5·6	1·1	5·1	100
Naval fighter	58·2	5·2	63·4	19·7	5·2	7·4	4·3	100
Fighter	57·3	3·0	60·3	20·8	4·9	9·6	4·4	100
Trainer	56·4	1·3	57·7	24·4	1·6	10·3	6·0	100
Heavy bomber	39·7	1·2	40·9	42·6	4·2	7·9	4·4	100

If published figures are taken for the total expenditure on British aircraft and rough allowances made for embodiment loan items, and the remainder equated to airframe weight produced, a reduction of about one-third is indicated for 1938–41. Actual figures for the later production were: of a heavy bomber, 13*s.* per lb.; a medium bomber, 19*s.* 6*d.*; a fighter, 27*s.* 6*d.* American figures seem to indicate something considerably higher. It is interesting to compare the price per pound before the war of a motor car commonly reported as 9*d.* in the U.S.A. and 1*s.* 3*d.* in Britain.

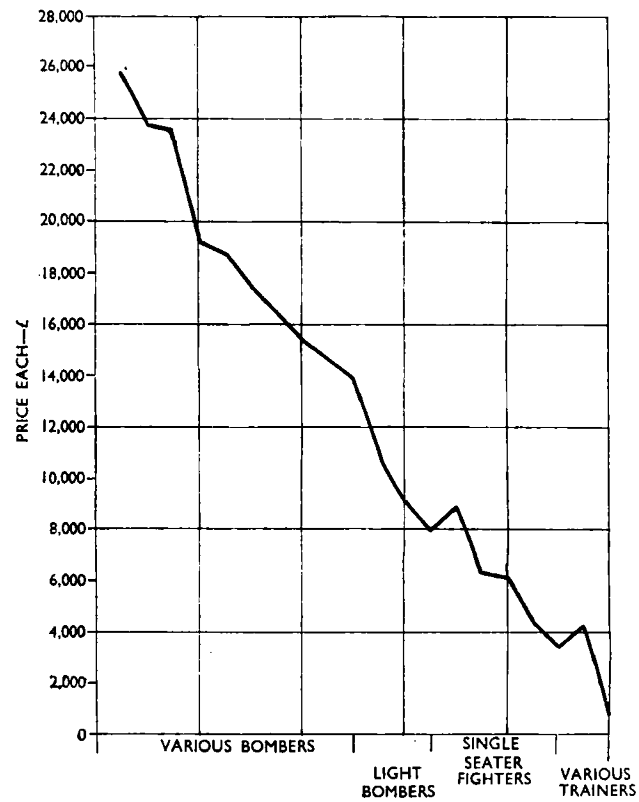


Fig. 11. Selling Price of Airframes to the Government

Excludes embodiment loan items and tooling.

Actual prices paid for typical British aircraft are shown in Fig. 11.

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