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SOME NOTABLE WARTIME OIL FIRES.

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At the outbreak of war there were in Great Britain some forty major tank installations holding some 90 per cent. of the total stocks of petroleum. Many of these installations were in vulnerable positions, and it was appreciated from the outset that they might well become targets for enemy aircraft. Ways and means of protection were discussed, and many of them were subsequently put into effect. The most important of these measures were the adequate bunding of the individual tanks, the bricking up of tanks to render them splinter-proof, and the provision of fixed foam installations. Obviously, however, these measures took some time to complete, and it was not till after the war had been in progress for some time that the precautions could be said to have been finalized. This applied in particular to the provision of mechanical foam compound, the development of which was proceeding very rapidly about that time. A brief review of some of these precautions has already been given to the Institute by Lieutenant B. Orchard Lisle of the U.S.A.A.F. in his paper presented in 1944. A more comprehensive account of modern practice has now appeared in the *Manual of Firemanship*, a comprehensive book on fire-fighting issued by the Home Office (Fire Service Department). In this, the chapter on " Fires in Oil Installations " deals very fully with the fire-fighting precautions already installed in most tank farms, and describes the method of handling a fire.

The first few months of the war passed off very quietly, and in Great Britain virtually without incident. It was only after the fall of France that the enemy turned the full severity of his air attacks on Britain, and even then they were directed primarily at the civilian population rather than at military objectives.

Fires at Land Installations.

Pembroke Dock.

On the afternoon of August 19, 1940, a single enemy plane made an attack on the Admiralty fuel-oil installation at Pembroke Dock, an attack which was to result in the most protracted oil fire which has yet occurred in Great Britain, due in the main to constructional works being in progress at the time and to half a gale coming from the most unfavourable direction.

The installation is situated on high ground on a promontory with the tanks in two rows in terrace formation. The single bomb which landed in the bunded area badly splintered two 12,000-ton tanks and set the spillage alight. The two tanks nearest the bomb collapsed and released their contents to flood with blazing oil the saucers surrounding them and the moats which were sited downhill. Owing to the strong north west wind, further tanks uphill were fired.

The first steps taken were an attempt to prevent the spread of fire from the moats down the hillside to the village, which lay below, and as many jets were got to work as the available resources permitted, whilst exhausting the 2½ million gallons of water stored on the site. Efforts were made during the first three days to obtain an adequate supply of water, because the tidal rise and fall made it impossible to draw water with fire service pumps without having to move them backwards and forwards as the water rose and fell. This problem was finally solved by ordering on barges on which pumps were mounted and a tug to supply a series of relays ashore. Furthermore, the vertical lift of some 200 feet added to the difficulty of pumping operations.

On the third day there was a violent surge of oil from the highest of the three tanks, and five firemen were overwhelmed and burnt to death. This surge spread fire over a wide area (some 500 feet from the tank) and closed the only approach road to the installation.

This was the first boil-over to occur at a large oil fire in Great Britain, although two others were subsequently experienced at Turnchapel. On the fourth day a seventh tank caught fire, after blowing off its roof, but the two tanks which first ignited had burnt out. During much of this time attempts were made to introduce foam into the burning tanks, but it was at this fire that the need for fixed pourers and other equipment which would permit foam to be introduced into the tanks themselves was first clearly demonstrated. Portable pourers were the only means available of getting foam into the burning tanks, for the reach of the foam equipment then in use, and comprised of No. 10 branches, was insufficient to project foam into the tanks from ground level. In any event, the very heavy up-draught due to the flames would have carried the foam away.

Efforts to extinguish the tanks with foam in the end proved abortive, because it was never possible to obtain the high rate of application which this and subsequent experience showed to be essential if any good was to be achieved. A total of 2800 gallons of foam compound was, for instance, used on one tank alone over a period of about nineteen hours, but the rate of application was insufficient, and the foam was destroyed as rapidly as it was applied. Under present practice such a quantity would be applied in one and a quarter hours.

Transport difficulties to such an isolated spot were considerable, although, whatever facilities had been available without the large quantity of pourers and special types of foam branches, it is doubtful if extinction could have been achieved in the face of the high wind and the difficulties in the supply of water. Matters continued thus for some days, water being used to hold the burning oil in the moats and saucers away from the tanks not involved, and efforts with foam being tried on the tanks on fire from time to time. During almost all these operations men on the fireguard were subjected to attack from the air, and relays were cut on several occasions by bombing or machine-gun fire.

In the end the fire virtually burnt out, after lasting for eighteen days, with the loss of seven tanks, of which two had been destroyed in the original attack and would in any event have been lost.

Reinforcements were brought in to deal with the fire from as far away as Birmingham (twenty-three brigades in all sending men), and further experience was gained of the problems facing fire-fighting and the billeting of large numbers of men in a very small locality.

Thameshaven.

All through the Battle of Britain the Thames estuary formed one of the chief targets for enemy attack, and on September 5, 1940, about 3 p.m., three tanks at Thameshaven were set on fire. One empty tank was also destroyed by a direct hit, but no fire resulted. By this stage in the war, Fire Service mobilizing arrangements had been brought to a satisfactory state, and a sufficient attendance, including a number of fireboats, was rapidly provided under the Regional scheme. Three tanks, two containing oil and one petrol totalling some 5000 to 7000 tons, were involved, but fortunately the wind was blowing the fire away from the main block of tanks. Water supplies at first proved a considerable difficulty, but satisfactory relays from the river were subsequently established, and the technique of feeding into a large dam from a fireboat in the estuary and setting a number of pumps to work from the dam was successfully practised.

During the evening the wind changed, and caused the fire to blow direct on to the main installation.

However, by about 2.30 a.m. the following morning the fire was reduced to one tank, and subsequently a determined attack with eight foam branches extinguished it in about one and a half hours.

Late the following afternoon, that is on September 6, however, the Thameshaven area was again the target for an attack, and a lubricating-oil tank was fired by a direct hit, the fire spreading to two other tanks which had been punctured by splinters. In this attack the fires proved particularly difficult to handle. In one of the tanks the valves and fittings had been severely strained by the explosion, and the leaking petrol was on fire. In this latter case, the fire was finally dealt with by putting a water-bottom on to the tank and raising the level of the spirit above the point of damage. This fire lasted in all from 6 p.m. on September 6 to 11 a.m. on September 12, a matter of some five and a half days.

On September 7, whilst this fire was being fought, a further attack was made, and a direct hit on a large spirit tank caused a fire. A second bomb made a direct hit on a large tank containing water, and this, though damaged, remained fairly serviceable, and provided a useful reserve. Other bombs fell amongst tanks containing either fuel oil or water, releasing the contents and flooding a considerable area with a mixture of oil and water which, fortunately, did not fire.

About 9 p.m. on September 16 yet a third fire was started at Thameshaven, this time involving two tanks of spirit containing in all about 9000 tons. Both were holed by bomb splinters, and the leaking spirit fired. In one of the tanks the hole was some 3 feet from the base of the tank, and operations were put in hand to pump out the contents. Pumping operations continued for the best part of a day and a half, when the reduction in head through the removal of the contents reduced the leak to the point where the tank could be plugged and the fire was then extinguished. In the second tank the lowest hole was some 15 feet above ground level. Here again the fire was principally outside the tank, and arrangements were made to draw off the contents. When the liquid head was sufficiently reduced, this tank also was plugged, and the fire thus extinguished. During this third fire an attack was made by enemy aircraft, and a bomb was dropped which split the roof and fired the contents of a petrol tank. A No. 10 branch was brought into immediate operation, and the fire extinguished in ten minutes. This third fire lasted in all for approximately three and a half days.

Some idea of the mobilizing problems involved may be gained from the fact that detachments from seventy separate brigades were in attendance at one or other of these three fires.

Avonmouth.

Around 9 p.m. on the evening of March 29, 1941, the Anglo-American Oil Company's tank farm at Avonmouth was hit. The fire started in a 120-feet diameter by 30-feet-high tank containing some 4800 tons of petrol, the roof being blown clean off by a direct hit. Sometime after 10.30 p.m. information was received that a second tank containing 3800 tons of kerosine was involved, and by about 3 a.m. the situation was getting serious, a third tank containing 2000 tons of kerosine having caught fire. These two tanks fired through the area surrounding them having been flooded with burning spirit from the damaged tank. To cool them off three deliveries (water) were played on adjacent tanks which were separated from those on fire by a bund wall. A quantity of kerosine was on fire in a bund containing six tanks adjacent to those on fire, but by a concentrated effort, using foam, this was extinguished, and the tanks were saved. A screen of fourteen jets was used to cut off the burning tanks from others imperilled.

The wind during this time was at gale force. Meanwhile the position was that three tanks were alight in one compound and, owing to the heat and layout of the farm, only one of the three burning tanks was accessible. Ten No. 2 and four No. 10 branches were used on the first tank, which was in due course extinguished, but whether this was due to the foam or because the oil had burnt out was not very clear. Once the first tank had been extinguished, at about noon, it was possible to turn attention to the other two tanks, which were out by 4.30 p.m.

The tank containing 3800 tons kerosine was attacked with two No. 2 and five No. 10 foam branches, and the fire was extinguished in twenty minutes. The layer of foam held, and the tank was finally cool three and a half hours later—*i.e.*, at 8 p.m., approximately two-thirds of the contents having been saved.

This fire was attended by a contingent of firemen from Northern Ireland, many of whom were part-time volunteers who had come over earlier in the month to take a spell of duty in Britain.

A further fire at Avonmouth on April 3, 1943, this time not caused by enemy action, though relatively small, presented some interesting technical features. It started with a mild explosion in an 80 feet by 30 feet tank containing some 510 tons of aviation spirit. The tank was surrounded by a blast wall, and the roof was insulated with a layer of cork. The explosion, the exact cause of which has not been satisfactorily explained—though several theories have been put forward—lifted the roof slightly and caused a gap varying from 7 inches to 10 inches wide between roof and side some 100 feet long. At this gap flames appeared. Steps were immediately taken to cool adjacent tanks with jets whilst preparations were made to introduce foam into the tank. A fixed-foam installation comprising one No. 20 and two No. 10 branches was in position, and undamaged by the explosion, and foam was introduced into the tank through these, as well as, in the early stages of the fire, through two No. 10 portable foam-making branches directed into the gap formed by the explosion between roof and wall. For some time, in spite of the considerable quantity of foam introduced, efforts appeared to make little headway, but three hours and twenty minutes after the call the fire was out.

After the fire had been extinguished and a dip taken of the contents of the tank it was found that these were unchanged, implying that no spirit had been involved in the fire. A layer of foam 12 feet thick was found in the tank. The fire burnt steadily in spite of all efforts, and was obviously due to vapour only. Calculations showed that the amount of vapour in the tank would have been sufficient to maintain the fire for some five hours.

Subsequent experience shows that, having laid down a blanket of foam on the contents sufficient to prevent their ignition, it would have been possible to shut off the foam and either allow the vapour fire to burn itself out or to extinguish it with a water-spray or jet. There were, however, certain obvious objections to this, for some water would have entered the tank and tended to break down the foam inside, whilst extinction of the issuing vapour might have resulted in setting up potentially explosive conditions.

In this case the cork insulation on the roof ignited, and would in any event have re-ignited the vapour until it had been suitably dealt with. Extinction of the cork presented some difficulty, and it had to be cut away from the roof with axes.

Gosport.

Between 12 midnight and 1 a.m. on Tuesday March 11, 1941, two tanks at the installation containing 4700 and 2020 tons respectively of Admiralty fuel oil were hit and the oil ignited. The evidence points to H.E. having penetrated the roofs and exploded in the ullage. Both tanks were walled, and the walls did much to confine the fire.

By concentrating the maximum of equipment on one tank at a time, the first was extinguished, but flashed twice after the first extinguishment. Subsequent investigations showed that very little of the contents were lost. The second tank proved more difficult, and a considerable proportion of the oil was salvaged by pumping it off. It was at one time feared that a boil-over might materialize, for considerable quantities of foam had been applied, but this fear proved unfounded. As it was essential to reduce the beacon effect by the next night, it was decided to allow the tank to burn out and to concentrate on keeping adjacent tanks which were not bricked up cooled off by means of jets. In the evening, as the coking stage had been reached, it was decided to put water into the tank, and the fire was completely extinguished after it had been burning for twenty and a half hours.

Falmouth (*Swanvale*).

On May 30, 1944, a formation of about ten hostile aircraft flying overland dropped bombs on Swanvale oil installation, Falmouth, shortly after midnight, destroying a 4000-ton semi underground tank and igniting the contents. The installation was located on sloping ground, and the escaping spirit flowed down the hillside to a small stream which ran in the valley bottom, imperilling a number of nearby houses. This spirit also flowed over a nearby tank and collected in a bomb crater close to it, and it was obvious that it would rapidly become involved if suitable steps were not immediately taken.

It was decided that the best prospects lay in transferring as much petrol as possible out of this undamaged tank (although at that time, because its surface was covered with burning petrol, it was believed to be on fire at the surface) whilst attempts were made to extinguish the tank which had been destroyed. In this way about 1¼ million gallons of spirit were safely transferred without incident.

A concerted attempt, using nine No. 10 foam branches, was made to extinguish the destroyed tank, and this was rapidly successful. When this had been accomplished it was verified that the second tank was not on fire.

After the fire in the destroyed tank had been extinguished it was found that petrol continued to flow in considerable quantities out of the face of a cutting which lay immediately below the tank. This flow, it was thought, was caused by a large pocket which had collected below the destroyed tank, the floor of which was damaged by the direct hit. This flow gave a great deal of trouble, but after many efforts it was found possible to control the flames while a barricade of empty drums, earth, etc., was built to confine it and form a pool, on the surface of which foam could be applied. Once the fire below was extinguished, it was possible to deal with the fire in the cascade itself.

A further serious factor, however, existed at this fire, and was caused by the escape of burning spirit from the upper tank down the sloping side of the hill towards a stream which ran in the valley bottom. This spirit covered a considerable area of ground and proved extremely troublesome to extinguish. Owing to the irregularities of the surface and to the very large area, the use of foam was considered in the first place but rejected, and attempts were made to deal with the fire by means of spray and fog nozzles. It was, however, found that the petrol flashed back continuously, and valuable experience in the use of water-spray and fog was gained. It was, for instance, quite apparent that only by providing sufficient spray nozzles to cover the whole area simultaneously could the fire adequately be prevented from flashing back. Nearby cottages which were imperilled by this ground fire were evacuated, and stringent precautions were taken to see that no naked lights were allowed within a considerable area, because of the petrol fumes which had collected everywhere. In an endeavour to control this ground fire, fog-nozzle equipment was used in conjunction with mechanical foam compound; the results were not spectacular, but the thin and rather watery foam thus produced was far more effective in dealing with the ground fire than was the water-spray alone. After some hours this combination of water-spray and foam succeeded in overcoming the fire, and the whole area was extinguished. The total time taken from the outbreak till the last flames were dealt with was some twenty-one hours. In the early stages of this fire, a bulldozer was used most effectively in order to fill in a track for Fire Service appliances, because the main approach road was blocked by burning spirit. The loss of spirit was virtually restricted to that contained in the upper tank, which was, to all intents and purposes, completely destroyed by the direct hit.

Fires on Tankers.

S.S. "Lucellum."

In the very early hours of December 20, 1941, information was received by the National Fire Service from the Naval Authorities that the motor vessel "Lucellum," a tanker of some 9000 tons, was on fire off Holyhead. Travelling in convoy, and carrying a cargo of approximately five million gallons of kerosine and light oil, she had been attacked by a single enemy plane and hit twice forward of the bridge by H.E. The ship was originally abandoned by her crew, and from the report received it appeared that the position was grave, but that there was a possibility of salvaging the vessel if sufficient fire-fighting equipment could be got to her rapidly. A fast motor launch was therefore detailed to put to sea with two light trailer pumps dismounted from their chassis, together with quantities of foam compound, and twelve firemen.

The "Lucellum" was reached at about 9.30 a.m., and was found to have three of her forward tanks alight as well as part of her superstructure. Fortunately, however, her engines had been left slow astern, and the fire was being kept away from aft. A Naval tug and a trawler were alongside at work with foam and jets of water, but a heavy sea was running, and it was impossible to bring alongside the launch with the fire-fighting gear. Men and equipment were therefore transferred to the vessel in relays by lifeboat. The fire was energetically tackled with foam on the oil and water on the ship's structure, but it had been impossible in the early stages to bring sufficient quantities of foam compound, and by 11 a.m. the supply was exhausted. At about 2 p.m. further launches with reinforcements both of men and material arrived, and really effective fire-fighting measures were then instituted. It was decided to take the ship in tow while the fire was being tackled, and by 6 p.m. fire in the three tanks had been extinguished. Eight light pumps in all were taken on board, but only six were actually used. The pumps were placed on the after-deck, and water pumped straight from the sea. Six No. 10 branches were used with inline inductors. The fires in the superstructure and between decks were extremely difficult to handle, but were finally extinguished by 11 p.m. Constant cooling of the steel work was necessary, because flakes of incandescent rust kept spalling off and dropping into the spirit. As a result of the resolute attack made on this fire, only the three tanks which were damaged in the original attack were involved, and a considerable proportion of the contents of each of these tanks was salvaged. It is estimated that in all only some 20,000 gallons of petroleum were lost. Approximately 2330 gallons of foam compound were consumed in extinguishing the oil fire.

S.S. " Liseta."

An explosion and the fire which subsequently occurred in the S.S. " Liseta," which occurred on February 3, 1943, was in many ways one of the most interesting ship fires to which the National Fire Service were called. The " Liseta " had just completed unloading a cargo of 2700 tons of petrol, and was steaming out tanks, when a series of almost simultaneous explosions occurred. The damage done to the ship is shown in two of the accompanying photographs, which illustrate very clearly the force generated by a large petrol explosion. The steel deck parted transversely from port to starboard, and the entire deck was folded backwards on top of itself, in two pieces, the forward portion over the forecastle, and the rear portion taking the bridge with it over the decking aft. The folding was such that the top deck of the wheel-house was almost exactly upside down. The explosion opened up the ship's plates, and she immediately began to take in water. Six Chinese members of the crew were killed, as was the Dutch captain, who was in his cabin over the bridge-house.

As a result of the explosion, the residual spirit in the unpurged tanks caught fire. The first step taken was to try to prevent the spread of this fire to the transverse fuel-oil bunker located immediately forward of the engine-room, between it and the pump-room, which was on fire. Almost the whole of the interior of the ship was exposed by the lifting of the deck, and jets of water got to work to wash the spirit down into the bottom in order to form a level surface, on which foam could be applied. Quantities of foam were then laid down in the interior of the ship, which resembled nothing more than an open tank, and the fire was successfully extinguished.

At this fire definite information was obtained that chemical foam and mechanical foam were not mutually destructive in practice, as had been generally considered the case. A fire-boat in attendance got a *chemical* foam-generator to work into the same compartment as a *mechanical* foam-making branch, and it was possible to observe closely the function of the two types of foam.

Owing to the destruction caused by the explosion it was never possible to decide a definite cause, but it is believed that it may have been due to the sparking of the flexible steel steam pipe used for purging operations on the rusty deck-plates. The value of light trailer pumps for salvage purposes was well shown at this fire, because the explosion caused considerable leakage into the engine-room, and a light pump which was lowered on a line through the engine-room casing kept the intake of water down until the salvage authorities were able to take over.

Conclusions.

One of the principle differences between an oil fire and, say, an ordinary fire of large proportions is the considerable quantity of foam equipment necessary.

The principal underlying extinction of an oil fire is to achieve the maximum possible rate of application of foam with the equipment available, and it has recently been decided that the standard to aim at should be at least 1 gallon per square foot of burning surface per minute, which means

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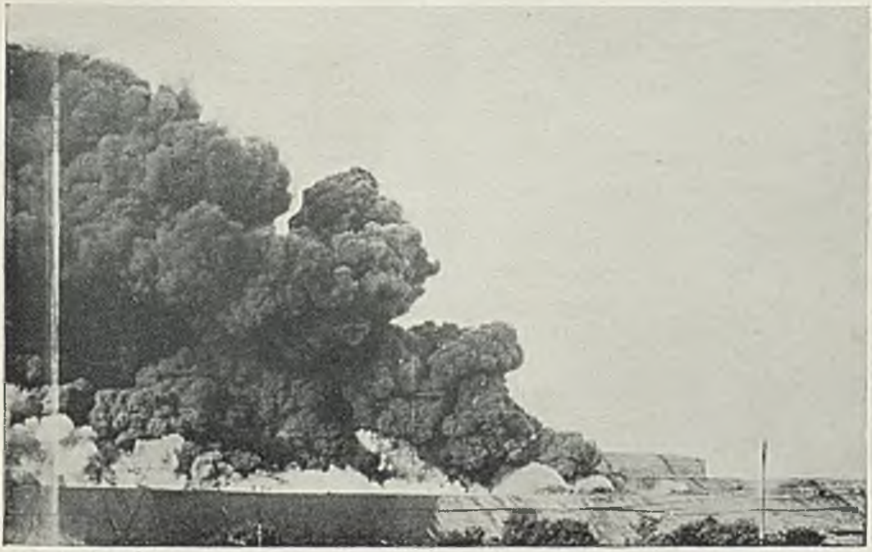
A LARGE OIL FIRE CAUSED BY ENEMY ACTION.

Note the magnitude of the smoke effects by comparing the size of the jets at work on the bund wall.



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PEMBROKE DOCK. ANOTHER VIEW OF THE FIRE TAKEN DOWNHILL OF THE MOAT.

Note the blackening caused by overflowing oil.

[*To face p. 8.*

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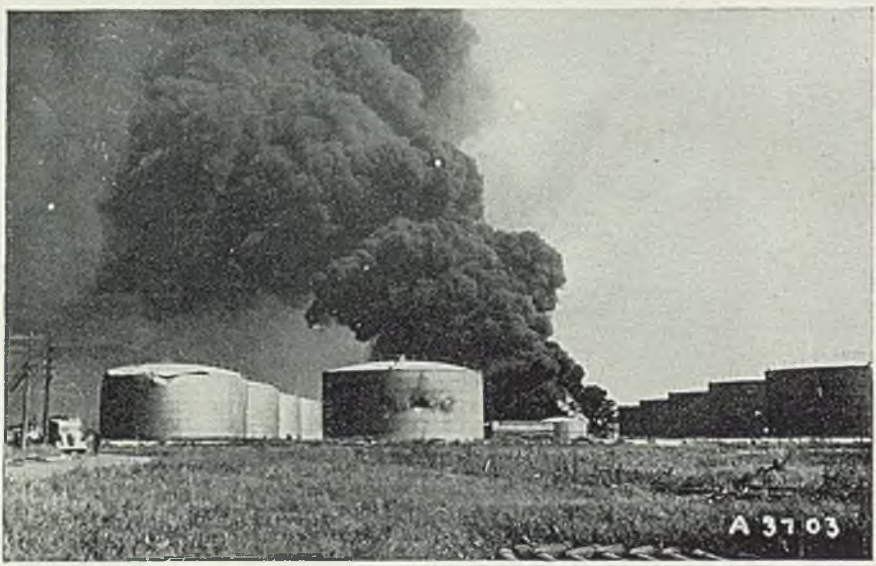
THAMESHAVEN. GENERAL VIEW OF SECOND FIRE.



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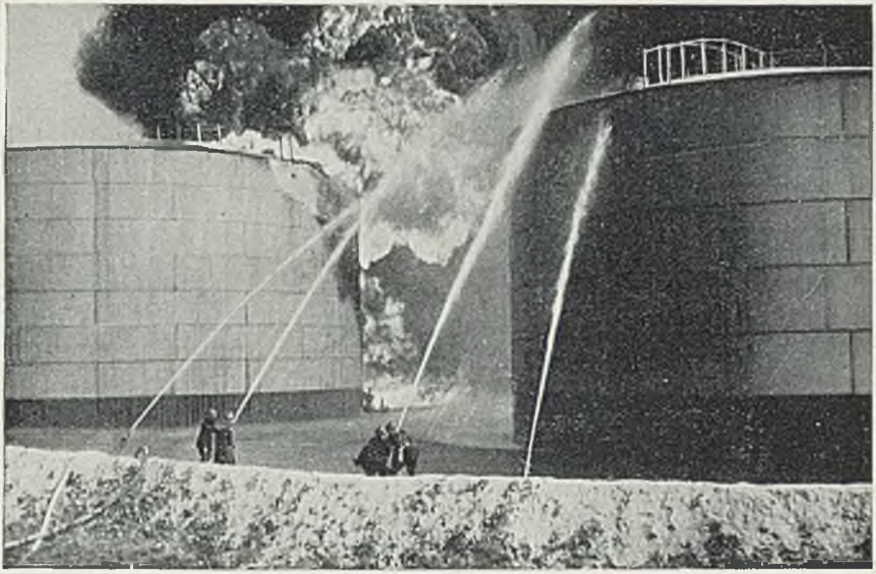
THAMESHAVEN. ANOTHER VIEW OF THE SECOND FIRE.



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TYPICAL EXAMPLE OF COOLING AN UNAFFECTED TANK TO LEEWARD OF ONE THAT IS BURNING.

Note that two portable directors are in use and that the men are well up on the bund wall.

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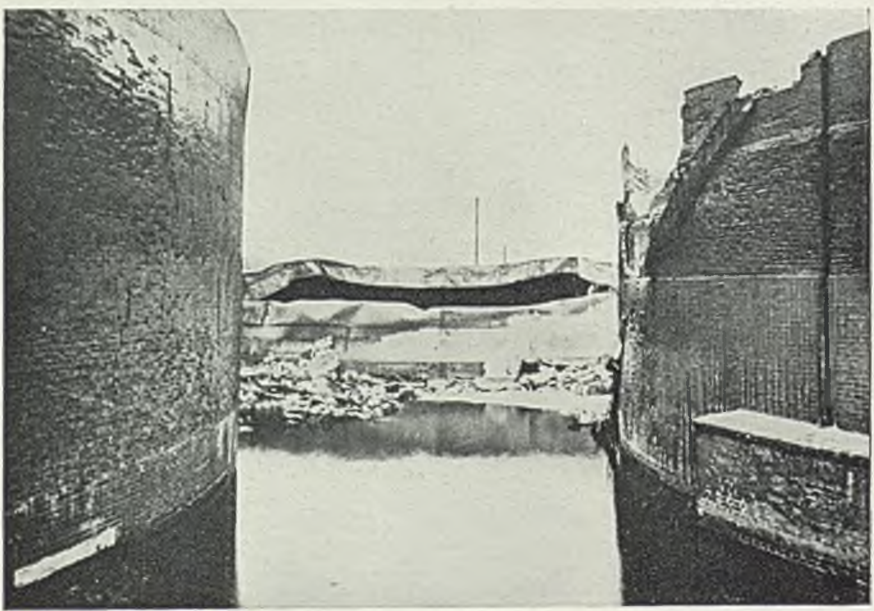
THAMESHAVEN. OPERATIONS IN PROGRESS FOR THE EXTINCTION OF A FIRE AT THE VALVE.

BURNT-OUT OIL TANKS.

Note the complete folding inwards of the sides of the tank in the foreground and the pool of free oil lying at the base of the tanks.



AVONMOUTH. PHOTOGRAPH SHOWING THE EFFECT OF HEAT ON BLAST-WALLING AND THE CHARACTERISTIC COLLAPSE OF A BURNT OUT TANK.

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AVONMOUTH. VIEW OF TANK WHICH HAS COMPLETELY COLLAPSED.

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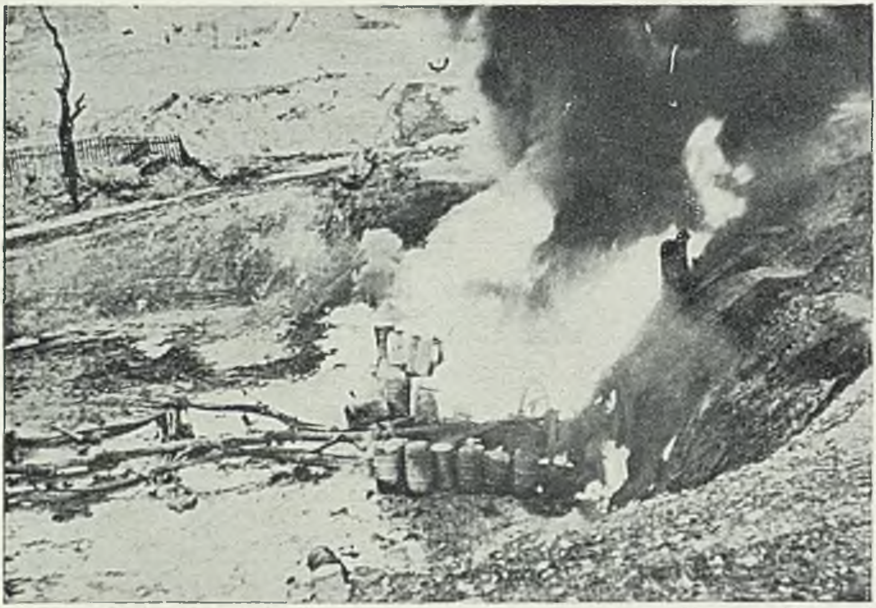
FALMOUTH. VIEW OF THE INTERIOR OF THE DAMAGED TANK AFTER EXTINCTION.



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FALMOUTH. STEPS TAKEN TO CONFINE THE CATARACT FIRE BY FORMING A DAM OF OLD OIL DRUMS, EARTH, ETC.

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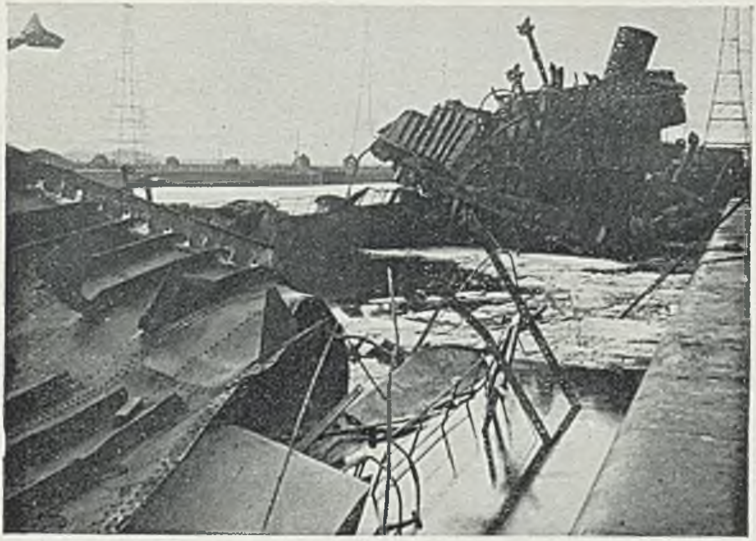
FALMOUTH. EXTINGUISHING THE CATARACT FIRE WITH FOAM.
Note the American fog nozzle equipment in use in the foreground.



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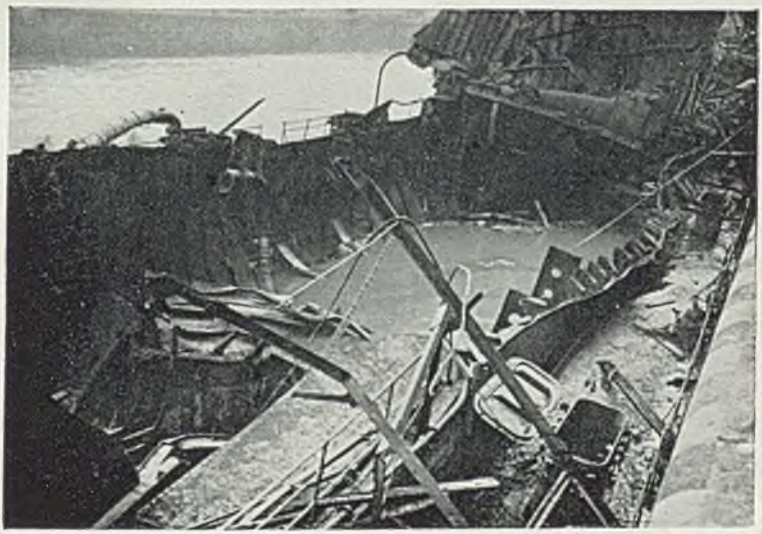
S.S. LISETA. VIEW FROM FOR'ARD SHOWING THE EXTENT OF THE DAMAGE.
Note the foam still present although this photo was taken some thirty-six hours later.



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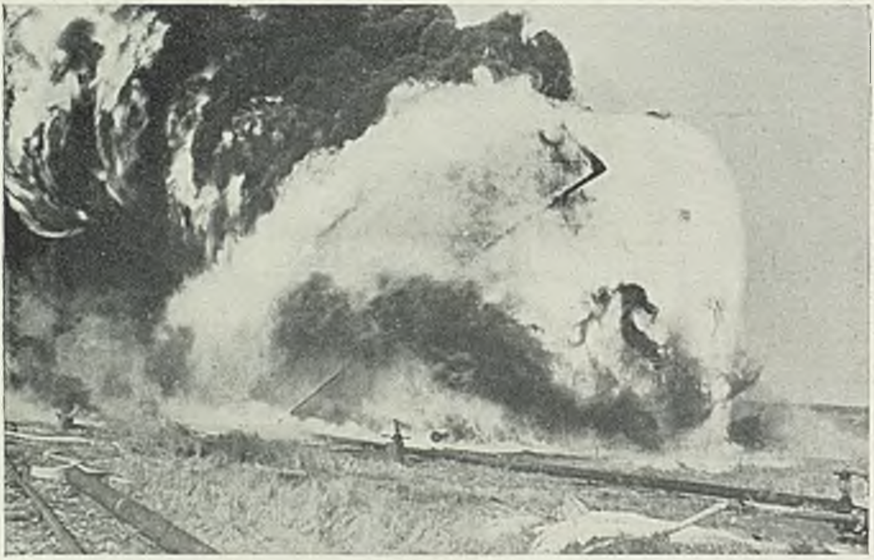
S.S. LISETA. VIEW OF THE INTERIOR OF THE VESSEL SHOWING THE INTERIOR AS THE TIDE FELL.



A SLOPOVER. THE OIL POURS OVER THE EDGE OF THE TANK, BUT IS NOT BLOWN UPWARDS, AS WITH A BAILOVER. THE BLACK SMOKE IS TYPICAL OF OIL FIRES.

Note the temporary pourer about to collapse.

building up a layer at a rate of 2-in per minute in a tank. Such a layer should be at least 1 ft thick, and, as it is impossible to achieve this in the theoretical time because of loss by heat destruction and updraught, the aim should be to complete it in 20 to 30 minutes. In a 112-feet diameter tank this rate of application involves the use of 13 No. 10 foam branches consuming 39 gallons per minute of foam compound weighing approximately 4 cwt. A large and well-organized transport system must be available, and it is essential that personnel on the fire ground should work systematically to handle quantities of that order. Rigorous control has to be enforced for handling the drums of foam compound so that they are opened, emptied into the inductor tanks and removed as soon as possible.

A second factor that has come to light from experience gained in fighting large oil fires is that only one tank should be tackled at a time. It is a waste of effort for resources to be split, and it is far better to concentrate the whole of the extinguishing equipment available on each tank in turn, and when one is extinguished to move on to the next. It is assumed that adequate steps will have been taken to prevent the spread of fire to other tanks threatened.

Fixed fire-fighting installations have proved their worth in war time and in peace time their provision is absolutely essential. To get foam into the tank has been proved at most of these fires to be one of the major problems, and this the fixed installation carries out immediately. The bricking up of tanks, originally an A.R.P. measure, has proved a great protection against the spread of fire by radiated heat.

During the war a great deal of work on the problems involved in fighting oil fires has been done by the Research and Experiments Department of the Home Office, and our knowledge has improved immensely both of the methods of producing foam and of the behaviour of oil on fire.

In conclusion it is desired to thank the Home Office (Fire Service Department) for permission to read this paper and to acknowledge assistance rendered by the Admiralty, the Ministry of Fuel and Power and the Petroleum Board.

THE INSTITUTE OF PETROLEUM.

A meeting of the Institute of Petroleum was held at 26, Portland Place, London, W.1, on Wednesday, October 10, 1945. Prof. F. H. Garner, O.B.E. (President), was in the Chair.

A paper on "Some Notable Wartime Oil Fires" was read by Mr. V. J. Wilmoth. [See pp. 1–9.]

Discussion.

The President said that Mr. Wilmoth had been referring entirely to fires in wartime, and it was a tribute to the fire-preventative steps taken by the petroleum industry that so few fires occurred in peace-time. This was quite different from the earlier history of the industry.

In 1940, after Dunkirk, the question of getting rid of oil stocks in the event of invasion was under consideration, and many experiments were carried out on methods of making petroleum fuels unusable. One method was the destruction of oil by fire, but it was at first surprisingly difficult to devise methods which would ignite oil under all conditions.

In the case of fuel oil it was particularly difficult unless the fuel oil was thoroughly atomised or there was some means of raising it to a sufficiently high temperature to ensure it burning continuously. Mr. Wilmoth had referred to one or two cases in which high-explosive bombs produced a fire, and it would be of interest to have some idea of the relative efficiency of incendiary and H.E. bombs used separately in causing fires.

The Author said he understood that a very detailed paper on certain fires which had occurred during the war might be read before the Institute at a later date, and that he, therefore, hoped that the present discussion would be confined to general principles rather than deal with the individual fires which he had described in his paper.

Mr. E. Thornton said this paper was so comprehensive (at least as regards fires attended by the N.F.S.) that it was impossible, in the absence of preprints, to deal adequately impromptu with the numerous points raised; he would therefore confine his remarks to one aspect of fire-fighting mentioned by the author and stressed in his conclusions—*i.e.*, that which concerned the problems of man-power and transport organization necessary to maintain the large rates of foam application now considered advisable. He agreed with the author in advocating these larger rates of application. In fact his own schemes for tankage protection had made provision for such rates from the very beginning, although they were adversely criticized at the time. What he was concerned about, however, was the attempt to provide these rates, using equipment and methods not designed for such quantities.

The author had spoken of 13 No. 10 branch pipes as a suitable number for a large tank. To keep one No. 10 branch pipe in action by means of an inline inductor supplied by the use of 2-gallon tins of foam compound meant bringing up and handling (*i.e.*, emptying) three 2-gallon tins of compound every two minutes. To keep thirteen separate fixed or mobile No. 10's in action by this means demanded a supply rate of twenty 2-gallon tins per minute, the decanting of these into inductors and the disposal of empties, etc. It was indeed a problem in organization of transport and man-power of staggering complexity, as the author had indicated. The speaker would like to pay a tribute to the way in which the N.F.S. had on occasion overcome these problems successfully, but he was still of opinion that it was a war-time triumph to be praised and then scrapped.

He had in mind a particular fire at Avonmouth, fortunately not caused by or attended by enemy action, when to keep a mere seven No. 10's in action (not thirteen, as now proposed) something like 100 men were utilized in the immediate vicinity of the tank for a matter of some three hours. Had the incident been accompanied by enemy action, the results might have been disastrous in the way of casualties. It is possible to handle twice this quantity of foam using only a very few men if larger types of inductor and of branch pipe are used, or even special pumps for compound, such fittings being, in fact, provided at Llandarcy. In the opinion of the speaker this question was important, and not just a personal fad. We had no right in wartime to concentrate 100 men on any target if there were ways of avoiding this, and in peacetime, with reduced N.F.S. and reduced works' brigades, it is doubtful if one could ever expect to collect 100 men quickly to deal with any one tank.

On both grounds, therefore, serious consideration should be given to the utilization of known methods and the devising of still further improved methods which would permit large quantities of foam to be supplied with the minimum man-power. This could be done by installing suitable equipment for the purpose, retaining the eminently suitable No. 10 branch pipes only for small and limited fires requiring one or two of them.

Mr. A. Frank Dabell said he agreed with the President upon the difficulty of igniting oil, even under favourable conditions.

A shovelful of glowing coke may, with impunity, be immersed in a bucket of petrol.

An incendiary bomb is rendered harmless by immersion in oil.

H.E. bombs rarely cause ignition.

He had seen a shell pass through a tank of petrol and result only in the release of the liquid down to the level of perforation.

He awaited with interest the detailed report dealing with ignition referred to by the President.

The author spoke of the speedy way in which oil reached fire condition. In his experience oil fires in general began with a small flickering flame, so small that it could be extinguished with a handkerchief, and when the stage of conflagration was reached, rarely had two fires called for identical treatment.

Yet all the fires described appear to have been fought at the top with foam, and foam only. There would seem to have been absence of appreciation that it is oil vapour—vapour only, and not liquid—that burns.

Moreover, in his opinion tank oil-fires should not be fought, but subtle measures employed. These in general called for operation at the base of tanks.

Neither could he agree with the declaration that foam was essential. Pipe-fitters were.

Solid combustibles when burning had of necessity to be fought—and upon their sites, but liquids were potentially mobile and readily transferable to chosen sites at lower levels. Moreover, when transfer is effected through closed ducts fire is immediately and automatically extinguished. Flame from oil running in even open trenches decreases and expires over comparatively short distances—the more rapidly when water is mixed with the oil or used as a vehicle.

In extremity, all risk may be eliminated by running the liquid into subsurface absorbent strata generally to be found within the reach of hand-dug wells.

Yet, if he understood the author correctly, tanks of oil standing on high ground at Pembroke had burned for eighteen days.

He thought, however, that the author spoke as an historian rather than an engineer.

THE AUTHOR : No.

MR. DABELL, continuing, said that presumably—on the fire sites—no prepared facilities had been found for rapid release of oil from the tanks nor for its passage through the encircling bunds, as there should have been.

Admittedly, it was easy to say after a disaster, this or that should have been done beforehand; but in the absence of such—even under fire—trenches could have been dug or pipes loosely laid from the outside of the bund to carry the oil away from the flames.

Artillery (always available in time of war) could have been relied upon to make openings—to any dimension, in both bund and tank, and that with speed and precision.

In many places in Great Britain tanks are to be seen grouped in dangerous proximity, and, in addition to or rather substitution for the brickwork commended, he recommended, in war or peace, fitting funnels to such tanks to allow greater facility of release to vapour generated by radiant heat.

The vapour released would be automatically ignited, and burn at varying distance above the funnel top.

In general, he thought the best example of the main principles governing the control of oil-fires was to be found in the treatment accorded the ordinary road tar-boiler when it was enveloped in flame arising from excessive firing on the part of the attendant.

Here the heavier-than-oil vapour released pours over the side of the boiler to make contact with the fire beneath until the critical 95/5 air/gas mixture obtains and the resulting fire converts the boiler into a cauldron with cumulative spectacular effect.

Text books may prescribe foam, but the experienced fireman directs a stream of water into the fire-box, extinguishing the burning coal and wood, cooling the base of the boiler, arresting vaporization, and starving the fire to extinction in a minute or two.

On a country road in Shropshire he had recently seen a small tar-boiler at work in the care of one man.

When asked what he did when his boiler caught fire, he replied, "I kicks un over and shovels it back." In other words, by scattering the tar on the road he had lowered its temperature, arrested vaporization, extinguished the fire, and obtained maximum salvage.

He commended the principles embodied to the authorities concerned.

Mr. J. W. Martin said it would be useful to have two things added to the paper—viz., the type of fittings which should be used on tanks and some information as to means of removing oil from the vicinity. With regard to the first point, if the author suggested a larger number of foam branches, then some Code of Standard Practice should be adopted. As regards removing the oil from the vicinity, very often the people on the site had not the facilities for doing this, and therefore he suggested there should be a Code of Practice whereby the contents of a tank could be removed by some emergency measure, such as additional branches with quickly made connections. He did not like the idea of funnels on tops of tanks, but if there was a Code of Practice for tank fittings, then they would all be much safer in dealing with oil-fires in the future.

No reference had been made to overseas fires. He took it these were similar to those which happened in Great Britain, but there had been considerable experience of these fires abroad. One interesting point mentioned in the paper was that cork insulation was inflammable, and he suggested it would be advisable to make it well known that cork was not entirely desirable to have on tanks in peace-time.

Dr. A. S. C. Lawrence asked how far the practice of stirring up fuel by cold air currents was likely to be used and would be likely to solve many of the troubles that had been mentioned.

Mr. E. Thornton asked if he might answer this question up to a point, as he was in close touch with the only work he was aware of now being carried out on this method. He had no authority to break security silence or to anticipate too much the final Home Office report which would follow in due course, but there could be no harm in giving some facts already established which provided a partial answer to Dr. Lawrence's question.

The first point dealt with the scale of operation. On a small scale, stirring up the contents of a tank containing burning fuel oil or even oils of lighter character, could result in extinction under the right conditions, and this was well tried and assessed up to the scale of a 9-feet-diameter tank. Problems of quantity and the optimum points of application of the air became more serious as larger and larger tanks were considered. There were alternative ways of applying the same principles which gave considerable promise.

That was as much as he felt authorized to divulge at the moment, but it could and should be interpreted as a guarded "yes" to Dr. Lawrence's question—*i.e.*, stirring up of the oil could solve some of the problems and troubles met with.

Major W. H. Cadman said he would like to make a suggestion as to the possible cause of some of these fires. Every oil fraction has its own temperature of self-ignition, even the heaviest fraction, so that if a fraction was heated up to that temperature or a little above it, it would spontaneously catch fire when exposed to air. Therefore it was quite possible that the conditions which existed as the result of bombing heated a certain section of the oil to a temperature above that of its self-ignition, and that immediately on being exposed to air it caught fire. He suggested this as a possible explanation of some of these extraordinary fires.

Some of the pictures shown by the author brought forcibly to his mind an experience he had in Persia. When the first wells were brought in there was no proper storage for the crude oil, and therefore a bund was placed round a large open space and the residue was put into it. A rather remarkable fire occurred on one occasion. There was a small refinery for local requirements near this lake, and it had been the practice to run the residue from the stills first into a tank to cool and then from the tank into the open reservoir. After a time, for reasons which he would not go into, the tank was cut out and the residue was run direct from the hot stills through a pipe into the reservoir. The night watchman several times reported in the hot season that he had seen flames coming from the end of that pipe, and one night the whole of the contents of that huge reservoir caught fire. That fire was due to self-ignition. No doubt the temperature of the residue oil from the stills was above its self-ignition temperature, and the whole lake of oil caught fire. It was of such an enormous extent that the idea of putting it out by foam or anything else available was out of the question. The only thing to do was to protect the embankment and try to prevent the burning oil from overflowing the bunds, as just below was a large settlement where many of the Persian employees were housed. He himself was on high ground watching, and saw exactly what the author had shown in some of his slides that evening—*i.e.*, steam rising above the oil. The outside of the embankment evidently became heated to such an extent that the water, which had accumulated underneath the oil, was converted into steam at the edge, and a white cloud of steam gradually developed around the whole of the lake. As soon as that steam cloud had spread right across the lake there were no more flames to be seen and the fire went out. From this experience he thought the question of self-ignition had a great deal to do with some of these fires.

The President said the point mentioned by Major Cadman was of importance with less volatile products such as fuel oils because these fires re-ignited themselves.

The fire-point has been defined as the temperature to which a product must be heated in order to burn continuously after the inflammable air-vapour mixture is once ignited, so that the fire-point temperature rather than spontaneous ignition temperature is the deciding factor. In practice, however, re-ignition often occurs even when all flames have been extinguished, and hence, spontaneous ignition temperatures are also of great importance : the spontaneous ignition temperatures of heavy kerosine or diesel oil fractions have been found to be lower than the more volatile fractions such as gasoline and than the less volatile fractions such as lubricating oils. With the less volatile products the fire point and spontaneous ignition temperatures are much closer together than for such products as gasoline. The presence of any material which could serve as a wick greatly facilitated the spread of oil fires and dried vegetation was particularly dangerous in this respect.

Mr. J. Ainsworth said that no reference had been made as to the advantages of underground storage compared with over-ground storage. Had the author any views on that question from the fire-fighting angle?

The Author replying to the discussion, and commenting on the point made by Mr. Thornton concerning the use of the N.F.S., said the paper dealt with oil fires from the war-time angle, and at the time of the particular fire mentioned, the N.F.S. was fairly lavishly equipped with men. In peace-time man-power would be a much greater problem. As regards portable equipment, he agreed that the present size of inductor tank and foam-making branch was not really adequate, but there were problems in making portable equipment too large. With permanent equipment there were fewer focal points to organize as regards foam supplies, etc., but from the war-time angle there was also the other side of the question that, as soon as a fixed installation of any description was adopted, the equipment was put out of action if there was a direct hit. It seemed peculiar but so often it seemed to happen that there was a direct hit on a vital point. For example, the bomb which caused the initial damage at Pembroke Dock landed squarely on the bund wall separating two tanks and destroyed the bund protection.

In reply to Mr. Dabell, regarding the difficulty of igniting oil, he said that he had no statistics as to the way fires were caused. Generally speaking, however, there were two main causes. Experience had shown that in the case of heavy-oil tanks if a high-explosive bomb penetrated the roof and entered the liquid before it exploded, the fuel oil would generally not catch fire. The fires caused by high explosives in heavy oil had mostly been due to a bomb penetrating the roof and exploding in the ullage of the tank. His personal opinion was that the fire was probably due to the fact that an oil mist was formed by vaporization of the oil due to blast which registered with the flash of the explosion. Then there was the combined high-explosive and incendiary bomb attack, which probably constituted the greatest danger, particularly with unbricked tanks containing spirit.

As regards the provision of flame-traps between bund walls, a great deal of work had been done in this connection, but they had to be correctly designed. Steel is subject to distortion, and the original design of flame-trap incorporating a steel baffle had been modified as the result of experience. The result was that better fire-resisting materials were being used, and he understood that the most modern type of flame-trap was thoroughly effective in passing oil from one side of a bund wall to the other without, at the same time, transmitting fire.

The suggestion to run the oil from the tanks and deal with it in the open, pre-supposed that there was somewhere to deal with the resulting large area of fire, but one of the chief problems facing most of the installations he had described was that there was nowhere to dispose of the oil. If all the tanks were full, it was not possible to pump from one tank to another, and he believed he was right in saying that to empty a 112-feet-diameter tank required a considerable number of hours. Most calculations seemed to show that a tank would burn down at approximately the same rate that it could be emptied, so that the chances of salvaging the contents of a tank on fire by pumping out were about 50–50. That was tried at Pembroke where a tanker was filled, but with such large quantities involved the method only went part of the way to solving the problem. The use of water was an interesting topic, and work was still going on in that connection. There was some divergence of opinion between ourselves and the Americans because in America they were very keen on water in dealing with oil-fires. On the other hand experience in Great Britain had shown that whilst it was good under certain conditions for extinguishing fires in heavy oil, it was not usually good for light spirit. In this case the danger from a flash-back was much too great unless the whole area could be covered simultaneously with spray or fog. With heavy oil not in a tank, water was probably the best extinguishing medium, but it must be a fairly heavy fuel oil in order to emulsify on the surface and hold the water globules long enough to cool it down below its flash point. With light spirit one did not get that cooling, because vapour formation was continuous even at atmospheric temperature, and the result was that there would be constant re-flashing. In effect, it was necessary, in the case of light spirit, to extinguish the whole flame simultaneously.

Referring to the suggestion by Mr. Martin for a standard code of practice for fixed foam equipment, he could only speak personally. In most cases the present standard of fittings was certainly below the generally accepted rate of application, but whether a national standard could be arrived at would be a matter for a higher authority. He agreed it would be a good thing, but if it were done he thought it might involve most of the oil companies in considerable expenditure, because, if top application were used, it would mean that in the case of a large tank between twelve and fourteen No. 10 foam-making branches would have to be installed, in place of four or possibly five, which was the usual number at present.

He had not referred to overseas fires, as he had only wished to deal with fires in Great Britain in which the local fire brigade, or after nationalization the N.F.S., were concerned. The other point mentioned by Mr. Martin with regard to cork was interesting. Cork was probably fixed to the roofs of the tanks with bitumen, which was inflammable, and cork also was inflammable. Moreover, from the point of view of the firemen it was an unpleasant material, because industrially some of the most difficult fires with which the Fire Service had had to contend were in spaces in which cork was used as an insulating medium. Cork held between two retaining panels could form an extremely difficult fire which would smoulder and run for large distances into the interstices.

He could not offer any comment on Major Cadman's remarks concerning self-ignition temperatures of various fractions except to say that the re-heating of oil altered its characteristics considerably. The fire in the open pit he mentioned might have been due to spontaneous combustion caused by sulphide of iron in the pipe carrying the oil. There was an analogy in the gas industry where the oxide of iron used in the purifiers was converted to iron sulphide. When the purifiers were cleaned out there was risk of spontaneous combustion unless certain precautions were taken.

As regards the oil lake fire being extinguished by steam, it was the fact that steam was used for small spirit fires in certain fixed installations, but he had never heard of it being used on a large open area. There was one case of smothering—which was not quite the same thing, however—he knew of a case where some oil tanks in basement of a building caught fire. It was not possible to get at the fire so all the openings were closed up with corrugated iron sheets held down and sealed with sandbags. The fire was thus starved of air and went out.

He had not touched on the question of the advantages or disadvantages of above-ground and below-ground storage because the Falmouth installation was the only one employing underground storage among the cases he had mentioned, involving fire, and there was no comparison between that and the other installations. The advantages, obviously, should be with the underground tank, and the fire at Falmouth brought that out very clearly. The underground tank was protected from radiated heat, and whereas, in the case of an above-ground tank, spirit on fire flowing around it would be almost certain to set it on fire, that was not so with the underground tank. Moreover, in dealing with a fire in an underground tank the foam was applied from ground level and there were none of the problems of getting foam to a surface 30 or 40 feet above ground. That was the chief reason why there was difficulty with the early fires; there was not sufficient portable equipment for delivering foam into the tanks and on to the actual surface on fire.

On the motion of the President, a hearty vote of thanks was accorded Mr. Wilmoth.

CLAY RESEARCH AND OIL DEVELOPMENT PROBLEMS.

J. C. Griffiths.

Introduction.

There are two fundamental methods of approach to the problem of maintaining or augmenting oil reserves; the first demands geological exploration to discover new oilfields, whereas the second is based on increasing the recovery efficiency in fields already under production. In either case the increasing difficulties of locating new oilfields or of producing more oil from those already found demand a more detailed knowledge of the reservoir rocks and their environment. Within this field of research the petrography of sedimentary rocks reigns supreme, and only by diligent pursuit of this subject can any spectacular advances be envisaged.[26]

According to Clarke,[5] the lithosphere comprises 95 per cent. igneous and 5 per cent. sedimentary rocks; of the sedimentaries 80 per cent. is assigned to the shales and clays, 15 per cent. to the sandstones, and 5 per cent. to the limestones. It is the purpose of this paper to outline the significance of the clay materials in the problem of oil exploitation and production.

Clay Mineralogy.

The extent of the development of the subject of clay mineralogy during the last decade is well illustrated by the comparison of Boswell's account[3] of the mineral composition of clays (1933) with that of Grim and his co-authors (1942).[11] Similar advances have been made in knowledge concerning colloid chemistry and base exchange, and the literature dealing with the different aspects of clay has therefore become overwhelming. Before considering the application of these studies to oil-development problems it is necessary to summarize the main facts concerning the composition and behaviour of the commonly occurring clay minerals.

The most recent views[11, 27] on the composition of clays suggest that they consist essentially of mixtures of two or more of a few mineral groups with or without some quartz, feldspar, and rare "heavy minerals." The commoner clay mineral groups are:

Kaolin Group.

This group includes the minerals kaolinite, dickite, and nacrite, which are complex aluminium silicates of the type[11]

$$(OH)_8Al_4Si_4O_{10}.$$

The valency requirements are completely balanced within the structure, and there is little tendency for replacement of the aluminium by iron, magnesium, etc.; kaolin minerals are therefore the most stable clay minerals.

Montmorillonite–Beidellite Group.

These minerals are also complex silicates of alumina, but with lower alumina–silica ratios than those of the kaolin group. The general formula is given by [11]:

$$(OH)_4Al_4Si_8O_{20} \cdot nH_2O.$$

In this structure there is a tendency for ions of lower valency to replace both the aluminium and silicon, leaving unbalanced charges which are neutralized by such bases as sodium, calcium, magnesium, etc.

Illite Group.

The illite group is not so well known as the previous types, but may prove to be one of the commonest clay minerals; it is assumed to be the fundamental factor in producing shaley structure in many of the finer-grained rocks. Its general composition is given as [11]:

$$(OH)_4K_y(Al_4Fe_4Mg_4Mg_6)(Si_{8-y}Al_y)O_{20}.$$

Its replacement behaviour varies, some forms of illite approaching the montmorillonite–beidellite types, readily undergoing base exchange, while others are more stable and resemble the kaolin group. This has led Grim [10] to suggest that the illite group may constitute an isomorphous series analogous to that of the montmorillonite–beidellite minerals.

Other Clay Minerals.

Many other clay minerals exist, but are less well known, and in most cases comparatively restricted in occurrence. Saponite, nontronite, hectorite, attapulgite, halloysite, and allophane are examples. The first three are end-members of the replacements, by various bases, of aluminium or silicon in the montmorillonite or beidellite group. Attapulgite appears to be a representative of a new group, while halloysite is related to the kaolin group, but shows some properties more allied to montmorillonite. There is some doubt whether allophane is an amorphous clay mineral or a mixture of silica and alumina, etc.

Derivations of the Clay Minerals.

The genesis of the clay minerals has been attributed to various agencies. Kaolinite is considered to be formed, when in bulk, by the hydrothermal decomposition of granitic materials; montmorillonite–beidellite minerals are characteristic of the rock called bentonite, and are there formed by decomposition of volcanic ash. Illite probably plays its biggest rôle in the older rocks where diagenesis has already commenced to reconstitute the clay material along the sequence of changes which lead to the development of various mica minerals, and in which illite appears to play a rôle intermediate between many clay minerals and the micas.

Within recent years evidence has accumulated which suggests that kaolinite and montmorillonite may be formed from similar parent materials and that their respective development depends on the existence of an acid or alkaline environment, which in turn depends on the presence or absence of intensive leaching.[27] Illite may arise under somewhat similar conditions in the presence of potassium ions.

Physical and Chemical Behaviour of the Clay Minerals.

The physical and chemical properties of the clay minerals are largely dependent on the stability of the lattice structure, and some account of this is necessary before considering the questions of base exchange, water adsorption, etc., in relation to the effect of clay minerals on production problems.

Lattice Structure of Clay Minerals.

The details of the lattice structure of the clay minerals have been usefully summarized by Hendricks,[14] the most outstanding feature being their layered character. This leads to the mica-like outward form of many of the clay minerals which are generally described as platey.

The kaolinite-type lattice is relatively stable, and this is considered to be due to the juxtaposition of H^{+} and ^{-}OH groups in the successive units which build up the crystal. The lattice of the montmorillonite type, on the other hand, is relatively unstable, and this is explained as due to the proximity of ^{--}O atoms in the adjacent units. In illite the repelling charges of the oxygens of the montmorillonite lattice units are in part neutralized by a base, generally potassium, and so the illite lattice, although less stable than the kaolin type, is more stable than the montmorillonite type.

Water Adsorption.

All clays adsorb water to some degree, a characteristic related to the large surface area of an aggregate of small particles. However, the different clay minerals show considerable variation in the volumes of water which they can adsorb.

Kaolinite shows this effect in the least degree, while illite is intermediate, some illites adsorbing relatively large amounts, whereas others approach the kaolinite type in this respect. Montmorillonite, however, is the most striking, adsorbing very large amounts of water. It has been reported [28] that a cube of montmorillonite-type clay can, without loss of shape, increase its volume 13·8 times by adsorbing water. This property is extremely important in oil-development problems, and the presence or absence of the adsorptive minerals is of fundamental importance in reservoir technology.

The adsorption of water in montmorillonite is related to the base-saturated nature of the particular mineral.[10] In general, sodium clays carry the most water, calcium and magnesium clays less, and hydrogen clays least. In addition, the particle size of the clay mineral affects the water adsorption, and the characteristic small size of the montmorillonite–beidellite types and their tendency to extreme dispersion in the presence of water tend to favour a high adsorption.

Clay minerals lose water on heating, and the thermal dehydration curves are characteristic of the different mineral groups.[12]

Base Exchange.

Base exchange is a stoichiometric exchange of ion for ion in the crystal structure and is best shown by montmorillonite, wherein bases such as Na^{+}, Ca^{++}, Mg^{++}, and H^{+} can replace each other within the mineral without destroying the lattice structure. This property depends essentially on initial replacements within the lattice of a tetravalent by a trivalent ion, etc., leaving an excess charge which is neutralized by a suitable base ion such as Na^+ or K^+.

The order of base replacement is given as follows :

$$Li^+ > Na^+ > K^+ > Mg^{++} > Ca^{++} > Ba^{++} > H^+.$$

Thus at equivalent concentrations calcium will displace sodium, etc., although it has been pointed out that each mineral group may have its own order of base replaceability, dependent on size of cavity in the lattice and ionic size of the replacing ion. This phenomenon is of importance in oil-development problems because of the practicability of replacing unfavourable by favourable ions on introducing simple solutions.

Base-exchange capacity varies within the clay minerals, montmorillonite once more proving to be the most highly reactive. In addition, base-exchange capacity increases with decrease in grain size. The relative degree of base-exchange reaction is given in Table I.

TABLE I.

Base Exchange Capacity.

(After Grim.[11]).

Clay mineral.	Milli-equivalents per 100 grams.
Montmorillonite	60–100
Attapulgite	25– 30
Illite	20– 40
Kaolinite	3– 15
Halloysite	6– 10

The nature of the exchangeable base saturating the clay mineral determines the characteristic properties of the mineral within its group, but it must be emphasized that more than one base may be present. Hence the following discussion is relatively simplified, in order that the general behaviour of clays commonly met with may be outlined and their particular applications suggested.

Hydrogen-Base-Saturated Clay.

Hydrogen-base-saturated clay originates as a surface deposit in regions of high precipitation due to leaching by rain-water carrying carbon dioxide. Its high shrinkage and water adsorption lead to mechanical instability, and landslips are characteristic of areas in which hydrogen clays are a dominant feature. Experimental cures have been attempted using base exchange as the working principle. Hydrogen clay is rarely encountered in oil-development work, but has been utilized in refining oils for " filtering " impurities and improving the colour of the lubricating-oil fraction.

Calcium-Base-Saturated Clay.

Calcium- and magnesium-base-saturated clays are physically similar and may be considered together. Calcium clay possesses the highest permeability of the commonly occurring types, and because calcium readily displaces many other bases, this is a relatively common subaerial clay. Kelley and Liebeg [15] attribute the dominance of magnesium in the marine clays to the ease with which magnesium enters the base positions of the clay lattice, and it appears probable that calcium clays originate for similar reasons from the migration of calcium-rich ground-waters through clayey sediments within the horizon of the ground-water table.

Calcium clay plays its chief part in agriculture, where it is generally considered as the most desirable type for development. A naturally developed calcium clay possesses the quality of tilth—that is, the soil structure is crumbly. The clay is in a flocculated condition, and so allows drainage to and from plant roots with reasonable ease. Artificial development of a calcium clay does not, according to some experts, necessarily lead immediately to a granular texture, but substitution of calcium for sodium generally connotes an increase in permeability.

Sodium-Base-Saturated Clay.

This is probably the best-known type, principally because it possesses well-marked properties which are useful in many industrial capacities. Sodium clay has a greater drying shrinkage than calcium clay. It is in a deflocculated condition and has a high water-adsorption capacity. It is relatively impermeable. In simple qualitative experiments it can easily be demonstrated that whereas sodium clay is permeable to sodium chloride solution, it is relatively impermeable to fresh water. This is the basis of the McKenzie–Taylor theory of the origin of oil and coal. McKenzie–Taylor [20, 21] has shown that many shales which form the cap rock of oil reservoirs are sodium-base-saturated, and on flushing with fresh water had become deflocculated and impermeable, thus providing anaerobic conditions in the sand below. On this basis it appears reasonable to suggest that the clay associated with oil and its accompanying saline waters is sodium-base-saturated, and therefore in a relatively highly peptized condition. Any contact with fresh water tends to develop an impermeable sheath between the fresh water and the reservoir fluids. These inferences, if correct, are fundamental in assessing reservoir performance during oil development.

Application of Clay Research to the Oil Industry.

The obvious contacts of clay with oil-development problems principally concern clay and shale in bulk as rock units, and considering the average sand reservoir rock * the question arises, Of what significance is clay? Perusal of the literature on the petrology of reservoir sands as exemplified in the case of the Third Bradford Sand [17] and the Californian Tertiary sands [25] gives direct evidence on this point, while indirectly the presence of clay in the producing sands of the Gulf Coast, Texas, can be safely deduced from the information in a report on mud acidizing.[19]

The Miocene producing sands of South Trinidad all contain a fair proportion (up to 10 per cent.) of clay fraction, and Muskat [23] states that, as the tendency of natural rocks to suffer hydration is not uncommon, it would be advisable to test for this effect in measuring the permeability of

* In the following discussion the reservoir rock is tacitly assumed to be a "sand" unless otherwise stated.

rock samples. It will, then, be understood that, in sand reservoirs, the presence of a small but significant clay fraction is the rule rather than the exception.

The precise significance of this clay fraction will now be analysed, and the order followed has been chosen as nearly as possible in sequence with the broad programme of development leading to an economic oil reservoir from the search for the pool to its eventual production.

Exploration.

This section is concerned with the purely geological aspect of locating an oil reservoir. Both geophysics and pure geology are employed in the search for oilfields; in the former, measurements are made of differences in bulk properties of the rocks, and their interpretation does not involve absolute knowledge of the effect of clay or any other rock type. Quite clearly, as geophysical methods measure physical properties of rocks and rely on differences in these rocks, any information on the "why" of these measurements would be illuminating. One branch of geophysical observations—electric logging—will be considered later, and many of the problems mentioned in connection with that method of well-logging can also arise in the wider field of geophysical investigations.

From the geological standpoint one of the principal weapons used to elucidate the stratigraphy and structure is palæontology—the study of fossil faunas which are to a large extent concentrated in clays. The palæontologist has perforce recognized that the term "clay" includes a variety of materials, and the recent emphasis on facies variations indicates the importance of possessing a second and independent line of evidence for ecological control. Information on the sedimentation of clays would be invaluable in this respect, and Frank [8] in a recent publication uses the proportion of clay minerals to differentiate the different clay types, and from this and other petrological evidence, has reconstructed the palæogeography of the period represented by the deposits.

There is no doubt that with the growth of knowledge on the origin of clays this line of investigation will develop considerably.

Drilling Practice.

The location of favourable "trap" conditions once inferred, the next step is to investigate the formations with the drill. In drilling, the oil industry's contact with clay is most extensive.

One of the most important items on the drilling programme is the selection of a suitable shale-base for the drilling mud. Much has been written on this problem, and sufficient is known to provide a useful summary of the necessary characteristics of the material.

The first requisite in a clay suitable for drilling mud is a high colloid content, and the ideal clay would therefore be a bentonite—that is, the most suitable clay mineral is one of the montmorillonite–beidellite group. This group gives the best dispersion and thixotropic character, for reasons already mentioned. Within the montmorillonite–beidellite group the base-saturated nature of the clay preferentially determines its efficiency. Sodium-base-saturated types are by far the most efficient. This has been adequately demonstrated both in the field and the laboratory, and the general rule is, the higher the colloid content the better the thixotropic character, and the higher the sodium-base saturation the better the dispersion, wall-building, gel strength, etc.

This represents the best approach to the problem of the average drilling mud. Special hazards demand special muds, and here again an extensive literature exists. Nearly all the common problems, such as gas-cutting and cement-cutting, loss of fluid to the formation, viscosity control, wall-building characteristics, etc., can be met by suitable chemical treatment, which principally affects the base-saturated nature of the clay mineral and either increases or decreases the dispersion. To take a simple example—a cement-cut mud results from flocculation of the normal sodium-base-saturated mud by calcium ions, and the corrective is to return to a sodium-base saturation by increasing the concentration of the sodium ions in the fluids—for example, adding sodium phosphate or tannate.

The normal shale-base muds of 70–80 lb./cu. ft. give place to the barite-weighted muds (100–130 lb./cu. ft.) when high formation pressures are expected or encountered, and this is an expensive change. It is generally accompanied by the addition of Aquagel, which is a natural bentonite specifically treated for use in drilling mud. Once again the most effective type is a sodium-base-saturated bentonite (montmorillonite–beidellite group).

One of the most difficult drilling problems which still remains to be satisfactorily solved is the safe penetration of " heaving shale." The term " heaving shale " has been used for a number of phenomena, but recent literature [1] tends to reserve the term for swelling and sloughing formations in which the swelling and sloughing are physico-chemical effects developed by contact with the fluids from the drilling mud. Baker and Garrison have analyzed this problem [1] and suggested that it was due in part at least to laminated formations in which the alternate laminæ are sodium- and calcium-base-saturated clays, the former swelling and disintegrating into the mud stream, the latter sloughing off in lumps and causing sticking of the pipe. Here the cause of the trouble is attributed to bentonitic-type shale—that is, to the montmorillonite–beidellite clay mineral group.

A silicate/brine mud has been used to counteract this effect, but has not proved entirely satisfactory, and is moreover expensive and difficult to handle, particularly if it is necessary to use heavy muds. The latest suggestion, not yet tried in the field, is the use of positive colloid muds,[2] which from a theoretical viewpoint would appear to provide a satisfactory solution.

Briefly, the normal mud behaviour is attributed to the negative charge associated with the clay micelle in the ionized mud. Conditions which lead to the optimum development of this ionization result in similar effects on formation clays liable to heave, and hence Bond suggests using a positive colloid mud to prevent the formation ionization. Basic dyes added to normal bentonite solutions result in the development of a positive colloid mud and act as neutralizers of the negative charge on the formation clay, thus removing the cause of formation swelling and heaving.

This does not by any means exhaust the contacts of clay with drilling procedure, but enough has been stated to show the outstanding importance of a thorough knowledge of the raw material, clay, in this section of oil development.

Completion Procedure.

After passing through the hazards of drilling to the reservoir rock and successful location of a " pay horizon," the next step is to obtain an electric log of the formations exposed in the hole and decide on the completion programme. Electric logging will, however, be considered in a succeeding section. The actual " completion " is a problem which, while satisfactorily executed in the average case, has rarely been subjected to a rigorous scientific control.

It has already been mentioned that washing a sodium-base clay with fresh water leads to the development of an impermeable sheath between the fresh water and the formation fluids, yet this is, in general, the basis of at least one commonly used completion method known as washing the well in. The deleterious effects of this method have been emphasized in a recent article on the use of different completion fluids in certain Californian fields.[7] Reduction in rates of flow, and even total loss of production in some cases, has been attributed to washing the " pay " with " sweet water " (fresh water). There is little doubt that this practice has had similar effects in many fields, where other factors, of which there are many, have been invoked in explanation. Indeed, if it were not for the high pressures generally associated with oil-bearing formations it would be surprising that any fluid should be produced at all after such harsh treatment.

The main problem at issue here is dependent on the composition of the reservoir rock. Limestone reservoirs and " clean " sand types are rarely affected, whereas the average reservoir sand containing a clay fraction which is almost certainly in equilibrium with the interstitial fluid, and is, therefore, sodium-base-saturated, would give a very definite reaction to such a procedure and is hardly likely to give a favourable one. Such practice usually results in the well not " coming in," and the general cure is to resort to swabbing and bailing to increase the pressure difference between formation and hole. The later history of such wells often contains reference to " sand trouble," and in the extreme of collapse of formation and/or casing. The alternative appears to be theoretically simple, in that the use of suitable chemical solutions not necessarily concentrated should prevent the formation of an impermeable " halo," and would in all probability, if properly constituted, result in cleaning the walls of the hole.

The second major problem which has been frequently noted in completion procedure is the " mudding off " of the producing formation. This term covers all degrees of trouble, from mud-cake on the walls of the hole to actual invasion and choking of the pores of the sand. The purely mechanical cure is the wall scraper or under-reamer, which, however, can only be effective in the simplest cases. A more drastic treatment is mud-acidizing, which is of wider application.

The composition of " mud-acid " is still a trade secret, but the fluid is specified as dissolving clay minerals and even quartz to some extent.[4] This process necessitates an inhibitor, and often a emulsifier among other rather expensive complications involved in the use of the acid. It would again appear simpler to discover the exact nature of the material causing the trouble—supposedly a clay—and treat the clay with a simple chemical solution to reduce the choking effect. In the majority of cases where the obstruction to flow is the drilling mud the clay is a sodium-base-saturated montmorillonite–beidellite; the cure would then appear to be the use of a solution of calcium or magnesium chlorides strong enough to exchange the calcium for the sodium, and so increase the permeability of the material. Such solutions should be cheaper and easier to handle and should obviate many of the complications resulting from the use of mud-acid.

A similar and allied problem is the choking of a gravel pack which is primarily used to prevent "sand trouble." It has been determined experimentally that the grain size of a gravel pack should be eleven to thirteen times the 10 percentile grain size of formation sand for efficient operation. The 10 percentile grain size of formation sand has similarly been found to be the critical size sufficient to cause bridging within the formation, and so prevent formation sand from passing into the casing. Bridging depends essentially on the uniformity of the sand-grain size-distribution—that is, sufficient material must be present in all grade sizes below the 10 percentile to build up in the formation, adjacent to the well-bore, a bridge consisting of grains of increasing fineness. While this uniformity may exist in the average case, the grain-size analyses, quoted in Table II, exhibit a very low frequency for material in the fine silt grade.

TABLE II.

Grain-Size Analyses of some Miocene-Producing Sands of Trinidad.

Grade scale.	Sand.		Silt.		Clay.
	Fine.	Very fine.	Coarse.	Fine.	
Microns.	250–125	125–62·5	62·5–15·6	15·6–3·9	<3·9
Sample.	Per cent. by weight.				
1	12	65	14	2	7
2	11	69	14	2	4
3	11	61	14	5	9
4	11	51	22	6	10
5	26	52	11	5	6

The "critical ratio of entrance" of a sand made up of uniform spheres in closest packing is, according to Fraser,[9] $0{\cdot}154D$, where $D =$ the diameter of the spheres. Hence in the sands quoted, taking 62·5 microns as the uniform diameter, and assuming the grains to be spheres under the conditions prescribed, the critical ratio of entrance is 9·6 microns. It will be noted that this diameter occurs within the range of the fine silt—that is, in the grade with the least percentage of material—and hence it appears probable that the material finer than 9·6 microns may fail to bridge on sands of 62·5 microns diameter or larger.

Hence in using gravel packs on certain formations the probability is that the clay fraction would either choke off the pack or be produced with the oil. In areas with which the author is familiar an insufficient number of trials have been made for a decision to be reached with regard to the cause of gravel pack failures.

Electric Logging.

Electric logging is one of the most important techniques employed in oil development. Interpretation of the log quite frequently determines the completion programme for a well and, in so far as the development of the field as a whole is concerned, correlation based on electric logs is of considerable value.

The electric log comprises two separate sets of curves which represent measures of electrical properties of the formation under conditions that occur in a bore-hole. The curves are designated the self-potential (or S.P. curve) and the resistivity (or R. curve), and are considered to reflect composition ("porosity") of the formation and the nature of the contained fluids respectively. Literature on the exact nature of the electric log is not extensive, and some of the recent publications are not inclined to clear the issue. Guyod [13] has followed the view generally held, that the S.P. log is chiefly a measure of the secondary effects—electrofiltration and electro-osmosis—rather than an inherent formation property, but this is questioned by Dickey.[6] Nevertheless it would appear that as the S.P. log obtained in a dry hole is similar to that obtained in a hole filled with fluid, the S.P. curve is a measure of a lithological property, and the secondary effects of electro-filtration and electro-osmosis essentially modify the "kinks" on the curve.

It may be further deduced from Dickey's paper and a subsequent article by Mounce and Rust [22] that the S.P. curve is a measure of the electrical charge on the clay, and is related to the ionization of the base-saturated clay mineral. Before the significance of the S.P. curve can be satisfactorily elucidated much more must be known of the physico-chemical properties of the formation clays.

The general interpretation of the S.P. curve is based on the relative difference in potential between the clay and the sand, and is empirical—that is, the curve is a measure of the difference in potential between clay and some other material—but it is not necessary that the latter should always be sand, although it can be shown to be so in the average case by coring the formation. Experimental support is found in the fact that in the average case the sand gives a negative value compared with the clay, and indeed the introduction of a small amount of clay into a sand tends to subdue this relative difference considerably. Hence the basis of the interpretation of the S.P. curve is not entirely secure, and its eventual elucidation is evidently bound up with the formation composition, and particularly that of the clay fraction.

Similarly the nature of the R curve is not clearly defined, but is interpreted as a relative measure by comparison with a fixed standard such as a salt-water sand—that is, the resistivity of an oil sand is larger than that of a salt-water sand. This appears to be a fairly safe interpretation, but is again empirical, and even with a more accurate approach, such as that attempted by Guyod,[13] the number of non-resolvable factors renders the analysis qualitative in the extreme.

In particular, the R. curve cannot alone decide whether an oil-sand will be an economic producer or not. One of the more obvious questions is connected with the effect of the interstitial water. Water can occur in a formation in at least four fundamentally different states, as follows :

(*a*) Pore water;
(*b*) Adsorbed as a layer around the grains;
(*c*) Water of hydration, principally of the clay minerals;
(*d*) Water of constitution of the clay minerals.

Pore water may be termed free water, and is that produced from an aquifer and, in an oil-sand, is the water sometimes produced with the oil. It is directly related to the porosity.

Adsorbed water is that fluid which exists as a thin sheath, generally continuous, on the particles of the formation. The proportion of adsorbed water is much larger in a fine than a coarse sand, due to the increased surface area per unit volume in the case of the former.

Water of hydration is the water that the clay mineral contains when in equilibrium with its environment. It can be large in amount when the clay mineral belongs to the montmorillonite–beidellite group; it also varies with the base on the clay, and is largest for the sodium ion.

Water of constitution is the water which is released from a clay mineral at relatively high temperature ($>300°$ C.), and which may therefore be neglected, as such temperatures are never met with in the environment of an oil-sand.

In actual production, if all the water is present as *c* and *d* it will not flow from the sand; this is, of course, an extreme example, but differences in water content of a formation can be considerable without affecting its oil production. It appears unlikely that the R. curve can distinguish between all these states, and here again knowledge of the clay mineral and its environment would assist in evaluation of these different factors.

Reservoir Technology.

In recent years this branch of oilfield development has been almost exclusively the field of the physicist and engineer, and core-analysis data form the basis for studies of reservoir behaviour, estimates of reserves, and secondary recovery projects. In general, experiments dealing with reservoir technology aim at the determination of the porosity, permeability, and saturation of the reservoir rock.

It must be obvious that there are two fundamental factors at the basis of all these studies—namely, the composition of the reservoir rock and the composition of the fluids. The fluids have been studied in some detail, but the reservoir rock has not received attention except in a few isolated examples.[16, 17, 18]

It is necessary, therefore, to consider the part played by the clay fraction in studying the porosity, permeability, and saturation in relation to reservoir technology.

Porosity.

In order to predict the behaviour of reservoir fluids, a laboratory test must be able to reproduce the results found in practice, and the most obvious method is to design the laboratory test so as to duplicate as nearly as possible conditions in the field.

The standard methods of measuring the porosity, for example, commence with the core sample dried, a condition never found in practice. As a result, the clay fraction occupies the smallest possible space, whereas it occurs naturally water-wet, in equilibrium with the interstitial fluids, and therefore occupies a much greater volume of the pore space. The porosity figure generally obtained is one near the maximum, and the amount of variation of the true porosity from that measured will depend essentially on the nature and amount of clay material.

Permeability.

A similar criticism to that levelled at porosity determinations can be developed for the methods of permeability determination, and here the effect is probably even more marked and the results more misleading. As mentioned by Muskat,[23] the permeability of a core to water may be very different from that to air, and it must be realized that the use of dry air on a dry core sample will once more give a maximum value which may never be approached under reservoir conditions, and which is therefore hardly representative.

In addition to this fairly obvious criticism, which it must be admitted was clearly recognized by Muskat,[23] the use of water, either " fresh " or distilled, is liable to vitiate the results because the flushing of a sodium clay with fresh water results in a maximum dispersion and swelling and the reduction of the permeability to zero in some cases.* The phenomenon, emphasized by many investigators in measuring permeability, of the core gradually choking, or showing a slow decline in permeability with time, is perhaps due to the gradual hydration of the clay minerals, and perhaps also due to base exchange with a solution with which the rock is not in equilibrium. This must be a very important factor in determining the effectiveness of induced water drive, repressuring by returning fluid to the formation, and secondary recovery by water-flooding.

For example, Pfister and McCormick [24] observed that although 10 per cent. brine solution is more viscous than fresh water, the brine enters the sand more readily than water, and they attribute this effect to the " shrinking " of the clay between the sand-grains on contact with brine.

Hence it appears indisputable that to obtain a reliable figure for the permeability of a reservoir rock, which is to be any reflection of reservoir behaviour, some liquid must be used for measurement.

A profitable field of research is therefore indicated in testing the permeability of the reservoir rock to different solutions, and this should lead to some measure of permeability control. Solutions could no doubt be designed to increase the permeability of the formation adjacent to the well-bore by, for example, reducing the clay mineral to its smallest possible proportions. These investigations would also prove significant in induced water-drive by injecting through down-flank wells solutions which can pentrate the less permeable sections of the formation and release more oil after primary

* Since this paper was written the deductions regarding changes in permeability of sands to different fluids have been in part confirmed by experimental work with air, water and sodium chloride solution, using rocks from Californian oil reservoirs (N. Johnston and C. M. Beeson, " Permeability of Reservoir Sands," *Petrol. Tech.* (*A.I.M.M.E.*), *Tech. Publ.* 1871, May 1945).

recovery has reached its economic limit. Secondary recovery by liquid drive must encompass work along these lines if the project is to become a success.

Saturation.

The oil content depends on the pore space and on the relative proportion of the fluid in the gas, oil, and water phases, and it has already been suggested that water may exist in the reservoir in many different states in relation to the clay. For example, it has already been observed that the finer the sand, the higher the water-saturation can be without rendering the rock unsuitable as an economic oil-producer. Similarly, the more adsorptive the clay, the higher the water-saturation may be before interfering with the oil production. Hence it can be envisaged that in a clayey sand where the clay is a sodium-base-saturated montmorillonite type the water saturation of, say, 30 per cent. may be resolved into, bound water 10 per cent., adsorbed water on all the grains other than clay 10 per cent., and pore water 10 per cent. Hence a single figure for water-saturation which neglects the exact function of the water in the reservoir rock can again be very misleading. Inasmuch as the water-saturation figure in common use in core analysis is used to fix that of the oil and gas, such an inaccuracy can give an entirely false aspect to the estimation of oil reserves and oil productivity.

Once again, therefore, it appears fairly obvious that reservoir rock composition and, particularly, the nature and amount of clay, play a vital rôle in reservoir behaviour. Indeed, it must be emphasized that physicists clearly recognize this by stating that their laws of behaviour apply to an " ideal reservoir "—made up of non-reactive spherical bodies.

Conclusion.

This review has attempted to indicate the various contacts of clay with oil-development problems, and it must be emphasized that the treatment is necessarily brief, because each facet of the problem represents a considerable field in itself. It can readily be seen that there is hardly a step in the development of an oilfield which does not involve clay in one way or another, and there can be little doubt that some of the most urgent and difficult oilfield problems will not be solved without clay research.

It must also be emphasized that this discussion of clay is but part of a larger problem—the study of the entire composition of the reservoir rock, an aspect of oil development which has been neglected. It appears strange that studies of source rocks, general geology, palæontology, composition of the reservoir fluids, and behaviour of those fluids, should all have received their share of attention, but that the reservoir itself should be considered as an unimportant passive bystander—sometimes referred to as a " stock-tank "—in all this desire to get the most oil quickly and cheaply.

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THE DEVELOPMENT AND LUBRICATION OF THE AUTOMOTIVE HYPOID GEAR.

By F. F. Musgrave.*

Introduction.

Automotive gears of the hypoid type have been widely used in the United States for many years. It is the purpose of the following survey to outline some matters of interest in connection with their development and lubrication; each a difficult problem. This will be done roughly chronologically, beginning with the year 1925, and for convenience the material for presentation is subdivided under the following principal headings :

I. The mechanical origins of the first automotive hypoid gear;

II. The early use, in lubricants, of the first addition agents, which were ultimately found to be acceptable;

III. The advantages to be gained through the use of adequately lubricated hypoid gears;

IV. Early attempts to make a practical lubricant for the first commercial hypoid rear axles;

V. Growth of lubricant production facilities and spread of hypoid gear manufacture;

VI. Developments in laboratory testing of extreme-pressure lubricants;

VII. Diversification of satisfactory types of lubricants and classification and clarification of knowledge;

VIII. The present hypoid gear lubricant situation in the United States—that is, the period 1940–1945;

IX. The future outlook for gears and for lubricants for automotive rear axles.

I. The Mechanical Origins of the First Automotive Hypoid Gear.

Whereas bevel gears and later spiral-bevel gears had been used in automotive rear axles, and worm-gear action was also known to have been employed, it was not until 1925 that satisfactory gear-generating machines could be built which would produce gears of the hypoid type up to definitely improved standards of accuracy, strength, and quietness of operation.[9, 12] The essential differences between the conventional spiral-bevel gear in use up to that time and the hypoid type which has since almost completely superseded it have been well set out as follows : [10]

" A hypoid gear is a special form of spiral-bevel gear in which the pinion axis is offset from the axis of the ring gear. This offset introduces an additional longitudinal sliding action, lengthwise of the tooth surfaces. The resultant sliding velocity on a hypoid gear is therefore greater than the involute sliding velocity on a spiral-bevel gear.

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" If the same pinion-tooth spiral angle is retained on converting from a spiral-bevel to a hypoid design, the thickness of the ring gear teeth is increased in proportion to the amount of offset. This results in a stronger tooth structure; but, if the original spiral-bevel tooth thickness was sufficient to give the necessary factor of safety with respect to fatigue life, the diameter of the ring gear may be reduced."

Thus the hypoid form of gearing combination offers the natural advantages of the spiral-bevel gear and the worm-gear without partaking unduly of the fundamental drawbacks of either.[13]

II. The Early Use in Lubricants of the First Addition Agents which were Ultimately found to be Acceptable.

It will later appear that the need for special lubricants was not apparent when the first hypoid axles were put in service. Many years of concentrated development work were actually required, however, to develop a generally useful hypoid lubricant. It is therefore interesting that the chemicals first commercially used were originally added to the then known lubricants of 1859 and 1869 respectively. These two patents [1] refer in one case to " the addition of sulphur " and in the other to the use of a lead soap cooked into a lubricant to give it a higher specific gravity. Neither Brown with his sulphur patent nor Hendricks with his " Plumboleum " thought of the possibility of higher load-carrying capacity (with " sulphur-treated oils ") nor of lower friction characteristics (with lead soap-treated oils), but the first satisfactory hypoid lubricants were made by the use of lead soaps and chemically active sulphur. The use of these two materials in the proper form together in a petroleum oil produced a lubricant which combined an exceptionally high load-carrying capacity with a relatively low coefficient of friction.

III. The Advantages to be Gained through the Use of Adequately Lubricated Hypoid Gears.

Assuming the gear and its lubricant to be ready for operation in an economical and mechanically reproducible combination, what advantages, if any, would accrue to the equipment manufacturer and to the public? There are several outstanding characteristics of hypoid gears in operation which actually did (and do) benefit both maker and user, and these may be briefly described as follows : [9, 10, 13, 21]

1. Inherently, hypoid gears are much superior (to the spiral-bevel type) as to quietness and tooth-strength capacity;
2. Design trends toward quiet operation at higher road speeds, decreased weight in unsprung parts, and lower body designs without obnoxious tunnels for propellor shafts, were all assisted by the introduction of the hypoid gear;
3. Lower manufacturing costs were possible on hypoids due to lesser sensitivity to accuracy in mounting or adjustment and smaller size in proportion to load than either spiral-bevel or worm types.

There were thus a number of valid reasons why hypoid gears should be used. The problem of providing adequate lubrication for them was not recognized when the first gears were cut by the new process in 1925,[9] and it was actually not until twelve years later, in 1937, that satisfactory hypoid lubricants were produced on a broad commercial basis. The intervening years were occupied in recognizing the lubrication problem after scientific study and in providing generally workable solutions.

IV. Early Attempts to make a Practical Lubricant for the First Commercial Hypoid Rear Axles.

As noted above,[9] no attention was paid to lubrication in trying out the first hypoid gears in rear axles. It so happened that although these particular gears were small enough and heavily loaded enough to require a powerful type of what we now call an extreme-pressure lubricant, such a product was by a matter of chance used in the trial runs. It was a proprietary lubricant about which the maker would reveal no details, later discovered to rely upon the presence of a lead soap and sulphur in a chemically active form for its then excellent performance qualities.

This product had been developed many years earlier, and was well known in automotive and other gear-using circles as a useful material in preventing scoring or scuffing of over-loaded gear teeth of various types. Almost ten years prior to the first hypoid-gear manufacture by an economically feasible method, this lubricant had been successfully used by a car manufacturer who found one season's model on the road with too great a load on the spiral-bevel geared rear axle. Too much power could be suddenly delivered from the engine, which caused a high percentage of axle failures in service. The use of this " trick " lubricant solved the problem, but it was only used temporarily, and in the next model the rear axles of this particular car were re-designed.

Between the years 1925 and 1932 various individual makes of automobile adopted the hypoid rear axles, but they were then compelled to specify the use of either this mysterious proprietary lubricant or one other —which was somewhat less effective for the most severe hypoid operations —in order to have satisfactory field experience. It was known that gear lubricants made by either of these companies would work, but why they did so was unknown. There were thus no clues as to how to effect improvements. One automobile manufacturer during this period issued a " hypoid-gear lubricant " specification based on the information that a lead soap was known to be present in the two proprietary preparations. Products were submitted which met all the individual requirements of this specification, but they proved completely unsatisfactory in use as hypoid lubricants.

By 1930 a new factor entered the situation through design developments in spiral-bevel gears. These had been made quieter in operation from year to year, but design limits were being reached. As faster-shifting transmissions came into operation it was possible to score conventional spiral-bevel gears under extreme conditions of inertia load.[2] In a paper presented in 1931 before the American Petroleum Institute entitled " Extreme Pressure Lubricants," Mougey and Almen of the General Motors Research Laboratories surveyed the existing situation and offered (in part) the following information, which is indicative of the facts and theories as known and believed at that time :

1. In automobile gears the pressures between gear teeth reach values as high as 400,000 lb/sq. in., with rubbing velocities ranging from 0 to 300 ft per minute. These figures suggested that the limit of capacity of ordinary oils was being reached;
2. It was shown that sulphur was an active ingredient in successful lead-soap lubricants;
3. It was suggested that the superior load-carrying properties of "extreme-pressure" lubricants were due to the formation of a separating film not of oil, but of some material formed directly on the surface of the steel;
4. Future automotive gears would probably demand extreme-pressure lubricants, but it was pointed out that such lubricants would have to be universally available before car manufacturers could employ such gears. Thus the need for co-operative development work was urged as between the automotive and petroleum industries.

Before the same group in 1932, Dr. Bridgeman of the Bureau of Standards outlined "The Problem of Extreme Pressure Lubricants"[3] in a paper which showed that the broad picture was beginning to fill in with detail, though much of it was as yet not in perspective. In this work the design factors of gear material, dimensions, and tooth design were coupled for consideration with the speeds, loads, and temperatures in operation and adequate lubricants were defined in the following performance terms:

1. Load-carrying capacity;
2. Tendency to cause or prevent wear;
3. Corrosiveness;
4. Stability or performance.

In co-operation with a committee from the petroleum and automotive industries, gear and bearing manufacturers and operators' organizations, the investigation began with a study of load-carrying capacity.

Nine commercial lubricants of various compositions were tested in four different lubricant-testing machines. Early results showed that broadly valid conclusions could not easily be reached, due to the large number of testing variables involved and "by the lack of basic information on lubrication in the extreme thin-film region and on the mechanism of the action of the newer type of chemical lubricants."[3]

Also in 1932 Wolf and Mougey of General Motors showed[4] that advances in gear design were urgently awaiting the development of satisfactory extreme-pressure lubricants. The paper also offered evidence of a laboratory-with-service correlation of the then commercially available lubricants which were listed under the following three general types:

(*a*) Sulphur–chloride treated saponifiable oil base with petroleum oil or sulphur–chloride treated petroleum oil;

(*b*) Sulphur-treated saponifiable oil base with mineral oil or sulphur-treated petroleum oil;

(*c*) Lubricants containing lead soap and sulphur.

In commenting it was pointed out that sulphur and chlorine were the most effective chemical additives then known, and that lead soaps were insoluble in most petroleum oils, tending to precipitate in storage or service or form a lead-sulphide sludge.

A commentary on the service qualities of extreme-pressure lubricants of this time is provided by one car manufacturer's announcement to its dealers in 1934,[6] suggesting that, since all its new cars and trucks would contain "extreme-pressure gear oils" in both rear axles and transmissions, these should be examined every 1000 miles, and that the gear oil must be discarded after 5000 miles of operation. This manufacturer was using spiral-bevel and not hypoid gearing in his rear-axle assembly.

The most popular type of extreme-pressure lubricant depended on a lead soap-sulphur combination in 1934 [7] for hypoid gear service, and in this year a formal distinction was drawn between various commercially available materials as follows: [8]

1. "Powerful extreme-pressure lubricants capable of lubricating hypoid gears when operated under very severe conditions of load and speed;
2. "Mild extreme-pressure lubricants, not capable of lubricating hypoid gears under these severe conditions, but capable of lubricating gears, such as spiral-bevel, etc., when they are operated under certain load and speed conditions that would cause scuffing if ordinary mineral oils were used."

This distinction was retained, and gradually became accepted as knowledge governing lubricant performance increased and as available and newly developed materials fitted in with experience already gained. By 1936 it was stated that [10] "the lead-soap active sulphur lubricant" (its shortcomings being fully recognized) "is the only type of powerful extreme pressure lubricant now available to the automotive industry." The petroleum industry was simultaneously urged to distribute as widely as possible an extreme-pressure lubricant suitable for the most severe service conditions, rather than to attempt to rely on the general use of "mild" extreme-pressure lubricants except for specifically designated and restricted types of operating conditions.

V. Growth of Lubricant Production Facilities and Spread of Hypoid Gear Manufacture.

In the period from 1931 to 1937 inclusive it became very evident that:

(*a*) hypoid rear axles were going to be used on an increasingly wide scale, and that;

(*b*) suitable lubricants would be found as a result of energetic and continuous co-operative effort.

Relying largely on the provision of an adequate supply of the lead soap-sulphur type of lubricant, more car manufacturers gradually changed over to hypoid gears, until a total of thirteen makes included them in their 1937 models. The article [11] in which this fact was announced made much of the confusion of the times in the minds of the petroleum refiners. The problems of generally distributing special hypoid lubricant and of providing special dispensing equipment with which to service cars at filling stations were emphasized with many misgivings. There were those who felt that the whole trend was a flurry, and that the near future would see a compromise solution in which a considerable number of lubricant formulæ would be completely serviceable in all cars at some low to intermediate level of extreme-pressure requirements.

The automotive industry knew what it wanted—viz., hypoid gears for quietness, economy, and dependability. The petroleum industry was not at this time sure how to satisfy the lubricant requirements of hypoids, but it did know that in addition to its usual gear oils some more expensive product would have to be supplied. Such a step was found to complicate tremendously both distributing and dispensing problems.

The tide had definitely set in, however, by 1937, and the inclusion of some of the lowest-price popular makes among the cars equipped with hypoid gears ensured that the wide distribution of suitable lubricants for them would have to be provided.

A report in the spring of 1937 to the Society of Automotive Engineers [14] showed that the Chevrolet Motor Company had tested and approved a total of 182 hypoid lubricants. This very large number was accounted for by the very general practice of several companies each supplying one lubricant to distributors who sold under their own brand names. Of the approved lubricants, about 90 per cent. contained lead soap in combination with chemically active sulphur. Of those which failed to gain approval the general formulæ were divided among the following types :

1. Mild type, lead soap-sulphur saponifiable–chlorine lubricants;
2. Lead soap lubricants with no sulphur and lead soap–sulphur saponifiable lubricants with very small amounts of active sulphur;
3. Sulphur–saponifiable lubricants;
4. Chlorinated lubricants;
5. Chlorine–sulphur lubricants;
6. Insoluble zinc oxide and soluble lead lubricant;
7. Plain mineral oil was submitted in one case.

Thus out of all the chemical types initially developed only one met with any substantial success as an extreme-pressure lubricant suitable for hypoid rear axles under tests as supervised by a car manufacturer. While the next few years produced a marked change in this situation, some of the testing procedures will first be examined by which the earlier hypoid or extreme-pressure lubricants were evaluated both mechanically and chemically on a laboratory scale.

VI. Developments in Testing of Extreme Pressure Lubricants.

In the search for suitable means of evaluating potential extreme-pressure lubricants both mechanical and chemical tests of great variety were employed. Invividually no one test procedure could yield more than a portion of the total information required. The mechanical tests used either special types of so-called " film-strength " or load-carrying machines on which large numbers of samples could be run rather quickly, or some actual dynamometer arrangement of gear-sets for laboratory running under specified conditions [4] or, most useful of all, road-test procedures such as were developed at the General Motors Proving Ground.[14] A list of references to five of the better-known laboratory testing machines is given in the paper on " Extreme Pressure Lubricants " already quoted.[4]

On the whole, these special laboratory devices helped very little in resolving the general problem. By their variety and their general tendency to rate a given lubricant as good or poor, depending both on test conditions and on the particular machine used, they rather retarded progress. The Bureau of Standards so-called " S.A.E. Extreme-Pressure Machine," however, must be considered an exception. A number of these units were built and distributed to co-operating laboratories so that a number of investigators could at least run preliminary tests on a common basis. The general characteristics of this apparatus were described as follows : [5]

" Probably the major reason why these [laboratory] machines were not entirely satisfactory was due to the fact that the ratio of pressure to applied load changed during the test run as the result of increasing area of contact caused by wear. This change made the test results very sensitive to differences in operating conditions, in particular to the rate of application of load. Accordingly, it seemed desirable to develop a machine in which the ratio of pressure to applied load would remain constant throughout the entire test run. An experimental apparatus based on this principle was built at the Bureau of Standards, and consisted of two self-aligning rolls acting under load, and so mounted that each could be independently driven. With this arrangement it was possible to vary the absolute and relative speeds of the rolls over wide limits. Provision was also made for applying load at various constant rates."

The use of this machine continues to the present time in a good many laboratories, and present hypoid lubricant specifications retain test limits on this apparatus which acceptable products must meet.

The best-known dynamometer type of test was called the *Gleason Four-Square Test*, developed in 1925 by the Gleason Company, which produced the first commercially operable hypoid gear-generating machine tools.[4] Test conditions are described as follows :

" The machine " (containing two hypoid axles under test) " is first brought up to a speed equivalent to approximately 25 m.p.h. in the car, and then the load is applied gradually, building up to the equivalent of full motor torque through second gear in about 1½ minutes.

" The test is run with the load on the drive side of the gears until the temperature reaches 200° F, and on the coast side for 8 hours, holding the temperature of the oil in the axle to a maximum of 250° F by water-cooling."

Excellent correlation of this test with service conditions was reported after twelve years of experience. It was also noted that " many attempts have been made to correlate the findings of these tests with various simpler tests but, to date, the results have been disappointing."

The General Motors Proving Ground test procedure, however, has found greatest acceptance of all the operational type of tests. Its details were incorporated in a laboratory dynamometer arrangement,[16] and the essential characteristics of a test of this kind are still in the existing hypoid-gear lubricant specifications. It was first described in 1937, as a *Scoring-Test Procedure*,[14] although it is now more generally known simply as a " Shock

Test." It consisted essentially of running the axle at high speeds—*e.g.*, 70 m.p.h.—when "the clutch is disengaged and ignition turned off. The car is permitted to coast until speed registers 65 m.p.h., when the clutch is engaged as rapidly as possible with transmission in high gear—with ignition turned off. The car, with clutch engaged—ignition turned off—is permitted to coast down to 40 m.p.h." After a total of fifteen shock loadings obtained by repeating this procedure, ten additional shock cycles were run in intermediate gear with the clutch being engaged at 45 m.p.h.

A test procedure such as this emphasised the service requirements of passenger cars, but did not necessarily correlate well with truck-type service. In trucks the hypoid gears are subject to long-time, low-speed loads at high torque, and when hypoids were finally adopted it was found that the best-known hypoid lubricant for passenger cars was not also the best for truck service.

However, this was a later development, and before considering it further, mention will be made of the more important chemical tests on hypoid lubricants.

There was initially such greater concentration on the problem of increasing the load-carrying capacity of lubricants that some other important properties of the chemical-petroleum oil blends were perforce overlooked for the time being. Among these are :

1. Physical and chemical stability in storage and in service;
2. Fluidity at all operating temperatures;
3. Potential corrosion of axle parts;
4. Potential wear.

The facts were stated [4] in 1932 that lead soaps were insoluble in most petroleum oils, and that the *stability* of the sulphur or chlorine compounds present in hypoid lubricants was far more important than their bare percentages. It was also soon recognized [5] that heating the hypoid lubricants for various periods of time caused a falling off in load-carrying capacity. This change varied considerably with the different types of lubricant. Naturally such high temperature changes were the product of reactions of both the chemical addition agents and of the mineral oil itself. This made it more difficult to evaluate the contribution of each to the total effect.

As to the solubility of lead soaps and the storage stability of this type of hypoid lubricant, a paper [15] in 1937 showed what could be done to improve these factors by careful manufacturing control to ensure uniformly small particle size. There remained,[4] however, the tendency of lead soaps to combine with the chemically active sulphur at the elevated temperatures of service conditions, thus forming a lead sulphide which could separate as sludge, thus impairing the original load-carrying properties of the lubricant.

The earliest published specifications of car manufacturers established test procedures for laboratory control of the above factors by a heating test for continuing miscibility of the additive with the oil vehicle, and by a high-temperature oxidation test, after which the gear lubricant was checked for thickening (viscosity increase), for deposition of insoluble materials ("naphtha insolubles") and for load-carrying capacity on the S.A.E. machine. Similar tests are still in use in present-day specifications, which usually further control the thermal stability of the petroleum base oil to some degree by specifying that oil of a minimum viscosity index (usually 85 Dean and Davis) must be used.

This latter stipulation provides for less variation in the fluidity characteristics over the range of operating temperatures than if lower-viscosity index oils were to be used. For the sake of additional protection against possible channeling of a semi-solid into an ineffective lubricant at low temperatures, it was recommended [10] in 1936 that lubricants lower than customary in absolute viscosity be used both summer and winter. This trend became so well-established that it is now customary to use one viscosity grade only the year through in all parts of the United States, except in the colder northwest, where a lighter grade is used in the winter months only.

At the beginning there was a good deal of confusion as to what constituted " corrosion " and what types of hypoid lubricants would be potentially corrosive in service. There was a tendency to believe that if enough sulphur were present in a lubricant to blacken a copper strip after an hour at 212° F, then the product was " corrosive," and it required time plus a considerable amount of both laboratory testing and field experience to demonstrate that this was not necessarily the case.

The presence of moisture was found to accelerate corrosive tendencies when present, and some types of sulphur and chlorine-containing lubricants proved particularly sensitive in this regard.[4] It also appeared that lead soaps, when present, diminished the tendency of certain lubricants to cause corrosion in service.[14]

The presence of sulphur of a suitable degree of chemical activity was defined for practical purposes by calling for an unaffected copper surface when exposed to the lubricant for 1 hour at 212° F, but definite attack at 300° F. To supplement this a simple laboratory steel-strip corrosion test was finally proposed,[17] and adopted as a useful part of the current hypoid-lubricant specifications. This test consisted essentially in exposing a strip of steel to a solution of the lubricant containing water, the whole being maintained at 200° F for 24 hours. Loss in weight of the strip was measured at the end of the test.

The problem of wear, how it was or could be caused, how to measure it, and where to find it in service, appears at intervals throughout the literature. Suffice it to say that a great deal of smoke has by this time blown away without any definite fire having been discovered. The origins of wear, even on laboratory machines, was often uncertain, and wear has never constituted a service problem in the field with lubricants commercially used in hypoid gears. No accepted specification tests were ever established, and the problem has at present receded into the background.

To sum up the experience of the years of growth of laboratory testing, it is evident that early work showed a variety of private, limited investigations,[20] whose results, when pooled in a co-operative spirit, finally brought the right degrees of emphasis to bear upon the various operating variables. In general, the most fundamental tests came to be (and are) performed on replicas of service units operated under conditions which closely simulate some type (or types) of service. The chemical laboratory tests have always been subsidiary to performance testing, but they continue to have their place in seeing that the service properties of the hypoid lubricants are properly rounded out.

VII. Diversification of Satisfactory Types of Lubricants and Classification and Clarification of Knowledge.

By 1937 the hypoid gear and its lubricants had settled down on a moderately scientific and serviceably satisfactory basis as outlined above. The next stage in development occupied in the years until 1940, and during this time more satisfactory lubricants were produced, while the basis for their evaluation became more firmly grounded as correlation grew between specification testing in the laboratory and actual experience in the field. Two major events transpired during this period. One was the extension of the use of hypoid gears into truck service; the other was the development of Hypoid Lubricant Concentrates of the sulphur-chlorine type which could be blended in small percentages with petroleum oils to produce finished products of such general utility and excellence of field performance that they came to be known generally as " all-purpose " or " universal " gear lubricants.

The principal advantage of the hypoid gear in truck design was stated in 1939 as follows: [18]

" The controlling factor in the use of the hypoid gear in truck axles is the fact that for the same ring-gear diameter the tooth section is far stronger than the corresponding spiral-bevel-gear tooth section. From the gear engineer's viewpoint this increase in tooth strength makes it possible to design a smaller axle for a given power transmission, or to provide a substantial increase in factor of safety in axle life without increasing the overall axle size or weight."

Simultaneously this paper pointed out that the requirements of truck operation made different demands on the lubricant from those of passenger-car operation. The lead soap, active sulphur passenger-car hypoid lubricants tended to permit scoring and scuffing of gear-teeth when operated over long periods under high-torque, low-speed conditions found in truck service. It was felt that the balance between the anti-welding properties contributed by sulphur and the anti-friction properties contributed by lead soaps (or by certain chlorine compounds) as required for hypoid gears in passenger cars would necessarily be different for trucks. Thus the petroleum industry was faced with the possibility of having to market two different types of hypoid lubricants, with all the consequent complications and difficulties involved in such a step.

A demonstration of the performance characteristics required from a truck-hypoid lubricant was offered in a test procedure described in this same paper,[18] wherein a dynamometer test using a truck axle had to operate without gear-tooth scoring for half a million revolutions under a heavy load at a speed equivalent to a little over 5 m.p.h. on the road.

The extreme desirability of having one hypoid lubricant available to meet both passenger-car and truck requirements led to rapid and extensive testing of the new sulphur-chlorine type concentrates, which ultimately proved them as satisfactory for service conditions in both types of equipment. These newer concentrates (containing inhibitors in some cases) were not as susceptible to the development of corrosion as measured by laboratory tests as had been found with earlier products utilizing these two chemical elements. As laboratory and field experience grew, the fear of actual corrosion difficulties in the field diminished, and the use of hypoid-gear lubricants containing a sulphur-chlorine concentrate continued to expand.

The new sulphur–chlorine concentrates had additional advantages over the lead soap–sulphur type of lubricant. These was the comparative ease of blending a small percentage of material in base oil compared with having to process a complete batch of lubricant in a refinery to introduce both lead soap and sulphur. The storage and service stabilities were also superior, and these concentrate treated gear lubricants could not form metallic sludges. Finally, and most important, they gave better performance characteristics than other known lubricants over the complete range of hypoid rear-axle-operating conditions. In consequence, refiners in general tended to adopt them so as to be able to distribute economically a single extreme-pressure gear lubricant, and the trend was away from the hitherto most popular, lead soap-active sulphur lubricant.

It should be noted, however, that on the whole the equipment manufacturers did not follow this trend. For initial filling of units at the factory they had developed a very early preference for a proprietary product containing lead soap, sulphur–saponifiable, and chlorine. There was also a limited use of the lead soap–sulphur type of lubricant in passenger cars. Rather than switch over to the newer type of sulphur–chlorine concentrate treated gear lubricant, the manufacturers have continued to use the products of the types mentioned. The lead–soap, sulphur–saponifiable and chlorine-containing product had always given satisfactory service, during the initial few thousand miles of vehicle service, and although it was not outstanding in its performance on the " shock " type of test at high speeds. in passenger-car axles, it did make a good truck-type hypoid lubricant.

Still, a different type of extreme-pressure lubricant has had limited but satisfactory field experience, in which the active chemicals were phosphorus, sulphur, and a saponifiable oil.[19] Like the product used so largely for truck factory fill, this material could not be satisfactorily distributed as a concentrate to produce a hypoid lubricant with the addition of a few per cent to a base oil. All three of these materials were best used when made *in situ* in the body of the lubricant of which they were to form a part. The phosphorus, sulphur–saponifiable product, like the others, did not perform to best advantage on the " shock " test in passenger-car hypoid gears.and, similarly, it did show to best advantage in truck-type hypoid service.

Chronologically it is of interest to note the dates at which the various hypoid-gear lubricant specifications appeared. The first equipment manufacturer's specification issued in 1937, and called by chemical and physical tests for lubricants which would be satisfactory in General Motors passenger-cars equipped with hypoid gears. Then in 1939 this company set forth its different requirements for a truck-type hypoid rear-axle lubricant.

In 1940 the Federal Government, through its Bureau of Standards, issued a " proposed " specification numbered VV-L-761 which called for " Lubricant; Gear, Universal (Hypoid and other types)." This combined the test requirements for lubricants for both passenger-car and truck rear axles. Products acceptable under this specification were widely adopted for general commercial distribution. In time the war needs of the U.S. Armed Forces caused both the Army and the Navy to issue their own specifications for hypoid-gear lubricants, but in both cases these were initially patterned exactly after VV-L-761.

These specifications all used as criteria the equipment-type and the bench-type of laboratory evaluations which had been so laboriously evolved during the preceding years. The general requirements can be listed under the following heads :

Minimum viscosity index and fluidity requirements;

Load-carrying capacities on the S.A.E. machine before and after heating the lubricant;

Heating and oxidation stability tests;

Foaming tests;

High-speed passenger car gear " shock " test;

Low-speed, high-torque truck-type gear " endurance " test. (No specific chemical requirements were included.)

The outstanding fact about the issuance of the Federal specification was the recognition by all concerned of the feasibility of writing a performance type of specification which could be expected to produce only gear lubricants which would perform well in the field in the lubrication of hypoid gears of all types.

VIII. The Hypoid-Gear Lubricant Situation in the United States from 1940 to 1945.

Significantly enough, the large expectations were not disappointed. During the past five years hypoid-gear lubricants from a multitude of suppliers have performed amazingly well under the greatest possible variety of both civil and military service conditions. Actual axle failures have been practically unknown, in spite of the scores of millions of vehicles involved. By far the most widely used type both in the United States and abroad has been made by blending suitable petroleum oils with the newer sulphur-chlorine concentrates. In fact these have been used exclusively for all gear lubricants supplied to the American Armed Services at home or abroad and for all Lend/Lease shipments.

It is a tribute to the soundness of the background on which these specifications were based that during this five-year period no necessity was found for any but very minor changes. In one instance it was made permissible to include a small percentage of a rust buffer in the gear lubricant to provide additional protection in those instances where an excess of free moisture might accumulate in the gear-case. The rust buffer would then act as an inhibitor of staining, rust formation, and potential corrosion. In another case the detailed requirements of one of the heating tests were modified slightly, having the effect of permitting a somewhat wider range of petroleum oils to qualify as satisfactory for use in hypoid-gear lubricants.

IX. The Future Outlook for Hypoid Gears and their Lubricants.

It is axiomatic that scientific developments are continually progressing through refinements of old forms into the emergence of new ones. For the future it may be assumed at once that automotive engineers will continue to demand more and more from hypoid gears, and therefore from lubricants. As better gear lubricants are produced through research, the mechanical stresses of temperature and load to which they will be subjected will be increased in severity. Thus the "wheel" composed of lubricant research and engineering design will be continually unbalanced, with greater strength now in this part and now in that. But it will continue to roll forward.

At the present time the existing specifications are being studied by a broadly representative group with a view to a more general modification of the individual test requirements. It is probable that the recommendations of this group will result in a new specification in which the emphasis is more evenly placed on the somewhat diverse requirements of passenger-car and truck-hypoid-axle service. It may be that as one result there will be an even greater degree of unanimity of acceptance of the new standards than was the case with the old, and that, as another, new and better combinations of automotive hypoid gears and their lubricants will be speeded on their way from the future to the present.

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THE INSTITUTE OF PETROLEUM.

THIRTY-FIRST ANNUAL REPORT, 1944.

The Thirty-First Annual Report of the Council, covering the activities of the Institute during 1944, is presented for the information of members.

Membership.

Details of membership are set out below :—

	Total, 31st Dec., 1944.
Hon. Members	13
Fellows	435
Members	579
Associate Members	592
Students	155
Total	1774

The above figures have been carefully checked, and include members with whom contact has been lost temporarily, but whose names are retained on the roll of the Institute.

The practice of presenting the membership in a summarized form will be resumed in the next Report.

The Council has to record with deep regret the deaths during 1944 of the following members of the Institute :—

	Date elected.	Class of membership.
G. K. Beaumont	1939	Student
W. Bolton	1919	Member
P. D. Bruce	1939	Student
A. P. Catherall	1916	Fellow
J. A. Child	1914	Fellow
F. G. Clapp	1927	Fellow
L. Clement	1931	Fellow
F. J. Cox	1938	Assoc. Member
James Cuthill	1924	Fellow
C. Dalley	1919	Fellow
W. Gray	1939	Fellow
H. J. Halle	1924	Fellow
G. S. Hay	1921	Member
F. D. St. Hilaire	1939	Assoc. Member
E. R. Lederer	1928	Fellow
F. A. Marr	1924	Assoc. Member
T. S. Masterson	1915	Member
J. Rennie	1916	Fellow
*B. I. Richardson	1920	Assoc. Member
J. McConnell Sanders	1923	Fellow

* Killed in action in Malaya, 1941.

Honours.

His Majesty The King has conferred the following honours upon members of the Institute during 1944 :—

C.M.G.

Robert S. Mackilligin, O.B.E., M.C. (Fellow).

C.B.E.

Major Kenneth Gordon, M.C. (Fellow).
Arthur C. Hartley, O.B.E. (Fellow).

M.B.E. (*Military*).

Major W. H. Cadman (Fellow).

Meetings.

Twelve meetings were held in London during 1944, of which two were joint meetings with the Society of Chemical Industry (Road and Building Materials Group).

A list of papers presented is given below :—

Date, 1944.	Subject.	Authors.
27th Jan.	" Mechanical Testing of Extreme Pressure Lubricants."	H. L. West.
17th Feb.	Exhibition of Films : " Oil from the Earth." " Protection of Fruit."	
2nd Mar.	" Recent Developments in Connection with the Application of Soil Stabilization in Practice."	J. S. Jackson.
24th Mar.	" Standard Methods for Testing Petroleum and its Products."	Editorial Sub-Committee.
24th Apr.	" Geophysical Methods Applied to Oil Prospecting."	J. McG. Bruckshaw.
9th May.	" Mountains and Oil."	J. V. Harrison.
1st June.	" Military Aspects of Industrial Oil Storage."	B. Orchard Lisle.
14th June.	" Oil Prospects in Portugal."	A. Beeby Thompson.
11th Oct.	" The Oilfield of England."	G. M. Lees and C. A. P. Southwell.
3rd Nov.	" Industrial Research."	Sir Harold Hartley.
13th Dec.	" Exploration."	V. C. Illing.
14th Dec.	" Factors Influencing the Structural Stability of Sand Carpets."	P. Alexander and J. F. T. Blott.

A Reception to the Visiting Indian Scientists was given on the 28th November, 1944, when Professor J. N. Mukherjee, C.B.E., D.Sc., read a paper entitled : " Diagnostic Characteristics of Crude Oil : Fluorescence Analysis in Ultra-Violet Light."

Publications.

The monthly publication of the *Journal* continued throughout 1944, despite the handicaps of paper restriction and war-time difficulties.

Standardization.

No less than forty-five active Committees and Panels of the Standardization Committee, with a total membership of over one hundred and sixty, met frequently during the year. The Council desire to place on record their appreciation and thanks to the members of these Committees and Panels.

Awards.

A Student's Scholarship of £50 was awarded jointly to J. R. Lyon and D. J. Mockford of the Royal School of Mines, and a Scholarship of £50 was awarded to R. B. Shearn of the Birmingham University.

Finance.

The audited accounts for the year, with the Balance Sheet, the Receipts and Payments Account of the Benevolent Fund, and the list of contributors to this Fund, are set out on the attached pages. The financial position of the Institute continues to be satisfactory.

Members will notice that the Cadman Memorial Fund appears as a new account. This Fund comprises contributions received from those associated with the Anglo-Iranian Oil Co., Ltd., to commemorate the work of the late Lord Cadman relating to petroleum, and has been handed to the Institute as Trustee.

The Institute will arrange for a lecture to be delivered, so far as is practicable, every year, but in no case less than once in every three years. This lecture will be called the " Cadman Memorial Lecture." The income of the Fund will be used to provide a " Cadman Memorial Medal " and an honorarium for the lecturer.

Research.

The Hydrocarbon Research Group Fund consists of contributions from five companies and the Ministry of Aircraft Production who have sponsored a project, undertaken by the Research Committee, which is concerned with physical properties of hydrocarbons, with particular reference to spectroscopy.

Council and Officers.

Early in 1944 the Council and Institute suffered a grievous loss in the death of Mr. Christopher Dalley while serving as President of the Institute. Professor F. H. Garner, O.B.E., was elected by Council to succeed Mr. Dalley.

Messrs. Ashley Carter, G. H. Coxon, A. C. Hartley, V. C. Illing, J. S. Jackson, and J. A. Oriel were elected Vice-Presidents, and Messrs. E. A. Evans, H. Hyams, D. S. Paul, C. A. P. Southwell, A. Beeby Thompson, R. R. Tweed, and C. W. Wood were elected members of Council.

Acknowledgments.

The thanks of the Council are tendered to the British Chemical Plant Manufacturers' Association for the use of their Committee Room.

The Council records its appreciation of the services to the Institute of Messrs. Price Waterhouse & Co., Auditors, Messrs. Ashurst, Morris, Crisp & Co., Solicitors, and the Westminster Bank, Ltd.

The Council also wishes to record its appreciation of the Institute staff for the way in which they have carried out their duties under difficult war-time conditions.

Approved for Publication by the Council of the Institute.

F. H. Garner, President.

Arthur W. Eastlake } Joint Hon.
Ashley Carter } Secretaries.

F. H. Coe, Secretary.

12*th December*, 1945.

THE INSTITUTE OF PETROLEUM.

(A Company limited by Guarantee and not having a Share Capital.)

BALANCE SHEET AS AT 31st December, 1944.

	£ s. d.	£ s. d.	£ s. d.	1943 £
Capital of the Institute under By-Laws, Section 6, Paragraphs 14 and 15 :—				
Life Membership Fund—				
As at 31st December, 1943		899 4 0		899
Entrance and Transfer Fees—				
As at 31st December, 1943	3891 19 9			3768
Received during year—				
Entrance Fees	107 2 0			121
Transfer Fees	15 15 0			2
		4014 16 9		
Profit on Sale of Investments—				
As at 31st December, 1943		351 10 11		351
Donations—				
As at 31st December, 1943		326 5 0		326
			5591 16 8	
Research Fund :—				
Balance as per separate account			138 3 1	128
T. C. J. Burgess Prize Fund :—				
As at 31st December, 1943			5 0 0	5
Cadman Memorial Fund :—				
Balance as per separate account			2730 0 0	—
War Contingencies Reserve :—				
As at 31st December, 1943		1937 3 8		1764
Addition during year		48 14 0		173
			1985 17 8	
Members' Subscriptions Received in Advance			106 16 6	186
Journal Subscriptions Received in Advance			551 11 1	478
Sundry Creditors, General Account			1030 2 11	947
World Petroleum Congress			247 14 3	241
Revenue Account :—				
Balance as at 31st December, 1943		4117 1 8		3209
Add Surplus for year as per separate statement		893 8 4		908
			5010 10 0	4117
			£17,397 12 2	£13,510

F. H. Garner, President.
G. H. Coxon, Chairman, Finance Committee.

	£ s. d.	£ s. d.	1943 £
Investments :—			
On Account of Capital, at cost—			
£461 12 0 3% Conversion Stock, 1948/53	491 12 6		491
525 0 0 3% Savings Bonds, 1955/65	525 0 0		525
500 0 0 3% Defence Bonds	500 0 0		500
664 6 6 3% London County Consolidated Stock, 1920	481 10 6		481
806 8 3 3% Manchester Corporation Redeemable Consolidated Stock, 1958	845 17 7		845
867 8 6 2½% Bristol Corporation Redeemable Stock, 1955/65	845 17 7		845
150 0 0 5% Wandsworth and District Gas Co. Debenture Stock	154 8 6		154
400 0 0 3% Metropolitan Water Board "A" Stock, 1963	346 10 7		346
125 0 0 5% Great Western Railway Co. Consolidated Preference Stock	105 4 9		105
150 0 0 3% Luton Corporation Redeemable Stock, 1958.	151 6 7		151
150 0 0 3% Smethwick Corporation Redeemable Stock, 1956/58	151 4 9		151
600 0 0 3% Bristol Corporation Redeemable Stock, 1958/63	597 7 3		597
(Market Value at 31st December, 1944, £5427.)	5196 0 7		5196
Cash awaiting Investment on Deposit with Post Office Savings Bank	395 16 1		
		5591 16 8	272
On Account of Revenue, at cost—			
£790 8 3 3% Conversion Stock, 1948/53	842 8 0		842
500 0 0 3% Defence Bonds	500 0 0		500
475 0 0 3% Savings Bonds, 1955/65	475 0 0		475
2000 0 0 3% Savings Bonds, 1960/70	2000 0 0		—
		3817 8 0	
(Market Value at 31st December, 1944, £3808.)			
On Account of Research Fund, at cost—			
£336 5 10 3% Conversion Stock, 1948/53 (Market Value at 31st December, 1944, £347.)		357 14 8	357
On Account of Cadman Memorial Fund, at cost—			
£2730 0 0 3% Savings Bonds, 1965/75 (Market Value at 31st December, 1944, £2744.)		2730 0 0	
Office and Library Furniture (excluding Presentations) :—			
As at 31st December, 1943	31 7 6		31
Additions during year	158 11 5		—
	189 18 11		
Less Depreciation	18 19 11		
		170 19 0	
Library Books (excluding Presentations) :—			
As at 31st December, 1943		—	
Subscriptions in Arrear :—			
Not Valued		—	
Sundry Debtors, less Bad Debts written off		571 13 5	464
Cash at Bank on Current Account and in Hand		1162 10 1	2365
Cash on Deposit with Post Office Savings Bank :—			
General Account	2747 15 3		2764
World Petroleum Congress Account	247 14 3		241
		2995 9 6	
		£17,397 12 2	£13,510

AUDITORS' REPORT.

We report to the Members of The Institute of Petroleum that we have examined the above Balance Sheet with the books of the Institute and have obtained all the information and explanations we have required. We are of the opinion that such Balance Sheet is properly drawn up so as to exhibit a true and correct view of the state of the Institute's affairs as at 31st December, 1944, according to the best of our information and the explanations given to us, and as shown by the books of the Institute.

3, Frederick's Place,
Old Jewry, London, E.C. 2.
19*th October*, 1945.

Price, Waterhouse & Co.,
Chartered Accountants.
Auditors.

THE INSTITUTE OF PETROLEUM.

REVENUE ACCOUNT FOR THE YEAR ENDED 31ST DECEMBER, 1944.

	£ s. d.	£ s. d.	1943 £
To **Administration Expenses :—**			
Staff Salaries	2009 13 11		*1674*
Printing and Stationery	196 19 8		*233*
General Postages	213 4 1		*186*
Telephone, Cables, Telegrams, and Travelling Expenses	47 8 2		*26*
		2467 5 10	
,, **Establishment Charges :—**			
Rent, less amounts recovered	433 14 4		*198*
Cleaning, Lighting, and Lift Expenses	200 4 11		*56*
Depreciation of Office and Library Furniture	18 19 11		
		652 19 2	
,, **Publications :—**			
Journal Publication Expenses	2103 19 4		*1654*
Abstractors' Fees	263 13 0		*188*
Postage on Journals	170 14 6		*144*
Cost of other Publications including Standard Methods	623 19 8		*158*
Provision for Doubtful Debts	2 5 8		—
		3164 12 2	
,, **Meetings :—**			
Hire of Hall, Pre-prints, Reporting		232 7 7	*211*
,, **Professional Fees :—**			
Legal Expenses	9 1 6		*75*
Auditor's Fee	42 0 0		*42*
		51 1 6	
,, **Students' Scholarships and Prizes**		100 0 0	*40*
,, **Library Expenditure**		6 17 3	*35*
,, **Branches and Sections :—**			
Students Section (Birmingham)	10 0 0		*8*
Northern Branch	10 0 0		—
		20 0 0	
,, **Sundry Expenses**		126 9 7	*97*
,, **War Risks Insurance**		7 3 6	*13*
,, **Donation to R.A.F. Benevolent Fund**		105 0 0	—
,, **Removal Expenses**		66 3 5	*32*
,, **Balance, being Surplus for Year, carried to Balance Sheet**		893 8 4	*908*
		£7893 8 4	*£6025*

	£ s. d.	1943 £
By **Subscriptions for 1944 received**	3498 10 0	*3125*
,, **Special Subscription**	20 0 0	*20*
,, **Subscriptions in Arrear, received during year**	506 8 6	*326*
,, **Sale of Publications**	3547 16 1	*2262*
,, **Interest and Dividends (Gross)**	320 13 9	*291*
	£7893 8 4	*£6025*

CADMAN MEMORIAL FUND

Income and Expenditure Account for the period ended 31st December, 1944.

	£	s.	d.
To Balance as at 31st December, 1944 . . . . . . Represented by £2730 3% Savings Bonds 1965/75 registered in the name of the Institute of Petroleum as Trustee.	2730	0	0
	£2730	0	0

	£	s.	d.
By Contributions received from those associated with the Anglo-Iranian Oil Company, Ltd.	2730	0	0
	£2730	0	0

RESEARCH FUND

Income and Expenditure Account for the Year ended 31st December, 1944.

	£	s.	d.
To Balance as at 31st December, 1944	138	3	1
	£138	3	1

	£	s.	d.	£	s.	d.
By Balance as at 31st December, 1943	128	1	4			
,, Interest received during the year	10	1	9			
				138	3	1
				£138	3	1

HYDROCARBON RESEARCH GROUP

Income and Expenditure Account for the period ended 31st December, 1944.

	£	s.	d.
To Bank Charges		4	3
,, Balance as at 31st December, 1944 . . . . . . Represented by Cash at Westminster Bank Ltd.	4999	15	9
	£5000	0	0

	£	s.	d.
By Contributions received from Members of the Group . .	5000	0	0
	£5000	0	0

BENEVOLENT FUND.

Receipts and Payments Account for Year ended 31st December, 1944.

Receipts.	£ s. d.	£ s. d.	*1943* £
Balance on 1st January, 1944 . . .		1106 17 9	*986*
Receipts during 1944 :—			
Subscriptions and Donations	190 7 9		*101*
Interest and Tax recovered	24 0 0		*19*
		214 7 9	
		£1321 5 6	*£1106*

Payments.	£ s. d.	*1943*
Benevolent Fund :—		
Grants in Aid	—	
Balance on 31st December, 1944* . . .	1321 5 6	*1106*
	£1321 5 6	

* The Balance on 31st December, 1944, was held as follows :—

	£ s. d.	£
Cash at Bank on Current Account . . .	98 10 9	*152*
Cash with the Institute of Petroleum . . .	43 17 9	*75*
£650 0 0 3% Defence Bonds at cost † . .	650 0 0	*350*
£600 0 0 3% Local Loans at cost † . .	528 17 0	*528*
	£1321 5 6	*£1106*

† (Market Value at 31st December, 1944, £1217.)

We have examined the above Receipts and Payments Account with the books and vouchers of the Fund and find it to be in accordance therewith. We have verified the Investments and the Balances with Bankers and the Institute of Petroleum comprising the Balance on 31st December, 1944.

3, Frederick's Place,
London, E.C. 2.

Price, Waterhouse & Co.
19th October, 1945.

(*Signed*)
A. E. Dunstan,
Chairman, Benevolent Fund Committee.

LIST OF DONORS AND SUBSCRIBERS DURING 1944.

Adams, A. C.
Andrews, B. G.
Auld, S. J. M.
Baylis, A. N.
Bell, O. A.
Blackmore, H. A.
Blakiston, J. H.
Bolton, R. P.
Brailey, B. S.
Braun, C. F.
Brodie, N. M.
Brown, C. B.
Brown, R. G.
Cameron, I.
Catchpole, W.
Charlton, H. E.
Chrisman, A. E.
Clement, L.
Clifford, Guy
Connor, W. W.
Cox, A. W.
Crichton, R.
Dailey, C.
Dewhurst, T.
Dolton, R. H.
Downs, W. W.
Driscoll, E. P.
Duck, A. E.
Dunkley, G. W.
Dunstan, A. E.
Dyson, G. M.
Ellis, J.
Evans, A.
Evans, E. B.
Eves, H. B. Heath
Farrant, V. M.
Farthing, V. L.
Fay, E.
Ferembre, R. G. de
Fox, D. A.
Garner, F. H.
Gent, E. L.
Godfrey, R.
Grant, J.
Gray, W.
Griffiths, P. M.
Harris, R.
Haworth, A. J.
Heaton, W. B.
Henson, F. R. S.
Hersch, L. H. J.
Howard, G. P. E.
Hunter, F. E.
Hunting, E. A.
Ivey, Terence
Jameson, J. A.
Kenyon, H.
Kidd, T. G.
McCreath, T. T.
McCue, C. F.
Mackilligin, R. S.
Maclean, T. T.
Macniven, H.
Mardall, E. G. C.
Marshall, R. W.
Masters, J. S. S.
Mesurier, L. J. le
Mitchell, R. G.
Moon, C. A.
Nixon, I. G.
Odams, R. C.
Owen, R. M. S.
Perks, A. J.
Pink, E. P.
Porter, P. N. D.
Purves, A. R.
Redgrove, E. R.
Richards, G. A.
Robathan, T.
Roger, A.
Sams, C. E. R.
Scott, L. D.
Scott, T. R.
Smallwood, W.
Southwell, C. A. P.
Spielmann, P.
Tait, E. J. M.
Taitt, G. S.
Taylor, J. F. M.
Thomas, H. C. H.
Thornley, G. H.
Tullett, G. V.
Tweed, R. R.
Underwood, A. J. V.
Walsh, D. M.
Walter, G.
Watson, A.
Webb, J. F. N.
Wigney, W. J.
Wilshere, L. A.
Wilson, W. J.
Young, R. H.

Staff of Shell Central Laboratories :
Cantor, J.
Morten, D.
Parr, R. W.
Parrish, J.
Taylor, T. M.
Werrett, L. A.

Trinidad Branch (I.P.)
Bushe, L. A.
Darley, H. C. H.
Fletcher, H. D.
Goodwin, J. A.
Harris, H. A.
Knights, J. W.
Kugler, H. G.
Lavington, H. V.
Middleton, F.
Murray, A. J. Ruthven-
Richards, A. H.
Scott, G. H.
White, L. K.

Barrett, Tagant & Gotts, Ltd.
Council of British Manufacturers of Petroleum Equipment.

THE INSTITUTE OF PETROLEUM.

The adjourned Thirty-Second Annual General Meeting of the Institute of Petroleum was held at Manson House, Portland Place, London, W. 1, on Wednesday, 12th December, 1945.

The President (Prof. F. H. Garner) occupied the Chair.

The Secretary (Mr. F. H. Coe) read the notice convening the meeting, and the Auditors' Report on the Accounts and Balance Sheet.

Report and Accounts for the Year 1944.

The Thirty-First Annual Report of the Council, covering the year 1944, having been circulated, was presented.

Mr. G. H. Coxon (Chairman of the Finance Committee), presenting the Accounts for the year 1944, said: I think the principal matter in which you will be interested is the Revenue Account, which shows that our income for the year was about £8,000 and our expenditure was £7,000, which is allowing us to build up a fund with which to meet possible expenditure in the future. The surplus is carried forward, so that it can be drawn upon at any time by the Finance Committee, subject to the Council's approval.

The Hydrocarbon Research Fund is kept entirely separate from the Institute funds. The money that goes into it is subscribed by the Ministry of Aircraft Production and five companies, as mentioned in the Annual Report, and there is a Committee of the subscribing parties, under the Chairmanship of Mr. H. C. Tett, which directs the work and allocates the funds. The Institute carries no responsibility for the finances other than the moral one of seeing that the expenditure is under control.

I know there has been some criticism because other companies are not getting the results of the hydrocarbon research. But any company that wants results from that work must subscribe to it. In other words, it is a partnership of those who subscribe, and the Institute is directing the work along the proper channels.

If any member wishes to ask questions concerning the Accounts, I shall be pleased to try to answer them.

There being no discussion of the Report and Accounts, the President moved :—

> " That the Annual Report for 1944, together with the Accounts and Balance Sheet, as audited by the Institute's Auditors, showing the position of the Institute's affairs as at 31st December, 1944, be approved and accepted."

Mr. E. A. Evans seconded.

The resolution was carried.

Auditors.

On the motion of Mr. G. A. Richards, seconded by Mr. R. J. Ward, the meeting re-elected Messrs. Price, Waterhouse & Co. (Chartered Accountants) as Auditors to the Institute.

Other Business.

Mr. R. J. Ward : There are three matters on which I should like some guidance.

A little time ago I received a list of proposed Council members. Our Institute is composite; but I could not help noticing that most of the gentlemen named in that list were all of the same cult. I do not know whether there is a definite percentage of representatives from each section of the Institute, or whether the Council nominees could all be of one section. I do not know whether the matter has ever been mooted before. In view of the fact that the list has been sent round, of course, there is no doubt that it is all in order.

Secondly, are there any limits to the number of nominations for membership of the Institute which a member can make in the year or at any one time? I noticed that in the current issue of the *Journal* there was a large group of these nominations proposed and seconded by the same two gentlemen. I noticed that the nominees were all of the same group and came from the same part of the world.

Thirdly, I want to raise the question of facilities for members. Once or twice I have desired to use the Institute, but I have been very reluctant to do so because of the burden on the staff and the facilities available. I had every courtesy and assistance from the staff; but one does not wish to trespass on their time. It would appear to me, however, that we ordinary members—and I speak as a very old member—are not, as yet, able to enjoy those facilities which will enable us to take full advantage of that to which we might be entitled. I know you have had difficulties in obtaining accommodation, and I should like to know whether any progress has been, or will be, made to obtain something more appropriate. The Institute should be run for its members. At present we know that it does excellent technical and scientific work of all kinds; but I think that some effort should be made in the direction of ensuring for members the use of the Institute's library and other accommodation as and when they so desire.

The President : We in the Council are very keen indeed to ensure that all sections of the industry are represented on the Council, but nominations for new members of the Council come from the general body of the membership of the Institute. It is the responsibility of individual members of the Institute to propose and elect the most suitable members of Council.

Coming to the second point, concerning the election of members of the Institute, the proposer and seconder of a candidate can be any member of the Institute who can sign a number of application forms. That, however, does not apply so far as the Council is concerned; in respect of the nomination of members for the Council, a member can sign only one form.

Mr. Ward : I want to know whether members are limited in respect of the number of candidates they can propose or second for election during any one year.

The President : No, there is no restriction whatsoever. I do not know whether or not you are referring specifically to the students.

Mr. Ward : I am.

The President : Students often start their course at a particular time and, naturally, they are all proposed *en bloc* for election to studentship of the Institute. Perhaps that explains why you saw so many names in the last list. It is to the advantage of the Institute for young people to join as students, provided they are suitable candidates.

Mr. Ward : That is quite true. I have noticed that there have been groups of nominees from the universities, nominated by people who know them. But this is the first time I have noticed so many of one particular group.

The President : During the past year the Council has given a very great deal of consideration to the problem of what the Institute is doing for its members. In the October *Journal* of the Institute there is an advertisement for a Technical Secretary and a Publications Secretary. When they are appointed the Institute will be in a very much better position to deal with the queries to which you refer.

The problem of the physical facilities provided by the Institute for its members has also engaged the attention of the House Committee of the Council. We recognize that the present building is not ideal for our purposes. The lecture hall is very good, but we are limited in respect of accommodation for members and for the staff. Therefore, the question of acquiring other accommodation has been considered. But decisions cannot be taken on points of that kind without serious consideration from very many angles.

Mr. Ward : Thank you very much.

Mr. L. V. Stevens : Would it be possible to indicate to members of the Institute, at the time when we elect members to the Council, what is the background of each nominee ? I find it difficult when I receive a list of people of whom I know very little and, therefore, do not feel competent to vote. If we could have a brief outline of the experience of each nominee, indicating the section of the industry with which he is concerned and what he has been doing in the industry, we should be in a much better position to elect a really representative Council.

The Secretary : With regard to the forthcoming elections to Council the ballot paper will include a full biography of each individual.

In addition, the Council decided this afternoon that a complete list of the members of Council should be included, giving the present occupation or designation of each member of the Council and the company with which he is connected.

This concluded the business of the meeting.