

## *The Narrow Margin of Criticality: The Question of the Supply of 100-Octane Fuel in the Battle of Britain*

The odds were great; our margins small; the stakes infinite.<sup>1</sup>

CHURCHILL'S rhetorical characterisation of the Battle of Britain, made from the vantage point of a Fighter Command control room at the climax of the Battle, has long been influential. It has been reflected, and sometimes amplified, in the memoirs of the pilots themselves. Alan Deere, a Spitfire pilot throughout the Battle, characterised the British victory as being won by a 'narrow margin'.<sup>2</sup> This phrase in turn has been used as the title of one of the most influential histories of the Battle.<sup>3</sup> The concept of the 'narrow margin', at least in terms of fighter resources engaged, has been questioned by more recent historians, but nonetheless the sense of implicit criticality is unquestioningly dominant in both the historiography and popular belief associated with the Battle.<sup>4</sup>

Various specific factors have been isolated to explain the critical margin of success for the Royal Air Force (RAF) Fighter Command, including the respective national production of replacement single-engined fighters by Britain and Germany, faulty intelligence informing Luftwaffe bombing strategy and the technological differences between the aircraft involved.<sup>5</sup> Within the latter category, recent accounts of the Battle, sometimes drawing upon the accounts of people intimately concerned with British fighter development and production, have isolated the supply of American 100-octane fuel as a critical advantage to British fighter performance. This identification has spread beyond specialist aviation history and can be found in histories of the petroleum industry: 'The advantages of 100-octane gasoline were proved in the

1. Churchill reflecting on the situation at the 11 Group command post at Uxbridge on 15 Sept. 1940, which he witnessed personally. The 15 Sept. was subsequently quickly adopted as the appropriate date for public commemoration of the Battle. W. Churchill, *The Second World War, Volume 2. Their Finest Hour* (London, 1949), 296.

2. 'Victory in the Battle of Britain was achieved by a narrow margin; how narrow, very few people realise'. A. Deere, *Nine Lives* (Manchester, 1999), 172. Deere served in 54 Squadron, based at Hornchurch.

3. D. Wood and D. Dempster, *The Narrow Margin* (London, 1961).

4. Alfred Price rejects the 'folklore' of 'the narrow margin' on the basis of a detailed analysis of operations on the 15 Sept., which indicates that only half the available British fighter strength was involved. A. Price, *Battle of Britain Day: 15 September 1940* (London, 1990), 138. The most recent controversy over the Battle which draws attention towards the naval dimension of British defence in 1940 implicitly accepts the strategic criticality of the Battle while advancing a different operational focus. B. James, 'Pie in the Sky?', *History Today*, lvi (Sept. 2006), 38.

5. Summaries of the relevant factors involved in the British victory are offered by numerous authors; e.g. A. Price, *Blitz on Britain 1939-45* (2nd edn., Gloucester, 2000), 85-94; or R. Overy, *The Battle* (London, 2000), 122-9.

Battle of Britain in 1940, when the 100-octane-powered British Spitfires outperformed the Messerschmitt 109s, fuelled on 87-octane gasoline.<sup>6</sup> Perhaps the most definitive statement of the evolution of this concept of a critically important fuel being supplied by an American agency is given by Richard Hallion: ‘... American suppliers delivered sufficient quantities of performance-enhancing 100 octane fuel to England in time for use by Fighter Command during the Battle of Britain, a contribution of profound significance to the operational success of both the Spitfire and Hurricane fighters.’<sup>7</sup> Hallion draws upon the account of Richard Hough and Denis Richards, who in turn derive their appreciation of 100-octane fuel from the testimony of Geoffrey Quill.<sup>8</sup> There is no doubt that Quill’s opinion represents a valid contemporary source as he was an ex-RAF fighter pilot and the chief Spitfire test pilot for the Vickers-Supermarine factory at Southampton at the time. In addition, he also completed a detachment as an operational Spitfire pilot during the Battle.<sup>9</sup>

Quill’s appreciation is shared by other authoritative commentators from the area of contemporary procurement and supply, such as Rod Banks.<sup>10</sup> Banks had been responsible for the supply of customised high-octane fuels for the RAF High Speed Flight in the early 1930s, which had involved the development of the winning Rolls-Royce-engined Supermarine designs in the Schneider Trophy races. Subsequently, he was intimately involved in the supply of tetra-ethyl lead (TEL) as an additive used to raise RAF fuel to 87-octane standard in the mid-1930s.

The appreciation of the importance of 100-octane fuel derived from such authorities has been repeated in subsequent works to the point of becoming axiomatic. But it should be noted that both Quill and some others among these commentators make the point that the introduction of 100-octane fuel for British combat aircraft took place alongside the introduction of the constant-speed, variable-pitch propeller.<sup>11</sup>

The conflation of these two technical factors in improving fighter performance in 1940 and the issue of the origin of the supply of the fuel

6. D. Yergin, *The Prize. The Epic Quest for Oil, Money and Power* (New York, 1991), 383.

7. R. Hallion, ‘The American Perspective’, in P. Addison and J. Crang, eds., *The Burning Blue* (London, 2000), 84.

8. ‘100-Octane Fuel’, in R. Hough and D. Richards, *The Battle of Britain. The Jubilee History* (London, 1989), 387, Appendix XII. Hough and Richards refer to quoted correspondence with Jeffrey Quill, although it should be stated that Quill’s statements in support of the importance of 100-octane fuel also emphasise the importance of the variable-pitch propeller and make no comment on sources of fuel supply. Quill’s belief that 100-octane fuel was not used by RAF Hurricane squadrons in France may be incorrect, as 100-octane fuel was supplied to the RAF in France in early 1940 and some captured British 100-octane fuel was even recovered from German aircraft shot down during the Battle of Britain.

9. J. Quill, *Spitfire. A Test Pilot’s Story* (Manchester, 1996). Quill served with 65 Squadron, based at Rochford and Hornchurch in Aug. 1940.

10. R. Banks, *I Kept No Diary. 60 Years with Marine Diesels, Automobile and Aero Engines* (Shrewsbury, 1978), 140.

11. P. Pugh, *The Magic of a Name. The Rolls-Royce Story. The First 40 Years* (Cambridge, 2000), 189.

will be examined in detail subsequently, but first the actual impact of 100-octane fuel alone on engine performance must be quantified. This can be appraised by moving beyond the later summaries of commentators, even authorities such as Quill and Banks, and taking into account the contemporary RAF performance evaluations of these technical improvements which have been published in recent military aviation history. The resulting quantification of the actual improvement in performance demonstrated by the use of 100-octane fuel can then be located within the relevant historical context. At the operational level, its impact must be considered within the context of air combat operations conducted in the Battle of Britain in 1940. This element is substantially lacking in the axiomatic understanding of the impact of 100-octane fuel.

The final element in this axiomatic understanding is the attribution of the supply of 100-octane fuel to the United States in isolation.<sup>12</sup> This national attribution of the supply of the fuel to the RAF must be tested against the evolution and utilisation of sources of supply historically used by the RAF, as indicated by relevant British governmental and RAF records held at the Public Record Office at Kew. Unpublished contemporary records from this source on the role of the Committee of Imperial Defence and the Air Ministry, apparently not previously used to test assertions of the importance of American supply of the fuel, reveal that the British actually employed a geographically diverse supply policy. They indicate that the British took deliberate steps to anticipate the potential problem of American neutrality legislation imposing a possible embargo on the delivery of fuel to belligerents. These steps ensured that a critical dependence upon American sources of supply in isolation would not develop and hinder the use of the fuel by the RAF in wartime.<sup>13</sup>

This reappraisal begins with the actual impact and limitations of 100-octane fuel on engine performance, which is frequently asserted but seldom quantified or explained.

The octane rating of fuel describes its pre-detonation performance; the higher the octane rating, the higher the pressure and temperature the fuel can stand before premature detonation of the fuel–air mixture occurs in the engine. Detonation can cause an immediate decrease in power being produced by the engine, as well as being mechanically dangerous. The danger of detonation was consequently a factor limiting the use of supercharging in aeroplane engines, which was a critical feature of aircraft piston-engine design in the Second World War.

Almost all aircraft piston-engines used in the war years employed a supercharger, driven by the engine and installed with it. Air inducted into the engine was compressed by the supercharger to counter the

12. The Hallion/Hough and Richards understanding is repeated by popular authors such as L. Deighton, *Blood, Tears and Folly. An Objective Look at World War II* (London, 1995), 352.

13. D.J. Payton-Smith, *Oil. A Study of War-Time Policy and Administration* (London, 1971).

effects of decreasing ambient air density at high altitudes. An engine equipped with a supercharger could maintain a higher density of ingested air at high altitude, and thereby increase the compression ratio and therefore the power produced by the engine.

Engine power was critical to the climbing performance, speed and manoeuvrability of an aircraft, and these factors were in turn critical to the effectiveness of fighter aircraft in combat. Increased performance due to increased engine power enhanced the chances of successful interception of enemy aircraft, as well as improving the chances of interceptions being accomplished from an advantageous tactical position. This could mean, for example having a height or speed advantage when contacting enemy aircraft which could be translated into an advantage in attacking and evading pursuit afterwards. Aircraft with superior engine power could attain a tactical advantage in avoiding or initiating contact. This was apparent to the aircrew involved and frequently a subject for comment and complaint.<sup>14</sup>

While superchargers were therefore essential for the high-altitude performance of piston-engined aircraft, they incurred an associated disadvantage at lower altitudes. Driving the impeller used by the supercharger to compress air ingested by the engine resulted in a reduction in the power delivered to the propeller. This loss of power at the critical point of translating engine power into forward motion was compensated by the increased density of air, and therefore engine power output, that a supercharger could supply at altitude. But at lower altitudes where ambient air density was higher, a critical limitation arose on the extent to which a supercharger could increase air density above the ambient norm.

This limitation stemmed from the detonation resistance of the fuel being used. While a supercharger compressed thin air at high altitudes, it also compressed denser air at lower altitudes. This meant that fuel pressure in the engine at low altitude could exceed the level tolerated by the fuel and cause premature detonation. To counter this, superchargers used an automatic barometric control valve to bleed off pressure in excess of the level which could be tolerated by the fuel used. This barometric limitation would decline as altitude increased and ambient air density decreased, until at a certain height the pressure of ingested air compressed by the supercharger would be below the level which actuated the barometric valve. This altitude was known as 'full throttle height' and occurred at approximately 18,500 feet for the Rolls-Royce Merlin III engines installed in the Spitfire and Hurricane fighters used in the Battle of Britain.

Below this altitude, the mechanically driven supercharger would still be compressing air to a higher density, but the possible increase in

14. For example, Tony Bartley's comments, when a Spitfire pilot with 92 Squadron, on Bf 109 raids during Oct. 1940 as '[having] the edge on the Spitfire for ultimate height...'. A.C. Bartley, *Smoke Trails in the Sky* (Wilmslow, 1997), 51. This was attributable to the higher power output at altitude of the Bf 109's engine.

engine power which resulted would be reduced as the excess pressure was vented by the barometric valve. Thus a proportion of the engine power used to drive the supercharger would be wasted owing to the barometric restriction imposed by the detonation resistance of the fuel used, although the proportion of power lost in this fashion would decrease as altitude was increased.

The introduction of 100-octane fuel allowed the supercharger to generate higher pressures of fuel-air mixture in the engine before detonation occurred. This was achieved by reducing the barometric restriction on supercharger compression. This allowed the supercharger to increase engine power output at altitudes below the full-throttle height of the engine where the barometric restriction on supercharger pressure was relaxed.

The normal maximum limitation on the supercharger compression of the Rolls-Royce Merlin III engine with the standard 87-octane fuel in use in British fighters in 1939–40 was +6.25 pounds per square inch (psi) above atmospheric air pressure. The use of 100-octane fuel allowed the barometric supercharger boost control limitation to be reduced and supercharger pressures to be increased. This raised the supercharger boost pressure limitation in the Merlin III from a maximum of +6 psi to up to +12 psi for short periods (not exceeding 5 min.).<sup>15</sup> The relative increases in supercharger boost and engine revolutions can be seen in the contemporary Pilot's Notes for the Spitfire II. These recommended the following power settings in terms of engine revolutions and supercharger boost pressures to be used with 87- and 100-octane fuel:

Take off to 1,000 ft—3,000 rpm at +7 psi/+12.5 psi;

Maximum climb (1-hr. limit)—2,850 rpm at +7 psi/+9 psi;

Combat (5 min. maximum)—3,000 rpm at +7 psi/+12 psi.<sup>16</sup>

Most reliable evaluations attribute an increase of up to 30% of engine power to this modification to the maximum supercharger boost pressure, with corresponding increases in both speed and rate of climb below the full-throttle height of the engine. This has been quantified as providing up to a 25-mph increase in speed below the full throttle height of the Merlin III engine used in the Spitfire I and Hurricane I which were deployed during the Battle.

So far this simply repeats the benefit in performance associated with the use of 100-octane fuel established by the existing historiography. But this benefit in performance must then be located in the operational

15. References to original supercharger boost levels on operations in mid-1940 and the increase permitted by the introduction of 100-octane fuel include A. Price, *The Spitfire Story* (London, 1999), 74; and M.J. Bowyer, *Interceptor Fighters of the Royal Air Force* (Wellingbrough, 1994), 58.

16. Air Ministry, *Air Publication 1565B, Pilots Notes, Spitfire IIA and IIB Aeroplanes, Merlin XII Engine* (anonymous Air Ministry publication, London, 1940, amended 1942).

context of the time, an issue which at best has been only imperfectly explored by the existing historiography.

Actual tests conducted on a Spitfire in early 1940 by the RAF indicate that the improvement in climbing performance associated with engine output on 100-octane fuel was far less significant than the concurrent increase in climbing performance given by the adoption of the variable-pitch propeller. Increased rate of climb was of vital importance for RAF fighters seeking to intercept incoming raids with relatively short warning times. This can be seen in Table 1.

The Spitfire I was the main variant in service during the Battle of Britain, produced by the Supermarine works at Woolston outside Southampton. The aircraft with the individual serial number N3171 was largely representative of the modification level of Spitfires in service in the summer of 1940, except for the lack of armour plate behind the pilot and the installation of Identification-Friend-or-Foe equipment. The absence of these two features largely accounts for the 122-lb. difference in weight between the two aircraft being compared. The weight differential involved would give a marginal advantage in rate of climb (but not in top speed) to the lighter aircraft, but this differential would not be outside the expected variation in performance caused by manufacturing tolerances such as the distribution of ballast between different airframes from the same production batch, the exterior surface finish of the aircraft, the minor modification of control surfaces on different airframes or marginal differences in engine output between different individual engines of the same type.

Table 1: Comparison of Spitfire performance on 87- and 100-octane fuel

Altitude (ft)	Spitfire IA (87-octane)		Spitfire IIA (100-octane)	
	Speed (mph)	Time to height	Speed (mph)	Time to height
10,000	320	3 min. 30 sec.	326	3 min. 24 sec.
15,000	339	5 min. 18 sec.	345	5 min. 0 sec.
20,000	353	7 min. 42 sec.	351	7 min. 0 sec.
25,000	345	10 min. 54 sec.	338	9 min. 36 sec.

Spitfire IA N3171: Merlin III engine, maximum supercharger boost pressure 6.25 psi; Rotol variable-pitch propeller, laminated windscreen; lacked armour plate and Identification-Friend-or-Foe (IFF) equipment; loaded weight 6,050 lb.; 87-octane fuel; tested by the Aeroplane and Armament Experimental Establishment (A&AEE), Boscombe Down, March 1940. Data from A. Price, *The Spitfire Story* (London, 1999), 82, ch. 4, Appendix C. Spitfire IIA P7280: Merlin XII engine, maximum supercharger boost pressure 9 psi; constant-speed propeller, laminated windscreen, armour plate and IFF; loaded weight 6,172 lb.; tested by the A&AEE, Boscombe Down, September 1940. Data from Appendix A, ch. 7, Price, *The Spitfire Story*, 114.

The Spitfire II was essentially identical to the Spitfire I, being mass-produced at the government-sponsored shadow factory at Castle Bromwich and entering squadron service in September 1940. The main difference between this and the Spitfire I was the use of a Rolls-Royce Merlin XII engine. This was similar to the Merlin III, except that it was designed to operate with the higher compression ratios and supercharger boost pressures associated with 100-octane fuel without modification, and it had a marginally higher full throttle height. The Merlin III required minor modification to use 100-octane fuel, chiefly to modify the barometric supercharger boost controller which restricted supercharger boost levels below full-throttle height, but otherwise, the Merlin XII boost settings and power output were similar to those available to a modified Merlin III on 100-octane fuel in a Spitfire I.

The marginal improvement in rate of climb and maximum speed offered by the use of 100-octane fuel can be compared with the more significant advantage provided by the use of the variable-pitch propeller. Spitfire I K9739 was the first to be tested by the RAF's Aeroplane and Armament Experimental Establishment at Martlesham Heath in June 1939, with the two-position fixed-pitch propeller that was standard equipment before the Battle of Britain. This Spitfire weighed 5,935 lb. fully loaded, 115 lb. lighter than N3171. The reduced weight, due to the lighter original propeller and the absence of a laminated windscreen, would have benefited the rate of climb which nevertheless was dramatically worse than the climbing performance of N3171 with a variable-pitch propeller but with identical engine output settings.

The critical difference can be seen by comparing the time to height results from Table 2 with the comparable figures for the two Spitfires in Table 1. The adoption of the variable-pitch propeller improved the time taken to climb to 20,000 feet by nearly 4 min. By contrast, the use of 100-octane fuel alone only improved the time taken to climb to the same altitude by less than 1 min. This indicates that the adoption of the variable-pitch propeller was four times more beneficial to the rate of climb than the use of 100-octane fuel. In other words, using the same yardstick of the time taken to climb to 20,000 feet, the adoption of the variable-pitch propeller improved Spitfire performance by 33%, while the use of 100-octane fuel only improved it by 6%.<sup>17</sup>

The performance benefit afforded by 100-octane fuel was only significant at maximum engine power settings at low altitudes for short

17. All performance figures taken from Price, *The Spitfire Story*, 81–2 and 114. Also the Aeroplane and Armament Experimental Establishment reports 692d and 692e, Mar. and Sept. 1940, T[he] N[ational] A[rchives], P[ublic] R[ecord] O[ffice], AVIA 18/682. While the issue of the performance benefits accruing from the use of 100-octane fuel and the constant-speed, variable-pitch propeller during the Battle are ignored by the official RAF history in favour of simple aircraft production and type comparisons, the official draft narrative indicates that the researchers involved were aware of an improvement in the rate of climb of up to 25% afforded by the latter to the Defiant, Hurricane and Spitfire. D. Richards, *The Royal Air Force 1939–1945. The Fight at Odds* (London, 1974), chs. I and VI. Official draft narrative in TNA, PRO, AVIA 46/211.

Table 2: Performance of Spitfire IA with two-position, fixed-pitch propeller

Height (ft)	Maximum speed (mph)	Time to height
10,000		5 min. 30 sec.
15,000		8 min. 6 sec.
20,000	366	11 min. 24 sec.
25,000		16 min.

Data from Price, *The Spitfire Story*, 81.

periods of time, such as providing a decreased length of take off run. While undoubtedly useful in some circumstances, it did not provide a similar improvement in performance at the lower power engine settings which were typically used by fighters to climb to operational height or to maintain patrol once airborne. Nor did it provide any performance benefit above the full-throttle height of the engine. The 'performance envelope' of 100-octane fuel must be understood and accounted for before any assertions of operational criticality can be accepted. It must also be disentangled from the complementary introduction of the variable-pitch propeller.

The introduction of the variable-pitch propeller followed a path similar to the development and introduction of 100-octane fuel. Initial moves to promote the introduction of this type of propeller were made by Roy Fedden of Bristol, the major competitor to Rolls-Royce in British aircraft engine manufacture. The Air Ministry had been convinced of the importance of large-scale production of the new type of propeller by 1937 and had facilitated the co-operation of both Rolls-Royce and Bristol in their manufacture with the establishment of the Rotol company to produce a Rolls-Royce-designed version. This supplemented production of the American-designed Hamilton Standard variable-pitch propeller under licence by the British aviation firm de Havilland. Hurricanes and Spitfires were being delivered from the factory with both types of the new propeller as standard equipment by the summer of 1940, while a crash programme in June of that year was undertaken to convert existing stocks of fighters in operational units with two-pitch propellers to the variable-pitch standard.<sup>18</sup> This

18. For the origin of the Rotol company, Pugh, *The Magic of a Name*, 188. The de Havilland version of the Hamilton Standard propeller was being tested on Hurricanes as early as the end of Aug. 1938. F.K. Mason, *The Hawker Hurricane. An Illustrated History* (London, 1990), 44. The Rolls-Royce Merlin II engine was adapted to include the hydraulic drive necessary for the constant-speed unit required by Rotol propeller in the form of the Merlin III used by all Hurricane I and Spitfire I variants produced during the Battle of Britain. Later variants of the de Havilland propeller also used this hydraulic drive. For the conversion process of existing Spitfires in Fighter Command with two-pitch propellers, E.B. Morgan and E. Shacklady, *Spitfire. The History* (Stamford, 1987), 53. The Messerschmitt 109 and 110 fighters used by the Luftwaffe in the Battle of Britain used VDM constant-speed, variable-pitch propellers based on licensed production of the Hamilton Standard.

innovation therefore entered common operational use on British fighters at almost the same time as 100-octane fuel, and the impact of these two developments is often understandably conflated as a result.

These limitations on the benefit provided by the fuel, coupled with the conflation of the more significant improvement to rate of climb afforded by the simultaneous introduction of the variable-pitch propeller, indicate that the impact of 100-octane fuel on fighter operations has often been simplified and even overstated.

To return to the larger contextual picture, any performance advantage enjoyed by one aircraft type in air combat was only important in so far as it conferred a tactical advantage. The improvement in speed and rate of climb afforded by the use of 100-octane fuel alone, without the addition of the variable-pitch propeller, cannot outweigh the primary importance of timely early warning and correctly anticipated command and control measures. These latter were made possible by the integration of radar, observer spotting and control oversight provided by the British system of air defence developed in the pre-war period by Air Marshal Sir Hugh Dowding, Commander-in-Chief of Fighter Command, and not by the use of higher octane aircraft fuel.<sup>19</sup>

In short, a two-minute delay by a controller ordering a squadron to scramble on an interception sortie could not be compensated for during the climb to operational altitude by the marginal benefit the use of 100-octane fuel conferred by itself. Height, and the advantage in tactical positioning it offered to British fighters during interception and combat, was more significant than short-term advantages in maximum speed at lower altitudes, even if these must be acknowledged as being marginally beneficial, and even if these offer an easy basis for performance comparisons on paper by later historians. Furthermore, once combat was joined, other less tangible issues such as the formations, tactics, experience and situational awareness of the pilots involved retained an importance in air combat which outweighed marginal increases in aircraft performance. Without a cohesive and detailed analysis of the impact of all of these factors in the operations of the time, advancing one apparently marginal factor to a position of critical importance is insufficient to explain the complex historical reality.

Many commentators, after identifying the supply of 100-octane fuel as being of critical importance to RAF fighter performance, go on to identify the supply of 100-octane fuel as a specifically American achievement. The supply of this fuel is often represented as having taken place just in time to be utilised in the Battle of Britain as a result of pro-Allied amendments of US neutrality legislation. This can

19. For the role of Dowding in the creation of the integrated air defence system in place by July 1940, J. Ray, *The Battle of Britain. Dowding and the First Victory, 1940* (London, 2000), ch. 1; Overy, *The Battle*, 43; Price, *Blitz on Britain*, 5–14; and Wood and Dempster, *The Narrow Margin*, ch. 3.

sometimes extend to the point of becoming some form of pre-lend-lease, pre-belligerency national contribution to the British war effort.<sup>20</sup> This characterisation hinges upon a limited understanding of the history of the development of 100-octane fuel and ignorance of the British strategic policy for the employment of high-octane fuel. This policy was established by the British in the form of decisions made during the period of pre-war rearmament by the Committee of Imperial Defence and the Air Ministry.<sup>21</sup>

The pre-war RAF was not unaware of the importance of detonation in aviation fuel. The search for fuels more resistant to higher compression ratios, with a higher 'anti-knock' or anti-detonation quality, had already resulted in the addition of TEL to lower octane rated fuel to arrive at the standard 87-octane fuel adopted by the RAF in the early 1930s. As early as 1935, the Air Ministry had taken steps to encourage the establishment of commercial supplies of TEL and lay the groundwork for continued supply in wartime with the formation of the British Ethyl Corporation, which followed the adoption of 87-octane in the RAF's DTD 230 fuel standard of 1936.<sup>22</sup>

The impetus for the development of 100-octane fuel originated in the United States, within a small clique of US Army Air Corps (USAAC) officers associated with the USAAC testing facility at Wright Field in the early 1930s.<sup>23</sup> Principal among these were F. D. Klein and James Doolittle. Klein was responsible for testing high-octane fuel at Wright Field and wrote an influential article on the performance increase provided by 100-octane fuel tested in a P-26A fighter in May 1934.<sup>24</sup> Doolittle, at that point an experienced research and development pilot in the USAAC reserve and the aviation manager of the oil company Shell, was instrumental in persuading Shell to invest in the production

20. Examples include L.F.E. Coombs, *The Lion Has Wings. The Race to Prepare the RAF for World War Two* (Shrewsbury, 1997); A. Furse, *Wilfred Freeman. The Genius Behind Allied Survival and Air Supremacy* (Staplehurst, 2000), 324; Pugh, *The Magic of a Name*, 229; Hough and Richards, *The Battle of Britain*, 387; Banks, *I Kept No Diary*, 234; and Hallion, 'The American Perspective', 84.

21. Few sources address this aspect of British rearmament procurement policy; limited but notable exceptions are Furse, *Wilfred Freeman*, 94–5, and Morgan and Shacklady, *Spitfire*, 55–6.

22. Banks, *I Kept No Diary*, 105 and 112. 'DTD' refers to the Air Ministry's Directorate of Technical Development, which specified official standards for components in RAF aircraft and equipment.

23. The octane rating of fuel referred to the presence of octane in the fuel, which had better anti-detonation value than the alternative, heptane – 87 octane indicated a mixture of 87% octane and 13% heptane. 100-octane indicated a fuel equivalent to 100% octane, and no heptane. Later in the war higher ratings would be classified by 'Performance Indicator Number' for their rich-mixture anti-detonation response on a percentile basis above that of 100-octane; fuel with a 100/130 PIN, for example, would be equivalent to 100-octane on weak-mixture engine settings, and equivalent to 30% more than 100-octane on rich mixture engine settings (G. Kerr, *Time's Forelock. A Record of Shell's Contribution to Aviation in the Second World War* (London, 1948), 34).

24. F.D. Klein, 'Aircraft Engine Performance with 100-Octane Fuel', *Journal of Aeronautical Sciences*, ii, no. 2 (1935). Copy held by Engine Sub-Committee of the Aeronautical Research Committee, Air Ministry, in TNA, PRO, DSIR 23/4984.

of 100-octane plant and in pressing the USAAC to adopt 100-octane as a new fuel standard, which it eventually did in January 1938.<sup>25</sup>

The production of 100-octane fuel depended upon the hydrogenation of a feedstock oil to create iso-octanes. Iso-octane could then be added to 87-octane fuel to raise the octane rating of the resultant mixture to 100. Shell and their main competitor, Standard Oil (New Jersey), began to build hydrogenation plants to produce the necessary iso-octanes in the United States; Shell at Martinez, Houston, Wood River and Wilmington; and Standard Oil at Baton Rouge. By mid-1936, these plants were approaching a production capacity of 10,000 tons of 100-octane fuel per year.<sup>26</sup>

Similar figures at the intersection of the military and industrial spheres were to perform an identical role in advocating the adoption of 100-octane fuel in Britain as they did in the United States. As the USAAC moved towards the adoption of 100-octane, Klein's article was circulated in the Air Ministry and Rod Banks outlined the possible operational importance of the fuel in a paper delivered to the Royal Aeronautical Society and Institute of Petroleum in January 1937.<sup>27</sup> Apparently as a direct consequence, the Air Ministry specified that future engine development should incorporate the capacity to use 100-octane fuel. Contracts were placed for the delivery of substantial quantities of 100-octane fuel, amounting to 74,000 tons of iso-octane per year from three supply sources, including one in Trinidad outside United States control.<sup>28</sup> By the end of 1937, the Air Ministry had accepted 100-octane as the future standard for the RAF, and by early 1938 it was decided that the authorised war reserve stock of fuel was to be composed of as much 100-octane as possible.<sup>29</sup>

Significantly, at the same time as the British were preparing to take these preliminary steps required to utilise 100-octane fuel, a committee was formed consisting of representatives from the leading oil companies, Imperial Chemical Industries and Air Ministry officers. Chaired by Sir Harold Hartley, the chairman of the Fuel Research Board, the objective of the committee was to recommend measures to ensure that

25. L. Thomas and E. Jablonski, *Bomber Commander. The Life of James H. Doolittle* (London, 1977), 129, 136 and 141–2.

26. K. Beaton, *Enterprise in Oil. A History of Shell in the United States* (New York, 1957), 535 and 561–3.

27. Pugh, *The Rolls Royce Story*, 189.

28. The contracts were with Trinidad Leaseholds for 17,000 tons per annum (p.a.) for 5 years, 32,000 tons p.a. from Shell for 5 years and 25,000 tons p.a. for 3 years from Standard Oil (New Jersey). Payton-Smith, *Oil*, 55. Each ton of iso-octane would be mixed with a ton of 87-octane fuel to produce two tons of 100-octane fuel; thus the 1937 contracts would provide up to 144,000 tons of 100-octane fuel per year, or a total of approximately 640,000 tons of 100-octane fuel by the end of 1942.

29. 'The Supply of Aviation Fuel', note for the Air Council by Air Member for Research and Development and Air Member for Supply and Organisation on 121st Progress Meeting, referring to 96th Progress Meeting, Oct. 1937, TNA, PRO, AIR 2/1686–74A. Composition of War Stocks decision, memo of High Octane Fuel Committee, 30 Apr. 1938, TNA, PRO, AIR 2/1401.

adequate supplies of 100-octane fuel could be supplied in wartime.<sup>30</sup> The immediate impetus behind this development was the possibility that the main existing source of supply—hydrogenation plants run by Standard Oil and Shell within the United States—might become inaccessible owing to the embargo requirements of the US Neutrality Acts on the outbreak of war. A further consideration was the fact that 100-octane supplies were purchased in dollars in the case of Shell and Standard Oil production in the United States and in Dutch guilders for Shell production from Curacao in the Netherlands West Indies and later on from the Netherlands East Indies. This presented a potential problem for British balance of payments and foreign currency exchange which was only resolved in the short- and medium-term future by the adoption of supply under the terms of lend-lease in 1941.<sup>31</sup>

The Hartley Committee eventually determined in December 1938 that three new hydrogenation plants should be funded partially at government expense in Trinidad and in Britain to expand British-controlled annual 100-octane fuel production capacity to 720,000 tons above the level already in prospect from existing supplies. At this point Shell and ICI had co-operated to build the first hydrogenation plant in Britain at Billingham on Teeside and further plants were being planned at Stanlow in Cheshire by Shell and Heysham and Thornton in Lancashire by the Air Ministry.<sup>32</sup> In January 1939, when the Hartley Committee report was adopted by the Committee of Imperial Defence, the Treasury was able to cancel one of the planned plants in Trinidad on the grounds of cost, in return for an expansion of the authorised war reserve from 410,000 tons to 800,000 tons, 700,000 tons of which were to consist of 100-octane. This represented an entire year's worth of estimated consumption on the basis of the major expansion and production schemes then in force and required an enormous investment in building the required protected underground storage infrastructure.<sup>33</sup>

RAF tests with 100-octane had begun in 1937, but clearance for operational use was withheld as stocks were built up. In March 1939, the Air Ministry decided to introduce 100-octane fuel into use with sixteen fighter and two twin-engined bomber squadrons by September 1940, when it was believed that the requirement to complete the war reserve stock would have been met, with the conversion of squadrons beginning at the end of 1939.<sup>34</sup>

30. For a brief summary of the Hartley Committee, Payton-Smith, *Oil*, 56.

31. It should be noted that British planning for the importation, storage and introduction of 100-octane fuel into service was funded prior to the introduction of lend-lease, and initial contracts for supply in US dollars with companies like Standard Oil (New Jersey) continued to be met from British convertible dollar resources in 1941.

32. Payton-Smith, *Oil*, 56–7.

33. TNA, PRO, AIR 2/3531.

34. Air Ministry File 3A, meeting of 16 Mar. 1939, TNA, PRO, AIR 2/3531. War reserve completion date from 'War-Time Requirements of Aviation Fuel for Air Ministry', Oil Control Board (39) 9, 18 Dec. 1939, TNA, PRO, CAB 77/1.

By the time war broke out, the available stocks of aviation fuel had risen to 153,000 tons of 100-octane and 323,000 tons of other grades (mostly 87-octane).<sup>35</sup> The actual authorisation to change over to 100-octane came at the end of February 1940 and was made on the basis of the existing reserve and the estimated continuing rate of importation in the rest of the year.<sup>36</sup> The available stock of 100-octane fuel at this point was about 220,000 tons. Actual use of the fuel began after 18 May 1940, when the fighter stations selected for the changeover had completed their deliveries of 100-octane and had consumed their existing stocks of 87-octane. While this was immediately before the intensive air combat associated with the Dunkirk evacuation, where Fighter Command units first directly engaged the Luftwaffe, this can only be regarded as a fortunate coincidence which was contingent upon much earlier decisions to establish, store and distribute sufficient supplies of 100-octane fuel.<sup>37</sup>

While much of this total stock had originated from production in the United States, the actual anticipated sources of supply assessed one month later and given in Table 3 indicate the actual diversity of supply which allowed operational use to go ahead.

It can be seen that, despite the preponderance of American supply, the extent of the existing accumulated reserve and the anticipated production from non-American sources of 100-octane do not conform to the blanket statements of dependency upon the United States alone which is asserted in many sources.

Table 3: Revised forecast of 100-octane fuel stock position: supplies due between 1 April 1940 and 31 December 1940 (figures in tons per annum)

Source	Quantity (tons)
Aruba	37,500
Stanlow	42,000
Anglo (Anglo-Iranian)	67,000
Trinidad	12,500
Palembang	14,000
Shell (United States)	60,000
Shell (the Netherlands East Indies)	120,000
Standard	30,000
Total	383,000

Data from The National Archives, Public Record Office, AIR 2/4512.

35. Air Ministry stocks, 21st Weekly Oil Position Report, 31 Aug. 1939, TNA, PRO, CAB 77/2.

36. Assistant Chief of the Air Staff memo, 24 Feb. 1940, TNA, PRO, AVIA 10/282.

37. 7th meeting of the Co-ordination of Oil Policy Committee, 18 May 1940, TNA, PRO, AVIA 10/282.

The extent and relative importance of this diversity can be seen in the Anglo-Iranian (British Petroleum (BP)) 100-octane plant in Abadan. The Abadan plant had been built as a private venture by BP and was producing 100-octane spirit which met the Air Ministry specification in June 1940 after production facilities had been expanded at Air Ministry request.<sup>38</sup> The first delivery of fuel from Abadan to Britain took place in July 1940, and by the end of the year 23,000 tons had been delivered. The importance of this can be seen from the fact that the total supplied from this single non-American source equates to the issue of 22,000 tons of 100-octane fuel between 11 July and 10 October 1940 by Fighter Command, almost exactly corresponding to the accepted span of the Battle of Britain.<sup>39</sup>

Shipments from Abadan were later reduced in light of the availability of oil of all kinds from the United States, as the shorter voyage across the Atlantic from America economised on the tanker tonnage required for importation. But it remained a viable alternative to American supply sources. In February 1941 continuing uncertainties over dollar purchasing before the passage of the Lend-Lease Act led to the temporary abandonment of the 'short-haul' shipping policy to the benefit of supplies from Abadan.

This reactive and dynamic process can also be seen in the case of the Shell/ICI hydrogenation plant at Billingham, which produced 30,000 tons of fuel in 1939.<sup>40</sup> This plant, and the delivery of further supplies of 100-octane from BP refineries in Iran, provided immediately available substitutes which individually had the contemporary capacity to supply Fighter Command with the quantity of 100-octane fuel expended in the Battle of Britain. Beyond this, the German conquest of the Netherlands in May 1940 had prompted the British to immediately occupy the Netherlands West Indies, where the main Shell and Standard Oil 100-octane refineries were located.

The RAF remained alive to the issue of continuing supply into the summer of 1940. When towards the end of August it was suspected that an oil embargo on belligerents might be implemented in US administration policy in response to Japanese expansion in south-east Asia, a further review of existing stocks and future production indicated that stocks of 100-octane had risen to 389,000 tons while more than 75,000 tons could be expected from non-US sources before the end of the year.<sup>41</sup>

38. J.H. Bamberg, *The History of the British Petroleum Company, Vol. 2. The Anglo-Iranian Years, 1928–1954* (Cambridge, 1994), 243–6.

39. Wood and Dempster, *The Narrow Margin*, 101–2.

40. Payton-Smith, *Oil*, 273.

41. 'Revision of 100-Octane Fuel Situation', 9th meeting of the Co-ordination of Oil Policy committee, 10 Aug. 1940. Annexure A to 10th meeting on 27 Sept. 1940. Specified sources of supply active between 1 Sept. and 31 Dec. 1940 as Stanlow—18,300 tons, Shell (United States and the Netherlands West Indies)—110,000 tons, Aruba—12,700 tons, Anglo (Anglo-American, e.g. Standard Oil, New Jersey)—23,000 tons, Palembang (the Netherlands East Indies)—17,500 tons, Anglo (Anglo-Iranian, e.g. BP)—34,000 tons and Trinidad—6,700 tons, TNA, PRO, AVIA 10/282. For the spectre of a US embargo in Aug. 1940, 'Possible Additional Sources of Aviation Fuel', 73rd meeting of the Oil Control Board, 19 Aug. 1940, TNA, PRO, CAB 77/3.

These facts significantly challenge the identification of the United States as the specific national origin of supply of 100-octane in isolation. While the development of 100-octane fuel and the early supplies of it to Britain in 1937–9 were heavily dependent on US production, this cannot be extended to become a critical dependency on American production alone once the extensive steps taken to ensure a diverse and reliable supply which were taken by the British during the period of rearmament are taken into account. The supply of 100-octane fuel to the RAF was the result of technological development initiated in the United States, but it was established and developed in Britain by a partnership of commercial oil companies and government agency within the cohesive framework of pre-war rearmament policy.

The United States was the single most important country of origin for RAF supplies of 100-octane fuel in the period 1939–40. Yet British importation plans in 1938 reveal that the United States was expected to contribute nothing to the initial accumulation of the war reserve up to March 1939, with the available storage capacity of about 103,00 tons in that month being partially filled with 12,000 tons from Aruba, 12,500 tons from Trinidad and 55,000 tons from the Shell hydrogenation plant at Pernis in the Netherlands.<sup>42</sup>

This geographical diversity in the relevant sources of supply can be seen as late as August 1940, when the fact that 6.3 million out of a total of 27.8 million tons of oil imports scheduled between May 1940 and April 1941 would originate in the United States could prompt the following observation:

There cannot, therefore, be any question as to the essential part that the U.S.A plays in our oil position.

Only 205,900 tons of the 1,324,300 tons of aviation spirit expected within this total—less than 16%—would, however, originate from the United States.<sup>43</sup> The original comment perhaps illustrates the dangers of reading too binary an interpretation into evaluations of American sources of supply, both in terms of oil and especially of aviation spirit. In 1940 the potential for increasing oil supply from the United States in the future remained substantial, and even at this stage existing importation from America provided nearly 23% of British oil imports at a time when planned supplies from the Middle and Far East could be jeopardised by Italian and Japanese aggression. Yet this American contribution still represented a minor component of actual historical British importation.

42. 'Position, 100-Octane Fuel Supplies', submitted to 327th Committee of Imperial Defence, 11 May 1938, TNA, PRO, AIR 2/337.

43. 'American Oil Policy and Empire Supplies', 71st meeting of the Oil Control Board, 15 Aug. 1940, TNA, PRO, CAB 77/3.

The continuance of 100-octane supply from American resources, first after the revision of the Neutrality Acts in November 1939 and then with the relief from dollar expenditure following the introduction of Lend–Lease in March 1941, was of substantial importance to the British war effort. But access to American supplies was only a component of a greater system of limited domestic and substantial worldwide production. This allowed the RAF to build up a massive stock of 100-octane fuel, and then permitted the introduction and expansion of the operational use of this fuel while extensive reserves continued to be accumulated. Nonetheless the British had taken substantive measures to create their own production resources of this fuel and had taken decisive steps to ensure that external sources of supply such as the Netherlands West Indies remained under their control. That the Air Ministry could eventually abandon Thornton, the last of the hydrogenation plants proposed by the 1938 Hartley report, at the end of 1941 was a direct consequence of the continuance and expansion of pre-war American supplies.<sup>44</sup>

Even so, the historical reality is that American sources were not solely responsible for the supply of 100-octane fuel to the RAF in 1940 and subsequently. The original reason for the development of the 100-octane plant at Thornton was to ensure that alternative and reliable sources were available to supply the quantity of 100-octane fuel demanded by British strategic planning. This pre-war planning ensured that by 1940 the Air Ministry was in the position to count on 100-octane production at Trinidad, Curacao, Aruba and Abadan overseas; and in the United Kingdom at Billingham, Stanlow and, by 1941, Heysham. This situation indicates how the popular conceptions of the criticality of the specifically American supply of this fuel simplify and distort a more complex reality. The reason the RAF was able to introduce 100-octane fuel for operational use in May 1940 was primarily because of the success of this pre-war procurement strategy and the massive investment in storage and fuel production it had stimulated from various geographical sources as a matter of deliberate policy.

The treatment of the supply of 100-octane fuel during the Battle of Britain in many sources therefore does not withstand close scrutiny. While the use of the fuel had an impact on the operational performance of British aircraft, too often the limitations to this benefit are not explored. In addition, the separate and distinct impact of the adoption of the constant-speed, variable-pitch propeller is often conflated with the introduction of 100-octane fuel. There is contemporary evidence to suggest that this had a significantly greater impact on British fighter performance than the use of 100-octane fuel did. Yet this has generally attracted less attention from aviation historians. Furthermore no author

44. Memorandum by Lord Beaverbrook, Minister of Aircraft Production, commenting on minutes of War Cabinet meeting, 7 Nov. 1940, TNA, PRO, AIR 19/254–12A and 20A.

has yet attempted any kind of detailed historical analysis of the possible specific advantages afforded by either technological improvement on the basis of actual combat results.

This expectation may well be problematic, as air combat represents a complex situation including many variables which change in importance rapidly over time, a situation in which existing documentary evidence cannot realistically be expected to provide the detail required to isolate the importance of specific individual aircraft performance improvements. These can easily defy attempts at systematic analysis. Nevertheless any assertion of criticality in military events must be substantiated—or otherwise fail as historical explanation. The impact of 100-octane fuel on operations has been asserted, and while it did manifestly offer a performance advantage to engines which were adapted to use it, the limitations involved are seldom explored, and as a result the case for it achieving a critical impact on operations has yet to be made. To return to the concept of the narrow margin between victory and defeat in the Battle, the operational impact of 100-octane fuel by itself can only be described as marginal, and perhaps even insignificant.

Beyond this question of operational analysis lies the issue of strategic supply linked to nationality. The historical reality of the sources of origin for the 100-octane fuel used during the Battle indicates that worldwide sources of production were involved in supplying the RAF. While oil companies in the United States were important sources of supply, they represented a minority of the supplies actually accumulated by 1940. The initial development of 100-octane fuel can accurately be described as an American achievement, yet by 1940 the responsibility for RAF use of the fuel can only credibly be placed on the pre-war planners in the Air Ministry and Committee of Imperial Defence who ensured that sufficient supplies were stockpiled and sufficient alternative sources of production established so that if American supply was withheld for political reasons the wartime use of the fuel on an enormous scale could still be permitted.

The concept of the narrow margin between victory and defeat involved in much of the historiography of the Battle of Britain increases the significance attached to the individual factors which contributed to the historical outcome. The selection, identification and quantification of these contributing factors must nonetheless be historically supportable. Attempts by later aviation historians to 'rediscover' the importance of the fuel, and identify it as a specifically American measure in isolation, seem to run the risk of being a retrospective attempt to insert and overstate the impact of an identifiably American national contribution to the Battle of Britain at a time which predates the fuller Anglo-American co-operation which developed subsequently. The history of the Hartley Committee and the supply and storage of 100-octane fuel for the RAF between 1937 and 1940 indicate that British strategic planning did not depend upon on this co-operation in the pre-war

period, and planning continued to ensure the existence of sufficient viable alternative sources of supply during the Battle of Britain.

Perhaps the final word on this aspect of the issue of 100-octane fuel supply and the return of the issue to the correct historical context of British supply policy can be taken from the British Official history. The conclusions of that work seem too often to be ignored by the historiography of the use of 100-octane fuel in the Battle of Britain:<sup>45</sup>

It was true that by 1939 it seemed increasingly unlikely that the American supplies would be withheld. But to have accepted anything less than absolute certainty, to have depended on the goodwill of foreign suppliers to meet the essential needs of the Royal Air Force, would have been a radical break with traditions that had governed British oil policy since long before the First World War.

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45. Payton-Smith, *Oil*, 57.