Note 14
Pistons for High-Power Engines

Materials (See the General Note on p6)

Cast-Iron and Steel

Effectively only cast-iron or steel were available for the pistons of the earliest internal combustion engines – the Lenoir gas engines from 1860, becoming petrol Otto-cycle engines from 1883 when Daimler built the first. With combustion temperature reaching over 2000C, even momentarily, it must have seemed obvious in any case that only such high melting-point materials (cast-iron 1230C; steel 1350C)(689) would be of any use. As late as 1913 a design offered for the Kaiserpreiz aero-engine competition with aluminium-alloy pistons was rejected simply on the grounds that such material could not be strong enough since the melting-point of aluminium was only 659C(468).

Cost then dictated cast-iron originally and this was universal in racing until 1906. Cast-iron Grand Prix (GP) engine pistons, e.g. Renault type AK 12.8L, In-Line (IL) 4cyl 165mm bore x 150mm stroke (henceforth Configuration x B x S in that order, figures only) meant a Mean Piston Speed (MPS) around 6 m/s at that date. It was equally obvious that piston mass must be minimised if MPS and therefore power was to be maximised. It is believed that Frederick Lanchester first used machined steel pistons in 1905 for a touring car (2). An advantage in weight would be secured in that 0.2%C/Fe mild steel permitted tensile stress 4 x the cast-iron limit (at room temperature) and so sections could be machined thinner. Maurice Sizaire certainly adopted steel pistons machined from solid billets in his pioneering and successful long-stroke 1907 Coupe de l'Auto 1.2L engine (1 cyl. x 100 x 150), to reach MPS = 12 m/s (361). Kept secret for 57 years afterwards, until the designer revealed it, was that these pistons had been machined too thinly and began to fail in the race. Clearly this had been anticipated and spares provided and, although replacement was against the rules, the drivers went off-course into a wood near the long circuit and changed the parts unobserved by stewards – not too lengthy a job with 1 cylinder (361). The lap time increases were put down to "calls of nature"! The 1907 Sizaire et Naudin was not at the limit of steel, however, - at least for a *brief* burst of speed – because the following year the stroke was lengthened to 250 to give 2L and MPS = 20 m/s (259). It appears that the 1906-07-08 S & N engines were actually limited by mean <u>valve</u> speed, not mean <u>piston</u> speed (the surrogate valve-speed factor "Bore x RPM" being constant at 4 m/s).

Other racing engines then followed the Sizaire lead to steel pistons (and low B/S ratio) and they remained the usual GP practice until WW1, although the 1914 French GP-winning Mercedes type M93654 4.5L (IL4 x 93 x 165) still used cast-iron. It reached MPS = 17 m/s (468) so that the castings must have been of improved quality since 1906.

Aluminium alloys pre-World War 1

The search for lighter pistons (Note I) had already led some designers to try aluminium regardless of its low melting-point and reduced hot strength, the attraction being an elemental density of 2.7 g/cc, 66% below the 7.87 g/cc of iron (alloying alters both figures). The discovery by Wilm in 1909 of age-hardening to give higher strength, after quenching from high temperature, when applied to an alloy comprising 4.5%Cu/0.5%Mg/0.5%Mn/94.5%Al (hereafter figures only), which he named "Duralumin" after his employer Durener Metallwerke, describing its properties in 1911 (667), opened-up new possibilities. Cappa of Aquila-Italiana used Al-alloy pistons, composition unknown but possibly Duralumin, in a 4.2L (IL6 x 82 x 132) non-GP racing engine in 1912 (621) which reached MPS = 16 m/s. Although one source (687) credits Cappa with using Al-alloy pistons in 1906 it seems doubtful as being pre-Wilm so that the metallurgy would have been suspect. The same source gives the French Corbin foundry as supplying Chenard-Walcker and Panhard with Al-alloy pistons before 1914. These would have been touring-cars. Source (663) says that the 1914 GP 4.5L Peugeots (IL4 x 92 x 169) had Al-alloy pistons. It is also known (617,413)* that Rolls-Royce tried them in the developed "40/50" 7.4L (IL6 x 114.3 x 120.65) engines built for the 1913 Alpine Trial, where power was wanted regardless of "cold-piston-slap" (due to the clearance necessary to accept the x2 expansion coefficient of Al compared to the cast-iron cylinder) (Note II). (**But see a correction in Note VIII*).

Refs (6) and (687) state that Miller in the USA produced Al-alloy pistons in late 1913 in a formula of his own which he named "Alloyanum" including Ni as well as Cu – which anticipated UK research (see later). Pistons of this sort were fitted by Miller in a 1914 GP Peugeot which finished 2nd in the 1915 500 mile Indianapolis race and won in 1916 (687), and were almost certainly in the same or a sister car which won in 1919.

Daimler tested Al-alloy pistons (probably Duralumin) in its Mercedes 1914 GP engine satisfactorily but, given the choice of those or cast-iron, the works drivers (who were also experienced manufacturing men) preferred the low-risk of the latter, as already mentioned (468). The result of a 1st, 2nd and 3rd against strong opposition over 752 km justified their decision!

More-or-less at the same date as the Miller and Daimler work, Walter Bentley in conjunction with his car suppliers DFP in France had obtained Corbin-cast pistons with the specification 12Cu/88Al and used them to raise the power of the 4 cyl. 2L DFP engine for class record-breaking at Brooklands (688). Although post-Wilm this alloy owed nothing to his work and was not heat-treated (667 – which has an incorrect chronology as pre-Wilm). These Corbin pistons overcame the piston failures which had previously limited power increases from the DFP, where cast-iron had cracked and very-light steel had broken their rings (688).

These early users of Al-alloys discovered that the low melting-point was irrelevant because the high thermal conductivity (4.5 x cast-iron) dispersed the heat too efficiently to affect the metal, provided that the crown and top skirt sections were adequate to pass this heat to the rings and hence to the cooled cylinder wall, or to oil splash under the piston. Tests later (671) would show that the crown temperature was actually around 200C lower than cast-iron and this produced the serendipititious gain that compression ratios could be raised on a given fuel without knocking. Bentley certainly took advantage of this in his 1914 DFP (688). A 1930 quotation can be inserted here to summarise qualitatively the gain from Al-alloy pistons:- “Light weight gives improved accelerating properties and the high thermal conductivity with absence of hot-spots gives good high-compression performance” (677).

Al-alloys in WW1 Engines

After WW1 broke out Bentley was sent by Briggs of the Royal Navy to Rolls-Royce and Sunbeam, who were designing new aero-engines, to show them his DFP results with Corbin piston alloy (688). The former company had tested their prototype 20.3L (V12 x 114.3 x 165.1) design with cast-iron pistons at 4.5 compression ratio in February 1915 and found that these burnt through the crown in only 20 minutes (617).* They were replaced successfully by Corbin-alloy parts with the crown thickness graduated according to the area receiving heat and skirts of the “Zephyr” type in which the middle third of the piston did not touch the wall (617,688). Sunbeam also adopted Corbin-alloy in their later WW1 aero-engines, which were based on pre-War Peugeot technology, and also used it in a racing engine for the first time in the 4.9L car (IL6 x 81.5 x 156) built surreptitiously for the 1916 Indy 500 in neutral USA (24). It finished 4th. (* *But see a correction in Note VIII*).

The Corbin-alloy, given the official designation L8 (645), was used by Ricardo for gravity die-cast pistons in his 1917 18.3L tank engine (IL6 x 142.9 x 190.5) (242) (which made the Mk V tank a really effective weapon) and in Wolseley-built Hispano-Suiza 11.8L aero-engines (V8 x 120 x 130) (671). The French-built units also, of course, had Al-alloy pistons and presumably of the same alloy.

WW1 Research on Al-alloys

Much UK national research effort was put into Al-alloys during WW1 at the Royal Aircraft Factory (RAF – later renamed the Royal Aircraft Establishment, RAE, after the 1 April 1918 formation of the Royal Air Force) and at the National Physical Laboratory (NPL). Test data were published after the War (671). Particularly interesting comparisons were made in a 1-cyl. portion of the RAF type 4d 13.2L aero-engine (V12 x100 x 140), which had 2 inclined overhead valves in an aluminium head and was air-cooled. The results were:-

1 cyl. 100 x 140 = 1100cc: all fully-skirted pistons: PH/B = 0.81: PH/S = 0.58

Piston ref.*	K	G	G	D
		Early-standard		1918 Standard
Piston Material	Cast-Iron	B4 alloy:- 7Cu/1Sn/1Zn/91Al	B4	B4
Bare Piston Mass g	806	573		647
Piston Assembly Mass** g	1113***	880		954
	Datum	**-21%**		**-14%**
Compression Ratio R	4.6	4.6	5.3	4.6
Mean Piston Speed (MPS) m/s	8.4	8.4	9.3	8.4
HP/Litre	15.5	16.4	17.7	16.8
	Datum	**+6%**	**+14%**	**+8%**

* Arbitrary report designations.

** Including estimated mass of 2 iron rings and 23mm o.d. steel gudgeon pin.

***Adjusting from: 3 rings and 18mm o.d. pin: to 2 rings and 23mm o.d.pin as used for the Al-alloy pistons, changes which were not relevant to the material.

In these figures note the smallness of the weight reduction between cast-iron and Al-alloy after the necessary thickening-up of the metal sections with the lighter material because of its lower hot strength, plus the unchanged rings and gudgeon pin which have to be added to the reciprocating mass. The extra mass of the 1918 standard, Piston D, which had much under-crown ribbing, indicates that the first Al-alloy design was not strong enough for the desired life – which would have been only 100 hours at most. The report (671) did not identify the reasons for the 6% to 8% power gain between Pistons K and G or D, running at the same speed, but it is deduced that these were:-

(1). Reduced friction from the lower side-thrust of the lighter piston;

(2). Ignition advance possible without knocking because of the 200C cooler crown.

Piston G also had a 4% better Specific Fuel Consumption than K. The heavier Piston D compared with G ran 10C cooler, presumably because the ribbing assisted heat transfer to oil splash, and could therefore have had more ignition advance and power. Reason (2) may therefore be more significant than (1).

The RAF took further advantage of a somewhat lighter and much cooler piston than K to raise both speed and compression ratio,as listed in the 3rd column, and gained another 8% of power. What the effect on life would have been cannot be known.

Racing Engine Material Change Comparison Post-War

The first Post-WW1 French Grand Prix, in 1921, was won by a Duesenberg 3L (IL8 x 63.5 x 117.475) from the USA, which very likely was fitted with Miller Alloyanum pistons. At 16.6 m/s its MPS showed no advance on the 1914 cast-iron Mercedes.

However, an interesting practical example of piston-material change, in a racing engine, is recorded in (645). A Peugeot 1913 GP 5.7L (IL4 x 100 x 180) – the actual winner of the French GP of that year – was brought to Brooklands post-WW1 and, over 1922-24, was fitted with various Al-alloy pistons (amongst other modifications). Those which were effective represented, for the reciprocating assembly, a mass reduction of about 40% from the original steel-piston assembly. Pistons representing assembly reductions of 60% and 50% suffered failures at very short lives. One reason for the much greater mass reduction in this Peugeot, compared with the RAF 4d given above, would be that the racing distances required from a set of pistons were so short compared to the 911 km of the 1913 GP – although admittedly flat-out on the Brooklands Outer Circuit with MPS up to 14.8 m/s, the pistons were changed after each season, at most. Another reason for the extra weight reduction may have been that the post-War pistons were of lower PH/B ratio than the 1913 parts, probably as 1 to 1.3 (597). The lower PH/B had been used in the 1915 Peugeot V8 aero-engine which was based on two blocks of the 1913 racing design (400,371).

Improved Al-alloys

The Al-alloy research at NPL under Rosenhain in WW1 led (amongst other useful materials) to “Y-Alloy” for pistons, comprising 4 Cu/2Ni/1.5Mg/92.5Al, which retained its strength better than Duralumin at piston temperatures (665), the figures being: (from 678, a 1933 paper)-

		At 250C		
		Duralumin	**Y-Alloy**	
Max. Tensile Stress	**Tons/Sq.In.**	**17**	**21**	**(+24%)**
	MPa	**262**	**324**	

Unfortunately a comparison with “Corbin alloy” was not given in the ref. paper. It is a curious fact that historical review studies written 70 years later, egs. 665, 666, 667, do not mention either Corbin or Bentley. Their 12Cu/88Al alloy, which performed such outstanding service in WW1 and continued in touring-car engines until the late ‘20s (698,699), receives only passing mention (out of chronological order) in (667). It is true, of course, that this high-Cu variety did not father any later material developments, unlike the “professional” NPL research.

Magnesium alloys

Having succeeded with Al-alloys some designers thoughts post-WW1 turned naturally to Mg (density 1.74 g/cc, a 36% reduction from Al; melting-point 649C). Ref. (468) records that a composition 13.5Cu/0.5unknown/86Mg, which won a piston-design competition in Berlin in 1921, was used for forged pistons in up-rated 1914-type 4.5L Mercedes GP engines which at least finished in the 1922 431 km Targa Florio, although in lowly positions. This alloy is not known to have been used in later Mercedes designs but presumably was unsuited to the Pressure-Charged (PC) engines which were built shortly afterwards.

Villiers tried Mg pistons in Mays’ highly-tuned Bugatti 1.5L (IL4 x 69 x 100) in 1923 but their crowns were nearly burnt through after little running (446).

To complete the mention of Mg for pistons at this point, since it seems to have been a dead end; Taylor used it satisfactorily in his first Alta Normally-Aspirated (NA) 1.1L (IL4 x 60 x 95) of 1928 (his later pre-WW2 engines were PC and employed Al-alloy pistons; Mahle die-pressed some Mg-alloy pistons for the special BMW type 328 2L (IL6 x 66 x 96) engines which took 1st and 2nd places in the 1940 closed-circuit Mille Miglia. In this case, the crowns were Cr-plated to prevent burning (30,695). Again, nothing seems to have followed from this. (Later: see Note IV).

Al-alloy Mainstream

Returning to the aluminium mainstream, pistons in Y-Alloy post-WW1 were cast and the material was not easy to forge. The Peter Hooker company were asked by NPL to work on this latter aspect in the mid-‘20s and, when Hooker’s went bankrupt in 1928, one of their staff, Devereux, formed High Duty Alloys (HDA) and carried on the research (666). Some of this was in conjunction with the Rolls-Royce laboratory and HDA were permitted to identify their “Hiduminium” products with the suffix “RR”. The forging work by HDA led to Hiduminium-RR56, formula 2Cu/1Ni/0.8Fe/0.8Mg/0.3Si/0.1Ti/95Al (703), which was used extensively for pistons in the UK in the ‘30s (666). The 0.1% Ti content was important as it refined the grain to improve the fatigue resistance. (Later: see Note V).

Ref. (666) records that HDA, after Devereux's persuasion of the Italian Marshal Balbo, provided forged RR56 pistons very quickly to replace the sand-cast parts in the twin Isotta-Fraschini engines of Balbo's Savoia-Marchetti S55 flying-boat after he landed in the UK in July 1933 and before he led his mass formation of these aircraft across the Atlantic (Note III).

However, RR56 was not recommended by either HDA or Rolls-Royce for the higher temperatures which were applicable to PC engines (678) and by 1933 it was superseded in such applications by Hiduminium-RR59 :- 2.5Cu/1.6Mg/1Ni/1Fe/1Si/0.1Ti/92.8Al (618,666,667,703) which compared in properties with Y-Alloy as follows (678);-

		After 30 min. soaking at 300C		
		Y-Alloy	**RR59**	
Max. Tensile Stress	**Tons/Sq.In.**	**13.7**	**15.5**	**(+13%)**
	MPa	**212**	**239**	

Forged RR59 pistons were the mainstay of UK high-power reciprocating aero and some racing engines up until at least 1966, eg. used in the Cosworth type FVA 1.6L (IL4 x 85.72 x 69.14) Formula 2 unit of that year, which began a new age of design (583). An example of piston material change-over to this alloy is given by the racing motor-cycle engines built by Velocette in 1939: their long-developed 350cc (1cyl. air-cooled x 74 x 81) NA machine had sand-cast Y-Alloy (73); their new supercharged 500cc (2cyl. contra-rotating air-cooled x 68 x 68.5) design (the "Roarer") had RR59 (652). On the other hand the 1st post-WW2 UK racing engine, the BRM T15 1.5L (V16 x 49.53 x 48.26) designed in 1948 originally for 2.8 atmospheres absolute inlet pressure (448) used forged Y-Alloy pistons at least up to 1951 (693). The small bore probably eased the cooling problem.

Hiduminium-RR58

HDA developed in WW2 for the Whittle jet engine centrifugal compressor impeller a variant of RR59 which could accept higher stresses at about 250C. This was done by reducing the Si content and adopting a new production process – semi-continuous casting (666). The formula was:- 2.5Cu/1.6Mg/1Ni/1Fe/0.2Si/0.1Ti/93.6Al (670, 703). This was designated Hiduminium-RR58. It was produced for many other medium temperature applications subsequently, including the structure of the Anglo-French "Concorde" Mach 2 aircraft (selected in 1962). It is not known which racing engine first used it for pistons, but it was in the Coventry-Climax FWMV Mk5 1.5L (V8 x 72.39 x 45.47) by 1965 at latest (34).

The RR58 alloy was still used in front-rank GP engines in 1996. A case is known where repeated piston failures in this material in a 3L (V10) running to about MPS = 25 m/s were cured by outside computerised assistance which analysed the stresses transverse to the forging grain more accurately and redesigned to reduce them. The unit concerned has been very successful subsequently (561). (Later: see Note VI re Thermal Barrier coatings).

Beryllium-Aluminium Alloy

A step forward was taken in 1998-2000 when Be-Al alloy pistons were used in the Mercedes-Benz-Ilmor types FO110G, H and J 3L (V10)(700) (the material was also employed for cylinder liners). These pistons were tried first in very-short-life high-power Qualification engines, and then, when proved, in races. The material could have been "Lockalloy", 62Be/38Al (692), developed originally for spacecraft structure in the '60s and later made available commercially. The elemental advantage of Be can be seen as follows (689,692):-

		Al	Be	
Density	**g/cc**	**2.70**	**1.83**	**(-32%)**
E : Modulus of Elasticity	**Mpsi**	**10**	**42**	**(x 4.2)**
(At room temperature)	**GPa**	**69**	**290**	
Melting-Point	**C**	**659**	**1281**	

The 62/38 alloying with Al produces a Tensile Strength/Density ratio equal to the best Al-alloy, at 210 MPa/(g/cc) but with an E/Density ratio 3 x higher, at 72 GPa/(g/cc) (696), both at room temperature. To judge by the melting-point advantage these relative gains would be bettered at high temperatures.

However, the cost of this Be/Al alloy when it was first introduced for GP disc brake calipers in 1996 was 6 x Al-alloy (419), which was regarded as excessive even by Formula One standards. Consequently its use in calipers was banned from the start of 1998, and further thoughts by the regulatory authorities led to a general ban on any metallic material in the engine with an E/Density ratio over 40 GPa/(g/cc) from the start of 2001 (700). Illien of Ilmor has since stated that the more expensive Be/Al parts had actually lasted longer, which offset partly the first cost.

A new Al-alloy has been developed to take the place of Be/Al and this is said to provide a small gain over RR58, although not having the weight and heat rejection advantages of the banned material (700). (Later: see Note VII).

SUMMARY of MATERIALS and PROCESSES

To give an overview of the piston alloy changes through the years, the following table consolidates the figures:-

Average %ages

(Excluding controlled %ages of impurities, such as S and P)

Name	Date													Data Source
		Cu	Mg	Mn	Ni	Si	Ti	Sn	Zn	Al	C	Fe	Be	
Cast-Iron	Up to 1914					3					4	**93**		618
Mild Steel	1907-14										0.2	**99.8**		618
Duralumin	1909	4.5	0.5	0.5						**94.5**				667
Corbin (L8)	1913	12		*						**88**				688
Alloyanum	1913	?			?					**?**				6,687
RAF B4	1917	7						1	1	**91**				671
Y-Alloy	1919	4	1.5		2					**92.5**				665
Mg-alloy	1921	13.5	**86****											468
RR56	Ca. 1930	2	0.8		1	0.3	0.1			**95**		0.8		703
RR59	Ca. 1933	2.5	1.6		1	1	0.1			**92.8**		1		618,666,667,703
RR58	1943.	2.5	1.6		1	0.2	0.1			**93.6**		1		670,703
Lockalloy	Ca. 1965									38			**62**	692
New Al-alloy	2001									**?**				700

*May have contained a small amount of Mn (698).

**0.5% unknown.

A few words are appropriate to summarise the racing piston manufacturing processes. Iron items were cast, of course. Steel pistons were machined out of solid forged billets. Al-alloy parts began as sand-castings. In 1926 die-casting was used by Delage, for a lighter piston at higher cost for a few racing units (gravity die-casting had been used for quantity production of the Ricardo tank engine in 1917 (242), and mass-production used pressure die-casting from 1927 (668)). However, sand-casting remained in use by some engine-makers up to 1956, although forgings were available from the early ‘30s. The difference this better process could make was illustrated dramatically in the Connaught-Alta 2.5L (IL4 x 93.5 x 90) engine in mid-1956; whereas their sand-cast pistons would last a GP at MPS = 20 m/s, they would fail in fatigue at a short life when run at 21 m/s (+4.5%), which was needed for a competitive performance. The forged pistons which were then fitted were safe up to 22.5 m/s (+12%(701).

When Be/Al pistons were used in 1998-2000 by Mercedes-Benz-Ilmor, they were machined (with some difficulty and with special precautions taken against toxic dust) from the solid (700), probably from extruded blocks as had been the method with Be/Al brake calipers in 1996-97 (707). It was reported that castings were available later, although not used by Ilmor (700).

Some thoughts on the Origins of Piston Material changes

Reviewing the origins of piston material changes in high-power engines, the first major move, from cast-iron to steel and high MPS, was begun in 1907 by Maurice Sizaire. He had been trained as a builders’ draughtsman and therefore was uninhibited by then-current engineering ideas.

The change from Fe-based to Al-based alloys, considered over the whole of the 90 years following 1911, was fathered by Wilm’s research leading to Duralumin. His work was aimed at a military purpose (the manufacture of lightweight cartridge cases (667) – which did not happen). However, the 1913 Corbin 12%Cu/88%Al-alloy, un-heat-treated, appears to have been quite independent of Wilm’s age-hardening discovery. The Corbin alloy was used first in car engines and only later for military purposes in the vast WW1 production of aero- and tank-engines. Miller in the USA also did his own light-alloy research in 1913 and made “Alloyanum” pistons for others before he built his own engines.

During and after WW1 and during WW2 all the Al-alloy improvments, starting from Wilm’s basis, were aimed at military engines and were adopted later for cars.

The time-spans between a new alloy formula being proved and the last-known choice for a racing engine of the previous specification are interesting:-

- Y-Alloy last chosen after RR59 introduced:- 1948 – 1933 = 15 years;
- RR59 last chosen after RR58 introduced:- 1966 – 1943 = 23 years.

If Lockalloy *was* the Be/Al alloy used in 1998-99, this was some 30 years after it was available commercially. These long time-spans suggest a conservative approach even in competition engine design. The fact that all new alloys since 1919 (at least until 2001) have originated from Government-funded research for military ends reflects the very high cost of bringing into service a new high-duty material. Even when a high level of failure can be accepted as the price for a winning advantage on the majority of races, the R & D cost of developing for themselves an improved alloy seems to have been beyond even the well-funded Grand Prix engine makers of the last decade.

The 2001 regulation change banning materials of Stiffness/Density ratio greater than 40 GPa/(g/cc) might well have ossified the situation, but it actually seems to have stimulated an improved Al-alloy at last, of unknown origin.

Postscript

It is regretted that this description of piston alloy development has concentrated on UK and some US experience. The excuse is the same as Dr. Johnson's, when reproached for a dictionary error – "Pure ignorance!" – in this author's case of foreign languages.

Notes

General

Wherever possible this paper quotes the average major chemical constituents of engine materials, since this is fundamental data. However, it must be remembered that in practice:-

- Specifications give acceptable %age ranges for each major element so as to reduce preparation cost – just as machined parts have tolerances;
- Specifications also give maximum %ages of impurities such as S and P because keeping these under control is essential to achievement of the declared properties;
- The manufacturing processes for the material also have to be developed and controlled – these have been improved over the years to give better properties even with the same chemical composition;
- The heat treatment of material is a vital part of the specification.

These details have had to be omitted, partly through lack of information and partly as being not appropriate for a general review.

Note I. Louis Coatalen, long-time Chief Engineer and Managing Director of Sunbeam, had a dictum in 4-cylinder pre-balanced crank days (which he undoubtedly did not mean to be taken precisely) that "An ounce off the piston is worth a pound off the crankshaft and a hundredweight off the chassis!" (24).

Note II. The problem of "cold-piston-slap", which made Al-alloy parts originally a complete non-starter for the normal Rolls-Royce luxury cars, was solved in 1919 by Hives, their experimental chief. He provided close-clearance Al-alloy pistons with axial slits in the skirts so as to take up the relative expansion (617).
It is reported that Harry Rush and Riley (Coventry) Ltd gained a joint Patent, No. 139,351 dated 22 April 1919, for an Al-alloy piston with 4 axial slots in part of the skirt for the same purpose (1023). How Hives' design stands in chronological or legal relation to this is unknown.

Note III. The Balbo story does not relate whether all 48 engines of the formation were modified or only the Marshal's – and , if the latter – what the other 23 aircrews thought about it! Nor does it explain how the Modification Procedure was handled – "Standardisation Without Test" presumably. Anyhow, it succeeded!

Notes added 15 October 2002/ 11 April 2005.

Note IV. Magnesium alloy pistons. Ref (468) states that the 1923 Benz RH 2L Grand Prix engine (IL6 x 65 x 100) had Mg-alloy pistons produced by Hellmuth Hirth. The engine did not give sufficient power to be competitive (although the car was well ahead of its time by being mid-engined).
Ref (740) states that the 1994 Cosworth Ford Zetec-R 3.5L Grand Prix engine (75^0V8 x 100 x 55.69) had pistons of forged Mg alloy*. It powered the 1994 Drivers' Champion. By this date it was standard GP practice to rebuild engines after use in one Qualification session (4 separate flat-out laps), fit another less-highly-stressed engine for the 300km race and then rebuild that also.

Note V. High Duty Alloys and Rolls-Royce. This author is uncertain of the precise origin of some of the Hiduminium-RR Al-alloys referred to in the text. Ref (666) by W.Doyle, former Technical Director of HDA, states "All the development of *forged* alloys was carried out by HDA" (this author's italics). Ref (718), seen later, ascribes to Hall and Bradbury of the Rolls-Royce Laboratories not only the casting alloys RR50 and RR53 but also the forging alloys RR56 and RR59 and adds "HDA was chosen….to produce them…".Ref (718) also notes that when RR58 was Patented post-WW2 it was in the names of two metallurgists, one from R-R and one from HDA.

Note VI. Thermal Barrier Coating for piston crowns. Such coatings are now available to reduce heat flow into the piston. Ref (1051) reports that the ceramic coating "Keronite", new for 2002, had been shown by tests to reduce under-piston temperature by 60C.

Note VII. Jurgen Hubbert, racing manager for Mercedes-Benz, admitted at the end of the 2001 season that the loss of Be/Al-alloy for pistons had a bigger negative effect than had been expected. This suggests that the new Al-alloy had not performed as forecast.

Note VIII: see overleaf.
(*But see a correction in Note IX overleaf).

Introduction of Al-alloy pistons to Rolls-Royce engines

Research during 2005 in the archives of the Sir Henry Royce Memorial Foundation (SHRMF) at Paulerspury and of the Rolls-Royce Heritage Trust (RRHT) at Derby has established accurately how Al-alloy pistons were introduced into Rolls-Royce car and aero engines, in order to increase volume-specific power output from increased piston speeds and compression ratios.

Firstly, to correct a misstatement in the main text of the Note, the 1913 Alpine Eagle 40/50 engines did *not* incorporate Al-alloy pistons instead of Cast-Iron. The Engine Parts Register ('E' code) exists in the RRHT archives, from E1 dated 17 Sept 1909 onward. This Register records the material of the piece listed. It has been searched by Mike Evans and no Al-alloy piston is listed for the period covering the 1913 Alpine Rally engine manufacture (his research was described in Rolls-Royce Enthusiasts Club (RREC) Bulletin No. 271, July/August 2005).

Secondly, it is necessary to correct another misstatement that the Cast-Iron pistons of the first Rolls-Royce aero engine (the V12 later named "Eagle") were burning through the crown in short order during early tests beginning in late February 1915.This information was provided by Maurice Olley some 50 years later (617) but it is not supported in any way by the letters of Henry Royce at the time from St Margaret's Bay (where Olley was also based at that date) reacting to the test reports being received from Derby (ref. 305, the "*Blue Book*"). Not only is there no mention of anything so serious as holes in the pistons but the engine designed for 200HP @ 1,600RPM was within 4 days tested at 225HP at that speed, had done a 4 hour continuous run inside 8 days and in 26 days had completed 6 hours continuously at 2,000RPM (+ 56% stress over the design RPM). These results could not have been obtained if there had been any significant short life trouble with the Cast-Iron pistons. It is certain that Olley was confused in his dating with a piston failure nearly 3 months into the bench development programme when running deliberately with weak mixture and probably at substantial parts lives. This failure was discussed in a 19 May 1915 letter, with Royce writing that it was "*quite evident that the centres of these*" (original type of) "*pistons are too hot*". He mentioned further on 9 June 1915 that, before the weak mixture test the pistons had "*behaved exceedingly well during normal running*". Many different types of Cast-Iron piston had been considered and continued to be designed and tested.

When W.O.Bentley gave his original (1958) reminiscences of visiting Derby to see Ernest Hives, the man in charge of the V12 testing, with his DFP Corbin-Al-alloy piston, his description suggested that it was within a few months of the outbreak of war on 4 August 1914. It is now known, because of a discovery in the SHRMF archive by the late Peter Baines (as recorded by Mike Evans in RREC Bulletin 270, May/June 2005) that it was actually not until a day or so before 8 July 1915. On that date Hives wrote to Royce to describe Bentley's visit and his handing over of the piston. Mike Evans has shown(Bulletin 271) that the consequence was a 1st all-Al-alloy* piston, part number E6806, dated 29 July 1915, actually for the standard 40/50car engine. Evidently this was for a trial test on a well-understood engine. An all-Al-alloy* piston for the V12 aero engine followed, E7031 dated 20 August 1915.

Rolls-Royce used the Corbin alloy for their Al-alloy pistons, i.e. 12% Cu, 88% Al (afterwards coded officially L8) for some 2 years but a letter of Royce to Harvey-Bailey (senior) at Derby, dated 8 August 1917, stated that the Air Board (of the Ministry of Munitions) had instructed a change to the (Royal Aircraft Factory (R.A.F.)/National Physical Laboratory) alloy B4. This had 7% Cu, 1% Zn, 1% Sn, 91% Al. Royce stated "*This matter is most urgent, as I consider the present alloy a source of danger*". Standardisation of B4 for pistons was therefore effected by X3136 dated 28 August 1917, to go into Eagle Series 8 from the imminent start of production of that development (which provided 350HP @ 1,800RPM, i.e. a 75% increase over the original contracted power). A description of various tests of B4 by the R.A.F. is included in the main text. It appears, from lecture notes on materials produced by Harvey-Bailey 20-odd years later (in 1939) that the problem with the Corbin alloy was that, with 12% Cu, it continued to age in service and become brittle. The B4 alloy, still being high in Cu, would have had the same defect but to a lesser degree.

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*Royce had had schemed and tested *composite* pistons after the Bentley information was given to him, having Al-alloy crown but Fe body, between 12 July1915 and 22 September 1915 but, at the latter date, decided that the all-Al-alloy piston was best (305).

Note IX

Cosworth type EC, aka Ford Zetec-R

The author was told in 2011 by Martin Walters, who developed this engine, that the Mg-alloy piston was not raced, having too short a life. The EC pistons were RR58 produced by a Cosworth-improved forging process.

NB. Correction Notes added in 2012

Because misstatements in the original text were from respected sources which are still extant and might be accessed they have been left in place and Notes VIII and IX added to draw specific attention to the earlier errors.