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FROM THE P L KAPITZA ARCHIVE

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Production and use of liquid oxygen†

P L Kapitza

P L Kapitza often repeated that "the task of a scientist is not only to be right, but to be able to demonstrate his rightness and to spread his ideas". Petr Leonidovich never spared his efforts or time in the spreading of ideas. In April 1938 he wrote a long (about 20 pages!) letter to V M Molotov in which he described a new method he had developed for the production of oxygen from air on an industrial scale. This letter is an excellent popular science article intended for o n e *reader. However, this reader was the Head of Government! Five and a half years later, Kapitza, having become a senior member of the government himself as head of Glavkislorod (Main Administration of the Oxygen Industry), an agency of the Council of People's Commissars of the USSR, on 2 December 1945 sent a 'Memorandum on Glavkislorod' to I V Stalin, chairman of the Council. This Memorandum, very detailed and thorough, contained the following very characteristic sentences: "It seems to me that the main problem is insufficient propaganda of our new ideas (one cannot be always complaining) and it would be very good if, for example, I were able to present a paper to our leaders on the importance of oxygen, if they could see our oxygen factory, etc. Then perhaps they would not treat oxygen production in a formal bureaucratically official manner ..."*

This excerpt speaks of the oxygen factory located at the Institute of Physical Problems (Installation TK-200 or Object No. 1, as this factory was called in the resolution of the State Defence Committee dated 2 March 1942). The oxygen factory at the Institute, commissioned in April 1943, produced 200 kg of liquid oxygen per hour and provided three-quarters of Moscow's oxygen demand. In January 1945 in Balashikha near Moscow a government commission took over Object No. 2, which was an oxygen turbine installation TK-2000 producing 40 tonnes of liquid oxygen in 24 hours, representing about one-sixth of oxygen production throughout the whole country! All these years P L Kapitza continued to spread the word about his 'child', which was the new oxygen production method. He also searched for more and more applications of oxygen in the national economy. He drew into this task many scientists, engineers, government officials, ...

†Paper presented at a meeting of the Division of Physicomathematical Sciences of the USSR Academy of Sciences on 18 June 1945 during a session of the Academy of Sciences celebrating the 20th anniversary of the Academy's foundation. This paper was prepared for publication and provided with a foreword and comments by P E Rubinin

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This paper presented here is the last 'propagandist' speech of P L Kapitza before he fell out of favour. It was presented on 18 June 1945 at a meeting of the Division of Physicomathematical Sciences celebrating the 220th anniversary of the Academy of Sciences of the USSR. The paper has not been published before.

Comrades! I am in some difficulty in drawing your attention to the production of oxygen and its use in the liquid form. This is an engineering rather than scientific problem and it would seem appropriate to present this topic to our Technical Division of the Academy of Sciences. However, I formulated and solved this problem as a physicist, and always worked in close contact with the Physics Division of the Academy. Since a full account of this task would include not only physics and technology, but also economics, I decided to remain faithful to my Division and to present my paper among physicists. I sincerely hope that the technical and economic problems, which I shall have to touch upon, will not cause you any difficulty.

In particular, one should point out that this work, to which I devoted the last few years, is closely related to the tasks set before Soviet physics by the War and a whole range of defence problems. All of us physicists have worked in the last few years largely as engineers and technicians. I think that our science and our physics has not lost because of this; on the contrary, it seems to me that it has served us well, or at least I feel that I have profited.

In 1938 I presented at the Division of Physicomathematical Sciences of the Academy my paper on an expansion turbine for the manufacture of liquid air.‡ Then the task of production of liquid air facing us was solved by applying a low-pressure cycle and turbine mechanisms. That work I described in greater detail at the time. The current work on the production of liquid oxygen is a continuation of the earlier efforts. Therefore, allow me to recall briefly those elements of the previous work which will be important for the understanding of the results of the current enterprise.

Because of the limited time, I cannot stop to consider the very interesting question of the importance of oxygen in our industry, in the technology of a whole range of manufacturing processes, since much has been written and spoken about this subject recently. I shall only remind

‡This is evidently the paper read by P L Kapitza at an extended meeting of the Presidium of the Academy of Sciences of the USSR held on 25 December 1938. An abridged shorthand report of this paper was published in *Planovoe Khozyaistvo* (2) 73 (1939) and in *Tekhnika—Molodezhi* (3) 28 (1939).

you that the ability to produce pure oxygen in large amounts has enabled us to intensify the most important branches of our industry, such as ferrous and nonferrous metallurgy, chemical industry, and coal gasification. Production of large amounts of pure oxygen thus makes it possible to raise the productivity of the basic branches of our industry. Therefore, large-scale oxygen production is one of our most important goals.

Oxygen is one of the most common chemical elements: the Earth's crust consist up to 40% of oxygen. However, one can quite certainly say that oxygen is easiest to extract from air, where it is present in its free state.

The most promising among the methods of extraction of oxygen from air is that which can be carried out in a thermodynamically reversible manner. Until now the only method put into practice has been the separation of the components of air by fractionation. This process involves liquefaction of air. Liquid air is then treated in the same way as a mixture of water with alcohol. Liquid air consists of a mixture of oxygen and nitrogen, which boil at different temperatures separated by about 13 °C. Nitrogen is the more volatile component and when liquid air boils, nitrogen is the first to escape. The fractionation columns for liquid air are in principle similar to those used in the fractionation of alcohol: they release gaseous nitrogen and the residue is oxygen, usually of 99% purity.

We can thus see that liquid air is a necessary stage in the production of oxygen.

Subsequently, we can evaporate and recover liquid oxygen but this involves heating; the result is gaseous oxygen.

It can be demonstrated that theoretically this process can be carried out in a fully reversible manner and very efficiently. In such a reversible process the energy losses in the production of $1\,m^3$ of oxygen at normal pressure and temperature are slightly less than 0.1 kWh. Some of the processes proposed so far cannot ensure this high degree of reversibility and such a high efficiency, and it is unrealistic to expect that this will become possible in the near future. At any rate, actual experience has shown that this is the most appropriate and promising approach.

The idea of production of liquid oxygen from air by liquefaction and subsequent fractionation was put forward simultaneously by the English scientist Bailey and the German scientist von Linde. The latter began his experiments adopting the above approach and constructed the first fractionating installation in 1895 and on 25 May of the same year he demonstrated it at the Physicotechnical Society in Munich. Thus, two weeks ago we passed the fiftieth anniversary of this event, which was the start of tackling the task of obtaining oxygen from air by fractionation. In these fifty years there have been several stages in the development of this subject, which I shall briefly recount because they are important for the subsequent understanding of the task facing us.

Before von Linde, oxygen has been obtained chemically from Berthollet's salt and has had a very limited range of applications, but even now this method has not lost its importance. It is used in enhancement of the physiological process of breathing. A patient is given oxygen as a tonic to intensify his breathing and thus maintain his strength to fight whatever illness he is suffering from. However, this demand for oxygen is not very large.

The next stage in the technology of oxygen production is closely related to the use of this gas in the intensification of combustion. I mean here an oxyacetylene burner used in metal welding and cutting. A very large amount of oxygen is required in this application. Oxygen production by the Linde method, based on the rectification of air, has made it possible to manufacture oxygen in sufficiently large amounts to satisfy the needs of the welding industry.

The Linde method of production of oxygen from liquid air is based on high-pressure cycles.

Air is cooled mainly by the work done against the forces binding gas atoms as it expands from a high to normal pressure. A series of heat exchangers can be used to force the gas to cool itself and gradually reach the liquefaction temperature.

Further improvements in this cycle were made by Claude. Claude added an expansion engine, forcing the gas to carry out work adiabatically not at the expense of the internal forces (binding gas atoms) during its expansion, but by the use of a piston engine in which the gas can work against external forces. The engine, resembling a steam engine in which steam is replaced with compressed air, can work at the expense of expansion of air from some pressure to its normal value; air is cooled in the process. In theory, it should be possible to reach the liquefaction temperature of air by forcing it to cool in this reversible manner. However, practical difficulties are encountered in respect of lubrication. At low temperatures, and we are speaking here of temperatures below −180 °C, all the lubricants solidify. Attempts to find lubricants which would remain soft at these temperatures have been unsuccessful. Therefore, such an engine cannot cool air to a sufficiently low temperature and, if this can be done, then the efficiency is low.

Right at the beginning of the development of techniques for air separation the physicist Rayleigh proposed a turbine as an expansion engine for the cooling of air. The advantage of the turbine is that there is no problem of lubrication: if the bearings are placed outside the low-temperature zone and the rotor remains in the cold zone, air can be forced to work during expansion without any lubricants. More precisely, a lubricant is needed in the bearings which are kept at normal temperatures. The thermal conductivity of the axle is so high that it is quite feasible to insulate thermally the bearings from the rotor. However, attempts to construct refrigeration engines based on turbines, made after Rayleigh's work, have been unsuccessful and the main reason for this is as follows.

The use of a turbine should be approached from a completely different direction.

The application of turbines and turbine mechanisms in the production of oxygen has become acute only when the need has arisen for large amounts of oxygen, i.e. when the amounts which can be generated by piston engines, operating at high pressures, have proved to be negligible.

We have here a close analogy with what is happening in energy conversion, when a piston steam engine has proved to be of insufficient size to generate high power in a single unit. It has then been necessary to go over to turbines.

This transition to turbines has not been entirely due to the energy gains because today the highest efficiencies are found in diesel engines and not in steam turbines. The transition has been stimulated by a different circumstance, namely by the feasibility of obtaining a high power from a single unit, which is possible only if turbines are used. It

P L Kapitza and M I Moroz in the control room of the Balashikha Oxygen Factory. Winter 1944/45.

seems to me that some general law is applicable here and it guides the development of technology. We can follow its action whenever the need arises to intensify some process: this law requires that discontinuous motion should be replaced with continuous motion. For example, when man has wanted to move faster, he has not lengthened his legs (although attempts of this kind employing stilts have been made), but in the final analysis he has gone over to the wheel, to continuous rotational motion. When the need has arisen to manufacture paper in large quantities, it has become necessary to employ continuously rotating hollander machines. Rotary machines have arrived in printing and it has been necessary to drop the flat-bed machines with periodic interrupted action. Finally, as I have mentioned already, the piston steam engine has been replaced with the turbine, which is a continuously acting steam engine. Naturally, when the demand for large-scale production of oxygen has become acute, the solution to this problem has been found to lie in the replacement of a piston expansion refrigeration machine, known as a reciprocating expander, which has been under development for about 50 years, with a refrigeration turbine. This is not just our problem; even before my work, it has been faced also abroad. Several serious attempts have been made to construct an expansion turbine. These attempts have led to the well-known success: an expansion turbine, made by the Linde company, has an efficiency of about 60% (this is the value supplied by the company, but the machines have not been tested and it is possible that the efficiency is, as usual, overly optimistic).

I have been able to show that the low efficiency of these expansion turbines is due to an incorrect approach to their construction. Gas is used in them in the same way as the steam in a steam engine. A high-pressure gas expands, does its work on the rotor, and therefore it cools; gradually this turbine can cool the gas to the liquefaction temperature. However, an expanding gas, which does work and cools, cannot be regarded as operating under the same conditions as steam. The fact that the steam and air are gases does not mean that refrigeration turbines should be constructed in accordance with the same rules as steam turbines. The critical velocity, viscosity, and density of air at low temperatures are very different from the corresponding properties of steam. A refrigeration turbine should be constructed not at all like a steam turbine, but more like a water turbine. This was proposed by me and an expansion turbine was constructed by analogy with a water turbine. It proved to be highly efficient and capable of producing liquid air by the turbine principle, which applies also to machines used in preliminary compression of air. This is because a highly efficient expansion turbine can use compressed air at relatively low pressures (several atmospheres, instead of 200 atmospheres). This has made it possible not only to replace a piston expansion engine with a rotating expansion turbine, but to dispense with piston engines in the compression of air and to adopt turbine engines in the form of turbocompressors.

At the earlier meeting I demonstrated a tiny turbine, which — in spite of its small dimensions — could produce up to 30 litres of liquid air per hour in a small unit. This tiny turbine was rotating at 45 000 rpm. In fact, this tiny turbine has not been the solution of the main problem for which it has been constructed, although it has revealed a number of advantages of the turbine method in refrigeration. A refrigeration turbine can be justified only when gas manufacture with large installations is adopted. Then only this turbine can produce liquid air on a scale unattainable by the piston method. This had to be proved.

However, the problem is that liquid air in such large amounts is unnecessary and it is senseless to construct an engine for the production of several tonnes of liquid air per hour, because there is no use for this liquid. Therefore, initially it has been necessary to construct a tiny engine, study all the laws which such engines obey, and only then build large engines. We have been helped in this by the fact that liquid oxygen is required in large amounts. The problem of production of large quantities of oxygen had arisen particularly during the War when a sharp increase in the demand for oxygen for oxyacetylene burners had been experienced. The American data suggests that the amount of oxygen used in such burners increased in the USA fivefold during the War. This is understandable: cutting and welding of steel sheets is very important in the manufacture of tanks, sea-going vessels, and other major metal structures. Liquid oxygen has the advantage over gaseous oxygen that it is easily transported. A steel cylinder contains no more than $9\,m^3$ of gaseous oxygen, which weighs about 10 kg, whereas the steel cylinder itself weighs 80 kg. However, in a heat-insulated container filled with liquid oxygen, the weight of oxygen is several times greater than the weight of the container. Therefore, the amount of liquid oxygen which can be carried by one lorry, would require at least ten lorries with the same traction power to carry the same amount of gaseous oxygen. There are also major advantages when liquid oxygen is handled in large amounts: the loss by evaporation increases proportionally to the surface, which rises in accordance with the square law, and the amount of oxygen enclosed in a given container is proportional to its volume. An increase in this volume also increases the time it will take for all the oxygen to evaporate from a container with a given insulation thickness. As a result, a container with a capacity of 13 tonnes of liquid oxygen, with the usual 20-cm thick insulation made of mineral wool, can be used to store oxygen for one and a half months. During this time it can be transported over large distances. Before the War, the Germans began widely to use liquid oxygen because it eases the transport problems, and this is now done by the Americans. Large amounts of oxygen are transported by the Americans mainly in liquid form and the cost of oxygen supplied to the point of its use consists mainly of the cost of transport. This has raised the question of the construction of high-power oxygen installations.

Quite unexpectedly we have subsequently found that the use of liquid oxygen in war applications is of greater importance than we thought. True, this has been proved not by us, but in Germany. All present here undoubtedly know from the press that liquid oxygen is a component of the fuel of the V-2 rockets used to bombard England. These rocket missiles carry, according to the British press, 5 tonnes of liquid oxygen. This amount of the oxidant imparts a rocket velocity of $1700\,km\,h^{-1}$ and can drive it to an altitude of 80 km. Moreover, such a rocket carries a load, which in war is an explosive, of 1 tonne over a distance of 330 km.

The use of oxygen in rockets and generally in war is of some interest. However, it seems to me that the ability to send loads at this velocity over large distances would be of some interest in the future in peaceful civilised life. The simplest calculations, based on the data applicable to the V-2, show the limits of dimensions of such a rocket and its range.

Scaling readily shows that the use of liquid oxygen should make it possible to construct a rocket weighing several tonnes which can fly a distance of about 2000 km. It would therefore be quite feasible to send, for example, a large amount of mail and parcels from Europe to America and the time this would require would be 10 min ... . If we calculate the useful load of such a mail rocket, assuming that a letter weighs on average 25 g, and if 1 dollar is charged for sending such a letter, we can see that a very good income can be obtained by the use of such a rocket and nobody can say that you are doing something wrong, although it might be that the country receiving such mail might not feel very comfortable ... . In any case, it might not feel as safe as before receiving mail by this method.

I would like to say only that without liquid oxygen such rocket mail would naturally be impossible.

However, apart from applications of liquid oxygen such as those in rocket engines, much of it is required also in oxyacetylene burners. Therefore, during the War it was necessary to construct installations for the production of liquid oxygen on a large scale and this was done in our country under the difficult war conditions. This was done in a special factory with a powerful installation. I would like to say a few words about this factory because time does not permit me to give you a more detailed description.

The principle of this installation is the same as used earlier in the installation for the production of liquid oxygen. The two types of installation differ only a little. The latter facility for the production of liquid oxygen is however approximately 100 times larger than that I described to you earlier and the final product is not liquid air, but liquid oxygen. Moreover, some changes have been made to the fractionation process. The usual fractionating columns employed in large-scale operations would have had very large dimensions. This has been avoided by a decision to intensify the fractionation process. The problem has been tackled in the USA in the oil industry and the work of the Russian engineer Podbel'nyak is particularly notable. Using the same idea, of intensifying the contact between the gaseous and liquid media, we have adopted a somewhat different technical realisation. Our own solution of the problem of intensification of separation by introduction, into a column, of rotational motion of its components has immediately given us considerable advantages. A fractionating column, which would have been 7 m high, has been reduced to a height of 2 – 3 m. This is very important, because a reduction in the dimensions of the fractionation apparatus reduces also the surface area and, therefore, the heat losses.

In the large-scale installations for the production of liquid oxygen, like those used in the production of liquid air, we have used the principle of low-pressure regeneration. It is then possible to dispense with the troublesome chemical purification of air before liquefaction, so as to remove carbon dioxide and moisture, and the whole air liquefaction process becomes much simpler.

Unloading of liquid oxygen produced at the Balashikha Oxygen Factory. Spring 1945.

This installation was constructed a year and a half ago and then taken over by a government commission, which worked very thoroughly, and decided that the installation is fully operable. It is now supplying Moscow and the surrounding regions with oxygen.

In this way during the War we constructed this installation, commissioned it, and demonstrated that in the single facility we can produce liquid oxygen in amounts approximately 7 times greater than those achieved in a single facility by the earlier methods. The analogy with a steam turbine is still there: a steam turbine in a single facility can provide a larger power than a steam piston engine. The theoretical assumptions have now been demonstrated in practice by this installation. This has immediately provided us with greater opportunities. The results can be seen, for example, from the following comparison. If we take all the existing installations for the production of oxygen and calculate the average productivity, then such a high-power installation as ours can replace 40 installations of the earlier type. Each of the older installations requires 25 workers and the total is 1000 employees. One high-power installation, equivalent to 40 of the older ones, requires the same number of 25 workers ... . Therefore, almost 1000 workers become free. This may not be such a large number in absolute terms. However, it is necessary to train young people in technical colleges for four years, releasing them from work. This is not an easy task in peacetime and even more so in wartime. Therefore, from the point of view of the national economy as a whole such a saving in the workforce may not be that small.

Oxygen produced in our installation is of high purity, because (as I have already mentioned) there is no need for preliminary chemical drying and purification of air which is to be liquefied.

The engine in this installation has proved very reliable: all the main processes involve rotational motion and it has a much smaller number of rubbing parts, so that the wear is slight. One such engine has already been operating continuously for over 4000 hours.

This work was recognised and we as well as some of our workers have been given state prizes.† We are proud that we were able to help the Red Army with our oxygen in its great victories.

All that I have said applies to the problem of liquid oxygen. We are now facing the task of production of large amounts of gaseous oxygen. It would seem that gaseous oxygen can be produced by evaporating liquid oxygen. However, this would not be economic because all the cooling effect would be lost and it should be recovered. This can be done by a number of ways, but any one of the selected methods should be economic, i.e. it should be possible to carry out the whole process in a manner as close as possible to full reversibility. This is an interesting physical problem. In general, it must be said that in no branch of technology is there such a variety of different

† On 30 April 1945 P L Kapitza was awarded the title of the Hero of the Socialist Labour by the Presidium of the Supreme Soviet of the Soviet Union for ''Successful scientific development of a new turbine method for oxygen production and for the development of a high-power turbine oxygen installation for the manufacture of liquid oxygen''. On the same day the Institute of Physical Problems had been awarded the Red Labour Banner order and many workers at this Institute and at Glavkislorod were given orders and medals.

systems used as in refrigeration. This is mainly because it is very difficult to achieve adiabatic cooling. Such is a continuous process, but it has to be carried out in a discontinuous manner by separating the stages so as to approach the adiabatic process as close as possible. The division of any refrigeration process into stages means that a large number of combinations of these stages is possible. We are also dealing with the fractionation, which (like the adiabatic process) should be continuous, but we are forced to divide it into two stages in one column. An ideal cycle would be that which would perform these processes continuously. As physicists, we faced the problem how this is best done. We were able to approach this process theoretically and to show what is the best division of a cycle that corresponds to single-stage operation, what happens in a two-stage process, etc. A graphical method has been used in which the second law of thermodynamics can yield a single-valued solution of any technical problem in this field. This method makes it possible to reject immediately some schemes which are not the best. Our work is close to completion and we are preparing to construct an installation for the production of gaseous oxygen. The future will show how well we can solve this last part of the oxygen problem. We are facing a number of difficulties, but I hope that we shall be able to overcome them.

We now have to think of uses for the large amounts of oxygen which have become available. We have to introduce oxygen in industry and reorganise, on this basis, our metallurgy and other branches of economy. In a paper presented at the Technical Council of Glavkislorod, which is now published, Academician I P Bardin calculated that if we use indicators which we hope to achieve and which do not seem to me to be too optimistic, and consider the introduction of oxygen in metallurgy, then for the equipment which we now have and in the same number of foundries now in existence, we should be able to approximately double the amount of cast iron and steel which is produced and at the same time free 40% of the workers and thus reduce the number of people occupied in this branch of manufacturing industry.† Indicators in other branches of technology give a similar picture. These new processes can be developed and introduced only after much further work, by overcoming many difficulties and after some failures. Probably the most interesting aspect is that it is necessary to experiment on a scale which physicists find difficult to understand. The construction of an experimental factory at a cost of 130 millions of roubles is, for example, an essential stage in such undertakings in metallurgy. If during the War we have been able to achieve such results, then if we tackle the task energetically in peacetime, there is no doubt that we can be successful ... .

We have overcome a strong enemy on the battlefield. However, the war with nature continues and if we do not exert all our efforts in this war, we shall cease to grow as a country. However, if we take up this fight together, we shall be the greatest, richest, and happiest country and this undoubtedly we shall achieve ... .

†See Bardin I P "Reconstruction of the Kosogorsk Factory in connection with the application of oxygen-rich blast"; this paper was published by the Bureau on the Applications of Oxygen of the People's Commissariat for Ferrous Metallurgy of the Soviet Union and the Technical Council of Glavkislorod of the Council of People's Commissars of the Soviet Union (Moscow, 1945).