by torch bearers. The bell started from the station at four o'clock in the morning and reached the summit of the hill at six.

As soon as the bell reached the point at which it was to be unloaded (Fig. 2), that is to say, in front of the south facade of the church, a part of the fence that surrounded the scene of operations was removed and the unloading was proceeded with. This operation was very easily effected by means of screw jacks and wooden rollers. The bell was thus transferred from the truck to a sort of wooden chair situated at nearly the same level, and then this chair, through rollers and a gin, was made to ascend an inclined plane formed of strong wooden beams. It was thus carried to a platform to the left of the church, where had been constructed a framework belfry (Fig. 6) in which it will await the construction of the belfry that is to finally receive it. —Le Genie Civil.

PORTLAND CEMENT.*

By SPENCER B. NEWBERRY.

THE Association of German Portland Cement Manufacturers includes representatives of 78 factories, of which 63 are located in Germany, 8 in Austria, 3 in Sweden, 2 in Denmark, 1 in Russia, and 1 in the United States. The total production of the German factories amounts to 11,350,000 barrels per year. The eighteenth annual meeting took place in Berlin last February, and the complete proceedings of this meeting have lately appeared. A number of important papers were presented, and the most prominent German cement experts took part in discussions of interesting modern questions relating to the chemistry and testing of cement. A brief abstract of the proceedings will therefore probably prove of interest to American engineers.

After the transaction of miscellaneous business, Dr. Goslich, of Stettin, reported on a question which had been referred to him. It appears that the United States agent of a German factory publishes a circular giving the results of tests of a number of German Portland cements, these results purporting to have been taken from the records of the royal testing station at Charlottenburg. The agent's own factory stands, of course, at the head of the list, the others appearing greatly inferior. It was stated that some of the tests at the station are made from samples taken from large shipments in actual use in building, others from samples sent direct from the factories, and that in the latter case the officers of the testing station have no proof that the samples come actually from the source represented. These tests should not, therefore, be made the basis of comparisons between the products of various factories. A resolution was introduced to the effect that the sense of the meeting was opposed to the publication of comparative tests for advertising purposes, with the intention of making the products of competing factories appear inferior. After considerable discussion the resolution was laid on the table, the chairman (Dr. Delbrück) remarking that the publication by one manufacturer of attacks upon another is not calculated to increase the respect with which German cement manufacture is regarded in America. Any manufacturer is free to claim whatever he sees fit for his own product; the complaint made refers only to reflections upon the products of others. In the opinion of the chairman, the publication of the discussion will be a sufficient warning against bitterness and enmity in the business competition of the members of the association.

REPORT OF THE COMMITTEE ON UNIFORM TESTING APPARATUS.

The committee submitted a list of articles, with dimensions, necessary for testing cement according to the official requirements. Dr. Böhm's hammer apparatus, used for making briquettes and cubes for tensile and compression tests, was criticised and its defects pointed out. Owing to the more or less slanting blow which the hammer gives, it was suggested that it might be well to abandon the present trip hammer form and adopt the drop hammer apparatus now in use in Switzerland and Munich. A new form of briquette mould was also recommended, the outlines of which are formed of intersecting circles. It was claimed that this form is much more simple to make with mathematical exactness than the ordinary German form of mould, the curved outlines of which are rather complicated. Prof. Martens, of the Charlottenburg testing station, and Dr. Gary opposed the proposed changes on the ground that the hammer apparatus and present form of briquette mould are already in most extensive use by manufacturers and engineers, and the substitution of apparatus of new design would cause widespread inconvenience. In their opinion the efforts of mechanicians should be directed toward the correction of existing defects in the hammer apparatus and the production of moulds of uniform outline and accurate workmanship.

The committee reported favorably on the Amsler-Laffon press for compression tests, pointing out its great superiority over similar machines of other make, and stating it to be the press of the future. Dykerhoff stated that an Amsler press had been supplied for the experiments on the effect of sea water on cement, now in progress at the island of Sylt, and a similar one for the Dykerhoff factory at Amöneburg. Twelve cubes of cement and sand were prepared, of which six were tested at Sylt and six at Amöneburg. The results were 4105 kilogrammes per square centimeter in one case, and 4165 kilogrammes in the other; a close agreement.

Dr. Prüssing, of Hemmoor, showed a new and greatly simplified compression press designed by him, a drawing and full description of which appears in the official report of the meeting. According to Dr. Prüssing, the chief reason why compression tests of cement are so seldom made is the high cost of the apparatus necessary. The new press is, however, very simple in design, and can be sold at a price of 350 to 400 marks (\$87 to \$100). It is claimed to be sufficiently accurate for the needs of engineers and architects.

Dr. Prüssing also exhibited and described an apparatus for representing graphically the progress of the setting of cement. The apparatus was invented by Prof. Goodman, of Leeds, England. It consists of a

trough in which runs a wheel driven by clockwork. The trough is filled with the paste of cement and water, and the apparatus set in motion. As the cement sets, the wheel gradually rises, running along the surface of the mass when the setting is complete. The curve thus described is recorded by a pencil on a sheet of paper at the back of the apparatus. The best cements show a nearly horizontal line for some hours, then a quickly rising curve, reaching its maximum within an hour and a half after the setting begins. Certain inferior cements show a curve which begins within twenty minutes but is not complete within many hours. (A similar apparatus was constructed several years ago by Prof. E. A. Fuertes, of Cornell University, and is still in use in the cement testing laboratory at that institution.)

REPORT OF THE COMMITTEE ON REVISION OF THE OFFICIAL REQUIREMENTS FOR CEMENT TESTING.

The committee proposed that to the official definition of Portland cement, "a product obtained by burning an intimate mixture of lime and clayey materials to the point of sintering and grinding the resulting clinker to powder," should be added the following: "Cement which contains more than 5 per cent. of magnesia is not to be considered true Portland cement." (The question of the effect of magnesia was fully discussed on the following day, and will be referred to later.) The committee further proposed that all recommendations in regard to tensile strength tests of neat cement be omitted from the requirements, leaving the test with three parts of sand the only one officially recognized. This proposal was made in consequence of the very misleading results obtained by tests of neat cement, such tests being generally recognized by manufacturers to be of doubtful value.

It was further suggested that it might be well to make a change in the fineness of the normal sand used for testing. The present requirement is that this sand should pass a 20-mesh and be held by a 30-mesh sieve. It was stated that this sand gives lower results when used in testing cements than some ordinary building sands, owing to the complete absence of the finer particles. The public, therefore, sometimes draws erroneous conclusions from these tests, considering the resulting figures to represent absolute strength, while they should be considered as only relative. No definite action was taken on the recommendations of the committee.

REPORT OF THE COMMITTEE ON THE INFLUENCE OF MAGNESIA IN CEMENT.

The majority of the committee, Dr. Schott, Herr Meyer and Dr. Arendt, reported as follows:

"Our investigations, in part extending over a period of five years, have failed to show an injurious effect from magnesia in Portland cement, in the composition of which the magnesia replaces an equivalent amount of lime."

Dykerhoff, another member of the committee, could not agree with this view, his experiments having led him to a very different conclusion, a statement of which was given in a minority report, the substance of which is given below.

Dr. Meyer described at length the experiments which led the majority of the committee to the conclusion that magnesia is a harmless ingredient in Portland cement. According to Dr. Meyer, this is always the case if the relation between the proportions of lime and magnesia on the one hand and silica, alumina and iron oxide on the other remain normal. So long as the ratio of silica plus alumina plus iron oxide to lime plus magnesia does not exceed 2.2, the presence of magnesia up to 8 or 10 per cent. caused no harmful expansion or cracking in the cement, even after several years. Further, any considerable percentage of magnesia in the raw material makes it extremely fusible and very difficult to burn properly without melting to a glass. For this reason cements containing much magnesia are practically shut out from consideration, owing to the impossibility of their passing the standard requirements as to tensile strength. It was therefore recommended that the resolution of the committee be adopted, and that thus a number of manufacturers should be relieved from the unjust requirement that the amount of magnesia contained in Portland cement should not exceed 3½ per cent.

Herr R. Dykerhoff then gave an account of his own experiments on this question. In these experiments the proportion of lime was purposely kept low, the ratio $\text{SiO}_2 + \text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3 : \text{CaO}$ being 1.83.

Two series of mixtures were made; in the first, magnesia was added to the mixture in various proportions up to 21 per cent.; in the second, the same amounts of magnesia were substituted for equal amounts of lime. The charges were burned to complete sintering, and all over or under burned portions were rejected. The resulting cements were tested for tensile strength with 3 parts sand, and for expansion, at intervals up to five years. Complete tables, showing the results in detail, are given. These results may be briefly described as follows:

1st. Magnesia added. Tensile strengths at four weeks about equal up to 18 per cent. magnesia. All showed good increase in strength up to six months, after which time the cements with 17 and 21 per cent. magnesia showed decided falling off in strength.

After two years all cements with over 4 per cent. magnesia showed a decrease in strength. At the end of five years the cements with 1 to 4 per cent. magnesia showed good strength, while those with 5 to 11 per cent. were weaker, and those with 17 and 21 per cent. magnesia showed a strength of 0. One cement with 6 per cent., lightly burned and not sintered, showed no noticeable decrease in strength in five years. Tests of expansion showed that in cements with 1 to 3 per cent. magnesia the expansion was slight up to one year, then practically ceased. With 4 per cent. and over the expansion during the later periods steadily increased with increased proportions of magnesia. Actual cracking was shown by the cement with 8 per cent. magnesia at the end of five years. Cements higher in magnesia all showed cracking at earlier periods.

2d. Magnesia substituted for lime. Two mixtures were made, with 6 and 11 per cent. magnesia. Both showed decided falling off in strength after six months, and both showed cracking at five years and three years respectively. Another cement, containing

18 per cent. magnesia, was lightly burned and not sintered, and showed steadily increasing strength and freedom from cracking up to five years.

From these experiments, Dykerhoff concludes that the harmful effect of magnesia in Portland cement is due to the dense condition which it assumes at the sintering temperature, in consequence of which the magnesia becomes hydrated only very slowly, and during hydration shows marked expansion. In light burned cements, on the other hand, like the American natural rock cements, the magnesia is in a far less dense condition, and readily becomes hydrated without injurious expansion. This view was confirmed by the addition of strongly sintered magnesia, separately prepared, to a cement nearly free from magnesia. With 10 per cent. sintered magnesia the strength was 0, and cracking appeared after two years. With 20 per cent. the cement disintegrated in four weeks. Light burned magnesia (magnesia usta), added in the same proportions, produced no injurious effect. Dykerhoff summarizes his conclusions as follows:

"The presence of magnesia up to 3 per cent. in Portland cement produces no change in its properties. From 4 per cent. on, however, magnesia, if sintered, whether added or substituted for part of the lime, has an injurious effect, producing increased expansion and decreased strength after long periods. This injurious effect is the stronger the higher the percentage of magnesia. If the cement is not sintered, however, a high proportion of magnesia, even 18 per cent., may be harmless."

Dykerhoff referred to the alarming results which strongly magnesian cements had given in England, France and Germany, on which he reported fully at the 1889 meeting, and which led him to investigate the effect of magnesia. The chief danger to the consumer lies in the fact that the evil effects of magnesia show themselves only after long periods, and cannot be detected by the usual short time tests. In consequence of the wide disagreement in the results obtained and the views held by the different members of the committee, Dykerhoff recommended that a new committee be appointed, to carry on further experiments in connection with the Royal Testing Station. Considerable heated debate ensued, in the course of which the chairman read part of a letter from Dr. Erdmenger, in which the writer stated that he could not indorse the resolution of the majority to the effect that magnesia is entirely harmless. Such a complete overturning of the prevailing dread of magnesia would be likely to cause doubt and perplexity. It is evident that in many places the use of strongly magnesian materials has produced uncertainty in the manufacture, and that in spite of the fact that almost every factory could point to good and lasting results, the general tendency has been to avoid the use of materials containing a high proportion of magnesia. To make matters somewhat easier for manufacturers using magnesian material, he recommended that the allowable limit of magnesia be placed at 5 per cent. instead of 3½ per cent.

The resolution of the committee was voted down, and the whole question referred back for further investigation to the same committee, with the addition of Professor Martens, of the Royal Testing Station, and others.

REPORT OF THE COMMITTEE ON THE ACTION OF SEA WATER ON CEMENT.

Herr Dykerhoff gave an account of the experiments in progress at the island of Sylt. These experiments are carried on at the joint expense of the German government and the Cement Makers' Association. It has generally been supposed that the presence of high percentages of alumina and sulphate of lime in cements rendered them more liable to attack by salt water. Tests were made with cements containing 5, 7.7 and 8.8 per cent. of alumina, with and without the addition of 1 and 2 per cent. of ground gypsum.

These cements were tested with 4 parts sand, and also with the addition of ½ part of lime paste (slaked lime). Up to the present time all these mixtures show about the same result, from which it appears that within certain limits the presence of higher proportions of alumina and sulphate of lime has no appreciable effect on the hardening in sea water.

It was found, however, that briquettes of cement lime mortar were somewhat attacked by sea water after 1½ to 2 years. Caudlot, in France, has pointed out the same effect. Since, in marine construction, moreover, a high degree of resistance is necessary, the testing of cement lime mortar has been discontinued in the experiments at the island of Sylt. Herr Sympher, inspector of construction at the North Sea Canal, is carrying on a series of tests of the effect of sea water on cement sand mortar. Up to 13 weeks the tests in sea water are on the average 20 per cent. lower than in fresh water.

Herr Sympher, in a communication to the association, reports that, in spite of the high quality and reduced price of modern Portland cements, the cost of cement mortar and concrete still reaches so high a figure that in some cases efforts must be made to find some cheaper material. This was the case in building the great gates and basins of the canal. Substitutes for Portland cement are found in hydraulic lime and Pozzuolana cement. Hydraulic lime is, however, objectionable on account of its slowness in hardening. Pozzuolana cement and other similar materials not claiming the name of Portland cement often show qualities which are in no way inferior to those of true Portland. The materials are, however, very variable. One excellent Pozzuolana cement proved utterly unfitted for use in sea water; another, which showed at first very high tests, fell off astonishingly in strength after storage for a few months in a dry warehouse. On this account the use of such materials was discontinued, and economy secured by lessening the proportion of Portland cement and replacing part of the cement by slaked lime. With one part of cement to eight, ten, or even twelve parts sand, concretes were obtained which fulfilled all usual requirements. The masonry of the Baltic Sea gates is chiefly built with mortar consisting of one part cement, one-half part lime and four parts sand. Thorough mixing is essential in the production of good cement lime mortar. This was secured by the use of mixing pans with edge runners. Tests of the cement lime mortar 1 : ½ : 4, taken from

* Report of the annual meeting of the Association of German Portland Cement Manufacturers.

the mixing pan, showed at twenty-eight days a tensile strength of 368 lb. per square inch, while briquettes of the same cement with three parts sand, made in the laboratory with the hammer apparatus, showed only 312 lb. Mixing pans are, however, seldom available in practical work, and Herr Sympher suggests that the cement and slaked lime should be mixed at the factory to insure a perfect mixture. This plan was opposed by Dykerhoff, on the ground that the proportion of slaked lime required is not always the same, and that the expense of packages and freight would make the lime far more costly to the consumer than it would be if bought where it is to be used. Dykerhoff suggested that efforts be made to induce manufacturers of machinery to supply mixing pans of simple design and low cost, suitable even for work on a small scale, since by their use the results obtained from cement lime mortar can be immensely improved.

ON THE PROCESS OF HARDENING IN PORTLAND CEMENT.

Dr. Tomei presented the results of a series of experiments on the action of solutions of ammonium chloride and of caustic soda on cement after various periods of hardening. It was found that the amount of lime, silica, and alumina extracted by these solvents diminished greatly with increasing age of the briquettes, both in the case of neat cement and cement with three parts sand. Much more silica was extracted from the sand briquettes than from those of neat cement, indicating a marked chemical action of the cement on the sand. Thin sections of hardened cement, under the microscope, showed a dense fine-grained groundwork, intermingled with a transparent, glassy mass which showed no action on polarized light. This was considered to be colloidal, hydrated silica. With increasing age of the briquettes this material shows a more and more distinctly crystalline character. It thus appears that colloidal silica plays an important part in the ultimate hardening of cement.

Dr. Tomei, and also Dr. Kosman, gave an account of the measurement of the heat of setting of cement by means of a calorimeter. The thermometer used was graduated to $\frac{1}{10}$ of a degree. Twenty grains of cement were placed in a small metal box, water to the amount of 32 per cent. added, and the box closed and dropped into the apparatus. The standing of the thermometer was noted at intervals, and the experiment considered finished when no further rise of temperature took place. With commercial cements this point was reached in from one to nine hours. Well burned plaster of Paris was found to evolve 39 calories; quicklime, 277 calories. The following were some of the results obtained with cements:

Stettin cement, slow setting.....	9.33 cal.
“ “ “ quick setting from long storage.....	7.75 “
Stettin cement, slow setting from addition of $\frac{1}{2}$ per cent. gypsum.....	3.69 “

A number of other papers were presented, chiefly of such a character that no brief abstract of their contents can well be given. Among these may be mentioned that by M. Gary, on the use of cement sewer pipes, and by Dr. Goslich, on concrete and other uses of cement. Full reports on new forms of grinding apparatus were presented and discussed, in the course of which the American Griffin mill and the German horizontal ball mill were fully described. Dr. Schoch described a new form of continuous kiln, consisting entirely of cast iron rings, one resting upon another. In this kiln the radiation of heat keeps the walls cooled to such an extent as to protect them from injury, and also to prevent the adhesion of the hot clinker. Illustrations of the peculiar form of dumping grate employed are given in the report.

THE COMMERCIAL MANUFACTURE OF LIQUID AIR AND OXYGEN.

A PAPER which, but for its sobriety of promulgation and validity of reasoning, might fitly be termed sensational, was read by Herr M. Schröter before the general meeting of the Association of German Engineers, held recently at Aachen—or Aix, as some term it. The essential features of this communication are here transcribed.

The condensation of difficultly condensable or so-called permanent gases is beset by the impediment that pressure alone is incapable of bringing about the end desired. Liquefaction cannot be achieved unless the gas be below its critical temperature. For gases commonly condensed to the liquid state on a commercial scale, the critical temperature is fairly high, e. g., for carbonic acid it is about 30° C., i. e., 86° F. For the main constituents of air, however, the critical temperature is far below zero Centigrade, and the attainment of so low a temperature has proved a greater obstacle than the production of the high pressure which is simultaneously requisite. The plan usually adopted consists in liquefying one gas by pressure at a low temperature produced by the evaporation of another more readily condensable, and utilizing the liquid thus obtained for cooling a yet less easily condensable gas to a temperature below its critical point. Thus carbonic acid and ethylene are convenient intermediaries in progressing from the ordinary temperature to the critical temperature of liquid air (say -140° C. = -220° F.). It is evident that a series of coolings thus arranged constitutes a laborious method of procedure, and the cost of the product is too great to allow of the application of liquid air for any but scientific purposes. A step has now been taken which removes the preparation of this particular material from the laboratory to the factory, and makes it as much a matter for the thermal engineer as is the design and running of an ordinary freezing machine. A few preliminary considerations are requisite for a comprehension of the rationale of the device about to be described.

It is indicated by theory that a freezing machine working with an easily liquefiable gas, e. g., carbonic acid or ammonia, would give a better result if the expansion of the compressed and partly liquefied gas were to take place in a cylinder in which it could do work, instead of through a throttle valve through which it merely blows off, changing in so doing from the liquid to the gaseous condition. In practice, however, the gain which would thus accrue is too small to be of importance, because the amount of work that

could thus be taken out of a vapor much below its critical point is vastly smaller than that which is involved in its change of state. Again it is generally assumed that in the case of a cold air machine it is essential that the compressed air shall, in expanding, do work, for otherwise—there being no change of state as the gas is far above its critical point—the final temperature after expansion, when all parts of the system have attained equilibrium, will be equal to the initial temperature, and no cooling will be effected. This is not strictly correct, for it presupposes that air is a perfect gas in which no intermolecular work is possible. It is true that the amount by which air departs from the behavior that may be postulated for a perfect gas—an imaginary entity—is not great, but it is perceptible, and what is more, was measured by Joule and Thomson forty years ago. These experimenters found that dispensing wholly with a cylinder in which compressed air could do work, and using only

Fig. 3

an outlet in the manner practiced for freezing machines, using easily liquefiable gases, the air was definitely and permanently cooled. The formula connecting the cooling effect with the original temperature and initial and final pressure of the gas may be written:

$$\text{deg.} = \frac{p_2 - p_1}{4} \left(\frac{289}{T_1} \right)^2$$

p_2 is the higher and p_1 the lower pressure in atmospheres, and T_1 the absolute temperature of the compressed air just before it passes the point of expansion. When $p_2 - p_1 = 10$, and $T_1 = 0^\circ \text{C.}$, the cooling effect $S = 2.64^\circ \text{C.}$ This cooling effect is so inconsiderable that it appears at once that a cold air machine with merely a throttle valve, and without an expansion cylinder, would be a valueless contrivance. It is therefore the more remarkable that Linde, the inventor of the apparatus shown in Figs. 1 and 2, should have been able to utilize this small difference in such a way as to cause it to yield a cumulative effect great enough to permit the attainment of the critical temperature of air, and, as an immediate and necessary consequence, of temperatures still lower, e. g., $-200^\circ \text{C.} = -328^\circ \text{F.}$, by simply handling liquid air like any other volatile liquid.

A diagrammatic view of the apparatus is given in Figs. 1 and 2. P_1 is the inlet and P_2 the outlet pipe of a compressor. The compressed air is cooled to about $10^\circ \text{C.} = 58^\circ \text{F.}$ by an ordinary water jacket, marked "cooler" in the figure. The air then passes down the "reverse flow cooler" shown on the right hand side of Fig. 1. It will be seen that connection with the outer annular space of this cooler is entirely cut off by a diaphragm at each end. The air flows through the throttle valve and expands, doing work and becoming

ingly cooled. This cooled air in its turn passes the throttle valve, and is again cooled by its expansion, and serves to cool the next portion about to pass the throttle. The air flowing upward is, at the point where it enters the annular case, at the low temperature attained a moment before by passage through the throttle, and the air on the point of passing the throttle is at the temperature which the portion next before it has reached by its own passage through the throttle. A gradation of temperature from the lower to the upper end of the reverse flow cooler obtains in both inner and outer sections thereof, and at the upper end both streams of air are at substantially the same temperature, viz., that fixed by the water jacket through which the delivery pipe of the compressor passes. The return current of air passes at this temperature back to the compressor, and is there driven once more through the system, heat due to the stroke of the compressor being taken up by the water jacket, so that air at a temperature not higher than 10°C. is constantly delivered to the upper end of the inner tube of the reverse flow cooler. In practice this most essential portion of the apparatus (shown for simplicity as two straight concentric tubes, see Fig. 1) consists of two spiral tubes, one within the other, 100 m. long and 10 and 4 cm. in diameter respectively. The whole is of course elaborately lagged to prevent the absorption of heat from external sources. The cycle of operations, consisting of compression, expansion, and cooling, continues until the temperature of the air in the apparatus falls in the receiver to a point below the critical temperature of air. A portion of the air thereupon liquefies, and a fresh quantity is accordingly introduced into the system by a second compressor (not shown) which serves to feed the main or circulating compressor. The process continues as before, until a sufficiency of liquid air has collected in the receiver.

The curves shown in the diagram (Fig. 3) give a complete history of one of the earliest trials made at the Munich testing station of the Linde Freezing Machine Company. The initial temperature, t_1 , was in this case below 0°C. , cooling being effected by an ammonia freezing machine instead of water, which would be adopted for permanent work. In consequence of this slightly lower initial temperature, the temperature of the return stream of air, t_2 , is (see also Fig. 1) below 0°C. These two temperatures are substantially identical, as, indeed, they should be with proper transference of heat from one side to the other of the reverse flow cooler; t_2 (see also Fig. 1) is the temperature on the high pressure side of the throttle valve, and t_1 that on the expansion side of the same valve. The gradual separation of these curves is in conformity with Joule and Thomson's equation; t_c is the critical temperature which has to be passed before liquefaction can occur, whatever the pressure. The lower temperatures given in this diagram were measured by an electric resistance thermometer. In considering the comparatively slow rate of cooling as given by the abscissae, which are in hours, it must be remembered that not only the air, but also a portion of the apparatus had to be cooled to a low temperature. At the first trial about eight liters of liquid, slightly blue in color, were obtained.

It follows from Joule and Thomson's equation, and from the known relations of the adiabatic compression of gases, that the apparatus is best worked with as large a difference of pressure and with as low a ratio of pressures as possible. Thus, high absolute pressures should be used, e. g., 150 and 50 atmospheres for the two sides of the throttle valve, these values giving a difference of pressure of 100 atmospheres and a ratio of 1:3. Such pressures, though high, are already used in practice for torpedoes and hydrogen cylinders for inflating military balloons.

So much for the liquefaction of air on a commercial scale; it remains to consider the production of oxygen from the air thus liquefied. Analysis of the gas produced by the evaporation of the liquid product obtained in the manner already described showed that

Fig. 1.

Fig. 2.

slightly cool. Thus with a pressure of 75 atmospheres on the upper side of the valve, and one of 25 atmospheres on the lower, air at an initial temperature of 10°C. is cooled through -12.76°C. in accordance with Joule and Thomson's formulae (see above). The slightly cooled air flows by the side tube leading from the "receiver"—see Fig. 1—into the annular casing of the reverse flow cooler, its course being indicated by the direction of the arrows. In thus flowing it receives heat from the air streaming along the inner tube in the contrary direction and about to pass the throttle valve, which is correspond-

ingly cooled. This cooled air in its turn passes the throttle valve, and is again cooled by its expansion, and serves to cool the next portion about to pass the throttle. The air flowing upward is, at the point where it enters the annular case, at the low temperature attained a moment before by passage through the throttle, and the air on the point of passing the throttle is at the temperature which the portion next before it has reached by its own passage through the throttle. A gradation of temperature from the lower to the upper end of the reverse flow cooler obtains in both inner and outer sections thereof, and at the upper end both streams of air are at substantially the same temperature, viz., that fixed by the water jacket through which the delivery pipe of the compressor passes. The return current of air passes at this temperature back to the compressor, and is there driven once more through the system, heat due to the stroke of the compressor being taken up by the water jacket, so that air at a temperature not higher than 10°C. is constantly delivered to the upper end of the inner tube of the reverse flow cooler. In practice this most essential portion of the apparatus (shown for simplicity as two straight concentric tubes, see Fig. 1) consists of two spiral tubes, one within the other, 100 m. long and 10 and 4 cm. in diameter respectively. The whole is of course elaborately lagged to prevent the absorption of heat from external sources. The cycle of operations, consisting of compression, expansion, and cooling, continues until the temperature of the air in the apparatus falls in the receiver to a point below the critical temperature of air. A portion of the air thereupon liquefies, and a fresh quantity is accordingly introduced into the system by a second compressor (not shown) which serves to feed the main or circulating compressor. The process continues as before, until a sufficiency of liquid air has collected in the receiver.