## CHAPTER VIII

# *Relationship of Government and Business After 1941 in Fuel Development*

### BRITISH DETERMINATION OF LEAN AND RICH MIXTURE QUALITY

IN 1941 the Army, the Navy, and the CFR started a joint study of methods of determining the rich mixture knocking properties of aviation fuels in laboratory engines. At this time the British required that lean mixture properties of their 100 PN be determined in a CFR engine using an engine technique long established for motor fuels and not involving supercharging. The rich mixture properties were determined in a single-cylinder supercharged engine equipped with an air-cooled cylinder from a poppet valve Bristol radial engine. None of the Bristol single-cylinder units were available in this country, and consequently refiners in this country shipping cargoes of 100 PN fuel to the British were in doubt as to whether the rich mixture PN was 125. Refiners usually solved this problem by being on the safe side, and this led to a waste of the scarce alkylate and other octanes.

### BRITISH USE OF SUPERCHARGED LABORATORY ENGINES FOR DETERMINATION OF RICH MIXTURE PROPERTIES

The British were dissatisfied with the use of the Bristol single-cylinder unit since this meant that a shipment or a sample of it had to go to England before its quality was definitely known. Also the Bristol single-cylinder was a cumbersome and expensive unit which could not be made widely available. Consequently, the British, late in 1940, started studies regarding the use of a CFR engine modified to use supercharging as a substitute for the Bristol engine. The British at the same time requested cooperative studies by suitably equipped laboratories in this country, and such studies were completed and reported early in 1941. When the Army-Navy-CFR cooperative studies of supercharging the CFR engine[1] started in this country there was already a considerable background of experimental work by a number of laboratories using modified and supercharged CFR engines. This background extended as far back as 1936 and was a major factor in the very rapid development of a suitable method. There was also a fair amount of data available from complete aircraft engines; thus, operating conditions could be so chosen that the CFR engine would give approximately the same answer as the complete aircraft engine. The cooperative studies resulted in agreement concerning a suitable engine method for determination of rich mixture properties. The method (then known as the 3C Method, currently the ASTM[2] F4 Method) used a supercharged CFR engine and was accepted by the British. The method was in limited use before Pearl Harbor and its wider use was limited by availability of equipment which had to be produced under high pressure by the Waukesha Motor Company. In view of the limited supply of units for 3C tests, PAW arranged for cooperative use of available units and controlled allotment of new units as they were made available by Waukesha.

## GRADE 100/125

Shortly after Pearl Harbor a rich PN of 125 was established for 100 PN fuel for the British and this became known as Grade 100/125.[3] Stocks suitable for producing Grade 100/125 for American use were not then available in sufficient quantity so 100 PN fuel for the Army and Navy continued to be required to have a lean rating of 100 PN without requirement of a rich PN. As a result of the lack of requirement of rich mixture properties of 100 PN fuel for American use there was wide variation in this property and fuels supplied varied from 100/104 to 100/130. Pratt & Whitney, Wright, and Allison engines had been developed on fuels of about 100/120 PN and when fuels of 100/104 were supplied to operating squadrons and engine manufacturers, difficulty was experienced with high-power operation at rich mixture. As a result of this difficulty it was necessary to limit take-off power to 90% of that normally permitted. This difficulty resulted in establishing Grade 100/125 for both British and American use and this was shortly modified to become Grade 100/130.

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[1] See pp. 600-601.

[2] American Society for Testing Materials.

[3] In grade designations the first figure always designates the lean rating and the second figure the rich rating. In this grade the lean rating was equal to isooctane, that is, 100 octane number, and the rich rating to isooctane + 1 cc lead.

## THE AROMATIC PROBLEM

### *Cat Cracked Gasoline*

With the establishment of the 3C Method a great deal of emphasis was placed on rich mixture properties. With characteristic American enthusiasm this property was considerably overemphasized by the oil industry and advertising appeared showing how many more bombs could be carried when cat cracked gasoline was blended in the fuel. With average available straight-run gasoline and alkylate producing a rich PN of 130, the lean rating might have to be as high as 110 PN and this would result in a great waste of alkylate. With other straight-run gasoline and hot acid or phosphoric acid octanes it was possible to make a rich PN of 130 without exceeding 100 lean PN, but such gasolines and octanes were in limited supply. In lieu of suitable straight-run gasolines, aromatics and the sensitive cat cracked gasolines (which largely owed their sensitivity and rich mixture properties to aromatics) became the desirable materials for making Grade 100/130 in maximum quantity. The Atlantic Refining Company and Shell, with the assistance of PAW, evolved a method of manufacturing cumene (isopropyl benzene) from benzol and propylene, the latter being a gas resulting from refinery cracking operations. Cumene lacked the disadvantages of benzol in regard to freezing and lack of lead response but had a higher boiling point and an undesirable effect upon volatility. For every 1,000 gallons of benzol which were allotted about 1,200 gallons of cumene could be produced; production soon reached about a quarter of a million gallons a day and it proved to be of considerable value in increasing the output of Grade 100/130. The use of cumene, however, was a definite reduction in effective quality since it somewhat reduced aircraft engine performance as a result of reduced volatility.

### *Self-Sealing Tanks*

American aircraft supplied to the British and the French, and used in France in 1939, had proved very vulnerable to fires resulting from bullets penetrating the fuel tanks. As a result General H. H. Arnold demanded that a tank be evolved which would seal itself at the bullet holes. Such tanks were then in use in Europe by the combat nations and had been considered standard combat equipment at McCook Field in the early 1920's. The self-sealing tank had been dropped by the Army in the middle 1920's because of weight and technical difficulties. All self-sealing tanks then used and currently use rubber or rubber-like materials as a means of sealing bullet holes. The rubber may be applied on the outside of the tank where it does not come in contact with fuel until the tank is penetrated by bullets or it may be used as a lining in the tank. The Germans and the British in general chose to use tanks with rubber or rubber-like materials on the outside whereas Wright Field, when it started to develop bullet-sealing tanks early in 1940, chose to use them as a tank lining. The Wright Field tank development was carried out cooperatively with the rubber industry and was exceedingly successful. The tanks were developed around existing 100 PN fuels which, in many cases, contained as little as 2% aromatics.

### *Self-Sealing Tanks and Aromatic Fuels*

Following Pearl Harbor, aircraft of the United States forces in the Pacific were forced to use 100 PN fuel which had been supplied to the British from the Dutch East Indies, and this fuel contained as much as 40% aromatics. With the 40% aromatic fuels the rubber tank linings swelled, disintegrated, and rapidly became useless. Rubber hose, carburetor diaphragms, and other rubber parts of the fuel system were similarly attacked, and a temporary limitation of 5% maximum aromatic content was put into force by the process of having PAW control the blends made to this figure. Limitation of

aromatic content to 5% was, however, never actually put into specifications. When Grade 100/125 fuel (containing up to 20% aromatics) went into service in this country, trouble was experienced with self-sealing tanks and other rubber components of the fuel system, although it was less severe than with 40% aromatic fuel. The problem of rubber or similar materials suitable for resistance to aromatic fuels was vigorously attacked, and a standard fuel containing 40% aromatics was established for testing all rubber parts which were exposed to fuel.

### *Aromatics Blamed for All Aircraft Operating Difficulties*

The Army and the rubber industry had done a magnificent job in rapidly evolving self-sealing tanks and could not be blamed for the difficulty with aromatic fuels. The difficulties with self-sealing tanks, the general distrust of the knocking properties of aromatic fuels by the engine manufacturers, and the overemphasis on rich mixture performance by the oil industry resulted in widespread distrust of such fuels throughout the operating branches of the Army and Navy. Almost all engine difficulties and many aircraft troubles were blamed on aromatic fuels, which were viewed with a blind prejudice which has partly persisted. Grade 100/130 fuel did not have a direct limit on aromatics in the specification but they were indirectly limited to about 20% by the requirement for heat energy content.

### *Aromatic Amines*

Early in 1942 shortage of components of good rich mixture quality for manufacture of Grade 100/130 led to investigation of a variety of means of improving this quality in stocks which had good lean mixture properties but which were deficient in rich mixture quality. Aromatic amines (see Appendix on Hydrocarbons) were studied by a number of laboratories and were found to be a very potent means for improving rich mixture quality although they either did not improve lean quality or somewhat reduced it. The British, who were extremely interested in improvement of rich mixture quality as a result of their preference for more sensitive fuels than were then current in the United States, apparently were the first to realize the possibilities of aromatic amines in regard to rich mixture quality. Shell (British) personnel loaned to the RAE seem to have been the first in the field and chose monomethyl aniline (hereafter methyl aniline) as the most attractive of the aromatic amines. The British interest appears to have been mainly one of improving engine performance rather than one of increasing supply. Wright Field, early in the 1930's, had studied aromatic amine additions to 68 PN leaded fuel under lean mixture conditions and found that they were of little or no value.

### *Aromatic Amine Program*

Aniline was proposed to PAW in 1941 by one of its consultants but was not pursued since it was known not to be soluble at low temperature in insensitive fuels having poor rich mixture quality. Standard Oil Company of California, at a slightly later date, proposed methyl aniline to PAW, and this proposal was carefully studied by PAW and others. Shortly after, Shell's California subsidiary approached the Army in Washington with the suggestion that xylidine be used. High-level Army staff in Washington accepted the Shell proposal and initiated a test program which eventually became the largest and most intensive (and most expensive) which had ever been devoted to investigation of an aviation fuel.

## XYLIDINE

Xylidine was much more desirable than methyl aniline, since xylidine used xylenes as a raw material whereas methyl aniline used benzol as its starting material. Benzol, of course, was a very critical material but if the amount used to manufacture cumene had been diverted to manufacture of methyl aniline, the net effect of the benzol on rich mixture quality would have been greatly increased. Xylene could be obtained in almost unlimited quantity from cat crackers and hydroformers[4]. It was known that xylidine was less effective than methyl aniline and that more xylidine would therefore be necessary for a given improvement in rich PN, but the potential supply situation favored the use of xylidine. It was eventually determined that any considerable increase in supply obtained by the use of xylidine necessitated dropping the lean rating somewhat, and Grade 95/130 (or thereabouts) containing 1% xylidine was produced and used for service in the United States but was not used for combat. The reduction of about 5 PN in the lean rating of Grade 95/130 involved a slight sacrifice in lean performance of aircraft engines but this was less than 5%. Xylidine is a much more powerful solvent than any of the aromatics[5] and thus introduced additional problems with such materials as rubber tank linings. Xylidine in gasoline is slowly removed by water when the gasoline is stored over water, and this difficulty caused concern in the Navy since gasoline on the carriers is stored over sea-water in tanks which are kept full of liquid, and in which a gallon of sea-water is pumped in order to obtain a gallon of gasoline.

### *Engine Operating Difficulties with Xylidine*

Use of xylidine in engines introduced a number of development problems, but these in general were a great deal less difficult than those which had been faced when lead was adopted. Starting of aircraft engines in cold weather is difficult since winter grade (thin) lubricating oils as used in automobiles are not a generally useful solution to the difficulty. Since aircraft may start a nonstop flight in freezing weather and land in the tropics, a heavy oil suitable for tropical use is regarded as the best solution for general operation. The heavy oil makes engine starting a very difficult problem in very cold weather unless the engine is heated or other measures taken. In the middle 1930's Weldon Worth at Wright Field invented and developed the dilution method of overcoming the starting problem. With the Worth method an airplane either stationed in a cold zone or landing there adds fuel to the lubricating oil after landing and before the engine is shut down. When the engine is started up the lubricating oil may contain as much as 40% gasoline which is evaporated out of the oil as the engine

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[4] See below, pp. 655-656.

[5] One per cent xylidine is equal to 5% to 7% aromatics in respect to solvent action on the synthetic rubbers used for such parts as self-sealing tanks.

is warmed up prior to take-off. The evaporation during warming up is never absolutely complete and materials of relatively high boiling point such as lead or xylidine present in the gasoline can be expected to be left in the lubricating oil. Materials of high boiling point such as xylidine tend to become mixed with the film of lubricating oil on the cylinder wall and to be thus swept down into the crankcase rather than burned with the gasoline. The use of xylidine could be expected to have some adverse effects on engine lubrication, and these did result since the engines were dirtier after a given period of service and the maximum period between overhauls was no doubt reduced; this factor in general, however, was not important in military service.

### *Grade 100/150*

In the meantime the British were in serious need of a fuel superior to Grade 100/130 which by this time had had its lead content increased to 4.6 cc per U.S. gallon as a means of increasing supply. The British by adding 2% to 2½% methyl aniline to Grade 100/130 and at the same time increasing the lead to 6 cc per U.S. gallon produced Grade 100/150. Parallel work in the United States produced a similar Grade 100/150 with 3% xylidine. Although this grade was submitted to an extensive test program in the United States, it did not go abroad for combat use. The test program in general indicated that Grade 100/150 in air-cooled engines was equal or slightly better than Grade 100/130 at lean mixture and slightly to considerably better at rich mixture. In mild liquid-cooled engines Grade 100/150 was significantly better than Grade 100/130 and tests in Packard-built Rolls Royce Merlins showed that it permitted about 30% more power than Grade 100/130 at both rich and lean mixture. This behavior of Grade 100/150 in mild liquid-cooled engines was confirmed by the British in the battle against the German V1 buzz bombs when the substitution of Grade 100/150 for Grade 100/130 resulted in 15% greater available power in fighter aircraft equipped with Merlin and Napier Sabre engines. The additional 15% in power enabled the fighters to catch and shoot down the buzz bombs which they could not do with Grade 100/130.

### *Controversy over Fuels Containing Xylidine*

By the time Grade 100/150 was on service test in the United States, fuels containing xylidine were the subject of a controversy in this country and were no longer being considered on their technical merits. The clash of opinion almost resembled the conflict between Fascist and Communist ideologies. The higher and intermediate levels of the Army staff in Washington were pro xylidine; Wright Field was in favor of limited service use but opposed to adoption for general service. The Navy, partly because of real problems of naval service and partly as a result of pressure by the Army, was violently opposed and finally flatly refused to accept such fuel. An impersonal appraisal of Grade 100/150 would indicate that it was neither as good as it was said to be by its Army proponents nor as bad as claimed by its opponents. For an air force whose major offensive power relied on mild water-cooled engines, even for bombardment, as did the RAF, Grade 100/150 would appear to be a contribution to offensive power. The RAF, however, had some bombers equipped with very severe air-cooled engines and in this case the advantage of Grade 100/150 was slight.

### *Severe and Mild United States Engines Using Xylidine*

In the case of the United States the advantages and disadvantages were much more evenly balanced. All naval aircraft were equipped with air-cooled engines, and supplementary water-alcohol injection[6] seemed to the Navy to be a better solution than xylidine. All Army bombardment aircraft used air-cooled engines although liquid-cooled engines were being considered. Grade 100/150 would have been of questionable value in Army bombers and particularly so in the case of B-29 aircraft operating against Japan, which were forced to use appalling conditions of engine severity in order to be able to take off with the necessary military loads. In the case of Army fighter aircraft, Grade 100/150 would appear to have had significant advantages. The liquid-cooled P-38 and P-51 fighters could have obtained considerable improvement in performance and this was recognized by Wright Field. The air-cooled

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[6] See below, p. 646.

Army P-47 fighter equipped with the Pratt & Whitney 2800 engine in the Army 8th Air Force in England, when using both Grade 100/150 and water-alcohol injection, was able to increase power to about 2,600 hp whereas only about 2,200 hp was available on Grade 100/130 with water-alcohol injection. (The power gain of 27% with Grade 100/150 cannot all be credited to the change in fuel.)

### *Effect of Xylidine on Production of Super Fuel*

At the time Grade 100/150 was on test both the Navy and the Army wished to obtain a fuel which was better in both lean and rich properties than Grade 100/130, and such a fuel became available in the form of Grade 115/145[7] at the end of the war in Europe. Grade 100/130 could be reblended to Grade 100/150 without loss of total production. In air-cooled engines Grade 100/150 was in general about equal to Grade 115/145 in regard to maximum available power but was inferior in potential cruising range. In mild liquid-cooled engines Grade 100/150, in general, was the equal of Grade 115/145 in respect to both maximum power and cruising range. Even in mild engines, fuels containing aromatic amines increased the amount of maintenance necessary. Grade 100/150, when operating with the increased power it permitted, showed a significantly greater tendency to preignition than did Grade 100/130 operated at its limiting permissible power. This preigniting tendency at times resulted in blowing pieces out of the Rolls Royce Merlin supercharger casing.

## SUPPLEMENTARY INJECTION OF WATER OR WATER-ALCOHOL

Supplementary injection of water through a supply system additional to the system which meters and supplies fuel dates back to about 1880 as a means of suppressing knock and overheating. This use of water was, however, applied to unsupercharged engines, did not increase power significantly, and sometimes slightly reduced it. Water injection in a supercharged engine offers possibilities of reducing knocking tendency, increasing power, and reducing the cooling problem.

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[7] See below, p. 651.

### *Alcohol Injection at Wright Field*

In the early 1930's J. F. Campbell at Wright Field was developing fuel injection on a Pratt & Whitney Wasp engine and was particularly interested in increasing power output. With the existing 68 PN fuel, power was limited by knock, and he tried straight grain alcohol which permitted a great increase of power for about a minute, following which three of the nine cylinders were blown off by preignition. Campbell then used 80% alcohol plus 20% water,[8] and this permitted a very considerable increase in power over that available with 68 PN fuel; despite the increase in power the cylinder temperature was markedly reduced.

### *Water Injection at Wright Field*

At the same time F. Prescott, also of Wright Field, was conducting work with a supercharged aircraft engine cylinder with a view to finding out whether the poppet valve cylinder was suitable for a high degree of supercharging or whether such supercharging would mean adoption of sleeve valve construction as indicated by Ricardo and Pye. Prescott found that 93 PN fuel limited the amount of supercharging he could use and he resorted to supplementary injection of water, the water used being about 30% (by weight) of the fuel supply. As far as the author knows, Prescott's work was responsible for indicating the potentialities of water injection in supercharged engines. If it was known to others, they both kept the knowledge to themselves and failed to do anything useful with it. Campbell's work also indicated the possibility of water's controlling cylinder temperature at high power although it admittedly did not show that this would occur when gasoline was used as fuel. Wright Field also accomplished two full-scale multicylinder tests using supplementary water or water-alcohol injection in the period 1936-1941. The second of these tests late in 1941 determined the value of water-alcohol from lean fuel-air mixture to rich fuel-air mixture and showed that the value was much greater at rich mixture.

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[8] The addition of water was based on the work of Ricardo, Tizard, and Pye.

### *"Anilol"*

Following the findings of Prescott there was sporadic development of water-alcohol supplementary injection in a number of laboratories, alcohol being used with water since water alone in aircraft would mostly be unusable due to freezing. This sporadic development did not lead, so far as the author knows, to complete aircraft engines equipped with water or water-alcohol supplementary injection of even an experimental type. Supplementary injection of "Anilol," a proprietary blend of aniline and alcohol, did come into use on the airlines using 68 PN gasoline. "Anilol" was first intended to replace the use of lead but was finally used as a means of both removing induction system ice in flight when operating under icing conditions and providing additional PN to permit emergency power (and particularly so when one engine became inoperative on a two-engine airplane).

### *European and Other Developments of Water Injection*

Water injection was both worked on and considered in Europe and particularly so in England during the period 1930-1940. Bristol in particular was active in this matter. The National Research Council in Canada published details in 1938[9] of tests of water injection in a supercharged Armstrong Siddeley Jaguar engine. The Canadians had difficulty in maintaining and distributing considerable supplies of 68 PN gasoline, their gasoline caches in the northern wilderness were only of 58 PN, and the ability to use 58 PN plus water injection in lieu of 68 PN was to them a matter of considerable national importance.

### *Pratt & Whitney Water Injection Development*

In any case, water or water-alcohol injection lay dormant until it was seriously taken up by Pratt & Whitney in September, 1942. Pratt & Whitney had previously been investigating how much water an engine could digest before it lost power when flying in a very severe rainstorm and had found that if it ingested twice as much water as fuel it would stop firing.

Pratt & Whitney found that water injection would permit 20% to 30% more power than could be obtained at rich mixture on the same fuel without water. Pratt & Whitney at first preferentially used water alone from considerations of supply but tested water-alcohol in parallel since it realized that cold weather or high altitude would necessitate the use of alcohol as an antifreeze. An automatic system for simple operation of supplementary injection in military service was rapidly evolved. If water injection was not in use, the power taken out of the engine was automatically limited; if further power was required for emergency, the pilot pushed a button which made the injection system operative if water was available but which prevented more power from being taken if the supply of water was exhausted. If water was available, the pilot could open the throttle and obtain 20% to 30% more power. The supply of water lasted only about 10 minutes at full emergency power and on being exhausted the throttle was automatically closed, thus reducing power to the maximum allowable on fuel alone. Several other essential functions were automatically controlled but will not be described.

With the water injection system it was found that 20% to 30% more power could be obtained without redesign of the engine cooling system and that the total weight consumption of liquid per horsepower hour was not higher than it was on fuel alone (in part because of the fact that fuel-air mixture used with injection was leaner than that used with the maximum power permissible on fuel alone).[10] Of course, the weight of liquid used per minute was 20% to 30% greater with injection since the power was 20% to 30% higher.

While Pratt & Whitney had, as mentioned above, concentrated on the injection of water alone for reasons of supply, they had found in 1941 that water-alcohol was superior to

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[9] M. S. Kuhring, "Water and Water-Alcohol Injection in a Supercharged Jaguar Aircraft Engine," *Canadian Journal of Research* 16 (A), August 1938, pp. 149-176.

[10] Of the 20% to 30% gain in power, about 6% resulted from leaning of the fuel-air mixture. Use of this rich mixture when running on fuel alone was largely dictated by engine cooling requirements but it was also used to suppress knock. While the rich mixture resulted in a loss of potential power, it nevertheless was the optimum compromise which resulted in the maximum possible power output with fuel alone.

water alone. As more and more power was taken from the 2800 engine water-alcohol was found to be necessary and a 50-50 blend of water-wood alcohol was found to be the best mixture. The wide general military use of grain alcohol largely eliminated the supply problem but this was not true for wood alcohol. Later work with injection on other makes and types of engine showed that water-wood alcohol was the best mixture in most but not all engines. The superiority of water-wood alcohol to water alone or water-grain alcohol appears to have been due in part to greater volatility which improved distribution in comparison with that obtained with water alone or water-grain alcohol.

Water-alcohol injection was eventually applied to all engines used in fighter aircraft by the United Nations. It was not used in bomber aircraft although it appears that it would have been useful at take-off with some types. It was planned to use water-alcohol injection in the Wright R-3350 engines in the B-29 bomber since this would improve the range and be particularly effective during the extremely arduous take-off. Water-alcohol injection was not so fitted, however, before V-J Day. Supplementary injection, of course, added to weight, mechanical complication, and complexity of operation since two fuel supplies had to be available. Pratt & Whitney, however, had determined that in emergency sea water (without alcohol addition) could be used in lieu of water-alcohol.

### *Patents on Water Injection*

When the Pratt & Whitney injection system was completely worked out and in service, patents were issued to Bristol covering practically all its essential features. In any case, however, the fact that supplementary water-alcohol injection became a standard article of service equipment was due to Pratt & Whitney. In practice the water-alcohol used was about 30% by weight (about 25% by volume) of the gasoline which was simultaneously supplied to the engine. Water-alcohol injection equipment is one of the few items of engine equipment which became standard for war service use which did not exist in even the form of an experimental model before the outbreak of war. The prewar investigations of water injection had all been conducted with laboratory apparatus, which was totally unsuitable for flight since it was manually controlled and without the automatic safety features necessary for flight use.

While a water-alcohol blend has proved to be the most practical fluid for supplementary injection up to 1949, investigation during the war by the NACA Aircraft Engine Research Laboratory (currently the Lewis Flight Propulsion Laboratory) showed that other materials blended with water may be greatly superior to an alcohol blend.

## GRADE 115/145

Shortly after Pearl Harbor the Army, the Navy, and the British evinced increasing interest in obtaining a fuel superior to Grade 100/130. The first emphasis was on a fuel superior in both rich and lean quality. Study of production of such a fuel indicated that if substituted for an equal amount of Grade 100/130, relatively enormous allotments of steel additional to those required for Grade 100/130 would be required. Neither the Navy nor the Army felt that the additional steel allotment could be tolerated in view of its effects upon output of such equipment as destroyer escorts and tanks. As an alternate to the fuel improved in both rich and lean quality, two fuels of about Grade 100/140 and known as OPC-1 and OPC-2 were produced and tested. It was hoped that the improved rich mixture quality of these fuels would give sufficient improvement in combat performance so that improvement in lean quality with consequent large requirements of additional steel for refinery construction would be unnecessary. It was thought that OPC-1 or OPC-2 could be produced at the same rate as Grade 100/130 without the necessity for additional plant by the use of more rich mixture components (principally from cat cracking), but in view of the later shortage of such components this view seems to have been in error. OPC-1 and OPC-2 showed no significant improvement in engine performance over that obtained with Grade 100/130.

The next effort at improved quality was the use of aromatic amines which resulted in Grade 100/150 discussed above.[11]

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[11] See above, pp. 644-646.

### *Army and Navy Interest in Fuels with Improved Lean Performance*

The Navy was particularly interested in increase of cruising range, and Grade 100/150 was no answer to this problem with the air-cooled engines of the Navy (and by the end of the aromatic amine controversy the Navy was in no mood to admit that Grade 100/150 was an answer to any of its problems). The Army was also interested in increased cruising range and while Grade 100/150 would provide this with part of the Army's long-range escort fighters, it was not a complete answer for all Army equipment.

As a result of joint Army-Navy-PAW studies it was agreed that as soon as the demand for Grade 100/130 showed signs of slackening, production of a new grade with improved lean quality should start. Production of the new grade did not involve construction of additional plant and was to be achieved by a lower total production of Grade 100/130 plus the new grade. The Navy and the Army arrived at a compromise in their requirements for the new fuel which became Grade 115/145, the Navy sacrificing its wish for a lean rating of 120. This new grade could be counted on to increase ultimate cruising range by a minimum of 4% to 5% in comparison with Grade 100/130 if suitable engine adjustments were made. Grade 115/145 went into production at about the time of V-E Day and for every gallon produced the production of Grade 100/130 dropped by about two gallons.

Grade 115/145 involved the use of a greatly increased percentage of alkylate, and constituents such as cat cracked gasoline and cumene were present in much reduced proportions. Not only was a considerable increase of alkylate content involved but the alkylate had to be of selected quality, and some of the alkylate going into Grade 100/130 was unsuitable for use in Grade 115/145. Cat cracking, however, remained an important factor since it has been a major source of the gases used to make alkylate.[12]

While Grade 115/145 does not represent the highest lean quality which can be made, the 15% increase over Grade 100/130 does represent a great deal more than the 15% increase in manufacturing difficulty and in the amount of plant required (in terms of steel). The octane of the octane scale when used with 4 cc lead will make Grade 153/153 but the production would be limited to about a million gallons per day. In fact, there are only about six hydrocarbons known which will give a lean quality of 150 PN with 4 cc lead. Triptane[13] will, with 4 cc lead, give a grade of about 150/270 but potential production of this is a great deal more limited even than that of the octane of the octane scale. The octane of the octane scale could be produced in large amounts without serious waste of crude oil but at the expense of enormous plant (steel) requirements. Triptane, however, is a different case since its large-scale production would in the light of present knowledge (1949) not only require astronomical quantities of steel but in addition would waste very large amounts of crude oil. Large-scale triptane production (10 million gallons a day) would furthermore require almost the entire chlorine production of the United States. This may be summarized by stating that no feasible chemical reaction is currently known for large-scale triptane production.

### *Effect of Engine Design on Performance at Lean Mixtures*

By revision of engine design, much improved lean Performance Numbers can be obtained. A mild engine such as the Rolls Royce Merlin will give Grade 100/150 a lean PN of about 150. With such mild engines Grade 115/145 will have a lean PN of about 145 and triptane plus 4 cc lead will have a lean PN of about 270. It will be noted that in these mild engines the rich PN becomes the lean PN and as a matter of fact, in such engines rich mixture ceases to be of any use as a means of increasing knock limited power output. While rich mixture ceases to be of value in regard to increasing knock limited power in mild engines, it nevertheless may have to be employed even at a sacrifice of power in order to make the engines cool satisfactorily. Mild engines have been discussed in terms of the liquid-cooled type. It appears that mildness is not confined to liquid-cooled engines and that mild air-cooled

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[12] See above, p. 611 and Technical Appendix B on hydrocarbons.

[13] See below, p. 656.

engines can be built if necessary although this will result in increased mechanical complexity. If milder engines had been generally available during the war, octanes such as alkylate might have been less important since cat cracked gasoline of about 90/130 PN could have given the same engine performance as Grade 100/130 did in the more severe engines.